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Reduced density is an environmental friendly and cost effective solution to increase resilience to drought in vineyards in a context of climate change

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ABSTRACT

Aims: Climate change imposes increasingly warm and dry conditions in most winegrowing regions. Mediterranean vineyards are particularly vulnerable and have registered, in most situations, declining yields over the past years. Although a majority of Mediterranean vineyards are still dry-farmed, yields can be increased by the implementation of irrigation. However, irrigation has an impact on increasingly affected water resources. An alternative solution to irrigation can be the adaptation of training systems. As can be shown by water balance modeling, low density non-irrigated vineyards are much less vulnerable to climatic drought compared to medium or high density vineyards. And while yields tend to be lower in low density vineyards, so are production costs. The aim of this study is to investigate to what extent low density vineyards can be a sustainable and cost effective adaptation for grape growing in dry climates.

Methods and results: A water balance model was applied to conceptual vineyards with different soil water holding capacities and different planting densities over recent past (1981-2010) and near future (2041-2070) climatic conditions for two winegrowing scenarios (Cabernet-Sauvignon in Bordeaux and Grenache in Avignon, Côtes du Rhône). Row spacings of 2.0, 3.0 and 4.0 m were investigated for vineyards with 100, 200 and 300 mm total transpirable soil water (TTSW), while inter-vine spacing, vine architecture, and canopy height were kept similar. Projected yields were estimated to vary according to vine density and water deficit based on a meta-analysis of data published in the literature. Production costs were calculated according to an operation-based costing methodology and compared among the different scenarios on a cost per hectare basis. Gross profit per hectare, defined as grape sales revenue minus production costs, was then computed for two grape sale revenue scenarios (1 €/kg and 3 €/kg). The modeled average fraction of transpirable soil water (FTSW) varied across the different winegrowing scenarios, climate periods (recent past or near future), and TTSW and row spacing assumptions. In soils with 200 or 300 mm TTSW, the 30-day average FTSW prior to modeled grape harvest roughly doubled when 4.0 m versus 2.0 m spacing was assumed in both the recent past and near future climate scenarios. In soils with 100 mm TTSW, water deficit was more severe overall and the effect of row spacing on average FTSW was less pronounced. Changes in projected yields were estimated as a function of vine density and FTSW based on relationships published in the literature. Yields decreased with decreasing vine density and increasing water deficits, while production costs decreased with decreasing vine density. When the assumed revenue from grape sales was lower (1 €/kg), the effect of reduced production cost savings outweighed the loss in revenue caused by reduced yields, leading to increased gross profit per hectare. On the other hand, when higher grape revenue was assumed (3 €/kg), the effect of reduced yield on revenue outweighed the associated reduction in production costs, leading to reduced gross profit per hectare.

Conclusions: Lower density, dry-farmed vineyards will experience less water deficit under warmer and drier climate conditions, although this difference is less pronounced in soils with less water holding capacity. When considering differences in yields, revenues, and production costs, lower density vineyards producing lower value grapes (1 €/kg) may also experience an associated increase in gross profit, while such vineyards producing higher value grapes (3 €/kg) might experience a decrease in gross profit.

Significance and impact of the study: The implementation of dry-farmed, low density vineyards provides a sustainable solution for grape growing by reducing the need for irrigation water. It allows maintaining vineyards in very dry areas where water is not readily available for irrigation and where other crops (except possibly olive trees) cannot be grown. Modeling of yield, revenue, and production costs shows that this solution is also economically viable, particularly for vineyards producing lower value (€/kg) grapes. Unlike goblet trained bush vine, low density trellised vineyards are perfectly adapted for mechanization.

KEYWORDS

vine, water deficit, water balance, planting density, production costwine

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INTRODUCTION

Climate change imposes higher temperatures and increasingly dry conditions in most winegrowing areas (Schultz, 2000). Water deficit induces early shoot growth cessation (Pellegrino *et al.,* 2005), reduced photosynthesis (Escalona *et al.,* 2000) and limits yield, in particular through a reduction in berry size (Ojeda *et al.,* 2001 ; Triolo *et al.,* 2018). Early water deficit around flowering can also jeopardize bud fruitfulness for the next season (Guilpart *et al.,* 2014). While moderate water deficits increase grape quality potential, in particular for the production of red table wines (van Leeuwen *et al.,* 2009), severe water deficits can harm grape quality. Yield reduction provoked by water deficit can threaten the economic viability of winegrowing. Although the vine is a drought resistant Mediterranean species (Chaves *et al.,* 2010), specific adaptations in plant material or viticultural techniques are necessary to maintain vine growing at economically sustainable yields while producing high quality wines under increasingly warm and dry climates.

Potential adaptations to cultivate vines under climate change conditions have been reviewed by van Leeuwen and Destrac (2017) and include irrigation, the use of drought resistant rootstocks and varieties, plantations in soils with medium to high soil water holding capacity (SWHC) and the use of drought resistant training systems like goblet trained bush vines or low density vineyards. Many studies have been published on the use of irrigation to relieve excessive water deficits in vines (Bravdo *et al.,* 1985 ; Dry *et al.,* 2001 ; Smart *et al.,* 1974). However, water resources are increasingly scarce (Ludwig *et al.,* 2011), or inaccessible at reasonable cost for many wine producing regions in the Mediterranean basin. Sustained irrigation can also lead to salinization, in particular when source water is saline and when winters are dry (Aragüés *et al.,* 2014). Hence, alternative solutions to irrigation must be considered for sustainable viticulture. The use of drought resistant plant material has the advantage of minimal environmental impacts and being neutral on production costs. Rootstocks have been classified according to their resistance to water deficits (Ollat *et al.,* 2016) and underlying physiological mechanisms have been studied (Marguerit *et al.,* 2012). Some authors have attempted to classify grapevine varieties according to their drought tolerance and in particular their isohydric or anisohydric behavior (Pou *et al.,* 2012 ; Schultz, 2003), but further investigation is needed to obtain an extensive classification based on physiological mechanisms and to assess consequences on wine quality potential. Water deficit in vines can develop due to climatic factors, such as reduced rainfall and increased reference evapotranspiration (ET_0), and due to soil related factors, such as total transpirable soil water (TTSW) (van Leeuwen *et al.,* 2009). Planting vines in soils with medium to high TTSW can reduce the detrimental effects of climatic drought. Regarding training systems, goblet pruned bush vines are acknowledged to be highly drought resistant (van Leeuwen and Destrac, 2017). However, the difficulty of mechanization, in particular for harvest, reduces their economic viability. Wide spaced, low density, trellised vineyards may be an interesting alternative solution to cultivate vines in increasingly warm and dry climates, because of their reduced water consumption. However, their economic performance also needs to be investigated.

A number of previous studies have evaluated the effect of different plant spacing on soil water content and plant water status, root and canopy development and other parameters. In general, closely spaced vines were found to dry their root zones more quickly and experienced greater water stress than wider spaced vines, particularly during the berry ripening period. In a dry-farmed experimental vineyard in West Cape, South Africa, measurements of soil water content of closer spaced vines and rows were significantly lower than for wider spaced vines, starting five weeks after flowering and continuing through ripeness, with this difference being more pronounced at deeper soil layers (Archer and Strauss, 1989). Two studies on the same vineyard also found mean leaf water potential to be more negative for closely spaced vines during the same pre-véraison through ripening period, with the associated water deficit also resulting in lower stomatal conductance and higher leaf temperatures (Archer and Strauss, 1989, 1990). A later study on the same vineyard with some minimal supplemental irrigation also found higher water content in the root zone of lower spaced, but observed a gradual decrease over the season not observed in closer spaced vines. The author hypothesized this might be due to less shading between rows and an associated increase in soil evaporation (Hunter, 1998b). Like the others, this study also found mid-day leaf water

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potential measurements of closer spaced vines to be significantly more negative during the berry ripening period. Furthermore, abscisic acid levels in xylem sap were greater at ripeness for the closer spaced vines when compared to wider spaced vines, while stomatal resistance increased and transpiration decreased more for closer spaced vines (Hunter, 1998b).

Studies generally found trunk diameters of closer spaced vines to be smaller than wider spaced vines, indicating reduced growth capacity as a result of more confined root volumes (Archer and Strauss, 1991 ; Hedberg and Raison, 1982 ; Winkler, 1969). Performing a meta-analysis using data from several publications, Champagnol (1984) found vines in more fertile soil could explore a maximum of 10 m^2 of soil surface, while those in less fertile soils were restricted to 4 m^2 of soil surface. Hidalgo and Candela (1969) showed greater root density under more closely spaced vines, and, likewise, the West Cape studies found the root densities (m/m^3) and leaf area index to gradually and significantly increase as vines were more closely spaced, which the authors hypothesized was the cause of observed differences in soil water content and water potential (Archer and Strauss, 1985, 1989). It was also found that the proportion of finer roots was greater in closer space vines (Hunter, 1998a). In spite of having higher leaf area index, the canopies of more closely spaced vines in a non-irrigated vineyard were less dense, providing better microclimate conditions and higher potential for quality grapes. It was hypothesized the lower vigor canopies were due to drier soil conditions and more negative water potentials resulting from the greater water extraction capability of the denser root systems of the more closely spaced vines (Archer and Strauss, 1990, 1991). This was not the case, however, in a later study in the same vineyard where a small amount of irrigation was applied just before and after véraison. In this case the closer spaced vines had more dense canopies and less desirable microclimate conditions (Hunter, 1998b).

Similar observations regarding water consumption, vine water status, and canopy density were obtained from a study in the Duero Valley, Spain with both irrigated and non-irrigated treatments at two different spacings. It was additionally observed in this study that irrigated vines consumed significantly more water overall than non-irrigated vines, which led to more vegetation and yield. There was little difference, however, between the various spacings in the irrigated treatments, although overall yield per unit of water consumption was lower when compared with non-irrigated vineyards. In the non-irrigated treatment, water consumption was generally higher and water potentials were more negative in the high density vineyard, but differences were not always significant (Yuste *et al.,* 2004). In the West Cape studies, the yield per hectare of the closer spaced vines was greater than wider spaced vines, but the yield per vine was lower. Hence, yield did not increase proportionally to vine density (Archer and Strauss, 1991 ; Hunter, 1998b). On the other hand, a study in a non-irrigated vineyard in Napa Valley, California found no significant differences in yield per acre between spacing treatments, resulting in more vines requested for a given yield in the more closely spaced vineyards. The author additionally hypothesized the yield per acre could have been higher on the wider spaced vines if the trellising accommodated more buds per vine. It was also observed that shoots were longer and had more leaves in wider spaced vines and there were no significant differences in berry composition, nor resulting wine quality between spacing treatments (Winkler, 1969). Another study found that wider spaced vines produced greater yield in the long-run when the trellising was adapted to handle greater capacity (Hedberg and Raison, 1982). On Cabernet-Sauvignon in Bordeaux, Dumartin and Cordeau (1979) found an increase in yield from 62 to 102 hL/ha when vine density was increased from 2,500 to 10,000 vines/ha. At the same time, grape quality potential was also improved with higher sugar, tannin and anthocyanin content and lower total acidity. In addition to the above vineyard studies, a number of studies on trees found increased spacing (i.e. stand density) improved the drought resistance and productivity of the stand by reducing the competition between trees for available water reserves (Giuggiola *et al.,* 2012 ; Gyenge *et al.,* 2011).

The aim of this research is to investigate the potential of low density, dry-farmed vineyards as an economically viable solution to grow vines under increasingly dry and warm conditions in a context of climate change. Water balance modeling is used to evaluate how wider row spacing (i.e. reduced vine density) impacts

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vineyard resilience to drought in different winegrowing scenarios, under current and future climatic conditions, and over a wide range of TTSW. Associated impacts on yield are estimated based on relationships from the literature and production costs are modeled for several row spacings. The resulting effects on gross profits per hectare are then considered as a function of sales value (€/kg) of the grapes produced. In this way, both the water use and economic effects of the different vine densities are evaluated.

MATERIALS AND METHODS

1. Water balance and phenology models

Water balance modeling was implemented according to Lebon *et al.* (2003) using climate data from recent past (RP) and near future (NF) climate scenarios for both an oceanic winegrowing region (Bordeaux area, France, Grande Ferrade weather station, F-33140 Villenave d'Ornon, longitude -0°34', latitude 44°50') and a Mediterranean winegrowing region (southern Côtes du Rhône France, INRA weather station F-84000 Avignon, longitude 4°52', latitude 43°95'). RP climate conditions were based on measured data from both stations for years 1981-2010. NF climate conditions were simulated according to Pieri *et al.* (2010) from a climate change scenario close to RCP 6.0 for years 2041-2070. The water balance models were run for combinations of three levels of TTSW (100 mm, 200 mm and 300 mm) and three different row spacings (2.0 m, 3.0 m and 4.0 m). Inter-vine spacing was fixed at 1.0 m, because light interception, vine transpiration and water balance are only marginally impacted by the distance between the vines on the row, as long as porosity remains low (i.e. the vines are close enough to fill the canopy). These assumptions result in planting densities of 5,000 vines/ha, 3,333 vines/ha and 2,500 vines/ha. Vines were assumed to be dry-farmed, with a trunk height of 0.7 m and a row height of 2.0 m, resulting in a canopy height of 1.3 m. Canopy width was estimated at 0.45 m. Porosity was estimated at 15 % for the 2.0 m spacing and 10 % for the wider row spacings, where individual vine vigor is likely to be greater. Soil albedo was fixed at 0.18, which is consistent with Pieri and Gaudillère (2003).

The date of 50 % budbreak was established at 90 growing degree days (GDD), as calculated using a base temperature of 10 °C and a starting count date at day of the year (DOY) = 1 (de Cortázar-Atauri *et al.,* 2009). The date of 50 % flowering and véraison were established using the grapevine flowering and veraison model (GFV) (Parker *et al.,* 2013, 2011) for Cabernet-Sauvignon in Bordeaux and Grenache in the southern Côtes du Rhône (Avignon). Harvest dates were assumed to be 40 days after véraison. Fraction of transpirable soil water (FTSW) was averaged over the 15 days around flowering and the last 30 days before harvest. These were considered an indicator of the severity of water deficit, where FTSW ranges from "0.0" (severe water deficit) to "1.0" (soil at full TTSW). It is generally considered that vines do not face observable water deficit when FTSW ranges between 1.0 and 0.4, and that water deficit gradually increases when FTSW decreases from 0.4 to 0.0 (Lebon *et al.,* 2003).

2. Yield and leaf area assessment

Yield is estimated for each scenario by accounting for differences in both i) planting density and ii) changes in average FTSW during the 30 days before harvest as calculated using the water balance model for each of the scenarios.

In one of the more complete studies on vine density, Hunter (1998b) presents yield data in kg per vine averaged over two growing seasons for densities ranging from 1,111 vines/ha to 20,000 vines/ha. This dataset was used to compute a relationship between vine density and individual vine yield (eq. 1):

$$y = 7.50\ e^{-000116x}$$ Eq. 1

where y = yield (kg/vine) and x = density (vines/ha).

Yields under conditions of no water stress (i.e. average FTSW > 0.40 during 30 days before harvest) for both the Bordeaux and Avignon winegrowing scenarios were assumed to be 9,000 kg/ha for 5,000 vines/ha vineyards. The relationship between vine density and yield in Eq. 1 was then applied to extrapolate yields down to 3,333 and 2,500 vines/ha.

A function based on Lebon *et al.* (2003) was then created to simulate yield reduction as a function of water deficit when FTSW < 0.40 (Figure 1). This additional effect of water deficit on yield was then applied to the base yields determined as

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described above for the different planting densities.

Exposed leaf area was estimated according to Murisier (1996), with leaf area/fruit weight ratios (LA/FW) calculated for all simulations using the yield calculations described above. The purpose is to check whether the LA/FW ratios remain above minimum levels required for fruit ripening.

3. Profitability analysis

A conceptual profitability analysis was performed, by first estimating changes in production costs per hectare for the different vineyard densities and then evaluating the effect of changes in yield on revenues per hectare for each of the different scenarios. The resulting gross profits per hectare for each scenario were then compared to understand the net effect of changes in production costs and revenues. This was done assuming two different values for the grapes produced (respectively 1 and 3 €/kg).

Operation-based production costs per hectare were calculated according to a methodology developed in Roby *et al.* (2008). Production costs were based on the assumption that vines were vertically trellised and cordon pruned by hand after mechanical pre-pruning. Vertical shoot positioning was carried out manually. Fertilization is applied according to current practices. Vineyard floor maintenance is managed through mechanical weed removal between the rows and chemical weeding underneath the rows. For mechanization, a 70 horse power (hp) inter-row tractor is used in the 2.0 m spaced vineyard and a 100 hp tractor in the 3.0 and 4.0 m spaced vineyards. Vines were mechanically harvested. Cost for labor, mechanization and consumables, as taken from Roby *et al.* (2008), are incremented by 15 % to account for inflation over the 2008-2019 period.

Revenue per hectare was calculated starting with the yield estimates developed for each scenario and then applying an assumed value of either 1 €/kg or 3 €/kg for the grapes produced. These values roughly correspond to the grape values associated with entry to mid-level and mid- to high-level wine respectively. Gross profit was then calculated to study the interactive effect of the production cost per hectare at different vine densities and the corresponding revenue effects of associated changes in yield for different scenarios. Gross profit is defined for this purpose as the difference between the total revenue generated by the sale of the goods (in this case grapes) minus the operation-based production costs of those goods sold. Naturally, however, this analysis cannot account for the value of land, or other (fixed, or indirect) costs that might need to be considered by growers in

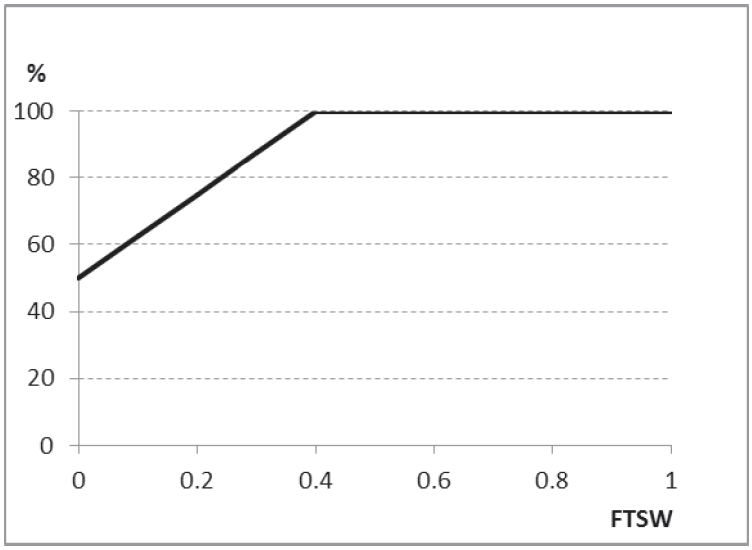


FIGURE 1. Yield as a function of average FTSW 30 days before harvest. Yield is considered to be maximum between FTSW = 1.0 and 0.4 and to decrease in a linear way between FTSW = 0.4 and 0.0. For the highest level of water deficit stress yield is considered to be 50 % of maximum yield compared to situations without water deficit.

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relation to their specific production circumstances.

RESULTS

1. Phenology

Under RP climate, for Grenache in Avignon, average 50 % budbreak was established for all simulation years at DOY = 102 (April 12), average 50 % flowering at DOY = 153 (June 3), 50 % véraison at DOY = 218 (August 6) and harvest at DOY = 258 (September 15). For Cabernet-Sauvignon in Bordeaux these dates are respectively DOY = 98 (April 8), DOY = 157 (June 6), DOY 223 (August 11) and DOY 263 (September 20). Under NF climate, for Grenache in Avignon, average 50 % budbreak was established for all simulation years at DOY = 83 (March 24), average 50 % flowering at DOY = 142 (May 22), 50 % véraison at DOY = 205 (July 24) and harvest at DOY = 245 (September 2). For Cabernet-Sauvignon in Bordeaux these dates are respectively DOY = 77 (March 18), DOY = 146 (May 26), DOY 210 (July 29) and DOY 250 (September 7). These phenology projections were used to run the water balance models for all years evaluated.

2. Level of water deficit (FTSW) modeled during flowering

Average FTSW during the period from one week before flowering to one week after flowering ranged from 0.93 to 0.46 for the various simulations (Figure 2). For the Bordeaux simulation, the average FTSW for 15 days around flowering only marginally decreases for the NF scenario, probably because flowering advanced by 11 days on average, which partly compensates for higher ET_0. And even for the 100 mm TTSW scenario, FTSW around flowering remained well above the water deficit threshold of FTSW = 0.40. In Avignon a more marked effect of climate change is shown. Average FTSW for 15 days around flowering is also lower for the NF scenario, but remains above the 0.40 water deficit threshold even in the most extreme case (average FTSW = 0.46 at 5,000 vines/ha for 100 mm TTSW). As all scenarios have FTSW around flowering above the water deficit impact threshold level, further analysis of any associated effect is not necessary. Only water deficits (FTSW) during grape ripening will be evaluated as described below.

3. Level of water deficit (FTSW) modeled during grape ripening

Average FTSW for the 30 days prior to harvest ranged from 0.54 to 0.02 for the various simulations (Figure 3). For the Bordeaux simulation, FTSW during this period did not decrease under NF climate conditions, except for the low (100 mm) TTSW scenario. Increasing row spacing from 2.0 m to 4.0 m substantially reduced water deficit during grape ripening, with average FTSW increasing from 0.31 to 0.54 for soils with TTSW = 300 mm, and from 0.17 to 0.35 for soils with TTSW = 200 mm. This increase was less for soils with TTSW

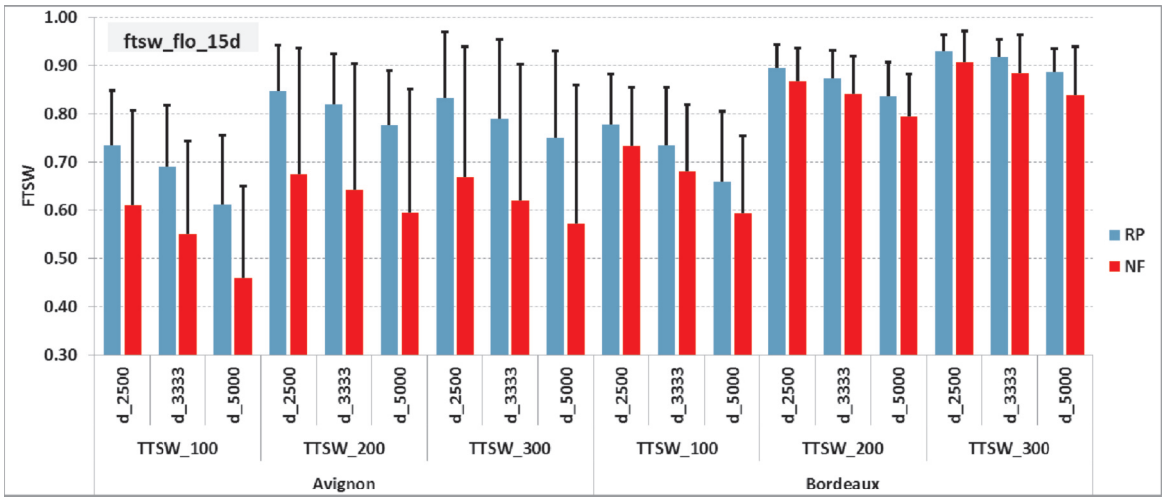


FIGURE 2. Average FTSW calculated over the 15 days around mid-flowering, for two regions (Avignon and Bordeaux), two climatic periods (RP = recent past and NF = near future), three values of TTSW (100; 200; and 300 mm) and three vine densities (5,000; 3,333; and 2,500 vines/ha).

= 100 mm, where average FTSW increased from 0.13 to 0.16. In Avignon, a similar trend is observed, although at greater water deficit levels overall. Under NF climate conditions average FTSW increased from 0.07 to 0.23 with TTSW = 300 mm and from 0.02 to 0.10 in soils with TTSW = 200 mm. For TTSW = 100 mm water deficit was severe for all planting densities.

4. Yield and exposed leaf area

Based on the relationship in Eq. 1, the yield of 9,000 kg/ha for a 5,000 vines/ha vineyard (row spacing = 2.0 m) was extrapolated to vine densities of 3,333 and 2,500 vines/ha (Table 1). With wider spacing, production per hectare decreases, but not proportionally to vine density. In addition, yields are assumed to decrease further once the intensity of water deficit drops below a threshold (FTSW < 0.40). Simulated yields are lower in Avignon compared to Bordeaux due to overall drier conditions and resulting water deficits in Avignon (Figure 4). Generally, yields in NF climate scenarios were also lower than for RP climate scenarios, except on soils with 200 mm and 300 mm TTSW in Bordeaux. The lowest yields (3,174 kg/ha) was projected for Avignon under NF climate scenario on soils with TTSW = 100 mm, for 2,500 vines/ha vineyards (see also Figure 4).

Exposed leaf areas were estimated according to Murisier (1996) and leaf area to fruit weight ratio was computed. Leaf area/fruit weight (LA/FW) decreased with wider spacing, but remain always > 1.0 m^2/kg of fruit. Similar decreasing trends in LA/FW were also observed at wider spacings in the West Cape studies (Archer and Strauss, 1991; Hunter, 1998b). The lowest LA/FW ratio (1.14 m^2/kg) was projected in 2,500 vines/ha vineyards in Bordeaux on soils with TTSW = 300 mm, in both RP and NF climate scenarios (data not shown).

5. Profitability analysis

Production cost was estimated at 7,046 €/ha for vineyards planted at 5,000 vines/ha (Table 2a), 4,572 €/ha for 3,333 vines/ha (Table 2b) and 3,608 €/ha for 2,500 vines/ha (Table 2c). When

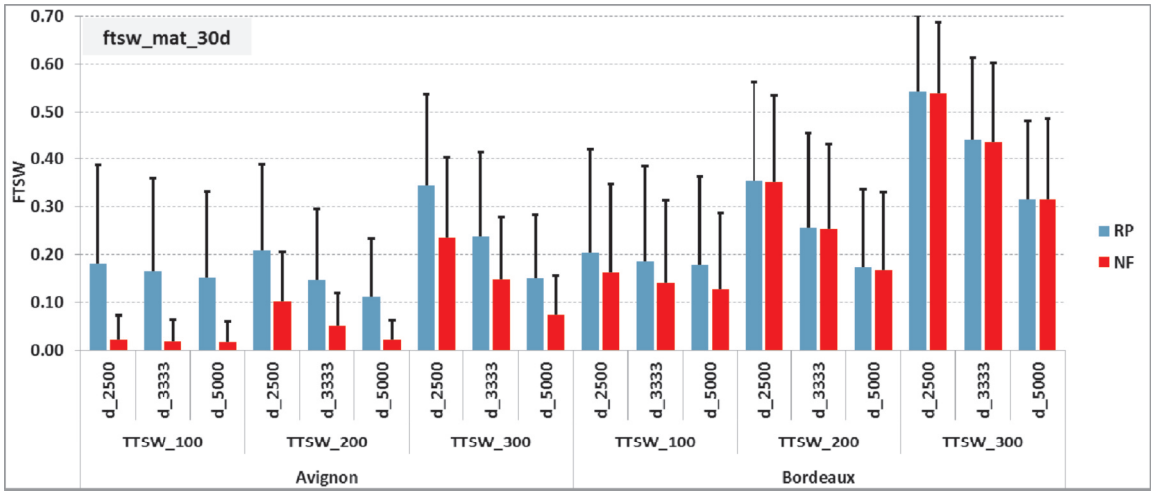


FIGURE 3. Average FTSW calculated over the 30 days prior to modeled harvest dates for two regions (Avignon and Bordeaux), two climatic periods (RP = recent past and NF = near future), three values of TTSW (100; 200; and 300 mm) and three vine densities (5,000; 3,333; and 2,500 vines/ha).

TABLE 1. Estimated yield as a function of vine density in situations without water deficit stress (average FTSW 30 days before harvest between 1.0 and 0.4) and exposed leaf area.

Spacing (inter row x inter vine)	vines/ha	Exposed leaf area m2/ha	Yield (kg/ha)
2 * 1	5000	12963	9000
3 * 1	3333	9149	7280
4 * 1	2500	6863	6014

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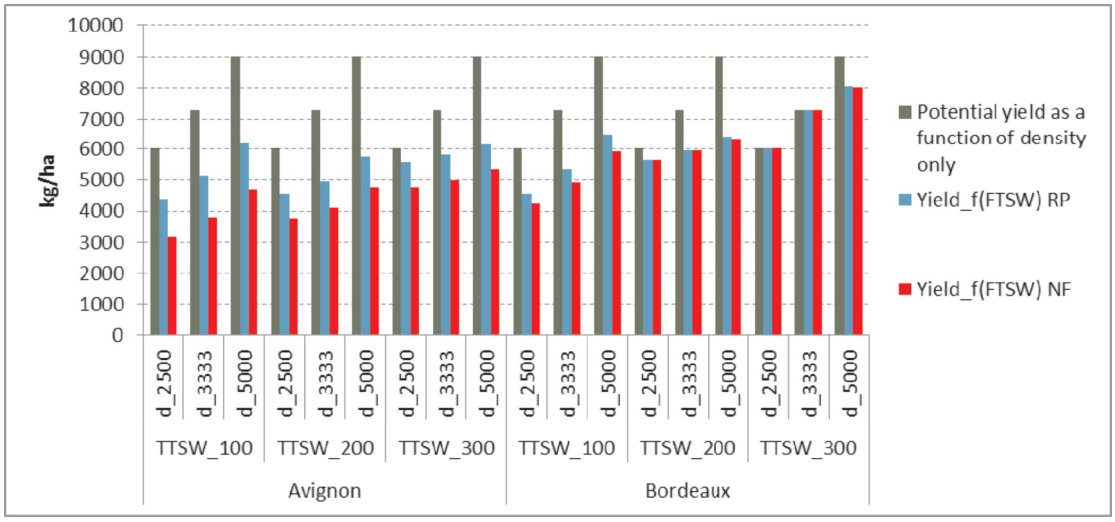


FIGURE 4. Yield simulations (kg/ha) for two regions (Avignon and Bordeaux), two climatic periods (recent past and near future), three values of TTSW (100 ; 200 ; and 300 mm) and three vine densities (5,000 ; 3,333 ; and 2,500 vines/ha).

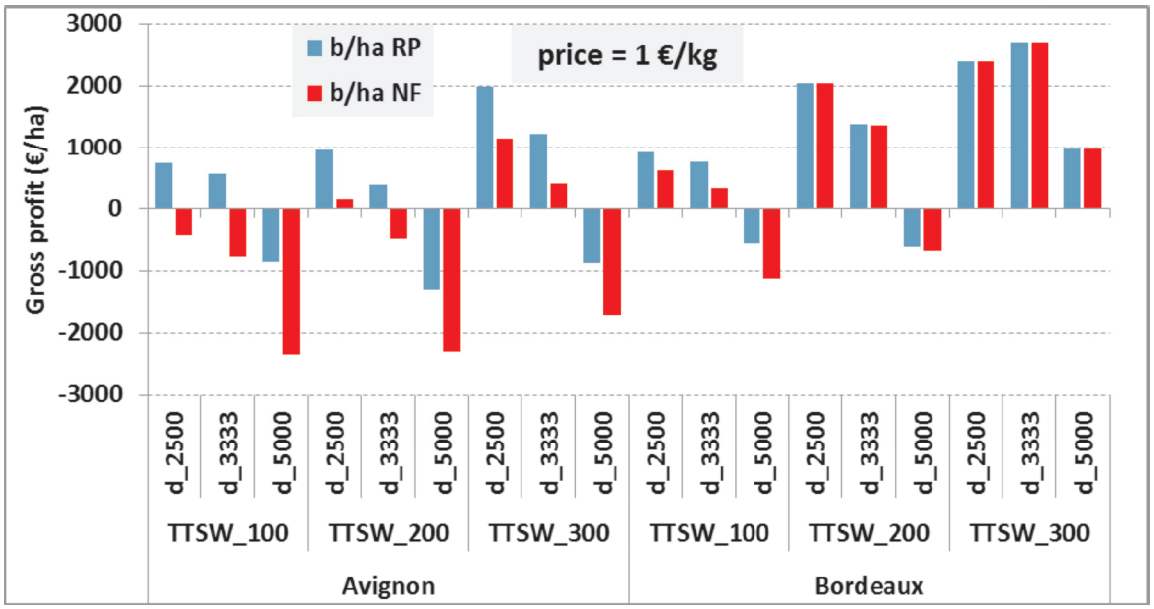


FIGURE 5. Gross profit (€/ha) when grapes are sold for 1 €/kg for two regions (Avignon and Bordeaux), two climatic periods (RP = recent past and NF = near future), three values of TTSW (100 ; 200 ; and 300 mm) and three vine densities (5,000 ; 3,333 ; and 2,500 vines/ha).

grapes are valued at 1 €/kg, and based on simulated yields for each scenario, gross profit per hectare increases with reduced vine density in most scenarios (Figure 5). When grapes are valued at 3 €/kg, however, the opposite is true, with gross profit per hectare being unchanged or decreasing, particularly in soils with TTSW = 100 mm (Figure 6).

DISCUSSION AND CONCLUSION

The modeled average harvest date for Grenache in Avignon under RP climate conditions was September 15 while it was September 20 in Bordeaux. These simulations are close to observed harvest dates in these regions for these varieties, attesting the ability of the models used to predict correctly the phenological stages.

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Under the NF scenario, these dates are advanced by 13 days, which is also consistent with Pieri (2010).

Yield simulations in this study under no water deficit are based on the relationship between yield per hectare and number of vines per hectare computed from data in Hunter (1998b) (Figure 4, green bars). With wider spacing, modeled yield per hectare declined, but not proportionally to the number of vines per hectare. Projected yield for low density vineyards (2,500 vines/ha) was around 6 T/ha (approximately 40 hL/ha). Under drought conditions, simulated yields are lower, down to just above 3 T/ha for low density vineyards in the driest scenario (Avignon, NF, TTSW = 100 mm). These yield projections are consistent with observed yields in dry-farmed, low density vineyards in southern Europe.

TABLE 2A. Operation-based production cost of a 5,000 vines/ha vertical shoot positioned (VSP) vineyard.

Type of work		Time for 1,000 vines	Cost per hour (€)	Time per ha (5,000 vines)	Cost per ha (€)
Pruning and associated works	Pre-pruning (labor)	0h25	17.25	2h10	36
	Tractor	0h25	20	2h10	42
	Material	0h25	5.75	2h10	12
	Wire placement	1h30	15	7h30	113
	Manual pruning (cordon)	10 h	17.25	50h	863
	Electric shear pruning	10 h	1.15	50h	58
Trellis maintenance	Trellis maintenance (labor)	3h	15	15h	225
	Trellis material				650
	Tractor	1h	20	5h	100
	Trunk tying	3h	15	15h	225
Fertilization	Labor	0h30	17.25	2,5h	43
	Tractor	0h25	20	2h10	42
	Sprayer	0h25	5.75	2h10	12
	Organic fertilizers				500
Soil maintenance by weeding under the row and tillage on inter-row	Weeding (labor, x 2 treatments)	0h45	17.25	3h45	65
	Tractor	0h45	20	3h45	75
	Material	0h45	5	3h45	19
	Chemicals (x 2 treatments)				150
	Tillage (labor, x 4 times)	0	15	6h40	100
	Tractor	0	20	6h40	133
	Material	0	3	6h40	20
Vine replacement (1 % per year)					550
Vegetative operations	Manual shoot positioning (x 2)	8h	15	40h	600
	Hedging (labor, x 2 times)	0h35	17.25	3h	50
	Tractor	0h35	20	3h	58
	Topping machine	0h35	14	3h	41
	Mechanized desuckering (labor, x 2)	1h10	15	5h50	88
	Tractor	1h10	20	5h50	117
	Desuckering machine	1h10	10	5h50	58
Mechanized harvest	Harvesting machine	0h35	230	3h	671
	Harvest transport (labor)	1h20	17.25	6h40	115
	Tractor	1h20	20	6h40	133
	Trailer	1h20	11.5	6h40	76
Spraying	Spraying (labor, x 8 treatments)	2h10	17.25	10h50	187
	Tractor	2h10	20	10h50	217
	Sprayer	2h10	11.5	10h50	125
	Chemicals (x 8 treatments)				480
TOTAL		58h		290h	**7046**

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Outputs of FTSW around flowering (Figure 2) show that even under NF climate scenario the risk of water deficit impacting bud fruitfulness is limited.

LA/FW ratio declines with wider spacing, but remains above 1.0 m^2/kg, which is considered as the lower limit to ensure correct sugar ripening of grape berries (Kliewer and Weaver, 1971). A LA/FW ratio of 1.4 to 1.6 m^2/kg is required to obtain maximum fruit coloration in Tokay table grapes (Kliewer and Dokoozlian, 2005). This value is consistent with Renard *et al.* (2001), who considered that 1.5 m^2 leaf area per kg of fruit is needed to ripen red varieties to full phenolic maturity under moderately cool climates. This is always the case at a density of 5,000 vines/ha, and in most simulations at 3,333

TABLE 2B. Operation-based production cost of a 3,333 vines/ha vertical shoot positioned (VSP) vineyard.

Types of work		Time for 1,000 vines	Cost per hour (€)	Time per ha (3,333 vines)	Cost per ha (€)
Pruning and associated works	Pre-pruning (labor)	0h20	17.25	1h05	19
	Tractor	0h20	23	1h05	25
	Material	0h20	5.75	1h05	6
	Wire placement	1h30	15	5h	74
	Manual pruning (cordon)	12h	17.25	40h	683
	Electric shear pruning	12h	1.15	40h	46
Trellis maintenance	Trellis maintenance (labor)	3h	15	10h	149
	Trellis material				345
	Tractor	1h	23	3h20	76
	Trunk tying	3h	15	10h	149
Fertilization	Labor	0h30	17.25	1h40	28
	Tractor	0h20	23	1h05	25
	Sprayer	0h20	5.75	1h05	6
	Organic fertilizers				300
Soil maintenance by weeding under the row and tillage on inter-row	Weeding (labor, x 2 treatments)	0h40	17.25	2h10	38
	Tractor	0h40	23	2h10	51
	Material	0h40	5	2h10	11
	Chemicals (x 2 treatments)				90
	Tillage (labor, x 4 times)	1h20	15	4h25	66
	Tractor	1h20	23	4h25	101
	Material	1h20	3	4h25	13
Vine replacement (1 % per year)					276
Vegetative operations	Manual shoot positioning (x 2)	10h	15	33h	495
	Hedging (labor, x 2 times)	0h30	17.25	1h40	28
	Tractor	0h30	23	1h40	38
	Topping machine	0h30	14	1h40	23
	Mechanized desuckering (labor, x 2)	1h	15	3h20	50
	Tractor	1h	23	3h20	76
	Desuckering machine	1h	10	3h20	33
Mechanized harvest	Harvesting machine	0h30	230	1h40	380
	Harvest transport (labor)	1h	17.25	3h20	57
	Tractor	1h	23	3h20	76
	Trailer	1h	11.5	3h20	38
Spraying	Spraying (labor, x 8 treatments)	2h	17.25	6h40	114
	Tractor	2h	23	6h40	152
	Sprayer	2h	11.5	6h40	76
	Chemicals (x 8 treatments)				360
TOTAL		64h		213h	**4572**

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vines/ha (except in Bordeaux on soils with TTSW = 300 mm, under both RP and NF climate scenarios). The lowest LA/FW ratio is reached at 2,500 vines/ha (1.14 m^2/kg) in Bordeaux, on soils with TTSW = 300 mm, for both RP and NF climate conditions. Hence, 5,000 vines/ha vineyards show better quality performances in Bordeaux for red wine production under RP climatic conditions compared to lower density vineyards. Under NF climatic conditions maturity is expected to advance by 13 days. This will probably allow growers to increase véraison-harvest duration and bring Cabernet-Sauvignon in Bordeaux to full phenolic ripeness, even at spacings with lower LA/FW ratios, at least at 3,333 vines/ha.

TABLE 2C. Operation-based production cost of a 2,500 vines/ha vertical shoot positioned (VSP) vineyard.

Type of work		Time for 1,000 vines	Cost per hour (€)	Time per ha (2,500 vines)	Cost per ha (€)
Pruning and associated works	Pre-pruning (labor)	0h20	17.25	0h50	14
	Tractor	0h20	23	0h50	19
	Material	0h20	5.75	0h50	5
	Wire placement	1h40	15	4h20	64
	Manual pruning (cordon)	12h	17.25	30h	518
	Electric shear pruning	12h	1.15	30h	35
Trellis maintenance	Trellis maintenance (labor)	3h	15	7h30	113
	Trellis material				300
	Tractor	1h	23	2h30	58
	Trunk tying	3h	15	3h30	113
Fertilization	Labor	0h30	17.25	1h20	22
	Tractor	0h20	23	0h50	19
	Sprayer	0h20	5.75	0h50	5
	Organic fertilizers				300
Soil maintenance by weeding under the row and tillage on inter-row	Weeding (labor, x 2 treatments)	0h40	17.25	1h40	29
	Tractor	0h40	23	1h40	38
	Material	0h40	5	1h40	8
	Chemicals (x 2 treatments)				70
	Tillage (labor, x 4 times)	1h20	15	3h20	50
	Tractor	1h20	23	3h20	77
	Material	1h20	3	3h20	10
Vine replacement (1 % per year)					276
Vegetative operations	Manual shoot positioning (x 2)	11h	15	27h30	413
	Hedging (labor, x 2 times)	0h30	17.25	1h20	22
	Tractor	0h30	23	1h20	29
	Topping machine	0h30	14	1h20	18
	Mechanized desuckering (labor, x 2)	1h	15	2h30	38
	Tractor	1h	23	2h30	58
	Desuckering machine	1h	10	2h30	25
Mechanized harvest	Harvesting machine	0h25	230	1h	230
	Harvest transport (labor)	1h	17.25	2h30	43
	Tractor	1h	23	2h30	58
	Trailer	1h	11.5	2h30	29
Spraying	Spraying (labor, x 8 treatments)	2h	17.25	5h	86
	Tractor	2h	23	5h	115
	Sprayer	2h	11.5	5h	58
	Chemicals (x 8 treatments)				250
TOTAL		65h30		164h	**3608**

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TABLE 3. Results of the 4-way ANOVA considering the effects on average FTSW during the 30 days prior to modeled harvest dates of site (Avignon or Bordeaux), soil TTSW, density and climatic scenario (RP or NF).

	DF	Mean sq	% variance explained	F value	Pr (>F)	Significance
site	1	6.32	46.4	313.96	<2E-16	<0.001
period	1	1.11	8.2	55.28	2.18E-13	<0.001
soil	2	3.28	24.1	162.79	<2E-16	<0.001
density	2	1.31	9.6	64.86	<2E-16	<0.001
site_period	1	0.60	4.4	29.94	5.59E-08	<0.001
site_soil	2	0.58	4.2	28.70	7.38E-13	<0.001
period_soil	2	0.07	0.5	3.30	0.0373	0.05
site_density	2	0.06	0.5	3.15	0.0433	0.05
period_density	2	0.00	0.00	0.14	0.87	ns
soil_density	4	0.24	1.8	12.11	1.25E-09	<0.001
site_period_soil	2	0.00	0.00	0.03	0.9668	ns
site_period_density	2	0.01	0.00	0.23	0.7926	ns
site_soil_density	4	0.01	0.01	0.68	0.6049	ns
period_soil_density	4	0.00	0.00	0.02	0.9994	ns
site_period_soil_density	4	0.00	0.00	0.01	0.9999	ns
residuals	1044	0.02	0.1			

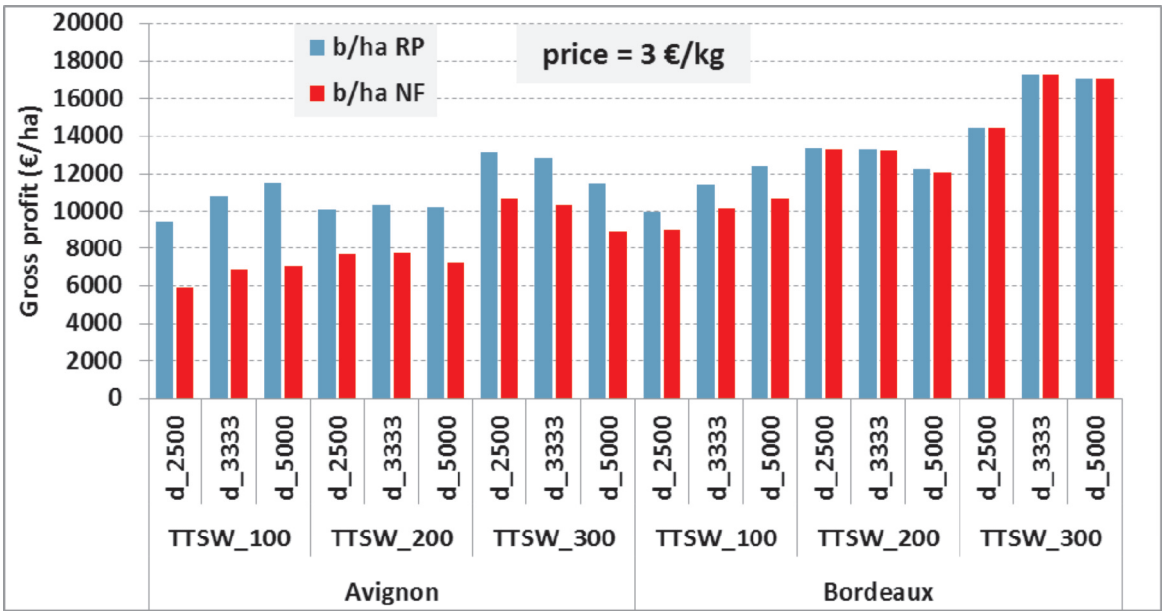


FIGURE 6. Gross profit (€/ha) when grapes are sold for 3 €/kg for two regions (Avignon and Bordeaux), two climatic periods (RP = recent past and NF = near future), three values of TTSW (100; 200; and 300 mm) and three vine densities (5,000; 3,333; and 2,500 vines/ha).

Row spacing is generally closer in cool and wet areas and can be as close as 1.0 m in Pauillac (Bordeaux), Champagne or Burgundy which leads to densities of approximately 10,000 vines/ha. In dry Mediterranean winegrowing regions planting densities are rarely over 5,000 vines/ha. However, under current appellation specifications, maximum row distance is similar in Côtes du Rhône (Avignon) and Bordeaux (2.5 m for a minimum density of 4,000 vines/ha). The driving idea behind including maximum row spacing in appellation specifications (and

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maximum yield) is to ensure sufficient LA/FW ratio, in order to create optimal fruit ripening conditions. In the future, however, the limiting factor for producing high quality wine might be tolerance to water deficit rather than optimal light interception. Hence, in order to use wide row spacing as an adaptation to drier conditions under climate change, appellation rules will need to evolve.

It is assumed that grapevines experience water deficit once FTSW decreases below 0.40 (Lebon *et al.,* 2003). For the Bordeaux simulations, the lowest FTSW around flowering was 0.59 (NF ; TTSW = 100 mm; d = 5,000 vines/ha). Hence, no impact of water deficit on bud fruitfulness is expected in Bordeaux under any scenario. For the Avignon simulations, average FTSW was 0.46 under NF climate at 5,000 vines/ha and TTSW = 100 mm which is close to the threshold and could potentially limit bud fruitfulness in extreme years. Wider vine spacing for this scenario, however, increases FTSW around flowering to 0.55 and 0.61 for 3,333 and 2,500 vines/ha respectively and will limit the risk of a decrease in bud fruitfulness due to water deficits during this sensitive period (Guilpart *et al.,* 2014).

From analysis of variance, a highly significant effect on FTSW during the 30 days prior to modeled harvest is shown for the site ($\alpha < 0.001$), soil (TTSW ; $\alpha < 0.001$), density ($\alpha < 0.001$) and climatic period considered (RP or NF ; $\alpha < 0.001$). Site explains the highest proportion of the total variance (46.4 %), followed by soil (24.1 %), density (9.6 %) and climatic period (8.2 %) (Table 3). FTSW overall is lower for i) Avignon compared to Bordeaux, ii) NF compared to RP climate conditions, iii) soils with lower TTSW and iv) higher planting densities. Highly significant interactions are shown for site and soil TTSW ($\alpha < 0.001$), soil and density ($\alpha < 0.001$) and site and climatic period ($\alpha < 0.001$). Smaller, though significant, interactions appear for period and soil ($\alpha < 0.05$) as well as site and density ($\alpha < 0.05$). Interactions between soil TTSW and other factors are due to the fact that in some scenarios FTSW is very small, because its values are bounded at zero. Interactions between site and climate scenario are due to the fact that climate change will have a bigger impact in the Mediterranean climate of Avignon than in the Atlantic climate of Bordeaux.

Water balance modeling shows that in Bordeaux, on soils with 200 to 300 mm TTSW, climate change will not increase vine water deficit during the ripening period for the NF (2041-2070). The most likely explanation is that the advance in phenology compared to RP (13 days) compensates higher ET_0 and, possibly, lower rainfall in this region. This observation is consistent with Pieri (2010). Climate change has a greater impact in reducing FTSW during grape ripening in the drier climate of Avignon. The biggest effect is shown in this region on soils with low water holding capacity (TTSW = 100 mm), where average FTSW during grape ripening may be reduced up to 9 fold.

Producers may be forced to abandon regions where winegrowing will no longer be economically sustainable under future climatic conditions (Hannah *et al.,* 2013), although they will try to maintain winegrowing in their current production regions through the implementation of adaptations (van Leeuwen *et al.,* 2013). A strong effect of soil TTSW on average FTSW is shown in this study. Lowest average FTSW during grape ripening are obtained on soils with TTSW = 100 mm. A potential adaptation to future drier climatic conditions would be to move, within existing winegrowing regions, vineyards to soils with higher TTSW. However, this adaptation is not always easy, because growers may not always have land available with higher TTSW and may need to buy new land to do so. Land with higher TTSW may be suitable for other crops and conflict may rise around the agricultural destination of such land.

An easier adaptation to drier conditions is to plant vineyards with wider row spacing. The underlying ideas are that vines transpire less because of lower sunlight interception and that each vine has access to greater soil water reserves at lower planting densities. The latter is only true when vine roots fully explore the soil. According to Champagnol (1984), in a high fertile soil, a vine can explore 10 m^2 of soil surface ; this area is 4 m^2 in a low fertile soil. In our study, the lowest density considered is 2,500 vines/ha, where each vine has access to 4 m^2 of soil surface. However, in our simulations this density results from a 4*1 m spacing (and not a 2*2 m spacing), which means vine roots may have difficulty in exploring the entire inter-row.

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TABLE 4. Increase of average FTSW during grape ripening when density is reduced from 5,000 to 2,500 vines/ha, for different climatic scenarios and soil TTSW, for Avignon and Bordeaux.

	d5,0000	d3,333	d2,5000	Increase for d5,0000 to d2,5000
RP				
avi_gr				
TTSW_100	0.15	0.17	0.18	0.03
TTSW_200	0.11	0.15	0.21	0.10
TTSW_300	0.15	0.24	0.34	0.19
bor_cs				
TTSW_100	0.18	0.19	0.20	0.02
TTSW_200	0.17	0.25	0.35	0.18
TTSW_300	0.31	0.44	0.54	0.23
NF				
avi_gr				
TTSW_100	0.02	0.02	0.02	0.00
TTSW_200	0.02	0.05	0.10	0.08
TTSW_300	0.07	0.15	0.23	0.16
bor_cs				
TTSW_100	0.13	0.14	0.16	0.03
TTSW_200	0.17	0.25	0.35	0.18
TTSW_300	0.31	0.44	0.54	0.23

Hence, more vigorous rootstocks may be necessary in the wider spaced vineyards. Pruning methods also need to be adapted, because the same bud-load per hectare needs to be divided over 2,500 m of row length in a 4.0 m spaced vineyard, compared to 3,333 m and 5,000 m in respectively 3.0 and 2.0 m spaced vineyards.

As water balance modeling implemented in this study shows, average FTSW during the grape ripening period increases up to 0.23 when row spacing increases from 2 m to 4 m, depending on TTSW, region and climatic scenario (Table 4; Figure 3). This is significant, given that the FTSW range of water deficit in vines runs from 0.40 to 0.00. The highest gain for FTSW is obtained in soils where TTSW is 200 mm or more; at TTSW = 100 mm there is still a gain in FTSW, but it is more limited. In Bordeaux, in the NF climate scenario, with 2,500 vines/ha, average FTSW during grape ripening is 0.16 or higher. In Avignon, with wide spacing (4 m), average FTSW in NF is 0.10 or higher, except on soils with very low TTSW (100 mm), where average FTSW during this period is 0.02.

There is also an important question about the effect of vine water deficit stress on resulting wine quality. In order to investigate this point, water balance models have been run for the Bordeaux area with measured climate data from 1961-2018, with the same TTSW values used in the current study (100, 200 and 300 mm) and for a widely used density (5,000 vines/ha) (Figure 7). During this 58-year period, for the most common situation under RP climate conditions in Bordeaux (TTSW = 200 mm), average FTSW during 30 days before harvest was 25 times between 0.00 and 0.10. These 25 dry years included many vintages with very high quality. Each year overall red wine quality is rated by wine brokers Tastet and Lawton (Samazeuilh *et al.,* 2006) on a scale from 0-20, where 20 is the best possible quality. Vintage quality is inversely correlated to average FTSW during the grape ripening period (Figure 8; $\alpha = 0.005$). Average quality score is 17.5 for vintages with FTSW < 0.10, while it is 14.0 for vintages with FTSW > 0.10. Not one very dry vintage in Bordeaux over the past 56 years obtained a poor quality score due to excessively dry conditions. This analysis shows that wine quality losses because of excessive drought are very rare, at least in Bordeaux. As a result, wide spacing cannot be recommended in the Bordeaux area in the RP, nor in the NF climate conditions, for the production of high quality red wines in

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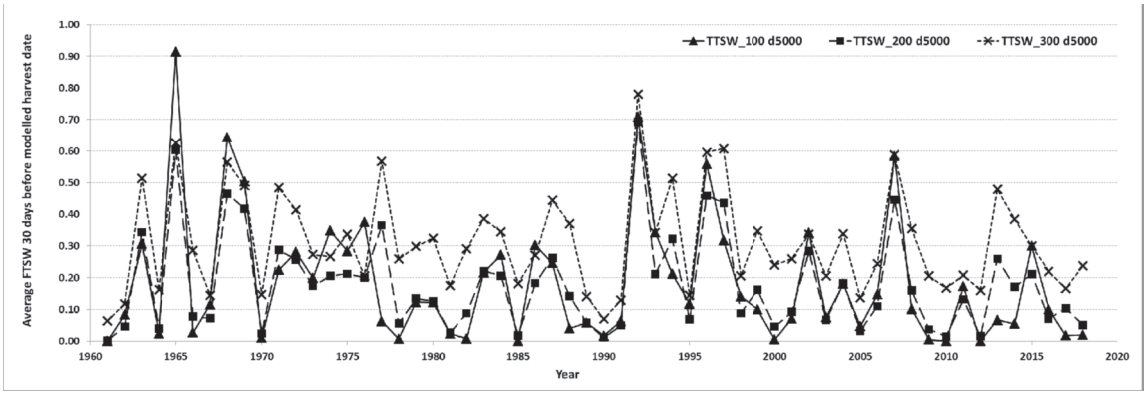


FIGURE 7. FTSW calculated over the 30 days prior to modeled harvest dates for Bordeaux from 1961-2018 for a 5,000 vines/ha vineyard at three values of TTSW (100 ; 200 ; and 300 mm).

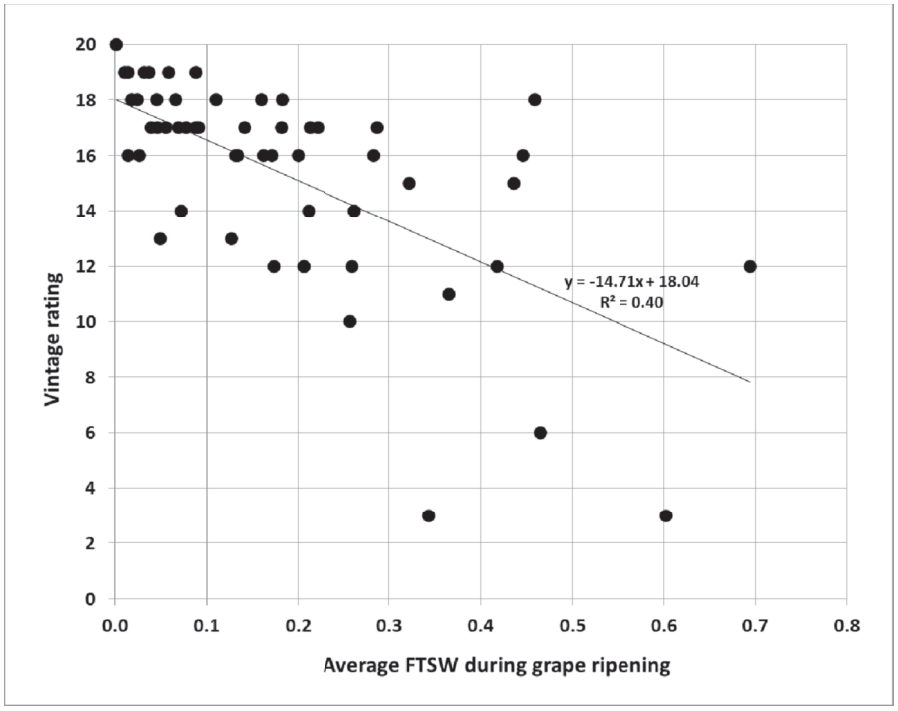


FIGURE 8. Correlation between vintage rating and FTSW during grape ripening in Bordeaux from 1961-2014.

soils with TTSW of 200 mm or higher, because water deficits will not be sufficient to meet quality requirements.

With wider spacing, yield decreases (Table 1) and so does production cost per hectare (Table 2). In this study, we simulated gross profits per hectare of vineyard (in €/ha), taking into account operation-based production cost and revenues simulated from yields, and an assumption of harvested grape values of either 1 €/kg (Figure 5) or 3 €/kg (Figure 6). At 1 €/kg, gross profit per hectare increases with decreasing density (i.e. it is higher for wider spaced vineyards). At this value of grapes, the effect of reduced operation-based production cost for low density vineyards is greater than the effect of reduced yields and revenue. At grape value of 3 €/kg, the effect of wider spacing on gross profit per hectare is less consistent. The tendency is that it increases with higher density of soils with TTSW = 100 mm (the effect of higher yields outweighs the effect of lower operation-based production costs), while it remains stable at soils with TTSW = 200 or 300 mm. Except in Bordeaux on soils with

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TTSW = 200 or 300 mm, gross profit per hectare decreases in NF climate scenarios, because of reduced yields. At 1 €/kg of grape value, reducing density can in any scenario compensate for this effect; this is not the case at a grape value of 3 €/kg or higher. The production cost analysis in this study does not take into account the value of the land, or any indirect costs. Yields are approximately 30-35 % lower in wide spaced vineyards. When land is cheap, production objectives (in hL for the entire estate) can be obtained on greater surfaces with low density compared to high density vineyards. This "extensive agriculture" approach may not be applicable in regions where land is expensive. Another limit of this study is that it does not address fixed production costs (overheads). When acreage under vine cannot be increased, overheads increase when yield is reduced due to a decrease in planting density. In that situation, increasing selling prices due to better wine quality and better image (because of resource protection) may be the solution.

Our analysis shows that wide spaced trellised vineyards can be an economically sustainable and environmentally friendly solution to cultivate vines and produce high quality wines in increasingly warm and dry conditions under climate change, except in situations where the value of grapes produced is higher. In some regions, low density plantations may already be common, but this is not a general situation. In the southern Côtes du Rhône, a region for which the climatic data was used in this study (Avignon), the Appellation rules impose a minimum of 4,000 vines/ha and a maximum spacing of 2.5 m between rows. Water deficits may not be sufficient in wide spaced vineyards on soils with medium to high TTSW in Bordeaux for NF climate scenario. Vineyards were traditionally cultivated in dry Mediterranean areas as goblet trained bush vines. This training system is highly drought resistant but these vineyards are increasingly uprooted because of difficulties for mechanization, in particular for harvest. Low density, trellised vineyards do not have this drawback. Irrigation is increasingly applied in Mediterranean vineyards, but potentially to the detriment of increasingly scarce water resources. Irrigation also has the drawback of potentially increasing soil salinity which could render a vineyard unfit for vine cultivation over time. Compared to the other adaptations to increasingly warm and dry conditions under climate change, wide spacings offer a cost effective and easy to implement alternative, with minimal environmental impact.

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