'Terroirs' and pedology of wine growing

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Introduction

In the climate-soil-vine ecosystem it is difficult, when studying soil in isolation, to determine its influence on the constitution and the quality of grapes and wines. Moreover, human factors must be added to the natural factors, since the wine grower may happen to transform the characteristics and properties of the soil with soil conditioners, chemical manures and sometimes with irrigation. For any given mesoclimate, plant (rootstock and cultivar) and soil, he can, by means of training systems, modify the forwardness, quantity and quality of the harvest. Finally, technological factors are decisive as regards vinification, treatment and conservation of wines.

Straightaway, it must be noted that there is no complete in-depth study of these ecosystems. This is because of the many factors at work:
- climatic conditions[9,10,23–25,28,51,64,90,96]
- the thermic and luminous microclimate of the exposed parts in relation to the training system[12,14,51,88,90]
- the cultivar and the rootstock[55]
- the yield[40]
- geographical and topographical factors[5,67,51,71]
- soil characteristics[23,27,36,45,52,56,66,68,72–74,82]
- mineral nutrition of the vine[31,32,33] and especially nitrogen nutrition[17,18,64]
- the hydric nutrition of the vine[8,15,23,24,26,28–30,56,58,59,65–67,73–76,78,79,81,84,92]
- the ecogeopedological milieu[47,48,70]

Terroir – A factor in the quality of grapes and wines

In spite of the interference of these factors, the 'terroir' seems to play an important role in the quality of wines, at least in those wine regions having fresh or temperate climates. Moreover, 'Appellations d'Origine Contrôlée' boundaries are fixed according to geological, topographical, morphological and agro-pedological criteria. Tasting reveals considerable differences according to the nature of the terroir. At Saint-Emilion, the flat sandy soils produce wines which are not deeply-colored but are thin and lacking in finish, and do not have the body, elegance and finesse of those obtained only a few hundred meters away on the calcareous sandstone (Sannoisian) or on the 'asteries' limestone (Stampian). This occurs despite the fact that black Merlot is the predominant cultivar everywhere and has the same training system. In the Graves area, where the soils have a large surface homogeneity (gravel-sand texture) but with different subsoils (clayish sandstone, asteries limestone, the predominance of siliceous pebbles or rough or fine sand) one may, with cultivars, rootstocks and training systems which are similar, obtain wines whose type and quality are variable in relation to the diversity of the subsoils[15,85]. However, the influence of the soil, in the Bordelais area too, is denied or at least challenged by several authors who attach more importance to the role of the climate, cultivar and technological factors[1,60,96]. It is, however, true that these authors have not carried out in-depth study on the Bordelais terroirs, but work in 'young' vineyards areas (USA, Australia); in such countries there is no hierarchy of the 'Crus' (growths), since empirical methods have not always led to the discovery of cultivars which are the best-adapted to local climatic and soil conditions. In a state like California where the difference in latitude is as great as that in France, Amerine[1] and Winkler[96] have distinguished five climatic zones and maintain that temperature has a bearing on the quality and the characteristics of wine. This is undoubtedly true as a preliminary statement but the association of cultivar and temperature is not the only factor as regards quality; some young Australian and American researchers concede that the quality of wine does depend on the climate-soil-cultivar ecosystem.

In France, what constitutes a quality terroir? Good terroirs are those permitting complete but quite slow maturation of cultivars. Moreover, a 'grand cru' is characterized by a certain regularity in quality in the various vintages. J. Ribéreau-Gayon and E. Peynaud[63] underline the fact that the grand cru is characterized by good wine composition from one year to another. In the 'premier grand cru' type of red wine, the must degrees (potential alcohol degree) in the last twenty years have varied from 11.5 to 12.3, and acidity of finished wines from 3.3 to 3.7 grams (H_2SO_4) per liter. Given the same conditions, a wine grower who is not classified will produce wine in which the deviation is much greater, the must degrees ranging from 9.8 to 12.8 for example, and acidity from 3.6 to 5.2 g/l. It is especially in poor years that the superiority of the grand cru becomes most apparent; moreover, one must note that the character of the cru dictates the character of the cultivar.

All this supposes that the soil attenuates the harmful effects of extreme climatic conditions such as long drought or heavy rainfall[73,74].

Finally, physical, chemical and physico-chemical factors in soils must limit production, since it has been established that beyond a certain level, which is variable according to the climatic conditions of the year, there is a negative correlation between yield and the quality of the harvest[40]. These limiting factors may be chemical (poor nitrogen nutrition or ion antagonisms, for example) or physical (insufficient water supply during certain phases of the vegetative cycle of the wine)[29,67,74,78].

Terroirs: study techniques

Soil analysis. A quick method of characterizing terroirs consists of carrying out physical, chemical and physico-chemical analysis of the soil and the subsoil. This kind of study has been conducted in various regions of the world and particularly in Italy by Fregoni et al.[31–34]. Such analysis is indispensable since it indicates the degree to which chemical manure and soil conditioners are necessary for the development and growth of the vine. But from an analytical viewpoint, the characteristics of the best terroirs vary considerably the world over.

In a few regions, certain authors have tried to establish a relationship between the quality of wines and the soil content of various assimilable elements (potassium, magnesium, phosphorous and various oligoelements such as boron, iron, manganese, copper and so on). Even though certain tendencies may be established locally, they no longer hold on a regional or world basis. At the moment, not one single soil constituent or element may be said to be an absolutely decisive factor in wine quality. The only one which is generally associated with wine quality is active calcium carbonate; this is not surprising since many quality vineyards are situated on calcareous parent material, and the abundance of calcium is a well-known factor in the structural improvement of soils. It has a direct bearing on their physical properties, but its presence in soil is not indispensable since there are many quality vineyards which are situated on acidic soils, where there is absolutely no active calcium carbonate (Grands Crus Classés in the High-Medoc for example). Moreover, it has been noted that nitrogen-rich land or land which has undergone excessive nitrogen fertilization[17,18,54,61,62] produces wines which are poor in anthocyanins and tannins. It also makes black Merlot more sensitive to rot; this is the case even if there is no increase in yield.

As regards topographical, morphological and physical characteristics, the best terroirs are in general (there are certain exceptions) situated on slopes, while plains or lowlands are not very favorable for the production of quality wine. They have soils which are well structured, highly permeable and well-aerated. Clay or pebble levels may have an influence on organoleptic character and the type of the wine, but it is possible to produce high quality wines on stony soils containing little clay, and inversely on clayish soils having a low pebble content.

At extremes of pH, certain deficiencies or toxicities may appear; with high pH values, there is a low degree of solubility of oligoelements in the form of cations (Fe, Mn, Zn, Cu)[87]. On the other hand, in acidic soils (pH lower than 5), aluminum, manganese and copper toxicity may be present[19,20]. However, soil pH does not have much influence on the quality of wines, since quality wines are produced on acidic, neutral and alkaline soils.

Determination of bioclimatic units. In the young wine-growing countries (USA, Australia, South Africa, etc.) where the best terroirs have not been totally delimited, the method used in the south of France[3,4] could prove profitable, at least in the beginning. Although crude in conception, this approach consists in determining bio-climate units defined by Gaussen's summer low-points and by floraring constants, in which various plants (spontaneous vegetation, but also cultivars) exhibit homogeneous phenological behavior. Bioclimatic units are subdivided in relation to edaphic factors: topographical, geological, pedological and agronomic. This technique, which has been used in the Aude 'Departement', has led, through empirical judgement but also through recent vine-wine experiments, to the splitting-up into zones of potential wine-production areas. The method allows the matching of certain cultivars to certain local climates and soils. However, although the improvement of quality is a constant preoccupation, quantitative aspects must also be taken into account in this type of vineyards.

Establishment of ecogeopedological sequences. In other regions where there is already a tradition of quality, the Val de Loire method (vineyards of Saumur-Champigny, Chinon and Bourgueil)[22,47,48,70] allows the identification of terroirs which are the most suitable for the production of quality wine. The method consists in objectively analyzing the viticultural value of a region in the light of a detailed soil study. First, ecogeopedological sequences of reference are established on the sandy-glauconitic chalk of the mid-Turonian. All things being equal, they are compared with sequences situated on other geological formations having a particular altitude, relief and meso-climate, and with different types of soils. A multilocal study (19 plots) was set up in 1979; the first phase of observation, which is currently under way, consists of testing the validity of the method and establishing a hierarchy of sequences based on wine-tasting, obtained with minivinifications. A second explanatory phase should enable the influence of the elementary components of each milieu to be quantified, particularly those apt to produce a quality wine which has its own type and only minimal interactions with prevalent climatic conditions.

Study of 'cru' quality terroirs. In regions where Appellations d'Origine Contrôlée terroirs are clearly delimited, and where the cultivars, the training system and yields are more or less fixed by legislation, a very finely detailed study is necessary of the factors which seem to have the greatest influence on the quality of harvests and wines. We shall now turn our attention to this type of terroir, citing as examples certain regions where detailed studies have been carried out.

Influence of geological and pedological factors

On a world scale, excellent quality wines are produced on the most diverse types of geological formations: schists (Porto, Moselle), chalk, limestone, marl or sandstone containing different amounts of active calcium carbonate (Champagne, Bourgueil, Chinon, Chablis, Saint-Emilion, Burgundy; Jerez, Rioja; Barolo, Barbaresco, Chianti, Marsala; Rheingau, etc.); clay (certain crus of Pomerol, Sauternes, etc.); sand (Nebbiolo d'Alba); schist granite and porphyry (Beaujolais)[24,25,32,35,56,70,81].

In the Bordelais, no geological formation (quaternary siliceous pebbles-sands but also tertiary limestones and

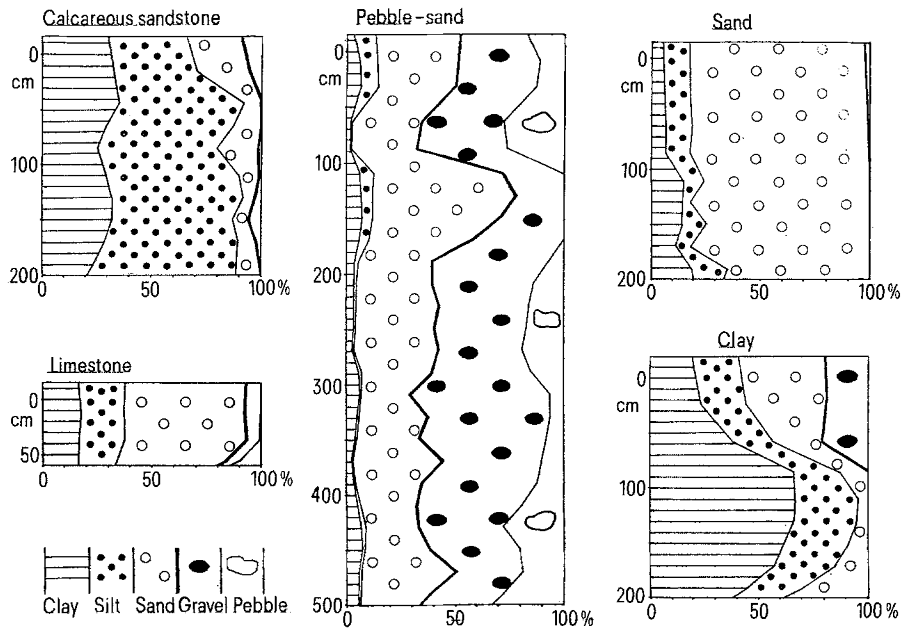


Figure 1. Principle types of wine producing soils in Saint-Emilion and Pomerol. Percentage of the different granulometric fractions of rough earth in relation to depth (cm).

sandstones, clays ...) can be said to be the best in quality. Moreover, on the same parent material, like the pebble-sand alluvials of the left bank of the Garonne, one can produce the excellent red wines of the Medoc and a part of the Graves, the dry white wines of the Graves and the sweet white wines of the Sauternais.

Given the diversity in parent material and in climate, it is not surprising that quality wines may be produced on soils which are pedologically very different: chernozems in Eastern Europe, rendzinas on limestone outcrops, calcareous brown soils, brown soils which are more or less leached, acidic leached soils and sometimes podzols. One could add to this list (and this is really surprising since they are normally excluded from Appellation d'Origine Contrôlée) soils which are hydromorphic from being engorged (the best cru of Pomerol)[30] and soils with perched water table (the best cru of Sauternes) which would normally have evolved towards the pseudo-gley type, had it not been for the fact that they have been drained since time immemorial[57, 59].

Certain cultivars apparently prefer certain parent material. For example the Nebbiolo and the Chardonnay are at their best on marl[32]; the Gamay gives a nice wine on the schist granite and porphyry of the Beaujolais but a very ordinary one on the marly limestones of Burgundy. In the south of Spain, the Palomino produces remarkable sherry on the whitish limestones of the upper Oligocene, known as 'albarizas' of Jerez. The same goes for Pedro-Ximenes on the 'alberos' or whitish lands of Montilla-Moriles[97].

Influence of soil texture and structure

A few examples chosen from the best Bordelais crus (figs 1 and 3) show that as in Burgundy (fig. 2: stoniness and clay)[45] and in other wine productng areas, the quality of wine does not seem to be related to a definite textural type, since in these terroirs one may note considerable variations in the gravel and pebble content (from 0% to more than 50%) and in clay content, which may be almost negligible in certain soils, but may reach 60%, as in the best Pomerol cru[36, 74].

Soil structure seems to play a much more important role. In the majority of cases, the best terroirs are characterized by a high degree of macroporosity, permitting rapid

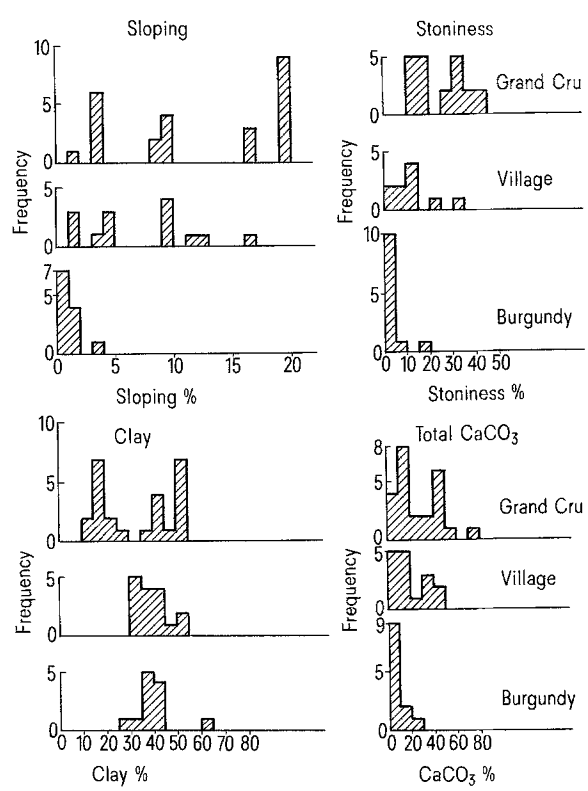


Figure 2. Histograms of criteria (Burgundy)[45].

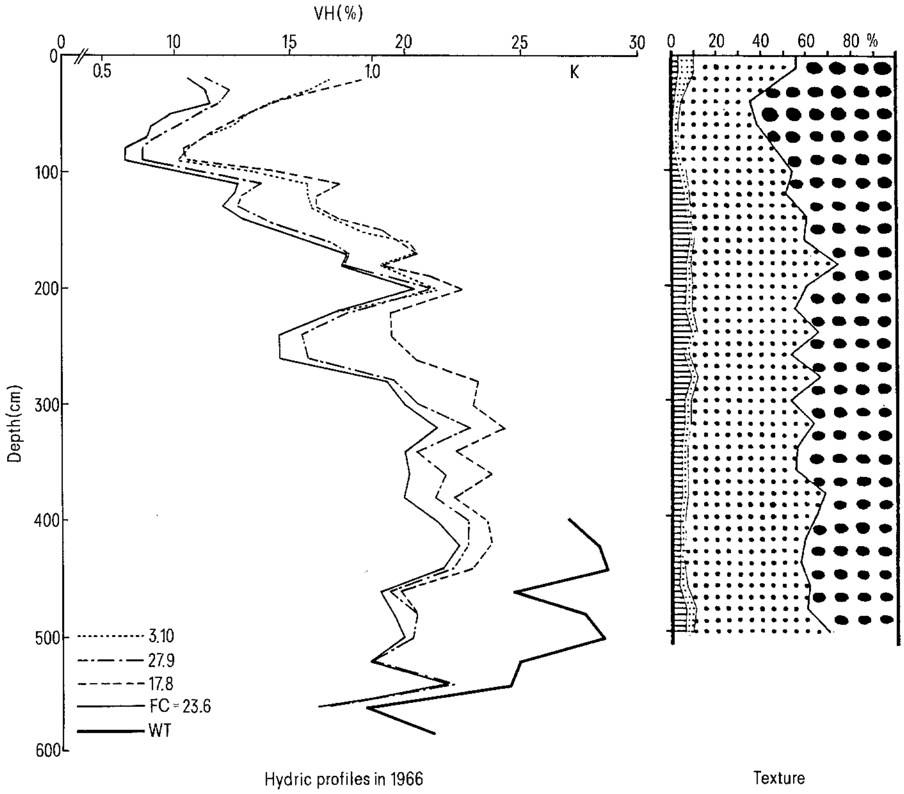
water percolation, and thereby preventing stagnation at root level. Coarse soils (gravel-sand) are of course permeable; however, clayish soils are only porous when there is sufficient humus (at least 10% of clay content) and calcium in abundance to flocculate the clay-humus complex (one must remember that many quality terroirs are situated on parent material containing active calcium carbonate). Apart from the high degree of permeability and aeration which characterizes them (exceptions will be mentioned in the chapter dealing with water supply to the vine) these soils are easily penetrated by the roots of the vine and are very resistant to erosion, since the particles are bound by a clay-humus cement.
The macroporosity of the soil and of the parent material sometimes enables roots to attain a considerable depth; 5–7 meters for the pebble-sand soils of Medoc, Sauternes and Graves of the Bordelais[15,56,73,74], and 4 meters through the diaclases of the 'albarizas' of Jerez[35]. In certain clayish soils, and especially in soils situated on compact non-karst limestones, root depth is sometimes limited (30–70 cm) in Burgundy[45] and Saint-Emilion[36]. The depth and the mode of colonization of the soil by the roots have repercussions of course on the mineral nourishment and the water supply to the vine.

Chemical properties and fertilization of wine-producing soils

The chemical poorness of soils is often held to be a factor of quality; in fact, the chemical and physico-chemical properties are very different according to the pedological type of origin, but especially in relation to the human hand which, in certain cases, has completely modified the original surface characteristics of soils: drainage, marl and other earth improvements, mineral fertilizers, organic or mineral additives. This may be the case to such an extent that these soils no longer have anything in common with the pedological characteristics of natural soils (this is especially true in the old podzols). In the gravel-sand soils on which the greater part of the best Bordeaux crus are situated, the poorness in assimilable mineral elements is, in many cases, legendary. While their mineral content (as a percentage) is low, it must be noted that given the great depth to which the roots of the vine go, large quantities of various cations and anions are available (fig. 3). It may be seen that the low level of assimilable elements in the upper layers of the soil favors the spreading out at a greater depth of roots which at that level find what they cannot find on the surface. This deep-rooting process provides much greater regularity in the water supply to the vine, and in this respect, low level of assimilable elements become a factor of quality.
On the other hand, superficial soils on limestone parent rock (table 1) seem much richer; however since root depth is limited to about 50 cm, they too are poor, and often poorer than certain Medoc soils.
Yet even when roots have at their disposal large quantities of assimilable elements, yields are not systematically high. It needs only one limiting factor for the soil to behave as though it was poor in all elements. In the gravel-sand soils of the High-Medoc, the Graves and Sauternes, these limiting factors may be (fig. 3):
– Acidity which hinders the assimilation of mineral elements and favors the solubilization of toxic elements such as copper, manganese and aluminium. However, a high levels of acidity (pH lower than 5) is quite rare nowadays, since this has been corrected, at least on the surface, with calcareous additives.
– An excess in potassium, which by ion antagonism limits the absorption of magnesium and reduces fructifi-

Table 1. Characteristics of soil on stampian limestone (Saint-Emilion)

Depth (cm)		0 to − 10	− 10 to − 25	− 25 to − 40	− 40 to − 50
Pebble (> 2 cm)	p. 100	7	14	9	15
Gravel (2 mm − 2 cm)	p. 100	12	11	9	12
Fine earth (0–2 mm)	p. 100	81	75	82	73
Coarse sand (200–2000 µm)	p. 100	52.2	49.2	48.6	43.2
Fine sand (50–200 µm)	p. 100	15.5	15.5	18.2	18.9
Coarse silt (20–50 µm)	p. 100	6.3	4.6	6.3	6.5
Fine silt (2–20 µm)	p. 100	16.3	19.2	15.9	19.5
Clay (0–2 µm)	p. 100	6.1	8.9	8.2	9.3
Actual moisture	p. 100	1.2	1	1.2	1
Organic matter	p. 100	2.4	1.6	1.6	1.6
Moisture holding capacity	p. 100	14.7	17.3	16.5	16.7
Organic carbon	p. 100	1.41	0.94	0.94	0.93
Total nitrogen	p. 100	0.121	0.071	0.079	0.084
C/N		11.6	13.2	11.9	11.1
Adsorbing complex					
K^+	meq/100 g	1.04	0.72	0.48	0.29
Na^+	meq/100 g	0.18	0.20	0.20	0.25
Mg^{++}	meq/100 g	0.96	0.80	0.85	0.69
Ca^{++}	meq/100 g	+	+	+	+
S	meq/100 g	+	+	+	+
Cation exchange capacity	meq/100 g	10.3	9.3	9.5	10.4
pH (water)		7.8	7.8	7.7	7.7
Total $CaCO_3$	p. 100	34.4	44.9	35.1	37.1
Active $CaCO_3$	p. 100	5.3	8.8	6.6	9.4
P_2O_5	p. 100	0.052	0.018	0.025	0.013
Free iron	p. 100	0.95	0.54	0.45	0.59



C (p.100)	N (p.100)	K^+ (mEq p.100 g)	Mg^{++} (mEq p.100 g)	Ca^{++} (mEq p.100 g)	CEC (mEq p.100 g)	pH	P_2O_5 (p.100)
0.85	0.070	0.27	0.07	0.59	4.6	4.6	0.040
0.39	0.035	0.14	0.04	0.28	2.7	4.9	0.050
0.20	0.022	0.12	0.09	0.21	2.2	5.0	0.034
0.11	0.014	0.11	0.09	0.28	1.8	5.1	0.025
0.19	0.017	0.27	0.05	1.18	3.5	5.2	0.025
0.14	0.011	0.21	0.11	1.02	3.2	5.1	0.019
0.12	0.011	0.27	0.13	1.25	4.0	5.1	0.019
		0.14	0.07	0.69	3.0	4.9	0.013
		0.14	0.10	0.49	2.5	4.8	0.014
		0.15	0.11	0.53	2.7	4.7	0.016
		0.15	0.11	0.49	2.9	4.6	0.006
		0.18	0.07	0.54	3.2	4.7	0.009
		0.17	0.05	0.43	3.2	4.7	0.006
		0.24	0.11	0.49	3.0	4.7	0.005
		0.15	0.07	0.49	3.1	4.7	0.005
		0.13	0.01	0.43	2.6	4.7	0.005
		0.21	0.04	0.38	2.5	4.7	0.004
		0.30	0.13	0.44	2.5	4.7	0.004
		0.40	0.05	0.59	3.2	4.6	0.004
		0.46	0.03	0.33	2.3	4.6	0.005
		0.36	0.13	0.39	1.8	4.6	0.005
		0.49	0.07	0.53	2.2	4.6	0.005
		0.46	0.13	0.59	2.7	4.6	0.004
		0.43	0.07	0.51	2.2	4.6	0.004

Analysis of fine earth

Figure 3. Medoc soil.

cation; this phenomenon is common in the best crus, where potassium additives, which are excessive for this type of soil, lead to a lack of magnesium.

– Above all, the lack of total nitrogen (which represents on average 0.05% of the weight of surface rough earth) associated with low humus content; then again, humus may stay localized in the upper layers of the soil and, therefore, great root depth will not improve the nitrogen nutrition, as is the case for other elements. In calcareous soils where humus, stabilized by active calcium carbonate, is not easily attacked by bacteria, the annual mineralization rate (about 1%) is only half that in other wine producing soils; this necessitates a nitrogen content twice as high to obtain equivalent nitrogen nutrition.

In short, the chemical factors which are the most favorable to wine quality correspond to a certain soil poorness resulting in low production levels. In general, everything happens in the Bordelais as though the temperature and the degree of sunlight enabled the synthesis of a limited quantity of coloring matter, aromas, and sapid elements, and it seems that these substances are diluted and deteriorated when there is too sharp an increase in yield.

Therefore, fertilization is not an automatic panacea for getting soil to its optimum production level, if the matter of quality of the wines is also important. Certainly, the vine must not suffer, since a plant which is ill (due to chlorosis, drying out of the stem ...) never gives good wine. Nevertheless, the existence of factors limiting production, such as a certain nitrogen lack or slight potassium-magnesium antagonism, does not seem to be detrimental to wine quality; on the contrary, it is often in plots like this, where this type of deficiency is present, that the best Medoc wines are produced[85].

If excellent quality wine is produced, then the empirical approach could predominate, and one could limit oneself to restoring to the soil those elements which are transferred through harvesting or lost by being washed away (maintenance additives). As for the poorest soils, the most serious shortcomings should be corrected with a chemical manure at the moment of trench ploughing. The appropriate fertilizers should be added, but this should be done carefully and rationally, as a result of a complete soil and sub-soil analysis[18].

Nevertheless, we have shown that for the Bordeaux area, the chemical properties of soils do not seem to have much specific influence on the quality of wines if excessive nutrition of the vine does not result in excessive production and if, conversely, the vine does not suffer from toxicity or a serious lack of any element. Excellent wines are produced on acid, alkaline or neutral soils, or again, on soils where the chemical constitution is balanced; others, however, are characterized by a deficiency in certain elements and important ionic disequilibrium (table 2: soil of Cantenac)[83]. Without doubt, the soils of the Premiers Grand Crus Classés of the Medoc are on average richer in organic matter (therefore in total nitrogen), in assimilable potassium and phosphorus (tables 3 and 4) but it is not because they are richer in these elements that they are Premier Grands Cru soils. On the contrary elements have been added to these soils because they belonged to very great crus where the owners have always taken the trouble to look after their soils. Indeed, these differences are evident on the surface but not at depth (beyond 60 cm) in those layers which are only slightly affected by chemical additives[27, 82]. As our knowledge stands at the moment, it is impossible to establish any correlation between the

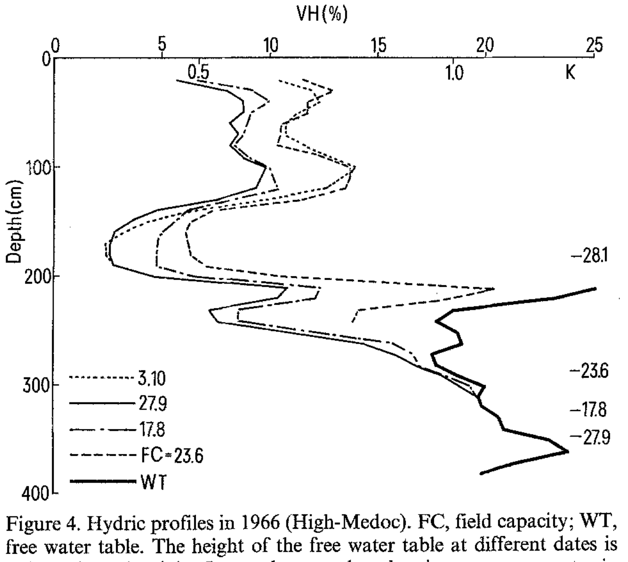


Figure 4. Hydric profiles in 1966 (High-Medoc). FC, field capacity; WT, free water table. The height of the free water table at different dates is indicated on the right. It may be seen that the vine consumes water in areas which, during winter, are occupied by the free water table. Subsequent to heavy rainfall the hydric profiles in the 23rd June was close to that corresponding to the field capacity. It may be noted that in spite of heavy rainfall (45 mm between 28th September and 2nd October) the upper part of the hydric profile on the 3rd October is close to the field capacity. Less than 24 h after the last rainfall, no more free water was left on the soil.

quality of wine and the soil content of any nutritive element, be it potassium, phosphorus or any other oligo-element. If there were such a correlation it would be easy, with the appropriate chemical additives, to produce great wine anywhere[82].

Water supply to the vine

Factors that we have looked at so far (parent material, type of soil, texture, chemical properties, etc.) certainly have a bearing on the character and type of wines, but none of them seems to have a really deciding influence as regards quality, i.e. the pleasure one obtains on tasting or drinking wine.

Another method is to study the water supply to the vine; this does seem to have a bearing on the quantity and the quality of the harvest and the approach integrates numerous factors:

– climatic factors: rainfall, sunshine, temperature, relative air humidity which together determine the evaporating power of the air i.e. the potential evapotranspiration;

– edaphic factors: parent material, topography, water table, structure and root arrangement, reserve of usable water, permeability, aeration and so on;

– biological factors: nature of cultivar and rootstock;

– human factors: techniques of soil upkeep, drainage, irrigation; training of the vine and particularly plantation density, trellising method, pruning, topping, etc. which result in a system in which water may evaporate.

Apart from the irrigation experiments to be mentioned below, the water supply to the vine has been the subject of a number of studies in lysimetry or on vines in pots[7,8,44,65,67]. These techniques have the disadvantage of reducing the lateral and vertical extension of the radicular system and of getting rid of the phenomenon of competition between plants. Since the pots are often isolated, 'oasis effects' may be seen. And finally since the pot is

Table 2. Typical characteristics of two Grands Crus Classés of the High-Medoc

Depth (cm)		Saint-Julien 0 – 30	– 30 – 70	– 70 – 110	Cantenac 0 – 30	– 30 – 70	– 70 – 110
Pebble and gravel	p. 100	33	25.5	20	45	50.5	48
Fine earth (0–2 mm)	p. 100	77	74.5	80	55	49.5	52
Coarse sand	p. 100	61.6	62.9	70.5	79.0	82.5	88.2
Fine sand	p. 100	9.2	10.6	10.0	8.5	5.7	3.4
Coarse silt	p. 100	6.6	5.5	4.5	3.3	2.8	1.8
Fine silt	p. 100	10.5	9.3	6.3	4.9	3.5	3.1
Clay	p. 100	11.1	9.9	7.6	3.1	4.7	3.0
Actual moisture	p. 100	0.8	0.8	0.6	0.3	0.3	0.2
Organic matter	p. 100	2.0	1.0	0.5	0.9	0.5	0.3
Organic carbon	p. 100	1.16	0.59	0.31	0.52	0.29	0.16
Total nitrogen	p. 100	0.091	0.057	0.030	0.049	0.030	0.019
C/N		12.7	10.3	10.0	10.6	9.7	8.4
Moisture holding capacity	p. 100	12.0	11.8	9.7	6.9	5.1	3.9
Adsorbing complex							
K^+	meq/100 g	0.30	0.16	0.16	0.29	0.27	0.26
Na^+	meq/100 g	0.15	0.17	0.25	0.16	0.13	0.12
Mg^{++}	meq/100 g	0.38	0.33	0.25	0.13	0.06	0.09
Ca^{++}	meq/100 g	6.04	5.24	2.83	0.62	0.36	0.50
Cu	mg/kg	55	15	2	93	47	18
S	meq/100 g	6.87	5.90	3.49	1.20	0.82	0.97
CEC	meq/100 g	7.45	6.05	3.80	3.10	2.30	1.75
100 S/CEC	p. 100	92.2	97.5	91.8	38.7	35.6	55.4
pH (water)		6.4	6.7	6.85	4.95	4.95	5.35
pH (KCl)		6.05	6.35	6.10	4.1	4.15	4.45
Free iron	p. 100	0.30	0.25	0.21	0.15	0.12	0.08
P_2O_5	p. 100	0.067	0.055	0.035	0.032	0.036	0.023

The soils of Saint-Julien are not rich but are chemically balanced. The soils of Cantenac are very poor: total nitrogen (0.027% of surface rough earth), calcium and magnesium, with potassium-magnesium antagonism; acidity (pH lower than 5) favors the solubilization of toxic elements such as copper and hinders the assimilation of mineral elements.

Table 3. Mean characteristics of soils of Grands Crus Classés of the High-Medoc (0–100 cm)

Depth (cm)		Premiers Grands Crus Classés – 0 – 30	– 30 – 55	– 55 – 100	Other Grands Crus Classés – 0 – 30	– 30 – 60	– 60 – 100
Pebble	p. 100	21	19	0	35	41	45
Gravel	p. 100	30	32	42			
Fine earth	p. 100	49	49	38	65	59	55
Coarse sand	p. 100	53.4	56.6	67.7	64.7	68.5	70.8
Fine sand	p. 100	11.0	11.4	9.1	8.9	10.1	7.1
Coarse silt	p. 100	6.0	6.7	4.3	4.0	3.5	3.7
Fine silt	p. 100	10.7	9.2	5.1	8.8	7.9	6.3
Clay	p. 100	15.8	13.7	12.4	11.3	8.3	10.9
Actual moisture	p. 100	1.0	0.9	0.8	0.8	0.6	0.7
Organic matter	p. 100	2.1	1.5	0.6	1.5	1.1	0.5
Organic carbon	p. 100	1.22	0.86	0.33	0.88	0.62	0.29
Total nitrogen	p. 100	0.095	0.070	0.029	0.077	0.051	0.034
C/N	p. 100	12.8	12.3	11.4	11.4	12.1	8.5
Moisture holding capacity	p. 100	16.8	15.0	11.1	12.8	10.4	10.8
Adsorbing complex							
K^+	meq/100 g	0.47	0.48	0.23	0.26	0.20	0.21
Na^+	meq/100 g	0.11	0.13	0.10	0.23	0.22	0.22
Mg^{++}	meq/100 g	0.65	0.44	0.24	0.47	0.36	0.37
Ca^{++}	meq/100 g	6.78	5.62	3.43	5.27	4.27	3.25
S	meq/100 g	8.23	6.67	4.00	6.23	5.05	4.05
CEC	meq/100 g	10.1	8.4	4.5	7.2	5.5	4.9
100 S/CEC	p. 100	82	80	89	87	92	83
pH (water)		6.4	6.6	6.6	6.3	6.3	6.3
pH (KCl)		5.6	5.6	5.6			
Free iron	p. 100	0.51	0.52	0.39	0.36	0.40	0.36
P_2O_5	p. 100	0.059	0.049	0.017	0.036	0.037	0.025

situated above the soil (except in rare cases where it is buried) the temperature of the roots is higher than in normal conditions. It is therefore difficult to transpose these experimental data to potential results in the field. Some studies have been carried out under natural conditions but, in most cases, humidity measurement was not carried out on the whole of the depth exploited by the roots. The result is that it becomes impossible to calculate the actual evapotranspiration, i.e., the quantities of water consumed by the soil-vine system. Moreover, capillary rise or phenomena of slow drainage have not always been taken into consideration; in certain cases these can falsify the estimation of actual evapotranspiration[26]. The only results that can be looked at with objectivity at the present moment, without pretending they are absolute, concern mainly the Bordelais area.

The water supply to the vine in the gravel-sand soils of the High-Medoc. The study was carried out with a neutron moisture meter, which provided hydric profiles expressed in volumic humidity in relation to soil depth (figs 3 and 4). The principle of the apparatus is the slowing-down of neutrons by hydrogen in the water; the flux of thermic neutrons measured thereby is proportional to the water content of the soil[2]. As the measurements are made in a tube which remains permanently in the soil, it is possible directly to determine the humidity in the soil in situ, always at the same levels and at very great depths. We have therefore been able to study for the first time the mechanism of water supply in these soils where, in spite of the depth, the reserves of available water are relatively limited.

An interesting peculiarity of the majority of the soils of the Grands Crus Classés of the High-Medoc is the presence of a free water table situated within reach of the roots, and whose level goes down progressively from the spring to the beginning of the autumn. During the first part of the vegetative cycle, when the vine is in full growth, the radicles develop in the 'drop-away' zone of the water table. They absorb the water which is stored in the micropores of the upper layers of the soil; this water is more or less replenished by rainfall. The radicles also absorb the water which is left in the soil by the water table as it drops away. Finally they have at their disposal water which is easily usable, which they absorb at the upper

Table 4. Characteristics of soils of Grands Crus Classés of the High-Medoc

Depth (cm)	Premiers Grands Crus Classés 0 – 30	– 30 – 55	– 55 – 100	Other Grands Crus Classés 0 – 30	– 30 – 60	– 60 – 100
Pebble and gravel (p. 100 of rough earth)	51 (*)	51	62	35 (*)	41	45
Clay (p. 100 of fine earth)	15.8	13.7 (*)	12.4	11.3	8.3 (*)	10.9
Organic matter (p. 100 of fine earth)	2.1 (*)	1.5	0.6	1.5 (*)	1.1	0.5
Exchangeable potassium (meq/100 g of fine earth)	0.47 (***)	0.48 (***)	0.23	0.26 (***)	0.20 (***)	0.21
P_2O_5 (p. 100 of fine earth)	0.059 (*)	0.049	0.017	0.036 (*)	0.037	0.025

Differences: * Probability threshold = 5 p. 100; *** Probability threshold = 1 p. 1000.

limit of the capillary fringe; the latter is a sufficiently aerated zone since the water content there is equal to the field-capacity (the micropores are full of water, while the macropores are full of air).
However, from August onwards, the vine stops growing and the dropping-away of the level of the free water table, which continues, is no longer compensated by a corresponding growth of the radicles. In these very coarse texture gravel-sand soils, where the height of capillary rise is limited to 30 or 40 cm, the role of the water table diminishes progressively. The water supply to the vine during grape maturation depends on rainfall, but also on the quantities of water stored in the soil at the moment of 'veraison' (the point at which the berries turn from green to red but are still not ripe, i.e. the beginning of maturation).
In the light of this, and particularly of the depth of soil exploited by the roots, it is not surprising that the old, deep-rooting vines resist drought well; this is true even during grape maturation when the water table no longer plays a role in the water supply to the vine. On the other hand, superficially rooted plants, particularly the young ones, suffer from a lack of water when the summer is a dry one.
However, when rainfall is particularly heavy, the vines are not very sensitive to excess humidity since the soils are characterized by a remarkably high degree of permeability. This is due to the coarse texture of the parent material which favors drainage, but is also due to the topographical location of the Grands Crus, on 'croups' (small hills) next to the Gironde (Garonne estuary) and its small tributaries; these conditions facilitate the evacuation of drainage water. The hydric profiles recorded after heavy rainfall (figs 3 and 4: hydric profiles on October 3rd) show that the rain water filters through very rapidly. The water content recorded 24 h after heavy rainfall only rarely and temporarily exceeds those values corresponding to the field-capacity, whereas in other types of soils which are rather impermeable and are badly drained, the roots would be soaked.
It must also be noted that in summer, water from rainfall remains localized in the upper layers of the soil (figs 3 and 4); consequently plants with superficial roots are the

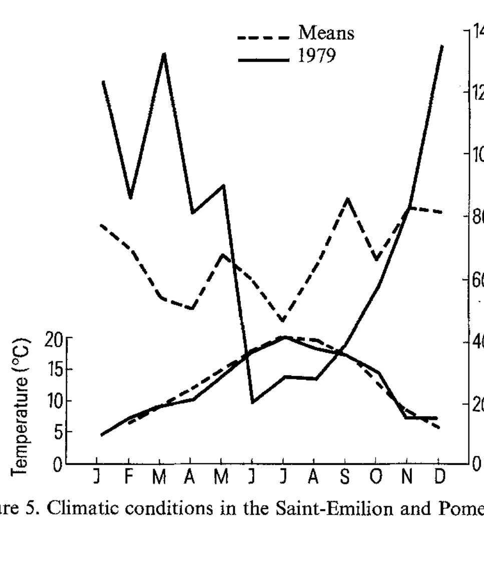


Figure 5. Climatic conditions in the Saint-Emilion and Pomerol region.

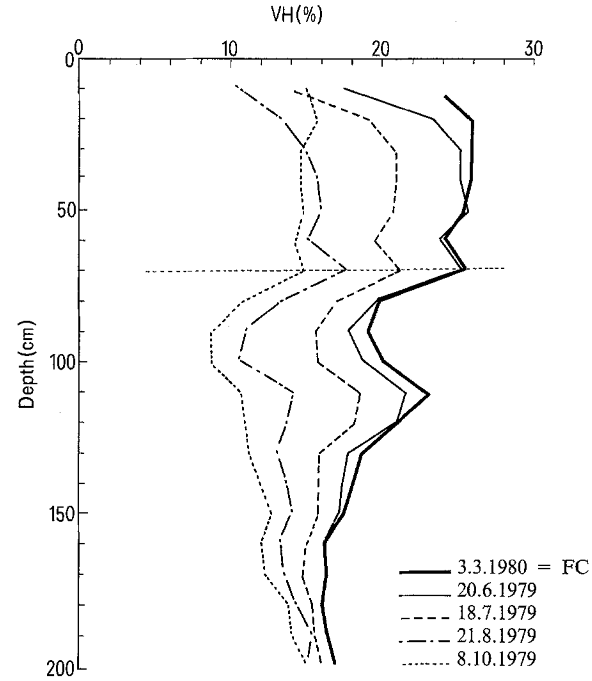


Figure 6. Evolution of hydric profiles in 1979 in soil C on limestone.

most affected by rainfall, whereas, as we have just seen, it is these very plants which are the most sensitive to drought.
In the High-Medoc, but also in the majority of Grands Crus Classés situated in the north of the Graves region, soil permeability and root depth limit the well-known effects of excessive rainfall during grape maturation: a rush of water into the berries causing them even to burst and provoking the onset of common rot, the dilution of the sugars and strong acidity. There is a much greater chance of harvesting mature and healthy grapes than in other wine-producing areas. In fact we have shown that the absorption of water (calculated by hydric profiles) after summer rain is clearly higher in soils with superficial roots, and that in consequence, the percentage of berries that burst and rot is much greater when the depth of the roots is shallow (table 7)[73–74,86].
Therefore in these soils where the old vines are deep-rooted, there are regulation phenomena which limit the effects both of extreme drought and heavy rainfall and which provide a hydric pattern not much different from one year to the next. The water content of such soils varies only slightly whatever the level of rainfall, unlike soils where the roots are shallow. Thus, the Grands Crus still produce quality wine when the months of August and September are marked by extreme climatic conditions (such as long drought or heavy rainfall). It is also clear why the best wines are produced by vines of a sufficient age (about 8–10 years in Medoc) which, having had the time to develop their root system in depth, thrive on these regulation mechanisms[73–74,76,78,79].
Water supply to the vine in other types of terroirs. Given these conditions, the question may be asked whether similar mechanisms exist in other types of terroirs, particularly in the limestone soils of Saint-Emilion, where the roots are superficial and where drought could pose the vine serious problems.

Studies carried out since 1978 by Duteau et al.[30] have shown that the field capacity expressed in volumic humidity is about 25%, but that, in the light of the very shallow soil depth and the fact that the roots do not go beyond 70 cm, the reserve of usable water is low. However, during a dry summer (fig. 5: 1979) the water supply is never too low since the parent rock, which is composed of very compacted limestone can, by capillary action, provide up to 35% (70% in 1985) of the water consumed by the vine between flowering and harvesting; this is quite considerable (fig. 6).

Similar questions may be asked about certain clayish soils of the Pomerol area; unlike the case with limestone soils, excessive water supply may be feared.

Such soils have a clay content as high as 60% (fig. 1) and are poorly aerated. Thus the root system remains localized in the first meter of soil. Moreover, in these more or less asphyxiating conditions, many radicles die each year, as has been observed on cultural profiles. However, these shortcomings are apparent only in this particular case. The field capacity expressed in volumic humidity is situated between 25% and 45% (fig. 7) which provides good but not excessive water supply, since only a few roots absorb it, and this at a shallow depth. Moreover, the mobility of the water, which in clay is already low, diminishes progressively during the drying-out of the subsurface layers, with the result that water reaches the vine only with difficulty during grape maturation. In 1979, actual evapotranspiration values during this period were similar to those in the limestone or gravel-sand soils of Saint-Emilion (table 5).

It may be noted (table 5) that in sandy soils (terroirs which are not so good) water is supplied to the vine in conditions which could be considered too favorable.

Another interesting phenomenon is when sharp cloudbursts fall on clayish soils which are partially dried-out; this often happens during grape maturation. First of all, the water filters through quite well, but then the swelling clays (composed essentially of smectites) make the soil so impermeable that some of the water (about a half in 1979, 1981 and 1984) runs off at surface level towards lower areas, whilst the rest slowly reaches the roots owing to the low level of soil macroporosity[30]. Thus water absorption is not necessarily excessive after heavy rain.

Influence on the constitution of the grape in the gravel-sand soils of the High-Medoc. The water supply to the vine undoubtedly has an influence on the quantity and quality of the harvest, but is difficult to pinpoint, given the association of many factors (temperature, sunlight, rainfall, mineral nutrition, etc.).

Table 5. Water supply to the vine in 1979 (wine growing soils of Pomerol and Saint-Emilion)

Periods		18 June/ 21 August	21 August/ 8 October
	PET (mm/day)	3.9	2.9
$\frac{AET}{PET} \times 100$	A) Clay	56	45
	B) Pebble-sand	72	45
	C) Limestone	67	51
	D) Calcareous and sandy sandstone	79	62
	E) Sand	74	76

PET = Potential evapotranspiration; AET = Actual evapotranspiration.

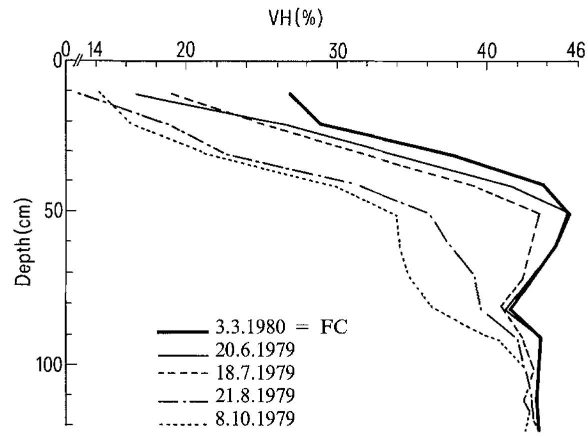


Figure 7. Evolution of hydric profiles in 1979 in soil A on clay.

Observations in the Bordeaux area, on various vintages indicate in general that:

– A large water supply during the growth period of the vine is a factor favoring the enlargement of berries[15, 63].

– In the best crus, the sugar content of grape juice at the mature stage depends only a little on the water supply to the vine during grape maturation (table 6). However, the global production of sugars per hectare (sugar content × yield), which is associated with photosynthesis and therefore with the water supply, is positively influenced by this[74, 79].

– According to the vintage, the organic acids content (anions) of musts, and particularly the malic acid content, seems to be higher when water is supplied to the vine in good conditions during grape maturation (table 6)[74, 79]. However, it is to be remembered that the respiratory combustion of organic acids depends largely on temperatures which may disturb the correlation and that these acids are more or less salified according to the particular year[74, 79].

– Excessive water absorption, as a result of very heavy rainfall during grape maturation, may cause a rush of water to the berries, causing them to burst, and this causes the onset of common rot. In the gravel-sand soils of the Medoc and the Graves, the bursting of berries and the development of common rot are much less likely the deeper the roots go (table 7)[73, 74, 86].

Influence on the quality of wines. Only comparable vintages, such as 1966 and 1967, can be considered here; this is when there was less than 2% difference in the maximum temperature, the average temperature and sunlight hours during grape maturation (High-Medoc). The main difference between these two years was the water supply to the vine which was large in 1967 (77% of PET) but small, though not too low, in 1966 (42% of PET).

Tasting of studied crus wines has shown that the 1966 vintage was richer (with respect to aroma, tannin, color), stronger, more supple and finer; moreover, all the 1966 harvest was kept, while in 1967 some of the production was of insufficient quality and was sold as second quality wine. However, a large increase in the water supply to the wine does not necessarily lead to mediocre wine, since 1967 was a good vintage in the studied area. It is rather high rainfall (264 mm in 1968) coupled with saturation of the profiles, if only temporary, which has a clearly unfavorable influence on the quality of wines[74].

Table 6. Quality of water supply to the vine during grape maturation and chemical composition of grape juice at the beginning of harvesting (Black Merlot)

	$\frac{AET}{PET} \times 100$ (%)	Reducing sugars (g/l)	Tartaric acid (meq/l)	Malic acid (meq/l)	TA + MA (meq/l)	$\frac{MA}{TA}$
1966	42	200	99	19	118	0.19
1973	69	198	113	14	127	0.12
1971	73	212	110	20	130	0.18
1967	77	202	97	38	135	0.39
1970	86	203	106	33	139	0.31
1972	90	209	114	57	171	0.50
r			0.47	0.69	0.79	0.65
α			0.3–0.4	0.1–0.2	0.05–0.1	0.1–0.2
1968	?	167	100	42	142	0.42
1969	?	181	128	40	168	0.31

AET = Actual evapotranspiration; PET = potential evapotranspiration; r = correlation coefficient; α = probability threshold (Student-Fisher); The statistical analysis deals only with the first six years. Owing to very heavy rainfall, causing water loss through drainage, it was not possible in 1968 and 1969 to precisely calculate AET. It may be estimated however, that the percentage of AET in relation to PET was high during these two years. Dosage techniques: Reducing sugars: Bertrand method. Tartaric acid: Kling -Peynaud method and OIV method for 1973. Malic acid: Microbiological dosage by *Schizosaccharomyces*.

Experiments in 50-liter pots were carried out on the Müller-Thurgau cultivar by Becker and Zimmermann[7]. After initial growing in a damp environment, four hydric supply patterns were administered during the period of flowering-veraison and veraison-harvest (1: dry-dry; 2: humid-dry; 3: dry-humid; 4: humid-humid).

Patterns 2 and 4 produced strong shoot growth and a higher yield due to larger bunches. Patterns 1 and 3 gave an acidity maximum which was higher just before veraison and then produced a more rapid degradation than 2 and 4. Patterns 1 and 2 hampered the increase in must sugar concentration. Wine tasting gave the following results: 1st: humid-dry; 2nd: dry-dry; 3rd: humid-humid; 4th: dry-humid.

Although these experiments were conducted in pots and used a different cultivar, some similarities with observations made in the field, in the Bordeaux area, may be seen. These results concur with others obtained in Israel[11] and Switzerland[49].

Irrigation of the vine. Of all fruit trees the vine is one of the most resistant to drought, and one which reacts all the better to water[92]. Irrigation is a method of production and quality control in dry regions; when administered properly it can result in an improvement in the quantity and quality of harvests and of wines but these may be offset by undesirable effects in root aeration[37,43,50,69,91,93,94].

In Israel and in other warm climates, where many experiments have been undertaken it is, according to Bravdo (whose report appeared in 1984)[11], the potential crop (charge) rather than the yield itself which is the major factor influencing quality. Intensive irrigation with increased potential crop and yield have increased quality. However, extremely low quality has been obtained in situations with intensive irrigation and low potential crop treatment.

In general, irrigation increases the weight of berries (and thus the annual yield) and the amount of total soluble solids (sugars) per hectare. Irrigation often diminishes the quality of wines through the increase in volatile acidity, due without doubt to a modification in the biochemical mechanisms of fermentation. This could be explained by the bursting of berries or by a biochemical degradation of alanine. The amino acid content increases with irrigation but diminishes when the potential crop is increased. Maturation is generally delayed by excessive irrigation; however, it is not only a question of delay but also of a change in the quality of the grape; when the irrigation of certain plots is modified to achieve the same content of total soluble solids as in plots which are irrigated less, levels of malic acid, tartaric acid and total acids are higher[11].

Excessive irrigation during veraison or during the maturation of grapes stimulates vegetative growth which, since they are in mutual competition, limits the accumulation of sugars and of anthocyanins in the grape[11].

Irrigation is frequently performed in Switzerland. Excessive water supply increases the vigor of the vine, as well as increasing the quantity of wood and grapes; however, the sugar content of the grape diminishes and acidity tends to remain high, especially with malic acid.

The experiments on Chasselas at Laytron[49] compare irrigation until veraison with irrigation until maturity. Irrigation until harvesting causes no increase in yield but a slight lowering in density and higher must acidity. Such late irrigation is therefore not recommended, and if heavy rainfall occurs, rot often sets in.

As a result of first studies, some of whose conclusions seem hasty and difficult to extrapolate from[67], irrigation studies using lysimetric techniques and in field (5 consecutive years on 7 cultivars) were carried out in the Mediterranean part of France[65]. Results differ according to the cultivars, and from year to year, even for the same cultivar (it is true that rainfall can be twice as heavy from one year to the next). Lysimetric tests have shown that drought causes an increase in tannoid substances and in anthocyanins in the skin, which becomes larger if the drought is more severe[8,65]. In field conditions, prudent irrigation does not harm quality. Intense drought is prejudicial to volume and to the quality of the wine.

Cinsaut reacts favorably to irrigation. Cultivars which are subject to shelling (coulure) – Grenache, Cinsaut and black Merlot – sometimes react very badly to sprinkling in July. As regards improving cultivars – Syrah, black Merlot and Cabernet-Sauvignon – careful and moderate irrigation slightly increases the economic yield without harming quality and without leading to over-production[65].

Table 7. Rotting rate in relation to root depth (Black Merlot)

Plots	Root depth (cm)	% of plants bearing rotten berries 19 Sept. 1967	% of rotten berries 23 Sept. 1968	% of rotten berries 22/26 Sept. 1969	% of rotten berries 23 Sept. 1971
G1	650		8	7	
M1	500	0	5	21	1.0
G2	370		20	24	
M2	270	12	41	43	1.6
G5	180		42	17	
M4	170	44	50	42	3.0
G6	140		50	6	
P	140		59	37	
M3	100	71	70	56	7.3

Conclusion

In-depth study of all the factors of the climate-soil-vine ecosystem is difficult; each has its own action but acts in synergia with or opposition to the others. The vine undergoes environmental constraints (climate, chemical and hydric state of the soil) but, like most living things, adapts and reacts, sometimes even modifying its environment. It seems that in the Bordeaux area the chemical properties of soils, which may be modified by chemical fertilizers or soil improvements, do not have a definite influence on the quality of harvests and wines. Certainly the characteristics are different according to the nature of the parent material and soils (calcareous or siliceous, clayish or gravelly) but the quality of terroirs is perhaps better explained by considering the physical properties of soils (architecture, structure, porosity, permeability and so on) and their consequences for root development and on regulation of water supply to the vine.

Extreme climates (either too hot, too cold, too wet, too dry) only rarely provide the conditions for producing high quality wines. In the areas where the climate is fresh or temperate, the best crus are those in which the grape ripens completely but slowly; such crus regularly produce high quality wines in spite of climatic variations. In this respect, the soil intervenes by limiting the climatic and particularly the hydric extreme conditions; the best crus would seem to be those which, because of their topography, physical properties (structure, macroporosity, microporosity) and root system development, limit the effects of either heavy rainfall or drought. Then again, there may be natural factors which the hand of man cannot easily modify; this is doubtlessly why a Grand Cru cannot be situated just anywhere on any terroir.

It is certain that man can and must intervene to improve terroirs, be it the working of the soil, drainage, and irrigation, or choice of trellising systems, of rootstocks and of cultivars in relation to the climate and soils. However, we still have little knowledge of the optimal values of the various parameters controlling the efficient functioning of the climate-soil-vine ecosystem.

In the future, the main area of research should be to define the notion of cru more clearly, studying more and more factors in order to explain the characteristics and differences in neighboring terroirs. From this point of view, the water supply to the vine has provided a primary explanation, since it offers a methodology integrating most of the factors associated with production and quality: edaphic, climatic, biological and human factors.

A detailed study of the various factors has recently been untertaken in Bordeaux (a collaborative effort between the Enology Institute and several research teams from the National Agricultural Research Institute) with particular emphasis on the physiology of the 'whole plant' (thermic and luminous microclimate of the exposed parts, without neglecting the 'pedoclimate' which certainly plays an important role in the functioning of the roots).

This will not constitute an automatic recipe for sucess but such studies should open up fresh interpretations and should contribute to maintaining the status of wine, and perhaps to improving it.

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Wine aroma

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Introduction

Among the various factors that contribute to the enjoyment of wine, its flavor is possibly the most important one. Flavor is the result of the interaction of chemical constituents with the sense of taste and smell of the consumer. Flavor is composed of volatile compounds, responsible for the odor, and nonvolatiles which cause taste sensations, such as sweetness, sourness, bitterness and saltiness. Compounds in wine that cause those limited flavor sensations experienced by the palate are sugars, organic acids, polymeric phenols and mineral substances. With a few exceptions those compounds need to be present in levels of 1% or more to influence taste.

Generally, the volatile components can be perceived in much lower concentrations, since our sense organs are extremely sensitive to certain aroma substances. Thresholds vary between 10^{-4} and 10^{-12} g/l[14,26]. As in many foods, the aroma of wine is caused by several hundred different compounds. Concentrations of individual components can range from 10^{-1} to 10^{-10} g/kg. Because there is no real character impact compound, wine aroma is formed by the balance of all those components.

The first studies on wine aroma were performed by Hennig and Villforth[30] in the mid forties. Using classical chemical methods they managed to identify a few compounds. In the late fifties Bayer et al.[9,10] were the first to apply gas chromatography in the field of wine aroma; they identified some higher alcohols and a few esters. Later on, applying gas chromatographic methods, many authors dealt with the aroma substances of grapes and wines, first using packed columns with low separation efficiencies, then employing high resolution capillary columns. Combined with sophisticated aroma enrichment techniques and spectroscopic methods, those separation techniques revolutionized wine aroma research.

It is beyond the scope of this paper to review the hundreds of papers on wine flavor in literature. Most of them are covered already in reviews[67,104] or surveys[100]. We rather intend to concentrate on compounds imparting characteristic odors to wines, their origin from various sources and the factors that influence wine aroma.

When dealing with wine aroma, a distinction is made between: 1) the aroma which originates from the grapes and the aroma due to modifications caused during grape processing, 2) the aroma produced by fermentation and 3) the bouquet which results from the transformation of the aroma during aging.

The amounts of the aroma components can be influenced by environmental factors (climate, soil), cultivar, the condition of the fruit, the conditions during the fermentation stage (pH, temperature, juice nutrients, microflora) and finally, the various postfermentation treatments (clarification, blending etc.).

The three groups into which the wine aroma is subdivided form the framework of the following essay. Additionally, some interesting off-odors are discussed in a separate chapter.