Terroir Influence on Water Status and Nitrogen Status of non-Irrigated Cabernet Sauvignon (*Vitis vinifera*). Vegetative Development, Must and Wine Composition (Example of a Medoc Top Estate Vineyard, Saint Julien Area, Bordeaux, 1997)

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Terroir effect on vine vigour, must composition and wine quality was investigated for Cabernet Sauvignon during a rainy vintage in a top estate of the Medoc area (Bordeaux, France). Soil was the only variable in this survey. Vine water status was determined by means of leaf water potential. Mild water deficits were observed only on a gravelly soil with a shallow root zone. Vine nitrogen status was determined by total must nitrogen content. Nitrogen status varied from deficient to unlimited. Nitrogen deficiency reduced vine vigour to a greater extent than did mild water deficits. The smallest berries, as well as the highest phenolic content for both must and wine, were observed under nitrogen deficiency. Both early mild water deficits and a nitrogen deficiency throughout the growth period were demonstrated to have beneficial effects on the phenolic content of berries and on wine quality. Two combinations of vine water status and vine nitrogen status led to the most highly appreciated wines: a low nitrogen status without water deficits and a medium nitrogen status accompanied by mild water deficits.

For any given vineyard terroir can be described as the combination of pedoclimatic conditions, vine components such as cultivar, clone and rootstock as well as viticultural techniques (pruning system, canopy management, etc.). Given this, terroir must be seen as a complex system with multiple variables: it is impossible to study all the variables in one experiment. Within a single estate (10 to 100 ha) in Bordeaux, there is generally no climatic variation but several types of soil. It is well known that the effect of the soil on vine behaviour is mediated through varying water-content levels and their effects on vine water status (Seguin, 1970; Seguin, 1986; Van Leeuwen & Seguin, 1994). Water deficits occur when transpiration exceeds the ability of the root system to supply water to the transpiring leaves. Mild water deficits are known to have positive effects on reducing berry size (Smart, 1974) and on berry skin anthocyanin and tannin content in red grape varieties (Matthews & Anderson, 1988; Van Leeuwen & Seguin, 1994; Koundouras *et al.,* 1999). Schultz and Matthews (1993) observed that in potted vines water deficits caused embolism in the xylem shoot apex, which stopped shoot growth. This has been confirmed in field studies (Matthews *et al.,* 1987; Van Leeuwen & Seguin, 1994; Naor & Wample, 1996). Given this consideration, it can be said that under mild water deficits vegetative growth is no longer in competition with reproductive development as a sink of photosynthesis resources. Hence fruits are primary sinks. This can partly explain the richer must and wine constitution obtained from vines having undergone mild water deficits.

Without the addition of nitrogen fertiliser, vine nitrogen status depends upon soil organic matter content, its mineralisation rate and the C/N ratio. It has been shown for Merlot (Delas *et al.,* 1991) and for Thompson seedless and White Riesling (Kliewer and Cook, 1971; Spayd *et al.,* 1994) that nitrogen fertilisation increases vigour.

In the Bordeaux oceanic climate rainfall can vary to a considerable extent from one season to another. In a dry season, such as 1990, high enological berry potential and therefore wine quality are strongly linked to mild water deficits (Van Leeuwen and Seguin, 1994). In a rainy season, this is less likely to occur even though a soil effect on wine quality is generally admitted to exist despite the rainy conditions. As a better understanding of the terroir effect can help growers in their vineyard management and grape selection, the effect of soil variation on vine vigour, berry constitution and wine quality was investigated in this survey during a rainy vintage. Vine water status and vine nitrogen status were measured by means of physiological indicators. In the case studied soil was the only variable differentiating blocks planted with the same cultivar and rootstock and with the same vine spacing and subject to the same canopy management. Conradie (1986) demonstrated that vine nitrogen uptake from bud break through fruit maturity is progressively less utilised for vegetative growth and increasingly more utilised by the fruit. This was confirmed by Soyer *et al.* (1995), who showed that vine berry nitrogen content closely reflected mineral nitrogen availability in the soil. Thus, berry total nitrogen content can be used as a physiological indicator of vine nitrogen status. However, the levels of total nitrogen berry content as an indicator of vine nitrogen status is poorly documented.

MATERIALS AND METHODS

Experimental location and plant material

The study was conducted in Léoville Las Cases vineyard, Saint-Julien, Haut-Medoc, Bordeaux area, France. Soil mapping of this vineyard revealed an unexpected soil variation: nine pedological types spread over only 100 ha. Four blocks planted with *Vitis vinifera cv.* Cabernet Sauvignon grafted on *Vitis riparia* L. rootstock were studied. Vine age was between 24 and 31 years. The four blocks were identified as 1G, 3A, 4H and 5P. Each block was set up on a different soil type. To avoid soil variation inside a block, only 100 vines were studied per site, all located around the soil pit studied. The soil type, texture, percentage of organic matter in fine soil, occurrence of water table and root zone depth are presented in Table 1.

The four blocks were less than 500 m apart. The altitude of the four blocks varied from 10 to 20 m and row orientation was identical. Hence it was accepted that no climatic variation occurred among the four blocks. This was confirmed by the vine phenology in 1997, which was similar for all the terroirs studied (bloom: May 25; véraison: July 21). The vines were spaced 1 x 1.1 m apart and double Guyot pruned; trunk height was 0,4 m from the soil surface. During vegetative development, vine canopy was mechanically cut at 1.1 m height for every block.

Water potentials

Pre-dawn leaf water potential (dawnΨ) and leaf water potential (leafΨ) were measured with a pressure chamber (Scholander *et al.,* 1965) equipped with a digital manometer (SAM Precis 2000, 33175 Gradignan, France). DawnΨ was measured at the end of the night on uncovered mature leaves. LeafΨ was measured on mature leaves exposed to sunlight, whether they were transpiring or not (Turner, 1981).

Nitrogen status

As in the preceding years, no nitrogen fertiliser was added in 1997. Hence vine nitrogen uptake resulted mainly from mineralisation of organic matter. Vine nitrogen uptake was estimated weekly, from véraison through harvest, by the berry total nitrogen content (Bell *et al.,* 1979).

Vine vigour

Dry leaf mass was measured on eight vines per terroir just before harvest. Leaf area per vine was deduced from the correlation obtained. Average total bunch mass per vine was measured on 30 vines per block on the day of harvest. Average pruning mass per vine was determined on 25 vines per block.

Must characteristics from véraison through harvest

From véraison through harvest one thousand berries were sampled weekly at random from 100 vines on each site. These berries were immediately counted and weighed to determine average fresh berry mass. Berries were pressed and the juice was gently centrifuged to remove suspended solids. Sugar content was measured by refractometry. Titratable acidity was measured manually with Bromothymol blue. The titration was done with 0.1 N NaOH to an end point of pH 7.0. Malic acid was determined using an enzymatic kit from Boehringer Mannheim.

On 200 berries anthocyanins were determined by the method of Ribereau-Gayon & Stonestreet (1965). The measurement of absorbency was conducted at a wavelength of 520 nm (optical distance: 1 cm). Tannins were measured by the IPT: "indice des polyphenols totaux" (Ribereau-Gayon, 1970). The wavelength used was 280 nm (optical distance: 1 cm).

Microvinification

Microvinification was conducted identically for all lots. For every terroir 50 kg of fruit were harvested on the same day (September 27). The fruit from each block was crushed and stems were removed. For every lot 40 kg were put into a 50L stainless steel tank. In order to have similar wine alcohol content for tasting, 1G, 3A and 5P must were chaptalised to obtain the same sugar content as found in 4H. Alcoholic fermentation and malolactic fermentation were enhanced with a selected yeast strain and a selected bacteria strain, respectively. All the wine-making parameters (fermentation and maceration temperature, pumping over frequency, draining away, etc.) were similar.

Wine tasting

Wines were tasted blindly by a panel of 15 professional tasters. They were noted by positive preference order from 1 to 4. The scores of all judges for a wine were summed. Least significant difference (LSD) was determined by a modified Chi^2.

Statistics

Water potential and vigour indicators data were analysed with the ANOVA procedure and the Newman Keuls test to determine least significant difference (Statbox Pro Software).

RESULTS

Water status

Soil water content was at a field capacity on all the soils studied in the spring (April), which is usual in the French oceanic area. In the Medoc 1997 was a rainy vintage: the rainfall in May, June and August was far above the average calculated over a 39-year span. Conversely, rainfall was a bit less than average in July and September (Table 2). From bloom through véraison total rainfall

TABLE 1

Soil and rooting characteristics of the studied plots.

	1G	3A	4H	5P
Type of soil	Neoluvisol on gravely soil	Planosol sedimorphe with heavy clay subsoil	Redoxisol with heavy clay subsoil	Podzosols
Gravel content	75%	15%	50%	15%
Water table	no	no	yes	no
Texture of fine soil in limits of root zone depth	Sandy clay	Heavy clay	Sandy clay	Sandy
Organic matter (% in fine soil) in the top 60 cm	1.5	1.2	0.5	2
Root zone depth (meter)	1	1.5	0.7	2

TABLE 2
Monthly rainfall in Saint Julien in 1997, compared with the long-term average.

	May	June	July	August	September
Rainfall 1997 (mm)	158.4	146.6	36	80	32.2
Average rainfall 1961–1990 (mm)	77.3	56.2	46.5	54.2	74.1

was 18 mm and from véraison to harvest 113 mm. From July through September 1997 5P dawnΨ data varied from -0.10 to -0.17 MPa, whereas over the same period 1G dawnΨ data varied from -0.12 to -0.30 MPa (Fig. 1). At three different stages (July, August and September), dawnΨ data were significantly lower for 1G than for the other blocks.

On August 23 midday leaf water potential showed no differences among the 4 soils (Fig. 2). Yet 1G leaf water potential was significantly more negative than that of the other locations at the end of the afternoon, being the beginning of the recovery period of vine water status. This confirmed the lower pre-dawn leaf water potential measured on 1G during the same period. Climatic conditions were identical for the four blocks studied. Thus water status differences observed in 1997 reflected mostly soil ability to supply water to the vine. Hardie & Considine (1976) and Van Leeuwen *et al.* (1994), showed that dawnΨ of -0.30 MPa reflected a mild water deficit, which induced slackening of shoot growth. Given this, 1G can be considered as the only block where vines underwent mild water deficits in 1997.

As 1G received as much rainfall as 5P, where no water deficit occurred, 1G water deficits reflected low water-storage capacity, due to a high proportion of gravel in the shallow root zone (Table 1). Conversely, on 5P the root zone was twofold deeper than on 1G, whereas the gravel content in the root zone was fivefold lower. These conditions were reflected in the high dawnΨ data collected from July to September on 5P. On 4H, despite the shallow root zone, no water deficits were detected. This was due to a permanent water table linked to the subsoil clay depression. Conversely, on 3A the subsoil clay is convex. Thus no water table can be formed ant the root zone is deeper (Table 1).

Nitrogen status

From véraison through harvest, berry total nitrogen content for 4H was threefold lower than for 5P and twofold lower than for 1G (Fig. 3). Berry total nitrogen content of 3A was between that of 4H and of 1G. Throughout this period the difference between berry total nitrogen content appeared to remain constant from one block to another.

Lower total nitrogen content for 4H reflected the low organic matter content in this soil (Table 1). Conversely, 5P soil organic matter percentage was fourfold higher than for 4H, with total berry nitrogen being threefold higher than for 4H. Thus, under the conditions of this survey, berry total nitrogen content appeared to reflect soil organic matter content closely.

Vine vigour

A strong correlation between leaf area (measured with a planimeter) and dry leaf mass was established. Total leaf area per vine (Table 3) was not significantly different for 1G, 3A and 4H, indicating that total leaf area per vine was not affected by water status for these 3 blocks. Hence, 1G mild water deficits were only due to low soil-water content available in the root zone depth. Moreover, significantly larger total leaf area per vine did not enhance water deficits on 5P. This confirmed the higher soil-water content in the root zone depth of 5P.

The significantly lower total leaf area per vine for 4H, in comparison to 5P was not due to water status, which was similar for both terroirs. The lower vine nitrogen status on 4H appeared to explain its weaker vigour. Furthermore, the total pruning mass per vine and the total cluster mass per vine were also significantly lower on 4H than on 5P.

As with total leaf area per vine, 4H and 1G showed no significant difference for total pruning mass per vine, nor for total leaf area per vine. Two vigour indicators, total bunch mass per vine

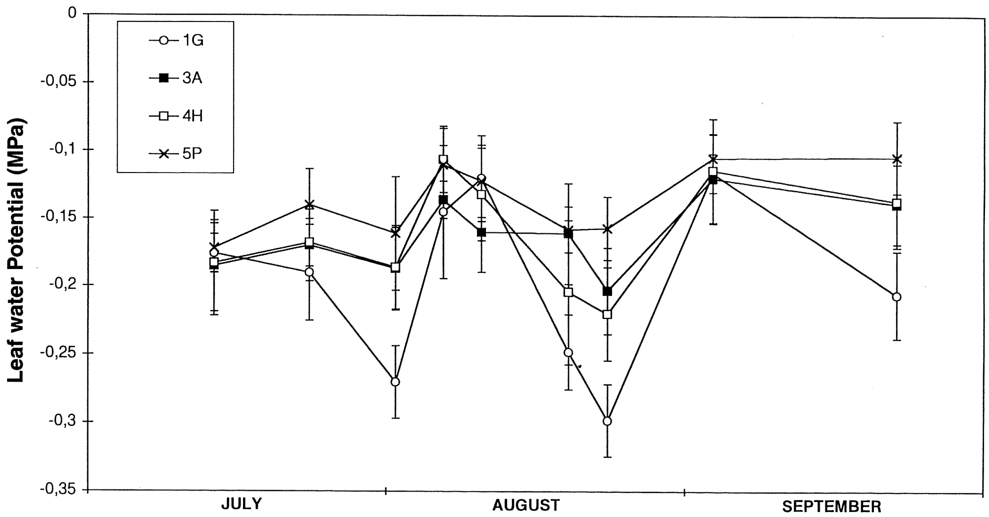

FIGURE 1
Dawn leaf water potential evolution from July through September 1997. Data are means of 8 measurements on 8 adjacent vines. Error bars indicate SE.

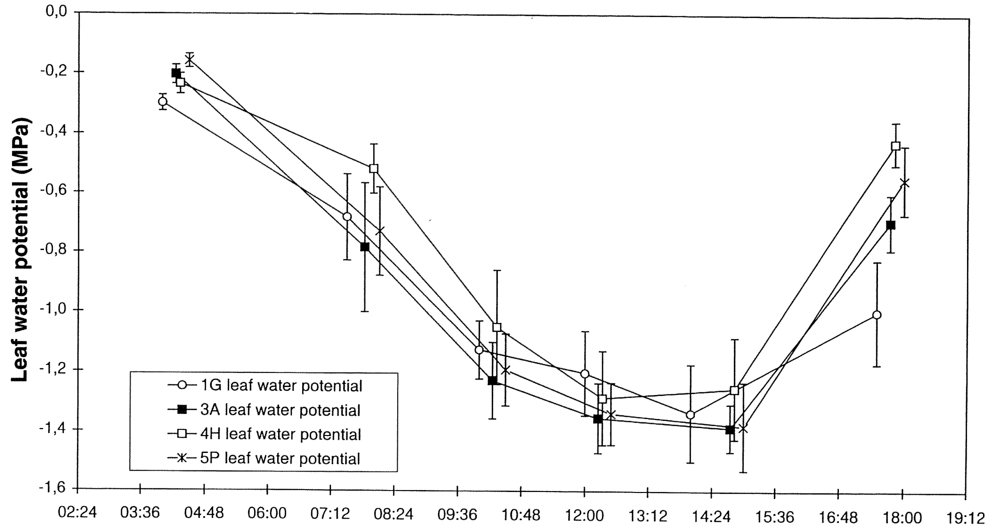

FIGURE 2
Diurnal leaf water potential on August 23, 1997. Data are means of 8 measurements on 8 adjacent vines. Error bars indicate SE.

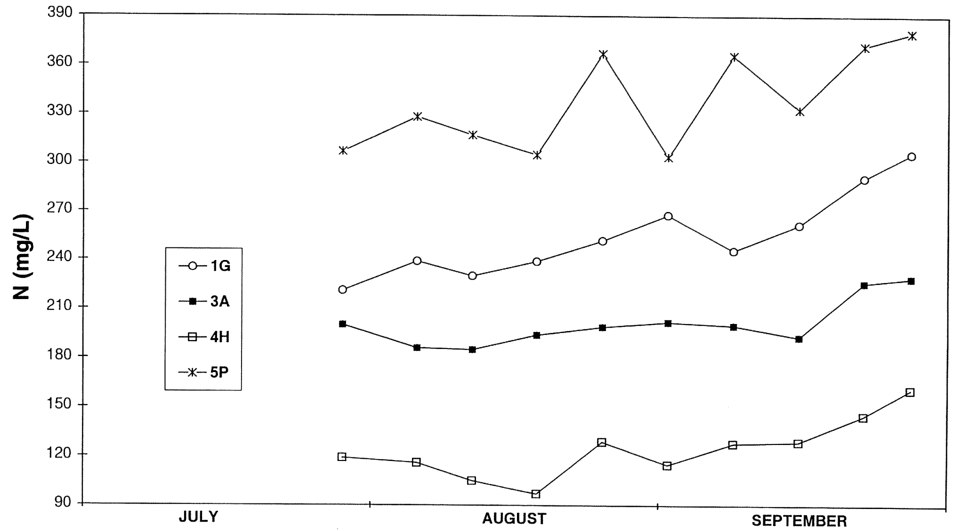

FIGURE 3
Berry total nitrogen content from véraison through harvest (1997).

TABLE 3
Vigour indicators: Total leaf area, total pruning mass and total bunch mass per vine.

	1G	3A	4H	5P
Total leaf area per vine (m2)	1.01 a(1)	0.96 a	0.8 a	1.46 a
Total pruning mass per vine (kg)	0.24 a b	0.31 b	0.19 a	0.43 c
Total bunch mass per vine (kg)	0.935 a b	1.09 b	0.765 a	1.103 b

(1) Values within rows followed by the same letter do not differ significantly.

and total shoot mass per vine, showed that 3A was significantly more vigorous than 4H, but no more than 1G. Thus the difference in nitrogen supply between 3A and 4H, which had the same water status, seemed to have had more influence on vigour than did variations in water status between 1G and 4H or between 1G and 3A.

Total leaf area per vine and total pruning mass per vine for 5P were significantly higher than for the 3 other terroirs, while 5P total cluster mass was significantly higher than 4H only. As the trellising and pruning system were the same on the four sites, this showed that low nitrogen status on 4H reduced total bunch mass per vine to a greater extent than did the mild water deficits on 1G. This further emphasised that low vine nitrogen status had a greater influence on vigour than did mild water deficits before véraison.

Fresh berry mass

From véraison through harvest 5P fresh berry mass was constantly 30% higher than that of 4H, whereas it was only 10% to 15% higher than that of 1G and 3A (Fig. 4). Fresh berry mass and total cluster mass per vine showed a strong linear correlation (R^2=0.92;

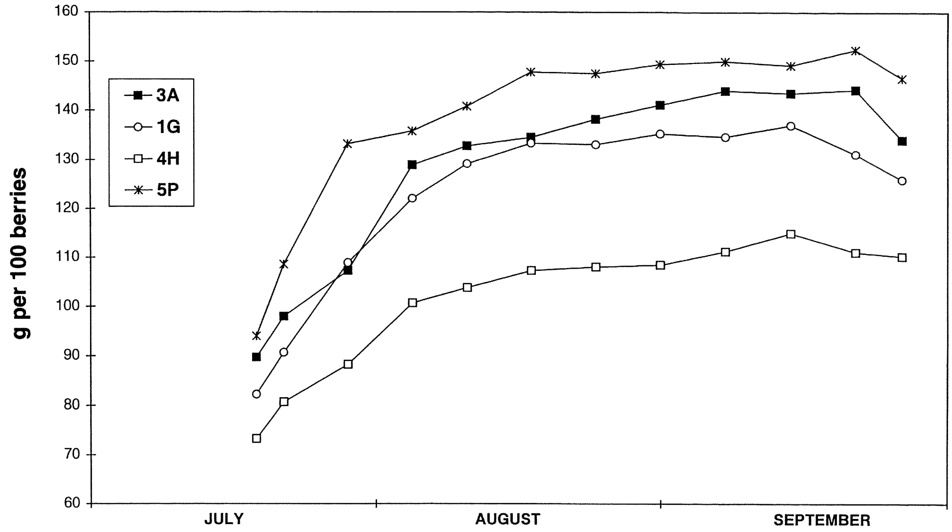

FIGURE 4
Fresh berry mass evolution from véraison through harvest (1997).

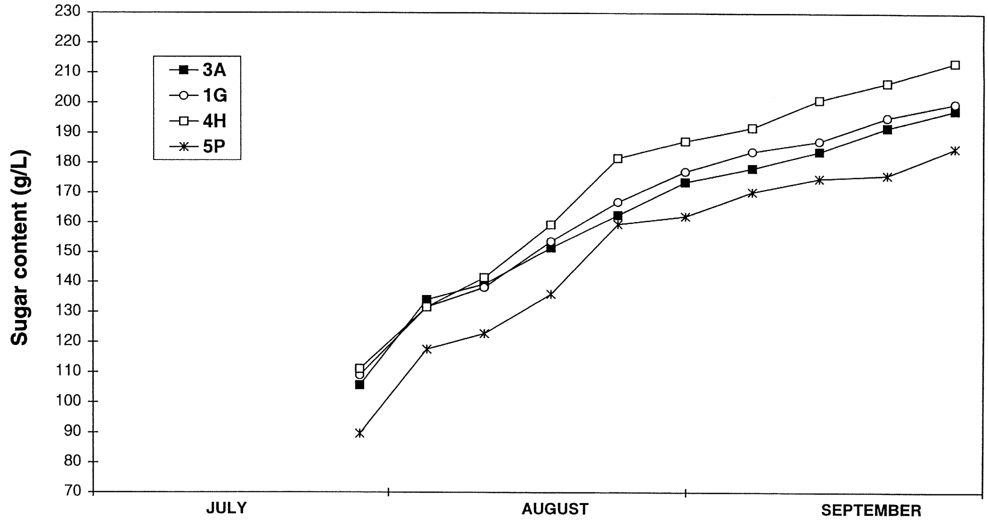

FIGURE 5
Must-reducing sugar content evolution from véraison through harvest (1997).

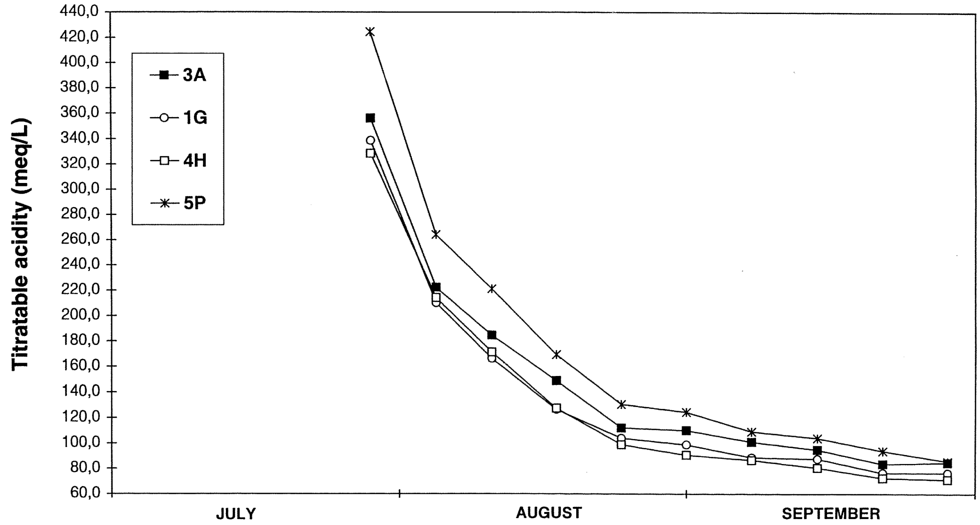

FIGURE 6
Must titrable acidity evolution from véraison through harvest (1997).

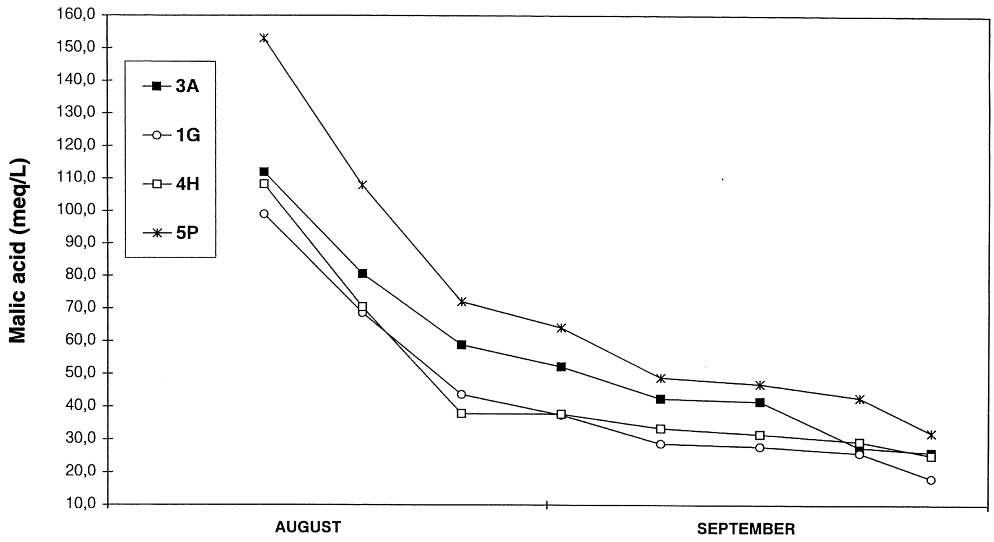

FIGURE 7
Must malic acid (meq/L) content evolution from two weeks post-véraison through harvest (1997).

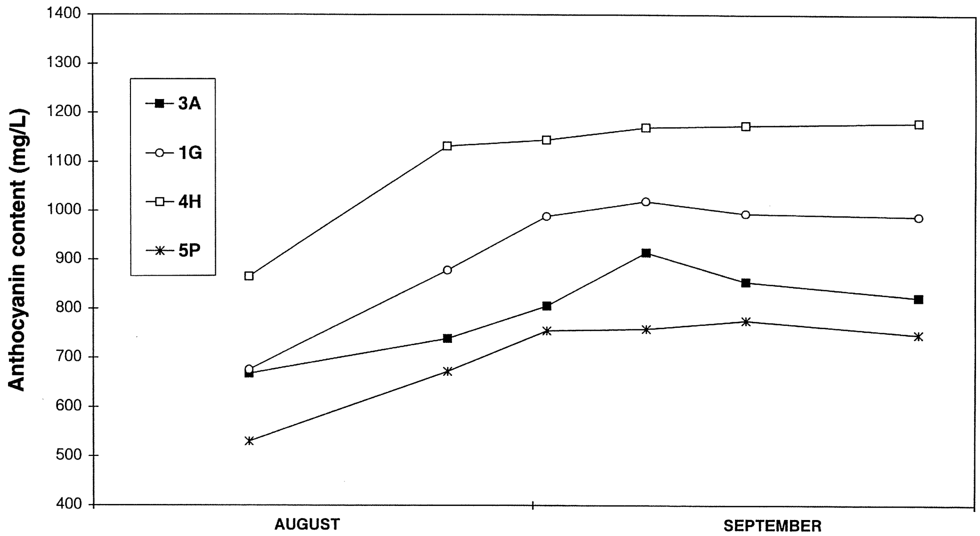

FIGURE 8
Must anthocyanin content evolution from two weeks after véraison through harvest (1997).

n=4), which demonstrated that flower abortion did not explain the yield difference between the sites.

Low fresh berry mass on 4H confirmed the low vigour previously observed. Lower fresh berry mass on 1G and 3A, compared to 5P, can be attributed to mild water deficits and lower nitrogen status respectively, even though these are not reflected by significant differences in total cluster mass per vine.

Berry composition through ripening

Must from 4H and 1G exhibited the highest sugar content and the lowest acidity, whereas the reverse was true on 5P (Figs. 5, 6 and 7). Must sugar content was less for 1G than for 4H. Even though titratable acidity on 1G and 4H was similar, malic acid content was nevertheless lower on 1G. As already shown by Van Leeuwen and Seguin (1994), vine water deficits enhance low must malic acid content. For the four sites a strong linear correlation (R^2=0.97; n=4) between average dawnΨ data (from July through September) and berry malic acid content at the harvest was observed.

Anthocyanins, tannins and wine appreciation

Anthocyanin content for 4H was almost twofold higher than for 3A and 5P, whereas the difference between 4H and 1G was less pronounced (Fig. 8). IPT differences followed the same hierarchy, with 4H and 1G exhibiting the highest tannin content (Table 4). The professional panel of tasters distinguished 4H and 1G as the best wines (Table 4). The most appreciated wines were also the highest in phenolic content. Wine phenolic content correlated closely with phenolic content (Table 4). Must phenolic content for 3A, 4H and 5P suggested that low nitrogen status without water deficits was linked to high enological potential for a red grape vari-

TABLE 4

Must phenolic content at the harvest, wine phenolic content and wine-tasting appreciation.

	1G	3A	4H	5P
Must anthocyanin content at harvest (mg/L)	989	823	1180	748
Must tannin content at harvest (IPT) (1)	33	29.8	36.5	28
Wine anthocyanin content (mg/L)	611	463	730	401
Wine tannin content (IPT)	54	50	70	43
Wine-tasting sum rate	50.5a(2)	39 b	58 a	21 c

(1) IPT = "indice des polyphénols totaux".

(2) Values within rows followed by the same letter do not differ significantly.

ety such as Cabernet Sauvignon. This confirmed the result of Keller and Hrazdina (1998) on continuously irrigated, potted Cabernet Sauvignon. They observed that excessive nitrogen fertilisation decreased win phenolic content. In a rootstock trial Delas *et al.* (1991) observed an increase of phenolic grape content for some of the rootstocks where nitrogen fertilisation was not applied. Hence, both early mild water deficits and lower nitrogen status throughout the growth period had beneficial effects on total berry phenolic contents and wine quality. This appeared to be linked to the limiting effect on the vine vigour of both of these factors.

DISCUSSION

With the same water status for both sites, lower nitrogen status on 4H than on 5P induced a decrease in vigour. The total leaf area per vine, the total pruning shoot mass per vine and the total cluster mass per vine were respectively 55%, 44% and 30% lower on 4H than on 5P. Considering these vigour indicators, 4H underwent a clear nitrogen deficiency in 1997. The total cluster mass per vine represented a calculated yield of 6.5 tons per ha for 4H, suggesting that nitrogen deficiency level was moderate, as it allowed an acceptable yield for a high-quality wine-producing vineyard.

Bell *et al* (1979) reported on continuously irrigated Thompson seedless that for a total nitrogen content of must at harvest ranging from 287 to 754 mg/L no significant difference occurred in crop mass per vine. Kliewer and Cook (1971) showed on potted vines that leaf area and trunk circumference increased linearly with increasing concentrations of nutrient solutions ranging from 0 to 4 mM of NO_3, whereas they remained constant with concentrations ranging from 4 to 8 mM of NO_3. This suggests that the Bell *et al* (1979) range of must total nitrogen content indicated no lack of nitrogen, because it was superior to the threshold value where nitrogen begins to have an effect on vigour. In 1997 5P must total nitrogen content (290 to 370 mg/L from véraison through harvest) fell within this range. Given this, 5P must total nitrogen data reflected no limiting vine nitrogen status. Moreover, 3A must total nitrogen content (185 to 230 mg/L) corresponded to an intermediate level of vine nitrogen status, between those of 5P and of 4H. This was emphasised by the fact that 3A vigour, estimated by the total pruning mass per vine and the total cluster mass per vine, was significantly lower than that of 5P and significantly higher than that of 4H, with no water status difference.

Conradie (1980, 1986) demonstrated that most of the vine nitrogen uptake occurs from bud burst through véraison. During this period nitrogen is increasingly allocated to fruit. From véraison through harvest Conradie (1991) observed a translocation on Chenin blanc of nitrogen from shoot, leaves and permanent structure to bunches. These observations were confirmed by constant or slightly increasing must total nitrogen content on the 4 sites in 1997, from véraison through harvest, despite different rates of berry diameter increase (Figs. 3 and 4). Low nitrogen status for 4h can thus be considered as reflecting limited vine nitrogen uptake since bud break. This could explain why the low nitrogen status of 4H reduced vigour more than did 1G mild water deficits for 1G. 4H low nitrogen status was constant through the vegetative and the reproductive periods (Fig. 3), whereas 1G mild water deficits appeared at the end of fruit set and were not permanent until harvest (Fig. 1).

Further investigations will be necessary to define more accurately the range of total nitrogen content in must leading to the best must and wine quality. Different total nitrogen contents data on 1G and 4H indicated that a nitrogen status varying from low to medium favoured the production of highly appreciated wine in this Bordeaux top estate. Yet 1G and 3A grape total nitrogen content data suggested that a medium nitrogen status was adequate to obtain a high-quality wine, if associated with mild vine water deficits. Conversely, under the conditions of this survey, without vine water deficits only nitrogen deficiency on 4H (90 to 150 mg/L of total must nitrogen) had an obvious positive effect on must and wine phenolic content. This positive effect on wine quality suggested that nitrogen deficiency should be maintained in the vineyard and that nitrogen deficiency in must should be corrected in the tank before and/or during the fermentation process. This practice is already followed with success in several Bordeaux vineyard areas.

CONCLUSIONS

This terroir survey, carried out during a rainy season in the Bordeaux area, revealed a soil effect on vine nitrogen status measured by must total nitrogen content. Despite the rainy vintage, we observed on a gravelly soil (1G) mild water deficits linked to low soil water content in the shallow root zone. Low nitrogen status was found on soil having a particularly low organic matter content (4H). We observed that low nitrogen status reduced vine vigour more than did mild water deficits. Yet when vines were subject to one of these limiting factors, the wines produced in this Bordeaux top estate were of significantly higher quality. Low vine nitrogen status induced high berry tannin and anthocyanin content, accompanied by low berry mass. It also reduced yield, but this may be acceptable in a very high-quality grape-producing vineyard.

Considering the benefits of low vine nitrogen status on the phenolic content of must and wine, it remains to define how this low nitrogen status can be managed more accurately in order to conserve the equilibrium between the highest possible wine quality and a decreased but economically acceptable yield.

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