QUALITATIVE PRECISION IRRIGATION IN THE VINEYARD

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Summary
The current environmental changes and viti-viniculture crisis have caused an adaptive evolution of the cultural techniques applied in Mediterranean vineyards. The increases of average temperatures as well as the significant increases of evapotranspiration, provoke a rising dryness during the vegetative cycle of the vine, as a result of a highly and precociously deficient hydric balance.

The viticulturists are increasingly faced with the following dilemma: either accepting the consequences of severe hydric restrictions or using irrigation with the aim of avoiding severe problems linked to decreases in the yield and quality of the harvest.

From the scientific knowledge principally developed over the last fifteen years, it is now possible to propose reasoned irrigation models to viticulturists, based on the control of the hydric state. This last point represents a fundamental element for the explanation of the physiological functioning of the vine, while taking into account the production objectives (yield, quality, type of wine, etc.). This approach is increasingly used in countries where irrigation is an indispensable technique for viticulture and is beginning to respond to a tangible demand of a large part of the European viticultural sector.

This article presents a series of information that have to do with the effects of different levels of hydric restriction on the yield and quality of the grapes and wines. It also describes a general and optimal model for the vine, in accordance with the phenological state and proposes also different irrigation strategies according to the objectives of the vineyard. Finally, this article provides some practical examples of commercial vineyards situated in different viti-vinicultural countries.

The interaction between many natural, biological, agronomical, and oenological factors establishes the characteristics of a wine. Via the handling of certain agronomic parameters (plant architecture, management of the soil and phytosanitary protection) or certain oenological parameters (type of vinification, development or blending), one can to a certain extent control the quality and typicity of a wine (Morlat y Asselin 1983). However, the viticulturist intervenes with difficulty with regards to certain natural factors such as the climate and the effect of the year (“Vintage”).

Water and Climate
The climate plays a fundamental role on the grape quality thanks to the action of its principal components, notably solar radiation, temperature, humidity and precipitation (Jackson 1986). The large number of climatic indices described in the scientific literature is a clear example of the importance attributed to climate in viticulture (Amerine et Winkler 1944, Branas *et al.* 1946, Huglin 1983, Constantinescu 1971, Hidalgo 1980, Jackson et Cherry 1988). The majority of these indices are established from values of temperature and sunlight. Tonietto and Carbonneau (2004) recently highlighted the importance of the hydric state of the vineyard by the introduction of an index of dryness and by the proposition of a climatic classification system based on several criteria.

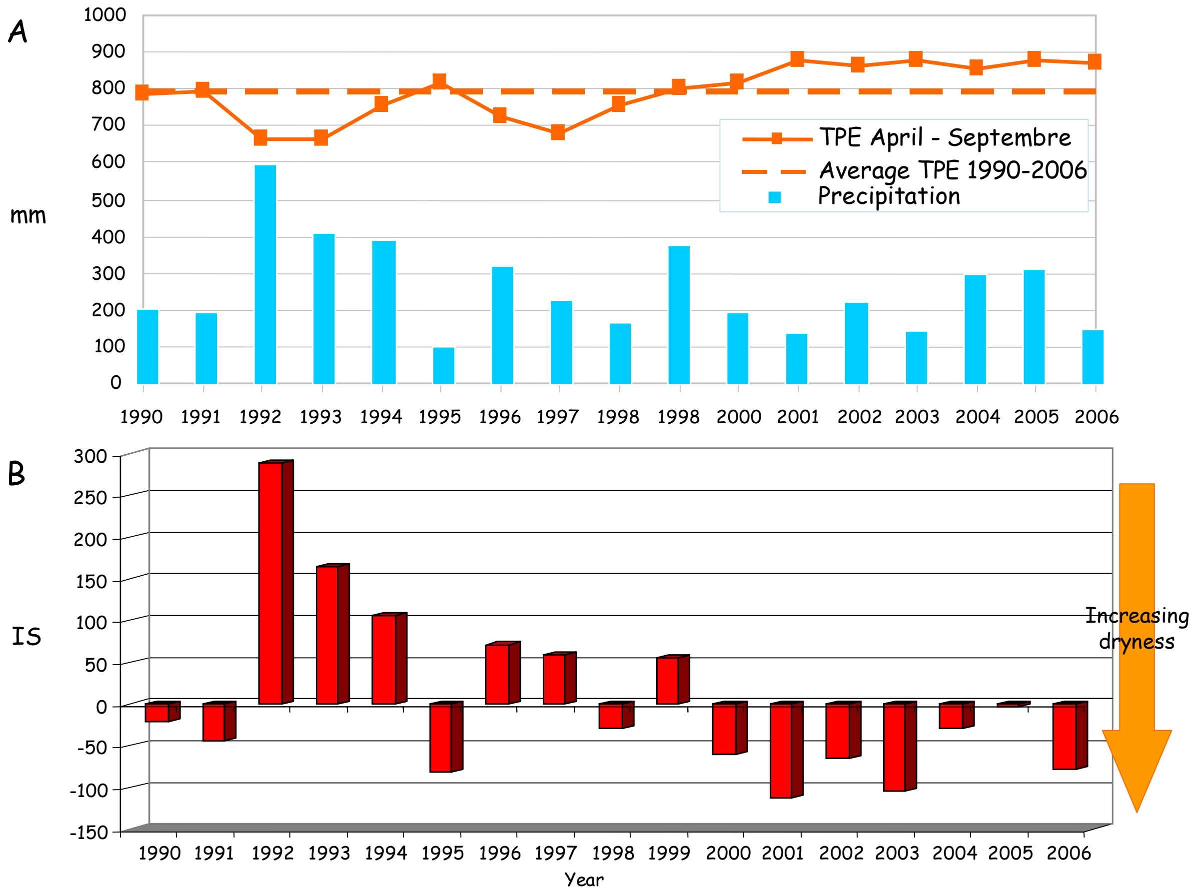
Water is a fundamental element for the vegetative and reproductive development of the vine and for the physiological and biochemical functioning. It is therefore a determinant factor on yield, grape quality and wine characteristics (Carbonneau 1998, Deloire *et al*. 2003a, 2003b, Ojeda *et al.* 2002, 2005).

During the maturation period, a progressive dryness of limited intensity so as to not affect photosynthesis in a significant manner, favourizes the accumulation of sugars, and particularly the phenolic compounds, at the expense of vegetative development (Seguin 1975, Bravdo *et al.* 1985, Carbonneau 1987). In fact, as the levels of hydric restriction increase, the richness of the compounds, which play a role on the quality (phenolics, sugars…), are accentuated despite a reduction of the yield linked mainly to the diminution in size of the berry. However if one surpasses a certain level of hydric restriction (optimal ?), the grapes do not gain any more compounds said to be "quality ones" and the yield continues to decrease (Ojeda *et al.* 2005). Very severe hydric restrictions can lead to a great weakening of the vine trunk. Furthermore, if this situation endures over several consecutive years, these hydric restrictions can occasionally cause problems for the survival of the certain grape varieties.

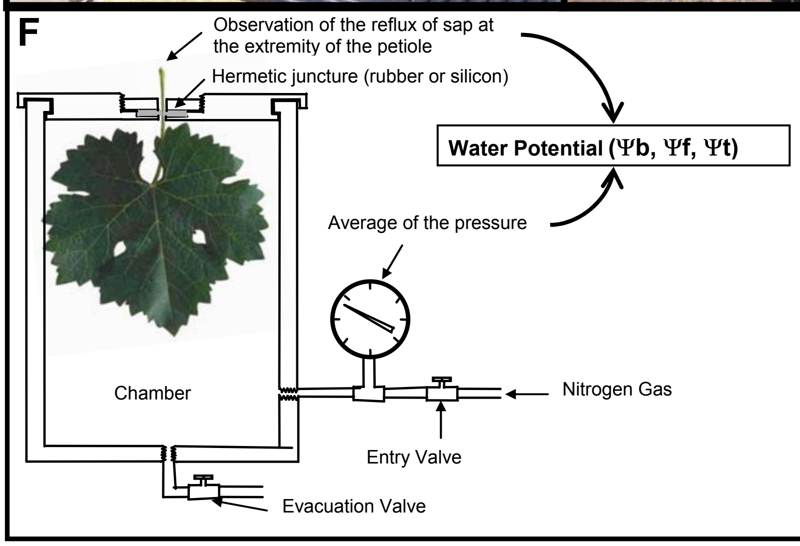
Climate Change

The Mediterranean viticultural zone does not escape the worldwide problem of global warming (Tondut *et al.* 2006). Since the last 10 years, the vineyards of this region have been suffering from the increasing temperatures, mainly during the vegetative cycle of the vine. This situation emphasizes the necessity to study more precisely the consequences that global warming entails for the dynamic growth of the grapevine, for the evolution and maturation of the grapes and for the adaptation of grape varieties.

This increase in average temperature is joined by a significant increase in evapotranspiration (schema 1). This situation causes increasing hydric deficiency conditions, which have gradually increased over the last ten years. Viticulturists are increasingly faced with the following dilemma: either accepting the consequences of severe hydric restrictions or using irrigation with the aim of avoiding severe problems linked to decreases in the yield and quality of the harvest.



Scheme 1 : A : Evolution of the total potential evapotranspiration (TPE) and precipitation; B : Evolution of the dryness index (IS : Tonietto et Carbonneau, 2004). Period April-September. Years 1990-2006. INRA, Pech Rouge Experimental Unit.



The method consists of placing the leaf in a closed chamber, while leaving the extremity of the petiole protruding. A compressed nitrogen gas reservoir allows for the increasing of the pressure inside the chamber. At a given moment, the sap exits and a drop appears at the extremity of the petiole which is found outside the chamber, under the atmospheric pressure. The pressure that is inside the chamber at that moment (read on the manometer) corresponds to the water potential of the leaf **(**Ψb, **Ψf, Ψt).**

Scheme 2 : The pressure chamber
A et B : French model on chariot for the displacement in the vineyard (photos kindly provided by Sferis, France) C : American Model, of the « bike pump » type, which avoids the use of the nitrogen gas reservoir (Chile); D : use of a large nitrogen gas reservoir to allow for a large number of daily determinations (Italy); E : 4x4 Quad equipped with a pressure chamber for an quick and easy displacement between the rows (Canada) ; F : Explanatory scheme for the use of the pressure chamber.
(Ψb : base potential; Ψt : stem potential at midday and Ψf : leaf potential at midday)

Methods of controlling the hydric state

In the vineyard, water comes from rain or groundwater sources. When this amount is not sufficient for the cultivation of vines, one must irrigate, or otherwise accept the consequences of the hydric restriction. According to the intensity and moment of the vegetative period during which the hydric restriction occurs determines whether the consequences will be favourable or not for the quality of the grapes and wine. It is for this reason that it is important to be able to measure the hydric state of the vineyard at the “parcelles” or group of “parcelles” scale. There are numerous techniques which exist that are direct or indirect (Ortega-Farías 1999, Hunter et Archer 2001, Hunter et Myburgh 2001, Gaudillère *et al*. 2002, Deloire *et al*. 2004), but the reference technique which remains indisputably is the leaf water potential (Carbonneau 1998, Choné *et al*. 2001, Ojeda *et al*. 2001, Williams et Araujo 2002, Deloire *et al*. 2004).

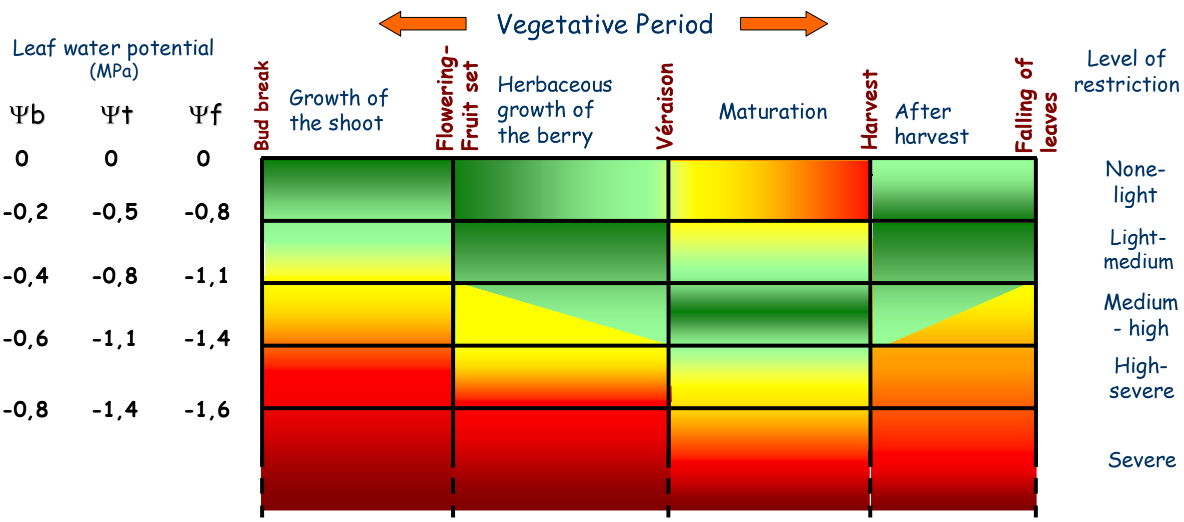
The use of the leaf water potential, determined thanks to the use of a pressure chamber (Scholander et al., 1965), has allowed for the establishment of solid threshold references, valid at the international scale and with a universal importance.

Up until recently, the use of this method was limited to the scientific domain. But over the last five years, it has progressively been adopted by viti-viniculture enterprises as a reliable tool to determine the right moment for irrigation (schema 2).

The hydric state of the vineyard: model for surveillance and control

Il est possible d’établir, sur la base de l’ensemble des connaissances scientifiques et empiriques dont nous disposons à l’heure actuelle, des états hydriques optimaux pour la vigne, en fonction du stade du cycle végétatif et de l’intensité de la restriction (schéma 3).

It is possible to establish, on the basis of all the scientific and empirical knowledge that we possess at the current time, the optimal hydric states for the vine, according to the vegetative cycle stage and intensity of the restriction (scheme 3).



Scheme 3 : Optimal hydric states (zones in green), un-favourable (yellow) et detrimental (zones in red) according to the vegetative period of the vineyard.

The levels of hydric restriction are expressed in megapascales (MPa).
The equivalence between the different potentials (Ψb : base potential; Ψt : stem potential at midday and Ψf : leaf potential at midday) is established from the studies of Carbonneau 2002, Williams et Araujo 2002, Sibille et al. 2005.

Period between the budding and flowering:

During the period between the budding and flowering, it is good for the plant to not undergo hydric restriction, or at least it should be light (Ψb between 0 MPa and -0,3 MPa), in order to not affect the normal growth of the shoot, indispensable for a good development of the leaf surface. This allows for a good alimentation of the grape bunches and for an adapted supply of reserves for the plant. One must not forget that the vegetative development is the first to be affected when the vine begins to undergo a hydric restriction. The growth of the shoots diminishes, and can even stop at restriction levels lower than those which affect the reproductive growth or photosynthesis (Williams *et al.*

1994). In order to avoid this type of restriction, it is common that in irrigated zones, the viticulturist irrigates during the winter rest period, in order to begin the vegetative cycle with sufficient water in the soil.

Period between flowering and fruit set:
A hydric restriction which is too severe during the first days following the flowering (values of Ψb ≤ -0,6 MPa) can reduce the flowering rate and number of berries per grape bunch via desiccation (Hardie y Considine 1976). The entire grape bunch can also be affected by a partial or complete dehydration of the rachis, provoked by an early hydric restriction.

Period between the fruit set and the veraison:
Between the fruit set and veraison, the hydric state has a great influence on the yield of the vineyard, due to the effect that it exerts on the size of the grape berry (Hardie et Considine 1976, Becker et Zimmermann 1984, McCarthy 1997, Ojeda *et al.* 2001). During this period, the hydric restriction does not have consequences on cellular division, but it diminishes the cellular volume (Ojeda *et al*. 2001). This diminution is irreversible, even if the restriction is interrupted between the veraison and maturity. In practice, this type of restriction can appear in zones with low precipitation where irrigation is a technique that is absolutely necessary for the cultivation of vines; this is the case in certain viticultural zones in Argentina or Chile. It can also appear with certain frequency, depending on the year, in viti-vinicultural zones in the south of Europe. These early hydric restrictions are rare in zones where irrigation is not necessary.
In certain circumstances, a large evapotranspiration demand during this period can lead to a severe dehydration of the grape berry; this physiological dysfunction is called "fla" in France and, it is the result of a battle for the water which is delivered to the grape and the rest of the plant, particularly in vineyards with a large load (Champagnol 1984, Galet 1995). This phenomenon is frequent in the Merlot vineyards in the center of Chile (Moreno Simunovic *et al.* 2003, Ortega-Farías *et al.* 2004).

The controlled reduction of the size of the grape berry can be a quality objective if we consider that the reduction of the grape berries conditions the relationship between the surface and volume, and therefore, also the dilution of the specific constituents of the skin, in the volume of must or wine (Singleton 1972, Cordonnier 1976, Ojeda *et al.* 2002). Hence, a moderate hydric restriction (Ψb between -0,3 MPa et -0,4 MPa), initiated in an early manner after the fruit set, will reduce the size of the grape berries all while increasing the final concentration of polyphenols and aromas. We can note a reduction of production due to, exclusively, the diminution of the size of the grape berry. This is the only element of yield that will be affected, which will have as a consequence, the production of looser grape bunches, that are better aerated and therefore healthier.

However, if the hydric restriction is too severe during this period, (Ψb ≤ -0,6 MPa), the weight of the berry will decrease in a significant manner. Furthermore, it will have consequences on the biosynthesis of certain polyphenols such as the tannins, proanthocyanidines, and in certain cases on the later synthesis of anthocyanins (Ojeda *et al.* 2002). In consequence, the harvest of a vineyard can be reduced by 30 to 50%, which can be worsened by a large qualitative loss.

The assimilation of nutrients can also be unbalanced if a significant hydric restriction is prematurely produced during the vegetative cycle. The absorption of water and that of nutrients are closely linked because the mineral elements are dissolved in the soil solution where the roots penetrate (Keller 2005), and also the moment where nitrogen, potassium, phosphorus and calcium are the most consumed corresponds to the period between the fruit set and the veraison Fregoni 1985).

Period between veraison and maturation/harvest:
The absence of hydric restriction during this period (Ψb between 0 et -0,2 MPa) produces excessive vigour and favourizes high yields in the vineyard. The "qualitative" components of the grape, such as the polyphenols and the sugars, decrease following a dilution effect provoked by an increase in the size of the grape berry (Ojeda *et al.* 2002). However, it can be an advantageous management strategy for a vineyard whose objective is a high production of sugar per hectare, as is the case for the industry of concentrated must or grape juice. On the other hand, a progressive restriction up to the period of maturation is conducive to a reduction in size of the grape berries and, in

consequence, a reduction in the yields, all while further favouring the concentration of the phenolic compounds and predominantly the anthocyanins.

The hydric state of the vineyard during this period in a large part, determines the type of wine to be obtained (Deloire *et al.* 2005). In an extreme situation, the total absence of restriction (Ψb between 0 et -0,3 MPa), produces herbaceous, diluted and acid type wines. When faced with a very severe restriction (Ψb lower than -0,8 MPa), red wines have the tendency to be very tannic, harsh, astringent and have high alcohol degrees. White wines lose a lot of their aromas. It is in intermediate hydric states (Ψb between -0,3 et -0,7 MPa) that the wines are the most balanced, and give profiles which lean towards those being very defined by fruits up until those which are more concentrated.

Period between the harvest and the falling of the leaves
Finalement, au cours de la période qui suit les vendanges, le fait que la plante récupère son état hydrique (Ψb supérieurs à -0,4 MPa) est un bonne chose. En effet, au cours de cette période, le cep, déjà exempt de raisins, oriente ses photoassimilats vers les zones de réserves, les racines, le tronc et les sarments (Champagnol 1984). D'autre part, l'assimilation de nutriments minéraux est accrue (Conradie 2005) et la croissance de ses racines reprend (Freeman et Smart 1976, Van Zyl 1984).

Finally, during the period which follows the harvest, the fact that the plant restores its hydric state (Ψb supérieurs à -0,4 MPa) is a good thing. In fact, during this period, the vine, already free of grapes, orients its photoassimilates towards the reserve zones, the roots, the truck and the branches (Champagnol 1984). Also, the assimilation of mineral nutrients is increased (Conradie 2005) and the growth of the roots resumes (Freeman et Smart 1976, Van Zyl 1984).

Irrigation strategies according to the vineyard objectives
As we have seen, the response of the vine to the hydric state is closely linked to the vegetative period. In irrigated zones, it is possible to establish an irrigation strategy in accordance with the vineyard objectives, the vegetative period and the level of hydric restriction (scheme 4)

Thus, for a vineyard which is oriented towards the production of concentrated must, where the objective is a high production of sugar per hectare, the irrigation strategy to be followed will be that of avoiding hydric restriction during the entire vegetative period (photo 4A) in order to favourize high yields from the majority of its components. This same strategy must be applied in young vineyards during their development, or in certain cases, for the production of varietal wines from white or red grape varieties, in which one aims to privilege certain "vegetal" or "spicy" notes, exemplifying a sought after typicity.

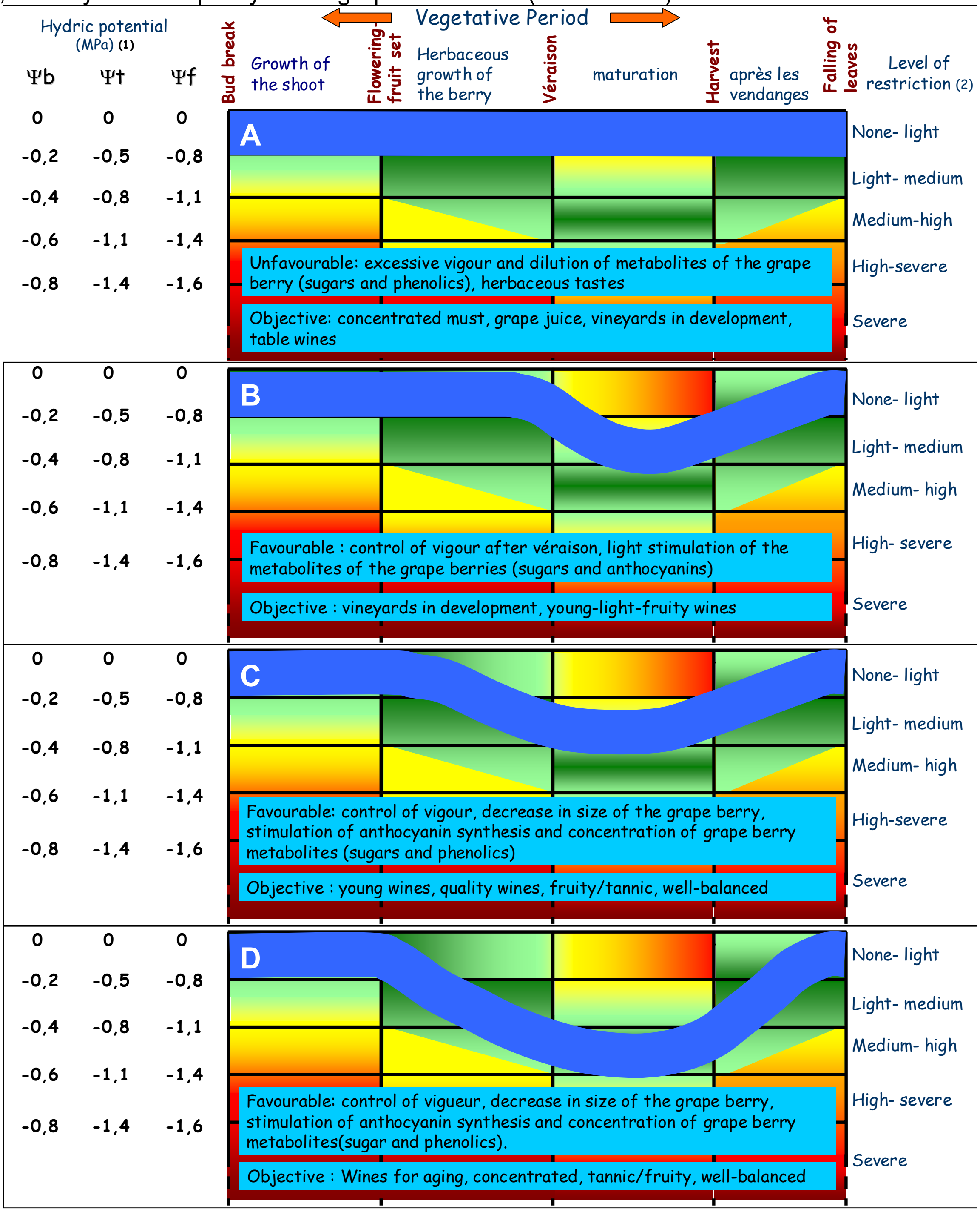
For a vineyard where the objective is to obtain an aromatic white wine or a light and fruity red wine, it is interesting to produce a light and progressive hydric restriction up until the end of the period comprised between the veraison and the maturation (photo 4B) with the aim of, not having a significant consequence on the size of the berries, nor on the photosynthesis, while favouring the accumulation of the sugars and anthocyanins (colour, for red wines) at the expense of the vegetative development.

For more concentrated red wines, the strategy of producing a progressive restriction up until the period of maturation leads to a reduction of the size of the grape berries and, hence the yields (photo 4C). This strategy furthermore favourizes the concentration of the phenolic compounds and principally the anthocyanins.

It is also equally possible to follow an evolution of the type in photo 4D, with the aim of assuring a greater control on the size of the berry, a significant increase of the phenolic concentration (more structure and colour) even though this can be at cost of a certain loss in aromatic intensity. This strategy is very adapted for red wine for aging and storing but it is not recommended for white wines, for which one must privilege the aromatic composition of the grape berry.

Which ever strategy is adopted, during the entire vegetative cycle, the hydric state of the vineyard must be situated within the optimal thresholds (green zones of the model), in order to assure a maximal pay off (scheme 5.4) and to avoid the problems caused by an excess (scheme 5.2) or a lack of water (scheme 5.3)

When the viticulturist does not use irrigation as a tool of control, there is no other choice than to accept the consequences of severe droughts which can cause the decrease, in a significant manner, of the yield and quality of the grapes and wine (scheme 5.1).



Scheme 4 : Different examples of possible irrigation strategies in accordance with the vegetative period and the type of product desired: (A) concentrated must, grape juice, base wines and young vineyards in development ; (B) base wines, light, fruity; (C) quality wines, well-balanced but with a predominance of fruit over the structure ; and (D) quality wines, concentrated, well-balanced and for aging.
(1) The levels of hydric restriction are expressed in megapascales (MPa). The equivalence between the different potentials (Ψb : base potential; Ψt : stem potential at midday and Ψf : leaf potential at midday) is established from the studies of Carbonneau 2002, Williams et Araujo 2002, Sibille et al. 2005.
(2) Approximative thresholds for evaluating the level of hydric restriction (Carbonneau 1998).

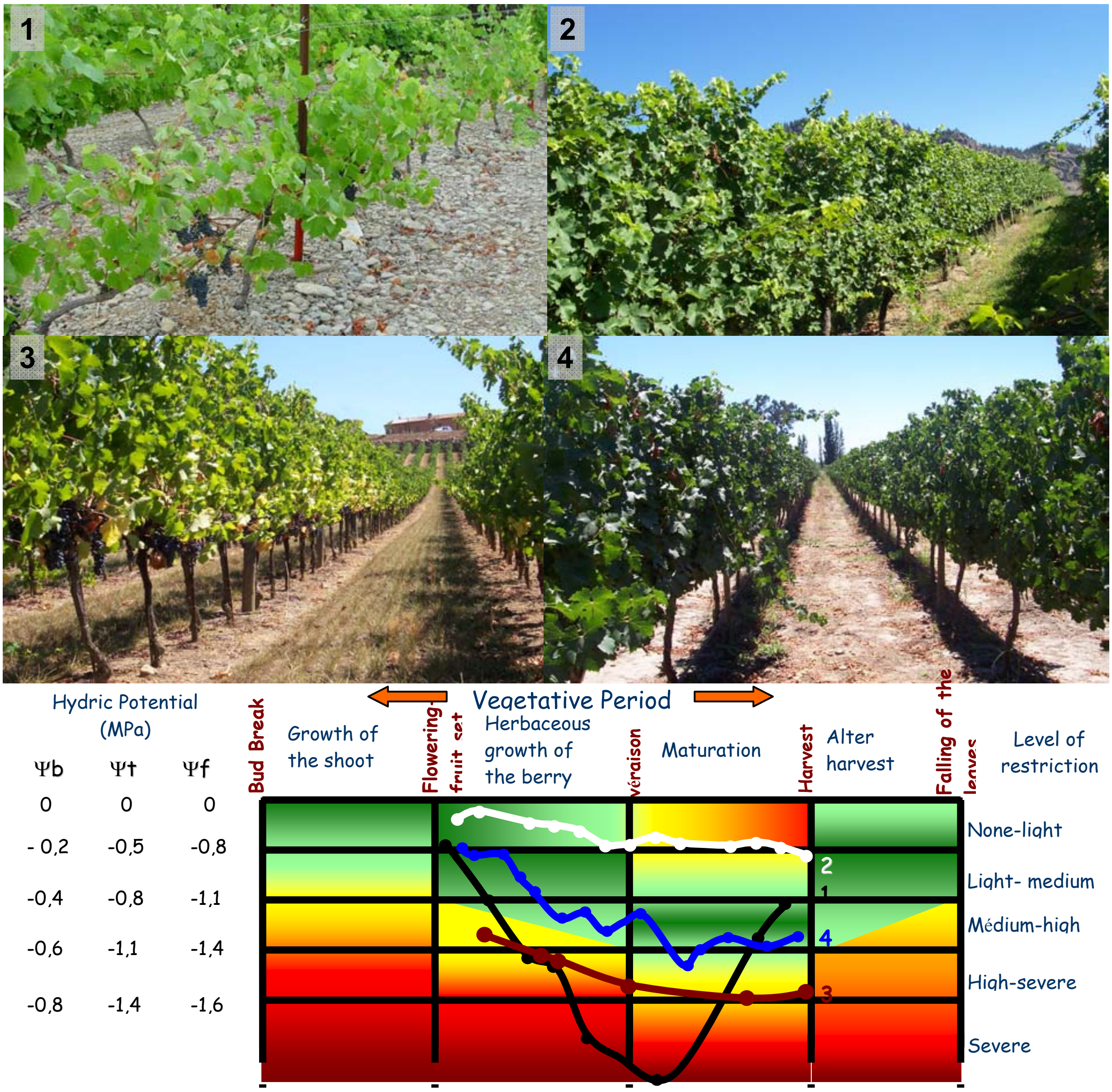


Schéma 5. Example of different cases of hydric state evolution in commercial vineyards (the numbers of the photos of the upper part correspond to the evolution curves of hydric potentials in the above scheme)

1) Syrah vineyard, on non irrigated terrain, in the South of France, submitted to a severe and early hydric restriction. One can observe the weak shoot development and the over exposition of the grape bunches, accompanied by a diminution of the yield and noticeable qualitative losses. *(The hydric potentials fall abruptly after flowering, positioning the vines in a severely dry zone for a large part of the vegetative cycle. The increase in potential towards the end of the cycle, caused by the influence of humid marine winds, allows for a partial recuperation of the vineyard reserves and assures its survival from one year to the next.)*

2) Sauvignon b. Plants of the Osoyoos region in eastern of Canada, submitted to excessive irrigation, principally after veraison, which favourizes an excess in the vegetative growth of the branches, hence impeding the normal maturation of the grape and an excess of herbaceous notes *(between veraison and harvest, the potentials demonstrate a hydric restrictriction of none to light).*

3) Merlot vineyard in the Italian region of Tuscany, submitted to an excessive hydric deficit caused by a inefficient functioning of the irrigation system. The plants demonstrate some yellowing characteristics and the leaves have initiated to fall at the base of the shoot, after veraison *(the hydric potentials have always been situated in the yellow and red zones of the scheme).*

4) « Parcelle » of Cabernet-Sauvignon of the Maipo Valley, in the center of Chile, characterized by an excellent vegetative balance, after veraison, following an adaptive control of the hydric state: one does not observe an increase in branching, which would be due to an excessive irrigation, nor a yellowing of the base leaves from an excessive hydric deficit *(the hydric potentials were always maintained in the green zones of the scheme)*

Conclusions

Hydric restriction is a fundamental tool for regulating the yield and quality of the grapes and wines. In order to practice a correct and precise irrigation, it is indispensable to characterize the hydric state of the vineyard by using a reliable methodology that reflects, without a doubt, the reality of the cultivation. The determination of the water potential is, for now, the only technique that reunites these characteristics. However, other more economical or easily manipulated techniques can be useful, under the condition that values obtained are correlated with those of the water potential measurements.

In regions where irrigation is not necessary, as is the case for the large part of the European vineyards, the control of the hydric state of the vineyard is realized, within certain limits, via soil management and cultivation of the vineyard. In these cases, the hydric state of the vineyard, linked with the useful water reserves of the soil, is one of the factors that best explains the variability of the year (“*vintage*” effect) and the characteristics of the “*terroir*”.

In regions with low precipitation, where irrigation is a technique that is absolutely necessary for the cultivation of vines, as is the case for the large part of viticultural zones located in the said « new world», it appears fundamental to understand with precision the responses of the vine given the hydric state, in order to be able to correctly choose the irrigation strategies to follow, in accordance with the objectives of the vineyard.

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