MODELLING SOIL WATER CONTENT AND GRAPEVINE GROWTH AND DEVELOPMENT WITH THE STICS CROP-SOIL MODEL UNDER TWO DIFFERENT WATER MANAGEMENT STRATEGIES

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Abstract

Background and aims: Many models have been developed to evaluate crop growth and development, but few are capable of simulating grapevine systems. The present study was carried out to evaluate the ability of the STICS model to represent grapevine phenology, biomass production, yield and soil water content in two situations differing with respect to rainfall distribution and water management strategies.

Methods and results: Simulations were performed for an irrigated vineyard in Chile and an irrigated and a non-irrigated vineyard in France. The crop model gave a good estimation of the main stages of grapevine phenology (less than six days difference between simulated and observed values). Soil water content was the best simulated variable ($R^2 = 0.99$), whereas grapevine evapotranspiration observed only in Chile ($R^2 = 0.43$) and leaf area index observed only in France ($R^2 = 0.80$) were the worst simulated variables. Biomass production, yield and their components were correctly simulated (within the 95 % Student confidence interval around the mean observed value). A comparison of the fraction of transpirable soil water and vine water potential measurements with the water stress indices calculated by the STICS model showed that the time and duration of the grapevine water stress period was correctly estimated.

Conclusions: Therefore, the STICS model was reasonably successful in simulating vine growth and development, and identifying critical periods concerning the vine water status.

Significance of the study: The STICS model can be used to evaluate various water management strategies and their impacts on grape production.

Keywords: model evaluation, *Vitis vinifera* L., water deficit, irrigation, phenology

Résumé

Contexte et objectifs : Plusieurs modèles ont été développés pour évaluer la croissance et le développement des cultures, mais peu sont capables de simuler les systèmes viticoles. Cette étude vise à évaluer la capacité du modèle STICS à simuler la phénologie de la vigne, sa croissance en biomasse, son rendement et le stock d'eau du sol dans deux situations qui diffèrent par l'ampleur et la distribution des précipitations et par la gestion de l'alimentation hydrique de la vigne.

Méthodes et résultats : Les simulations ont été faites pour un vignoble irrigué au Chili et pour deux parcelles expérimentales, une irriguée et une autre non irriguée, situées en France. Le modèle donne de bonnes estimations des principaux stades phénologiques (moins de six jours de différence entre les valeurs observées et simulées). Le stock d'eau du sol est ressorti comme la variable la mieux simulée ($R^2 = 0.99$), tandis que l'évapotranspiration (mesurée seulement au Chili) et l'indice foliaire (mesuré seulement en France) sont les moins bien simulés ($R^2 = 0.43$ et 0.80, respectivement). La production de biomasse, le rendement et ses composantes ont été correctement simulés (compris dans l'intervalle de confiance à 95 %). En comparant les valeurs de fraction d'eau du sol transpirable par la plante et les potentiels hydrique de la vigne mesurés au champ d'un côté et les indices de contrainte hydrique calculés par le modèle STICS de l'autre, il ressort que la date de début et la durée de la période de stress subit par la vigne ont été correctement estimés.

Conclusions : Le modèle STICS a permis de simuler correctement la croissance et le développement de la vigne, et de mettre en évidence les périodes critiques concernant la contrainte hydrique que subit le vignoble dans les situations étudiées.

Signification et impact de l'étude : On peut donc envisager l'utilisation du modèle STICS pour évaluer plusieurs stratégies de gestion de l'eau et leurs impacts sur la production de la vigne.

Mots clés : évaluation du modèle, *Vitis vinifera* L., contrainte hydrique, irrigation, phénologie

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INTRODUCTION

Water resource management is a key issue in viticulture that justifies modelling efforts to estimate the crop-soil water balance and yield. First, the growth and development of grapevines and the grape yield and quality build-up are closely related to water constraints (Gómez-del-Campo *et al.*, 2002; Gu *et al.*, 2004). Secondly, in regions under a Mediterranean climate, water is the most limiting resource, so efficient water use (and irrigation, when available) is required.

Pellegrino *et al.* (2005) extensively described the effects of water stress (estimated from the fraction of transpirable soil water) on leaf emergence and lateral branching. If the water supply fits to the potential evapotranspiration, vegetative growth is considered excessive as it competes for assimilates with reproductive development. This has a negative effect on flower bud initiation and fruit ripening, and promotes disease development (Smart *et al.*, 1991; Valdés-Gómez *et al.*, 2008; Zahavi *et al.*, 2001). Severe water stress can also be detrimental, with a strong reduction in leaf area expansion, thus limiting light interception, and net assimilation rate (Pellegrino *et al.*, 2005), with consequences on the transfer of sugars to grapes. Grape yield formation is sensitive to water stress, particularly the number of berries per cluster and of clusters per vine (Matthews and Anderson, 1989). Grape quality is also affected by the time-course of water stress during berry development (Ollat *et al.*, 2002). For example, water deficit can affect the phenolics concentration in the berry skin, either directly through biosynthesis of these compounds or indirectly through the reduction of berry size and the resulting increase in the skin/pulp weight ratio (Ojeda *et al.*, 2002; Ollat *et al.*, 2002). Production of high quality grapes thus requires an optimal soil water deficit pattern, ranging from a zero-to-mild deficit before flowering to a moderate deficit during reproductive development (Pellegrino *et al.*, 2006).

In regions under a Mediterranean climate, rainfall is irregularly distributed throughout the year and scarce during the grapevine growth period. Moreover, climate change models predict that conditions will be more arid in the future (Alcamo *et al.*, 2007; Magrin *et al.*, 2007). In many dry lands within the Mediterranean arc, grapevines for wine production are grown without supplementary irrigation, and their water supply depends on rainfall. The crop and soil management strategy may, however, alter the water balance, e.g. shoot trimming affects the transpiration flux, soil tillage or mulching affect soil evaporation. Irrigation is required and allowed in other wine producing regions, like Chile, with drier climates during the grapevine growth period. Regulated deficit irrigation is required to ensure that water deficit levels will be optimal at the different growth periods and to meet the growers' grape and wine production objectives (Chaves *et al.*, 2007).

In this context, modelling the water balance and yield components in vineyards would be useful for evaluating existing or alternative crop and soil management strategies, or for estimating water requirements at regional scale (Abraha and Savage, 2008). Simulation evaluations could be carried out for different soil and climate conditions, including future climate change scenarios. Most generic crop model platforms like CropSyst (Stockle *et al.*, 2003), DSSAT (Jones *et al.*, 2003) and Apsim (Keating *et al.*, 2003) cannot be used for grapevine simulations. A few specific crop models have been proposed for the simulation of stress-free grapevine growth (Bindi *et al.*, 1997; Wermelinger *et al.*, 1991). As an example, the model proposed by Poni *et al.* (2006) predicts the daily carbon balance and dry matter accumulation in vertically positioned grapevines. However, this model does not take into account the root-soil system and then grapevine growing in nitrogen or water stress conditions cannot be simulated. To our knowledge, only two models have been developed to simulate grapevine growth in water and/or nitrogen stress conditions: VineLogic (Walker *et al.*, 2005), which was originally designed for decision support with respect to specific problems of salinity in Australia and the model of Nendel and Kersebaum (2004), which has not been validated yet under various field conditions.

Recently, the STICS generic crop-soil model (Brisson *et al.*, 2003) has been adapted for grapevines and evaluated for many vineyards throughout France (García de Cortázar-Atauri, 2006). It was extensively described by Brisson *et al.* (2009) and in the documentation available online (www.avignon.inra.fr/stics). The model simulates, on a daily time step, biomass production and the water and nitrogen balances of the soil-crop system, including under water limiting conditions. The time interval between phenological stages depends on temperature. The fruit growth is described by the dynamics of dry matter accumulation and water content. Dry matter growth is modelled using thermal time and final potential dry weight. To model water content dynamics, two components are defined, one of which is related to the berry phenological stage and the other to the water status of the plant (Brisson *et al.*, 2009). Harvest date is decided according to the berry water content, which is highly correlated with its sugar content (García de Cortázar-Atauri, 2006). The light intercepted by row crops is calculated using a simple geometrical approach and separating the diffuse and direct components of radiation. Radiation use efficiency may vary during the development phase, increase with higher CO_2 concentrations in the atmosphere and be reduced under extreme temperatures or water or nitrogen stresses.

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The leaf area index varies through the different phases of growth, stability and senescence; it can be limited by temperature, water or nitrogen stresses, and by a poor source-sink ratio. Dry matter partitioning is computed through the proportion of sink strength of the various types of plant organs. The crop water stress is calculated on the basis of a crop demand vs. soil supply approach (Lebon *et al.*, 2003). The soil water balance results from rain, irrigation, soil evaporation (Brisson and Perrier, 1991), crop transpiration calculated from the energy balance (Brisson *et al.*, 1999) and possibly limited by the soil water availability, run-off and drainage. Root absorption is partitioned among soil layers in relation with their respective root density. Water transport in the soil basically occurs through a mono-dimensional « tipping bucket » model: water cascades down, progressively filling up 1-cm soil layers until field capacity.

The present study was designed to evaluate the ability of the STICS model (version 6.2) to simulate the soil water content, grapevine phenology, biomass production and yield in cropping systems that included irrigation practices and differed from those tested by García de Cortázar-Atauri (2006). It involved two experiments carried out in an irrigated Cabernet sauvignon vineyard in Chile and in irrigated and non-irrigated Aranel vineyards in the south of France.

MATERIALS AND METHODS

1. Site and experimental design

We used data from two experimental sites cropped with grapevine (*Vitis vinifera* L.) for the model calibration and testing. One was located in the Pencahue Valley, Maule Region, Chile (35º22' S; 71º47' W), and the other near Montpellier, France (43°31' N; 3°51' E). Both sites are under Mediterranean climatic conditions but with different rainfall amount and distribution. Pencahue Valley has a mean annual rainfall of 692 mm, with more than 550 mm (80 %) falling during autumn and winter months i.e. between April and September, whereas the Montpellier Region has a mean annual rainfall of 748 mm, with 520 mm (70 %) of the rain falling in autumn and winter i.e. from September to March).

A comparison of climatic conditions during the 2003/04, 2004/05 and 2005/06 growing seasons in Pencahue with those during the 2004, 2005, 2006 growing seasons in Montpellier showed that they were fairly similar (table 1). Nevertheless, the seasonal mean air temperature was significantly higher at the French location, since the seasonal mean minimal air temperature at the Pencahue site was 3-8 ºC lower than in Montpellier. On the other hand, precipitation (Prec.) was more abundant in France than in Chile during the 2003/04 and 2004/05 growing seasons. Only the 2005/06 season was dryer in

Table 1 - Mean air temperature (Temp.), precipitation (Prec.), daily potential evapotranspiration (PET) and climate water deficit (Prec.-PET) averaged or summed over three periods of the grapevine growth cycle, for the Montpellier (M) and Pencahue (PV) experimental sites.

	Budbreak to flowering		Flowering to veraison		Veraison to harvest	
	PV	M	PV	M	PV	M
2003/04						
Temp. (°C)	15.5	14.7	21.0	22.5	20.7	23.0
Prec. (mm)	115.6	259.0	0.4	31.8	0.3	47.2
PET (mm day^{-1})*	3.8	3.6	6.1	5.3	4.8	4.0
Prec.-PET (mm)	-117	12.9	-381	-282	-327	-96
2004/05						
Temp. (°C)	14.1	16.0	21.3	23.7	19.7	23.3
Prec. (mm)	46.6	87.4	27.8	51.6	23.2	15.4
PET (mm day^{-1})	3.3	4.0	5.9	5.4	4.4	4.9
Prec.-PET (mm)	-160	-152	-345	-278	-273	-162
2005/06						
Temp. (°C)	14.8	16.4	19.8	24.2	19.4	22.9
Prec. (mm)	18.0	21.4	36.0	2.2	6.6	21.0
PET (mm day^{-1})	3.2	3.9	5.4	5.5	4.5	5.0
Prec.-PET (mm)	-180	-189	-302	-359	-300	-124

* Calculated by the Penman-Monteith model

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Montpellier than in Pencahue because of unusual drought. The climate water deficit (Prec.-PET) was systematically and significantly higher at the Pencahue site, particularly during the last period of the growing seasons.

The experiment in Pencahue Valley (PV) was carried out through three growing seasons during the 2003-2006 period on a commercial Cabernet sauvignon vineyard. The soil texture was a sandy loam containing 57.5 % sand, 27.5 % silt, and 15.1 % clay. The effective rooting depth was between 0.5 and 0.6 m because of a compacted layer observed at 0.6 m depth. The vines in PV were planted in 1994 at a spacing of 1.2 m within rows, and 3 m between rows (2,800 plants ha^{-1}) on their own roots. The vines were trained to a vertical shoot positioned system at a height of 2.1 m, with rows running north-south. Vines were irrigated using 3.5 L h^{-1} drippers spaced at 1 m intervals within row. Irrigation started in October (10 cm shoots) or November (flowering) depending on the soil water content and continued until April (after harvest). During the irrigation season, water was applied three or four times a week. Water application was based on reference evapotranspiration (ETr) multiplied by an « irrigation coefficient » considered as favourable for good quality production (Ortega-Farías *et al.*, 2004; Ortega-Farias *et al.*, 2007b). The ETr was calculated using the Penman-Monteith equation according to FAO irrigation and drainage guidelines (Allen *et al.* 1998). Three observation areas with 30 vines (108 m^2) each in the plot were used for data collection.

The field experiment at Montpellier (M) was conducted during the 2004 to 2006 period (three growing seasons) in a commercial Aranel (white variety) vineyard grafted on Fercal rootstock. The soil at the experimental site was deep, homogeneous and classified as clay-loam, containing 31 % sand, 35 % silt and 34 % clay. The effective rooting depth was around 3 m; it was estimated from the variations of the soil water profile (Celette *et al.*, 2008). The vines had been planted in 1997 in NW-SE oriented rows (2.5 x 1.2 m, i.e. 3,333 plants ha^{-1}) and trained to a vertical shoot positioned system at a height of 2.0 m above the soil surface. Two types of cropping systems were used: i) with drip irrigation (MI) with a water application of 100 % of the Penman-Monteith reference evapotranspiration during the period from budbreak to harvest date (Allen *et al.*, 1998); water was applied two to three times per week (3,400 m^3 ha^{-1} in 2005, 7,400 m^3 ha^{-1} in 2006); and ii) with no irrigation (MNI) and two replications of this treatment.

2. Data collection

a) Phenology and harvest date

The main phenological stages – budbreak, flowering, setting and veraison – were identified for each growing season using the development scale proposed by Eichhorn and Lorentz (E-L) and modified by Coombe (1995). Each stage was monitored when 50 % of the flowers and/or berries had reached the main phenological stages (Carbonneau *et al.*, 1992; Riou and Carbonneau, 1994; Williams *et al.*, 1985). Bud break was considered when 50 % of buds reached the stage 5 in E-L scale. Also harvest date was considered when the berries reached the decision criteria defined by the wine grower.

b) Grapevine growth

From 2004 to 2006, at the MI and MNI experiments, the leaf area index (LAI) was estimated regularly from April to October by using the LAI-2000 device (LI-COR Incorporated, Lincoln, Nebraska, USA). This device was calibrated in 2004 and 2005 from a direct measurement of leaf area. To this end, all leaves from 16 shoots were sampled from each treatment and replication. The individual area of the sampled leaves was measured from a digital photograph with image processing software (Ad Oculos version 3.1, DBS Gmbh, Germany) and the mean leaf area per shoot, per vine and per unit ground surface area was then calculated. A significant correlation ($r = 0.94$) was obtained between the LAI-2000 and the direct leaf area measurements. LAI was not monitored on the PV experiment.

On the M experiment, shoots collected for leaf area measurements were also used to estimate leaf, stem and grape dry biomasses. In the PV experiment, six shoots per replicate were sampled for dry matter estimation. All material collected was oven dried at 60 °C until no further weight loss could be detected (from 72 to 98 h). Total dry matter (TDM, leaf, stem and fruit) and total fruit dry matter (FDM) per ground surface area were then calculated.

c) Soil water content

On the PV experiment, volumetric soil water (m^3 m^{-3} of soil) was measured every two weeks from September to February by a time domain reflectometer (Trase, Soil Moisture Equipment Corp, Santa Barbara, California, USA). For each replicate, two pairs of rods (60 cm length) were inserted vertically along the plant row, with one pair located adjacent to an emitter and the other midway between two emitters located close to adjacent vines. Total soil water content (SWC, in mm) was calculated from these measurements on the basis of two assumptions. Before irrigation onset, the soil moisture values were considered homogenous, and then the mean of the two soil moisture measurements was multiplied by the root depth to estimate the water content. After irrigation onset, the soil was considered in terms of three different compartments, with one corresponding to the soil zone irrigated by drippers in the row (0.8 x 0.8 m), and the two others not irrigated, i.e. one located between

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the drippers in the row and the other in the inter-row. The soil moisture in this latter volume was considered as decreasing linearly until veraison and from this stage on the soil moisture values were considered as equal to the wilting point. This latter consideration was based on the fact that no irrigation was applied to this area and no significant rainfall occurred from December to February.

On the M experiment, the soil moisture was measured at monthly intervals during the growing season (April to September) with a neutron probe (CPN 503 DR, Campbell Pacific Nuclear Inc.) within aluminium access tubes (43-45 mm diameter). The soil and root distribution heterogeneity was taken into account by placing six 3-m tubes per replicate, with three located 2.4 m apart along the grapevine row (midway between the vines), and three others located in front of them in the middle of the inter-row. Also, one 5-m tube was installed on each replicate. Measurements were performed every 0.2 m to a depth of 1.6 m, and then every 0.4 m. Soil moisture was not monitored in the MI treatment, but the soil water potential was measured with tensiometers at 0.5, 0.75 and 1 m depth.

d) Grapevine water stress

Total Transpirable Soil Water (TTSW) was calculated from soil moisture monitoring carried out in both sites, by adding the differences from the wettest and the driest soil water content among profiles as proposed by Celette *et al.*(2008). Fraction of Transpirable Soil Water (FTSW) was calculated at each soil moisture measurement to evaluate the grapevine water stress level, which, in turn, relates to leaf water potential (Pellegrino *et al.*, 2004).

On PV, midday stem water potentials were measured on five leaves per vine per replicate (i.e. 15 per treatment) every two weeks from fruit setting to harvest. The leaves were bagged with both plastic sheet and aluminium foil at least 1 h before measurement. On the M experiment, predawn leaf water potentials were measured on six vines (two leaves per stock) per replicate (i.e. 12 per treatment) every three weeks from the end of June to grape harvesting (beginning of September). This measure was done at the end of the night (between 2 h prior to, and at dawn) on uncovered leaves. At both experimental sites, plant water status was measured by the pressure chamber technique.

Water stress indices obtained on field, FTSW and the plant water potential (predawn in Montpellier, and stem in Pencahue), were compared to STICS indices of water stress. The STICS model calculates two water stress indices, with one acting on transpiration and radiation efficiency use (*swfac*) and another on leaf growth (*turfac*) (Brisson *et al.*, 2003). These water stress indices are fractions ranging between 0 and 1, which reduce the above mentioned processes. They are calculated as linear functions of the soil water content available at rooting depth. It is essential to correctly estimate SWC in order to be able to accurately estimate these indices and consequently biomass production and transpiration.

e) Vineyard evapotranspiration

On the PV experiment, an eddy correlation system was installed in the central part of the vineyard to measure the energy balance components and meteorological variables above the vine canopy. The latent heat flux (energy used in the vine evapotranspiration (ETvine)) was obtained using a Krypton Ultraviolet Hygrometer (KH20, Campbell Sci., Logan, UT, USA. The minimum fetch-to-instrument height ratio was about 200:1, sufficiently large to preclude horizontal advection. A detailed description of the sensors and their installation and operation in grapevines was previously provided by Ortega-Farías *et al.* (2007a). Measurements were obtained from December 14th 2004 to February 25th 2005 during the first season, and from November 7th 2005 to March 2nd 2006 during the second.

f) Yield components

Yield was measured at harvest on five vines per replicate on the PV experiment. A random 10-bunch sample was taken from each treatment replicate and berry number per bunch and berry mass were determined. On the M experiment, 12 vines per replicate (i.e. 24 per treatment) were used for yield evaluation and berry number per bunch was evaluated on 20 randomly selected bunches.

g) Model calibration and evaluation

The grapevine varieties used in this study had to be parameterized. Brisson *et al.* (2003) pointed out that in the STICS model varietal differences are expressed through two parameter classes: i) those determining the growth and development stages of the crop, and ii) those determining potential berry mass and potential berry setting. For the first set of parameters, a 3-year dataset containing the dates of the main phenological stages for Cabernet-Sauvignon in many vineyards in the Maule Region, and independent from the PV experiment, was used. For the Aranel variety, phenological data collected during the 2004 growing season were used. The two varietal berry parameters, i.e. potential berry mass and potential berry setting, were obtained by model optimization, as described by García de Cortázar-Atauri (2006). Data used for this optimisation were from growing seasons 2003/04 at the PV site and 2004 at the M site.

Different parameter values were obtained for the two varieties (table 2). The Aranel cultivar appeared to set 35 degree-days earlier and to stop leaf growth 150 degree-

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Table 2 - Crop development and berry growth parameters calculated and optimized for the two grapevine varieties. The end of the juvenile phase stage corresponds to the time of maximal acceleration of the leaf growth rate. Degree-days were calculated on a 10 °C basis.

Plant parameters	Units	Cabernet Sauvignon	Aranel
Crop development phases (calculated)			
budbreak – end of juvenile phase	ºCd	25	25
end of juvenile phase – maximal leaf area index	ºCd	1050	1200
budbreak – fruit setting	ºCd	350	315
start of fruit setting - end of fruit setting	ºCd	91	91
total berry development	ºCd	1450	1450
Berry growth (optimized)			
Potential berry mass	g	0.66	1.07
Potential berry setting	berry bunch^{-1} °C d^{-1}	1.27	2.25

days later than Cabernet-Sauvignon. Aranel had a higher potential berry setting and a higher potential berry growth than Cabernet-Sauvignon.

A range of inputs was measured and provided for the simulations: soil characteristics (field capacity, wilting point and bulk density), technical parameters (plant density, canopy geometry, fruit load, water and nitrogen fertilisation, trimming date), initial values of the major crop (phenological stage, root depth and total nitrogen in the plant) and soil (soil moisture at the start of the simulation) state variables.

The model was evaluated on the main agronomic and water balance variables for the 2004/05 and 2005/06 growing seasons at the PV site, and 2005 and 2006 at the M site. Several statistical indicators were calculated to quantify the discrepancy between variables simulated (s) by the model and observed (o) in the experiments, as proposed by Brisson *et al.* (2002): bias, coefficient of determination (R^2), relative root mean square error (RRMSE) and model efficiency (EF).

RESULTS

1. Phenology and harvest date

Budbreak, flowering and harvest dates were simulated with no more than six days of difference relative to the observed values (table 3). Predictions on the M experiment were more accurate that those obtained at PV, probably because at the first site the phenological parameters were estimated with a dataset from the same plot, whereas at the second site they were estimated from a completely independent dataset. As was stated before, a 3-year dataset containing the dates of the main phenological stages for Cabernet-Sauvignon in several vineyards in the Maule Region, and independent from the PV experiment, was used in calibration processes.

2. Soil water content

The total soil water content at field capacity (SWC) was more than fivefold higher in the M (about 1,100 mm on 3 m depth profile) (Celette *et al.*, 2008) than on the PV experiment (nearly 180 mm on 0.6 m depth profile) (Ortega-Farias *et al.*, 2007a) as showed in figure 1. SWC remained at a high level until flowering in all situations because rainfall took place during this period and grapevine transpiration and soil evaporation were limited. After this stage, the last two processes rapidly increased. Thus, SWC decreased in the MNI treatment down to a level close to the permanent wilting point (slightly higher than 500 mm) during both growing seasons (2005 and 2006). However, in the MI treatment, irrigation maintained SWC close to the field capacity (around 1,100 mm) as the applied water volumes were close to the potential evapotranspiration values. The high SWC values in the MI treatment were corroborated by the soil water potential measurements, which were around -0.1 MPa in 2006 and higher than -0.2 MPa in 2005 for the top 50 cm soil layer along all grapevine growth season. In the PV experiment, SWC decreased from flowering to harvest to a level midway between the permanent wilting point (66 mm) and the field capacity (180 mm), as a mild water stress was imposed through irrigation deficit in order to increase berry quality (figure 2). Considering pooled data (Montpellier plus Pencahue Valley) SWC was well simulated in both situations during the two growing seasons (figure 3b), as shown by the significant high model efficiency (0.99) and significant determination coefficient (0.99, $p < 0.01$) values and by the low RRMSE value

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(0.08) (table 4). Separately, Montpellier showed a better statistical performance than Pencahue Valley. Although the whole soil water content was properly simulated for both experimental sites, water content was generally overestimated in the upper soil layer (0 - 60 cm) (mean over all overestimation of 35 mm in relation to a mean over all SWC of 128 mm) and underestimated in deeper soil layers (60 - 200 cm) in the M sites (mean over all underestimation of 55mm in relation to a mean over all SWC of 342 mm) (data not shown).

Despite the high contrast in SWC, and in relation with the very different root depths, the extent of grapevine water restriction was similar in the PV and MNI treatments (figure 2): the fraction of transpirable soil water (FTSW) at grapevine budbreak was close to or higher than 0.6 in both treatments and experimental years. Subsequently, FTSW decreased to a value close to 0.4 at flowering and 0.1-0.2 around harvest. These similar soil water dynamics explain why measured dry matter production did not

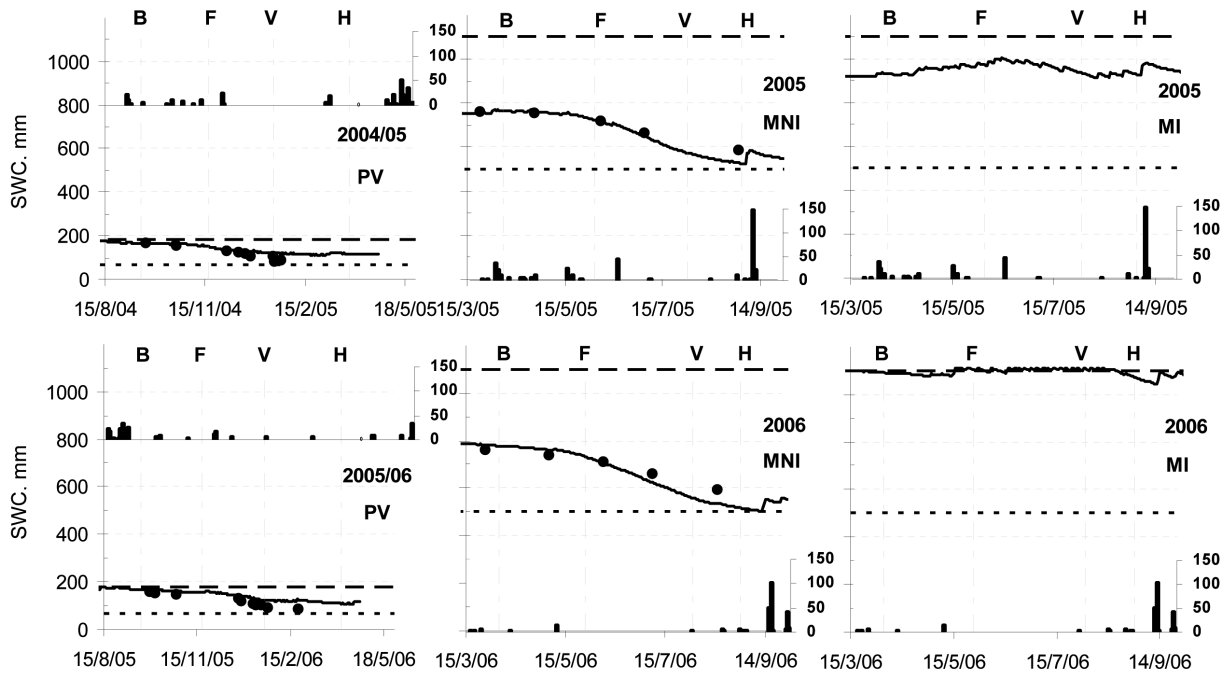


Figure 1 - Simulated (line) and observed (solid symbols) values of soil water content (SWC).
Vertical dotted lines represent the main grapevine phenology stages (B: budbreak; F: flowering; V: veraison and H: harvest). Vertical bars represent rainfall (mm). PV is the irrigated site in Chile, MI and MNI are the irrigated and non-irrigated treatments in France, respectively. Field capacity (thick dotted line) and wilting point (thin dotted line) are also represented.

Table 3 - Observed (O) and simulated (S) dates of vine phenology for each treatment.

	Budbreak			Flowering			Harvest		
	O	S	*Diff.*	O	S	*Diff.*	O	S	*Diff.*
2004/05									
PV†	17 sep.	16 sep.	*1*	18 nov.	24 nov.	*-6*	28 mar.	1 apr.	*-4*
MI	6 apr.	4 apr.	*2*	3 jun.	2 jun	*1*	3 sep.	5 sep	*-2*
MNI	6 apr.	4 apr.	*2*	3 jun.	2 jun	*1*	3 sep.	4 sep.	*-1*
2005/06									
PV[1]	21 sep.	22 sep.	*-1*	20 nov.	23 nov.	*-3*	6 apr.	2 apr.	*4*
MI	4 apr.	5 apr.	*-1*	27 may	27 mai	*0*	30 aug.	29 aug.	*1*
MNI	4 apr.	5 apr.	*-1*	27 may	27 mai	*0*	30 aug.	28 aug.	*1*

†PV was the irrigated site in Chile; MI and MNI were the irrigated and non-irrigated treatments, respectively, in France.

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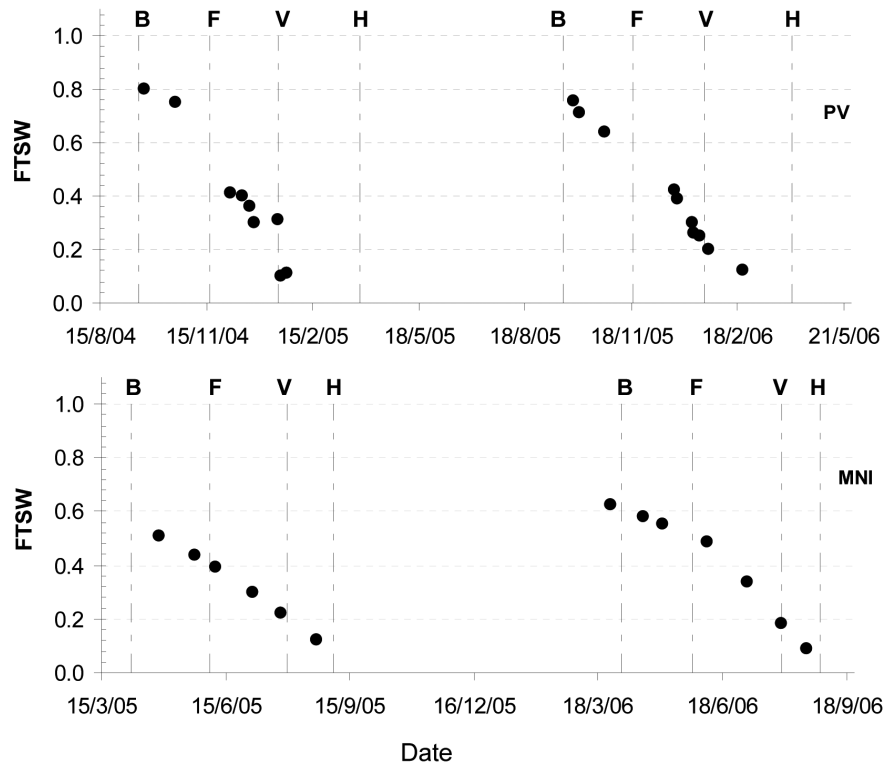


Figure 2 - Seasonal evolution of measured fraction of transpirable soil water (FTSW) during the period 2004-06.
Data for Pencahue (PV) and Montpellier non-irrigated (MNI) experiments. Vertical dotted lines represent the main grapevine phenology stages (B: budbreak; F: flowering; V: veraison and H: harvest).

Table 4 - Statistical indicators for the model simulation of total and fruit dry matter, leaf area index (LAI), soil water content and vine evapotranspiration.

	Total dry biomass ($t\ ha^{-1}$)	Fruit dry biomass ($t\ ha^{-1}$)	LAI	Soil water content (mm)	ETvine
Montpellier					
Bias	-0.23	-0.15	0.48	11.52	---
R^2 †	0.88**	0.88**	0.80**	0.98**	---
RRMSE	0.36	0.37	0.36	0.04	---
Efficiency	0.87	0.83	0.67	0.78	---
Pencahue					
Bias	-0.73	-0.19	---	-21.1	0.07
R^2	0.91**	0.96**	---	0.91**	0.43**
RRMSE	0.21	0.20	---	0.20	0.29
Efficiency	0.64	0.90	---	0.15	---
Pooled Data					
Bias	-0.35	-0.16	0.48	-9.13	0.07
R^2	0.87**	0.87**	0.80**	0.99**	0.43**
RRMSE	0.32	0.36	0.36	0.08	0.29
Efficiency	0.86	0.85	0.67	0.99	---

†Significant relationship at $p < 0.01$ between observed and simulated values is indicated by **

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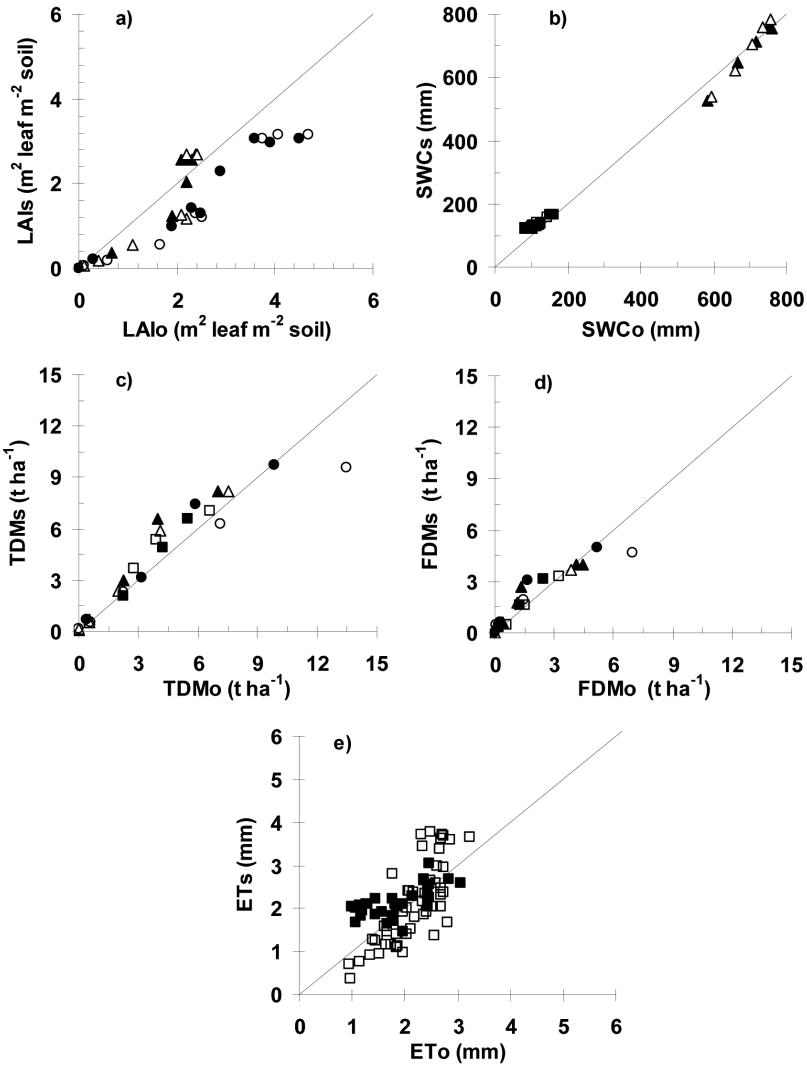


Figure 3 - Comparison of observed (o) and simulated (s) values of a) leaf area index (LAI), b) total soil water content (SWC), c) total dry matter (TDM), d) fruit dry matter (FDM) and e) vine evapotranspiration (ET).

Square symbols represent the Chilean site (PV), and triangles and circles represent the non-irrigated (MNI) and irrigated (MI) treatments in France, respectively. Solid and open symbols represent the 2004/05 and 2005/06 seasons, respectively.

substantially differ between the PV and MNI treatments (figure 4).

Regarding evapotranspiration, the simulated values were compared with the ET values measured in the PV experiment (figure 3e). In general, the daily ET values were distributed around the 1:1 line and the growing season time-course was correctly simulated by the STICS model throughout the two seasons (figure 5). However, the statistical indicators were not as good as the other simulated variables (table 4).

3. Water stress

The *swfac* index decreased when the FTSW value was close to 0.4 (figure 6). In the same way, the *swfac* index decreased for predawn leaf water potential (ψ_{pdl}) values lower than -0.3 MPa and midday stem water potential (ψ_{mds}) values under -0.6 MPa. Sibille *et al.* (2007) reported threshold values of -0.2 to -0.4 MPa for ψ_{pdl} and -0.5 to -0.8 MPa for ψ_{mds} in vines with moderate water stress. These latter values confirm the good performance of STICS in predicting the initiation of water stress. The *turfac* index also decreased under similar threshold FTSW and water potential values, yet with a steeper slope. For high water stresses (i.e. FTSW values below 0.20 and ψ_{pdl} and ψ_{mds} lower than -0.6 and -1.1 MPa), the two water stress indices of the model stabilized, and leaf growth simulation was reduced by about 50 % of the potential leaf growth (without water stress).

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4. Growth and yield

The STICS model provided good simulations of total and fruit dry mass for the pooled data (table 4). The model efficiency and R^2 values were higher than 0.85 for both variables, but the RRMSE values were higher for fruit dry biomass than for the total dry biomass estimation. The bias value indicated a small overestimation of both variables, mainly for the intermediate values (figure 3c and 3d, figure 4). Comparing both sites individually, statistical indicators for model performance show no important differences (table 4). Generally, the grapevine growth dynamics were well simulated by the model in the PV and MNI treatments for both years. In the MI treatment, a good simulation was obtained in 2005 but not in 2006 when the total and fruit dry biomass were underestimated at harvest (figure 4).

The performance of the STICS model to simulate LAI in the M experiment was lower than that obtained for the other variables (table 4). Figure 7 reveals a delay in the simulated LAI growth in relation to the observed data between budburst and two weeks before veraison in MNI. In spite of this delay, the simulated maximum LAI matched the observed values. In the MI experiment, underestimations were obtained for all seasons, which could partially explain the underestimation of biomass production during the 2006 season.

Regarding yield, the STICS model provided a correct estimation of grape yield (table 5) in all conditions, even though a slight overestimation was noted. The prediction of the number of berries per unit area and single berry weight were slightly better for the PV experiments than for the MNI and MI treatments. For both experiments in Montpellier, an underestimation of berry number and an overestimation of berry weight were obtained. In the PV experiment, the values estimated for the two last variables were within the 5 % confidence interval with respect to the observed values.

DISCUSSION

1. Grapevine phenology and harvest date

A good simulation of the grapevine phenology and harvest date is important, as it affects the timing of both water uptake and growth. The prediction error for the development stages was generally lower than half a week, which is interesting with respect to the usefulness of the model to predict phenological stages in a climate change context. In Europe, observed drifts in phenological

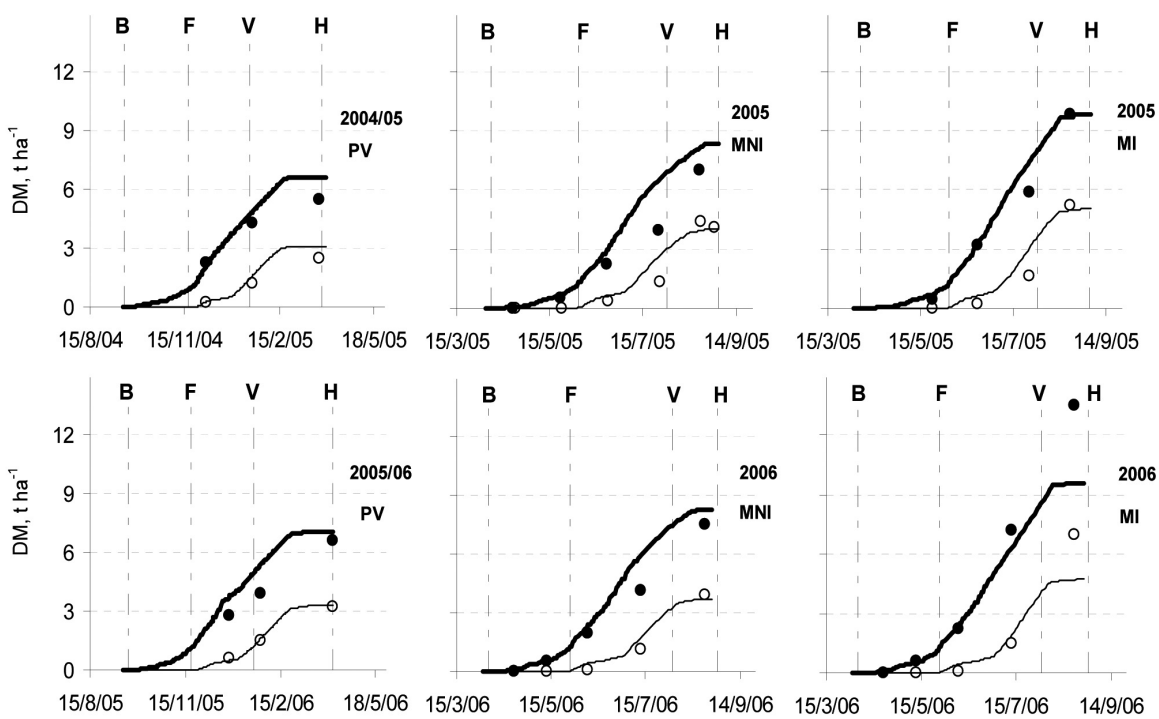


Figure 4 - Total (bold line) and fruit (thin line) dry matter (DM) simulated with the STICS model.
Solid and open symbols are the observed values of total dry matter and fruit dry matter, respectively. Vertical dotted lines represent the main grapevine phenology stages (B: budbreak; F: flowering; V: veraison and H: harvest). PV is the irrigated site in Chile; MNI and MI are the non-irrigated and irrigated treatments in France, respectively.

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timing have been from 6 to 18 days over the last two or three decades (Duchene and Schneider, 2005; Jones *et al.*, 2005) and changes of the same extent are expected over the next decades (García de Cortázar-Atauri, 2006). The good phenology and harvest date simulations could be explained by the form in that STICS calculates it. Budburst is predicted by using the BRIN model, which takes dormancy and post-dormancy periods into account (García de Cortázar-Atauri *et al.*, 2009). The following phenological stages are calculated using the thermal time concept (growing degree days – GDD) (Bonhomme, 2000). For the harvest time estimation, the model simulates sugar content dynamics using two components, one of which relates to the berry phenological stage (in

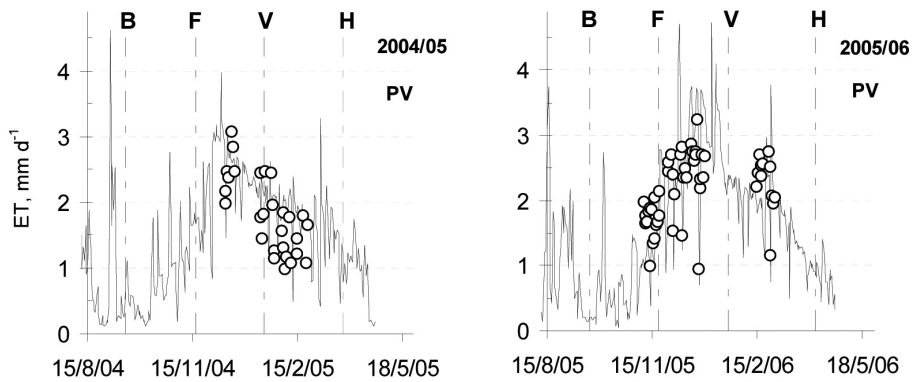


Figure 5 - Daily time-course of evapotranspiration (ET) observed (open circles) and simulated by the STICS model (line) on the PV experiment.
Vertical dotted lines represent the main grapevine phenology stages (B: budbreak; F: flowering; V: veraison and H: harvest).

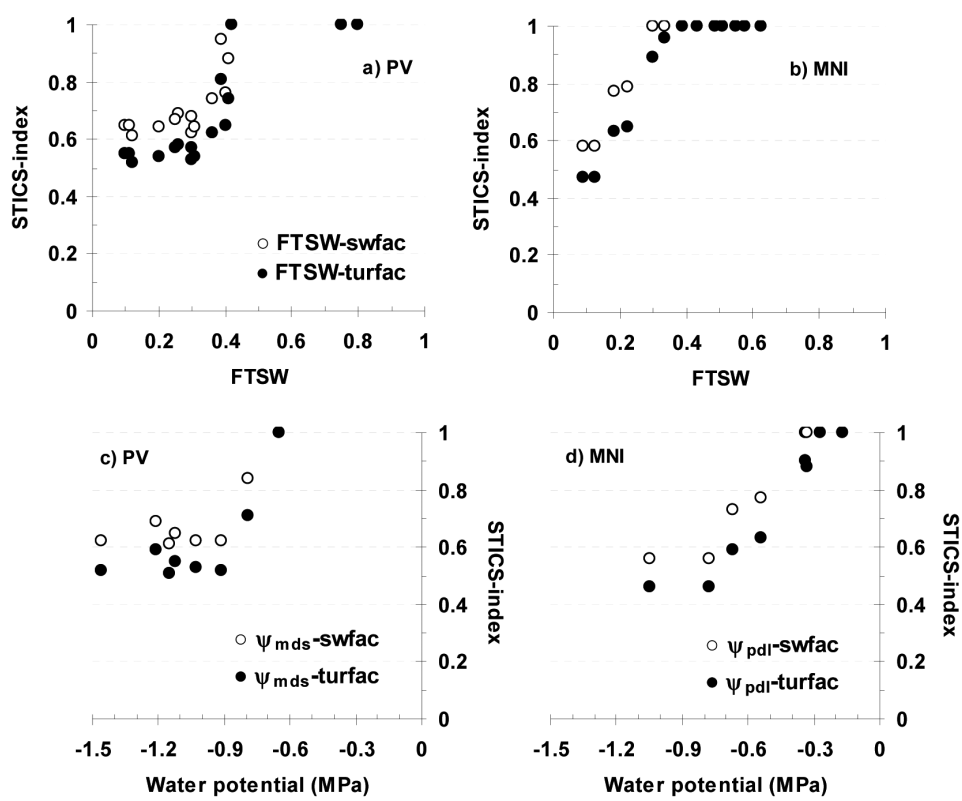


Figure 6 - Relationships between indicators of water restriction (fraction of transpirable soil water FTSW) and water potential (predawn, ψ_{pdl} and stem, ψ_{mds}) versus the STICS indices of water stress (*swfac* and *turfac*).
Data for Pencahue (PV) and Montpellier non-irrigated (MNI) experiments. STICS indices are dimensionless.

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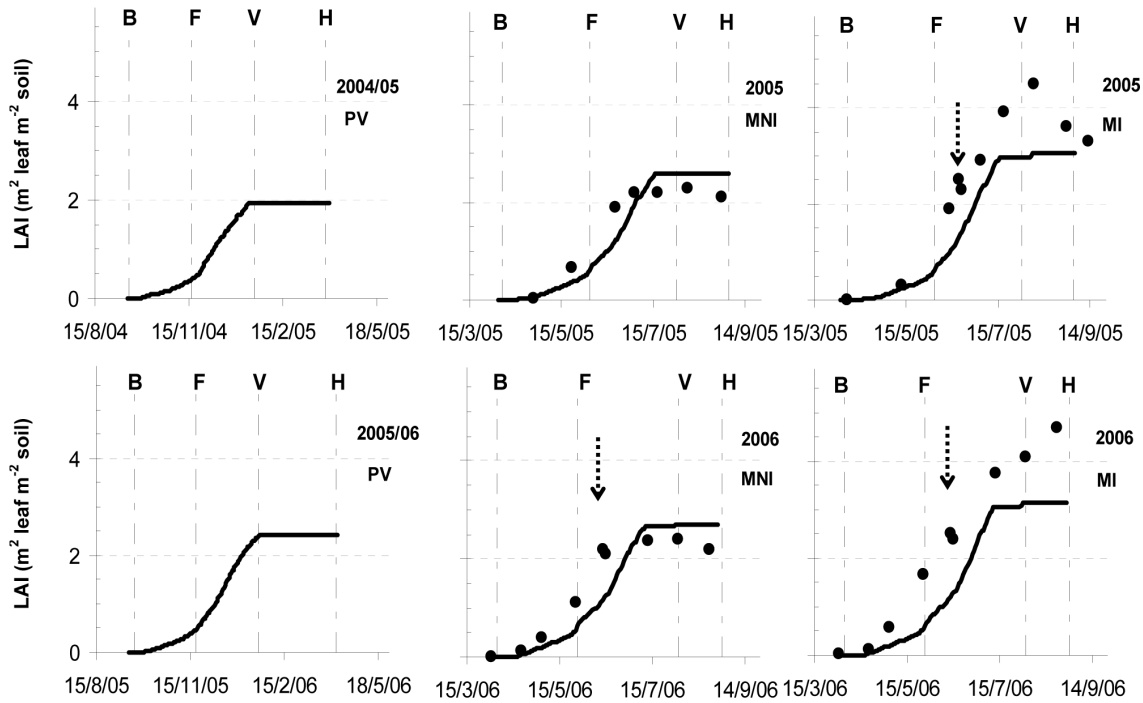


Figure 7 - Simulated (line) and observed (solid symbols) values of grapevine leaf area index (LAI).
Vertical dotted lines represent the main grapevine phenology stages (B: budbreak; F: flowering; V: veraison and H: harvest). Dotted arrows represent trimming dates. PV is the irrigated site in Chile; MI and MNI are the irrigated and non-irrigated treatments in France, respectively.

days) and the other depends on the water status of the plant (expressed as the difference between the crop temperature estimated by the STICS model and the air temperature). Then all phenological stages (except the harvest date, which relates to the maturity stage required by the grape grower) are directly connected to climate. In this case water and nitrogen balances have little influence on this process.

2. Soil water content and water distribution

Total soil water content was well simulated by the model at both experimental sites. However, it is necessary to take into account the possibility of error compensation among components of the water balance. In this respect, the different experimental situations at Pencahue valley and Montpellier were complementary for evaluating whether the grapevine water soil content simulated by the STICS model was offset by a bias in other water balance components. In both situations, water flux to deeper soil layers than the rooting zone was neglected. At PV, a compacted soil layer below the root zone limited vertical water flux. At Montpellier, the measurements of soil moisture (obtained with a neutron probe), soil water matrix potential and soil physical properties indicated that drainage as well as capillary rise of water were not significant over 3 m depth (Celette *et al.*, 2008). Drip irrigation and precipitation were measured and used as model inputs. Surface runoff was neglected on the PV because there was no rain during the grapevine growing period. At Montpellier, little runoff was measured during the vine growing period (Celette *et al.*, 2008) because of the low rainfall intensity and frequency (there were only two days with precipitations greater than 20 mm in 2005 and none in 2006). Vine evapotranspiration measured only at Pencahue Valley was satisfactorily simulated by the STICS model for both seasons as indicated by a relative root mean square error less than 30 % and a significant linear relation (0.43). Therefore no bias was detected in total soil water content due to any other water balance components.

Concerning to water distribution in the soil, various hypotheses could explain the previously mentioned overestimation of water content until 0.6 m depth and the underestimation below this level (in the Montpellier experiment). This could have been due to an imprecise estimation of the evaporation/transpiration ratio or of the surface infiltration-soil evaporation ratio. The latter flux is substantial in vineyards as most of the soil surface is bare. The poor simulation of water content in the upper soil layer could also have been due to an underestimation of the soil water flux from the upper to the deeper layers. In the model, following the tipping bucket approach, this flux occurs only when the surface soil layer is at field capacity, which rarely occurred in the non-irrigated

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Table 5 - Observed (O) and Simulated (S) yield and yield components values (mean ±. Student confidence intervals at 95% (C.I.)).

	Yield (t.ha^{-1})		Berry number m^{-2}		Berry weight (g)	
	O ± C.I.	S	O ± C.I.	S	O ± C.I.	S
2004/05						
PV†	9.7 ± 1.0	12.3	820 ± 233	1059	1.10 ± 0.10	1.16
MI	17.3 ± 1.7	18.6	1204 ± 202	1006	1.37 ± 0.06	1.84
MNI	14.3 ± 0.9	14.8	1385 ± 186	988	1.17 ± 0.06	1.49
2005/06						
PV	12.0 ± 2.1	13.1	1196 ± 147	1142	1.00 ± 0.17	1.14
MI	16.3 ± 0.4	17.4	1479 ± 223	1015	1.45 ± 0.05	1.71
MNI	12.3 ± 0.3	13.5	1327 ± 158	1001	1.32 ± 0.06	1.35

†PV was the irrigated site in Chile; MI and MNI were the irrigated and non-irrigated treatments, respectively, in France.

treatment because of the high soil evaporation and low rainfall frequency. This bias in the simulation of the water distribution in the soil profile has little impact with respect to modelling the total soil water content, but it is crucial for the prediction of the nitrogen balance, as nitrogen mineralization takes place, in general, in the upper soil layer as shown by Celette *et al.* (2009).

3. Water stress and grapevine growth and yield

Seasonal variations in water restriction on the PV and MNI experiments followed a pattern that is common in balanced vineyards producing good quality wines (Pellegrino *et al.*, 2006). FTSW values were above 0.6 close to budburst, equal to 0.4 close to flowering and 0.1-0.2 around harvest. Pellegrino (2003) and Pellegrino *et al.* (2005) indicated that the first value does not limit growth processes or gas exchanges. With FTSW values lower than 0.4, the same authors showed that grapevine leaf growth (leaf number and area) is limited whereas net assimilation rate is not. Results for the *swfac* evolution in moderate water stress conditions showed us that this index controlled properly gas exchanges. For high water stresses, leaf growth was reduced in the model only by about 50 % of the potential leaf growth, which is not correct in field conditions because many authors have observed that leaf growth and gas exchange almost stop under high water stress (Intrigliolo and Castel, 2006; Patakas *et al.*, 2005; Pellegrino *et al.*, 2006). This model behaviour could explain the discrepancies noted between the simulated and observed yield and its components. The berry weight overestimation was the result of the underestimation of moderate water stress simulated by STICS after veraison. In other words, water flow to the berry would be overestimated by the model which would result in a yield overestimation.

The STICS model underestimated LAI between budburst and near veraison in the Montpellier non-irrigated and irrigated experiments. However, after veraison, LAI was correctly estimated in the MNI treatment. The initial underestimation did not significantly affect the final estimation of total and fruit biomass production, particularly in the MNI experiment. This could be explained by the fact that LAI was higher than 2.0 and thus a high proportion of incident radiation could be intercepted. At Montpellier, LAI was also underestimated in the irrigated experiment after veraison and to a larger extent in 2006. This could explain why biomass production was largely underestimated. Poor estimates of LAI noted in the MI experiment could have been associated with the assumption made in the STICS model that grapevine leaf growth stops after veraison (García de Cortázar-Atauri, 2006). This would apply in balanced commercial vineyards, but when water, nutrition and thermal conditions are favourable (as in the MI experiment) grapevine growth is almost continuous (Huglin and Schneider, 1998). The STICS model was parameterized in commercial grapevine growing conditions with a maximal dry biomass production of 11 T ha^{-1}, so values higher than this threshold could not be simulated by the model in the MI experiment in 2006. The very high levels of water and nitrogen application for MI in 2006 produced vines that were beyond the usual growth state range, which could explain the poor quality of the simulations in this situation.

CONCLUSION

The STICS model provided good simulations of the grapevine phenology, growth and soil water content for the irrigated and non-irrigated vineyards studied in France and Chile. This is interesting because the model has been

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parameterised and used for vineyards without irrigation and with little nitrogen fertilisation, so the results of this study highlight the robustness of the model with respect to adapting to new situations.

The comparison of water stress indices calculated by the STICS model with water stress indicators measured in the field (FTSW and plant water potential) indicated that the water stress period was correctly estimated. Although the modelling of water stress during the harvest period was imperfect, the good estimation of water stress initiation and grapevine phenology could be interesting with respect to potentially using the STICS model to identify critical water management periods for the system. If the model was used for irrigation management according to planned water stress patterns, it could allow users to estimate grapevine water requirements under different soil and climate conditions, including climate change scenarios, and to define regional water policies such as maximal cropping area in relation to regional water resources.

The STICS model was reasonably successful in simulating grape yield and their components at both locations. This provides an opportunity to study different water management strategies and their impacts on grape production in relation to production objectives.

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