SOIL PARAMETERS IMPACT THE VINE-FRUIT-WINE CONTINUUM BY ALTERING VINE NITROGEN STATUS

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Abstract

Aims: A three-year study was conducted in the Vaud vineyards of Switzerland to evaluate the effects of « terroir » on the ecophysiology and fruit composition of *Vitis vinifera* L. cv. Doral (a white variety) and the characteristics of the produced wine.

Methods and results: The impact of soil on the vine-fruit-wine continuum was evaluated at 13 sites during three seasons. Except for soil, the vineyards presented almost identical climatic characteristics and used similar cultivation techniques. We monitored the nitrogen status of the vines by measuring yeast assimilable nitrogen (YAN) in the must. The soil modulated vine nitrogen status by its fertility and rooting depth. Low vine nitrogen status induced a high soluble solid content, low malic acid content, and high pH in fruits and resulted in small berries and low vine vigour. Wines were produced in a standardised manner from each site; then, they were subjected to sensory and chemical evaluation. YAN in musts was the parameter that best explained the variation in wine sensory characteristics. Wines made from grapes with low YAN values had negative sensory characteristics such as astringency and low aromatic complexity.

Conclusion: This work provided evidence of how soil can influence fruit composition and the sensory attributes of wine. Vine nitrogen status in relation to soil characteristics was a key parameter contributing to the terroir effect.

Significance and impact of the study: This study focuses on the whole vine-fruit-wine continuum and uses scientific rigour to investigate the terroir effect over a number of vintages.

Key words: terroir, vine nitrogen status, soil effect, wine quality, vine-fruit-wine continuum

Abbreviations: PCA principal component analysis; SSC soluble solid content; YAN yeast assimilable nitrogen

Résumé

Objectif : L'objectif de cette étude menée dans le vignoble vaudois (Suisse) était d'évaluer l'influence du terroir sur l'écophysiologie de la vigne et sur la qualité des raisins et des vins issus de *Vitis vinifera* L. Doral (un cépage blanc).

Méthodes et résultats : L'effet du sol a été évalué en étudiant 13 sites différents lors de trois millésimes (2007-2009). À l'exception du type de sol, les différents sites présentaient des caractéristiques climatiques ainsi que des méthodes culturales similaires. Le type de sol a influencé l'alimentation azotée de la vigne et plus particulièrement la teneur en azote assimilable par les levures des moûts. Sur les terroirs favorisant une faible alimentation azotée de la vigne, les baies étaient de taille plus petite, les moûts présentaient une teneur en sucres ainsi qu'un pH supérieur et des teneurs plus faibles en acide malique. Les raisins de chaque site ont été vinifiés selon un protocole standard, puis les vins ont été analysés chimiquement ainsi que lors de séances sensorielles. La teneur en azote assimilable des moûts a été le paramètre qui expliquait le mieux les différents profils sensoriels des vins. Les vins issus de moûts ayant une faible teneur en azote assimilable ont été jugés négativement lors de l'analyse sensorielle car ils présentaient de l'astringence et une plus faible complexité olfactive.

Conclusion : Cette étude met en évidence l'influence du type de sol sur la composition des raisins ainsi que sur les caractéristiques sensorielles des vins. L'alimentation azotée de la vigne en relation avec le type de sol a été un paramètre important de l'effet terroir.

Signification et impact de l'étude : Cette étude a évalué l'effet terroir lors de trois millésimes sur la physiologie de la vigne, la composition des raisins et la qualité des vins.

Mots clés : terroir, alimentation azotée, qualité des vins, sols

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INTRODUCTION

In recent years, terroir characteristics (i.e., the environmental conditions where grapes are grown) have become increasingly important for the wine industry. Viticulture and winemaking techniques have improved markedly over the course of the last century. However, to improve the technical aspects of wine production, a better understanding of how environmental conditions affect fruit and wine quality is needed.

In addition to climate, soil also makes a major contribution to the terroir effect. However, the role of soil has not been studied widely and is still debated. For example, neither Noble (1979) nor Bader and Wahl (1996) found any relationship between soil and wine, whereas other authors have observed that soil affects both grape and wine composition. Most of the studies on this subject have described the effects of soil, but few have identified the contributing factors. The water-holding capacity of soil and its influence on vine water status may contribute to the soil effect (Zufferey and Murisier, 2007; van Leeuwen *et al.*,, 2009). However, except for soil water availability, little evidence is available showing that other factors contribute to the effect of soil on wine. Wine characteristics have been reported to depend on soil fertility (Choné *et al.*,, 2001; de Andrés-de Prado *et al.*,, 2007), soil texture (Reynolds *et al.*,, 2010) and soil depth (Coipel *et al.*,, 2006).

In this study, the modulation of vine nitrogen status by soil and its influence on fruit and wine characteristics were examined. Nitrogen is one of the most influential mineral nutrients in the physiology of the grapevine and has major implications for winemaking (see Bell and Henschke, 2005, and literature cited therein). Factors influencing vine nitrogen status can be divided into three groups: genetic factors, cultivation practices, and environmental factors. Genetic factors include cultivars and rootstocks (Holzapfel and Treeby, 2007) and cultivation practices include the time, form and rate of fertilisation (Spayd *et al.*, 1994; Linsenmeier *et al.*, 2008; Neilsen *et al.*, 2010), and soil management (Spring, 2001). However, little research has been reported on the dependence of vine mineral uptake on environmental conditions, particularly on soil parameters.

Therefore, we conducted this study to analyse the relationship between wine attributes and soil properties. We used vineyards presenting almost identical climatic and topographic characteristics. The same viticultural cultivation techniques and winemaking protocols were followed. Because the vineyards were situated on different soils, we assumed that any differences between the wines could be attributed to the soil. Our objective was to determine whether vine nitrogen status is a key environmental factor contributing to the variable attributes of wines produced from different soils.

MATERIALS AND METHODS

1.Vineyard sites

The study was conducted on 13 sites in the La Côte region of Vaud vineyards (Switzerland), approximately 40 km east of Geneva. The climatic features of this region include a mean July temperature of 18.6 °C, a mean annual rainfall of 945 mm, and a growing season rainfall of 583 mm. With a heliothermal index of 1600, this region belongs to the class of « cool viticultural climate » (Tonietto and Carbonneau, 2004). The sites were planted with *Vitis vinifera* L. cv. Doral, which is a Swiss white cultivar resulting from a cross of Chasselas x Chardonnay. Each site (circa 250 m^2) is located in the middle of a wider commercial vineyard (on-farm approach). Vines grafted on 3309 Couderc were planted in 2003. After an installation phase, the project was conducted over three vintages (2007-2009). Vines were trained in espalier (single Guyot with vertical shoot-positioned foliage) with south-north row orientation. The planting density was 6400±700 vines/ha. The sites presented almost identical topographic (altitude and slope) characteristics and were situated no more than 60 km away from each other. Therefore, the climatic parameters were considered to be homogenous. The yield was limited by cluster thinning at the stage of pea-sized berries. The non-irrigated plots were cultivated by the winegrowers. Fertilisation practices were recorded for each location. The range of nitrogen (N) fertilisation (soil fertilised with urea) was between 0 and 50 kg N/ha per year. The average N fertilisation rate per ha and year was 25 kg N for locations on bottom moraines and 15 kg N for those on colluvial and gravelly moraines. Floor management was permanent sod with a grass and legume mixture between rows and herbicide-treated strips under the vines.

The majority of the soils in the study area are made up of alpine moraines, a heterogeneous mixture of unevenly sized debris. The different soils were identified according to Letessier and Fermond (2004) and then regrouped in two categories for this paper: one group of bottom moraines (eight sites) and a second group consisting of colluvia (two sites) and gravelly moraines (three sites). The bottom moraines originated from eroded material underneath a glacier (~1 km in thickness) that was thus under great pressure. Consequently, soils belonging to this category are highly compact. Gravelly moraines are characterised by a high coarse element content (>60%). Colluvia are deposits found at the foot of a slope and originate from progressive erosion of the dominating slope. Soil samples were taken randomly from 10 points in each site on 28.9.2010 and were then analysed

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by the Swiss soil testing service (Sol-Conseil, Nyon). The properties of the two soil categories are summarised in Table 1. The total lime content was under 12% for each vineyard.

2. Vine analysis

Total leaf area (TLA) was determined for a selected number of sites (10 vines per site) during the 2008 and 2009 seasons. The area of an individual leaf was computed as described by Carbonneau (1976).

The cane pruning weight was estimated by taking 50 pruned branches at the penultimate position on the fruit branch at every site. The branches were weighed after being standardised to one meter and removal of the lateral shoots.

Foliar analysis was performed to determine the levels of leaf nitrogen (Kjeldahl method) and phosphorous. The samples consisted of 30 leaves taken in the cluster region at veraison. Yeast assimilable nitrogen (YAN) was estimated by near-infrared (NIR) spectroscopy (WineScan®, FOSS NIRSystems, USA). The YAN assessment is based on the formol titration of Sörensen (Aerny, 1996). We used the juice of 200- berry samples harvested at eight time points from veraison to harvest to assess YAN.

We assessed vine water status by analysing the carbon isotope composition ($\delta^{13}C$) of musts (Gaudillère *et al*.,, 2002). After pressing the grapes, a sample (few millilitres) of juice was taken and autoclaved. Then, the dry extract was converted into CO_2 using pure oxygen. The $\delta^{13}C$ was determined by continuous flux mass spectrometry (Avice *et al*., 1996).

To estimate root distribution, trenches were excavated during August 2009 at eight different sites. Four pits were dug on the bottom moraine sites, and four were dug on the colluvium or gravelly moraine sites. At each site, one trench was dug parallel to the vine rows to a depth of at least 1.5 m. The trench had a width of 1.2 m and was situated at a distance of 20 cm from the vine row. Trench wall profiles were used as numbering planes. Root numbers were evaluated using a quick method of counting roots in each 10-cm layer. The results are expressed as the number of root interceptions per 10-cm x 120-cm layer.

3. Grape and wine analysis

Fruit maturation was monitored at each site every two weeks from veraison to harvest. Two hundred berries were gathered from each site, weighed fresh and manually juiced. The analytical parameters were measured using the WineScan® instrument at the oenological laboratory at Agroscope Changins-Wädenswil. The wine composition was assessed at bottling via NIR spectroscopy.

The harvest date was determined separately for each site to achieve the same degree of grape ripening. At each site, 150 kg of grapes were manually harvested and used for winemaking. Microvinification was then conducted identically for all lots by the same winemaker. The same fermenting yeast was added to all lots (CY 3079®, Lalvin), and 300 mg/L of diammonium phosphate was added to each must to aid the completion of fermentation.

Table 1 - Soil properties (0-50 cm).

Soil properties	Soil categories	
	Bottom moraines	Colluvia, Gravelly moraines
Soil pH	**7,8** ± 0,5	**7** ± 0,8
Organic matter (%)	**1,3** ± 0,4	**1,6** ± 0,4
Clay (%)	**19** ± 5	**20** ± 5
Silt (%)	**35** ± 5	**29** ± 5
Sand (%)	**44** ± 9	**51** ± 10
P^1 (mg/kg)	**137** ± 53	**98** ± 53
K^1 (mg/kg)	**204** ± 66	**207** ± 22
Mg^1 (mg/kg)	**350** ± 230	**167** ± 27
Ca^1 (mg/kg)	**28'920** ± 21'474	**5'126** ± 5'774
N_{min} [2] (kg/ha)	**13,8** ± 8,9	**21,7** ± 10,9

Values are the mean ± standard deviation of the sites belonging to each soil category. No significant difference was observed between the two soil categories. [1]Reserve elements measured by the [NH_4-Ac.+EDTA 1:10] extraction method. [2]Soil mineral nitrogen (NO_3^- and NH_4^+).

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Table 2 - Root number and diameter as a function of soil depth and soil category. Values are the mean of measurements from four sites for each soil category.

Soil depths	Soil categories	Root diameters		
		> 5 mm	1-5 mm	< 1 mm
0-50 cm	Bottom moraines	2^{ns}	7^{ns}	126^{ns}
	Colluvia, Gravelly moraines	6^{ns}	4^{ns}	96^{ns}
50-100 cm	Bottom moraines	0^{ns}	5^{ns}	82^{ns}
	Colluvia, Gravelly moraines	1^{ns}	2^{ns}	82^{ns}
100-150 cm	Bottom moraines	0^{ns}	1^{ns}	7^{a}
	Colluvia, Gravelly moraines	0^{ns}	0^{ns}	45^{b}

Soil category means with different letters are significantly different at $p<0.05$. ns: not significant.

Sensory analysis of the experimental wines was conducted two months after bottling by a panel composed of 13 experienced tasters (ages ranging between 24 and 62 years). The panel was trained in two 3-h sessions to describe the aromas and mouth-feel properties of wine. Reference standards were prepared to represent the descriptors and were used during training to calibrate the panel. During the test sessions, the wines were characterised using a conventional profile (ISO 13299, 2003). They were evaluated in duplicate according to a completely randomised design (Williams latin square). The panellists rated the intensities of 19 sensory attributes on a computer using FIZZ software (Biosystèmes, Couternon, France). Scores were obtained by averaging the scores of all judges for two replicates.

4. Statistical analysis

Statistical analysis was carried out with R software (R Development Core Team, Vienna, (Austria). Duncan's test was used for mean differentiation. Relationships between variables were analysed by simple linear regression (Pearson's correlation). The significance of the regression is indicated with asterisks: *, **, *** indicate significance at $p<0.05$, 0.01, and 0.001, respectively. The grape composition data were analysed with a two-way ANOVA procedure. Sensory data were examined with Principal Component Analysis (PCA) using a correlation matrix to determine whether the soil categories could be separated from each other.

RESULTS

1. Rooting depth

Root distribution in relation to soil category was studied for a number of selected sites (Table 2). The only significant difference between the two soil categories was observed at a depth of 100-150 cm for the numbers of small roots (< 1 mm). Vines on bottom moraines had very few roots in the zone below one meter, whereas vines located on colluvia or gravelly moraines still showed well-developed root systems in that zone. Although the number of large roots (> 5 mm) in the upper part of the soil was not significantly different between soil categories, the p value was only slightly over the significance threshold ($p=0.053$).

For sites on bottom moraines, the root depth seemed to be more limiting than in the four sites on colluvia and gravelly moraines, where roots were still present at the maximal depth of 1.5 m. However, in all four cases, no roots were found at depths over 1.5 m in bottom moraines.

2. Vine nitrogen status

Nitrogen fertilisation rate ranged from 0 to 50 kg/ha. On the majority of locations, however, nine out of 13 received less than 30 kg/ha of mineral nitrogen, which is considered to be a low rate of fertilisation for grapevine. No relationship was observed between fertilisation rate and vine nitrogen status (Spearman's rank and Pearson's correlations). Furthermore, nitrogen fertilisation was not significantly different between soil categories. Although nitrogen fertilisation was not exactly identical, it was homogenous enough to be considered as a minor factor influencing the vine nitrogen status.

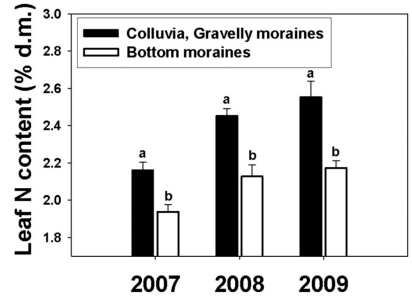


Figure 1 - Nitrogen content of leaves at veraison expressed as % of dry matter.

Vertical bars indicate the standard error of the mean. Means between soil categories with different letters are significantly different at $p<0.05$. 2007-2009.

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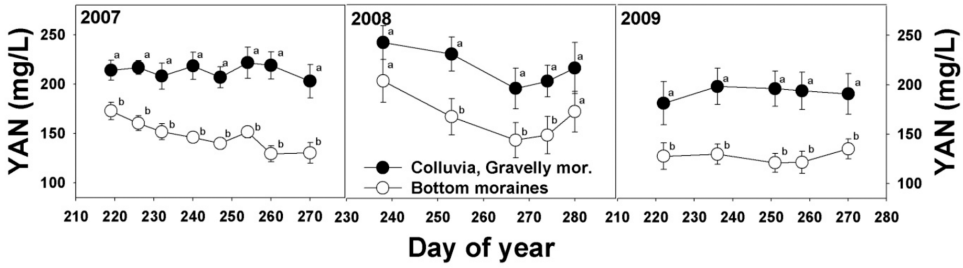


Figure 2 - Seasonal evolution of yeast assimilable nitrogen (YAN) in grapes for each soil category.
The final data points correspond to the harvest. Vertical bars indicate the standard error of the mean. Soil category means with different letters are significantly different at p<0.05. 2007-2009.

Mean leaf nitrogen content was grouped by soil category (Fig. 1). Leaf nitrogen content at veraison (onset of maturation) was significantly lower for vines established on bottom moraines for all three seasons. Leaf nitrogen content was significantly lower in 2007 than in the other years for both soil categories. The YAN level in berries was also dependent on soil category (Fig. 2). Vines growing on bottom moraines showed significantly lower nitrogen content in musts for all three vintages (-20% to -30%). Differences between the two soil categories were noticeable from veraison to harvest.

3. Vine physiology

Total leaf area per vine (TLA) was measured at several sites in 2008 and 2009 and compared to the YAN levels in grapes at harvest (data not shown). We observed a tendency towards a correlation between the two parameters in 2008 (R^2=0.31), and this correlation was strong in 2009 (R^2=0.69***). In that year, sites with the highest YAN values tended to have a total leaf area two-fold greater than sites with the lowest YAN values.

Cane pruning weight was positively correlated with YAN during two seasons (2007: R^2=0.37*; 2009: R^2=0.59**). This relationship was observed in 2008, but it was not significant (R^2=0.27). Berry weight was positively correlated with YAN in 2007 (R^2=0.68***).

YAN was positively correlated to leaf nitrogen content for all three years (R^2 > 0.51** for each individual year), whereas it was negatively correlated with leaf phosphorous content in 2008 and 2009 (data not shown). Vines on bottom moraines tended to have higher phosphorous levels in leaves, but the difference was only significant (*) for 2009 (data not shown).

The results for vine water supply are depicted in Figure 3. In 2007 and 2008, the values for $\delta^{13}C$ from all sites ranged from -27.7‰ to -25.2‰. These values of $\delta^{13}C$ correspond to no water deficit (van Leeuwen *et al.*, 2009). In 2009, the values for $\delta^{13}C$ ranged from -26.5‰ to -25.2‰, with the exception of one site (-26.5‰ to -23.5‰) where the water regime was more restricted. We observed no effect of soil categories on vine water status. Furthermore, no correlation between vine water and nitrogen status was observed.

4. Fruit composition

A significant positive relationship existed between YAN and the malic acid content in grapes at harvest over the three years (R^2 > 0.47* for each individual year). Soluble solid content (SSC) tended to be negatively correlated with YAN (significant (*) only in 2008). Except for 2009, YAN was correlated with must pH. Soil category had a significant effect on the average level of all fruit parameters except for titratable acidity (TA) and tartaric acid content (Table 3). For the majority of fruit parameters, the vintage effect was the dominant factor, and soil category accounted for only a tiny fraction of the observed variation. In contrast, YAN was the parameter most affected by soil category, and vintage exhibited no significant effect on it. Berry weight was moderately affected by soil category but not by year. Thus, the model only poorly explained berry weight variation (Residuals = 79%). Between years (vintage effect), we observed a significant difference between the means of most fruit parameters, except for YAN and berry weight (Table 4). On average, the vines on bottom moraines showed

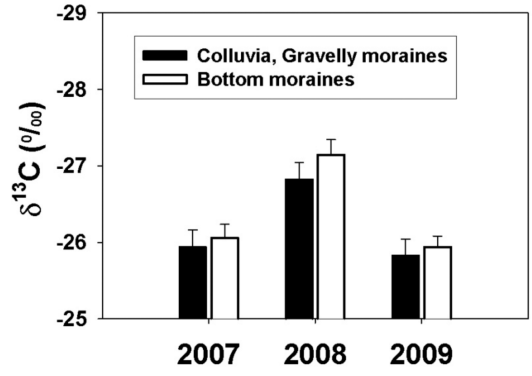


Figure 3 - Carbon isotopic composition in must sugars ($\delta^{13}C$) at harvest in the different soil categories.
Vertical bars: standard error. Means were not significantly different for the three years.

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Table 3 - Effects of soil and year on fruit parameters at harvest. Percentage of variance attributable to soil category and year.

Fruit parameters	Soil categories (%)	Years (%)	Residuals (%)
SSC (ºBrix)	7*	71***	22
pH	3*	80***	17
Titratable acidity (g/L)	1^{ns}	87***	12
Tartaric acid (g/L)	1^{ns}	71***	28
Malic acid (g/L)	3*	80***	17
YAN (mg/L)	30***	9^{ns}	61
Berry weight (g)	11*	10^{ns}	79

The data were analysed by two-way ANOVA. 2007-2009. *, **, *** indicate significance at p<0.05, 0.01 and 0.001, respectively. ns: not significant.

Table 4 - Effects of soil and year on fruit parameters at harvest.

	Soil categories		Years		
Fruit parameters	Bottom moraines	Colluvia, Gravelly moraines	2007	2008	2009
SSC (ºBrix)	21,4^{a}	20,7^{b}	20,2^{a}	20,5^{a}	22,2^{b}
pH	3,08^{b}	3,12^{a}	3,02^{b}	3,05^{b}	3,23^{a}
Titratable acidity (g/L)	9,8^{ns}	10,0^{ns}	9,4^{b}	12,5^{a}	7,9^{c}
Tartaric acid (g/L)	8,0^{ns}	7,8^{ns}	8,7^{b}	8,1^{a}	7,2^{c}
Malic acid (g/L)	3,4^{b}	3,9^{a}	3,3^{b}	5,4^{a}	2,3^{c}
YAN (mg/L)	146^{b}	204^{a}	165^{ns}	196^{ns}	163^{ns}
Berry weight (g)	1,72^{b}	1,84^{a}	1,73^{ns}	1,85^{ns}	1,75^{ns}

The data were analysed by two-way ANOVA. 2007-2009. Titratable acidity is expressed in g tartrate/L. Means with different lettersare significantly different at p<0.05. respectively. ns: not significant.

smaller values of YAN (-40%), malic acid (-15%), and pH (-1%) but higher soluble solid content (+3%) than those on colluvial or gravelly moraines.

5. Wine characteristics

Wine pH was positively correlated with YAN in 2007 and 2008 (R^2>0.60**). For all three vintages, wines produced from vines growing from bottom moraines showed lower pH values (data not shown).

The results of the sensory analysis are depicted in Figure 4. In 2007, YAN was positively correlated with the olfactory complexity score (R^2=0.36*). Moreover, YAN was also positively correlated with the colour intensity score (R^2=0.35*) and the overall quality score (R^2=0.43*). The negative correlation between YAN and the astringency score was particularly strong (R^2=0.82***). In 2008, YAN was correlated with the perceived acidity (R^2=0.43*), astringency, and persistence scores. Although the relationship was not significant, the overall quality score was positively related to YAN. In 2009, significant correlations were observed between YAN and the wine sensory descriptors olfactory complexity, overall quality, and persistence. The wines made from grapes grown on the two soil categories exhibited significant differences in the sensory analysis for all three years. The wines produced from vines on bottom moraines were mainly characterised by a high astringency score, low olfactory complexity, and a low overall quality score.

DISCUSSION

For the three years of this study, YAN in berries and leaf nitrogen content were closely correlated, as corroborated by Holzapfel and Treeby (2007). In addition, antagonism was observed between the nitrogen and phosphorous levels in leaves, as previously described (Bell, 1994; Maigre, 2002). This relationship might be explained by the fact that low vine nitrogen status tends to diminish vigour. Therefore, phosphorous becomes concentrated in less biomass, thus explaining the higher phosphorous content of nitrogen-deficient vines.

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Mycorrhizal fungi, which are responsible for phosphorous acquisition in field-grown vines (Schreiner, 2007), may also play a role. Nitrogen-induced reductions in root carbohydrates might limit the carbon available for mycorrhizae (Keller, 2005).

Vine vigour is an essential criterion in viticulture, and it is defined as the annual vegetative biomass. Vine vigour was positively correlated with YAN, as reflected in both total leaf area (TLA) and cane pruning weight. Vines with low nitrogen status (YAN) had a smaller TLA and a lower cane pruning weight. Plant vegetative growth is highly

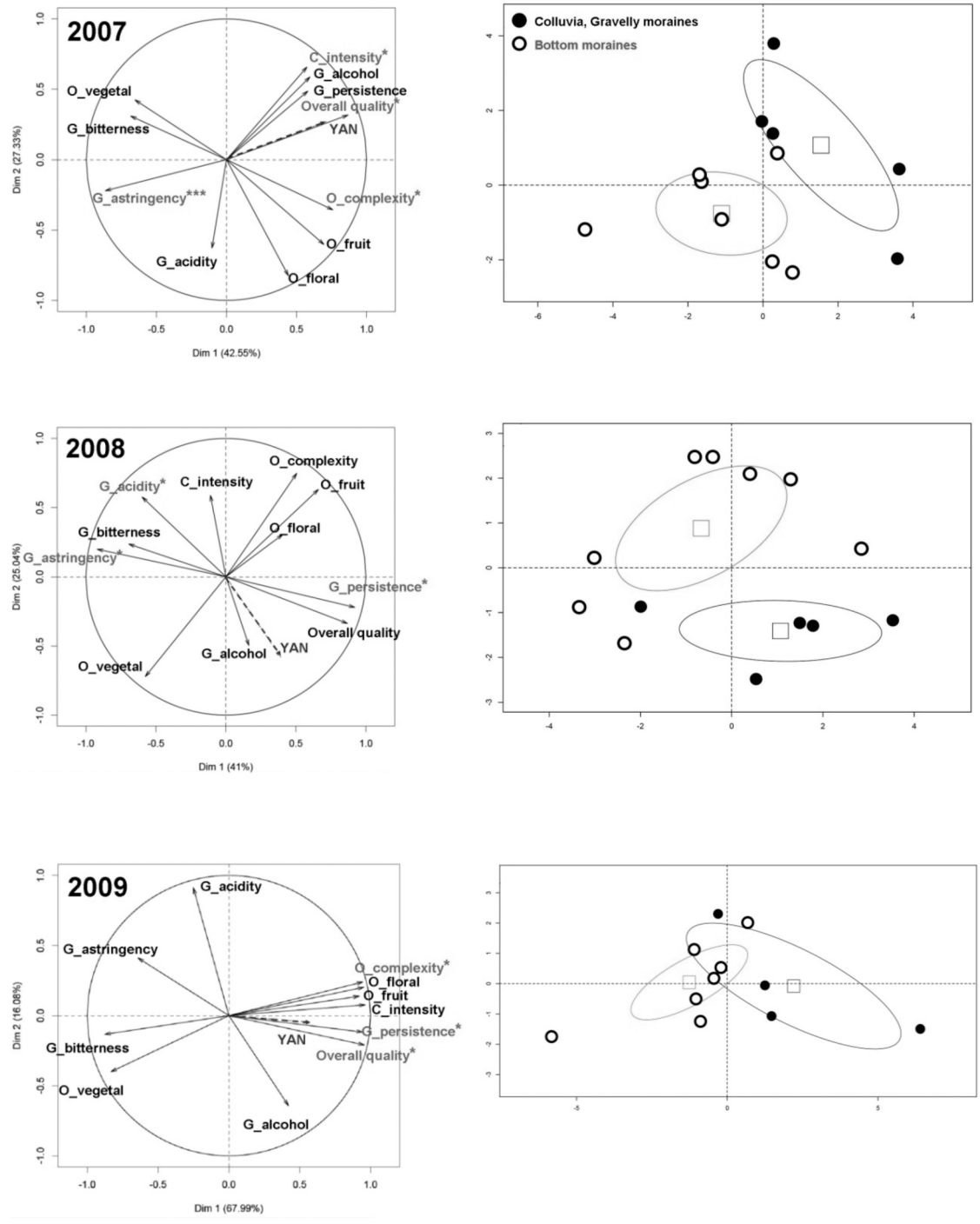


Figure 4 - PCA representation of the sensory variables: C_=colour, O_=olfactory, G_=gustatory. Yeast assimilable nitrogen (YAN) at harvest figures on the graph as illustrative variable.

Sensory variables are depicted in gray when they were significantly correlated to YAN. *, **, *** indicate significance at p<005, 0.01 and 0.001, respectively. Barycentre of each soil category are represented with their confidence interval at 95%. 2007-2009.

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related to nitrogen uptake (Gastal and Lemaire, 2002). Spring *et al*. (2009) reported that YAN was negatively correlated with TLA in a trial involving hedgerows of varying heights. Excessive leaf surface area can increase nitrogen demand and thereby lower the vine nitrogen status via a dilution effect. However, we did not observe a dilution effect in our study, and nitrogen was a limiting factor for vine vigour; vines with low nitrogen status produced less biomass. The link between vine nitrogen nutrition and vine vigour was confirmed by the relationship between vine nitrogen status and berry weight. Sites with low vine nitrogen status had smaller berries.

Most authors have reported an increase of YAN with ripening (Stines *et al*., 2000; Rodriguez-Lovelle and Gaudillère, 2002; Keller, 2010), but we did not observe this pattern over the three-year period. However, their YAN levels tended to be higher than those reported herein. In our study, the YAN levels were rather constant and did not vary with fruit maturity.

Nitrogen availability for grapevines is invariably related to water supply because nitrogen (nitrate is the primary source for grapevines) can only enter roots if it is first dissolved in water (Keller, 2010). Furthermore, Spring *et al*. (2009) reported that fruit nitrogen levels were lower during dry years. However, no correlation between YAN and vine water status was observed in this study. The effect of soil on vine nitrogen status was strong and overshadowed the effect of water supply.

Vine nitrogen status was found to be related to soil category. Vines planted on bottom moraines showed a significantly lower nitrogen status over the three years. Soil has been reported to have an influence on vine nitrogen status (Rankine *et al*., 1971; Choné *et al*., 2001; Peyrot des Gachons *et al*., 2005). The difference in vine nitrogen status between the two soil categories might be explained by different soil rooting depth. Indeed, the root distribution was different between the two soil categories. The difference in rooting depth was probably the result of soil compactness. Whereas the colluvia and gravelly moraines were deep and loose soils, the bottom moraines were characterised by highly compact mother rock (Letessier and Fermond, 2004) due to the great pressure (1 km of ice represents up to 800 T/m^2) from the Würm glaciation. Here, the high compactness of the bottom moraines seemed to limit root penetration, explaining the influence of this soil category on rooting depth. Morlat and Bodin (2006) emphasised the importance of soil depth on vine behaviour and fruit composition. Moreover, Cortell *et al*. (2005), who studied variations in vine growth in a commercial vineyard in Oregon (USA), observed a strong association between soil rooting depth and vine vigour. Myburgh *et al*. (1996) correlated vine vegetative growth with root development as impacted by the root resistance of the growing medium. Morlat and Jacquet (1993) proposed a relationship between maximum rooting depth and aboveground vine vigour. Since we observed no differences in water supply ($\delta^{13}C$) among soil categories, the higher vine vigour on colluvia and gravelly moraines was the effect of better nitrogen supply due to deeper roots. Although it was not significantly different between the two soil categories, soil fertility might cause variations in vine nitrogen status. Soil fertility was reported to have an impact on fruit parameters and might be an important factor in the terroir effect (Choné *et al*., 2001, Peyrot des Gachons *et al*., 2005, de Andrés-de Prado *et al*., 2007). Here, both the physical and chemical characteristics (soil rooting depth and soil fertility) of the soil affected the quantity of nitrogen available to the plant and accounted for the difference in vine nitrogen status observed between the two soil categories.

Variations in fruit composition were found to be related to the vine nitrogen status imposed by the soil. Vines on bottom moraines produced grapes with significantly higher SSC values and lower YAN values (Table 4). These observations indicate a relationship between vine nitrogen status and fruit sugar accumulation. Therefore, vine nitrogen status impacts carbon partitioning within the plant. These results confirm previous research indicating that environmental stresses (such as moderate nitrogen deficiency) enhance the SSC value of grapes (Choné *et al.,* 2001; Keller, 2005). YAN and malic acid content were positively correlated over the three-year study period. Increased malic acid in must with higher vine nitrogen status has been observed in the majority of studies (Keller *et al.,* 1998; Maigre, 2002; Hilbert *et al*., 2003). This relationship can be explained partially through vine vigour. Vines with a large N supply develop a denser canopy, which, in turn, affects the microclimate (temperature and sun exposure) of the grapes. Ultimately, this results in less degradation of malic acid in the berries (Ruffner, 1982). The effect of nitrogen may be more direct because plant nitrogen metabolism is related to organic acid metabolism. Nitrogen assimilation leads to the alkalinisation of plant cells, which is counteracted by the production of malic acid (Martinoia and Rentsch, 1994). In addition, higher vine nitrogen status was related to higher must pH in 2007 and 2008. Several authors have reported a relationship between vine nitrogen status and must pH (Spayd *et al.,* 1994; Keller *et al.,* 1999). Keller (2010) suggested that this relationship may be explained by the higher potassium uptake associated with roots with high nitrate uptake.

In this study, we investigated the influence of two major environmental parameters, soil and climate (through the vintage effect). The influence of the yearly climate was stronger than that of the soil. Previously, van Leeuwen *et al*. (2004) described the overwhelming effect of yearly climate on grape composition. Yearly variations of climate

are empirically important for determining grape and wine quality in a septentrional vineyard. However, YAN was not influenced by the vintage in our study, in contrast with most studies (Bell and Robson, 1999; Nicolini *et al*., 2004; Spring *et al*., 2009). Instead, YAN was the fruit parameter most affected by soil type. A corroborating study by van Leeuwen (2010) also showed that YAN was primarily influenced by the soil. Furthermore, YAN was the only fruit parameter found to be more influenced by soil than by climate (vintage).

The chemical characteristics and sensory qualities of the wines were closely correlated with vine nitrogen status. Similarly to must pH, wine pH was positively correlated with YAN, except in 2009. Some authors have observed the same relationship between nitrogen in must and the pH of must and wine (Kliewer *et al*., 1991; Spayd *et al*., 1994). YAN levels in must were found to be negatively associated with the astringency score. Astringency is elicited by polyphenolic compounds and has been reviewed extensively by Brossaud *et al*. (2001). Astringency is a primary attribute of red wine; however, white wine also contains (although to a smaller extent) polyphenols such as catechin, caffeic acid, and quercetin (Maggu *et al*., 2007). In white wine, high polyphenol content causes bitterness (Ribéreau-Gayon *et al*., 1998). In the present study, perceived astringency was considered to be a negative sensory attribute because it was negatively correlated with overall quality score. Moreover, it is well known that nitrogen deficiency stimulates the production of secondary metabolites such as polyphenols (Keller, 2010). For instance, the shikimate acid pathway, which is responsible for the production of many plant secondary metabolites, is stimulated under nitrogen deficiency (Weaver and Herrmann, 1997). Consequently, the unpleasant astringency observed in our study might be due to compounds (likely polyphenols) in the fruits that result from modifications of plant metabolism to adapt to a low nitrogen supply. Accordingly, Choné *et al*. (2006) reported a higher polyphenol content in musts made from Sauvignon blanc grapes with low nitrogen nutrition.

We observed that vine nitrogen status is a key factor that determines wine quality. The overall quality score was positively correlated with the level of nitrogen compounds present in the grapes at harvest during the three-year study period. Wine quality was always lowest for wines made from grapes with low YAN values. The positive influence of vine nitrogen status on wine sensory quality has been previously documented (Conradie, 2001; Torrea and Henschke, 2004; Spring and Lorenzini, 2006). Furthermore, the untypical aging off-flavours (UTAs) observed in some white wines have been related to vine nitrogen status (Hoenicke *et al*., 2001; Linsenmeier *et al*., 2007). Indeed, UTA wines lose their varietal character and begin to exhibit atypical aromatic flavours such as naphthalene notes (mothballs) (Winter, 2003). Nitrogen deficiency has been identified as a factor underlying UTAs, as shown by a negative correlation between YAN in must and UTA levels (Gessner *et al*., 1995).

Vine nitrogen status might influence wine sensory attributes in two ways: i) the synthesis of flavour/aroma compounds in grapes and ii) the influence of YAN on yeast metabolism. Peyrot des Gachons *et al*. (2005) suggested that low vine nitrogen status is detrimental to the production of thiol precursors in Sauvignon blanc grapes and therefore negatively impacts the aromatic expression of wine. Volatile thiols also play a role in the flavour of several other varieties (Tominaga *et al*., 2000). Our observations regarding the relationship between YAN and wine aroma complexity confirm the importance of vine nitrogen status for white wine aroma. In addition, next to sugars, nitrogenous compounds are quantitatively the most important yeast nutrients (Henschke and Jiranek, 1993). The concentration of nitrogen compounds in must (YAN) is known to affect yeast metabolism and thereby to influence the duration of the fermentation and the formation of aroma/flavour compounds in the wine (Rapp and Versini, 1995; Bell and Henschke, 2005). Nevertheless, knowledge of the effects of vine nitrogen status on the formation and accumulation of grape compounds that influence wine sensory attributes is surprisingly limited. Therefore, further work is required to elucidate the links between vine nitrogen status, secondary metabolites in grapevines, and the environmental conditions in which the grapes are grown.

CONCLUSIONS

This work provides evidence of how geopedology can influence vine physiology, fruit composition and wine characteristics. Soil, through its fertility and vine rooting depth, was found to be an important environmental parameter that modulates vine nitrogen level, vine physiology, fruit composition and the characteristics of the resulting wine. Vine nitrogen status is a key factor contributing to the terroir effect, which usually depends on fertilisation practices. Because we used similar fertilisation practices, soil parameters were primarily responsible for the variations in vine nitrogen status. The characteristic that best explained the variable sensory characteristics of the wines made from grapes from the different sites was the level of yeast assimilable nitrogen in the must.

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