Influence of Climate, Soil, and Cultivar on Terroir

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Abstract: The three main components of terroir—soil, climate, and cultivar—were studied simultaneously. Vine development and berry composition of nonirrigated *Vitis vinifera* L. cv. Merlot, Cabernet franc, and Cabernet Sauvignon were compared on a gravelly soil, a soil with a heavy clay subsoil, and a sandy soil with a water table within the reach of the roots. The influence of climate was assessed with year-to-year variations of maximum and minimum temperatures, degree days (base of 10°C), sunshine hours, ET_o, rainfall, and water balance for the period 1996 to 2000. The effects of climate, soil, and cultivar were found to be highly significant with regard to vine behavior and berry composition (an example being anthocyanin concentration). The impacts of climate and soil were greater than that of cultivar. Many of the variables correlated with the intensity of vine water stress. It is likely that the effects of climate and soil on fruit quality are mediated through their influence on vine water status.

Key words: terroir, soil, climate, cultivar, vine, water deficit

Terroir has been acknowledged as an important factor in wine quality and style, particularly in European vineyards (Falcetti 1994). It can be defined as an interactive ecosystem, in a given place, including climate, soil, and the vine (rootstock and cultivar) (Seguin 1988). Some authors also include human factors such as viticultural and enological techniques in their definition of terrior (Seguin 1986). It is difficult to study the effect of all the parameters of terroir in a single experiment. Many authors have assessed the impact of a single parameter of terroir on grape quality: climate (Winkler et al. 1974, Huglin 1978, Gladstones 1992), soil (Seguin 1975, van Leeuwen and Seguin 1994), cultivar (Riou 1994, Huglin and Schneider 1998), or rootstock (May 1997). The effects of vine water and nitrogen status, linked to soil type, have been shown for Cabernet Sauvignon (Choné et al. 2001) and Merlot (Tregoat et al. 2002). Two studies have investigated the combined effects of two terroir parameters: soil and climate (Duteau et al. 1981) and soil and cultivar (van Leeuwen 1995). Rankine et al. (1971) attempted to study the effects of soil, climate, and cultivar; however, the soils were situated in different climatic zones, making it difficult to separate the effect of soil and the effect of climate.

In this study, the influences of climate, soil, and cultivar were examined simultaneously. Three red cultivars grown on three soil types located in a homogeneous climatic zone were used. The influence of climate was studied through the year effect. Our objectives were to assess the influence of the three parameters on vine development and grape composition and to establish a scientific basis for a better understanding of how terroir influences vine behavior.

Materials and Methods

This study was carried out from 1996 through 2000 in three Saint-Emilion vineyards located in the Bordeaux region. The sites were located at the following coordinates: plot G, lat. 44°56'21", long. 0°11'21"; plot S, lat. 44°56'13", long. 0°10'59"; plot A, lat. 44°56'06", long. 0°10'51". The *Vitis vinifera* L. cultivars were Merlot (clone 181), Cabernet Sauvignon (clone 191), and Cabernet franc (clone 326). All three cultivars were grafted onto 3309C rootstock.

Three soils were studied. The first was a gravelly soil, Arenic Eutrudept, containing over 50% stones in every identified layer explored by the root system. The fine earth was mainly composed of sand (Figure 1A). Rooting depth was limited to 1.2 m by an impermeable layer. Soil water-holding capacity was 40 mm (calculated according to Leclech 2000).

The second soil had very heavy clay subsoil between 0.3 and 0.6 m in depth (Albaquic Hapludalf). The amount of clay in this layer was greater than 60% (Figure 1B). Soil water-holding capacity was 168 mm.

The third was a sandy soil with a sandy-clay texture below 1.0 m in depth (Sandy Typic Psammaquent) (Figure 1C). The water table was close to the surface, varying from 0.6 m at the end of the winter to 1.6 m at the end of the summer. Observations of a soil pit showed that rooting depth was 1.35 m. Thus, it can be considered that roots remained in contact with the capillary zone above the water table throughout the growing season. No water-holding capacity was calculated for this soil because vine water uptake from the water table was unlimited.

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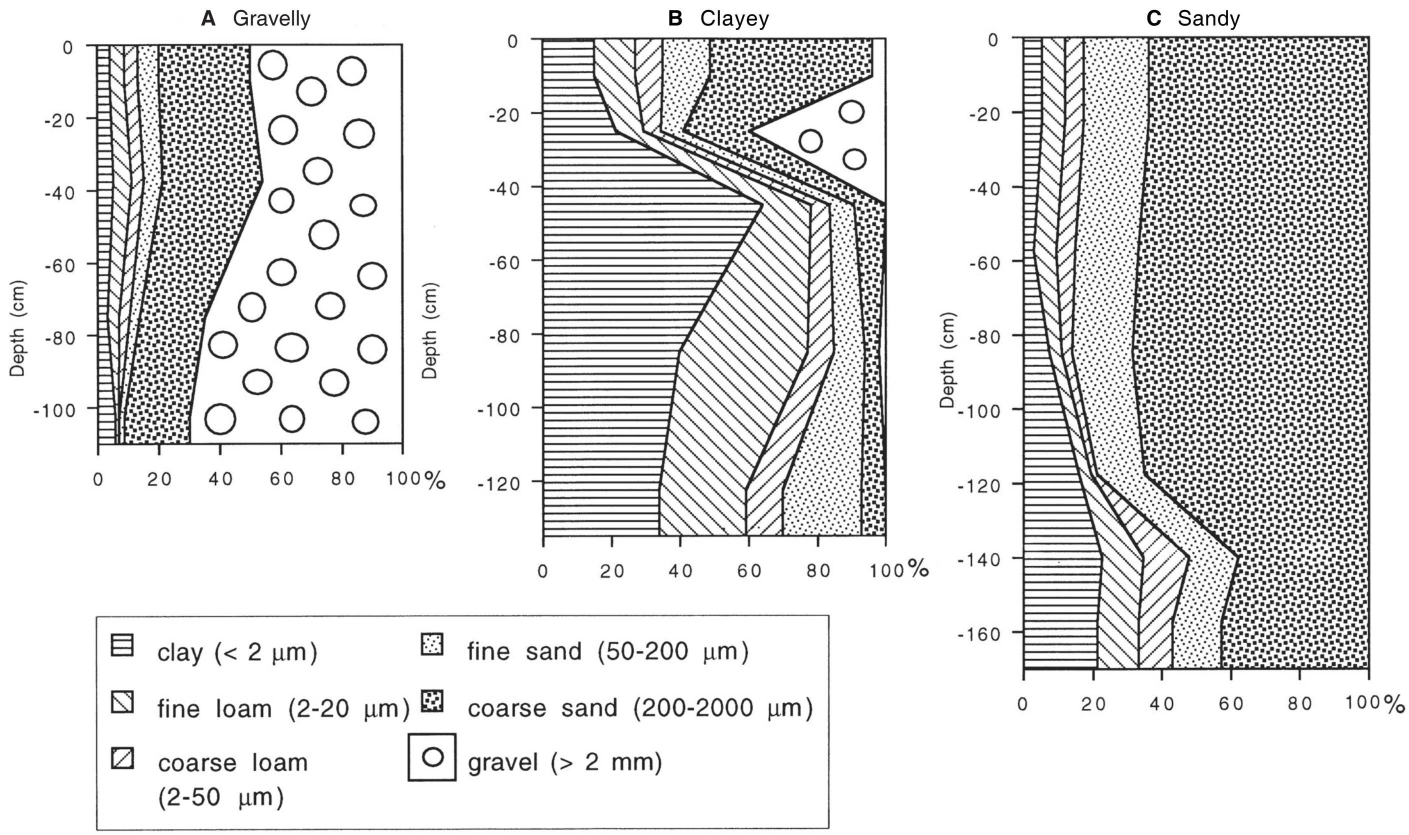

Figure 1 Percentage of clay, loam, sand, and gravel in the root zone of (**A**) gravelly soil, (**B**) clayey soil, and (**C**) sandy soil.

Climatic parameters vary both spatially (regional climatic variations) and in time (year effect). Since the plots were located less than one km apart, climate was considered to be homogeneous among the plots in a given vintage. Therefore, the effect of climate was studied in terms of year-to-year variations in temperature, rainfall, ET_o, sunshine hours, and water balance (vintage effect). Climatic data were measured on site with an automatic weather station (BV14/15/15; CIMEL, Paris, France). Mean high and low temperatures, degree-day base of 10°C, average daily sunshine hours, average daily ET_o (reference evaporation, calculated according to Penman 1948), rainfall, and water balance among phenological stages were calculated for each combination soil x cultivar and then averaged. Water balance was modeled as rainfall – $k*ET_o$ (mm). Given the characteristics of the trellis system, crop coefficient was estimated as $k = 0.6$ from flowering to harvest and $k = 0.3$ from budbreak to flowering (Riou et al. 1994).

On each of the three soil types, a homogeneous plot of mature vines was chosen. Within each plot, four adjacent rows of 25 vines of Merlot, Cabernet Sauvignon, and Cabernet franc were grafted next to each other in 1994 using T-bud grafting. The previous cultivar on the three sites was Merlot and the grafting was done onto the Merlot. The purpose was to rapidly obtain vines with a developed root system for each combination soil x cultivar. Vine density was 6,000 vines per hectare with vines at 1.2 m x 1.4 m (vine x row spacing) in a north-south row orientation. The trellis system was composed of two fixed wires, located 0.4 m and 1.2 m from the soil surface, and two mobile wires. A vertical shoot-positioned training system was used and vines were hedged at 1.5 m in height at the end of June, leaving 1.1 m foliage height and 0.4 m foliage width. Vines were hedged a second time at the end of July and a third time mid-August. Vines were simple-Guyot pruned (one cane with five buds, one spur with two buds). Weeds were controlled by cultivation. Pesticide applications were carried out on the same dates with the same products in each plot. All plots were dry-land farmed.

Phenology, vine development, and vigor. Dates of budburst, flowering, and veraison were noted when 50% of the buds, flowers, or berries reached the given phenological event. They are expressed as "day of the year" (number of days after January 1). On 30 vines per plot, the length of one shoot per vine was measured every 10 days up to the cessation of growth. To prevent the accidental cutting of these shoots by the hedging machine, they were positioned horizontally on the lowest wire of the trellising system. Although such positioning can obviously influence shoot growth, data remain comparable among experimental plots. Growth cessation was considered to have occurred when average shoot growth within a plot was less than 5 mm/day (which is about one-tenth of maximum shoot growth rate) expressed in the number of days after April 1. Total shoot length at growth cessation was used as an indicator of vine vigor. Vine vigor was also estimated by average pruning weight, measured in December. Total leaf area per vine was determined before harvest with a leaf area meter (LI-COR, Lincoln, NB), according to Ollat et al. (1998).

Yield. Yield was limited by severe pruning (7 buds/vine). Average yield was 1.1 kg/vine (6.6 tonnes/ha). Yield variations among plots were mainly due to variations in berry and cluster weight. Berry weight was measured once a week from veraison until ripeness on a sample of approximately 800 berries.

Berry composition. While 800 berries per plot were sampled once a week from veraison to harvest, only berry composition at harvest date was used in this analysis. Sampling was carried out on the two inner rows of each block. Harvest date was determined for each cultivar when the increase in sugar accumulation slowed and anthocyanin concentration peaked (Figure 2). Harvest of Merlot preceded harvest of Cabernet franc by 7 to 10 days depending on the climatic conditions of the vintage. Harvest of Cabernet franc preceded harvest of Cabernet Sauvignon by 7 to 10 days. The sample was pressed at 0.5 MPa in a pneumatic micropress (Bellot, Gradignan, France), except for 200 berries used for skin analysis. The juice samples were analyzed for soluble solids by refractometry (expressed in g sugar/L); total acid concentration by titrimetry (expressed in g tartaric acid /L); pH; malic acid using an enzymatic method (Boehringer, Mannheim, Germany; expressed in g/L); tartaric acid by colorimetry after reaction with vanadic acid (expressed in g/L); and potassium by spectrophotometry (expressed in g/L).

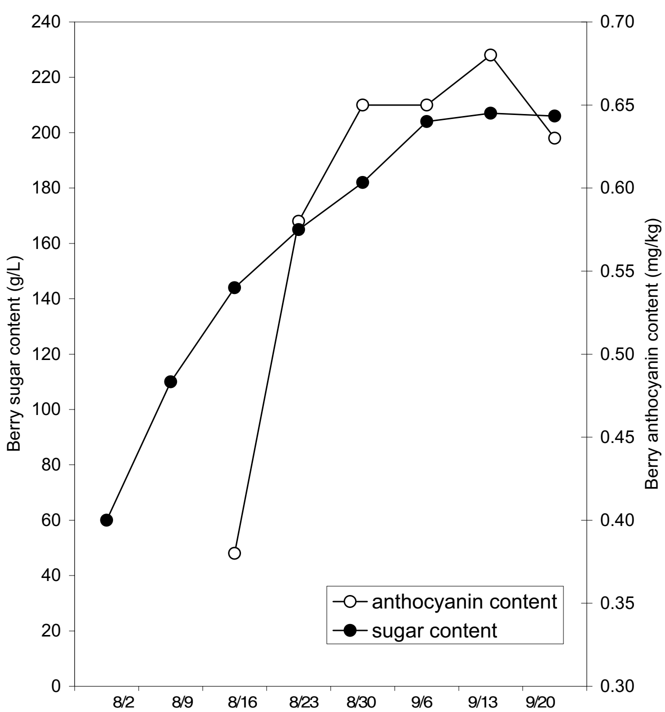

Figure 2 Accumulation of sugar and anthocyanins in the berries of Merlot grapevines during the 1999 growing season on sandy soil.

Pulp ripening was calculated by assessing the sugar/acid ratio as a function of a climatic index (Duteau 1990). According to this author, during the first four weeks after veraison, S/TA ratio is a linear function of Ó{((average temperature-10) + (maximum temperature-10)) / 2}. The slope of the linear regression represents the pulp ripening speed.

The skins of 200 berries were separated and mixed in a 250-mL solution containing 12% ethanol and 5 g/L tartaric acid at pH 3.2. After six hours of agitation, the anthocyanin concentration of the extract was determined by measuring optical density at 520 nm before and after decoloration by sodium bisulfite (Glories 1978). Berry anthocyanin concentration was expressed in mg/kg of grapes.

Vine mineral nutrition. Vine mineral nutrition was assessed by measuring petiole N, P, K, and Mg content at veraison (expressed in % of dry matter). Petioles were sampled on leaves opposite to clusters (Champagnol 1984). The K/Mg ratio was also calculated.

Vine water status. Vine water status was assessed by measuring predawn leaf water potential (Ød; Scholander et al. 1965) once every two weeks from three weeks after flowering until harvest (each value given is the result of six replicates). According to Ojeda et al. (2002), water deficit stress is considered null when 0 MPa > Ød > -0.2 MPa, weak when -0.2 MPa > Ød > -0.4 MPa, medium when -0.4 MPa > Ød > -0.6 MPa, and strong when Ød < -0.6 MPa. We considered the minimum predawn leaf water potential values before veraison (that is, the most negative value, which is itself the average of six replicates) as an indicator of early season water stress and the minimum predawn leaf water potential values between veraison and harvest as an indicator of the intensity of the stress. The lowest seasonal predawn leaf water potential values were always measured postveraison. Pre- and postveraison water deficits are not independent, as the occurrence of a preveraison water deficit increases the chance of attaining a great postveraison water deficit. In some cases (1998) cumulative effect of pre- and postveraison water deficits may exist.

Statistical analysis. Data analysis was done by ANOVA based on a split-plot design, with soils as main plots and cultivars as subplots. Vintages were treated as blocks. Means were separated by Newman-Keuls test ($p < 0.05$). Percentages of variance attributable to soil, cultivar, vintage, and soil x cultivar interactions were calculated. Soil x vintage and cultivar x vintage interaction effects were tested with residual error. The software used was Grimmersoft StatBox and Microsoft Excel (Redmond, WA).

Results

Climatic conditions. Mean maximum temperatures between budbreak and harvest were similar from 1996 to 2000, except for 1998 when the mean maximum temperatures were somewhat lower (Figure 3). Mean minimum temperatures during the same period were higher in 1999 and 2000, compared to 1996, 1997, and 1998. In 1996 it was warm from flowering until veraison, but cool from veraison to harvest. The opposite occurred in 1997. In 1998 the growing season was relatively cool, while in 1999 it was rather warm. Mean temperature in 2000 was close to 1999, but during the ripening period days were warmer and nights were cooler. Degree days from budbreak to harvest varied from 1371 in 1996 to 1522 in 1999 (Figure 3). Degree days in 1997 were particularly high (1507°C), due to slow ripening and, consequently, a long period from veraison through harvest (Table 1). Degree days were also high in 1999 because of high mean temperatures.

Mean sunshine hours were high in 1996 and 1997 and low in 1998, 1999, and 2000 (Figure 3). From budbreak to flowering, daily sunshine hours were highest in 1997; from flowering to veraison, highest in 1996; and from veraison to harvest, highest in 2000. Sunshine hours were low from veraison to harvest in 1998. Seasonal mean daily ET_o was similar among the five vintages studied (Figure 3). Between veraison and harvest, mean daily ET_o was low in 1996 and high in 1999 and 2000. Rainfall from April through September was low in 2000 and 1997, average in 1996 and 1998, and high in 1999 (Figure 4, page 212). Rainfall was evenly distributed from March through October in 1996, 1999, and 2000. The year 1998 was characterized by a wet spring and toward the end of the season, but the summer months were relatively dry. In 1997, most rain fell between flowering and harvest. In the Bordeaux area, the water balance is generally positive until flowering, indicating that soils may remain close to field capacity until flowering. Thus, the water balance from flowering to harvest provides an indication of the dryness of the vintage. The apparent soil water deficit during this period was very high in 2000, high in 1998, and moderate in 1996, 1997, and 1999 (Figure 3).

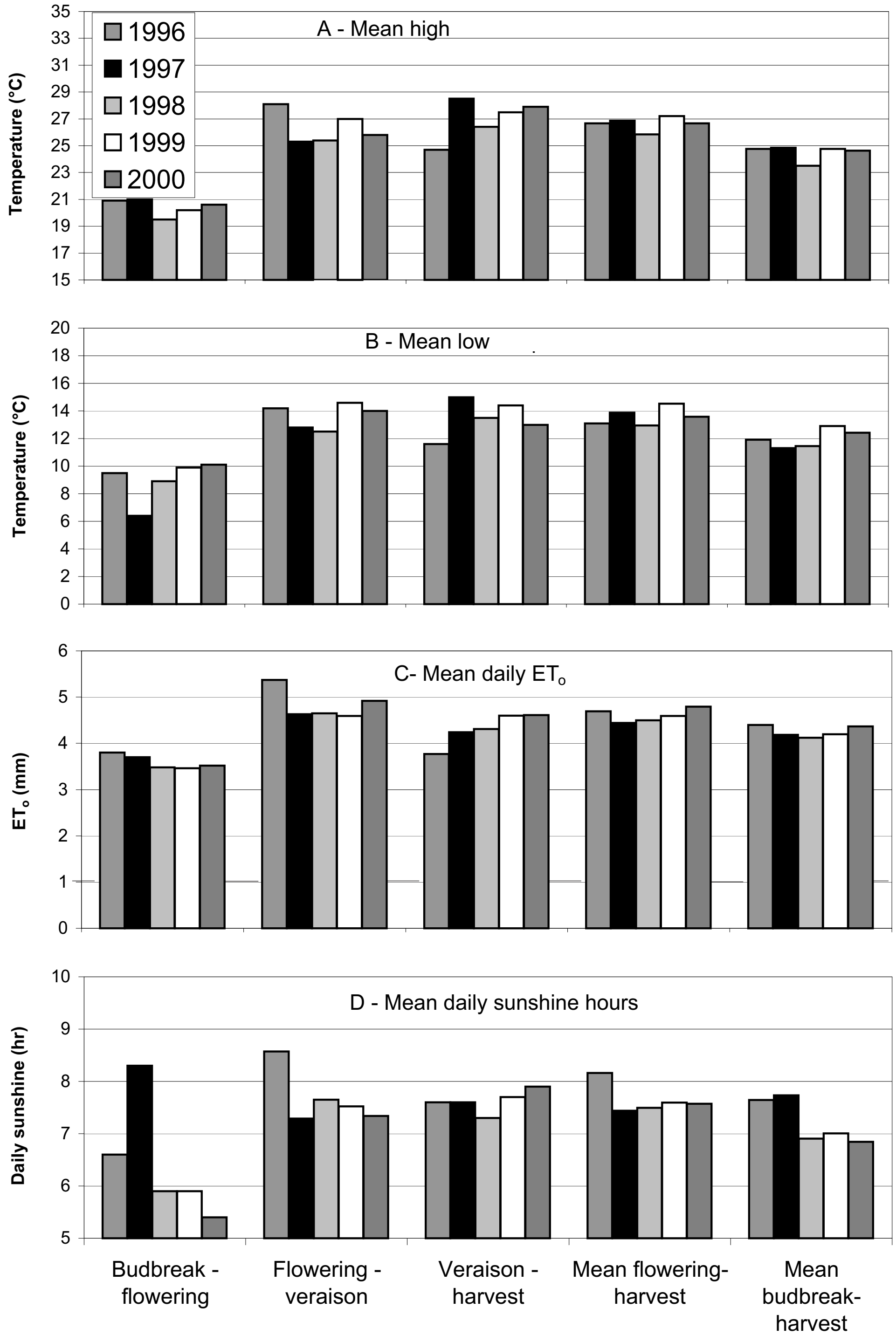

Figure 3 Climatic parameters as a function of phenological stages: (**A**) mean high temperature (°C); (**B**) mean low temperature (°C); (**C**) mean daily ET_o (mm); (**D**) mean daily sunshine (hr).

Phenology. Budbreak, flowering, and veraison were early in 1997, but harvest date was comparable to the other vintages because of slow ripening (Table 1). Budbreak was late in 1996. The date of veraison was very much influenced by the vintage (83% of the total variance; Table 2, page 213).

Figure 3 (continued)

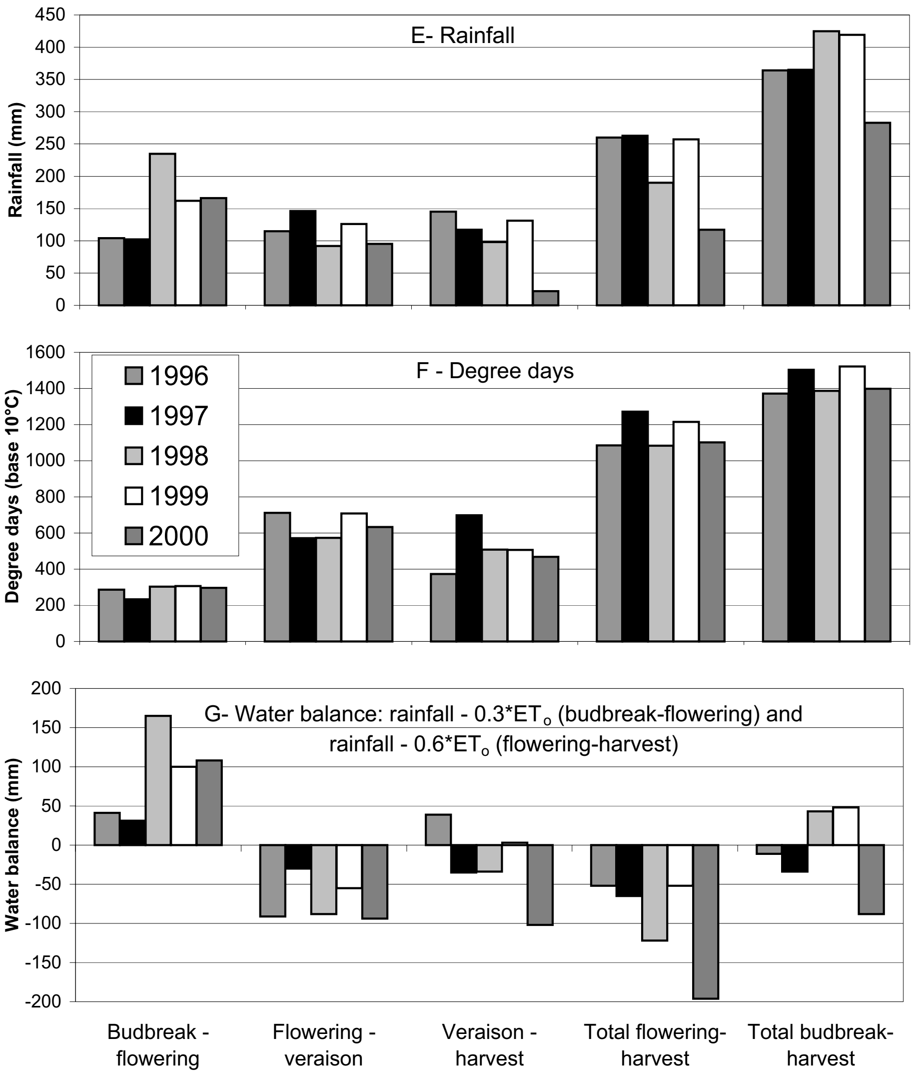

Figure 3 (continued) Climatic parameters as a function of phenological stages: (**E**) rainfall (mm); (**F**) degree day base 10 (°C); and (**G**) water balance rainfall – k*ET_0 (mm).

The difference between earliest date of veraison (1997) and latest (1996) was 17 days in this study (Table 3, page 214). Compared to Merlot and Cabernet franc, the buds of Cabernet Sauvignon break later, but the intervals between budbreak to flowering and flowering to veraison are shorter such that the date of veraison of the three cultivars were similar (Table 3). The ripening period of Cabernet Sauvignon was significantly longer than those of the other cultivars (Table 1) because of low ripening speed (Table 3). The veraison date of Cabernet franc was late, but ripening speed was comparable to that of Merlot, resulting in a harvest date between that of Merlot and Cabernet Sauvignon. Few differences in phenological stages were dependent upon soil type. This justified the simultaneous harvest of each given cultivar on the three soils.

Berry composition at maturity. Cultivar, soil, and vintage explained 41%, 32%, and 15%, respectively, of the total variance of berry sugar concentration at harvest (Table 2). Merlot grapes had the highest sugar followed by Cabernet franc and Cabernet Sauvignon (Table 3). The clayey soil produced fruit with the highest sugar concentration at harvest. The difference between the 2000 vintage and the 1997 vintage was, on average, 20 g/L. Berry sugar concentration at ripeness was related to ripening speed (r = 0.73, n = 45, $p < 0.001$).

Table 1 Effects of soil, cultivar, and vintage on the number of days separating phenological stages.

	Soil			Cultivar[a]			Vintage				
Stage	Gravel	Sand	Clay	M	CF	CS	1996	1997	1998	1999	2000
Budbreak – flowering	61 ns[b]	59 ns	60 ns	63 a	61 a	56 b	55 c	64 a	67 a	60 b	55 c
Flowering – veraison	64 b	65 a	64 b	64 b	68 a	62 c	64 a	63 a	64 a	66 a	64 a
Veraison – harvest	50 a	49 b	51 a	46 b	46 b	58 a	47 c	60 a	51 b	46 c	45 c
Flowering – harvest	114 ns	114 ns	115 ns	110 c	114 b	119 a	111 d	123 a	115 b	112 c	109 e
Budbreak – harvest	175 ns	173 ns	175 ns	173 b	175 a	176 a	166 d	187 a	182 b	172 c	164 d

[a]M: Merlot; CF: Cabernet franc; CS: Cabernet Sauvignon.

[b]Data analyzed by ANOVA based on a split-plot design, with soils as main plots, cultivars as subplots and vintages as block effect. Means compared by Newman-Keuls test ($p \leq 0.05$).

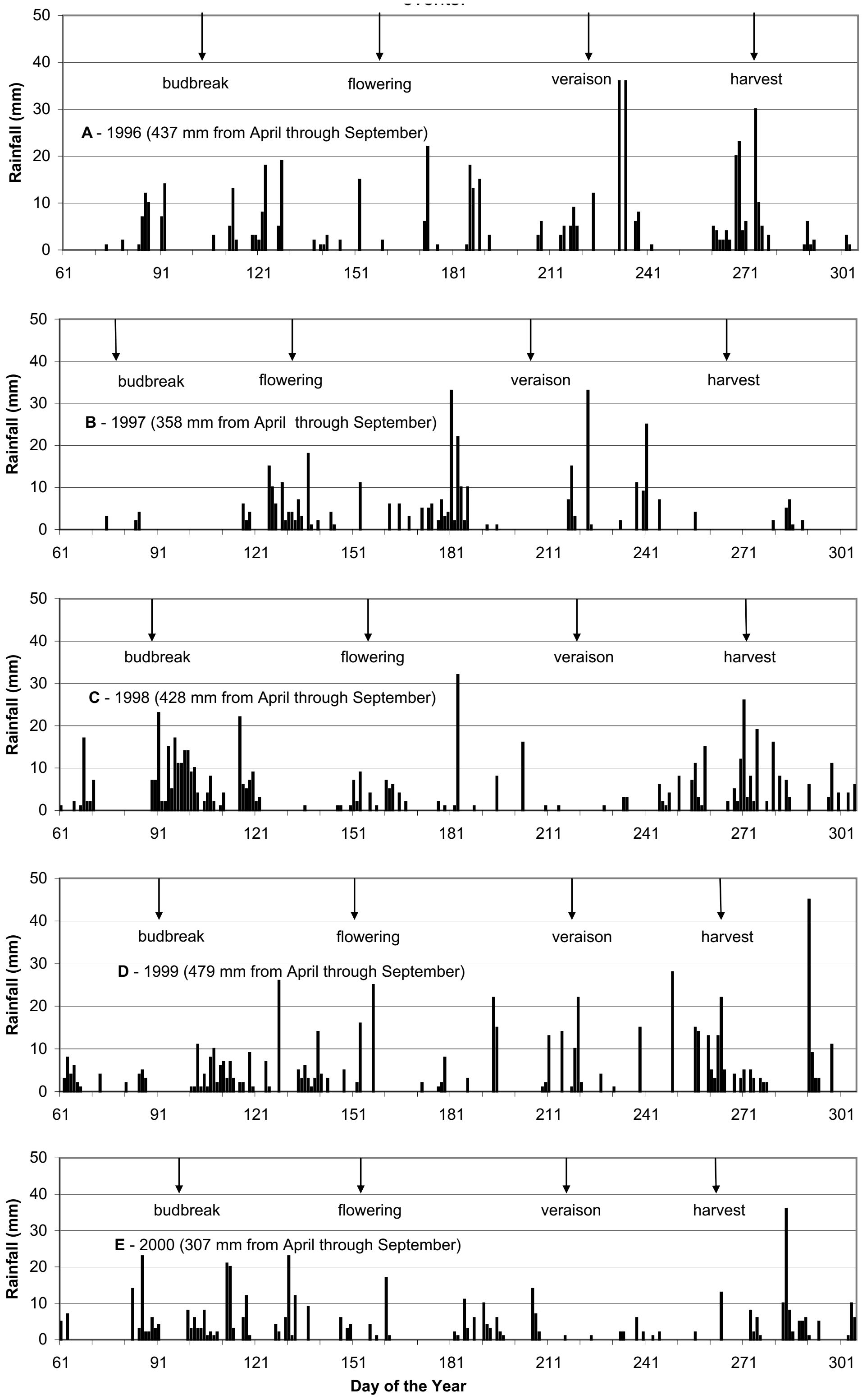

Figure 4 Daily rainfall from March through October in (**A**) 1996, (**B**) 1997, (**C**) 1998, (**D**) 1999, and (**E**) 2000 in the Saint-Emilion region (Bordeaux, France). Total rainfall is given for the period from April through September. Average dates are indicated for the main phenological events.

Grape juice acidity and pH were mainly determined by vintage (Table 2). For tartaric acid, some variation existed among vintages (41% of the total variance); 1998 was characterized by low berry tartrate concentration. Tartaric acid concentration did not vary significantly with soil or cultivar. Berry malic acid was most highly dependent on vintage (62% of the total variance), with 1996 characterized by very high concentrations and 1998 by very low concentrations. The effect of cultivar on malic acid (19% of the total variance) was also highly significant: Cabernet Sauvignon containing, on average, 50% more malate than Cabernet franc and Merlot. The soil-dependent variation was not very great (4% of the total variance). Total acidity was closely related to malic acid concentration ($r = 0.93$, $n = 45$, $p < 0.001$) but not to tartaric acid concentration ($r = 0.24$, $n = 45$, ns). Potassium concentration was determined by cultivar (33% of the total variance) and vintage (23%).

Berry anthocyanin concentration. Berry anthocyanin concentration was not influenced by cultivar (Table 3). The effect of vintage (41%) was slightly higher than that of soil type (30%). The high-quality vintages, 1998 and 2000, produced grapes with high anthocyanin concentration, but so did average vintages, 1996 and 1999. Anthocyanin concentration was low in 1997. The gravelly and the clayey soils produced grapes with a high anthocyanin concentration, unlike the sandy soil.

Vine vigor. Total shoot length and growth cessation were highly influenced by vintage (39% and 73%, respectively, of the total variance) and soil type (40% and 13%, respectively), but much less so by cultivar (Table 2). Growth cessation occurred earlier in dry vintages (1998 and 2000) and on gravelly and clayey soils where vines were subjected to water deficit. The difference between growth

Table 2 Percentage of variance attributable to soil, cultivar, vintage, and the interaction soil x cultivar.

	Soil (%)	Cultivar (%)	Vintage (%) (block)	Soil x cultivar (%)	Residual (%)
Sugar (g/L)	32 ***[a]	41 ***	15 *	2 ns	10
Ripening speed	7 **	63 ***	22 ***	3 **	6
Tartrate (g/L)	2 ns	5 ns	41 *	2 ns	50
Malate (g/L)	4 *	19 ***	62 ***	4 ns	11
Total acidity (g/L)	3 **	18 ***	70 ***	1 ns	7
pH	6 *	10 ***	73 ***	1 ns	11
Potassium (g/L)	0 ns	33 ***	23 *	4 ns	41
Anthocyanin (g/kg)	30 **	3 ns	41 **	1 ns	26
Veraison (day of year)	1 **	12 ***	83 ***	0 ns	3
Total shoot length (cm)	40 **	1 ns	39 **	3 *	17
Shoot growth cessation (days from April 1)	13 *	2 **	73 ***	1 ns	11
Berry weight (g)	31 **	24 ***	16 ns	5 ns	24
Yield (kg/vine)	32 *	1 ns	25 ns	12 *	30
Berries per vine (number)	15 *	6 ns	41 *	11 ns	27
Pruning weight (g/vine)	28 **	21 ***	20 *	9 *	22
Yield/pruning weight ratio	15 ns	7 ns	40 *	3 ns	34
Leaf area index (m^2/m^2)	12 *	19 ***	50 ***	4 ns	15
Leaf area/fruit weight (m^2/kg)	2 ns	13 *	45 **	3 ns	36
Petiole N content (% dry matter)	24 *	1 ns	35 *	4 ns	36
Petiole P content (% dry matter)	24 ns	2 ns	32 ns	13 **	29
Petiole K content (% dry matter)	42 **	32 ***	4 ns	9 **	14
Petiole Mg content (% dry matter)	75 ***	0 ns	15 **	2 *	7
Petiole K/Mg ratio	70 ***	8 ***	6 ns	7 ***	22
Minimum predawn leaf water potential preveraison (MPa)	30 *	3 ***	44 *	1 ns	22
Minimum predawn leaf water potential veraison to harvest (MPa)	40 **	2 ***	44 **	1 ns	13

[a]*, **, ***, and ns indicate significance at $p < 0.05$, 0.01, 0.001, and 0.05, respectively.

cessation in a dry (2000) and wet vintage (1999) was 52 days. The difference in growth cessation on the gravelly soil and that on the sandy soil was 19 days. Berry weight was affected by soil type (31%) and cultivar (24%) but not significantly by vintage. Berry weight was highest on the sandy soil (high water supply to the vines) compared to the other two soils. Berry weight was lower for Cabernet Sauvignon and Cabernet franc compared to Merlot. Berry weight was higher in 1997 (wet vintage), but the difference with the other vintages was not significant. Pruning weight was significantly affected by soil type (28% of the total variance), cultivar (21%), and vintage (20%). Pruning weight was high in 1997 and low in 1999 and 1996. Pruning weight was high on the sandy soil, low on the clayey soil, and intermediate on the gravelly soil. Among the cultivars studied, pruning weight was highest for Cabernet franc and lowest for Cabernet Sauvignon, but soil and cultivar interacted significantly for this variable.

Yield. Yield was affected by soil type (32% of the total variance) but not by vintage or cultivar (Table 2). Yield on sandy soil was 32% higher than that on clayey soil and 62% higher than that on gravelly soil. Yield differences can be explained by higher berry weight on the sandy soil (+20% compared to clayey soil and +17% compared to gravelly soil) and more berries per vine. Soil effect on yield interacted with cultivar effect. The leaf area/fruit weight ratio was greatly influenced by the vintage (45% of the total variance) but less so by cultivar (13%). Soil type did not affect this parameter.

Vine mineral nutrient status. Petiole nitrogen was dependent on vintage (35% of the total variance) and soil type (24%), but not on cultivar (Table 2). Petiole nitrogen content was high in 1997 and 2000 (Table 4). Petiole nitrogen content was low on sandy and clayey soils. Petiole P content was negatively correlated to petiole N (r = - 0.43, n = 36, $p < 0.01$). Petiole K content was influenced by soil type (42% of the total variance) and cultivar (32%), but these parameters interacted (9%). Petiole K content was high on gravelly soil and low on clayey soil. Petiole K was high for Merlot compared to Cabernet franc and Cabernet Sauvignon. Petiole K content was correlated to must K (r = 0.46, n = 36, $p < 0.01$). Petiole Mg content was predominantly affected by soil type

Table 3 Effects of soil, cultivar, and vintage on berry composition at ripeness and vine vigor.

	Soil			Cultivar[a]			Vintage				
	Gravel	Sand	Clay	M	CF	CS	1996	1997	1998	1999	2000
Berry pulp constitution at ripeness											
Sugar (g/L)	200b[b]	202b	222a	221a	210b	194c	206b	200b	209b	206b	220a
Ripening speed	1.04a	0.94b	1.13a	1.24a	1.18b	0.70c	0.92c	0.85c	1.25a	1.05b	1.10b
Tartrate (g/L)	6.0ns	5.9ns	5.8ns	6.1ns	5.8ns	5.8ns	6.1ab	5.8bc	5.0c	6.3a	6.2ab
Malate (g/L)	1.9ab	2.2a	1.7b	1.5b	1.7b	2.6a	3.6a	1.5c	0.8d	1.9b	1.9bc
Total acidity (g tartaric acid/L)	5.6b	5.9a	5.3b	5.1b	5.3b	6.4a	7.7a	5.0c	4.5d	5.2c	5.6b
pH	3.51a	3.42b	3.45b	3.52a	3.42b	3.43b	3.24c	3.49b	3.61a	3.46b	3.50b
Potassium (g/L)	1.87ns	1.83ns	1.87ns	1.95a	1.72b	1.87a	1.99a	1.87ab	1.79b	1.91ab	1.76b
Berry skin composition at ripeness											
Anthocyanin (g/kg)	0.92a	0.73b	0.97a	0.86ns	0.85ns	0.92ns	1.00a	0.66b	0.88a	0.86a	0.96a
Veraison (day of the year)	215b	217a	215b	214c	219a	215b	221a	204d	220b	217c	217c
Vine vigor											
Total shoot length (cm)	330b	467a	281b	376ns	360ns	343ns	347bc	409ab	256c	477a	308bc
Shoot growth cessation (days from April 1)	163b	182a	164b	165b	171a	172a	185a	179a	150b	193a	141b
Berry weight (g)	1.21b	1.41a	1.18b	1.39a	1.23b	1.19b	1.23ns	1.39ns	1.26ns	1.18ns	1.28ns
Yield (kg/vine)	0.91b	1.47a	1.11b	1.12ns	1.22ns	1.14ns	-[c]	1.02ns	0.92ns	1.29ns	1.42ns
Berries per vine	764b	1023a	941ab	815ns	972ns	942ns	-	723b	737b	1088a	1089a
Pruning weight (g/vine)	340b	405a	303b	339b	398a	311b	328b	410a	350b	304b	354b
Yield/pruning weight ratio	2.79ns	3.59ns	3.95ns	3.37ns	3.09ns	3.86ns	-	2.53b	2.83b	4.43a	3.98a
Leaf area index (m^2/m^2)	1.52b	1.91a	1.56b	1.94a	1.64b	1.40c	-	1.20d	2.16a	1.81b	1.48c
Leaf area/fruit weight (m^2/kg)	3.00ns	2.63ns	2.49ns	3.45a	2.49b	2.17b	-	2.13b	4.38a	2.53b	1.78b
Vine water status											
Minimum predawn leaf water potential preveraison (MPa)	-0.23b	-0.10a	-0.27b	-0.20b	-0.23c	-0.17a	-0.17b	-0.11b	-0.36a	-0.15b	-0.22ab
Minimum predawn leaf water potential veraison to harvest (MPa)	-0.45b	-0.15a	-0.38b	-0.35b	-0.35b	-0.29a	-0.17c	-0.24bc	-0.54a	-0.27bc	-0.43ab

[a]M: Merlot; CF: Cabernet franc; CS: Cabernet Sauvignon.

[b]Data analyzed by ANOVA based on a split-plot design, with soils as main plots, cultivars as subplots, and vintages as block effect. Means are compared by Newman-Keuls test ($p \leq 0.05$).

[c]- indicates no data collected.

Table 4 Effects of soil, cultivar, and vintage on petiole N, P, K, and Mg content.

	Soil			Cultivar[a]			Vintage			
	Gravel	Sand	Clay	M	CF	CS	1997	1998	1999	2000
N (% dry matter)	0.62a[b]	0.52ab	0.47b	0.52ns	0.55ns	0.54ns	0.60ab	0.48bc	0.45c	0.63a
P (% dry matter)	0.13ns	0.16ns	0.18ns	0.16ns	0.15ns	0.16ns	0.17ns	0.14ns	0.18ns	0.12ns
K (% dry matter)	3.45a	3.16a	2.50b	3.52a	2.73b	2.86b	3.17ns	2.87ns	3.01ns	3.09ns
Mg (% dry matter)	0.49c	0.80b	0.95a	0.74ns	0.77ns	0.73ns	0.74a	0.83a	0.61b	0.81a
K/Mg ratio	7.22a	4.10b	2.68c	5.59a	4.16b	4.26b	5.02ns	4.02ns	5.38ns	4.24ns

[a]M: Merlot; CF: Cabernet franc; CS: Cabernet Sauvignon.

[b]Data analyzed by ANOVA based on a split-plot design, with soils as main plots, cultivars as subplots, and vintages as block effect. Means are compared by Newman-Keuls test ($p \leq 0.05$).

(75% of the total variance). Petiole Mg content was high on clayey soil and low on gravelly soil. It was negatively correlated to petiole K content (r = -0.63, n = 36, $p < 0.001$). The petiole K/Mg ratio was mainly affected by the soil type (70% of the total variance), but the effect of soil strongly interacted with the effect of cultivar for this variable. This ratio was high on the clayey soil and low on the gravelly soil. There was no apparent relationship between petiole N, K, P, or Mg contents and berry composition. The only significant correlation was between petiole Mg content and berry sugar content (r = 0.48, n = 36, $p < 0.01$).

Vine water status. Vintage had the greatest effect on vine water status in this study (44% of the total variance). The seasonal progression of the Merlot predawn water potential at the gravelly soil site during all five vintages is given as an example (Figure 5). In 1998 and 2000 vines were subjected to medium to strong water deficits (Table 3), except on sandy soil (water table within reach of the roots). Vines experienced defoliation after veraison on gravelly soil. Water deficit stress occurred very early in the 1998 season. Only minimal water deficit stress was measured in 1996 and 1997. In 1996, preveraison water deficits tended to be greater than those measured in 1997 ($Ø_d$ = -0.17 and -0.11 MPa, respectively, ns), but the period from veraison to harvest was wet (Figure 3E). No water deficits occurred before veraison in 1997 due to heavy rains in June (Figure 4B), but September was dry and a weak water deficit was registered just prior to harvest ($Ø_d$ = -0.24).

A significant effect of soil on vine water status was measured (40% of the total variance for minimal $Ø_d$ during the veraison to harvest period and 30% for minimal preveraison $Ø_d$, Table 2). A small but significant effect of the cultivar on vine water status was shown: $Ø_d$ is less negative for Cabernet Sauvignon than it is for Merlot and Cabernet franc.

Vine water status had an effect on vine development and berry composition. Even when the three cultivars are considered together, this effect remained significant (Table 5). Water deficit stress accelerated growth cessation. Berry sugar and anthocyanin contents increased as vines became more stressed. Water deficits reduced total acidity. Most variables, except those linked to acidity, were correlated equally to early water deficits (minimum $Ø_d$ preveraison) and to the intensity of the water stress (minimum $Ø_d$ veraison to harvest).

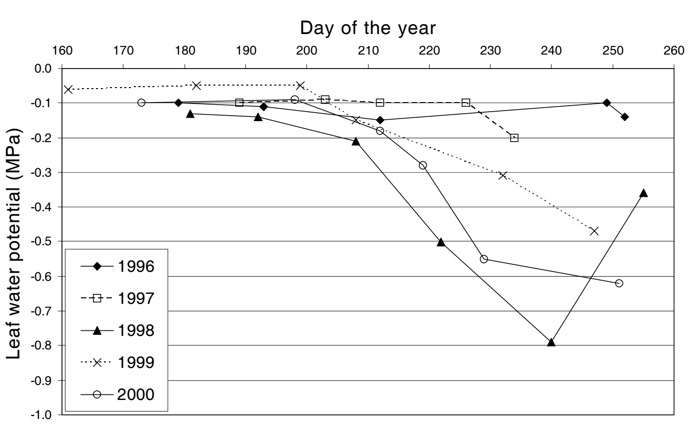

Figure 5 Seasonal dawn leaf water potential of grapevines at the gravelly soil site. Each point represents the mean of six replicates.

Discussion

This is the first study in which climate, soil, and cultivar, the three main parameters of terroir, were studied simultaneously. Previous studies have only examined one or two of those parameters at the same time, such as climate (Winkler et al. 1974, Huglin 1978) or cultivar (Huglin and Schneider 1998). Little data have been published concerning the impact of different soil types. This study allowed us to determine which factors had the greatest effect on growth and development of the vegetative and reproductive organs of the vine and subsequent effects on the wine. Among the variables measured in this research, berry weight, berry sugar concentration, berry anthocyanin concentration, and must total acidity have a direct influence on wine quality. Berry weight is mainly influenced by the soil type, followed by the cultivar. Berry sugar concentration depends mainly on the cultivar and the soil type, but also on the vintage. There is a significant effect of vintage and soil type on berry anthocyanin concentration, but this variable is not determined by the cultivar. Total acidity and pH of the grape juice depend on the vintage and, to a lesser extent, on the cultivar and the soil type. Total acidity is mainly determined by malate, which is highly variable among vintages and cultivars, and less so by tartrate.

Yield did not affect the fruit-quality data, possibly because yield was low compared to other grape-producing areas of the world. Yield was not correlated with berry sugar concentration (r = 0.06, n = 36, ns), with berry anthocyanin

Table 5 Correlations between vine water status and vine development and berry composition

	Minimum $Ø_d$ preveraison	Minimum $Ø_d$ veraison to harvest
Shoot growth cessation (day of year)	0.680 ***[a]	0.782 ***
Total shoot length (cm)	0.658 ***	0.638 ***
Sugar (g/L)	-0.322 *	-0.272 ns
Anthocyanin (mg/kg)	-0.483 ***	-0.402 **
Ripening speed	-0.528 ***	-0.524 ***
Berry weight (g)	0.387 **	0.351 *
Total acidity (g/L)	0.339 *	0.515 ***
pH	-0.336 *	-0.613 ***
Malate (g/L)	0.390 **	0.516 ***
Tartrate (g/L)	0.211 ns	0.102 ns
Sugar/acid ratio	-0.426 **	-0.527 ***
Veraison (day of year)	-0.312 *	-0.088 ns

[a]*, **, ***, and ns indicate significance at $p < 0.05$, 0.01, 0.001, and 0.05, respectively.

concentration (r = -0.32, n = 36, ns), or with berry skin total phenolics concentration (r = 0.08, n = 34, ns). However, yield was positively correlated with grape total acidity (r = 0.41, n = 36, $p < 0.05$) and grape malic acid concentration (r = 0.50, n = 36, $p < 0.01$) and negatively correlated with grape juice pH (r = -0.48, n = 36, $p < 0.01$). The leaf area/fruit weight ratio did not affect berry sugar concentration, skin anthocyanin, or total phenolic concentration. In this study, the leaf area/fruit weight ratio was high (average = 2.7 m^2/kg of grapes), because of large leaf area per vine and moderate or low yield. Kliewer and Weaver (1971) found that berry size, sugar concentration, and anthocyanin concentration increased with the leaf area/fruit weight ratio up to 1.4 m^2/kg. In this study, the ratio was under 1.4 m^2/kg in only 2 of 36 measurements. That might explain why no significant influence of yield, or leaf area/fruit weight ratio, is shown on grape potential, except for a slight incidence on juice acidity.

Soil may influence vine development and fruit ripening through mineral supply. Petiole Mg content was highly dependent on soil type and, to a lesser extend, on vintage; petiole K content was dependent on soil type and cultivar; and petiole N content was dependent on the vintage and the soil type (Table 4). However, no direct relationship could be established between soil N, P, K, and Mg content (data not shown) and petiole content for these minerals. The only significant correlations that could be established concerned petiole K content and juice K content, as well as petiole Mg content and berry sugar content. Mineral nutrient uptake by the vine or the ability of the soil to provide those nutrients did not appear to have a significant impact on fruit quality in this study, which is consistent with the conclusions of Seguin (1986).

The climatic conditions of the vintage can influence grape quality through the amount of insolation, temperature, or water balance (rainfall – k*ET_o (mm)). High sunlight stimulates berry anthocyanin accumulation (Smart 1985, Keller and Hrazdina 1998, Bergqvist et al. 2001, Spayd et al. 2002). In the five vintages studied, sunshine hours did not differ to a considerable extent during the veraison to harvest period; but in 1996, sunshine hours were high during the flowering to veraison period. This might explain high anthocyanin concentration in this vintage. However, no general link can be established in this study between average daily sunshine hours and vintage quality. Wine quality in the Saint-Emilion region has been rated in the popular press as 87/100 in 1996, 81/100 in 1997, 98/100 in 1998, 83/100 in 1999, and 99/100 in 2000 (Suckling 2003). Average daily sunshine hours from flowering to harvest was high in 1996, but wine quality was only average in that vintage. High temperatures reduce anthocyanin accumulation (Buttrose et al. 1971, Kliewer and Torres 1972). Spayd et al. (2002) indicate an optimum temperature range for anthocyanin synthesis between 30 and 35°C. In this study, mean high temperatures never exceeded 29°C. Although the temperature of sun-exposed grapes can be several degrees higher than ambient temperature (Bergqvist et al. 2001), it is unlikely that, in the maritime Bordeaux climate, anthocyanin synthesis is depressed by excessively high temperatures. This would seem to hold true even in 1997, when mean high temperatures peaked during the veraison to harvest period. No clear relationship can be established between quality ratings of the vintages and mean high or low temperatures.

Variations in water deficit from one vintage to another can be simulated by means of a water-balance model: rainfall – k*ET_o (mm). ET_o does not vary to a considerable extent from one vintage to another in the Bordeaux area (Figure 3C), but rainfall during the flowering to harvest period can be highly variable (263 mm in 1997; 117 mm in 2000). Water deficit between flowering and harvest was severe in 2000, moderate in 1998, and weak in 1996, 1997, and 1999. Many studies indicate the positive impact of moderate water deficit stress on phenolic compound synthesis and grape quality (Duteau et al. 1981, Matthews and Anderson 1988, van Leeuwen and Seguin 1994, Ojeda et al. 2002). Here, optimum quality was reached in vintages where low summer rainfall led to a water deficit stress (2000 and 1998).

The intensity of vine water deficit stress depends not only on climatic parameters but also on the water-holding capacity of the soil. In this study, the sandy soil parcel included a water table within reach of the roots. Even in a dry vintage, vines do not face water stress on this soil type. In contrast, the gravelly soil had a low water-holding capacity: water stress can be severe on this soil. Finally, the clayey soil was subject to early but moderate water deficits.

A strong relationship exists between improved grape quality and water deficit before veraison, when water deficit probably affects grape quality indirectly. An early water deficit provokes early shoot growth cessation and reduces berry size. Under these conditions, berry sugar and anthocyanin concentrations are increased because of greater ripening speed. Total acidity is reduced, as berries contain less malic acid. Grape quality is high on the soils that induce water deficit, especially on clayey soils where water deficits occur early in the season but are moderate. Good vintages are those when vine water uptake becomes limiting early in the season, as in 1998.

Conclusion

The three main parameters of terroir—soil, cultivar, and climate (through the vintage effect)—were studied simultaneously. The highly significant effects of these three parameters on vine development and berry constitution are shown. The effect of climate was greatest on most parameters, followed by soil and cultivar. Vine mineral uptake did not appear to have a critical effect on fruit quality. Sunshine hours and temperatures did not have a determining impact on the quality of the vintage. The effects of climate and soil on vine development and grape composition can be explained in large part by their influence on vine water status. Vintage influences vine water status through varying amounts of summer rain, while soil influences vine water status through its water-holding capacity and, possibly, accessibility to the water table. The best vintages were those in which the water balance from flowering to harvest was most negative. The best soils were those on which water deficits resulted in earlier shoot-growth slackening, reduced berry size, and high grape sugar and anthocyanin concentrations, thereby increasing grape quality potential.

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