

A vine physiology-based terroir study in the AOC-Lavaux region in Switzerland

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ABSTRACT

Understanding how different pedoclimatic conditions interact with vine and berry physiology, and subsequently impact wine quality, is paramount for a good valorization of viticultural terroirs and can help to optimize mitigation strategies in the face of global warming.

The aim of the present study was to establish terroir zones in a steep slope region in Switzerland based on vine and berry physiology. The study area, Villette in the AOC Lavaux, was a unique experimental site due to the homogeneity of plant material in a relatively small microclimate (140 ha) and a multiplicity of different expositions, soil types and altitudes. Vine and berry physiology as well as temperature of twenty-two plots were monitored during three consecutive seasons to investigate whether a link with pedoclimatic parameters can be established.

The annual temporal variation of the average temperature was 142 growing degree days (GDD) over all years. Remarkably, spatial temperature variability was twice as high, with a variation between most extreme plots of 395 GDDs on average over all years. PCA and hierarchical clustering of assessed vine and berry physiological parameters resulted in a vintage dependent grouping of plots differing between years, which was not congruent with geological entities. This highlights the importance of the vintage effect, which had a large influence on vine and berry physiology and impacted terroir zones more than soil groups. Important differences in budburst and flowering were observed between plots, whereas altitude was the main driver of precocity in all years, being relatively independent of the vintage, which confirms the importance of topography in viticultural terroirs.

The results of the present study help point out the potential and limits of vine and berry physiology-based terroir mapping. Furthermore, the study provides important information regarding the ripening kinetics of Chasselas grapes in relation to different pedoclimatic conditions, and it highlights the considerable spatial variability of the ripening potential of steep slope vineyards. Our study provides important information to growers in terms of the adaptation of plant material and agronomic strategies of different plots in view of global warming.

KEYWORDS

viticultural terroir, berry ripening, temperature variability, phenology, climate change

Supplementary data can be downloaded through: <https://oenone.eu/article/view/3756>

INTRODUCTION

The French word “Terroir” describes a defined area with homogeneous environmental features that are likely to confer typical wine qualities identified through collective memory and conveyed from generation to generation within a territory marked by social context, and cultural and technical choices (Tomasi *et al.*, 2013; Vaudour *et al.*, 2015). Terroir thus represents the complex interaction of soil, plant and climate in combination with the socioeconomic history of a given region (Leeuwen & Seguin 2006, Anderson *et al.* 2012, Tomasi *et al.*, 2013). Although plenty of terroir studies have been conducted in recent decennia, there is still a clear need to better understand the spatial and temporal variability of grape composition and vine physiology, that reveals the typical qualities of terroir units across a given territory. A detailed pedoclimatic characterisation of viticultural terroirs can contribute to higher consumer appreciation of wines from small traditional production regions facing increasing pressure on the global wine market, and often unable to compete with large scale viticulture due to higher production costs on slopes usually too steep for mechanisation.

Multiple approaches focusing on different physiological and pedoclimatic aspects of the “terroir equation” have been used. Nevertheless, the most researched aspects of viticultural terroirs is still the characterisation of soil variability (White *et al.*, 2007) combined with physiological and berry quality based methods, as well as the vinification and sensory assessment of wines from different terroirs (Bodin and Morlat, 2006). Several studies have shown the links between the grape metabolome and variability of soil properties. However, a strong vintage effect has been found to be mostly dominant over soil and terroir effects in some previous studies (Anesi *et al.*, 2015; Mazzei *et al.*, 2019; Pereira *et al.*, 2006b; Tomasi *et al.*, 2013; Tomasi *et al.*, 2011; Wang *et al.*, 2015). Anesi *et al.* (2015) highlight a clear terroir-specific effect on the berry transcriptome and metabolome, which persists over several vintages and allows each vineyard to be characterised by the unique profile of specific metabolites.

Zoning approaches using a vegetation index (NDVI) have also been proven to be performant in assessing terroir variability (Martínez and

Gómez-Miguel, 2019). Simulation modelling was applied to zone viticultural terroirs of cv. Aglianico in Italy, using soil-plant-atmosphere data which took into account the combined effect of soil characteristics (in terms of physical properties affecting the soil-water balance and plant-water availability) and climatic conditions. The use of these models highlighted the potential to make predictions about the effects of climate change scenarios on vineyards or terroir systems, and it demonstrated that such an integrated approach to a hybrid land evaluation can help analyse the future of terroir areas (Bonfante *et al.*, 2015; Bonfante *et al.*, 2011; Bonfante *et al.*, 2018). Recently, the microbial communities present on the surface of vine, grape berry and soil were assessed using state of the art molecular tools, and differences between vineyards plots were highlighted (Barata *et al.*, 2012; Pinto *et al.*, 2014).

It is evident from different soil studies that soil type greatly influences wine quality (Trégoat, 2003, Renouf *et al.*, 2010). Nevertheless, it is impossible to define the “best adapted” soil for wine production and terroir expression, since excellent wines can be produced on a wide diversity of soils (van Leeuwen *et al.*, 2018).

As is common in soil and vine physiology studies, the correlation between moderate water deficit and terroir perception has been evidenced (van Leeuwen *et al.*, 2009, Reynard *et al.*, 2011).

The increase in temperature during the growing season caused by global climate change (IPCC, 2018) advances vine phenology and ripening periods (Duchêne and Schneider, 2005; Jones *et al.*, 2005; Schultz and Stoll, 2010; Spring *et al.*, 2009), leading to increases in sugar concentration and losses in acidity, due to increased malic acid respiration (Rienth *et al.*, 2016; Ruffner *et al.*, 1976). Consequently, wines end up with higher alcohol levels, higher pH and lower acidity, as well as changed aromatic profiles, due to an alteration in berry secondary metabolism (Mira de Orduna, 2010; van Leeuwen and Darriet, 2016; van Leeuwen and Destrac-Irvine, 2017).

In Switzerland, the Federal Office of Meteorology and Climatology, MeteoSwiss, has reported an overall increase in annual average temperature of 2 °C in the past 150 years. In the viticulture regions of the canton of Vaud, where the study was conducted, average temperatures

from April to October had increased by 1.5 °C (<https://www.meteosuisse.admin.ch/home/climat/changement-climatique-suisse/evolution-de-la-temperature-et-des-precipitations.html>) from 1958 until 2008 (Bloesch *et al.*, 2008). Other northern European wine growing regions, such as the Loire valley, have seen increases of 1.3 °C in the past 50 years, giving an increase of between 270 and 330 GDD in the different subregions (Quénol *et al.*, 2012). Analogue observations have been made in all wine growing regions worldwide (Duchêne and Schneider, 2005; Jones, 2006; Jones *et al.*, 2005).

Altogether, global warming is expected to modify and threaten the wine typicity and terroir expression of traditional wine growing regions, depending on how grapevine varieties will adapt to new temperature regimes, and how soils will be able to mitigate the effect of changes in rainfall and evapotranspiration.

According to van Leeuwen and Seguin (2006), optimal grape maturity is crucial to obtaining maximum terroir expression, which is achieved when the precocity of the variety is suited to the local climatic conditions in such a way that full ripeness is reached by the end of the growing season. Therefore, the variety needs to be well adapted to the prevailing climatic conditions, notably to temperature. Temperature perceived by the vine within a plot is, however, modulated by pedoclimatic characteristics, such as topography, altitude, sun exposure and thus intercepted radiation (de Rességuier *et al.*, 2020). Terroir studies can therefore help to identify plots or subregions within growing areas that have the potential for producing high-quality wines in future climatic conditions. In order to evaluate the latter, different approaches can be used, for which environmental vineyard characteristics (soil, geomorphology, temperature and moisture regimes) can be either be treated as single parts which are then combined, or together in an integrated approach (Bonfante *et al.*, 2015; Bonfante *et al.*, 2017; Bonfante *et al.*, 2018).

The Swiss canton of Vaud (3800 ha) comprises eight AOC-certified areas, one of which is Lavaux (736 ha), which can be subdivided into several sub-regions of different sizes, such as the study area, Villette (140 ha). In recent years, terroir studies focusing in particular on pedoclimatic characteristics have been conducted in most regions in Switzerland, revealing a great

diversity of soils (Letessier and Marion, 2007). A recent study conducted in the entire canton of Vaud was carried out on ten different varieties in a total of 130 micro-plots, providing important information about cultivar adaptation to different sites. However, the study was performed on a relatively large scale considering the small structure of Swiss viticulture (Reynard *et al.*, 2011). Like previous studies in other regions (van Leeuwen, 2010; van Leeuwen *et al.*, 2018), the main conclusion of this terroir study was that the soil water holding capacity plays a crucial role in terroir perception, because of its indirect effects on vine and berry physiology (berry growth, sugar and available nitrogen content) (Reynard *et al.*, 2011; Zufferey, 2007). The latter study paved the way for more fine-scale mappings of different growing regions, which appears necessary to make the most of the high diversity of terroirs encountered in Switzerland.

According to recent genetic studies, the most planted white grape variety (> 60 %), *Vitis vinifera* L cv. Chasselas, originated in the lemanic arc region (Vouillamoz and Arnold, 2009) and plays a central role in most Swiss viticulture terroirs. Chasselas, is classed as an early ripening or precocious variety, which is well-adapted to cool winegrowing regions, where average temperatures range from 13 to 15 °C during the growing cycle. Such, for viticulture, relatively cool growing temperatures were encountered from the 1950s to the 1980s in the Lavaux region, but have already increased substantially due to global warming as aforementioned.

One of the most emblematic Chasselas regions is AOC-certified Lavaux, established by monks in the 11th century (<https://www.region-du-leman.ch/en/Z9278/lavaux-unesco-terraced-vineyards>), where vines have been planted on steep terraced slopes overlooking Lake Geneva at different altitudes and expositions. The slopes are mostly too steep for the mechanisation of viticulture in this area, and therefore production costs are very high, threatening the economic success of small wine producers. To maintain an economically sustainable wine industry in this viticulture patrimony it is crucial to make consumers aware of the uniqueness of the region, which could help to increase their willingness to accept higher wine prices. Another concern of Swiss winegrowers is whether the autochthonous variety, Chasselas, which is among the most precious grape

varieties globally, will still be able to adapt well to the future temperature conditions of the region in which it has been grown for thousands of years.

In order to better valorize this vinicultural patrimony, the aim of the present study was to provide a methodology based on vine physiology and berry quality in order to analyse small scale differences between plots in the production area, Villette, a sub-region of Lavaux. A further objective was to examine whether physiological measurements and pedoclimatic characterisations can help to identify the plots or sectors of the region which could adapt best to future global warming, and to determine where it will be necessary to adapt cultivation methods and plant material in the future.

MATERIAL AND METHODS

A network of 22 plots in the Lavaux subregion Villette was established in 2017 with the aim of covering maximum pedoclimatic diversity (Figure 1A). All selected plots were planted with *Vitis vinifera* L. cv. Chasselas on the rootstock 3309C, guyot-pruned and trained in a vertical shoot positioning system, with vine age ranging from 15 to 25 years.

In all plots, the phenological stages of budburst (BBCH 09) and flowering (BBCH 65) were recorded according to Lorenz *et al.* (2008) on 100 randomly chosen vines throughout all three growing seasons (2017 to 2019).

Berry development was monitored on a weekly basis starting around one week before véraison. 300 berries per plot were randomly selected from all parts of the clusters, put in plastic bags and transported to the laboratory. Average berry weight was determined and berries were pressed for subsequent analysis of total soluble solids (TSS), yeast assimilable Nitrogen (N_{ass}), degree Oechsle and main organic acids (tartaric and malic acid) by FTIR (Fourier Transform Infrared Spectroscopy). For the monitoring of sugar loading in berries, the approximation suggested by Deloire (2011) was used: sugar content per berry was calculated by multiplying sugar concentration (mg/mL) in grape juice by berry mass (g). To assess vine water status photosynthetic carbon isotope composition, the $^{12}\text{C}/^{13}\text{C}$ ratio (also known as $\delta^{13}\text{C}$) was analysed in sugars of must samples from berries from the last sampling stage. In addition to the $\delta^{13}\text{C}$ analysis, midday leaf water potential (Ψ_{leaf})

measurements were carried out on 16 August 2018, as this was the year with a marked water deficit. It was simultaneously measured by three teams with three Scholander pressure chambers (Scholander *et al.*, 1965) to cover a maximum number of plots within a relatively small time-frame of 14:00 to 16:00. Ten non-sun exposed, adult leaves from the shaded side of the canopy were selected. Ψ_{leaf} could only be assessed on a limited number of plots; i.e., those which showed the most pronounced signs of water stress (growth cessation and leaf yellowing).

The total exposed leaf area (ELA; twice the canopy height + row thickness minus % of gaps, which were estimated visually) was measured when the canopy was fully developed at the end of June / beginning of July using a standard measuring tape and divided by yield to obtain ELA per yield expressed in m^2kg^{-1} . Pruning weight was determined during the winter by sampling 30 lignified shoots per plot from the second last bud of the fruit cane, each cut to 1 m, weighed with a standard scale and expressed in g per m of shoot. Leaf nitrogen content was assessed using an N-tester on 30 leaves per plot in August of each year. Temperature probes, Tinytag Talk2-TK-4023 (Gemini Data Loggers, United Kingdom) were installed on eight representative plots in 2017 and in the remaining plots in 2018 to record maximum, minimum and daily average temperature once an hour during the vegetative period (April to October). The data loggers were set up on vine posts in the vineyard, with probes installed inside solar radiation shields (Type RS3), at a height of approximately 1.8 m.

Precipitation and temperature data were retrieved from the Agrometeo (<http://www.agrometeo.ch/>) station of Bourg-en-Lavaux (BeL) (which corresponds to the location of plot 19). The Winkler degree day summation (Winkler *et al.*, 1974) was calculated, as it is well-adapted to studying the influence of temperature on vine development. This index is based on the sum of mean temperatures above 10 °C, from 1 April to 31 October. Because temperatures were measured inside the plots, just above the canopy, and not with a classical weather station, this temperature sum is referred to as the “Canopy Winkler Index” (CWI), as mentioned in a previous study conducted in Bordeaux, France (de Rességuier *et al.*, 2020).

Exposition, altitude and inclination were retrieved from DEM (Digital Elevation Model, swisstopo 2013, 2 m resolution) with QGIS.org (2017, QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.org>). The potential intercepted solar radiation between 1 April and 30 September (2 m resolution) was calculated using ArcGIS 10.2 – solar Analyst® (Figure 3). Geology and pedology data, as well as soil hydromorphy data, were retrieved from previous studies (scale of 1:12500) (Zufferey *et al.*, 2004).

A detailed description of the methodology applied, as well as exhaustive soil maps are available on the website: <https://www.prome>

terre.ch/s3/site/1557734974_04rap00p008733terroirspedo6dzaleylutry.pdf. Soil hydromorphy was assessed visually. Changes in the oxidation state of iron and, consequently, its redistribution into stains of different colours are very good indicators of type of excess water. This characteristic was used to visually assess soil pits and to group soils into four categories as shown in Figure 1F: i) Soil with a slight redoxic character or with lateral water circulation (blue diagonal stripes in figure 1F), ii) Temporary excess water at a depth greater than 50 cm (light blue in figure 1F), iii) Temporary excess water visible at a depth of less than 50 cm (dark blue in figure 1F), and iv) Redoxicity of the sub-

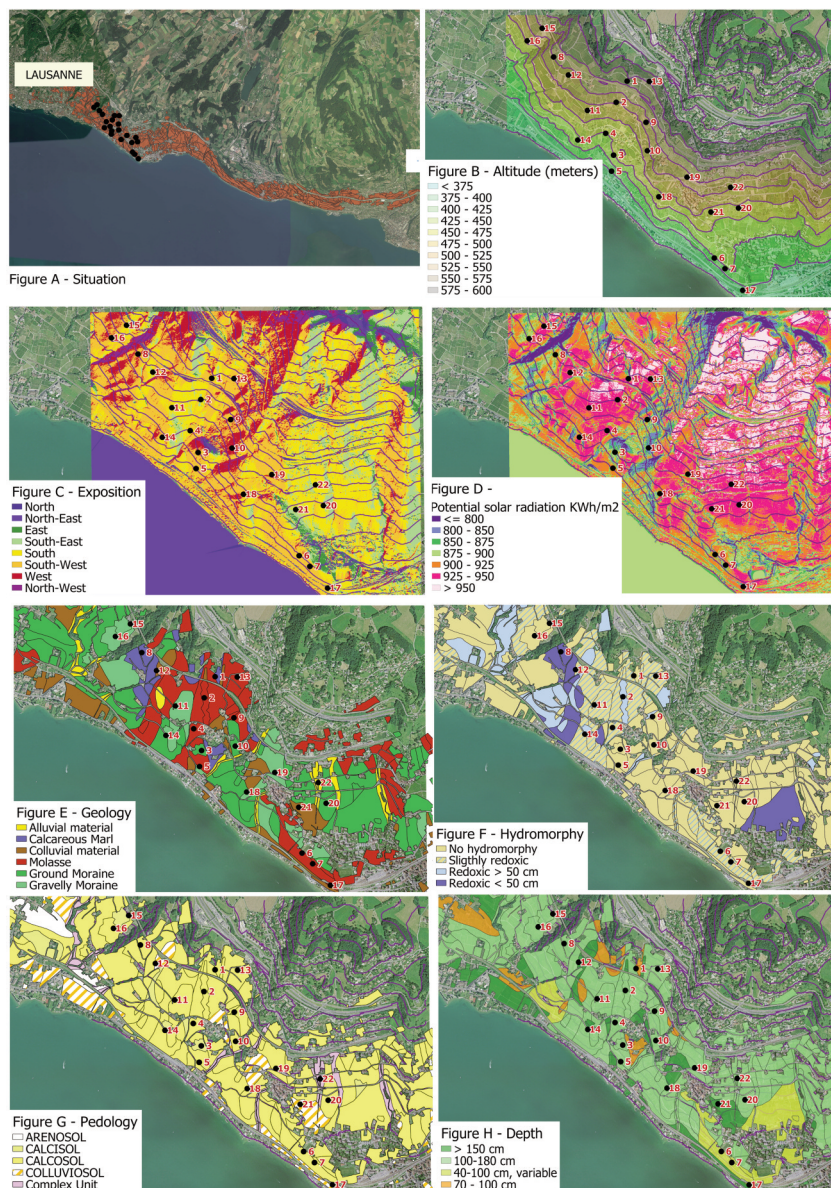


FIGURE 1. A: Localisation, B: Altitude (2 m resolution), C: Exposition, D: Potential solar radiation (2 m resolution), E: Geology, F: Hydromorphy, G: Pedology, and H: Soil depth of the study region (1:12500).

surface and/or permanent excess of water to a depth of less than 80 cm (not present in the study area).

A principal component analysis and a hierarchical clustering were performed using the R package FactoMinR (<https://cran.r-project.org/doc/FAQ/R-FAQ.html#Citing-R>) and only data available for all plots in all three years were included. Graphing and curve fitting were performed with Origin pro 2016®.

RESULTS AND DISCUSSION

The mapping of geology, altitude, soil hydromophy, exposition, pedology, soil depth and calculated intercepted radiation is illustrated in Figure 1 (B-F). The lowest plots are situated at around 375 m.a.s.l. and the highest up to around 575 m.a.s.l.. These differences in altitude correspond to a theoretical temperature difference of 1.3 to 2 °C. Regarding soil parent material, Figure 1E shows that the soils of the plots are rather heterogenous and can be grouped into plots on alluvial material (22), calcareous marl (plots 8 and 12), colluvial material (plot 21), molasse (plots 2, 4, 5, 6, 7, 9, 13 and 17), ground moraine (plots 14, 18 and 20) and gravelly moraine (plots 11, 15, 16, and 19). All the soils are calcareous with basic pH, except for plot 15,

which is not calcareous on the top layer, but has a basic pH.

The global PC analysis (Figure 2, A-C) followed by hierarchical clustering based on total inertia (Figure 2, D-F), shows pronounced differences in the regrouping of different plots between the three vintages, which did not overlap well with soil entities. In 2018, the variability of the plots was less pronounced, and the plots were only regrouped into 3 clusters, whereas in 2017 and 2019, 10 clusters were necessary to decrease statistical variability between plots satisfyingly. This indicates that in 2018 the prevailing climatic conditions of less rainfall during the vegetative phase, higher temperatures, and thus more evapotranspiration, smoothed out differences in the vine response of different plots.

The clusters that were created differed in composition from year to year and were not congruent with sections of the same soil parent material. This shows that, in the present study site, the vintage effect modulated vine physiology more than the soil effect. Similarly, previous studies in Burgundy (Roullier-Gall *et al.*, 2014), with Merlot, Cabernet Franc and Cabernet-Sauvignon grapes in Bordeaux (Pereira *et al.*, 2006a), and with Aglianico in Italy (Mazzei *et al.*, 2019) highlight the importance of

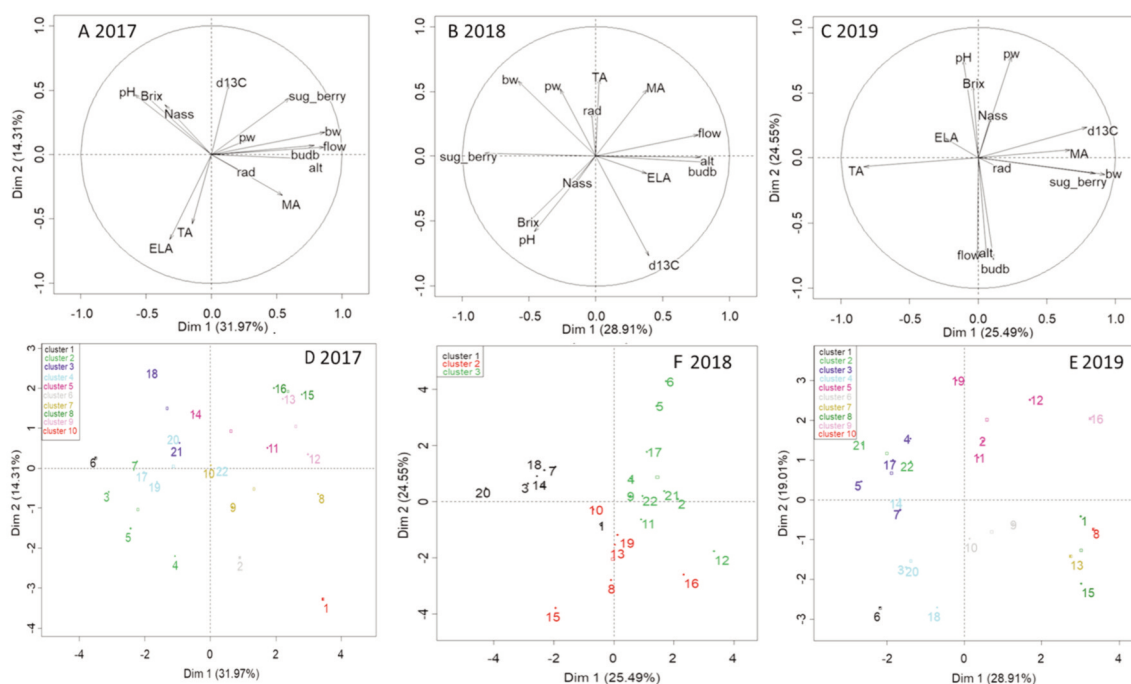


FIGURE 2. Principal component analysis of assessed parameters in 2017 (A), 2018 (B), and 2019 (C), and corresponding hierarchical clustering of 2017 (D), 2018 (E) and 2019 (F).

the vintage effect compared to the soil effect. However, other studies have shown that the spatial variability of soil was also able to maintain differences in terroir expression between very different vintages (Bonfante *et al.*, 2017). This discrepancy between previous terroir studies may be due to the more or less important differences in soils; studies on very different soils have shown that the soil-based clustering of plots is more robust and less impacted by vintage variability than clustering for more homogenous soils of other studies (Bonfante *et al.*, 2017), as is the case in the present study (Figure 1, G and H). Nevertheless, the experiments conducted here focused on plant-based measurements, and soils were not studied in-depth in individual plots.

As can be concluded from the PCA (Figure 2), the main driver of phenology was the altitude of plots, which was persistently highly correlated with the date of budburst and flowering over all years. Plots at higher altitudes consistently showed later budburst and flowering. This has been observed in previous studies (Burgos *et al.*, 2010), and can mainly be explained by the temperature decline with altitude, which is in the range of 0.65 °C to 1.0 °C for 100 m gain in elevation (Guyot, 1997).

However, as opposed to the study of Burgos *et al.* (2010), which showed that exposed leaf area

per kg correlated well with precocity, the present study showed that the ELA to yield ratio was a less important driver for phenology than altitude. This could be attributed to the fact that most plots in the present study had very similar ELA to yield ratios, which were within or above the optimal range, situated between 1.0 and 1.2 m².kg⁻¹. It is generally accepted that ELA to yield ratios above 1.2 m².kg⁻¹ for the variety Chasselas do not lead to quality gains or changes (sugar accumulation) in vine (Murisier and Zufferey, 1997; Zufferey *et al.*, 2012).

1. Climate and phenology

For the annual comparison of vintages, the climatic data of the official meteorological station of BeL (corresponding to plot 19) was used and is graphically summarised in Figure 3. The mean annual temperatures were 11.1 °C in 2017, 11.9 °C in 2018, and 12.0 °C in 2019. Average mean, minimum and maximum temperatures during the growing seasons (April to October) of all plots are depicted in Figure 4, showing that 2017 and 2019 had the same average temperature of 16.4 °C, with 2018 being considerably warmer with 17.5 °C. Thus, according to Jones' classification (Jones, 2006), the 2017 and 2019 temperatures correspond to those of intermediately warm wine growing regions (15-17 °C) suitable for early to medium ripening varieties, such as Chasselas, Pinot noir, Chardonnay or Riesling. Meanwhile - also according to Jones' classification - the growing season temperature of 2018 is characteristic of "warm" wine growing regions, where varieties with medium heat requirements, such as Merlot, Cabernet-Sauvignon and Syrah, are grown and recommended and can achieve good maturity levels suitable for high quality wine production (Jones, 2006).

The average CWI was 1527 ÷ 75 with 1514 GDD in 2017, 1640 GDD in 2018 and 1427 GDD in 2019, and an average temporal variability between years of 142 ÷ 47 GDDs. This highlights the considerably increase in heat accumulation during the growing season in 2018 compared to the other two years. The autochthonous variety, Chasselas, is classed as an early ripening or precocious variety which is well-adapted to cool winegrowing regions with average temperatures of between 13 and 15 °C during the growing cycle. According to van Leeuwen *et al.* (2008), Chasselas needs around 1204 GDD to achieve good maturity levels.

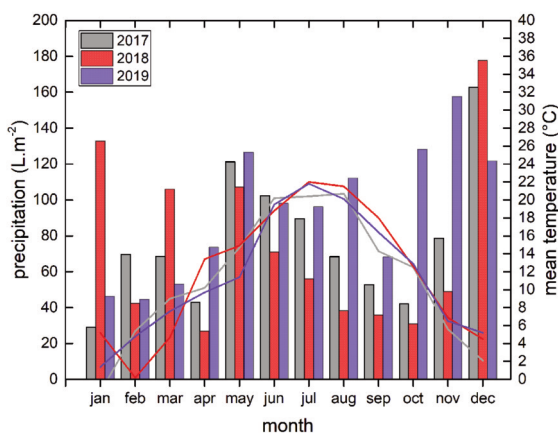


FIGURE 3. Climatograph of monthly average temperatures and precipitation of the Bourg-en-Lavaux weather station (plot 19). Berry-related parameters were taken from the last sampling date (sug_berry: sugar amount per berry, Nass: yeast assimilable nitrogen, pw: pruning weight, budb: day of budburst, flow: day of flowering, alt: altitude, rad: calculated intercepted radiation, TA: tartaric acid concentration, MA: malic acid concentration, ELA: exposed leaf area per kg yield).

Such relatively cool growing temperatures and, for viticulture, relatively low GDDs were encountered in the 1950s to 1980s in the Lavaux region, but have since increased substantially due to global warming as aforementioned, which raises the question whether Chasselas is and will be still well adapted to the study region.

With respect to global warming, 2017 and 2019 can be considered to be “classical” vintages of the Lavaux region, compared to the past two decades. However, 2018, as for many other wine growing regions as well, was an exceptionally warm year with temperatures (Labbé *et al.*, 2019) and precipitations that are to be expected more regularly in a future of climate change. It is therefore an interesting year to evaluate, how more extreme climatic conditions influence vine physiology and berry quality of different Chasselas plots, and which parcels will require adaptations in terms of agronomic strategies, rootstocks and cultivars earlier than others (van Leeuwen and Destrac, 2017).

The individual temperature readings of all the plots (Table 1) highlight the high spatial variability of temperature, despite the relatively small size of the studied region. The differences in monthly mean temperatures between most extreme plots were on average $2\text{ }^{\circ}\text{C} \pm 0.45$ and 395 ± 88 GDDs, which corresponds to a difference of more than two Winkler classes (Winkler *et al.*, 1974), thus theoretically requiring an adaptation to later ripening varieties in plots, which accumulate the highest GDDs. Such a high spatial variability has been recorded

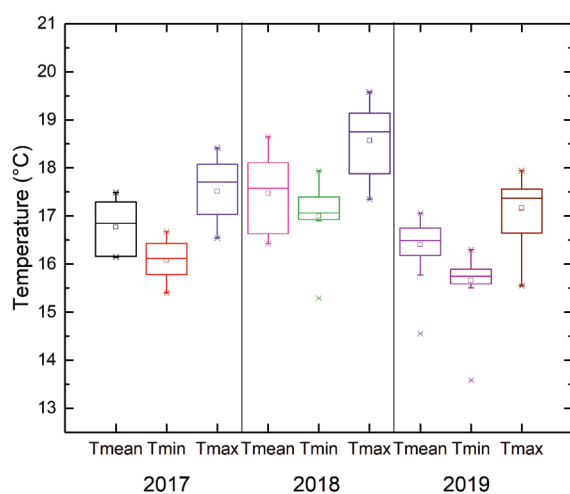


FIGURE 4. Mean, minimum and maximum temperature of all studied plots in 2017, 2018 and 2019.

for other viticultural regions, such as in a recent study in the Bordeaux appellations, Saint-Émilion, Pomerol and their satellites, with CWI spatial variations of up to 320 GDDs (de Rességuier *et al.*, 2020). The latter study, however, involved a vineyard surface area of 19,233 ha and is thus considerably larger than the Villette area studied here. The high variability observed in the study region can be mainly attributed to large differences in altitude, as well as to differences in exposition and possibly to the differing proximity of plots to the lake (Burgos *et al.*, 2010). These results highlight the variability of the ripening potential of the analysed plots and emphasise the need for taking such microclimatic variations into account in future AOC regulations, as is being discussed for Swiss winegrowing regions at the time of writing. The precise characterisation of high spatial temperature variability within a region also represents very valuable knowledge for the adaptation of agronomic and plant material-based mitigation strategies in view of global warming.

This temperature variability mediated phenology accordingly. Budbreak (BBC 09) occurred on average over all plots and years on 11 April and mid-flowering (BBCH 65) on 12 June. The long-term average date for budbreak between 1958 and 2008 of Chasselas in the canton of Vaud, AOC la Cote (recorded in Pully), was 23 April, and that of flowering 25 June with start of harvest on 8 October (Spring *et al.*, 2009). Considering only the last 20 years (2000 to 2020) a substantial advance of phenology is observed, compared to the 1958 to 2008 period, with budbreak that occurred on average on 16 April and flowering the 15 June. In the present study, average budbreak of all plots was earliest in 2017, occurring on 3 April, followed by 2019 on 12 April. Interestingly, budbreak was latest in 2018, on 18 April, owing to cool temperatures at the beginning of the year. This difference was caught up due to warm temperatures in 2018 between budburst and flowering, which was reached on 8 June in 2017, 5th June in 2018 and 24th June in 2019. This phenological data for Chasselas in Pully highlights that 2017 and 2019 were within the tendency of the 2000 to 2020 period, whereas 2018 showed significant advances which are more frequently to be expected in the future.

The window of budburst between the earliest and latest plots for all years was 8.6 days, and for

TABLE 1. Annual mean (T_{mean}), minimum (T_{min}) and maximum (T_{max}) temperatures and growing degree days (GDD) of 2017, 2018 and 2019 of all plots from April till October.

Plot	Altitude (m.as.l)	Exposition	2017				2018				2019			
			T_{mean}	T_{min}	T_{max}	GDD	T_{mean}	T_{min}	T_{max}	GDD	T_{mean}	T_{min}	T_{max}	GDD
1	560	S-W	16.4	15.6	17.3	1424	16.6	15.9	17.5	1480	16.3	15.5	17.2	1408
2	500	S	16.2	15.8	16.5	1379	16.5	15.6	17.3	1426	15.8	15.0	16.6	1307
3	450	S-W	17.3	16.5	18.2	1604	17.5	17.4	18.8	1670	16.6	15.8	17.4	1463
4	450	S-W	16.8	16.1	17.7	1511	18.6	17.1	18.0	1887	16.6	15.9	17.5	1468
5	400	S-W	17.5	16.7	18.4	1642	16.4	17.9	19.6	1415	16.2	15.7	16.6	1366
6	420	S-W	17.4	16.4	18.1	1624	18.3	17.6	19.2	1814	17.1	16.3	17.9	1552
7	410	S-W	17.1	16.4	17.8	1554	17.3	16.9	17.7	1606	16.4	16.0	17.4	1439
8	530	S-W					17.4	16.9	17.8	1618	17.1	15.5	16.4	1513
9	520	S-W					16.4	17.2	19.0	1415	16.1	15.6	16.5	1359
10	490	W					17.9	17.2	18.8	1733	16.6	15.9	17.5	1470
11	490	S					18.1	17.1	19.3	1770	16.7	15.9	17.7	1498
12	520	S-W					17.8	17.0	18.7	1710	16.4	15.5	17.4	1421
13	580	S-W					16.6	16.9	18.5	1520	16.3	15.6	17.1	1413
14	440	S					16.4	17.5	19.1	1415	16.2	15.7	16.7	1369
15	520	S-W					18.0	17.1	18.9	1744	16.4	15.6	17.3	1425
16	470	S-W					17.8	17.0	18.7	1703	16.5	15.8	17.5	1458
17	390	S-W					16.7	15.3	17.9	1463	14.6	13.6	15.5	1100
18	470	S-W					18.3	17.5	19.2	1805	16.8	16.0	17.8	1510
19	510	S-W	16.2	15.8	16.5	1379	17.3	16.9	17.7	1606	16.0	15.6	16.4	1349
20	470	S					18.1	17.4	19.0	1772	16.8	16.0	17.7	1505
21	470	S					18.5	17.5	19.5	1849	16.9	16.1	17.9	1527
22	500	S					17.6	17.1	18.3	1670	16.7	15.9	17.6	1482
Avg	477		16.4	15.9	16.9	1515	17.5	17.0	18.6	1640	16.4	15.7	17.2	1427

flowering it was 5.3 days. This variability was highest in 2019, when differences in budbreak between the earliest and latest plots reached 12 days and were reduced to 6 days for flowering. Interestingly, the spatial variability of phenology was smallest in 2018, when budbreak occurred much more homogeneously, with differences between earliest and latest plots reduced to only 4 days. Flowering date variability between the earliest and latest plots was significantly reduced in comparison to budbreak, with 6 days in 2019 and 2017, and only 4 days in 2018 (Figure 5). This reduced window for flowering between plots is observed in other studies as well (de Ressaúier *et al.*, 2020).

As stated earlier the main driver of budbreak and flowering was altitude; the highest plots, such as 1, 8, 13 and 15, 16 were consistently the latest in all years (Figure 5). The chronological order of plots starting flowering was the same as for budburst for most plots in all years (Figure 5). Altogether, these observations indicate that in warmer and drier years - which are expected to occur more frequently in the future - the main

phenology stages, and thus ripening, occur more homogeneously, which could alleviate small scale terroir differences under upcoming climatic scenarios. This observation indicates that under future climate a regrouping of traditional terroir zones may be required.

According to several studies and empirical observations, the optimal harvest “window” in traditional high quality winegrowing regions where terroir expression is considered to be optimal is between 10 September and 10 October (van Leeuwen, 2010; van Leeuwen and Seguin, 2006). Despite the discussed advanced phenology, the last sampling date (just before the first plots were harvested and sampling was stopped) was 20 September in 2017, 19 September in 2018 and 30 September in 2019. However, plots consistently showing later budburst and flowering are most likely the ones with the best potential for the production of high quality Chasselas in future warming conditions, because such plots will ripen later during cooler periods of the year, thereby maintaining higher acidity and lower alcohol

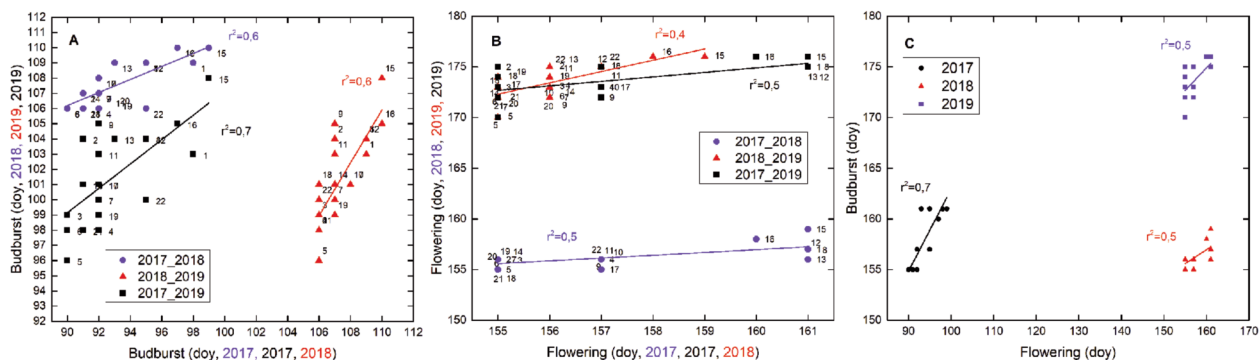


FIGURE 5. Correlation of budburst (A), flowering (B) and between budburst and flowering (C) of all years and plots.

levels, which leads to high terroir expression (van Leeuwen and Seguin, 2006).

2. Precipitation, plant water regime and berry maturity

Annual rainfall in 2017 and 2019 was very similar, with values of between 928 and 1020 l.m⁻². However, in the April to September period, there was considerably lower rain in 2017, with only 510 l.m⁻², compared to 2019, with 703 l.m⁻² (Figure 3). Precipitation in 2018 was significantly lower than in 2017 and 2019, with only 366 l.m⁻² from April to September. Most renowned winegrowing regions have an annual rainfall of between 300 and 1000 l.m² per year (van Leeuwen, 2010). Rainfall in 2017 and 2019 was thus relatively high in comparison to traditional rain-fed viticulture regions, but this can be considered as typical for the Lavaux region. 2018 was a remarkably dry year for the region, with only 50 % of the precipitation in 2019 and 70 % of that in 2017 during the growing season, and signs of water stress, such as early cessation of shoot growth followed by leaf yellowing, were already observed in June 2018 in some plots, which is not common in this area.

The average values for the main compounds which determine berry quality in all plots at the last sampling date in the three different years are depicted in Figure 6 (A-E). The $\delta^{13}\text{C}$ analysis (Figure 6E) shows that no water deficit ($\delta^{13}\text{C} < -26$) was experienced by the vines in 2017 and 2019, and that water deficit was mild (-24.5 to -26) to moderate (-23 to -23) in 2018 (Rienth and Scholasch 2019). No differences were found in N_{ass} between different years; however, a greater variability between plots can be observed in 2019 (Figure 6F).

Total soluble solids (TSS in °Brix), as a proxy for sugar concentration, were 18.8 °Brix in 2017, 19.3 °Brix in 2018 and 18.6 °Brix in 2019 and were not significantly different in the three years (Figure 6A). In 2018, all plots combined had the highest TSS at the last sampling date. This can be explained by higher temperatures and a water deficit (Figure 6E) during ripening, which favoured sugar accumulation and caused a concentration mediated by the reduction in berry volume due to lower water availability, as observed in previous studies (Ojeda *et al.*, 2002; Ojeda *et al.*, 2001; Rienth *et al.*, 2014; Scholasch and Rienth, 2019; van Leeuwen *et al.*, 2009). The lower sugar quantity per berry in 2018 can be explained by the reduction in berry size (Figure 6C), which was greater than the increase in sugar accumulation, thus resulting in a lower total amount of accumulated sugar inside the berry.

The variation between the highest and lowest plots in TSS was 13.4 %, 13.2 % and 26.0 % in 2017, 2018 and 2019 respectively. Interestingly, sugar content per berry showed considerably greater yearly variations than sugar concentration (Figure 6C) with 27 % in 2017, 56 % in 2018 and 35 % in 2019. It may be possible to explain the higher spatial variation in berry sugar content in 2018 by the differences in water availability between plots due to differences in soil hydromorphy, which caused greater water deficits in well-drained plots in 2018.

In 2017, berry sugar content and berry size was significantly higher than in 2018 and 2019. This could be due to high temperatures during the month of June 2017 (Figure 3; Table 1), when the green berries were still in their first growth stage, during which they undergo a rapid

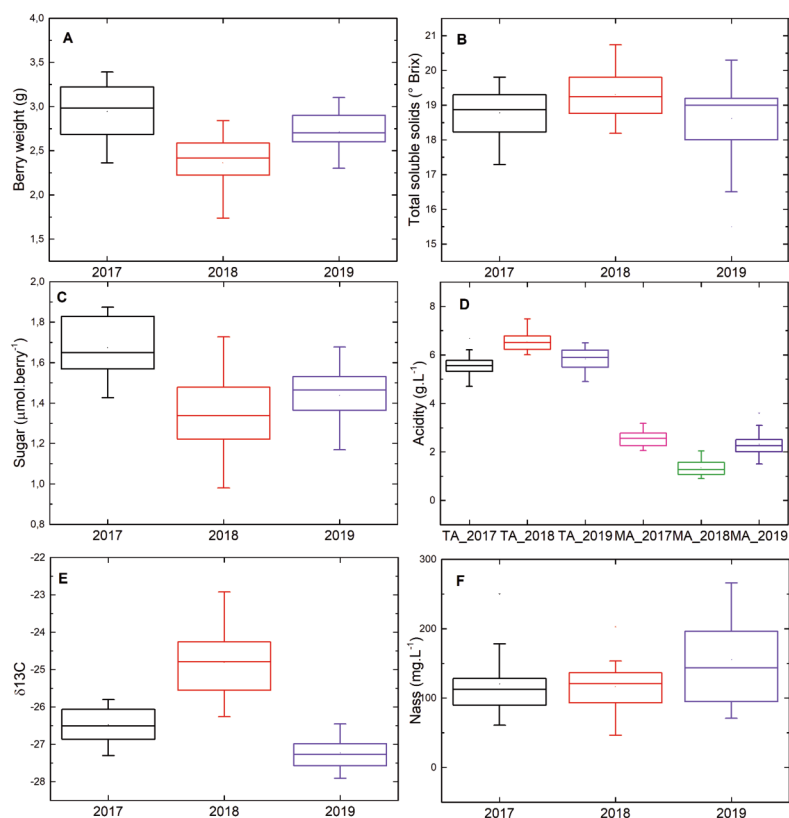


FIGURE 6. Average values of compounds analysed at the last berry sampling stage. (A) Berry weight, (B) Total soluble solids- TSS, (C) Sugar per berry, (D) Acidity (separated in malic acid (MA) and tartaric acid (TA)), (E) $\delta^{13}\text{C}$ (F) and Nass (assimilable nitrogen).

increase in berry weight and volume as a result of cellular expansion and multiplication, both processes being directly accelerated by temperature (Keller, 2010). Furthermore, 2017 was the year with the coolest temperatures in September, which could have extended the ripening phase, thus the cessation of phloem unloading into the berries.

Differences in tartaric acid (TA) concentration between vintages were less marked than those of malic acid (MA) (Figure 6 C), which can be explained by the higher temperatures in 2018, leading to a faster degradation of MA during ripening (Etienne *et al.*, 2013; Luchaire *et al.*, 2017; Pellegrino *et al.*, 2019; Rienth *et al.*, 2016; Torregrosa *et al.*, 2019). TA showed a less marked vintage effect, because it is not metabolised after véraison (Rösti *et al.*, 2018) and is thus relatively independent of temperature; however, it is exposed to concentration/dilution effects mediated by differences in berry volume, which explains its variation. Accordingly, TA concentration was

highest in 2018, the vintage year with the lowest berry weights.

The different metabolisms of MA and TA can be well-illustrated by considering the variation between the highest and lowest concentrations. TA variation was 36 %, 23 % and 27 % and was up to the three times higher for MA with variations between the lowest and highest plots of 45 %, 85 % and 90 % in 2017, 2018 and 2019 respectively.

In terms of the different analysed berry compounds, the correlation among plots was rather low overall, as can be illustrated by the TSS values for different vintages in Figure 7 (A, B and C). Interestingly, when considering the ratio of MA to TA (Figure 7 (D, E and F)) as an independent parameter of berry volume, the correlation was found to be higher. This can again be attributed to the non-catabolisation of TA. Also worthy of note was that MA degradation was relatively consistent among plots between different vintages (Supplementary Figure 1). Plots consistently exhibiting a high MA/TA ratio, resulting in a higher total acidity,

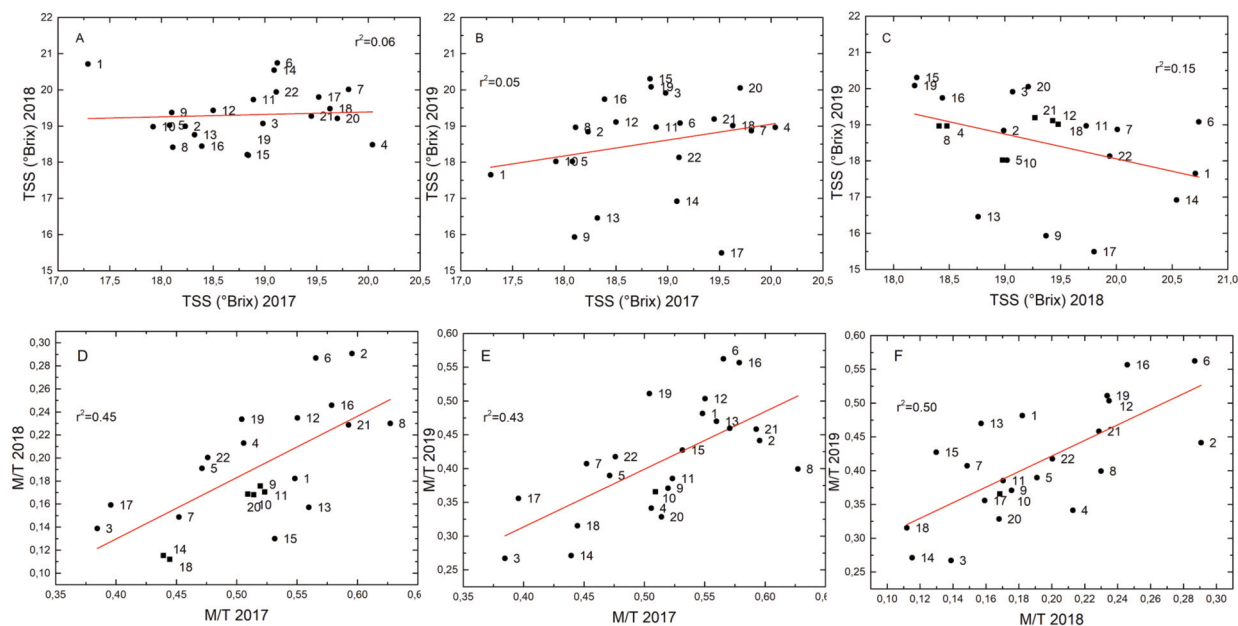


FIGURE 7. Correlation of TSS and M/T ratio for all plots and years on the last sampling date.

are supposedly better adapted to future climatic conditions; for example, plots at high altitudes or with less sun exposure. Chasselas plots, however, consistently showed low MA/TA ratios, thus lower total acidity, might therefore require adaption of agronomic strategies, rootstocks and/or varieties in the near future.

Correlations between $\delta^{13}\text{C}$ and different characteristics of berry quality on the last sampling date are illustrated in Figure 8. In 2017, $\delta^{13}\text{C}$ showed no correlation with berry weight, Nass or TSS; however, in 2019, a tendency for lower berry weight and a slight water deficit can be noted. In 2018, a mild (-24.5) to moderate water deficit (-23 to -24.5) was correlated with a reduction in berry size (Figure 8A), but only a trend in higher sugar concentration can be observed (Figure 8B). It is well-known that water deficits can cause a reduction in berry size depending on their severity and time of occurrence during berry development (Ojeda *et al.*, 2001; Ojeda *et al.*, 1999; Scholasch and Rienth, 2019). The analysed carbon in berry sugars might also, to a small extent, come from reserves that were built up in previous seasons, depending on abiotic and trophic factors (Hunter *et al.*, 1995); therefore, it does not necessarily totally reflect the water deficit of vines in one season. This is indicated by the rather weak correlation between LWP and $\delta^{13}\text{C}$ (Figure 8C). Thus, in addition to $\delta^{13}\text{C}$ analysis, water stress was directly assessed via

Ψ_{Leaf} measurements in 2018. Due to the logistics and duration of each measurement, however, this could, only be done on a limited number of plots, which were chosen via visual assessment and when adult leaves showed pronounced signs of water stress (leaf yellowing).

As can be seen in Figure 8, Ψ_{Leaf} in most affected plots reached values as low as -1.5 MPa, corresponding to severe water stress. However, most of the assessed plots were within the range of mild to severe water stress, with values of between -1.1 and -1.3 MPa (Rienth and Scholasch, 2019; van Leeuwen *et al.*, 2009; Zufferey, 2007). It is well known that water deficits can cause a reduction in berry size, depending on their severity and time of occurrence during berry development (Ojeda *et al.*, 2001; Ojeda *et al.*, 1999; Scholasch and Rienth, 2019). Berry volume followed a bell shaped curve < -1.3 Mpa, whereas milder water deficit did not impact final berry size (Figure 7B). When plotting Ψ_{Leaf} against TSS, several previous studies showed a bell shaped relationship between water deficit and sugar concentration (van Leeuwen *et al.*, 2009; Zufferey, 2007; Zufferey *et al.*, 2017; Zufferey *et al.*, 2018), with moderate to severe water deficit (-1.1 to -1.3 MPa) positively affecting the sugar concentration of berries, and severe water deficit decreasing it; this, however, is not supported by our data (Figure 7A). Despite having a relatively negative water potential on the day of

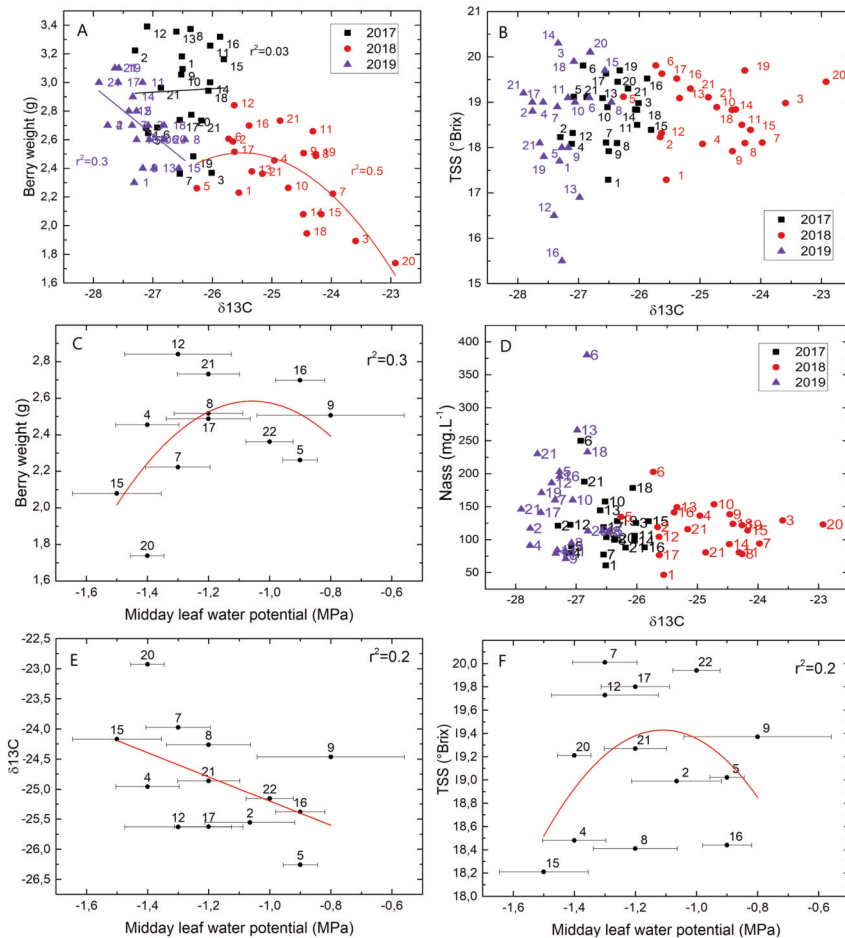


Figure 8. Correlation of $\delta^{13}\text{C}$ vs berry weight (A), $\delta^{13}\text{C}$ vs TSS (B), $\delta^{13}\text{C}$ vs N_{ass} (D) for all plots and vintages; Only for 2018: LWP vs berry weight (C), LWP vs $\delta^{13}\text{C}$ (E) and LWP vs TSS (F).

measurement, plot 8 did not show higher TSS at the end of the season. This is very likely because this block is situated on very hydromorphic soil (Figure 1), which did not, therefore, cause a water deficit during the season. However the plot showed a low leaf water potential due to a high VPD (Vapor Pressure Deficit) at the time of measurement. This highlights the limits of measuring Leaf Water Potential at midday, as it can be highly influenced by short-term environmental fluctuations. When water deficit was severe (-1.3 MPa), sugar accumulation was transiently impeded, as was the case for plots 4 and 15. Such a bell shape relation of water deficit on sugar concentration has been shown in several previous studies on different varieties (van Leeuwen *et al.*, 2009; Zufferey, 2007; Zufferey *et al.*, 2017; Zufferey *et al.*, 2018).

Winemakers and most physiological studies generally focus on sugar concentration expressed as TSS, density, $^{\circ}\text{Oechsle}$, or $^{\circ}\text{Baume}$; however,

with these units it is not possible to conclude on berry sugar uploading by the phloem. From a physiological point of view, nonetheless, berry sugar content can be useful for assessing when grape berries reach so-called physiological ripeness and cease to import sugars into the berry towards the end of ripening. Therefore, in the present study, we also took into account sugar accumulation during ripening on a per berry basis as proposed by Deloire (2011);

Figure 9 illustrates different pattern of mean sugar accumulation of the three years and highlights that in 2017 phloem unloading ceased earlier than in 2019 and 2018, the year were most likely water deficit slowed down sugar accumulation during mid-ripening. Interestingly, patterns of individual parcels, show a high heterogeneity (Figure 10 (2017) and supplementary Figures 2 (2018) and 3 (2019)) and plots that showed similar patterns of sugar accumulation were regrouped in each year. This

way it can be noticed that in 2017, several plots did not achieve physiological ripeness, meaning that sugar accumulation did not cease before the last sampling date, as can be most clearly seen in Figure 10A. Conversely, Figure 10C regroupes plots that finished sugar unloading well before the last sampling. Higher temperatures during ripening in 2018 accelerated sugar accumulation and advanced cessation of sugar uploading in most precocious plots (Supplementary Figure 2A). Sugar accumulation patterns can also give information about the water deficit experienced by the vines. This can be seen in 2018, when in several plots the influence of water deficit slowed down sugar accumulation during the ripening phase (Supplementary Figure 2B). The sugar accumulation patterns in 2019 (Supplementary Figure 3) were similar to those in 2017. The analysis of sugar accumulation patterns of plots can represent a valuable tool for characterising the precocity of vineyard plots, and thus for assessing their potential in view of future climatic conditions; cultural practices and plant material can then be adapted accordingly. As such plots in which sugar accumulation ceases relatively early before harvest may be less well-adapted to future

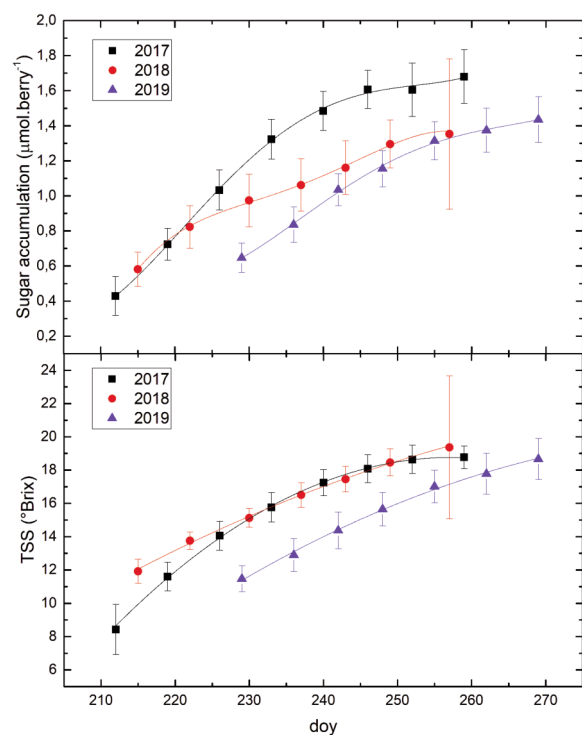


FIGURE 9. Evolution of average sugar accumulation per berry and average sugar concentration of all plots in each year.

temperature conditions and agronomic strategies and plant material would need to be adapted earlier and vice versa for plots where phloem sugar unloading ceases later.

CONCLUSION

The conducted study aimed to identify homogenous groups of vineyard plots using relatively simple vine and berry physiology-based measurements and eventually establish a relation to pedoclimatic characteristics in a small viticultural steep slope terroir in the AOC Lavaux in Switzerland. The clustering of plots resulting from assessed parameters did not, however, yield consistent results between climatically distinct years, highlighting the complex relationship between plant and berry physiology and geological entities. Our study confirms that vintage climatic variations (the vintage effect) highly influence vine physiology and berry ripening, which made it impossible to consistently regroup vineyard plots in the studied region by plant- and fruit-based measurements. However, the study was only conducted for three years and a longer observation period may have yielded more consistent findings. Furthermore, the present data highlights the vast spatial temperature variability within a relatively small viticulture region, which provides a very valuable basis for making decisions on agronomic and plant material-based mitigation strategies in the context of global climate change. The methodology applied here enabled us to identify important differences in the phenology of the studied plots, thus providing useful information for growers regarding future climate change scenarios and the adaptation of cultural practices, as well as choice of plant material (variety and rootstock) to mitigate future global warming.

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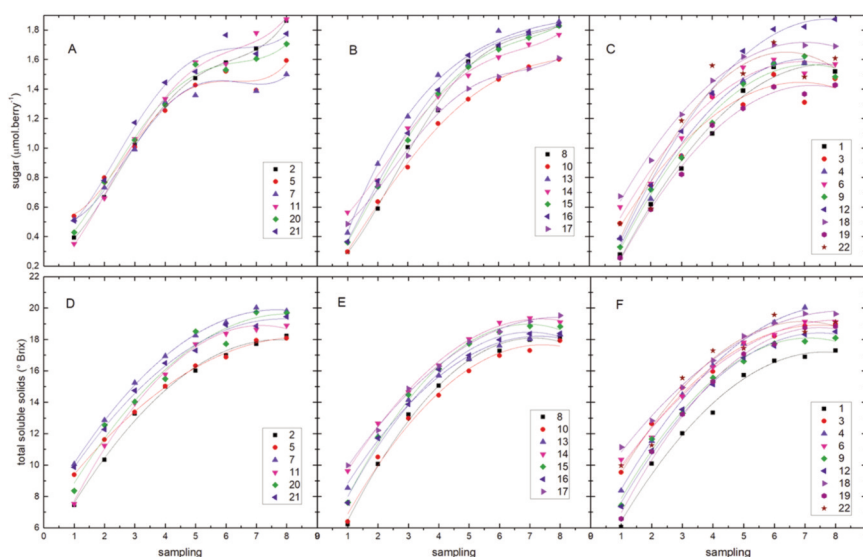


FIGURE 10. Example of a re-grouping of plots according to their sugar accumulation (quantity and concentration) patterns in 2017. A (sugar.berry⁻¹) and D (TSS): plots that slowed down sugar accumulation at mid-ripening followed by a late increase, B (sugar.berry⁻¹) and E (TSS): plots, where sugar accumulation never ceased, C (sugar.berry⁻¹) and F(TSS): plots, where sugar accumulation had already ceased 2 to 3 weeks before final sampling.

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