A water stress index based on water balance modelling for discrimination of grapevine quality and yield

Rémi Gaudin, Kamal Kansou, J. C. Payan, Anne Pellegrino, Christian C. Gary

A WATER STRESS INDEX BASED ON WATER BALANCE MODELLING FOR DISCRIMINATION OF GRAPEVINE QUALITY AND YIELD

Rémi GAUDIN[1*], Kamal KANSOU[2], Jean-Christophe PAYAN[3], Anne PELLEGRINO[4] and Christian GARY[5]

1 : Montpellier SupAgro, UMR System, 2 place Viala, 34060 Montpellier, France
2 : INRA, UR 1268 BIA Biopolymères Interactions Assemblages, rue de la Géraudière, 44316 Nantes Cedex 3, France
3 : Institut Français de la Vigne et du Vin, Pôle Rhône-Méditerranée, Domaine de Donadille, 30230 Rodilhan, France
4 : Montpellier SupAgro, UMR LEPSE, 2 place Viala, 34060 Montpellier, France
5 : INRA, UMR System, 2 place Viala, 34060 Montpellier, France

Abstract

Aims : A water stress index based on a water balance model was tested as a tool for classifying the water stress paths experienced by grapevines in various French Mediterranean vineyards. The relations between the index value and grapevine yield and berry quality (sugars, organic acids, anthocyanins) at harvest were investigated.

Methods and results : A data set of 102 situations, each combining one location, one variety, one vintage and one water regime (irrigation or, most often, no irrigation), was collected for the study. The Fraction of Transpirable Soil Water (FTSW) was simulated by a unique-soil-reservoir water balance model at a daily time step. Five classes of water deficit were delimited from specific decreasing thresholds of FTSW over four periods between flowering and harvest. These thresholds were derived from predawn leaf water potential values because over decades, grapegrowers and researchers have shared references and built expertise by using this variable throughout the Mediterranean region. A water stress index resulting from the levels of water deficit reached at each of the four periods of the cycle was calculated. This index was correlated with yield per vine, berry weight, and berry sugar and organic acid contents but not with berry anthocyanin content.

Conclusion : A simple water stress index, based on the water balance model, exhibited significant correlations with yield and berry quality for various cultivars and pedo-climatic conditions in Mediterranean vineyards.

Significance and impact of the study : This water stress index is a valuable tool for explaining the variations in grape yield and quality of grape among various locations and years because it reflects the vineyard water stress history, in relation to rainfall regime and soil conditions. Improvement would come from the simulation of FTSW during winter, notably for soils of high Total Transpirable Soil Water. One potential application is the quantification of water stress change brought by irrigation in Mediterranean vineyards, and its relation to grapevine production.

Key words : water stress index, water balance model, yield, berry quality, *Vitis vinifera* L.

Résumé

Objectifs : Un indice de stress hydrique dérivé de l'état hydrique du sol simulé par un modèle de bilan hydrique a été testé pour différencier la diversité des parcours hydriques observés dans les vignobles de la zone Méditerranéenne. Les relations entre cet indice et le rendement et la qualité des baies (sucres, acides organiques, anthocyanes) à la récolte ont été explorées.

Méthodes et résultats : La base de données comprend 102 individus. Chacun d'entre eux correspond à la combinaison d'un lieu, d'une variété, d'un millésime et d'une modalité (irriguée ou le plus souvent non irriguée). La fraction d'eau transpirable du sol (FTSW) a été simulée à l'aide d'un bilan hydrique caractérisé par un seul réservoir de sol, fonctionnant au pas de temps journalier. Cinq classes de déficit hydrique ont été définies sur la base de seuils coulissants de FTSW sur quatre périodes allant de la floraison à la récolte. Ces seuils ont été choisis en référence à des valeurs de potentiel de base sur lesquelles s'accordent les experts et professionnels de la vigne en zone méditerranéenne. L'indice de stress calculé résulte ainsi de la trajectoire de FTSW simulée par le bilan hydrique pour chaque combinaison de la base de données. Cet indice est corrélé au rendement par vigne, au poids des baies et à leur contenu en sucre et en acides mais pas à leur teneur en anthocyanes.

Conclusion : L'indice de stress hydrique, construit sur la base d'un modèle de bilan hydrique, montre des corrélations significatives avec le rendement et des paramètres de qualité de la récolte pour une large palette des cépages et des conditions pédoclimatiques de la région méditerranéenne.

Signification et impact de l'étude : Cet indice de stress hydrique est un outil intéressant pour comparer les caractéristiques quantitatives et qualitatives des récoltes de différents millésimes et différents vignobles, en relation avec la pluviométrie et les sols. Des améliorations sont à attendre d'un fonctionnement en continu du modèle de bilan hydrique (intégrant la période hivernale), notamment pour les sols de grande réserve hydrique. Une application de cet outil pourrait être la quantification du changement de stress hydrique découlant de l'irrigation en zone méditerranéenne, pour une gestion coordonnée de la qualité et de la quantité du produit.

Mots clés : indice de stress hydrique, modèle de bilan hydrique, rendement, qualité des baies, *Vitis vinifera* L.

manuscript received 18th March 2013 - revised manuscript received 27th November 2013

*Corresponding author : gaudin@supagro.inra.fr

INTRODUCTION

For many red grapevine cultivars, berry quality relies upon a progressive reduction of water availability after flowering to reach moderate water deficit during the ripening phase (Matthews *et al*., 1987; Matthews and Anderson, 1988; Ojeda *et al*., 2001, 2002). The relationships between water availability and berry yield and quality, together with the identification of relevant variables to diagnose the level of water deficit, have been investigated in numerous studies during the last decades.

The grapevine water status can be assessed by soil water measurements, including soil water content or soil water potential measurements (Pellegrino *et al*., 2004). However, these measurements may be difficult in many vineyards, due to deep plant rooting and soil stoniness (Van Leeuwen *et al*., 2009). Under such conditions, leaf water status measurements are an alternative to soil measurements for the diagnosis of the level of water deficit experienced by the plant. Leaf water potential at predawn (Ψpd), at midday (Ψmin) or on non-transpiring leaves (Ψstem) have been widely used as indicators of water stress in vineyards (Van Leeuwen *et al*., 2009, 2010). Thresholds of water deficit levels with regard to grapevine production have been validated from the use of Ψpd (Ojeda *et al*., 2001). A major constraint in the use of leaf water potential-based indicators, specifically Ψpd, is the high measurement frequency required over the cropping seasons, due to their short validity after a rainfall event. To overcome the limits described above, attempts have been made to assess plant or soil water status from modelling approaches. A climate-based model was shown to be reliable to predict Ψpd in non-irrigated Mediterranean vineyards (Taylor *et al*., 2012). However, a local calibration of the model was necessary. Grapevine Ψpd was also shown to be tightly correlated with the Fraction of Transpirable Soil Water (FTSW), which can be simulated with soil water balance models (Lebon *et al*., 2003; Pellegrino *et al.,* 2004).

Substantial progress in vineyard soil water balance modelling was made over the last decades. Riou *et al.* (1989) parameterized a simple model of light interception. This model was used in a simple water balance model, based on a unique soil reservoir to simulate soil water content at a daily time step. This latter water balance model was improved to describe the transpiration response to soil water availability (Riou and Lebon, 2000; Lebon *et al*., 2003; Pellegrino *et al.,* 2004). Pellegrino *et al.* (2006) have used this modelling approach to build a diagnosis tool simulating the pattern of water stress experienced by grapevines under Mediterranean conditions. Later developments have been the adaptation of the model to intercropped vineyards (Celette *et al*., 2010), with a soil water reservoir split into two compartments in order to consider the soil volume explored by both the intercrop roots and the grapevine roots (Celette *et al*., 2005, 2008).

The present paper is aimed at setting up a simple index based on application of the water balance model (Lebon *et al*., 2003), and to evaluate its relationship with yield and berry quality at harvest. A synthetic water deficit index was computed from the time-courses of simulated FTSW and existing relationship between FTSW and Ψpd. The yield and berry quality indicative value of this index was therefore tested on a

Table 1 - Description of the vineyard data base

Department	Vineyard	Variety	Year	Number of elements
Vaucluse	Beaumes-de-Venise I, II and III*	Grenache	1999-2001-2002	9
	Gadagne	Syrah	2001-2002-2003	9
		Grenache	2001-2002	5
	Serres	Grenache	1998-1999-2000-2001-2002-2003	17
	Violès	Grenache	2001-2002	4
	Sainte-Cécile-les-Vignes	Syrah	2002-2003	8
Var	Lalonde-les-Maures	Grenache	2002-2003	2
	Puget Ville	Grenache	2002-2003	2
	Vidauban	Grenache	2002-2003	2
Bouches-du-Rhône	Lançon-de-Provence	Syrah	2002-2003	4
Gard	Aspères	Syrah	2000-2001-2002-2003	16
Hérault	Sauteyrargues	Syrah	1998-1999-2000-2001-2002-2003	12
		Grenache	1998-1999-2000-2001-2002-2003	12

*Different value of Total Transpirable Soil Water (TTSW) for I, II and III large data set combining different cultivars and contrasted pedo-climatic conditions of various vineyards in the French Mediterranean region.

MATERIALS AND METHODS

1. Vineyard locations and characteristics

A total of 102 situations, each combining one location, one variety and one vintage (example : Gadagne x Grenache x 2 002) were used in this study (Table 1).

Vineyards (total of 15) were all located in the southern French departments : Vaucluse (8 vineyards), Var (3 vineyards), Bouches-du-Rhône (1 vineyard), Gard (1 vineyard) and Hérault (2 vineyards). The cultivated varieties, Grenache and Syrah, were grown on bare soil. Irrigation was supplied for 37 of the 102 combinations.

2. Weather measurements

Daily mean temperature and cumulated rainfall were recorded in each vineyard from March to September. Daily reference evapotranspiration (ETo) was given by the nearby Météo France meteorological station.

3. Soil water balance model and parameterization

The water balance model was described by Lebon *et al.* (2003). This model calculates at a daily (i) time-step, the time course of Available Soil Water (ASW_i) and the Fraction of Transpirable Soil Water ($FTSW_i$). An important parameter of the model is Total Transpirable Soil Water (TTSW).

At day i, the water balance equation applies to the ASW term :

$ASW_i = ASW_{i-1}$ + Rain – Runoff – Soil evaporation – Grapevine Transpiration

with : Transpiration = $[\min \{ 1 , FTSW_{i-1}/0.4 \}]\ k_c\ ET_0$.

$FTSW_{i-1} = ASW_{i-1} / TTSW$

A drainage term can appear at day i as a result of the upper limit of ASW_i at TTSW.

The canopy architecture (height and width of full vegetation, porosity) and structure (inter-row and inter-plant distances) were used to calculate the maximum crop coefficient, k_{c_max} (Riou *et al.*, 1989, 1994). Pieri and Gaudillère (2005) showed that the more precisely these two parameters (TTSW, k_{c_max}) were acquired, the better was the simulation by the water balance model. The phenological stages (budburst, flowering, bunch closure, veraison, maturity) and harvest time were noted.

TTSW was calculated from direct soil water content profiles in some situations. When unavailable with this method or from soil profile assessment with values of retention capacity and wilting point, TTSW was indirectly calculated by inversion of the soil water balance model, based on measurements of Ψpd (Pellegrino *et al.*, 2006). At budburst, ASW was set at TTSW, assuming a full recharge of the soil water reserve. Gaudin and Gary (2012) have shown that this condition was quite often realized in vineyards with low to intermediate TTSW (below 200 mm). For larger TTSW (two vineyards in Vaucluse), we analysed the rainfall data from the previous autumn and winter in order to know if replenishment of the soil water reserve was partial or complete at budburst.

4. Seasonal change in soil water status with regard to grapevine production

Fifteen experts of the French Mediterranean region were asked to design an “optimal water deficit trail” based on Ψpd thresholds according to the type of red wine production they were targeting. Then, the Ψpd thresholds were converted into FTSW thresholds, using the relationship parameterized between these two variables by Lebon *et al.* (2003) and Pellegrino *et al.* (2004). Optimum thresholds were sufficiently homogeneous to build a unique diagnosis grid, as described in Table 2. This latter relied on five water status zones from flowering to harvest, which were

Table 2 - Definition of the five zones of water status in the diagnosis grid

Zone	Water status	Target yield	Type of wine expected
-2	Excessive wetness	high yield	Low concentration, high acidity, herbaceous flavour, “unbalanced”
-1	Moderate wetness	50-90 hL/ha	Fruity, low to medium concentration, “balanced”
0	Medium, mild dryness (Optimal)	30-50 hL/ha	Fruity, medium concentration, “balanced”
1	Moderate dryness	20-30 hL/ha	High alcohol level, jelly flavour, high concentration, “balanced”
2	Excessive dryness	low yield	High alcohol level and flavour, astringent, “unbalanced”

associated with five contrasted production objectives. The zone « 0 » was associated to an intermediate yield of 30 to 50 hL/ha. A yield of 50 hL/ha (60 hL/ha in some instances) is the upper yield commonly validated by the French legislator for the attribution of a registered designation of origin to several wines of Languedoc.

The FTSW boundaries for each water status zone decreased from flowering to harvest as soil water content generally declines under vineyards conditions (Figure 1). Four periods were delimited, two between flowering and veraison and two between veraison and harvest, with specific upper and lower FTSW thresholds. Similar durations (days) were set for the two periods before and after veraison. The time from budburst to flowering was considered to be not relevant for the discrimination of water stress trails as rainfalls in autumn and winter are often complemented by rain episodes preventing drought at this stage.

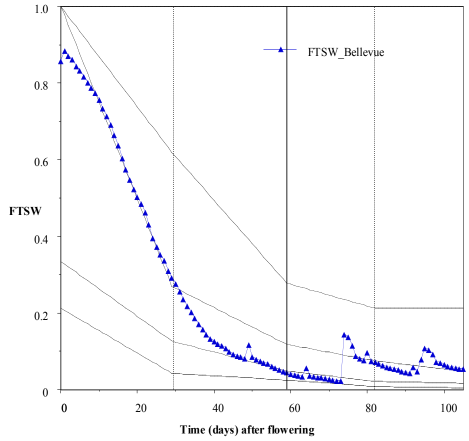

Figure 1 - Changes in the five zones of water status from flowering to harvest (from top to bottom: excessive and moderate wetness, optimal, dry and excessive dryness).

The vertical lines represent the veraison stage (full line) and the two intermediate times (mid flowering-veraison and mid veraison-harvest; dotted lines). Bellevue_2003 is an example. FTSW = Fraction of Transpirable Soil Water.

5. Design of a water stress index of vineyard water status from flowering to harvest

Changes in the simulated FTSW for each of the 102 situations were compared to the diagnosis grid zones to calculate a synthetic water deficit index (Figure 1, Table 3). The water status zone (-2 to 2) in which the simulated FTSW was mainly present was determined for the 4 periods from flowering to harvest.

Basically, this approach consisted in counting the number of days of simulated FTSW in each zone. When FTSW was equally represented in two zones during one period, then the main represented zone was determined from the mean FTSW and the FTSW thresholds of the zone. The water stress index resulted from the mean of the four main zones during the four successive periods. Vineyard water status was determined on the base of the water stress index values (Table 4). Four classes of water stress index were delimited. A minimal size of 4 combinations (vineyard x year x cultivar) was imposed for each class in order to conduct further statistical analyses. An example of the method is presented for the location "Bellevue" and the year 2003, for which the water stress index was -0.25, and therefore the vineyard water status considered as "Optimum" (Figure 1 ; Tables 3-4).

6. Yield and berry quality measurements at harvest

Yield per vine, berry fresh weight, sugar content, average amount of sugar per berry, total acidity content and concentration, and anthocyanin content were determined at harvest.

In each vineyard, the grapes of 20 vines were harvested and weighed with an electronic balance

Table 3 - Calculation of the water stress index. Example: data from "Bellevue x 2003" water balance simulation.

Water status zone	Number of days of simulated FTSW in each water status zone			
	Flo – ½ [Flo; Ver]	½ [Flo ; Ver] – Ver	Ver – ½ [Ver ; H]	½ [Ver ; H] – H
-2	0	0	0	0
-1	21	1	6	12
0	8	26	3	11
1	0	3	14	0
2	0	0	0	0
Main zone	**-1**	**0**	**1**	**-1**
	Water stress index = mean of the four main zones = -0.25			

Flo: Flowering on June 3, Ver: Veraison on August 1, H: Harvest on September 16
FTSW, Fraction of Transpirable Soil Water

(Gram K1T-150SE). A sample of 200 berries (2-3 berries per cluster randomly harvested on the vine) was collected, weighed with a high precision electronic balance (Sartorius, model BP4100) and crushed. The resulting mixture was centrifugated and analyses were made on the supernatant in accordance with the OIV standards (OIV, 1999). Reducing sugars were measured by refractometry; total acidity was titrated using NaOH and color indicator; and anthocyanins were measured by photometry at 520 nm (Ough and Amerine, 1988).

7. Statistical analyses

The effects of water stress index on grapevine yield and quality components were assessed from an analysis of variance, followed by mean comparisons (Tukey's test), using StatBox (c) software.

RESULTS AND DISCUSSION

1. Range of variation of the water stress index

The water stress index ranged from -2.0 to +1.25 for Grenache and from -1.5 to +1.0 for Syrah (Figure 2). Most values were between -1.5 and +0.75. The dry class had only 4 plots of each variety (Table 4). This distribution was mainly caused by the rain regime and climatic conditions between budburst and maturity. However, the hypothesis of full soil water refilling at budburst also highly influences the water stress index. It is likely that this assumption was not accurate for 2 vineyards in Vaucluse with cultivar Grenache (TTSW = 225 mm at Beaumes-de-Venise III and TTSW = 260 mm at Violès).

Indeed, total rainfall recorded at the nearby meteorological station (Carpentras, Vaucluse) was insufficient in 2002 (autumn 2001 and winter 2001-2002) for a complete recharge of any soil with intermediate (> 200 mm) to large TTSW. Rainfall during the period from April to July was low (14 mm to 39 mm per month), except May (116 mm). However, this latter rainfall event was likely insufficient to modify the water pattern from a dry situation as about 40 mm of the 160 mm were simulated to be lost by soil evaporation and a few mm of additional loss are expected due to runoff. For other years, soil water recharge was likely to be complete for these vineyards in Vaucluse, whatever the TTSW value. Thus, only 3 water balances (for Grenache variety) could have been over-estimated: 1 for Beaumes-de-Venise III, 2 for Violès.

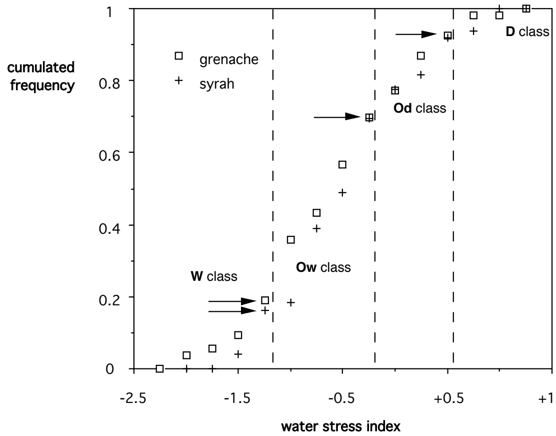

Figure 2 - Distribution of Grenache and Syrah varieties into the four classes of water stress index: W (wet), Ow (Optimum wet), Od (Optimum dry) and D (Dry).
Arrows indicate the cumulated frequency at the upper limit of W, Ow and Od classes (it is 1 for D).

The level of soil water recharge at budburst needs to be accurately determined because early *vs* late water deficit are expected to result in contrasted yield and berry quality, even if their water stress index are similar. The timing of water stress has impacts on growth (Matthews *et al.*, 1987), grape composition and thus quality (Matthews and Anderson, 1988; Ojeda *et al.*, 2002). In the present study, the contrasted FTSW patterns over the cropping season lead to different values of stress index. Most of the FTSW simulations belonged to the wet and optimum wet zones before veraison, and tended towards the optimum dry and optimum zones after veraison. Should the soil be dry before veraison, sudden high increase in FTSW after veraison is unlikely because of the generally low rain amounts during this period under a Mediterranean climate. The greater increase

Table 4 - Distribution of the data set for the two cultivars (Grenache or Syrah), based on their water stress index class

Water stress index class	Vineyard water status	Distribution of the sample	
		Grenache	Syrah
[-2;-1.25]	W (Wet)	10	8
[-1;-0.25]	Ow (Optimum Wet)	27	28
[0;0.5]	Od (Optimum Dry)	12	9
[0.75;2]	D (Dry)	4	4

Table 5 - Correlations between the water stress index (partial and full notations) and yield and berry quality at harvest for Grenache and Syrah

	Flowering to veraison	Veraison to maturity	Flowering to maturity
Harvest per vine	Grenache **	Grenache **	-0.45 ***
	Syrah *		-0.19
200 berry weight	Grenache **	Grenache ***	-0.61 ***
	Syrah ***	Syrah **	-0.52***
Must sugar content		Grenache *	0.31*
			Syrah: 0.21
Amount of sugar per berry	Grenache *	Grenache ***	-0.42 **
	Syrah **		-0.30 *
Must acid content	Grenache ***	Grenache ***	-0.58 ***
			-0.31 *
Amount of acid per berry	Grenache ***	Grenache ***	-0.75 ***
	Syrah ***	Syrah **	-0.51 ***
Must anthocyan content	Grenache *		0.24
			Syrah: -0.17
Amount of anthocyan per berry			Grenache: -0.12
		Syrah *	-0.23
Ratio sugar / acid	Grenache ***	Grenache ***	0.64 ***
			Syrah: 0.30 *

Levels of significance: 5%*, 1%** and 1‰***

in FTSW patterns in our study resulted in a transition from optimal to excessive wetness (0 to -2 in Table 2), from moderate dryness to moderate wetness (+1 to -1) and from excessive dryness to optimal (+2 to 0), for 16 of the 102 situations.

2. Yield and berry quality parameters at harvest

Compared to Syrah, Grenache exhibited higher correlations between the water index and yield and berry quality components (Table 5). The use of partial water stress indices for pre-veraison and post-veraison also resulted in lower correlations for Syrah than for Grenache, notably for the yield per vine. The higher variability in FTSW patterns for Grenache with both wetter and drier dynamics compared to Syrah could explain this varietal difference.

In accordance with other studies (Koundouras *et al*., 1999; Van Leeuwen and Seguin, 1994), berry weight and sugar and acid contents per berry were linearly correlated to the water stress index for cv Grenache (Figures 3-4). It should be noted that the decrease in berry weight was 6-fold higher than the decrease in sugar per berry when the water stress index increased (-0.236-g *vs* -0.0391-g decrease for berry weight and sugar per berry, respectively). This explains why the sugar concentration in berries slightly increased when the water stress index increased (Table 5). Applying the linear relationships for index -1.5, 0 and +1.5 gives respectively 511, 625 and 803 berries per kg, then 212, 222 and 238 g of sugar per kg (there is roughly a gain of 8.5 g of sugar per kg of must by unit of water stress index).

3. Classes in yield per vine, berry weight and berry sugar and acidity contents and concentrations can be discriminated by the water stress index

In Figure 5, yield and quality components were plotted as a function of the water stress index classes across all 102 combinations, including both cultivars (Grenache and Syrah) (Table 4). The results were in agreement with the literature (Van Leeuwen and Seguin, 1994; Koundouras *et al*., 1999; Chacon *et al*., 2009). The Wet water status corresponded to vineyards with high yield, big berries and low concentration of sugar while the Dry water status showed the opposite trend. The Ow and Od (Optimum wet and dry, respectively) were intermediate. The differences among classes were lower for Syrah than Grenache, when considering sugar and total acidity concentrations, possibly due to the lower range of soil water pattern (Figure 2).

No difference in anthocyanin content was observed between the water stress index classes (Figure 5). As anthocyanins are located in the skin, changes in berry size greatly influence their concentration (Matthews and Anderson, 1988; Ojeda *et al*., 2002). But the regulation of the anthocyanin biosynthesis pathway is complex, and the effect of water deficit on their final

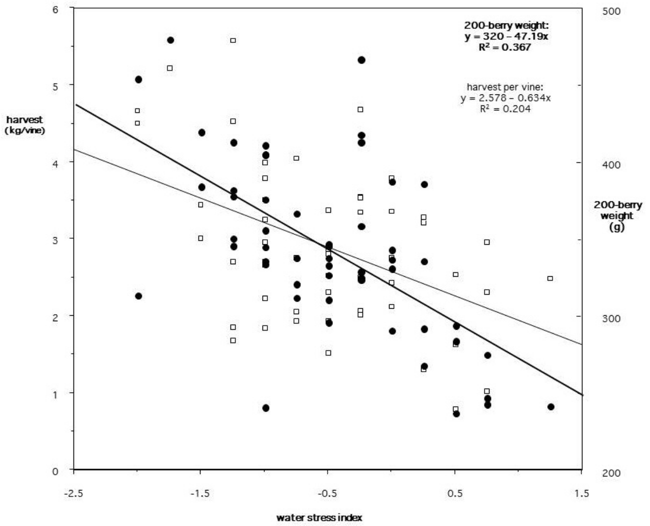

Figure 3 - Production per vine (open symbol) and 200-berry weight (full symbol) as a function of the water stress index for the Grenache cultivar.

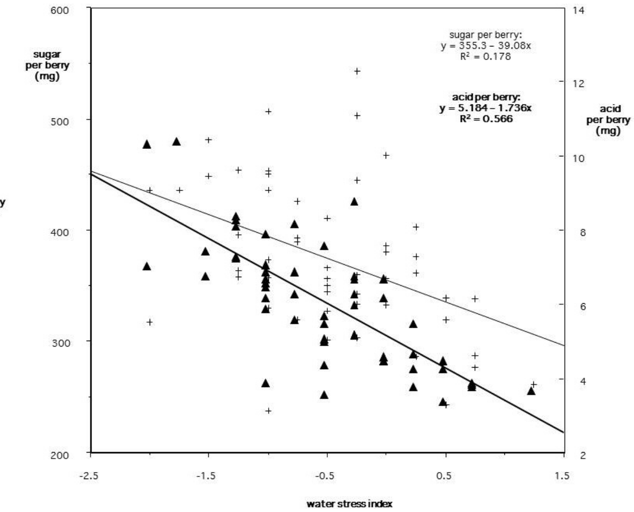

Figure 4 - Sugar (plus symbol) and acid (triangle symbol) contents per berry as a function of the water stress index for the Grenache cultivar.

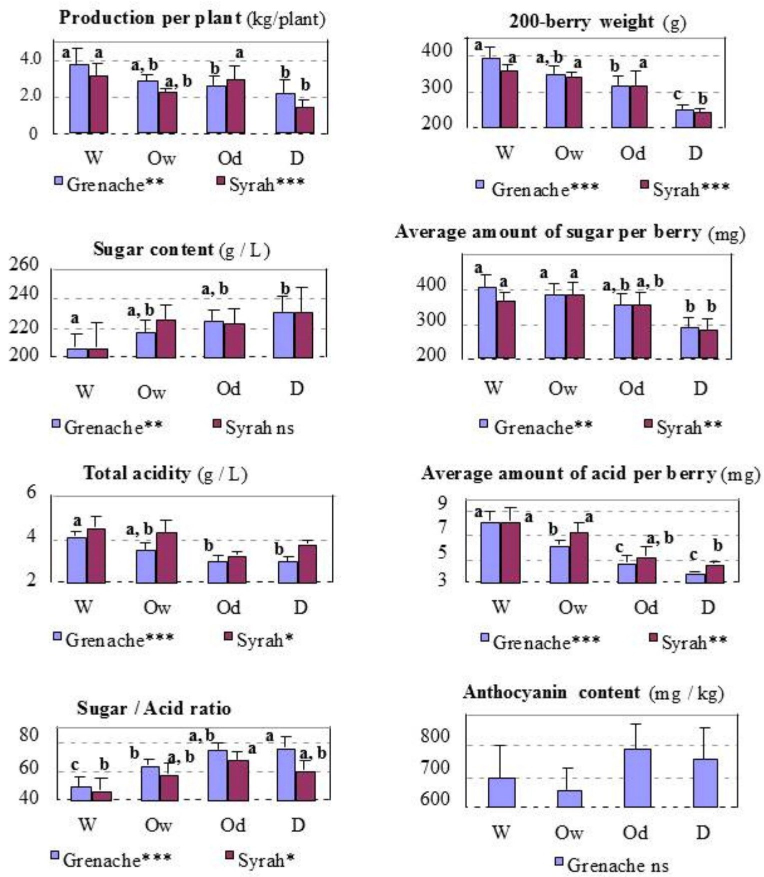

Figure 5 - Harvest parameters (production per plant, 200-berry weight, must sugar content, acidity) of the Grenache and Syrah cultivars in relation with the vineyard water status determined from the water stress index: W (wet), Ow (optimum wet), Od (optimum dry) and D (dry).

Different letters indicate significant differences among treatments. Levels of significance: 5%*, 1%**, 1‰***, and not significant (ns).

content cannot be simply interpreted (Ollé *et al*., 2011). Notably, temperature plays a major role in anthocyanin synthesis and degradation. Optimum berry temperature for anthocyanin synthesis was reported to be around 30 °C, but above 35 °C anthocyanins stop accumulating or may even be degraded (Keller, 2010). Such high temperatures can be common in Mediterranean vineyards. The temperature effect could hide some influence of the water stress on anthocyanin content in our study.

4. How could the synthetic water deficit index be improved?

The analysis could be improved by the application of a continuous water balance including the post-harvest period, and enabling the calculation of a more realistic budburst FTSW for the situations of high TTSW, in order to reduce the error in predicting the time course of water deficit during the next crop cycle (Roux *et al*., 2014). However, this could not be made with our data set because the climatic data for the period of time between harvest and the following budburst were missing for most of the locations.

A recent application has been the change of water availability that can be brought by irrigation. An experiment performed at Rivesaltes (Coulon, 2012; Gaudin *et al*., 2012) has shown that moderate water supplies (30-60 mm) were necessary to obtain a fruity wine (Cabernet-Sauvignon). The calculated water stress index was -0.50 (class Ow, Table 4) with irrigation and 0.25 (class Od, Table 4) without irrigation for 2010 and - 0.50 (class Ow) with irrigation and 0 (class Od) without irrigation for 2011. For these two years, irrigation enabled the move from Od to Ow, that is, better yield and a fruitier wine with lower alcohol level, as targeted by the producer.

CONCLUSIONS

Water balance modelling was used to characterise the water stress path of Mediterranean vineyards and calculate an index that could be used to discriminate yield and berry quality variables. The index was computed from the position of the water stress at successive periods in the reproductive stage of grapevine, relatively to FTSW thresholds. These thresholds were derived from the aggregation of multi-expert knowledge of the optimum water stress trail, based on Ψpd thresholds and existing relationship between Ψpd and FTSW.

The synthetic water stress index provided a good overview of the water stress experienced by the grapevines. It exhibited a significant correlation with the grape yield, the 200-berry weight and the amounts of sugar and acid per berry. The reason was clearly the prevalence of different hydric conditions for different vintages under the Mediterranean climate, which could hide the influence of other factors such as temperature. Improvements of the water balance modelling (and hence improvements of the index calculation) could be considered with a continuous water balance and data acquisition on a year-round basis, notably in deep soils with a great potential of water storage. Future research could aim at designing dynamic tools that would enable correction of any attended water stress path (calculated at any time before harvest) towards a new one compatible with the winegrower objectives. Calculation of this water stress index in real time could help winegrowers to adapt cultivation of various fields, with selection of the best irrigation schedules for each combination of soils characteristic and grapevine variety.

REFERENCES

Celette F., Wery J., Chantelot E., Celette J. and Gary C., 2005. Belowground interactions in a vine (*Vitis vinifera* L.) – tall fescue (*Festuca arundinacea* Shreb.) intercropping system: water relations and growth. *Plant and Soil*, **276**, 205-217.

Celette F., Gaudin R. and Gary C., 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *Eur. J. Agro.*, **29**, 153-162.

Celette F., Ripoche A. and Gary C., 2010. WaLIS – A simple model to simulate water partitioning in a crop association: the example of an intercropped vineyard. *Agric. Water Management*, **97**, 1749-1759.

Chacon J.L., Garcia E., Martinez J., Romero E. and Gomez S., 2009. Impact of the vine water status on the berry and seed phenolic composition of "Merlot" (*Vitis vinifera* L.) cultivated in a warm climate: consequences for the style of wine. *Vitis*, **48**, 7-9.

Coulon V., 2012. Irrigation de la vigne au domaine Cazes: détermination des conditions d'irrigation optimales et mise en place d'un outil de pilotage. *Mémoire de fin d'études*, École d'ingénieurs de Purpan, Toulouse.

Gaudin R. and Gary C., 2012. Model-based evaluation of irrigation needs in Mediterranean vineyards. *Irrigation Sci.*, **30**, 449-459.

Gaudin R., Coulon V., Cazes E., Gary C. and Wery J., 2012. Monitoring of irrigation in a Mediterranean vineyard: water balance simulation versus pressure chamber measurement. *In: Proc. 7th Int. Symp. on Irrigation of Horticultural Crops*, Geisenheim (Germany), 16-20 July 2012, *Acta Horticulturae* (in press).

Keller M., 2010. Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists. *Aust. J. Grape Wine Res.*, **16**, 56-69.

Koundouras S., Van Leeuwen C., Seguin G. and Glories Y., 1999. Influence de l'alimentation en eau sur la croissance de la vigne, la maturation des raisins et les caractéristiques des vins en zone Méditerranéenne (exemple de Némée, Grèce, cépage Saint-Georges, 1997). *J. Int. Sci. Vigne Vin*, **33**, 149-160.

Lebon E., Dumas V., Pieri P. and Schultz H.R., 2003. Modelling the seasonal dynamics of the soil water balance of vineyards. *Functional Plant Biology*, **30**, 699-710.

Matthews M.A., Anderson M.M. and Schultz H.R., 1987. Phenologic and growth responses to early and late season water deficits in Cabernet franc. *Vitis*, **26**, 147-160.

Matthews M.A. and Anderson M.M., 1988. Fruit ripening in *Vitis vinifera* L. : responses to seasonal water deficits. *Am. J. Enol. Vitic.*, **39**, 313-320.

OIV, 1999. *Recueil des Méthodes Internationales d'Analyse des Vins et des Moûts*. Publication OIV, 341p.

Ojeda H., Deloire A. and Carbonneau A., 2001. Influence of water deficits on grape berry growth. *Vitis*, **40**, 141-145.

Ojeda H., Andary C., Kraeva E., Carbonneau A. and Deloire A., 2002. Influence of pre- and postveraison water deficit on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. *Am. J. Enol. Vitic.*, **53**, 261-267.

Ollé D., Guiraud J.L., Souquet J.M., Terrier N., Ageorges A., Cheynier V. and Verries C., 2011. Effect of pre- and post-veraison water deficit on proanthocyanidin and anthocyanin accumulation during Shiraz berry development. *Aust. J. Grape Wine Res.*, **17**, 90-100.

Ough C.S. and Amerine M.A., 1988. *Methods for Analysis of Musts and Wines*. John Wiley, New York, 377 p.

Pellegrino A., Lebon E., Voltz M. and Wery J., 2004. Relationships between plant and soil water status in vine (*Vitis vinifera* L.). *Plant and Soil*, **266**, 129-142.

Pellegrino A., Gozé E., Lebon E. and Wery J., 2006. A model-based diagnosis tool to evaluate the water stress experienced by grapevine in field sites. *Eur. J. Agronomy*, **25**, 49-59.

Pieri P. and Gaudillère J.P., 2005. Vines water stress derived from a soil water balance model – sensitivity to soil and training system parameters. *In : Proc. XIVth Int. Conf. GESCO*, Geisenheim (Germany), 23-27 August 2005, Schultz H. (ed.), pp. 457-463.

Riou C., Valancogne C. and Pieri P., 1989. Un modèle simple d'interception du rayonnement solaire par la vigne - vérification expérimentale. *Agronomie*, **9**, 441-450.

Riou C., Pieri P. and Le Clech B., 1994. Consommation d'eau de la vigne en conditions hydriques non limitantes - Formulation simplifiée de la transpiration. *Vitis*, **33**, 109-115.

Riou Ch. and Lebon E., 2000. Application d'un modèle de bilan hydrique et de la mesure de la température de couvert au diagnostic du stress hydrique de la vigne à la parcelle. *Bull. O.I.V.*, **73**, 755-764.

Roux S., Brun F. and Wallach D., 2014. Combining input uncertainty and residual error in crop model predictions : a case study on vineyards. *Eur. J. Agronomy*, **52**, 191-197. http://dx.doi.org/10.1016/j.eja.2013.09.008.

Taylor J.A., Acevedo-Opazo C., Pellegrino A., Ojeda H. and Tisseyre B., 2012. Can within-season grapevine predawn leaf water potentials be predicted from meteorological data in non-irrigated Mediterranean vineyards ? *J. Int. Sci. Vigne Vin*, **46**, 221-232.

Van Leeuwen C. and Seguin G., 1994. Incidences de l'alimentation en eau de la vigne, appréciée par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (*Vitis vinifera* variété Cabernet franc, Saint-Émilion, 1990). *J. Int. Sci. Vigne Vin*, **28**, 81-110.

Van Leeuwen C., Tregoat O., Choné X., Bois B., Pernet D. and Gaudillère J.-P., 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes ? *J. Int. Sci. Vigne Vin*, **43**, 121-134.

Van Leeuwen C., Pieri P. and Vivin P., 2010. Comparison of three operational tools for the assessment of vine water status : stem water potential, carbon isotope discrimination measured on grape sugar and water balance. *In : Methodologies and Results in Grapevine Research*. Springer Science Netherlands and Business Media, Dordrecht, pp. 87-106.