Received: 6 November 2020 | Accepted: 28 January 2021 | Published: 19 March 2021
DOI:10.20870/oeno-one.2021.55.1.4531

Topoclimate and wine quality: results of research on the Gewürztraminer grape variety in South Tyrol, northern Italy

Carlo G. Ferretti

GIR - Geo Identity Research, Bolzano, Italy

*corresponding author: carlo.ferretti@geoproject.it

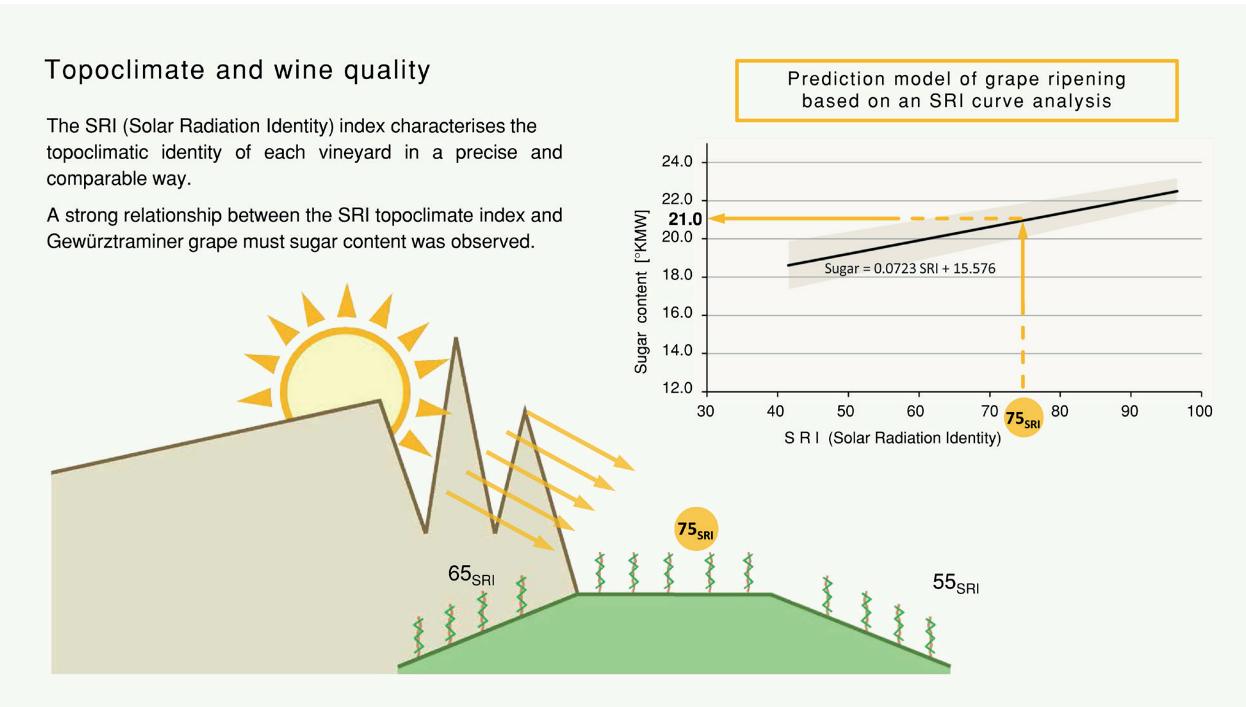
ABSTRACT

The aim of the study was to identify the ecological indicators that facilitate predictive analysis and to search for patterns in local geographical information to identify risks and opportunities in viticulture. The study focused on environmental factors that significantly affect the ripeness of the Gewürztraminer grape variety cultivated near Tramin, a village in northern Italy. In particular, the reliability of the new Solar Radiation Identity (SRI) topoclimate classification method was tested, along with its predictive capability in terms of the biosynthetic activity of the vine and the quality of its grapes. The SRI index characterises each vineyard in a precise and comparable way and helps to understand the way in which the topoclimate acts as an important abiotic stress factor for vines. A direct relationship between grape must sugar content and the SRI topoclimate index was observed. Our findings indicate an increase in sugar content of approximately 0.8 °KMW for every 10 points of the SRI index. Thus, a novel prediction model of grape ripening based on an SRI curve analysis is proposed. The correct application of the SRI index could be useful for discriminating and predicting geographical charactersitics of a given area strongly connected to ecological diversity and wine quality. It could support decision making in viticulture in terms of, for example, correctly matching vineyard and grape varieties, reducing wine vulnerability and production risk and predicting optimal ripeness and harvesting days. The use of the SRI prediction curve could help in adopting a more sustainable approach to agriculture and in finding new methods for adapting to climate change, such as by improving the match between the cultivars' phenological status, vineyard location and growing season average temperature.

KEYWORDS

Solar Radiation Identity (SRI) index, climate change, wine quality, terroir, topoclimate, temperature rise, ripening, harvest date, sugar content, ecological indicator, Alpine ecosystem, Gewürztraminer.

GRAPHICAL ABSTRACT



INTRODUCTION

The combination of many natural components such as geography, soil, climate and grape variety, together with local culture and winemakers, influences the quality of wines all over the world. The environment of a given place is thus causally linked to the grape ripening process and involves many factors which, in order to be interpreted, should be analysed together and differentiated in a comparable way. In particular, the geomorphology of the territory and microclimate are local geographical features that serve as natural ecological resources. A single ecological element does not necessarily determine the specificity of place for a particular grape variety; it is rather the combination of many geographical elements that creates distinctive conditions for vineyards and their wines (Jackson, 2014). These factors influence the biosynthetic activities of plants and their phenology, thus promoting biodiversity and the qualitative predispositions of grapes and wine. It is always necessary to observe and precisely classify all those environmental elements that can affect the vegetative, productive and qualitative expressions of a cultivar. This is a difficult challenge for vineyards set in geographically complex territories, like the Alto Adige DOC (Controlled Designation of Origin) wine region, in the middle of the Alpine mountains in northern Italy.

In South Tyrol, viticulture takes place within a complex geographical mosaic: within a distance of a few kilometres, it is possible to find high mountains or glaciers, deep valleys, sunny slopes, flatlands and hills covered with vineyards. The variety of Alpine landscapes and their geographical characteristics create extremely fertile conditions for biodiversity (Fischer *et al.,* 2008; Sitzia and Trentanovi, 2011), because the land suitability of plants and cultivars is governed in nature by the terroir and features of the environment (Ferretti, 2020a; Costantini and Bucelli, 2008). These characteristics act as abiotic stresses on the different varieties of vine and they define those environmental sub-zones which are more or less appropriate for different grape varieties, as well as stimulate the phenological attitude and biosynthetic processes of different vines of the same variety (Chamura, 2018). The different factors that influence the terroir and the responses and biosynthesis processes of the vines include growing environment (Texeira *et al.,* 2013), microclimate (Asproudi *et al.,* 2020; Reynolds *et al.,* 1986; Lee *et al.,* 2007), exposure to solar radiation and topoclimate (MacNeil, 2001; Cortell and Kennedy, 2006; Smart, 1987; Ferretti, 2020b; Tscholl *et al.,* 2019), daily rainfall amount and crop levels (Intrigliolo and Castel, 2008), ripening stage of the grapes (Sánchez Palomo *et al.,* 2007; Yue *et al.,* 2020), geology and soil (Ferretti, 2019a; Ferretti, 2019b; White *et al.,* 2007; Roullier-Gall *et al.,* 2014). Grape quality varies according to the daily temperature range during the ripening period, which affects sugar and anthocyanin composition (Weaver and McCune, 1960; Spayd *et al.,* 2002; Coombe, 1986). During grape ripening, cool night-time temperatures favour sugar accumulation and restrict vegetative growth (Falcão *et al.,* 2010; Palliotti *et al.,* 2014). The different soil temperatures also regulate the biochemical processes that are vital for the plant (Frey *et al.,* 2013). Microbial activity responds to an increase in soil temperature; for example, the more intense the microbial activity, the higher the rate of decomposition of organic matter and the exchange of nitrogen and mineral phosphates (Pietikäinen *et al.,* 2005). Rainy days during ripening can result in poor berry development and erratic ripening; the timing of ripening is also highly impacted by soil water content, because water has a high specific caloric capacity (Tesic *et al.,* 2002). Exposure to sunlight is important in terms of berry composition and metabolism and affects fruit ripening and grape quality (Smart *et al.,* 1988; Tarara *et al.,* 2008). Shortwave solar radiation is the primary source of fruit warming, while fruit size, albedo, wind direction and net long-wave radiation are less important (Smart and Sinclair, 1976).

It is clear that any abnormal event that causes stress in a plant and interferes with its delicate physiological process will not only have direct effects on crop productivity, but also on vine and grape quality. One of the most important - or at least the most taken into account - quality indicators is the must sugar content. The sugar composition of berries has a key role in wine quality, since it determines the alcohol content and the amount of residual sugar in the resulting wines. In South Tyrol, the sugar content at harvest defines the quality and economic value of the lot sold by the vine grower to the wine cellar. Depending on the picking day (either brought forward or delayed) chosen by the winery and its winemaker, the ratio between acidity and sugar in the harvested grapes can vary; this is a means of defining the style of a wine, which can be balanced, dry or sweet.

Sugar concentration is related to titratable acidity (Pedri, 2014) and alcohol content is quantified in wines after alcoholic fermentation (Jordão *et al.,* 2015). In order for yeast to ferment properly, the optimum amounts of saccharides and nitrogen and level of acidity must be obtained in the must (Ribéreau-Gayon *et al.,* 2006). Therefore, one of the basic parameters of particular interest for this research was sugar content, as it conditions the wine making process and affects the quality and overall taste of the wines (Cioch-Skoneczny *et al.,* 2020). Finally, it is important to remember that the concentration of sugar in must is also influenced by cryptogamic diseases and cultural management; for example, grapevine orientation, grape rootstock, defoliation, fertilisation and irrigation practices (van Leeuwen *et al.,* 2009) all have a variable effect on sugar accumulation in grape berries.

Pedri and Pertoll (2012) define the following factors and sub-factors typical of the place of origin that affect the characteristics of grapes and wines in South Tyrol: soil and soil geology (parent rocks, geopedology, physical and chemical properties), climate (macroclimate, microclimate and annual climatic variations), geographical situation and topoclimate (altitude, slope and orientation of the vineyard). The knowledge and detailed analysis of these ecological indicators make it possible to precisely catalogue each vineyard and to understand its impact on, for example, the grapevine's biosynthetic activity, the quality of the wine it produces and, not least, its resilience to climate change.

Climate change is exerting an increasingly profound influence on vine phenology and grape composition, ultimately affecting vinification, wine microbiology and chemistry and the sensory attributes of wine. Among the most important climate change-related effects are advanced harvest times and temperatures, increased grape sugar concentrations that lead to high wine alcohol levels, lower acidities and modification of varietal aroma compounds (De Orduña, 2010). As far back as 2005, Duchêne and Schneider (2005) showed that over the previous 30 years the estimated alcohol level of Riesling grapes in Alsace had increased by 2.5 % (v/v) due to warmer ripening periods and earlier phenology. Thus, in order to address climate change and its now visible influence on both viticulture and wine quality, an increasingly precise knowledge of the ecological stresses of a given geographical area needs to be rapidly acquired. Such knowledge will contribute to the search for new approaches to adaptive and more flexible crop management, which more precisely should be based on the equilibrium of the dynamic ecosystems and integrate new technological solutions. While it is not the only factor to be considered for adapting grapevines to climate change, phenology plays a major role in the distribution of current cultivars (García de Cortázar-Atauri *et al.,* 2017) even in South Tyrol (Ferretti, 2020b). Thus, different strategies must be researched strictly according to effective environmental scenarios and implemented to find ways of adapting vines to future conditions in the Alpine area.

Because the capacity to adapt to climate change will depend on being able to interpret ecological indicators in great detail and understanding the vine environment using a multidisciplinary approach, this research has measured the above-mentioned factors in the southern part of the South Tyrol wine region. The different ecological factors were analysed separately, in order to assess their actual impact on the degree of ripeness and, therefore, the phenological response of the Gewürztraminer grape variety, which is historically grown in the region.

MATERIALS AND METHODS

1. Geographical settings

The focus area of this research was the province of South Tyrol, a wine region in northern Italy (latitude 46° 30' N) within the central-eastern part of the vast and articulated geographical environment of the Alps, which extend for more than 1,000 km from France (longitude 5° 40' E) to Austria (longitude 16° 20' E). The Alpine morphology is based on strong vegetational and microclimatic contrasts related to the almost exclusively mountainous area, with marked differences in elevation between the valley bottom and the top of the mountains, ranging from 200 m to over 4,000 m above sea level (ASL). The valleys are flanked by steep slopes and cliffs, often marked by high rocky walls, with quite large alluvial bottoms, around which the majority of the vineyards grow. There are extensive plateaus above the main valleys in the mid-mountain area. Between the valley floors and the plateaus, smaller and discontinuous morphological terraces are arranged on several levels of the valley sides. Because of the very favourable climate here, especially in the foothills, vines have been grown for many centuries at altitudes of between about 200 m and 1,300 m ASL.

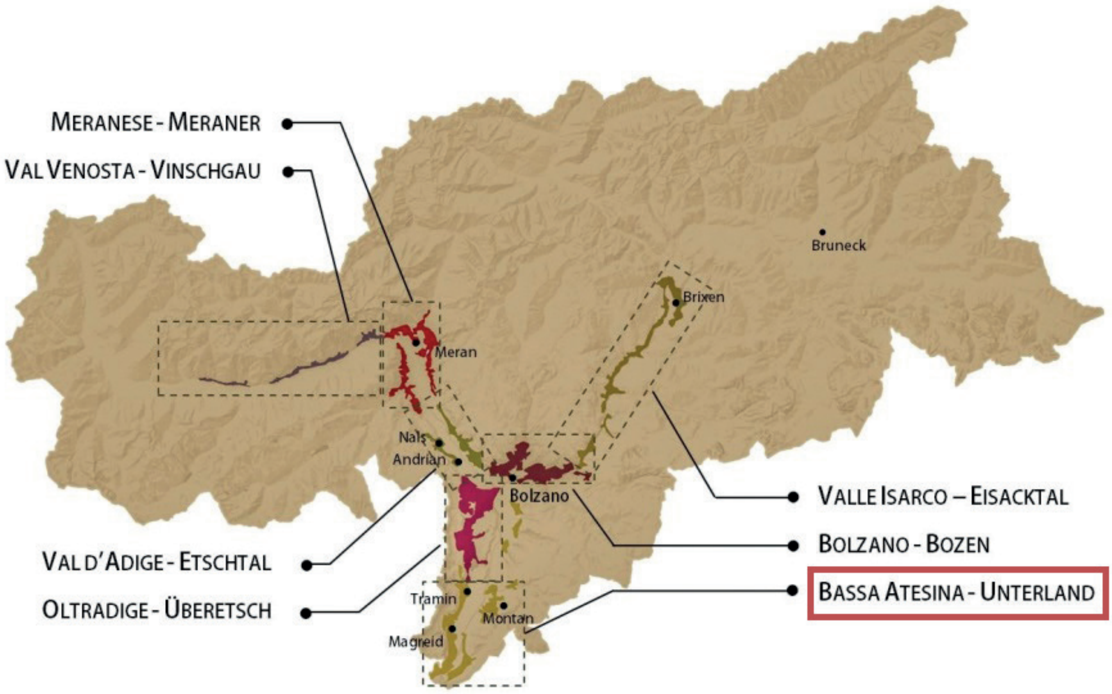


FIGURE 1. South Tyrol and geographic sub-regions.
Bassa Atesina - Unterland is located in the southernmost part of the region.

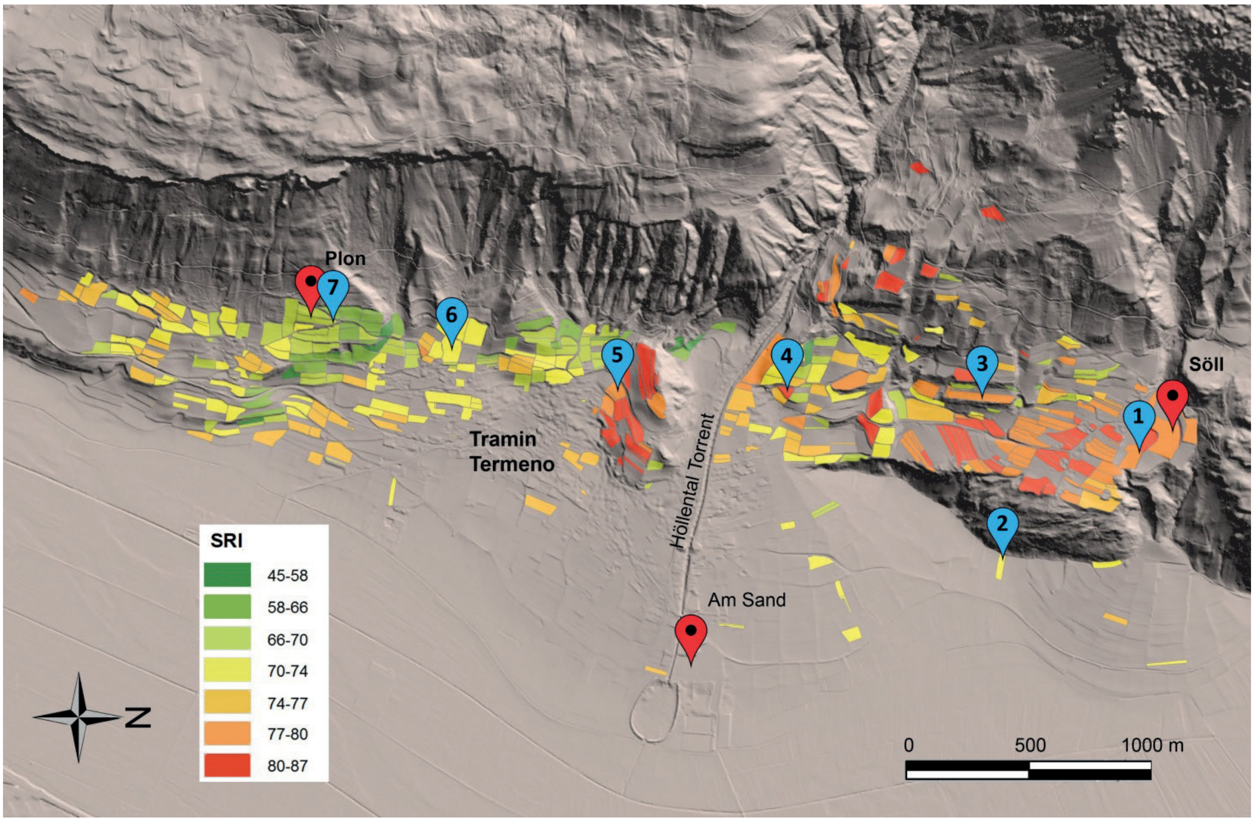


FIGURE 2. Location of all the Gewürztraminer vineyards at Tramin and their SRI index (see §6. Vineyard Solar Radiation Identity (SRI) index).
Blue markers show the seven vineyards studied using the VGI method. Red markers indicate the three environmental monitoring stations described in §4. Local climate.

TABLE 1. Simplified Vineyard Geopedological Identity (VGI) classification for seven vineyards within the study area near Tramin.

Vineyard	Texture class NRCS - USDA	Permability k (m/sec)*	pH	Parent rock (Prevalent)	Sedimentary process	Ground water	Soil mineralogy** (%)
1	loam	1.2E-01 ÷ 6.3E-01	8.1	Metamorphic and ancient sedimentary	Undifferentiated till deposit	no	Qz (34), Do (15), Ca (5), Phs (38)
2	silt loam	3.7E-02 ÷ 8.6E-02	8.4	Dolomite	Mixed fan: stream and debris flow	no	Do (51), Qz (22), Ca (7), Phs (14)
3	loam	1.0E-01 ÷ 2.5E-01	8.3	Metamorphic and ancient sedimentary	Glacial lodgment till deposit	no	Qz (35), Do (19), Ca (6), Phs (35)
4	sandy loam	2.5E-01 ÷ 4.0	8.4	Dolomite	Ancient mixed fan deposit	no	Do (50), Qz (22), Ca (5), Phs (17)
5	loam	1.4E-02 ÷ 1.2E-01	8.2	Dolomite	Ancient mixed fan deposit	no	Do (37), Qz (29), Ca (1), Phs (25)
6	loam	4.8E-02 ÷ 2.2	8.2	Dolomite and ancient sedimentary	Mixed fan: stream and debris flow	no	Do (43), Qz (22), Ca (11), Phs (18)
7	silt loam	5.7E-01 ÷ 6.6E-01	8.6	Ancient sedimentary	Gravity driven deposit	no	Qz (38), Do (16), Ca (16), Phs (24)

(*) according to Milan and Andjelko (1992).

(**) Prevalent minerals: Qz: quartz; Do: dolomite; Ca: calcite; Phs: phyllosilicates.

The studied wine territory fits into this varied geographical context and is located in the Bassa Atesina sub-region, south of Bolzano city, near the villages of Tramin, Magreid and Montan (Figure 1).

2. Geopedology

The geological history of the Alpine region has defined all the geographical elements that characterise the landscapes and thus the many natural ecological factors that control the phenological behaviour of the vines. During the formation of the region's mountains and deep valleys, erosion of the more friable rocks has made it easier to form morphological terraces, which are today cultivated with vineyards. Glaciers, rivers and landslides shaped these morphological terraces and thin layers of sediment were deposited both at the margin of the valley floor and along the steep valley sides. Here we find a wide range of Quaternary sediments, which were deposited side by side or on top of each other in the last few millennia: different glacial, debris flow, landslide, alluvial fans or alluvium sediments, as well as slope debris, colluvial deposits and eluvium often reworked by anthropogenic action. Thus, the properties of the soils have been influenced by the geological history of the area, which has shaped their physical structure, mineral composition and acidity. Dolomite, limestone and ancient sedimentary rocks mixed with porphyry and metamorphic deposits from the north of the region are present in the southernmost part of South Tyrol. Near the villages of Tramin, there are fine soils of fluvial-glacial origin from ancient sedimentary rocks, with a significant silty-clayey component coloured by iron oxides, like hematite. Calcium carbonate and dolomite minerals result in soils with a pH ranging from slightly alkaline to strong alkaline. For the restricted research area at Tramin (Figure 2), an analysis of seven vineyards with different geopedological conditions was carried out applying the Vineyard Geological Identity (VGI) method (Ferretti, 2019a). The VGI method entails the use data and information obtained from the research technologies of applied geology and the documentation of the physical, mineral and chemical characteristics of soil sediments in a comparable manner. This method is useful for discriminating and predicting the geographical components strongly connected to the ecological diversity of each vineyard.

Ferretti (2019a) and Table 1 list the geopedological classification components of the vineyard soil sediments at Tramin, which highlight their lack of homogeneity due to the complex and varied geological evolution of this portion of the Alpine territory.

3. Regional climate

The climatic conditions of South Tyrol are closely linked to its geographically distinct location within the Alps. The size of the area and the fact that it is completely surrounded by high peaks and mountain ranges mean that it has its own protected macroclimatic conditions. South Tyrol is among the driest areas of the Alps with an annual rainfall of 600 to 1,100 mm and an unusually sunny climate, with more than 300 days of sunshine a year (EURAC Research, 2018). An interesting fact about the local climatic conditions of consequence for viticulture is the variation in air temperature with elevation, with variations of 0.6 to 1.0 °C per 100 m in the summer season (Ferretti, 2020a).

Also of consequence for viticulture could be the future ecological impact of climate change (van Leeuwen and Darriet, 2016). Climate change has been apparent in the Italian Alps and in South Tyrol in recent decades with increases in air temperatures, especially minimum temperatures (Acquaotta *et al.,* 2014; Zebisch *et al.,* 2018). In the last 25 years, we have measured a regular and constant temperature increase of up to 4 °C during the budding season; this induces an earlier vegetative cycle and earlier ripening and causes the harvest to take place some three to five weeks earlier (Figure 3). Several regional climate models have predicted the overall effects of individual or combined climate change-related variables (Stock *et al.,* 2005; White *et al.,* 2006; Hall and Jones, 2009); these experimental data are in line with the forecasts of the temperature-based model of Lebon (2002). Even the quality analyses on red grape must, which have been carried out on test vineyards in the second week of September for the last thirty years, show a regular trend: sugar content has increased from about 15 to 20 °Babo and contemporary titratable acidity has decreased from about 14 to 7 g/l (Haas, 2019).

4. Local climate

Because a fundamental ecological factor is the specific temperature requirements of a given grapevine variety (Parker *et al.,* 2013), one of the aims of the research was to identify any influence of the microclimate on the ideal phenological ripening process of the grapes. The timing of phenology (budburst, flowering and *veraison*) and consequently the harvesting period, is driven mainly by vineyard environmental conditions, air temperature (Parker *et al.,* 2011), rainfall and soil water content (Tesic *et al.,* 2002), sunlight (Spayd *et al.,* 2002) and soil temperature (van Leeuwen *et al.,* 2018).

To cover the vast geographical area studied, the data from twelve different weather monitoring stations in the Bolzano Province in the southern part of South Tyrol were initially evaluated. However, these are located outside the vineyards and their data was therefore not found to be significant for a highly detailed study of an area in a mountainous environment.

To ensure maximum reliability in terms of microclimatic data, the more detailed part of the study focused on a single grape variety and a very restricted production area of about six square kilometres around Tramin; thus the microclimatic variables were reduced, while a statistically significant amount of vineyard data was kept.

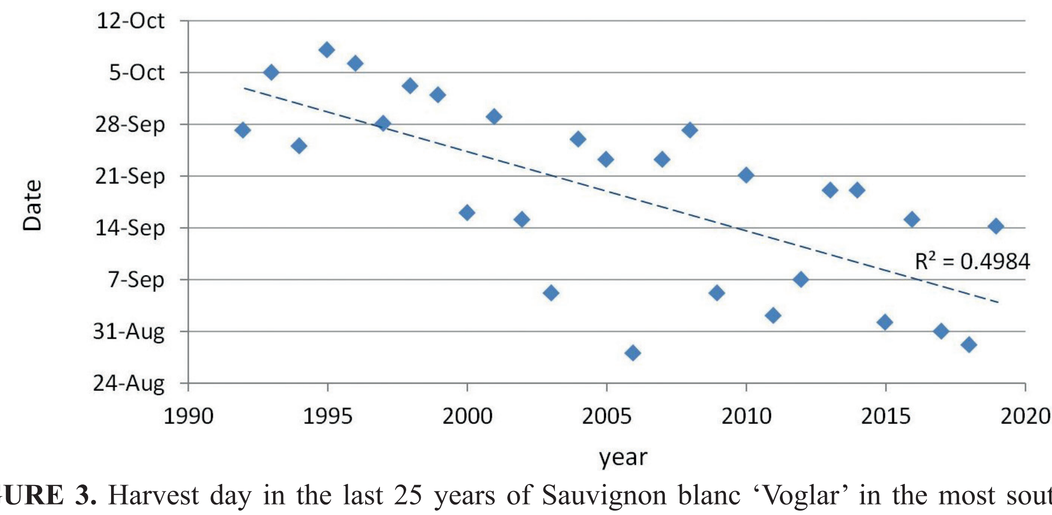


FIGURE 3. Harvest day in the last 25 years of Sauvignon blanc 'Voglar' in the most southern part of South Tyrol.

In the early 1990's, the harvest normally took place in early October; in recent years, harvesting has taken place at the end of August.

TABLE 2. List of the three complete environmental monitoring stations used for the research.

Station ID	Name	Location		Hight m s.l.m.	Vineyard's SRI index
D3	Söll	46°21'40.2"N	11°14'35.0"E	429	78.6
FF	Am Sand	46°20'41.1"N	11°15'06.8"E	235	76.3
D4	Plon	46°19'54.3"N	11°14'03.9"E	339	68.2

Three complete environmental monitoring stations were installed near the village of Tramin, in order to monitor and sample many environmental parameters throughout the 2019 growing season (Table 2). The three stations are located approximately 2 km apart and cover a strip of land around Tramin that stretches from north to south (Figure 2). The parameters measured by the three stations were: air temperature, solar radiation, dew point (steam to liquid), vapour pressure (liquid to vapour), relative humidity, rainfall, foliar wetting and wind speed and direction, as well as soil and subsoil salinity, temperature and humidity at various depths.

5. Soil temperature and moisture

A further environmental stress analysed in the study was soil temperature, as it influences the biochemical and nutritional processes of the plant. The heat absorbed by the first layers of soil through solar radiation is the energy charge that contributes to biochemical reactions of plants. Soil temperature in the root zone impacts phenology and timing of ripeness (van Leeuwen *et al.,* 2018); it depends on water content and energy balance (which is related to soil mineralogy, colour, coverage and solar radiation on the soil), as well as to the vineyard's altitude and topography. Warm soil in the root zone generally results in better wines (Bodin and Morlat, 2006; van Leeuwen, 2001; Tesic *et al.,* 2002). Temperature fluctuations are induced by a number of factors, such as a convective exchange with air, irradiation and rainwater. Ground temperature was measured continuously at the foot of each monitoring station by 12 sensors placed at 10 cm intervals down to a depth of 1.2 m. Humidity sensors were installed in combination with temperature sensors. Soil moisture sensors determine volumetric water content (VWC) by measuring the dielectric constant of the soil using capacitance technology and soil temperature.

6. Vineyard Solar Radiation Identity (SRI) index

The South Tyrol wine-growing region is characterised by numerous small production sub-zones, with more than 26,000 vineyards which differ greatly in their geographical features, influencing the quality of the grapes. Geographical features (altitude, exposure, inclination and micro-climatic conditions) can mainly be identified in the topoclimate and as a whole they constitute an important natural ecological resource of a given area. In a recent study, the new solar radiation identity (SRI) method (Ferretti, 2020a) was proposed to accurately classify the topoclimate in complex geographical environments. The aim of the SRI method is to make it easier to evaluate the impact of the vineyard's geographical conditions on both the vegetative growth of different grape varieties and the quality of the wine they produce.

The SRI index is a new approach to applied research and decision making in the viticultural sector; it was implemented to classify the geographical identity of vineyards in a more precise and comparable way. It is derived from a scientific analysis of vineyards and it is used for the discrimination and synthesis of complex environmental conditions of vineyards in mountainous areas. The topoclimate consists of numerous independent variables related to the vineyard, namely: slope, orientation, position and exposure, mountain shade and the position and zenith of the sun on the horizon. SRI goes beyond just an irradiance rate by giving a specific vineyard an identity value related to the topographic shape of the vineyard (derived from a high detail digital terrain model (DTM)) and the time variable. Thus, every index accurately takes into account both the changing height of the sun and the shading scenarios. SRI's database is also accurately related to the real size of every mono-varietal vineyard, which in our case represents the reference lot for the production of a homogeneous batch of wine.

With its highly detailed geospatial analysis, the SRI method, represents the whole viticultural area and catalogues the topoclimatic value of each single vineyard within a simple numerical index rate (Figure 4). All the regional vineyards were classified within the two extreme values of the SRI index and normalised between 0 and 100, according to the following standardisation algorithm:

$$SRI = ((SR_v - SR_{min}) / (SR_{MAX} - SR_{min})) \times 100.$$

SR_v = potential solar radiation received by the single vineyard measured in kWh/m^2 for the grape growing period of about 120 days (D'Onofrio, 2011), assumed to be between 1st May and 1st October. SR_{min} and SR_{MAX} are respectively the lowest and the highest values within the wine region. The calculations were executed with a raster cell resolution of 5 × 5 m, precisely shaped on each vineyard's real topographical position and then averaged to give a representative value of its topoclimatic identity. It is thus possible to obtain a complete database for each vineyard, including those of the Gewürztraminers studied here, with which to analyse, verify and precisely compare its ecological conditions. These quantitative data help to characterise the potential of each vineyard and are useful for discerning the influence of ecological factors on the quality of musts and wines. The index rate can thus be linked to the biosynthetic activity of the vines, as well as to the quality of the vineyard's grapes and wine.

7. Grape must sugar content

To ensure the reliability of the study, the territorial research focused on a single grape variety and analysed a total of 315 data of Gewürztraminer grape musts, harvested in 256 vineyards located in the Bassa Atesina sub-region (Figure 5), from a total area of 69.2 hectares, which represents 12 % of the total Gewürztraminer cultivated in South Tyrol. Grapes were harvested at altitudes of between 208 and 612 m in which the vineyards' SRI index varies from 47 to 84. In 2019, the grape harvest took place from 20 September to 15 November during the weeks that were dedicated to late harvests. The ripeness of the grapes was determined by analysing the sugar content of the must. Assuming that most of the solids are sucrose, must weight can be converted directly into amount of dissolved sugar, which is close to the true value and defines a first wine quality classification (Peth *et al.,* 2017). Many countries use different measurement units of the must's weight (Hopfer *et al.,* 2015). In Austria and South Tyrol, sugar content in must is measured in percent by weight (g/100 g) with the Klosterneuburger Mostwaage. Their scale shows Klosterneuburger sugar degrees (°KMW), also adopted from Italian viticulture as Babo degrees.

Must analysis was carried out immediately after the delivery of the grapes to the cellar, on must coming from the first pressing. Sugar content was measured on production batches of grapes. Such data are used by wineries to define the quality and economic value of the lot. This testing procedure was chosen to verify the practical applicability of the research methods to general practice in wineries and real wine production chains located in a large area of vineyards.

A more detailed analysis of must quality was carried out on a restricted area near Tramin - on vineyards from the geographical sub-zone of Söll, St. Jakob, Plon and Pinzon. A dataset of 48 selected vineyards from a single winery was analysed. The cultivation practices in the vineyards, although not exactly the same, are highly comparable. The harvest was carried out on 3 and 4 October 2019. These dates, carefully chosen by the oenologist, were when the desired degree of optimal ripeness of the grapes had been reached. The vineyards lie at altitudes of between 232 and 535 m, have a SRI of between 64 and 80, comprise a total area of 12.5 ha and provided a total of 87 t of grapes in our study.

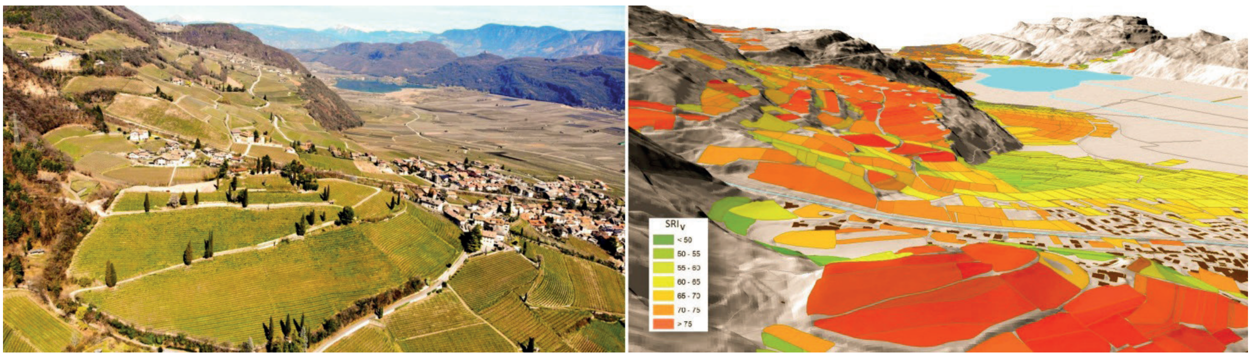


FIGURE 4. Comparative image from almost the same point of view between vineyards of the Söll geographical unit and their SRI indexes.

This way of representing them simplifies the distinction between the different geographical predispositions of the vineyards.

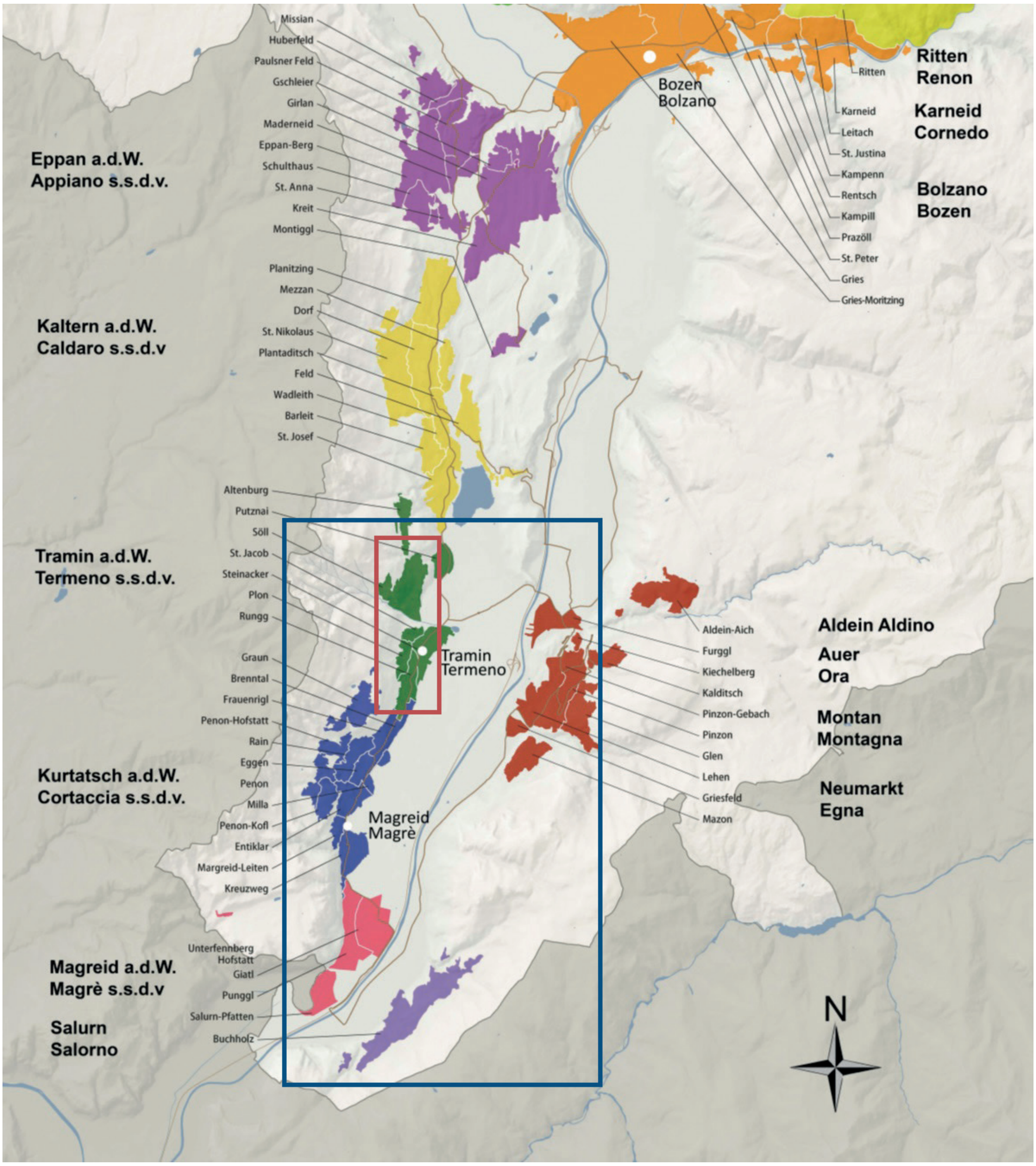


FIGURE 5. Base map of the new geographical units proposed for Bassa Atesina and the most southern part of South Tyrol, listed in their respective municipalities.

Blue box = the location of the Gewürztraminer vineyards harvested in 2019 between 20 September and 15 November;

Red box = restricted area near Tramin with vineyards harvested on 3 October and 4 October (see Figure 2)

RESULTS

1. Air temperature

The harvesting period is mainly driven by growing season air temperature (Parker *et al.,* 2011) and the specific temperature requirements of the grapevine variety (Parker *et al.,* 2013). The long-term analyses for all three environmental monitoring stations installed at Tramin, indicate that their seasonal temperature trends correspond; daily averages increased between April and May and the peaks in temperature occurred between the end of June and mid-August. The data comparison between Plon and Söll confirms a reduction in air temperature with altitude of approximately 0.9 °C per 100 m (Table 3). On the one hand, this matches the typical regional values during the summer period, which show temperature decreases of 0.6 to 1.0 °C for every 100 m in altitude. On the other hand, the research shows that neither the altitude nor the relative reduction in temperature significantly affected the day of harvest or the quality of the must samples from the Bassa Atesina. In fact, only a weak positive relationship (Pearson's $r = 0.21$, $p < 0.05$) was confirmed between the vineyards' altitude and the sugar content of their musts (Figure 6). We found that the harvest date is conditioned more by both rainy days and the schedule of the winery's activities. The harvest of vineyards at altitudes of between 210 and 600 m was sometimes carried out on the same day. Nevertheless, the winemaker confirmed that in the small area examined at Tramin, the trend in seasonal air temperature or the vineyard altitude from about 230 to 550 m affected the timing of phenology in terms of budburst, flowering and *veraison*, delaying it by five days at higher altitudes in comparison to grape vines on the valley floor.

The detailed analysis of the temperatures in the vegetative period highlights the considerable microclimatic temperature differences within a small area of only 6 km^2 around Tramin. Table 3 shows that while the Am Sand station - which is at a lower elevation than the others -

TABLE 3. Average daily air temperature during the period between 23 March and 15 October 2019.

Monitoring station	T°C Avg.	T°C Max	T°C min	ΔT°C Avg.	ΔT°C Max	ΔT°C min
Söll (429 m)	17.8	25.1	12.1	13.5	20.7	5.4
Plon (339 m)	18.8	24.9	13.4	10.8	15.2	2.9
Am Sand (235 m)	18.2	27.1	11.1	14.9	20.5	6

Am Sand has lower minimum values, which is unusual when compared to its low altitude, but it is affected by the microclimate comprising very local cold air currents descending from the mountain.
ΔT = daily thermal excursion in the 2019 period from 5 September to 5 October.

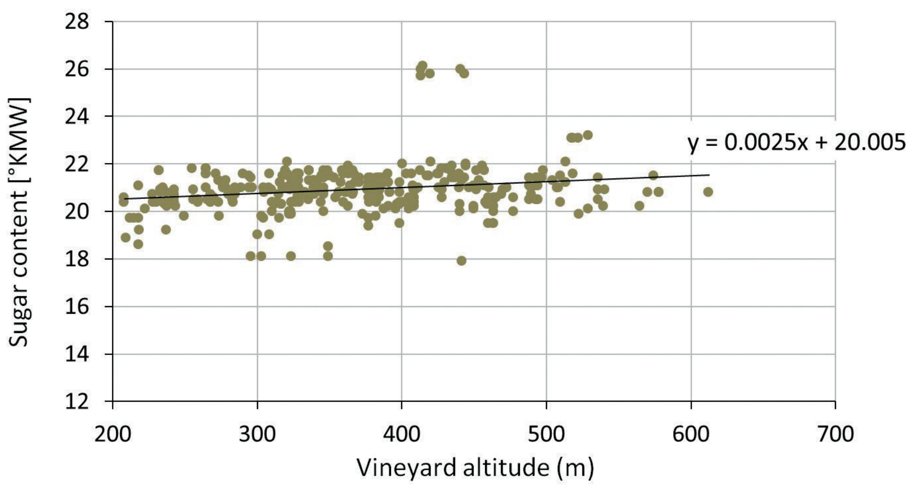


FIGURE 6. Comparison between harvest date and vineyard altitude with a statistically significant ($r = 0.21$, $p < 0.05$) correlation. The harvest day may follow the wineries' schedules. The vintage at different altitudes was sometimes carried out on the same days.

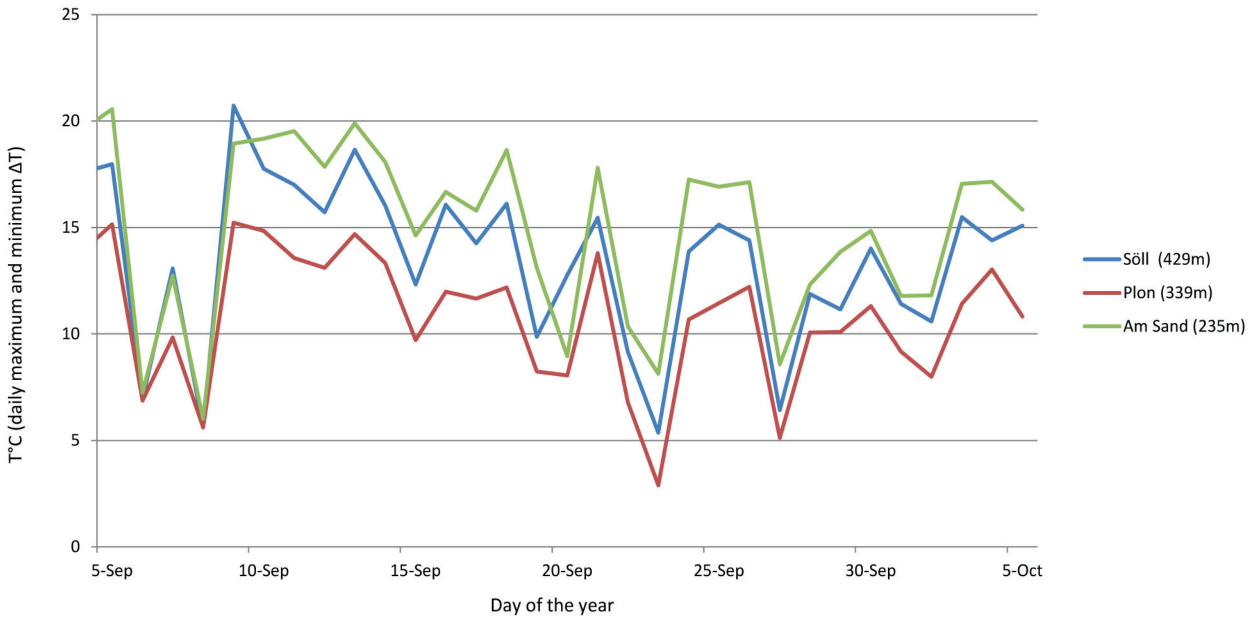


FIGURE 7. Diurnal temperature variation during the 2019 pre-harvest month.

The graph shows differences between the environmental monitoring stations. The Am Sand station is particularly noteworthy, recording the highest diurnal variations between low and high temperatures.

has higher daily peaks in temperature, the minimum and average temperatures are abnormally low. This can be explained by comparing the day/night temperature range between the stations. At Am Sand there is a higher diurnal temperature variation (Figure 7). Here, the night-time temperatures are between 2 and 3 °C lower than in Plon. This can be attributed to the particular microclimate, typical of an Alpine mountain environment. In particular, local cold air currents sink during the night from the high mountain cliffs made of dolomite rocks which overlook the village of Tramin to the west. These fresh air currents are channeled through the narrow valley of the Höllental Torrent and reach the Am Sand station placed at the end of the valley. Daily temperature differences between the three monitoring stations reach up to approximately ΔT 6 °C, with differences between the maximum temperatures of up to +1.5 °C and between the minimums down to -3.5 °C.

2. Rainfall

There were 78 rainy events in the 197 days monitored between 23 March and 31 October 2019. The rain events registered by the three monitoring stations were simultaneous and had the same intensity. For some sporadic events, different amounts of rainfall between the stations were recorded, due to the mountainous area, which favours local thunderstorms with of differing strengths. The total quantity of rainfall at each of the three stations in the April to October period was very similar: Söll = 686 mm, Plon = 683 mm and Am Sand = 664 mm.

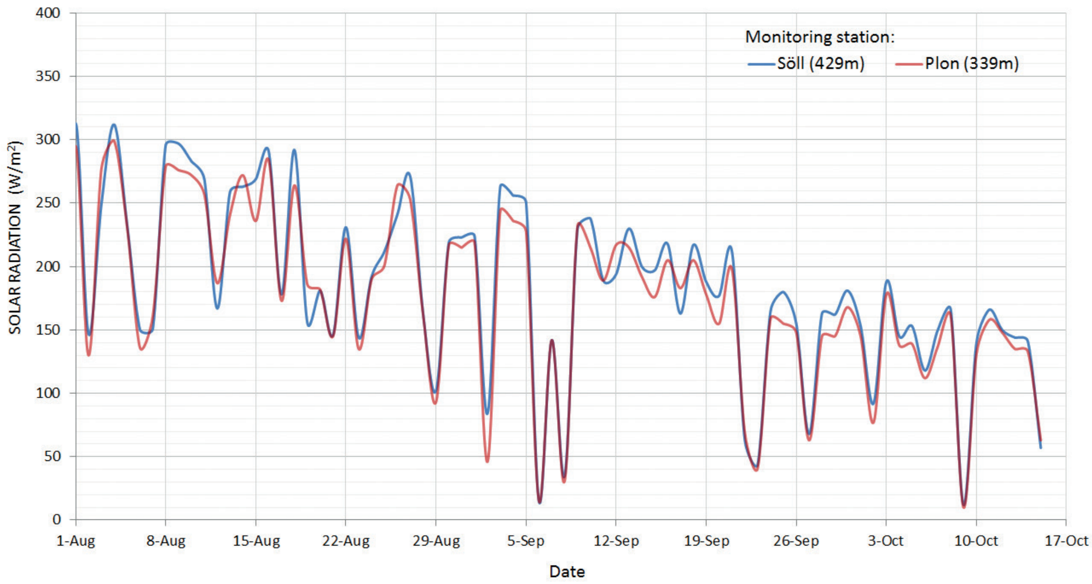
3. Solar radiation

Solar radiation was measured using the two weather stations in Söll and Plon. Solar data was sampled continually on-site with a pyranometer from May to October 2019.

Solar irradiance is measured in W/sqm and represents the power of the sun's rays falling on a given surface in the form of electromagnetic radiation. Its trend over the whole measured period was highly cyclical between the night-time minimum and the daytime maximum (Figure 8). There was a seasonal trend for an increase in spring/summer and a decrease in autumn/winter. The Söll station, located in the northern part of the area, recorded a higher level of irradiance than the Plon station, which was located in the south.

On sunny days a maximum difference in energy W/sqm of up to 14 % was measured in favour of Söll. These differences are due to the dissimilar topoclimate situations. The geographical evaluation of the two vineyards indicates that both are oriented towards east-south-east, but the first is less steep and covered daily by late-afternoon shade from the mountains.

(8a)



(8b)

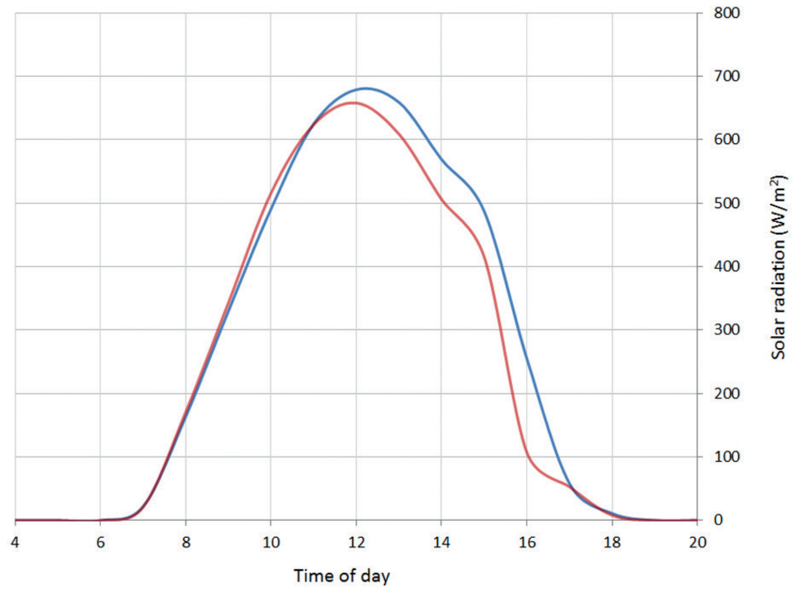


FIGURE 8. Solar radiation (SR) graphs: (8a) the daily mean values measured in Plon and Söll between August and October 2019; (8b) values from 30 September. The total SR measured in the afternoon was +13.5 % at Söll (2,720 W/sqm) compared to Plon (2,350 W/sqm). The comparison indicates higher energy at Söll.

4. Soil moisture

The change in soil moisture measured at the Plon and Söll stations precisely follows the cyclical nature of the rain events. The humidity level varies seasonally: in the subsoil it is around 18 % in late summer, increasing with autumn rains and frost and at its highest in winter, settling at around 30 %. Early harvest dates likely correspond to the highest levels of water shortages at the end of the season. Throughout the growing season the soil in Plon is constantly 8 % wetter than that in Söll. This is in line with the lower permeability of Plon's silt loam soils compared to Söll's loam soils. It also explains the lower soil temperature and higher thermal capacity of Plon described in the following sub-section, since more energy is needed to heat the volume of soil richer in water.

5. Soil temperature

In local wine-growing practices, a permanent grassy cover is left on the soil, which is never ploughed or directly exposed to air. The temperature data of the most superficial soil show a diurnal

TABLE 4. Minimum, maximum and average temperature detected in superficial soils at 10 cm depth, between 15 April and 15 October 2019.

	Altitude	Air temperature	Soil temperature		
Station	m a.s.l.	T°C avg.	T°C avg.	T°C Max	T°C min
Söll	429	19.2	18.6	19.7	17.5
Plon	339	20.2	17.6	18.4	16.7

Note that the air temperature in Söll is about 1 °C lower than in Plon, but the soil in Söll is on average 1 °C warmer. This effect is due to both higher solar radiation at Söll and the soil characteristics.

trend similar to that of the air temperature, with minimums during the night and maximums in the afternoon. The soils heat up in the morning and respond to the solar radiation they receive. Also, the rains have an instantaneous impact on the soil temperature and quickly cool them, even at depth. The data collected show that the daily temperature range in the more superficial soil depends mainly on solar radiation, as well as on the physical and mineral nature of the soil, in particular texture and moisture. With the same energy availability, a wet soil heats up less than a dry one. The air temperature, however, acts on the soil with a monthly and seasonal return of time. It can be observed that the air temperature in Söll is on average about 1 °C lower than in Plon, but the soil at 10 cm depth in Söll is on average 1 °C warmer than in Plon (Table 3). Thus, the Söll vineyard has warmer soil, although it is approximately 100 m higher than Plon and the air temperature is colder. The temperature of the soil depends not only on the solar radiation that reaches it, but also on its physical properties of texture and humidity. As described above, Plon's soil is finer and wetter than that in Söll.

Figure 9 illustrates the thermal soil model at Söll and Plon. First of all, the direct relationship between solar radiation and temperature can be observed and the two soils also have different thermal diffusivity. In the morning, Plon still tends to cool down, despite the increase in solar radiation energy, while Söll responds to it more directly and increases its temperature as soon as the sun's rays reach the vineyard. The soil in Söll is warmer on the surface than in Plon. Söll has higher specific heat and accumulates more energy, which then returns to the plants and the environment.

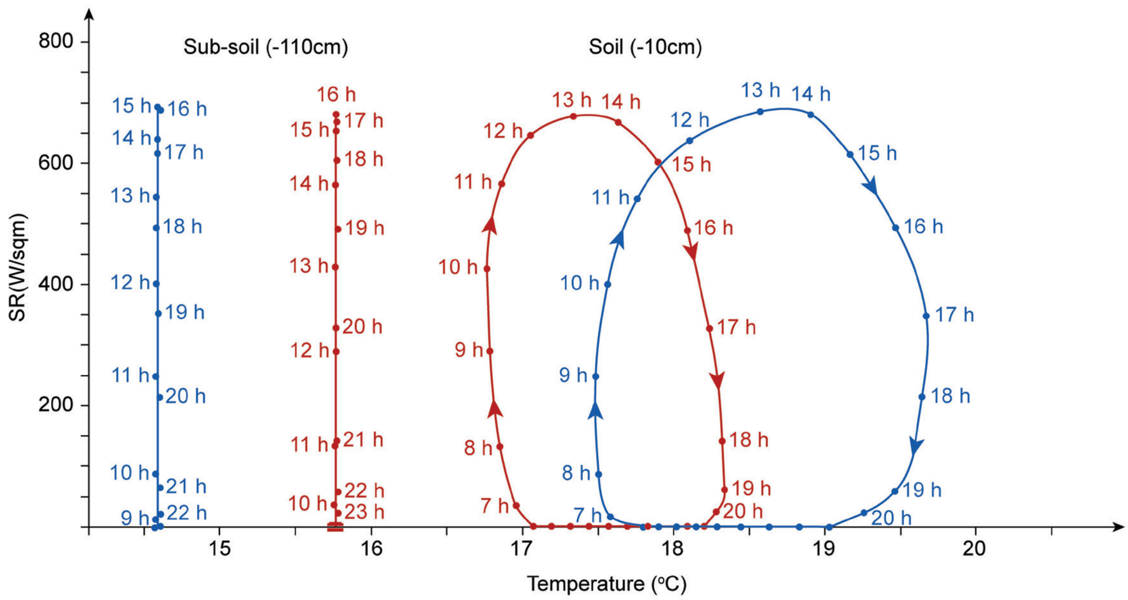


FIGURE 9. Comparison of the thermal model in Plon (red lines) and Söll (blue lines), average temperature per hour between 15 April and 15 October 2019.

Lines and arrows represent the daily temperature cycle in the soils at a depth of 10 cm and in the subsoils at -110 cm. Close to the surface the soil is warmer and the temperature trend is cyclical, linked to solar radiation. The Söll soil is warmer and responds more directly to solar radiation. By contrast, deep down there is no influence of solar radiation on the temperature and the subsoil in Söll is colder.

The subsoil that regulates the temperature in the root zone at a depth of below 40 cm, stays at a constant temperature in the short term, without daily fluctuations. The surface soil layer acts as an insulator, stopping the direct influence of solar radiation at depth. In the long term during the year, the thermal trend is divided into three main phases: heating (April to June), maximum temperature (June to August) and cooling (September to December). The thermal behaviour of each of the two stations is seasonally similar, but they differ in absolute temperature values in the medium- or short-term. Söll has a faster response to seasonal air temperature than Plon: the subsoil heats up more and faster in summer and cools down more in winter.

Research has found that the temperature in the subsoil of Söll is always lower than in Plon, with differences of up to - 1.5 °C. By contrast, near the surface the soil of Söll is warmer than that of Plon - on average 1 °C during the whole growing period of the vine.

6. Grape must quality

The quality of the grapes is evaluated by examining the sugar content of the must on harvest day. The results of the analysis of all these data indicate quite a strong correlation between harvest date and sugar content, which is more evident in the minimum values. An increase in sugar over time can be seen with a corresponding progressive physiological ripening of the grapes (Figure 10). The late harvest increase in sugar is instead related to the concentration of sugar resulting from the dehydration of the fruit (Guillaumies *et al.,* 2011), which is superimposed on that from the physiological ripening process of the grapes. The harvest data trend, in particular the physiological maturation highlighted in Figure 10 by the sugar rise over time confirms the reliability of the data collected and the correct direction of our research. The distribution of the total data cloud is still very dispersed; however, a medium positive relationship emerged between harvest date and sugar content with a linear regression from the estimated model, y = 0.274x - 1,175.8, Pearson's r = 0.33 and $p < 0.001$. This is consistent with the local geographical situation and the large sample of data analysed; considering that plant responses to abiotic stresses are dynamic and complex (Cramer *et al.,* 2011), it is thus not fully linear. There are important geographical differences in the Alpine study area and, above all, the wine-growing and wine-producing choices of the wineries had a fundamental influence on the quality of the harvested products; for example, grape picking did not always take place at the moment of the optimal ripening stage of the grapes for each vineyard; the harvest was sometimes interrupted by rainy days, which results in erratic

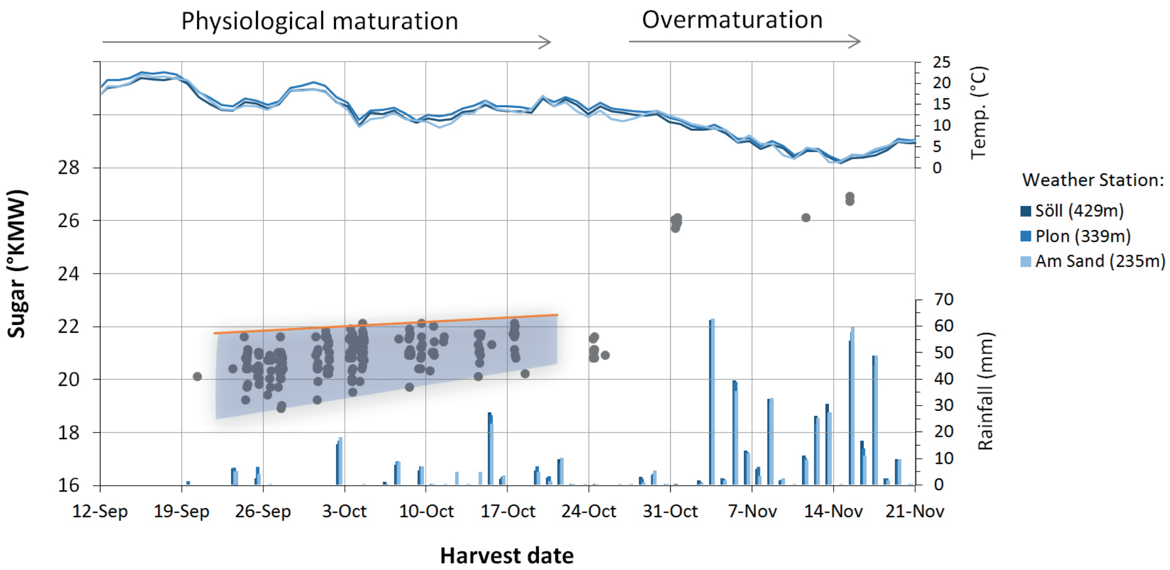


FIGURE 10. Sampled must sugar content and harvest date.

The red line marks the physiological ripening limit of the Gewürztraminer variety for 2019 in Bassa Atesina. Late harvests of the last weeks can be distinguished in November. The blue shaded area highlights the sugar content and ripening differences in the sub-region; these are related to the many ecological factors and viticultural practices of this wine zone. Bars on the x axis represent rainfall.

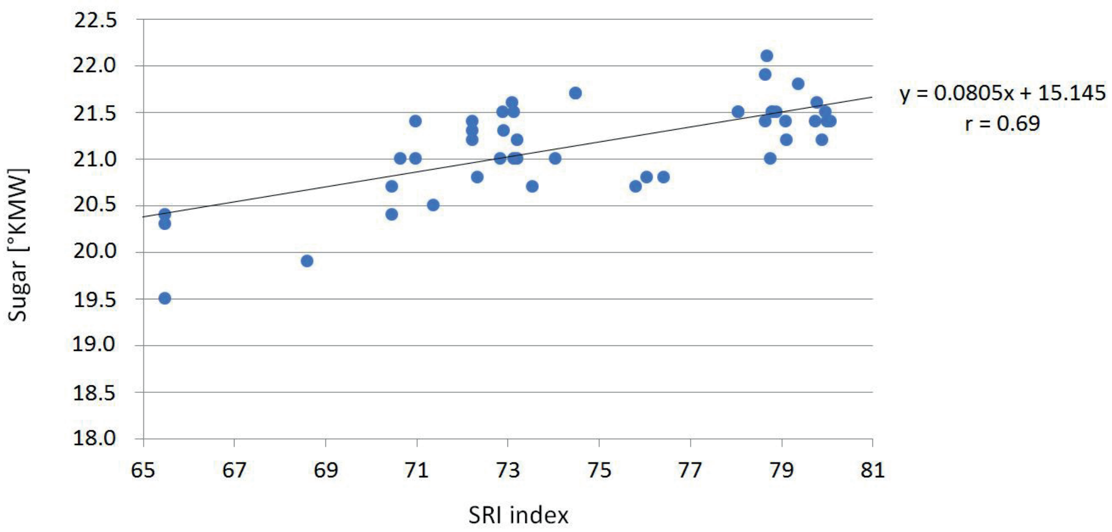


FIGURE 11. Sugar ripeness and SRI index for the vineyards at Tramin harvested on 3 and 4 October 2019.
The graph shows a range of data strictly regulated by ecological factors. In particular, we observe an increase in sugar content with an increase in SRI, which represents the topoclimatic identity of each vineyard.

grape ripening, or was dependent on winepress availability and cellar scheduling (sometimes the delivery of the grapes is scheduled within a narrow time slot, during which the winepress can only be used for one grape variety at a time).

In order to filter the analysed data from the afore-mentioned anthropic and environmental variables, or from cryptogamic diseases and to better finalise the research on ecological indicators, a smaller and more controlled area around the village of Tramin was studied. We analysed 48 vineyards which each have a single wine cellar. They apply uniform and more controlled viticultural procedures and have an espalier planting structure, with all grapevine rows oriented approximately north-south. The quantity of grapes produced in each vineyard is about 0.7 t/ha. The date of harvest was chosen carefully by the oenologist to occur on 3 and 4 October 2019 when the desired optimal ripeness of the fruit had been reached. The results of the analysis revealed a clear correlation between sugar content and SRI topoclimate index for this more restricted, homogeneous and controlled geographical context (Figure 11). The graphical correlation was evaluated using a multivariate linear statistical analysis, which best reflects our study case, as it has more than one dependent variable. A strong statistical relationship between the two variables SRI and sugar is expressed by the linear regression with estimated model $y = 0.0805x + 15.145$, Pearson's $r = 0.69$ and $p < 0.001$.

DISCUSSION

1. Air temperature

The results of the microclimatic analysis show a significant diurnal air temperature variation within the small area studied at Tramin. The air temperature data collected in this research can be used as a qualitative ecological indicator of the area, but these cannot be quantitatively traced back to all the vineyards. However, quite variable microclimatic conditions were found, which could affect the phenological response of the local grapevines and, therefore, define a different maturation rate and quality of the musts analysed in the research. Thus, for the study area, some correlation between air temperature and sugar content of the grapes at harvest may have been possible and therefore have been checked. In view of this, SRI and grape sugar content were verified, specifically in a few vineyards in the Höllental valley, but no evidence of such effects on must sugar content was found. However, only three of the vineyards studied are along the Höllental, thus the data population was too small for a statistical test. It should also be noted that Gewürztraminer is not grown on the valley floor, where higher temperature fluctuations are recorded, as this area is not traditionally suitable for its growth. However, it is possible that the above-mentioned microclimatic conditions could affect the organoleptic features of grapes and wine, which have not been studied in our research.

2. Rainfall

The cumulative amounts of daily rainfall are very similar within the restricted area around Tramin. Even in the months before harvesting, the rainfall amounts were homogeneous, (Figure 10). Therefore, differences in rainy days or amounts of rainfall could not be linked to differences in ripeness within the observed restricted wine area. However, it should be noted that when comparing vineyards in which harvesting took place on different days, rainfall may still represent a selective ecological element for vine biosynthetic activity; vineyards can therefore be differently affected by sunny or rainy weather conditions near the time of harvesting. In fact, rainy, overcast or low-temperature weather conditions can affect physiological grape ripening and result in similar sugar content of musts harvested on different days before or after the rain. We can conclude that rain does not represent an ecological variable for the qualitative analysis of musts pressed on the same day, but it does represent a variable environmental factor for grapes harvested in locations distant from each other and on different days. However, as described below, in this kind of data analysis it is important to always take into account the fact that soils have differing capacities for retaining the same amount of rainfall.

3. Radiative energy

The fact that Söll receives more solar energy than Plon seems to be in contrast with the average air temperatures, which are approximately 0.8 °C lower than those in Plon. However, the sampled environmental data show that the solar radiative energy reaching the vineyard and air temperature are two separate ecological indicators that can differ significantly in a mountainous environment. A further important result is that the SR value difference of 14 % registered at the weather stations is fully in line with the SRI index value calculated using the Solar Radiation Identity method (Ferretti, 2020a). The SRI index for Söll is in fact 15 % higher than that for Plon. The instrumental measurement of the SR value confirms the correctness and reliability of the SRI index method. This index can be efficiently used as an indicator of both the environmental stress to which the vines are subjected and the ecological potential of each vineyard. We can use the SRI index as a practical and suitable reference to predict the biosynthetic activity of the vines. Because solar radiation interacts with several variables (*e.g.*, grape variety, soil and its type of cover, training system and row orientation, etc.), the SRI index should be contextualised to the experimental conditions to obtain more accurate information.

4. Soils humidity and temperature

In our study, the soils of Tramin were found to be physically affected by their humidity and temperature. Soil moisture information can be used qualitatively in our study and be linked to the extremely variable characteristics of the local soils, but because we only have a few measuring stations, such information cannot be quantitatively traced back to all the vineyards observed.

The differences in soil temperature are related to the physical characteristics of the soil, in particular on the texture, which is the cause of lower permeability but higher moisture in Söll soil compared to that of Plon. Montheith and Unsworth (1990) confirm that thermal conductivity is higher in porous soil, compared to a clayey soil containing the same amount of water. The minerals in the soils of Plon and Söll are similar and have less influence on the differing thermal behaviour of the studied soils. The analysis of soil temperature revealed it to be of ecological importance in the local soils, which can vary significantly in the vineyards around Tramin. Research has also shown that soil temperature is causally related to the amount of solar radiation received by the vineyard. Our results show that soil temperature predictions in the short-term were least sensitive to air temperature changes occurring during the day or week. Therefore, soil temperature can also be better qualitatively described by the SRI index, in order to conduct a predictive evaluation on the vineyards' biosynthetic processes and their topoclimatic potential.

5. Sugar content

Figure 11 shows that sugar content maintains a variation range of approximately 1° KMW at the same SRI. This is an admissible inaccuracy for the research carried out due to the complex, natural, physiological processes being dependent on the environmental diversity that differentiates the vineyards around Tramin. Some of these inconstant ecological factors were qualitatively identified in our study: the geopedological differences in the soils, microclimate and air temperature, soil temperature, exposure of the bunches after thinning and, last but not least, the method of sampling the must. Regarding the latter, it should be noted that we collected sugar-ripeness data on large lots of grapes in order to verify the practical applicability of the research to a wide geographical area and to real winemaking procedures. Future research refinements could include considering more controlled situations and testing the SRI method in detail in other geographical contexts and on other wine varieties. We also believe that in order to be more technically useful the analysis of ecological indicators must include the evaluation of practical situations on an industrial scale and not only in micro-vinification conditions.

6. Vineyard height

A further interesting result of the research, which should be examined in future studies on Gewürztraminer and other wine varieties, is the fact that only a weak correlation was found between vineyard altitude and the sugar content of the grapes. It is therefore possible that some of the direct correlations between altitude and sugar content reported in other studies (Pedri, 2014) dealing with vineyards scattered over large areas depend more on other ecological factors which affect physiological maturation, such as solar irradiation, local air temperature, microclimate and soil type. In fact, the topoclimatic analysis of all our vineyards indicates a medium relationship between SRI and height, expressed by an estimated model $y = 64.15 + 0.027x$, Pearson's $r = 0.4$ and $p < 0.001$. The results of recent regional level SRI analyses (Ferretti, 2020a), have shown that solar irradiation on vineyards in the South Tyrolean wine region tends to increase with altitude and this ecological evidence might better explain some altitude-related physiological plant responses.

7. Vineyard topoclimate

The present study has found that the variability in sugar content is mainly regulated by a single ecological factor: the vineyard's topoclimate. We have also tested that the topoclimate is adequately represented by the SRI index. The accuracy of the SRI index allows incidence on ripening to be quantitatively estimated: an increase in SRI of 10 points corresponds to an increase in sugar content of about 0.8 °KMW. As the ability to maintain high quality wine and to adapt to climate change will depend on our aptitude in predicting the significance and influence of ecological indicators, a prediction model based on SRI indexes is proposed.

The strong correlation between SRI and sugar having been confirmed by the study, it is now possible to develop a prediction model for SRI/ sugar content, even outside the experimental data range of this research: the tested vineyards by Tramin have SRI indices of between 64.8 and 82.6, while the SRI values of the 2,732 Gewürztraminer vineyards in the whole of the South Tyrol wine-growing region vary between 40 and 92.

The proposed prediction model is based on the analysis of finite subfamilies of variables obtained within the measured datasets, with a particular focus on quantitative variables for ranges close to SRI = 3.5. Box plot-type statistical graphs in Figure 12 show more precisely the shape of the distributions of these data subfamilies, representing the statistical data listed in Table 5.

TABLE 5. Report of the statistical analysis data of the finite subfamilies of variables shown in Figure 12

SRI	64.8 - 69.0	69.0 - 73.0	73.0 - 76.0	76.0 - 79.0	79 - 82.6
Min	19.5	20.4	19.9	20.8	20.5
Q1	19.9	20.8	20.7	20.875	21.2
Median	20.3	21.0	21.0	21.2	21.4
Q3	20.4	21.3	21.525	21.5	21.5
Max	20.8	21.5	21.7	22.1	21.8
IQR	0.5	0.5	0.825	0.625	0.3
Mean	20.2	21.0	21.2	21.4	21.3
σ	0.50	0,35	0.39	0.41	0.34
σ^2	0.25	0.12	0.15	0.17	0.12
Lower Outliers	0	0	0	0	1

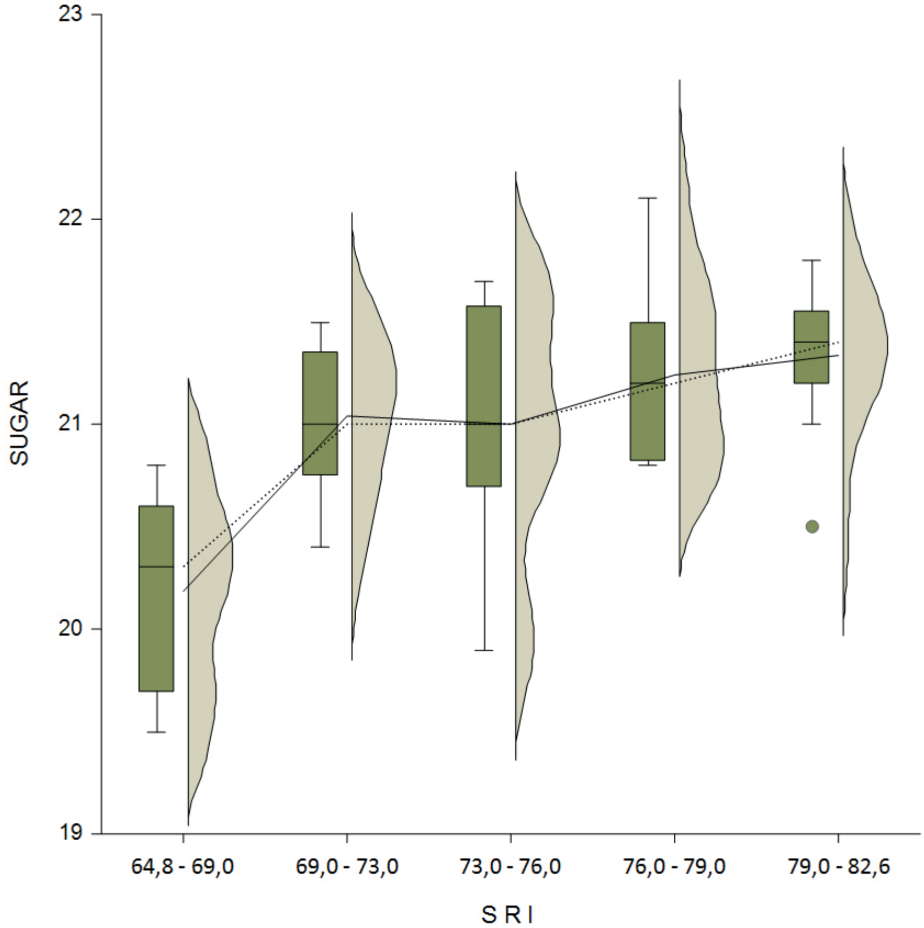


FIGURE 12. Analysis of finite sub-families of data, combined chart of box plots (dark green) and density pots (light green), with connecting lines between groups of means (dots) and medians (continuous). The dot corresponds to a statistical outlier.

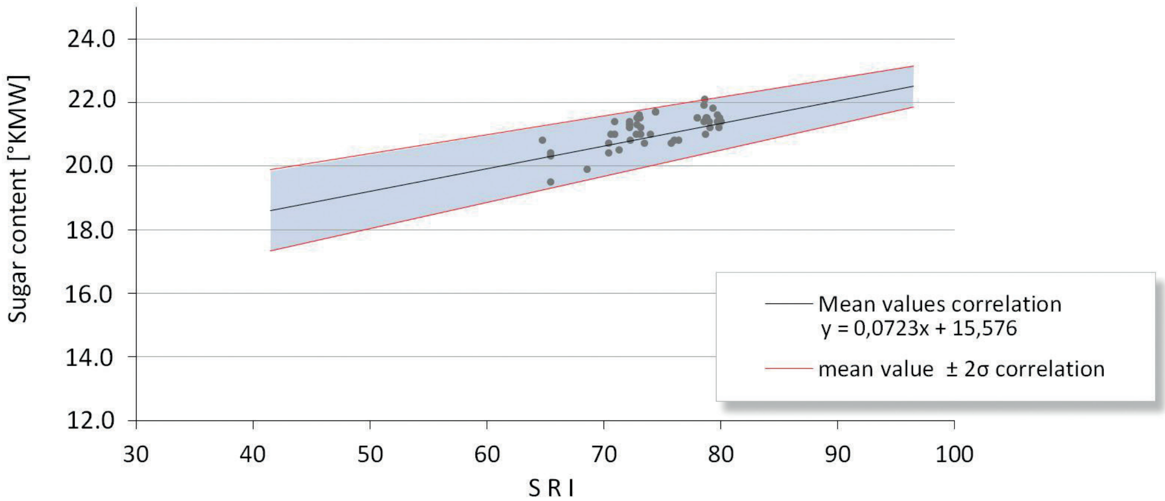


FIGURE 13. Prediction model of the Gewürztraminer grape sugar ripeness based on an SRI curve analysis.
Black line shows the mean trend of expected values, red lines define upper and lower limits of statistically significant data (equal to 95 % of normal distribution). Dots represent the measured values. The blue band between red lines identifies a deviation range due to the variability of the natural physiological processes between vineyards, due, for example, to microclimate, anthropic factors (viticultural practices, clone, rootstock) and soil (texture, minerals, temperature, humidity).

A correlation analysis by linear regression of the values thus obtained for each sub-family of data allows us to define the central value of the distribution, with the confidence levels indicated in Table 5 and the following linear correlation of the mean values:

Sugar content = 15.675 + 0.0707 SRI;

Pearson's $r = 0.91$; $p < 0.5$; $\sigma = 0.46$

To complete the model, the estimated parameter must be accompanied by a range of plausible values based on the variability σ of the data populations, with a 95 % confidence level as shown in Figure 13.

This model aims to estimate the physiological response of a vine variety - in this case the Gewürztraminer - in a wider topoclimate stress condition, which is typical of the mountainous South Tyrol winegrowing region.

The aim of the study is to integrate the monitoring and assessment of ecological and environmental indicators into management practices. This model could assist the search for new approaches to adaptive and more flexible crop management, based on the equilibrium of the local dynamic ecosystem. New strategies would also need to be implemented to find ways of adapting vines to future climate conditions in the Alpine area, according to a well-known environmental scenario. For example, a vineyard with a low SRI could facilitate the adaptation of current cultivars to an increase in temperature; in contrast, the growth of grapevines at high altitudes requires more energy and therefore vineyards with higher SRI values which are more appropriate for the cultivar should be sought. Low SRI values can also be considered to favour the acidity so sought after for biodynamic cultivation or for sparkling wines.

CONCLUSIONS AND IMPLICATIONS

The ability to recognise and understand the influence of different ecological factors on both the vine's biosynthetic activity and features of its grapes, will be a significant challenge for viticulture and final wine quality in the future. The quantitative classification of ecological indicators facilitates predictive analysis and the search for patterns in information related to terroir to identify risks and opportunities in viticulture. Thus, we investigated the ecological factors that can significantly affect the ripening process of the Gewürztraminer grape variety, cultivated in the geographically multifaceted South Tyrol wine region.

The research studied a restricted geographical area, focusing on the measurement and analysis of main abiotic ecological factors, particularly geographical ones. The study was conducted with the awareness that other features of the terroir also influence plant physiology and that vine and fruit quality are affected by many biotic and human factors. However, in order to analyse such different environmental factors quantitatively, they have to be identified individually and then reinterpreted together in a comparable way. A sectorial research procedure is more suited to the identification of certain ecological elements that may have a significant physiological effect on the vine. Such data should ultimately be interpreted in an interdisciplinary way, involving scientific knowledge of viticulture and oenology.

The present study has identified the geographical factors that, within the observed geographical context, have a major impact on grape ripening: air temperature, soil temperature and topoclimate. Topoclimate is a very significant ecological component of the environment, which affects the vine phenology and grape quality. It can be concluded from our results that more research should be carried out on the many studied vineyards, to better determine the importance of the three above-mentioned ecological indicators, in terms of their effect on both phenological processes and the aromatic biosynthesis of the grapes. In fact, in addition to the topoclimate, other components of abiotic stress that are important for the examined wine area can be attributed to different soil types and the diverse microclimates of the mountainous environment, as well as to related ecological parameters such as temperature, biochemistry and biological aspects of the different soils. Our research has also highlighted a significant qualitative variability in musts, which is correlated with both cultivation and winery practices.

The analysis carried out on 48 selected vineyards near Tramin revealed a direct relationship between the grape must sugar content and the SRI topoclimate index. Our findings indicate an increase in sugar content of approximately 0.8° KMW for every 10 SRI index points. Thus, a novel prediction model of grape ripening based on an SRI curve analysis is proposed. Furthermore, the research confirmed the presence of other types of abiotic stress related to the local vineyard soils, in which we measured different temperatures and moisture content correlated with their respective textures. During the vegetative period, a local loam soil is 1 °C warmer at the surface than at depth and it is much more responsive to diurnal solar radiation changes, being on average 1.5 °C warmer than a silt loam soil. The study provides evidence that the radiative energy of the sun reaching the vineyard and air temperature in the vineyard are two separate ecological indicators that can differ significantly in a mountainous environment.

The present research has validated the SRI method, which makes it possible to assess with greater precision the ecological impact of the topoclimate in viticulture, in particular on grape ripening and the environmental adaptation of the cultivar. The findings suggest that it is still possible to assure and improve the quality of the local wines and to match the most suitable cultivars to a given area by, for example, applying greater rigour in the selection of vineyards with similar geographical identities and then ensuring that they each maintain their own optimal processing, grape harvesting and vinification procedures.

Not only can the SRI index be used to discriminate and predict the geographical factors linked to ecological diversity and wine quality in the South Tyrolean wine-growing region, but its use could be widened to a more general scale. The use of the SRI prediction curve could help to adapt our environmental approach to agriculture. It could support decision making in the viticultural sector on matters regarding, for example, the correct matching of vineyards and grape varieties, the reduction of wine vulnerability or production risk, the prediction of optimal ripeness and best harvesting days. It could contribute to preserving the typical varietal characteristics of grapes, as well as to providing new ways of adapting local viticulture to climate change, managing future vines and ensuring high quality wines.

Acknowledgements: The author acknowledges S. Febbroni and S. Marighetti for sampling and GSA analysis, GIR Geo Identity Research for the statistical survey and geographical data, the Kellerei Kurtatsch and Kellerei Tramin for facilitating this research work and wine producer A. Kofler and the winemaker W. Stürz for their helpful comments and suggestions for improving the paper.

REFERENCES

Acquaotta, F., Fratianni, S., & Garzena, D. (2014). *Temperature changes in the North-Western Italian Alps from 1961 to 2010. Theoretical and Applied Climatology*. ISSN 0177-798X. Theor Appl Climatol. https://doi.org/10.1007/s00704-014-1316-7

Asproudi, A., Petrozziello, M., Cavalletto, S., Ferrandino, A., Mania, E., & Guidoni, S. (2020). Bunch Microclimate Affects Carotenoids Evolution in cv. Nebbiolo (*Vitis vinifera* L.). *Appl. Sci., 10*. 3846. https://doi.org/10.3390/app10113846

Bodin, F., & Morlat, R. (2006). Characterization of viticultural terroirs using a simple field model based on soil depth. I – Validation of the water supply regime, phenology and vine vigour, in the Anjou vineyard (France). *Plant Soil, 281*. 37-54. https://doi.org/10.1007/s11104-005-3769-z

Cioch-Skoneczny, M., Satora, P., Skoneczny, S., & Pater., A. (2020). Determination of the oenological properties of yeast strains isolated from spontaneously fermented grape musts obtained from cool climate grape varieties. *Eur. Food Res. Technol. 246*. 2299–2307. https://doi.org/10.1007/s00217-020-03574-0

Coombe, B. (1986). Influence of temperature on composition and quality of grapes. In: *ISHS Acta Horticulturae, Proceedings of the International Symposium on Grapevine Canopy and Vigor Management.* Davis, CA, USA, Volume XXII IHC, pp. 23–35. https://doi.org/10.17660/actahortic.1987.206.1

Cortell, J. M., & Kennedy, J. A. (2006). Effect of shading on accumulation of flavonoid compounds in (*Vitis vinifera* L.) Pinot noir fruit and extraction in a model system. *J. Agric. Food Chem. 54*: 8510–8520. https://doi.org/10.1021/jf0616560

Costantini, E. A., & Bucelli, P. (2008). Suolo, vite ed altre colture di qualità: l'introduzione e la pratica dei concetti "terroir" e "zonazione". *Italian Journal of Agronomy, 1*(Suppl), 23-33.

Cramer, G. R., Urano, K., Delrot, S., Pezzotti, M., & Kazuho, S. (2011). Effect of abiotic stress on plants: a system biology prospective. *BMC Plant Biology. 11*. pp. 163. https://doi.org/10.1186/1471-2229-11-163

D'Onofrio, C. (2011). Caratterizzazione funzionale della biosintesi degli aromi delle uve durante lo sviluppo dell'acino e controllo della qualità aromatica delle uve. *Italus Hortus, 18*(2): 39-61. http://hdl.handle.net/11568/147297

De Orduña, R.M. (2010). Climate change associated effects on grape and wine quality and production. *Food Research International. Vol. 43*. 1844–1855. https://doi.org/10.1016/j.foodres.2010.05.001

Duchêne, E., & Schneider, C. (2005). Grapevine and climatic changes: A glance at the situation in Alsace. *Agron. Sustain. Dev. 24*, 93–99. https://doi.org/10.1051/agro:2004057

EURAC Research (2018). *Climate change and consequences for South Tyrol*. www.eurac.edu/Klimareport.

Falcão, L. D., Burin, V. M., Chaves, E. S., Vieira, H. J., Brighenti, E., Rosier, J. P., & Bordignon-Luiz, M. T. (2010). Vineyard altitude and mesoclimate influences on the phenology and maturation of Cabernet-Sauvignon grapes from Santa Catarina State. *Journal international des sciences de la vigne et du vin. Vol. 44 No. 3*. https://doi.org/10.20870/oeno-one.2010.44.3.1470

Ferretti, C. G. (2019a). Relationship between geology, soil assessment and terroir of Gewürztraminer vineyards: a case study in Dolomites of northern Italy. Elsevier. *Catena* (179) 74–84. https://doi.org/10.1016/j.catena.2019.03.044

Ferretti, C. G. (2019b). *Analisi e descrizione delle zone ristrette.* UGA Unità geografiche aggiuntive Alto Adige Südtirol. Consorzio vini Alto Adige. p. 279. http://www.provincia.bz.it/agricoltura-foreste/agricoltura/downloads/6_2019_03_Lagenbericht_definitiv_klein.pdf

Ferretti, C.G. (2020a). A new geographical classification for vineyards tested in the South Tyrol wine region, northern Italy, on Pinot Noir and Sauvignon Blanc wines. *Ecological indicators Elsevier*. https://doi.org/10.1016/j.ecolind.2019.105737

Ferretti, C.G. (2020b). Land suitability of the different cultivars in the South Tyrol wine region (Italy). *AS Agricultural Sciences, 11*. pp. 11. https://doi.org/10.4236/as.2020.1111064

Fischer, M., Rudmann-Mauer, K., Weyland, A., Stöcklin, J. (2008). Agricultural Land Use and Biodiversity in 572 the Alps. Mountain Research and Development. *International Mountain Society. 28*(2):148-155. https://doi.org/10.1659/mrd.0964

Frey, S. D., Lee, J., Melillo, J. M., & Six, J. (2013). *he temperature response of soil microbial efficiency and its feedback to climate. Nature climate change. Vol 3*. pp. 395-398. https://doi.org/10.1038/NCLIMATE1796

García de Cortázar-Atauri, I., Duchêne, E., Destrac-Irvine, A., Barbeau, G., de Rességuier, L., Lacombe, T., Parker, A. K., Saurin, N., & van Leeuwen, C. (2017). Grapevine phenology in France: from past observations to future evolutions in the context of climate change. *OENO One*, *51*(2), 115–126. https://doi.org/10.20870/oeno-one.2017.51.2.1622

Guillaumies, S., Fouquet, R., Kappel, C., Camps, C., Terrier, N., Monconble, D., Dunlevy, J., Davies, C., Boss, P., & Delrot, S. (2011). Transcriptional analysis of late ripening stages of grapevine berry. *BMC Plant Biol, 11*. 165. https://doi.org/10.1186/1471-2229-11-165

Haas, F. (2019). *Perizia tecnica di modifiche dovute prevalentemente al cambiamento climatico*. Laimburg Research Center. 10 p.

Hall, A., & Jones, G. V. (2009). Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. *Australian Journal of Grape and Wine Research, 15*. 97–119. https://doi.org/10.1111/j.1755-0238.2008.00035.x

Hopfer, H., Nelson, J., Ebeler, S. E., & Heymann, H. (2015). Correlating wine quality indicators to chemical and sensory measurements. *Molecules, 20*. 8453–8483. https://doi.org/10.3390/molecules20058453

Intrigliolo, D. S., & Castel, J.R. (2008). Effects of Irrigation on the Performance of Grapevine cv. Tempranillo in Requena. *American journal of enology and viticulture, 59*. 30–38. https://www.ajevonline.org/content/59/1/30.short

Jackson, R. S. (2014). *Wine Science: Principles and applications*. Elsevier Academic Press. pp. 996. ISBN: 978-012-373646-8

Jordão, A. M., Vilela, A., & Cosme, F. (2015). From sugar of grape to alcohol of wine: sensorial impact of alcohol in wine beverages. *Beverages, 1*. 292-310. https://doi.org/10.3390/beverages1040292

Lebon, E. (2002). Changements climatiques: Quelles conséquences pour la viticulture. In: *CR 6èmes Rencontres Rhodaniennes*. pp. 31–36. Institut Rhodanien, Orange, France

Lee, S. H., Seo, M., Riu, M., Cotta, J., Block, D., Dokoozlian, N., Ebeler, S. (2007). Vine microclimate and norisoprenoid concentration in Cabernet Sauvignon grapes and wines. *American journal of enology and viticulture, 58*. 291-301. https://www.ajevonline.org/content/58/3/291.short

MacNeil, K. (2001). *The Wine Bible*. Workman Publishing. pp. 26-29. ISBN: 1-56305-434-5

Milan, V., & Andjelko, S. (1992). *Determination of hydraulic conductivity of porous media from grain-size composition* (No. 551.49 V 986).

Montheith, J. L. & Unsworth, M. H. (1990). *Principles of Environmental Physics*. Butterworth-Heinemann. 291. ISBN: 9780123869104

Palliotti, A., Tombesi, S., Silvestroni, O., Lanari, V., Gatti, M., & Poni, S. (2014). Changes in vineyard establishment and canopy management urged by earlier climate-related grape ripening: A review. *Scientia Horticulturae. 178*. 43-54 https://doi.org/10.1016/j.scienta.2014.07.039

Parker, A., Garcia de Cortázar-Atauri, I., Chuine, I., Barbeau, G., Bois, B., Boursiquot, J.-M., Cahurel, J. Y., Claverie, M., Dufourcq, T., Gény, L., Guimberteau, G., Hofmann, R., Jacquet, O., Lacombe, T., Monamy, C., Ojeda, H., Panigai, L., Payan, J.-C., Rodriquez-Lovelle, B., Rouchaud, E., Schneider, C., Spring, J.-L., Storchi, P., Tomasi, D., Trambouze, W., Trought, M., & van Leeuwen, C. (2013). Classification of varieties for their timing of flowering and veraison using a modelling approach. A case study for the grapevine species *Vitis vinifera* L. *Agric. For. Meteorol., 180*. pp. 249-264. https://doi.org/10.1016/j.agrformet.2013.06.005

Parker, A., Garcia de Cortázar-Atauri, I., van Leeuwen, C., & Chuine, I. (2011). General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Aust. J. Grape Wine Res., 17*. 206-216. https://doi.org/10.1111/j.1755-0238.2011.00140.x

Pedri, U. (2014). Auswirkungen Unterschiedlicher Standorte auf Trauben und Weinqualität der Sorte Gewürztraminer. *Mitteilungen Klosterneuburg. 64*(1) 56-170

Pedri, U., & Pertoll, G. (2012). Der Einfluss des Standortes auf die sensorischen Eigenschaften der Weine verschiedener Rebsorten. *Obst und Weinbau.* 04/2013

Peth, D., Drastig, K., & Prochnow, A. (2017). Quantity- and Quality-Based Farm Water Productivity in Wine Production: Case Studies in Germany. *Water. 9*. pp. 88. https://doi.org/10.3390/w9020088

Pietikäinen, J., Pettersson, M., & Bååth, E. (2005). Comparison of temperature effects on soil respiration and bacterial and fungal growth rates. *FEMS Microbiology Ecology. 52* (1). 49-58. https://doi.org/10.1016/j.femsec.2004.10.002

Reynolds, A. G., Pool, R. M., & Mattick, L. R. (1986). Influence of cluster exposure on fruit composition and wine quality of Seyval blanc. *Vitis, 25*. 85-95. https://doi.org/10.5073/vitis.1986.25.85-95

Ribéreau-Gayon, P., Dubourdieu, D., Donèche, B., & Lonvaud, A. (2006). *Handbook of enology, Volume 1: the microbiology of wine and vinifications*. Wiley, New York. 512. ISBN: 978-0-470-01034-1

Roullier-Gall, C., Boutegrabet, L., Gougeon, R. D., & Schmitt-Kopplin, P. (2014). A grape and wine chemodiversity comparison of different appellations in Burgundy: Vintage vs terroir effects. *Food Chem. 152*. p.100–107. https://doi.org/10.1016/j.foodchem.2013.11.056

Sánchez Palomo, E., Diaz-Maroto, M. C., Vinas, G. M. A., Soriano-Perez, A., & Perez-Coello, M. S. (2007). Aroma profile of wines from Albillo and Muscat grape varieties at different stages of ripening. *Food Control, 18*. 398-403. https://doi.org/10.1016/j.foodcont.2005.11.006

Sitzia, T., & Trentanovi, G. (2011). Maggengo meadow patches enclosed by forests in the Italian Alps: evidence 624 of landscape legacy on plant diversity. *Biodiversity and Conservation 20*(5). pg. 945-961. https://doi.org/10.1007/s10531-625 011-0006-3

Smart, R. E. (1987). Influence of light on composition and quality of grapes. In Grapevine Canopy and Vigor Management. W.M. Kliewer, *Acta Hortic. 206*. 37-48. https://doi.org/10.17660/actahortic.1987.206.2

Smart, R. E., & Sinclair, T. R. (1976). Solar heating of grape berries and other spherical fruit. *Agric. Meteorol. 17*. 241-259. https://doi.org/10.1016/0002-1571(76)90029-7

Smart, R. E., Smith, S. M., & Winchester, R. V. (1988). Light quality and quantity effects on fruit ripening for Cabernet Sauvignon. *American journal of enology and viticulture, 39*. 250-258.

Spayd, S. E., Tarara, J. M., Mee, D. L., & Ferguson, J. C. (2002). Separation of Sunlight and Temperature Effects on the Composition of *Vitis vinifera* cv. Merlot Berries. *American journal of enology and viticulture 53.* 171-182 https://www.ars.usda.gov/ARSUserFiles/5550/2002_Spayd_AJEV_53_171-182.pdf

Stock, M., Gerstengarbe, F., Kartschall, T., & Werner, P. (2005). Reliability of climate change impact assessments for viticulture. L. E. Williams (Ed.). *Proceedings of the VII international symposium on grapevine physiology and biotechnology.* Vol. 689, pp. 29–39. Davis, USA: Acta Horticulturae. https://doi.org/10.17660/actahortic.2005.689.1

Tarara, J. M., Lee, J., Spayd, S. E. & Scagel, C. F. (2008). Berry Temperature and Solar Radiation Alter Acylation, Proportion and Concentration of Anthocyanin in Merlot Grapes. *American journal of enology and viticulture* 59: 235-247.

Tesic, D., Woolley, D. J., Hewett, E. W., & Martin, D. J. (2002). Environmental effects on cv. Cabernet-Sauvignon (*Vitis vinifera* L.) grown in Hawke's Bay, New Zealand. 2. Development of a site index. *Aust. J. Grape Wine Res., 8*, 27-35. https://doi.org/10.1111/j.1755-0238.2002.tb00208.x

Texeira, A., Eiras-Dias, J., Castellarin, S.D., & Gerós, H. (2013). Berry Phenolics of Grapevine under Challenging Environments *International Journal of Molecular Sciences, 14*(9). 18711-18739. https://doi.org/10.3390/ijms140918711

Tscholl, S., Tasser, E., Raifer, B., Schmid, A, Moser, F., Katz, H., Gartner, E., Quendler, S., Vonmetz, L., & Egarter Vigl, L. (2019). Die geländeklimatische Standortbewertung von Weinbauflächen in Südtirol. *Laimburg Journal*. 1/2019. https://journal.laimburg.it/index.php/laimburg-journal/article/view/56

van Leeuwen, C. (2001). Choix du cépage en fonction du terroir dans le Bordelais. *Journal International des Sciences de la Vigne et du Vin*. Hors Série: Un raisin de qualité : de la vigne à la cuve, 97-102.

van Leeuwen, C., & Darriet, P. (2016). The Impact of Climate Change on Viticulture and Wine Quality. *Journal of Wine Economics. 11*(1). 150–167. https://doi.org/10.1017/jwe.2015.21

van Leeuwen, C., Roby, J.-P., & de Rességuier, L. (2018). Soil-related terroir factors: a review. *OENO One, 52*(2), 173–188. https://doi.org/10.20870/oeno-one.2018.52.2.2208

van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D., Gaudillère, J. P. (2009). Vine water status is a key factor in grape ripening and vintage quality for red bordeaux wine. How can it be assessed for vineyard management purposes? *Journal International des Sciences de la Vigne et du Vin. 43*, 121–134. https://doi.org/10.20870/oeno-one.2009.43.3.798

Weaver, R. J., & McCune, S. B. (1960). Influence of light on color development in Vitis Vinifera Grapes. *American journal of enology and viticulture, 11*. 179-184.

White, M. A., Diffenbaugh, N. S., Jones, G. V., Pal, J. S., & Giorgi, F. (2006). *Extreme heat reduces and shifts United States premium wine production in the 21st century.* Proceedings of the National Academy of Sciences of the United States of America, 103-30. 11217–11222. https://doi.org/10.1073/pnas.0603230103

White, R., Balachandra, L., Edis, R., & Deli, C. (2007). The soil component of terroir. *Journal of Vine and Wine Sciences, 41*(1). 9-18. https://doi.org/10.20870/oeno-one.2007.41.1.860.

Yue, X., Ren, R., Ma, X., Fang, Y., Zhang, Z., & Ju, Y. (2020). Dynamic changes in monoterpene accumulation and biosynthesis during grape ripening in three Vitis vinifera L. cultivars. *Food Research International*, 109736. https://doi.org/10.1016/j.foodres.2020.109736

Zebisch, M., Vaccaro, R., Niedrist, G., Schneiderbauer, S., Streifeneder, T., Weiß, M., Troi, A., Renner, K., Pedoth, L., Baumgartner, B., & Bergonzi, V. (2018). *Rapporto sul clima – Alto Adige 2018*. Bolzano, Italia: Eurac Research.