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Impact of training system, soil management and soil water holding capacity on vine water status in a changing climate over 60 years in the Cognac production area

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ABSTRACT

This study investigates the impact of vine training systems on water deficits in the Cognac region (France), through the application of a vine water balance model, taking into account different soil water holding capacities (SWHC) and soil management strategies, including grass cover. Using climate data from the SAFRAN gridded database, over 2 million simulations were performed for the period 1962 to 2021 to quantify the response of grapevine water status under varying training systems and environmental conditions. Indices based on simulated relative stomatal conductance were developed to characterise the intensity of grapevine water deficit during the critical flowering-to-maturity period.

Results show a significant trend of increasing water deficit between 1962 and 2021, particularly in the north-western part of the region, affecting 23 % of the Cognac production area. Sensitivity analysis of the water balance model indicates that SWHC is the predominant factor influencing grapevine water status, explaining nearly 80 % of the variance in water deficit days. The simulations further suggest that adjustments in canopy width and grass cover have a significant effect on the duration and severity of water deficit.

The methodology developed in this research allows quantifying the relative importance of major drivers of vine water deficits: SWHC, training system parameters and vineyard floor management, under different climatic conditions. It can be used as a basis for providing easy-to-implement vineyard management strategies to mitigate the effects of climate change in viticulture. It was applied to the Cognac region, but the workflow developed is applicable to any grape-growing region in the world.

KEYWORDS: Terroir 2024, grapevine, water status, modelling, sensitivity analysis, FTSW, climate change

INTRODUCTION

The Cognac vineyard region stands as France's foremost producing area planted with white grapes, encompassing nearly 87,000 hectares. Dominated by the Ugni blanc grape variety, which covers 98 % of the area, this region is acknowledged for producing Cognac (https://www.cognac.fr), an oak-barrel-aged wine brandy with protected origin. The region's terroirs, which are recognised for producing spirits with particular characteristics, are identified using a classification encompassing 6 Crus (Bernard, 1980). The base wines for high-quality Cognac must be low in alcohol and high in acidity. Because the distillation process results in a 90 % decrease in volume, high yields are mandatory to achieve economic profitability.

In the context of climate change, no significant changes in rainfall patterns have been observed in mainland France (Terray and Boé, 2013). However, rising temperatures have led to higher evapotranspiration rates, increasing the risk of drought. Similar to all agricultural crops, increased water deficits typically lead to reduced yields in vineyards (Gambetta *et al*., 2020). Numerous studies have shown that vine water status affects not only yield but also the concentration of sugars, as well as aromatic and phenolic compounds, which are critical for grape and wine quality (van Leeuwen *et al*., 2009; van Leeuwen *et al*., 2020). Climate change projections indicate trends towards increased warming and drying (IPCC, 2022), prompting extensive research to understand the effects of water deficit on vine performance in vineyards planted both in arid and more humid regions (Mirás-Avalos and Araujo, 2021).

In the Cognac region, which is characterised by a temperate climate with an oceanic influence, the idea that water deficits may possibly lead to the need for implementing irrigation is not intuitive, especially in a vineyard traditionally managed under rain-fed conditions. Nevertheless, this question may arise, because high yields are mandatory to reach profitability in Cognac production and they can be achieved by minimising water deficits during critical periods for the construction of yield components. However, the use of water for vineyard irrigation raises concerns about environmental sustainability, as it involves the extraction of water from rivers or aquifers, competing with other essential human uses (Hoekstra and Mekonnen, 2012). Climate change is expected to exacerbate these challenges by reducing freshwater availability (Grafton *et al*., 2013; Tramblay *et al*., 2020). Nevertheless, it is also possible to limit vine water deficits through cultural practices, including both modulating the architecture of vines and soil management practices and hence avoiding the need for irrigation (Buesa *et al*., 2021; Costa *et al*., 2016; Neupane and Guo, 2019).

The water balance of vineyards is influenced by several factors: (i) climate-related water availability, *i.e*., precipitation and evaporative demand; (ii) soil water holding capacity (SWHC) determined by rooting depth, soil texture, the proportion of coarse elements, bulk density and soil organic matter content; (iii) exposed leaf area, which affects plant transpiration and varies according to the vineyard training system (Reynolds and Vanden Heuvel, 2009); (iv) direct water evaporation from soil surface and water use by cover crop (Celette *et al*., 2010).

Physical experiments comparing different vineyard training systems, including soil-climate interactions, are challenging and expensive (Hunter, 1998a; Hunter, 1998b). Such trials require data acquisition over multiple years and the results may be valid for site-specific soil and climate conditions and are not always easy to extrapolate (Hunter *et al*., 2020). Numerical simulations offer a practical alternative, allowing the effects of vineyard architecture to be considered over much larger spatial and temporal scales. Using well-established models, simulations can identify key trends and assess the impact of different parameters on key output variables.

Several types of models have been used to characterise water deficit in grapevine such as empirical models using machine learning (Brillante *et al*., 2016), functional-structural plant models (Zhu *et al*., 2018), generic soil-crop models such as STICS (Valdés-Gómez *et al*., 2009) or soil water balance models (Gaudin *et al*., 2014). Lebon's soil water model (Lebon *et al*., 2003) was selected for this study due to its minimal data requirements for both climatic and training system parameters. Its simplicity and relatively low computational cost enable its application at a regional spatial scale over an extended period, facilitating the introduction of variations in training system parameters and grass cover percentage.

This model has been calibrated and validated in both warm and moderately dry (Languedoc, southern France; Pellegrino *et al*., 2006) and cool to temperate sub-humid environments (Alsace, northern France; Lebon *et al*., 2003).

This study aims to assess the influence of different vine training systems and soil management practices on water deficits in the Cognac region between 1962 and 2021. Using Lebon's soil water model, we calculated annual indicators such as the number of days with moderate and severe water deficits during the simulated yield-critical phenological phases of the grapevine. These calculations included a range of canopy management practices, different soil water holding capacities (SWHC), accounting for the local diversity of soils present in the region, and soil management strategies such as grass cover, to compare their effects on vine water status with those resulting from the effects of the training system parameters.

MATERIALS AND METHODS

Grapevine soil–water balance was modelled using Lebon's soil-water model (Lebon *et al*., 2003), integrating solar radiation interception by leaf canopy based on the simple geometric canopy model by Riou *et al*. (1989). The Lebon model is specifically designed for vineyards with vertical shoot positioning training systems (VSP) and includes a detailed soil–water balance routine that separates the transpiration from grapevines (Tv) and evaporation from bare soil (Es). We added a module of cover-crop transpiration

(Tcc). Each day *i*, the water balance model calculates available soil water (ASW) as:

$$ASW_i = ASW_{i-1} + RR_i - Tv_i - ES_i - Tcc_i \ [1]$$

where RR is the daily precipitation amount.

Grapevine transpiration *Tv* at day *i* is calculated as:

$$Tv_i = k_i \cdot \frac{gs_i}{gsmax} \cdot ET_{0i} \ [2]$$

where k_i is the fraction of incoming solar radiation intercepted by the row estimated from Riou *et al.* (1989) model, ET_0 is the reference evapotranspiration, gs/gsmax is the relative stomatal conductance of grapevine estimated from the fraction of transpirable soil water (FTSW) using the relationship described in Pieri and Gaudillere (2005):

$$\frac{gs}{gsmax} = 1 - e^{-5FTSW} - e^{-5} \ [3].$$

Bare soil evaporation Es is calculated in two stages, following a rainfall event. First, soil evaporation is governed by incoming solar radiation and evaporative demand of the atmosphere (*i.e.*, ET_0): soil evaporation is the product of ET_0 and the fraction of solar radiation that is not intercepted by the grapevine canopy, hence intercepted by the soil in the inter-row, *i.e.*, ($1-k_i$). Second, when cumulative soil evaporation reaches a threshold of 5 mm, top soil is considered as dry. Es is then reduced because of soil hydraulic resistance to evaporation (see Lebon *et al.*, 2003; Brisson and Perrier, 1991; for more details).

We introduced a cover-crop module which is a simplified version of the cover-crop module proposed by Celette *et al.* (2010). It partitions the inter-row water consumption by either bare soil or cover crop according to the proportion of inter-row covered by the cover crop rcc so that the inter-row evapotranspiration ET_i equals:

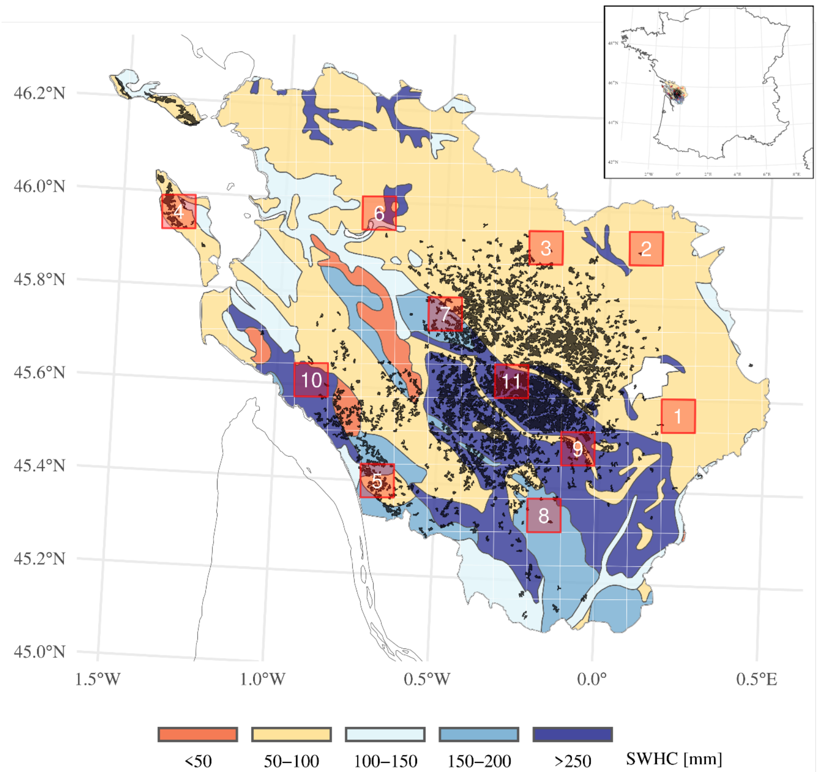
$$ET_i = (1 - rcc) \cdot Es_i + rcc \cdot Tcc_i \ [4]$$

where Es_i is the bare soil evaporation and Tcc_i is the cover crop transpiration estimated as:

$$Tcc_i = (1 - k_i) \cdot \frac{gs\prime_i}{gsmax\prime} \cdot ET_{0i} \ [5]$$

where gs'/gsmax' is calculated using the same relationship as used for the grapevine by Pieri and Gaudillère (2005) for grapevine, but by calculating FTSW with an SWHC of 30 mm for the cover crop. This value is rather low, as compared to measurements of Celette *et al.* (2008), who found for non-permanent intercrop an SWHC of approximately 60 mm. This choice was made to assume the selection of low-competitive grass covers.

The transpiration rate of the cover crop depends only on the water availability in the soil. We assumed that the LAI of the cover crop did not change during the year and therefore did not affect the transpiration rate of the cover crop. This simplistic assumption was made considering that the cover crop would be mowed frequently to control its development with the vineyard.



Pixel nb	SWHC [mm]	mGST [°C]	mGSP [mm]	Alt [m]
1	75	17.1	401	146
2	75	17.0	380	89
3	75	16.8	350	95
4	81	17.7	307	5
5	116	17.8	358	31
6	125	17.2	337	19
7	148	16.9	346	71
8	176	17.3	384	116
9	183	17.5	357	79
10	209	17.6	362	22
11	210	17.8	350	40

FIGURE 1. Vineyards of Cognac region identified with the Corine Land Cover database (black polygons) plotted over the French national soil water holding capacity (SWHC) map defined by classes (www.gissol.fr). The 11 selected pixels, representing the total variability of climate and SWHC conditions over the area, are marked in red. SWHC, average temperature and cumulative precipitation from April to September (mGST and mGSP, respectively) and elevation (Alt) for each of the selected grid cells are shown in the table on the right of the figure.

Inputs for the water balance model include reference evapotranspiration (ET_0), daily air temperatures for canopy development, solar radiation [to compute k_i, the rate of incoming solar radiation intercepted by grapevine rows, using the Riou *et al*. (1989) model and precipitation].

Reference evapotranspiration was calculated using the Hargreaves temperature method (Hargreaves and Samani, 1985). Solar radiation was estimated based on temperatures, using the model proposed by Hargreaves and Samani (1982). Daily minimum and maximum air temperatures, along with rainfall data were obtained from the SAFRAN (système d'analyse fournissant des renseignements adaptés à la nivologie) near-surface reanalysis data, provided by Météo-France (Soubeyroux *et al*., 2008). A part of this dataset, covering a grid with a resolution of 8 km from 1962 to 2021, has been extracted for the Cognac vineyard area, comprising 244 grid cells (Figure 1).

Canopy development in the model was simulated using a degree-day model starting after bud break, as described by equation 3 in Lebon *et al*. (2003). The canopy is modelled to expand from budburst until 10 days post-flowering, at which point growth is assumed to cease due to mechanical trimming.

For each year and every grid cell, the subsequent phenological stages were simulated. Three phenological models were used: the combination of the Smoothed-Utah model, which simulates dormancy break by accumulating chilling units, and the Wang and Engel model, which simulates the post-dormancy phase leading to budburst (Morales-Castilla *et al*., 2020); the GFV model for flowering (Parker *et al*., 2011); and a sugar ripeness model (GSR), parameterised to estimate the date when the grape sugar content reaches 170 g/L for the Ugni blanc cultivar (hereafter referred to as maturity; Parker *et al*., 2020).

To assess the sensitivity and response of the model to different SWHCs and different viticultural practices (such as soil cover management and training systems), several input parameters were set to different values. In the canopy development simulations, five input parameters were adjusted to reflect the diversity of training systems in the region: row spacing (2, 2.7 and 3 m), canopy height (0.9, 1.2 and 1.5 m), canopy width (0.5, 1 and 1.5 m), canopy porosity (5, 12 and 20 %) and row azimuth (0, 45 and 90 degrees). Soil management diversity was represented by three levels of grass cover (0, 35 and 70 %), which are common in the region. SWHC values were obtained by averaging each class from the French national soil map (www.gissol.fr), weighted according to the area of each SAFRAN grid cell (Figure 1). In addition, to capture the spatial and temporal evolution of the water deficit in relation to climatic conditions, three fixed SWHC values were also tested: 75, 150 and 250 mm.

A flowchart detailing the complete modelling chain used in this work is shown in Figure 2. All models and simulations were coded and run using R software. Every possible combination of different input parameters was simulated, resulting in a total of 5,000 runs per year for a single grid point. These calculations were performed on the University of Burgundy's computing centre, using 64 processors in parallel. The analyses of all simulations, considering all possible combinations, were performed on 11 grid points, from 1962 to 2021, selected to represent the diversity of the region in terms of average SWHC, climatic conditions (temperature and rainfall during the growing season) and altitude (Figure 1). Based on the analysis of the results from

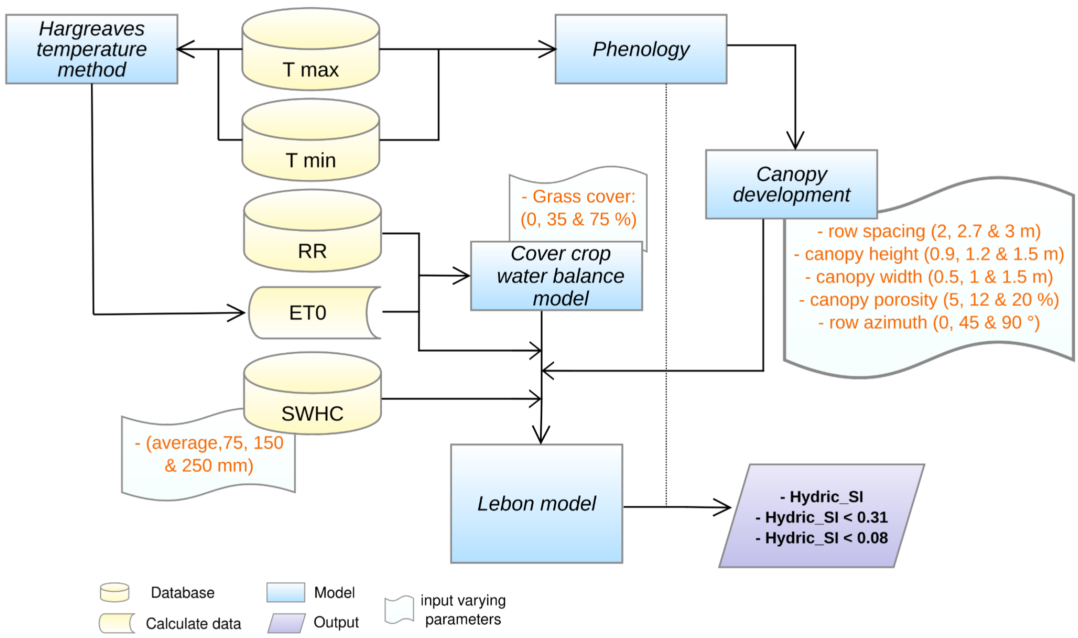


FIGURE 2. Flowchart characterising the modelling steps with the different input parameters in orange (the values taken by these parameters are then written between brackets). T max = daily maximum temperatures (°C); T min = daily minimum temperatures (°C); RR = mainfall (mm); ET0 = reference evapotranspiration (mm); SWHC = soil water holding capacity.

these 11 grid points, three combinations of parameters related to canopy development were selected to represent cropping systems with typically low, medium and high-water deficits. These combinations were then used to run simulations over the entire region (244 grid points).

To quantify the intensity of water deficit, we used relative stomatal conductance as an indicator of grapevine water deficit, following threshold values. These values were scaled using the classification proposed by van Leeuwen *et al*. (2009). In this classification, grapevine water status is assessed according to physiological indicators, such as leaf water potentials and grape juice δ^{13}C. To retrieve the relative stomatal conductance corresponding to each threshold of this classification, we first used the relationships between predawn leaf water potential and FTSW (see Figure 3 in: Lebon *et al*., 2003). Then, the conversion of FTSW in relative stomatal conductance was based using equation 3 (see above). FTSW and relative stomatal conductance thresholds of each water deficit class are shown in Table 1.

Based on the relative stomatal conductance (gs/gsmax) thresholds identified in Table 1, three indices were calculated from the daily outputs using the simulated phenological stages (from flowering to maturity) to represent grapevine water deficit. These indices are (i) the average relative stomatal conductance between flowering and maturity (Hydric_SI), (ii) the number of days with at least moderate water deficit between flowering and maturity with relative stomatal conductance below 0.31 (Hydric_SI < 0.31), and (iii) the number of days with severe water deficit between flowering and maturity (Hydric_SI < 0.08). The evolution of the flowering-to-maturity period length, as well as the average temperature and cumulative precipitation during this period, were also examined.

To assess the impact of climate change on these indices, the slope of the linear trend line for the various parameters between 1962 and 2021 was plotted and analysed. This slope is referred to as the ‘trend’ in this article. In addition, the indices were averaged over the last 30 years (1992–2021) to indicate the absolute values for the pixels studied. A linear mixed effects model (LMM) was used to analyse the contribution of different training system parameters to the simulation of water deficit. This analysis was performed using the *varpart* function from the *vegan* package in R (Borcarde *et al*., 1992; Oksanen *et al*., 2013).

RESULTS

1. Training system and soil management effect

The temporal evolution of the number of days with at least moderate water deficit during the flowering-maturity period from 1962 to 2021 is highly variable according to SWHC, grass cover and training system parameters (Figure 3). In this figure, separate columns represent soil management practices (grass cover percentages of 0 %, 35 % and 70 %). For each grid cell (lines), the simulations are run with the specific local SWHC and climatic conditions. For each grid cell and grass cover combination, 423 simulations were run to assess the effect of the vineyard training system, by modifying the five parameters incorporated into the model. Based on the simulations conducted, we identified (i) a training system that exhibits the lowest average simulated water deficit, characterised by reduced exposed leaf area (minimal canopy height and width), wide row spacing, and moderate to high canopy porosity, aligned east-west (row azimuth of 90°; depicted by the green curve in Figure 3); (ii) a training system that exhibits the highest average simulated water deficit, marked by a large exposed leaf area (maximal canopy height and width), close row spacing, and moderate to low canopy porosity, oriented north-south (row azimuth of 0°; represented by the red curve in Figure 3); (iii) an intermediate training system that assumed central values for the parameters, representative of the majority of training systems currently used in the region (canopy height = 1.2 m, canopy width = 0.7 m, row spacing = 2.7 m, canopy porosity = 12 %, row azimuth = 0°; black curve in Figure 3).

When averaging the index over the whole period (1962–2021) for each of the simulations in each panel of Figure 3,

TABLE 1. Relative stomatal conductance and fraction of transpirable soil water (FTSW) estimated from the relationship between predawn leaf water potential and FTSW according to Lebon *et al*. (2003) and the FTSW/relative stomatal conductance relationship according to equation 2 (see Pieri and Gaudillère, 2005). Midday stem water potential, midday leaf water potential, pre-dawn leaf water potential and δ^{13}C thresholds are sourced from van Leeuwen *et al*. (2009).

	Midday Stem Water Potential [Mpa]	Midday Leaf Water Potential [Mpa]	Pre-dawn Leaf Water Potential [Mpa]	δ^{13}C	FTSW	Relative Stomatal Conductance
No water deficit	0	0	0	-29	100 %	1.0
Weak water deficit	-0.6	-0.9	-0.2	-26	36 %	0.84
Moderate to weak water deficit	-0.9	-1.1	-0.3	-24.5	21 %	0.66
Severe water deficit	-1.4	-1.4	-0.8	-21.5	1 %	0.08

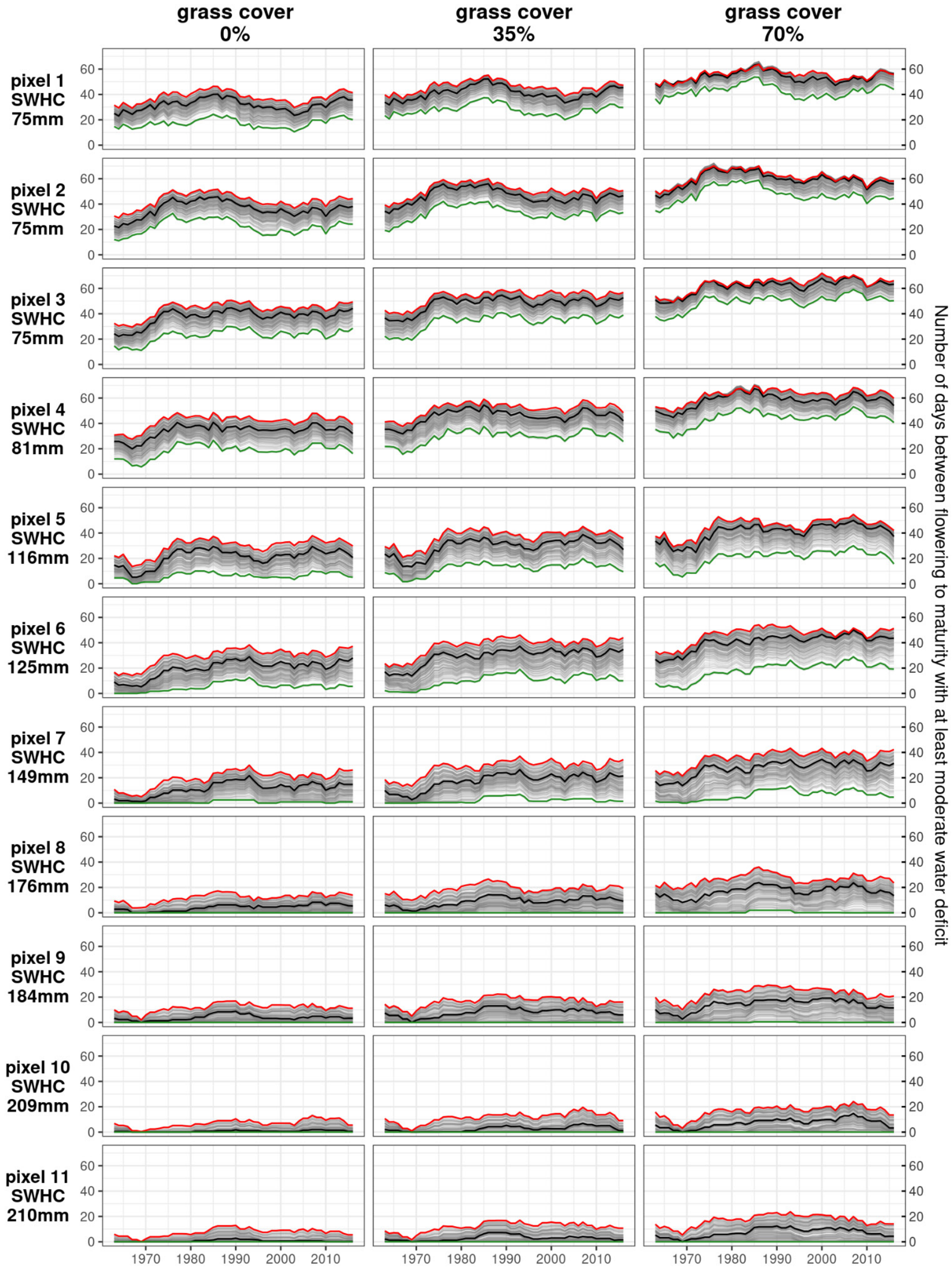


FIGURE 3. Ten-year moving average evolution of the simulated number of days with at least moderate water deficit (Hydric_SI < 0.31) in the Cognac production area for a wide range of vineyard training systems and floor management conditions. This figure illustrates the trends across 11 grid cells, selected for representing soil water holding capacity (SWHC) ranging from 75 to 210 mm, under three different grass cover scenarios (0 %, 35 %, and 70 %). Each plot contains 423 curves representing the simulation runs based on all tested vineyard training system parameters. The black curve depicts the median scenario representing a commonly used training system in the area (canopy height = 1.2 m, canopy widt = 0.7 m, row spacing = 2.7 m, canopy porosity = 12 %, row azimuth = 0°). The red curve indicates a training system with greater water use, resulting from a larger exposed leaf area (ELA; canopy height = 1.5 m, canopy width = 1 m, row spacing = 2.5 m, canopy porosity = 12 %, row azimuth = 0°), leading to more frequent water deficits. In contrast, the green curve reflects a management system designed to reduce ELA and thus water deficit (canopy height = 0.9 m, canopy width = 0.5 m, row spacing = 3 m, canopy porosity = 20 %, row azimuth = 90°).

TABLE 2. Average (last 30 years: 1992 to 2021) and trend (based on the linear trend over the period 1962–2021) of the different modelled indicators for quantifying the intensity and frequency of water deficit for each of the 11 pixels studied. The FM period corresponds to the duration of days between flowering and maturity; the increase in HydricSI is calculated as a percentage, with reference to its average value over the entire study period. Moderate and severe water stress refers to the number of days between flowering and maturity when each of these levels of water deficit is observed. The percentages in brackets refer to the fraction of simulations showing a significant change, also identified with * (when at least one simulation shows a significant evolution).

Pixel	FMperiod (1992-2021) [nb days]	Decrease FM (1962-2021) [nb days]	Increase HydricSI (1962-2021) [%]	Moderate stress (1992-2021) [nb days]	Increase moderate stress (1962-2021) [nb days]	Severe stress (1992-2021) [nb days]	Increase severe stress (1962-2021) [nb days]
1	106	-11.3 *	+14.4 (0%)	40.8 ± 9.2	+3.8 (0%)	25.9 ± 6.8	+5.3 (0%)
2	106	-9.1 *	+16.5 (0%)	45.2 ± 9.4	+5.9 (0%)	29 ± 7.7	+7 (0%)
3	108	-6.5 *	+29.6 (81%) *	50.6 ± 10	+13.2 (25%) *	33.2 ± 7.8	+13.1 (55%) *
4	103	-8.9 *	+20.1 (0%)	46.3 ± 10.6	+6 (0%)	29.7 ± 8.2	+9.5 (0%)
5	103	-7.8 *	+16 (0%)	31.2 ± 10	+8.1 (0%)	14.9 ± 6.3	+6.6 (0%)
6	106	-6.5 *	+26.6 (100%) *	33.8 ± 10.5	+17.1 (96%) *	16.4 ± 7.3	+13 (98%) *
7	107	-6.3 *	+19.8 (96%) *	23.2 ± 10.5	+13.7 (78%) *	8.6 ± 5.6	+8.3 (82%) *
8	105	-9.1 *	+2.7 (0%)	12.3 ± 7.7	+4 (0%)	3.4 ± 3.2	+2.7 (1%) *
9	104	-10.4 *	+2.2 (0%)	10.8 ± 7.7	+2.6 (0%)	2.3 ± 2.7	+1.6 (0%)
10	104	-5.4 *	+2.5 (0%)	7 ± 6.1	+2.1 (0%)	1 ± 1.6	+0.9 (0%)
11	102	-9.7 *	+1.3 (0%)	6.8 ± 6.2	+2.2 (0%)	0.9 ± 1.4	+0.8 (0%)

and after calculating the standard deviation of these values, it is observed that pixels with low SWHC (pixels 1 to 4, < 100 mm) have lower standard deviations (between 3 and 4 days of moderate-to-severe or severe water deficit) than pixels with SWHC greater than 116 mm (between 5 and 7 days). Simulated vine water status is more sensitive to training system parameters when SWHC is high, in contrast to soils with low SWHC where these parameters have a smaller effect. For grid cells with SWHC higher than 176 mm, the water deficit is low, regardless of the training system and vineyard floor management practices implemented. By adopting specific training system parameters, the simulations show that the number of days with at least moderate water deficit between flowering and maturity can be reduced to zero over the entire period studied for these soils.

Regardless of the SWHC values, a consistent pattern of increased water deficit is observed with higher grass cover percentages. On average, when the percentage of grass cover expands from 0 % to 70 %, there is an increase of 22 to 24 days for pixels 1 to 4 (SWHC < 100 mm), 14 to 19 days for pixels 5 to 7 and less than 10 days for pixels 8 to 11 (SWHC > 175 mm; Figure 3).

2. Temporal evolution

For each of the 11 pixels, the evolution over the study period of the different indicators related to the intensity of water deficit simulated by the model was analysed, independently of the combinations of training systems and grass cover. The long-term trend from 1962 to 2021 and the average over the recent period (1992–2021) of the flowering to maturity period and vine water status indicators are summarised in Table 2. Of the 11 pixels, pixels 6 and 7 showed large and significant changes in all water deficit indicators, leading to increased water deficits in the 1962–2021 period in the vast majority of combinations (between 78 and 100 %; combinations including SWHC, management system and grass cover). Pixel 3 also showed significant changes but with less convergence between the scenarios tested (between 25 to 81 %).

Considering the effect of the simulated combinations of training system and grass cover on three levels of water deficit with fixed canopy management parameters (medium, high and low, represented by the black, green and red curves in Figure 3, respectively) at a regional scale, a significant increase in water deficit over the 1962–2021 period was observed in one zone of the region. Figure 4A shows the evolution of the HydricSI indicator linearly interpolated over the study period, assuming a SWHC of 150 mm. Of the 244 pixels analysed, 57 (representing 23 %), all located in the north-western zone of the region show a significant increase in the index. Pixels 3, 6 and 7 (Table 2) fall within this zone. This trend is also reflected in the simulations with a SWHC of 75 and 250 m, as well as in the averaged value from the map (Figure S1).

The simulated duration from flowering to maturity decreased significantly for all selected pixels (Table 2), as well as on a regional scale (Figure S2). At this scale, the decrease is between 13 and 5 days, with a mean of 8.5 days, resulting in an average duration of 105 days for the region over the period 1992–2021. This decrease in duration is the result of a significant increase in temperature over the period. An

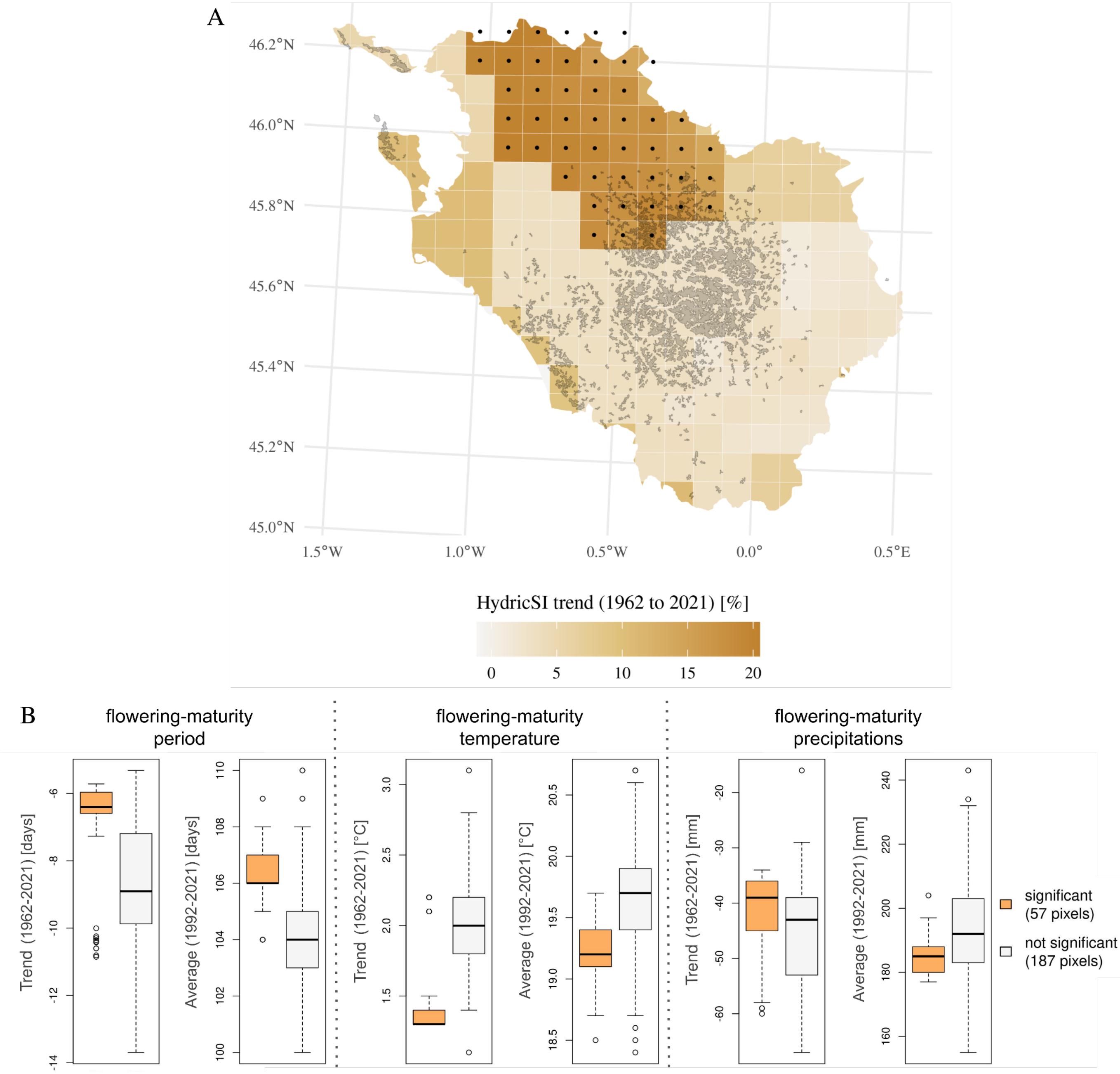


FIGURE 4. A) Trend in the intensity of water deficit from 1962 to 2021. The percentage for each pixel is based on the average increase observed from 1962 to 2021 of the HydricSI (Average of modelled relative stomatal conductance between flowering to maturity). Black dots in the pixels indicate a significant trend. Grey polygons represent vineyards. B) Linear trend from 1962 to 2021 and average values over the last 30 years (1992–2021) of flowering-to-maturity duration (days), average temperature and cumulative precipitation, separated by significant and non-significant pixels (refer to map in A).

average increase of 1.8 °C is observed at the regional scale, with variations ranging from +1.1 to +3.1 °C depending on the pixel. Although a decreasing trend in cumulative precipitation (between –16 and –67 mm) is observed over the region during this period (Figure S1), this trend is significant for only 3 pixels.

The duration of the flowering to maturity period has a strong influence on the number of days with water deficits: the longer this period, the higher the probability of water deficits. In the north-western zone of the production area, this period tends to shorten less due to a less pronounced increase in temperature (Figure 4B).

3. Contribution of training system and soil management

A linear mixed effect model (LMM) was used to analyse the contribution of different training system parameters to the simulation of water deficit, expressed in terms of the indices used as output variables. For each of the outputs of the water balance model, the contribution of the parameters was similar in magnitude. In this section, the results are the number of

TABLE 3. Partial variance in water deficit stress explained by the different parameters of the water balance model, using a linear mixed-effects model. This table presents the partial R^2 values indicating the proportion of the variance attributed to each of the fixed parameters, distinct from annual and spatial grid cell variations. In the three columns on the right part of the table, the median of the simulated number of days with severe water deficit between flowering to maturity is indicated for all runs with the value of the parameter under consideration fixed to each of the tree values defined in the experiment (low, medium and high; value shown directly under each parameter in the left column). The median is averaged across the 11 selected grid cells. The numerical range indicated by the ± values represents the maximum range between grid cell medians.

Parameters / input values	R^2 part	R^2 part (%)	Average number of days with sever water deficit		
			low	medium	high
SWHC 75 / 150 / 250 mm	0.3495	82.10	29.4 ± 8	4.0 ± 3.1	0 ± 0
canopy_height 0.9 / 1.2 / 1.5 m	0.0049	1.15	2.3 ± 2	4.1 ± 3.1	5.4 ± 3.6
canopy_width 0.5 / 0.7 / 1 m	0.0266	6.25	1.4 ± 1.6	3.8 ± 3	7.1 ± 4
row_spacing 2 / 2.7 / 3 m	0.0036	0.85	5.2 ± 3.6	4.1 ± 3.1	2.7 ± 2.4
canopy_porosity 5 / 12 / 20%	0.0002	0.05	4.3 ± 3.4	4.1 ± 3.2	3.7 ± 3
row_azimuth 0 / 45 / 90°	0.0018	0.42	4.7 ± 3.4	4.2 ± 3.3	2.9 ± 2.3
Grass cover 0 / 35 / 70%	0.0391	9.18	1.8 ± 1.6	4.1 ± 3.1	8.0 ± 3.9

days with a severe water deficit and can be extrapolated to the other output indicators. The model, which included both fixed effects (training system parameters, SWHC and % of grass cover) and random effects (annual variation and grid point characteristics), explained 57 % of the total variance (R^2).

The total variance explained by the fixed effects represents an R^2 of 0.43 (Table 3). SWHC emerged as the dominant predictor explaining the variation in the number of days with severe water deficit (82 % of the total variance explained by the linear mixed model). This was followed by grass cover (9.2 %) and canopy width (6.3 %) in terms of the proportion of variance explained. In the configurations tested, canopy height, row spacing and azimuth had relatively little influence, each accounting for less than 1 % of the variance explained. Furthermore, canopy porosity had a negligible effect, contributing less than 0.05 % of the variance. The influence of each parameter was further illustrated by the median number of days with severe water deficit simulated by the model across all grid points. These medians were then averaged over all pixels, as summarised in Table 3. The analysis shows that canopy width and grass cover have the potential to induce a change of up to 6 days in water deficit duration, depending on their configurations. Conversely, canopy height, row spacing and orientation appear to have more limited effects, changing water deficit duration by an average of 1-3 days. More specifically, at the pixel level, by setting the SWHC to 150 mm, different combinations of parameters characterising canopy development were used in the model, allowing the construction of scenarios without water deficit (Figure 5).

At the scale of the Cognac production region, considering the scenario with the lowest transpiration relative to the median scenario, the average number of days with at least a moderate water deficit decreases from 30.5 days (with a standard deviation of ± 16 days across the region) to 10.5 days (with a standard deviation of ± 9 days). Considering a SWHC of 150 mm for the region, the scenario with the lowest water deficit averages less than one day, compared to 17 days for the median scenario and 34 days for the scenario with the highest water deficit. Maps illustrating these results are shown in the supplementary data (Figures S3, S4, S5 and S6).

DISCUSSION

1. Effect of soil water holding capacity (SWHC)

SWHC is by far the greatest contributor to the variance explained by the model of the number of water-deficit days from flowering to maturity. SWHC depends on soil texture and the percentage of coarse elements, which cannot be modified by the producer, but also on vine rooting depth, which can be promoted by adequate pre-planting soil preparation (van Zyl

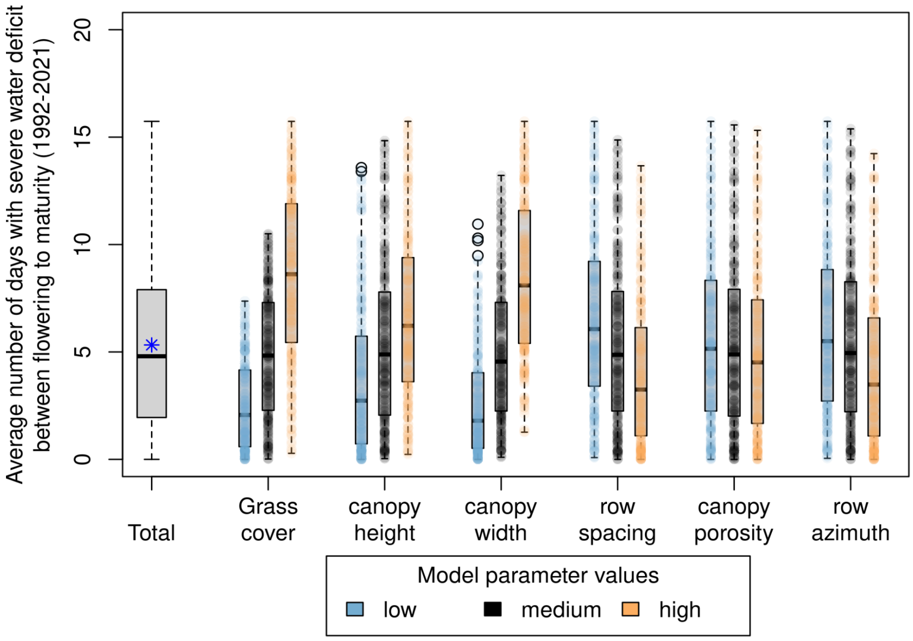


FIGURE 5. Average number of days with severe water deficit at the pixel scale (with SWHC fixed at 150 mm) simulated over all combinations of parameters (729), presented as boxplots. For each parameter value, a boxplot of the 423 simulations is shown, categorised according to the lower, middle and higher values chosen for the parameter considered (values indicated in the first column of Table 3). An asterisk (*) on the total box plot indicates the mean of the data.

and Hoffmann, 2019) or the use of vigorous rootstocks (Ollat *et al.*, 2015). In the Cognac region, many growers also cultivate food crops like cereals. Historically, vineyards were located on soils with low SWHC, while cereals were cultivated on soils with higher SWHC. Relocating vineyards to soils with higher SWHC could be an option when water deficits become detrimental due to climate change. However, the impact of this adaptation measure on food safety needs to be considered.

2. Training system and soil management

The parameters linked to the training system and soil management also play a role, and by selecting scenarios that reduce vine transpiration, it is possible to significantly reduce the number of water deficit days. van Leeuwen *et al.* (2019) applied Lebon's soil water model, analysing the impact of changes in SWHC and vineyard density on water deficit in Mediterranean (Avignon) and Oceanic (Bordeaux) climates in response to climate change. Their results demonstrate that low-density vineyards (*i.e.*, wide spacing) provide a sustainable solution for grape growing in dry climates, by reducing water consumption and possibly the need for supplementary irrigation. Training system specifications are less restrictive in the Cognac-producing region compared to most other wine-production regions in France with protected origin, offering opportunities for adaptation to climate change through modifications of training system parameters. Agro-environmental measures have limited chemical weeding to a maximum of one-third of the row spacing, leading to increased grass cover in vineyards of the Cognac region. Given that the percentage of grass cover is the third largest contributor to the variance in water deficit days from flowering to maturity, as explained by the model, appropriate management of this parameter with regard to water deficit stress risk is important. Growers can adjust it from year to year, and even within a single season, depending on the climatic conditions of the vintage (Vanden Heuvel and Centinari, 2021).

Therefore, adjusting the training system and soil management parameters to reduce water deficits are worthwhile options for adapting to climate change. Our simulations did not account for other soil management practices, such as fertilisation. More sophisticated models, such as STICS (Brisson *et al.*, 2003), can be used to simulate the effect of training system parameters and soil management (including fertilisation) on yield, which is a key driver of profitability in the Cognac region. This approach has already been applied in viticultural contexts (Fraga *et al.*, 2018; Valdés-Gómez *et al.*, 2009; Yang *et al.*, 2022b).

3. Water deficit evolution during the flowering–maturity period; impacts on yield and quality

The flowering-veraison phenophase represents an important period for berry responses to water deficits and several studies investigated the impact of water deficit during this period on grapevine yield and wine quality (Chacón-Vozmediano *et al.*, 2020; Gaudin *et al.*, 2014; Ramos and Martínez-Casasnovas, 2014; Valdés-Gómez *et al.*, 2009; Yang *et al.*, 2022a). These studies generally report a yield decrease as the water deficit increases, but the timing of the water deficit is also relevant. While post-veraison water deficits minimally affect berry weight, it is suggested that avoiding water deficits throughout the vegetative period maximises production, which is an objective in the Cognac production area (Hardie and Considine, 1976; Ojeda *et al*., 2001). Although the precise impact of water deficit on yield is beyond the scope of this study, the model outputs can be used to predict trends in yield under the different scenarios (increase in yield when HydricSI decreases, decrease in yield when HydricSI increases). The impact of vine water status on grapevine yield was previously estimated with Lebon's or WaLis (an improved version of Lebon's model) soil water balance model in southern France (Gaudin *et al*., 2014; Naulleau *et al*., 2022), showing the feasibility of the approach. However, obtaining accurate yield estimates from water balance model outputs still needs some fine-tuning.

Water deficit affects secondary metabolites in white grapes and wines (Kovalenko *et al*., 2021; Savoi *et al*., 2016; Savoi *et al.,* 2020). The effect of water deficit on cognac quality is not well documented, but, likely, a modification in secondary metabolites in grape berries (aroma compounds or precursors and phenolic compounds) affects quality. These aspects require further investigation.

This study shows that the duration of the flowering–maturity period impacts the number of days with water deficit, which increased in parts of the region where the duration of the flowering-maturity period was the least reduced (as a result of a limited increase in temperature). A similar observation was made by Yang *et al*. (2022a) for the Alsace wine-producing region (France), using projected climate data. These authors demonstrated that the late-ripening Riesling cultivar is exposed to a higher mean temperature increase (1.5-2.5 °C), and related water deficits, compared to Müller-Thurgau (1-2 °C), an early variety with a shorter flowering-to-ripening period. This suggests that late-ripening grape varieties, such as Ugni blanc, could be more vulnerable to climate change, particularly in cooler regions, because the period during which they are sensitive to water deficit decreases more slowly compared to that of early-ripening varieties.

4. Modelling aspects

The Lebon model used in this study has been the subject of several evaluations that have demonstrated its ability to reflect both vine water status and soil water content relatively accurately (Gaudin *et al*., 2014; Pellegrino *et al*., 2006; Schultz and Lebon, 2005). However, as with any model, water balance modelling necessarily involves several uncertainties. To assess the impact of different sources of uncertainty on the results, sensitivity analyses are required. The Lebon *et al*. model has hardly been subjected to such studies, but it has been shown that estimating the available soil water capacity in the field is challenging and that its adjustment can be effectively done using vine water potential measurements (Pellegrino *et al*., 2006). It has also been recognised that the propagation of initial errors (soil water status at the beginning of the cycle) varies significantly depending on the plot, which can lead to significant errors in soil moisture estimation (Roux *et al*., 2014). The present study demonstrates the sensitivity of the model to several parameters, in particular the available water capacity and the canopy dimensions (governing the radiation interception), which thus strongly influence the transpiration rate of the vine.

In Lebon's model, canopy width has a substantial effect on the crop coefficient (kc) of the vine, especially at a width of 1 m. Hence, the choice of a canopy width of 1 m has a strong influence on the simulated water deficit indicator. Although this width may seem high compared to most vineyard configurations, it is common in the Cognac production region, where high pruning (*i.e*., high trunks), is widely practised in training systems with limited trellising (Figure S7). This pruning technique improves the protection of the grapes from direct sunlight and scorching. However, the vegetation shape of this training system is not a rectangle but resembles an inverted triangle or a polygon with a narrower base width. In Lebon's model, only one vegetation width can be set as an input variable, leading to a possible overestimation of the exposed leaf area (ELA) and associated transpiration in our modelling exercise. Trimming the vines to more narrow rows reduces transpiration, but exposes the grapes to more sunlight due to reduced shade, which is not desirable for this type of distilled wine production. Hence, the management of the row width is a trade-off between the reduction of vine transpiration and the protection of grapes from direct sunlight. While virtual plant models (Louarn *et al*., 2008; Prieto *et al*., 2020) could potentially provide more accurate estimates of exposed leaf area (ELA), they operate at different temporal and spatial scales and are significantly more complex than Lebon's model. Therefore, direct implementation of these models into Lebon's framework is not realistic. However, these advanced models could be applied to a subset of standard vines representing the diversity of canopy management in the region. By comparing their results with those of Lebon's model, it could be possible to better assess the accuracy and limitations of the current model and explore potential improvements.

This study primarily considers the effect of SWHC on stomatal conductance and uses a single grapevine phenology and maturity model coupled with a soil water balance model. While this approach has revealed significant variability in water deficit exposure and the effects of different training systems and vineyard floor management practices, the main limitation is the lack of validation with experimental data. To increase the robustness of the results, it would be valuable to validate the model outputs against measured indicators of vine water status, such as $\delta^{13}C$ or water potentials, within the region.

5. Climate data and spatial scale

The present work is based on 8 km gridded climate data and national synthetic maps estimating SWHC. The effects of fine-scale topographic niches and microclimatic variations are not considered. Furthermore, it has been shown that local rainfall variability during the vine vegetative period can lead to large variations in water deficits (Bois *et al*., 2020). The SWHC values derived from the www.gissol.fr database play an important role in the modelled water deficits. When one single value of SWHC is set for the entire region, as we did when analysing the temporal evolution of the different indicators, a different segmentation is observed at the regional level. The demarcation between some pixels is abrupt, with significant variations in the water deficit indicators between two neighbouring 8 km grid cells. This may be due to climatically homogeneous zones in the SAFRAN analysis and issues with thresholds when moving from one pixel to another. These zones correspond to areas of irregular shape where horizontal climatic gradients, especially for precipitation, are weak (Quintana-Seguí *et al*., 2008). These homogeneous zones, of which there are approximately eight at the scale of the region studied, are responsible for these abrupt variations in indicator values between neighbouring pixels of each zone (Figure S8). An interpolation method, as well as other data sources from agro-climatic weather stations in the region, could be feasible approaches to correct these biases. Finally, the SAFRAN database tends to underestimate the daily temperature range (*i.e*., the daily difference between maximum and minimum temperature; Quintana-Seguí *et al*., 2008). As a consequence, solar radiation and reference evapotranspiration derived from the Hargreaves temperature method (Hargreaves and Samani, 1985) are also likely to be underestimated with a positive effect on the estimates of ET_0 and solar radiation.

CONCLUSION

This study investigates the impact of site (climate and soil water holding capacity) and viticultural practices (soil cover management and training system) on grapevine water status through vine water balance modelling, using the Cognac wine-producing region as a study area. Over the period 1962–2021, an increasing water deficit trend was observed, particularly in the north-western part of the region, affecting significantly 23 % of the Cognac production area. Soil water holding capacity (SWHC) is the major driver of vine water status, explaining almost 80 % of the variance of simulated days during which grapevines were exposed to moderate to severe water deficit. The number of days with water deficit can also be modulated through vineyard floor management practices and training system parameters, although to a much lesser extent. When assuming a SWHC of 150 mm or more, simulations indicate that it is possible to reduce the number of days with severe water deficit to fewer than one day during the critical period from flowering to maturity. In the context of the Cognac vineyards, canopy width and the percentage of grass cover had the most significant effects, while row spacing, porosity and canopy height had little impact on vine water deficit. The results of this study open avenues to growers for efficiently managing vine water status in a changing climate context.

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