Water Balance Indices for Tropical Wine Grapes

Antônio Heriberto de Castro Teixeira,
Jorge Tonietto and Janice F. Leivas

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72751

Abstract

Over the last few decades, the Brazilian semiarid region has appeared as one of the main tropical wine production areas in the country. The aim of this research was the elaboration and application of water balance indices to upscale them in the wine grape growing regions of the Petrolina and Juazeiro counties in the states of Pernambuco (PE) and Bahia (BA), respectively, simulating different pruning dates along the year. Previous energy balance measurements were used for relating the crop coefficient (Kc) with the accumulated degree-days (DD_{ac}). The model was applied to upscale the water balance indices during the growing seasons (GS). It was concluded that if irrigation water is available, the best pruning periods are for GS from May to July because of better natural thermal and moisture conditions. Much care should be taken for pruning done in other periods of the year, with regard to the effect of increasing thermal conditions on wine quality. The classifications and delimitations done, joined with other environmental characteristics, are important for a rational planning of the commercial tropical wine production expansion, mainly in the actual situations of climate and land use changes together with rising water competition along the years in the Brazilian semiarid region.

Keywords: evapotranspiration, crop coefficient, vineyard adaptation, water resources, *Vitis vinifera*

1. Introduction

The influence of climatic variables during the vineyard growing seasons on wine quality is well known because they influence the grapevine growth and then the berry composition. For wine grape crops, plant phenology, wine quality, and yield are very dependent on climate at regional, local and microclimatic scales [1–4]. For any of these spatial scales, considerations of grape site selection, cultural practices, and water management are important, which are very important issues for potential adaptations to different climate scenarios; however, large-scale climate has been the focus for assessing the climate change impacts [5–8].

The optimal vineyard response to air temperature (T_a) ranges between 20 and 35°C [9]. According to Fraga et al. [3], a 10°C basal temperature (T_b) is needed for the growing season onset. However, high thermal conditions contribute to increase sugar content in grapes, resulting in large alcohol concentration and low acidity in wines, rising pH [2, 10–12]. There are also important secondary thermal effects, such as increase of pest and disease risks, like downy and powdery mildew, especially under rainy conditions [4, 13, 14].

Rising thermal conditions (T_a > 30°C) should increase suspended solid concentrations, but high Brix levels may be attributed to large evapotranspiration (ET) rates [15]. According to Webb et al. [16], high T_a during the harvest period may reduce berry quality due to increasing ET. These issues make the rational water management an important issue for controlling water deficiencies and excesses, and the need of vineyard water requirements (WR) quantification [12, 17, 18].

Taking into account the water balance, on the one hand, warming conditions can directly affect the vineyard WR, which, together with low precipitation (P) amounts, promote high levels of aridity and water demand. On the other hand, high soil moisture throughout the growing season may cause excessive vigor, increased risks of pest and diseases, and other problems related to wine quality and to the balance of its chemical components [4, 9, 19–21]. All these thermohydrological effects during the vineyard growing seasons on wine quality and production show the importance of water accounting to delimitate areas and seasons with suitable climatic aptitude for winemaking processes.

A large number of climate models have been used worldwide to classify winemaking regions by using different methodologies. For aptitude delimitation, aiming at grape and wine production, one can apply bioclimatic indices based on the thermohydrological requirements. The multicriteria climatic classification (MCC) system proposed by Tonietto and Carbonneau [22] has been used under temperate climate conditions in Europe [23] and in South America [24, 25]. However, the method has worked well considering a single, 6-month growing season per year under temperate climate conditions.

Over the last years, the Brazilian semiarid region has appeared among the main tropical wine-producing areas in the country, typically growing under irrigation conditions and trained mainly in vertical shoot-positioning systems. With proper irrigation and cultural management practices, the farmers can produce grapes and carry out winemaking at any time of the year, allowing a potential average of between two and three vineyard-growing cycles per year, in accordance with and depending on each variety. The T_a rising with a consequent increase in ET rates and aridity in this region will affect both the wine grape quality and vineyard water requirements.

The coupled effect of increasing water consumption and decreasing precipitation, together with land use change, makes it important to elaborate and upscale indices for subsidizing winemaking adaptations and water productivity improvements. Vineyard water variables have been quantified in this region by point measurements [26, 27] but to upscale these punctual results, tools such as remote sensing and geographic information system (GIS) can be

http://dx.doi.org/10.5772/intechopen.72751

used. For the vineyard climatic suitability determination, one can apply water balance indices by using GIS and long-term weather data [4, 18, 21, 28]. For the vineyard water balance indices used in this chapter, distinctions are important between reference (ET_0) and actual (ET) evapotranspiration. ET_0 is the water flux from a reference surface, not a shortage of water, which may be considered as a hypothetical grass surface with specific characteristics, while ET is the real water flux occurring from the surfaces in a specific situation involving all environmental conditions [29].

This chapter aims to elaborate on and apply water balance indices to be scaled up by using a GIS in the wine grape growing regions of Petrolina and Juazeiro counties, located respectively in the semiarid regions of Pernambuco (PE) and Bahia (BA) states, simulating different pruning dates along the year. These indices were delimitated and analyzed, generating criteria for a rational expansion of irrigated and rain-fed vineyards with higher probability of success for tropical wine elaboration. The results generate criteria for a rational expansion of irrigated and rain-fed vineyards with higher probability of success for the Brazilian tropical wine elaboration, under the actual scenario of rising water competition by irrigated agriculture and nonagricultural sectors.

2. Materials and methods

2.1. Study region and data set

A net of agrometeorological stations was used throughout interpolation processes in a GIS environment. The stations are spread in the Petrolina (PE) and Juazeiro (BA) counties, with seven of them inside irrigated farms and the other seven in the natural vegetation, called "Caatinga." The gridded weather data well characterize the horizontal thermohydrological contrast between these mixed agroecosystems (**Figure 1**).

According to Teixeira [19], in the Brazilian Northeast semiarid region, disturbed currents from the South, North, East, and West influence the climatology. Excluding the places of high altitude, all areas present long-term annual T_a higher than 24°C, with the average maximum of 33°C and the average minimum of 19°C. The warmest months are October and November when the Sun is close to the zenith position with low cloud cover, and the coldest ones are June and July at winter solstice in the Southern hemisphere. The thermal homogeneity strongly contrasts with the spatial and temporal heterogeneity of the rainfall regime, with the rainy period from November to April (90% of the annual total), the period January to April representing 68% of the annual rainfall. The weather variables in the current study involved a 10-year period (2003–2012). Monthly data were used to calculate the reference evapotranspiration (ET0) by the Penman-Monteith method [29].

2.2. Modeling vineyard water balance indices

Previous Bowen ratio energy balance data from Teixeira et al. [26] for the cv. *Syrah* in the Brazilian semiarid region were used. **Figure 2** shows the details of the field experiment carried out in Petrolina (PE), Northeast of Brazil.

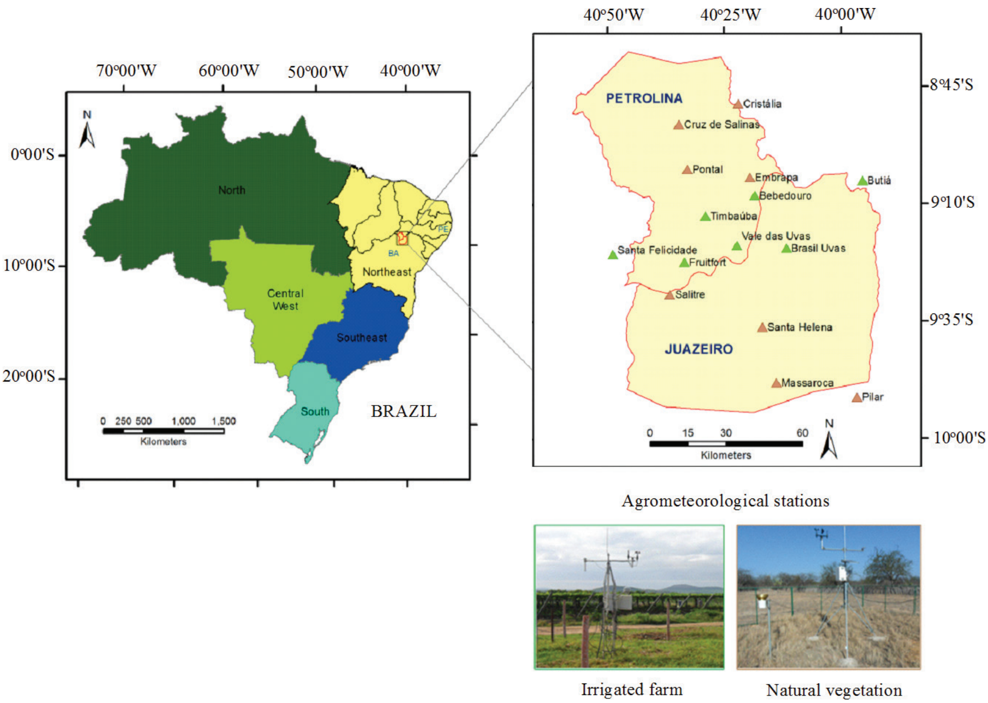

Figure 1. Petrolina and Juazeiro counties, respectively in Pernambuco (PE) and Bahia (BA) states, in the Brazilian Northeast, together with the agrometeorological stations used for the interpolation processes.

The energy balance equation for the wine grape can be expressed by means of bulk energy and heat fluxes:

$$R_n - \lambda E - H - G = 0 \tag{1}$$

where R_n is the net radiation, λE is the latent heat flux, H is the sensible heat flux, and G is the soil heat flux.

The vineyard λE was obtained by a partitioning parameter:

$$\lambda E = \frac{R_n - G}{1 + \beta} \tag{2}$$

where β is the Bowen ratio:

$$\beta = \gamma\left(\frac{\Delta T}{\Delta e}\right) \tag{3}$$

and γ (kPa °C^{-1}) is the psychrometric constant, ΔT(°C) the temperature gradient measured by dry thermocouples, and Δe (kPa) is the water vapor pressure gradient measured by the difference between dry and wet thermocouples over the height interval above the vineyard canopy surface.

Figure 2. Measurements of gradients of air temperature, vapor pressure and wind speed; incident and reflected shortwave; net radiation; acquisition data system; and soil moisture in Bowen ratio system of wine grape.

Actual evapotranspiration (ET) was derived from the latent heat of vaporization (λ), density of water, and λE. The field experiment was close (3 km) to Bebedouro station (**Figure 1**), which ET0 data allowed the acquirement of the crop coefficient (Kc) along the crop stages [29]:

$$Kc = \frac{ET}{ET0} \tag{4}$$

Considering a base temperature (T_b) of 10°C, Kc was related with the accumulated degree days DD_{ac} [30]:

$$Kc = aDD_{ac}^{2} + bDD_{ac} + c \tag{5}$$

where $a = -2 \times 10^{-7}$, $b = 4 \times 10^{-4}$ and $c = 0.54$ are the regression coefficients ($R^2 > 0.70$).

Further, Kc was used to obtain the ET under potential conditions, which in turn considered the vineyard water requirements (WR), using the cv. *Syrah* as a reference wine grape in the study region. WR for a growing season (GS) was acquired by simulating different pruning date and considering a 4-month mean GS duration under the Brazilian semiarid conditions:

$$WR_{GS} = Kc_{GS} ET0_{GS} \tag{6}$$

Five Kc values were taken into account, being DD_{ac} zero at the start of a GS, while the other DD_{ac} values were calculated, along the GS, with the average T_a for the subsequent months. The five-Kc averaged values and the total ET0 for a GS ($ET0_{GS}$) were considered for acquiring WR_{GS}.

Another indicator, the water balance difference (WBd), was applied to quantify the magnitude of excess or deficiencies of water in the vineyards on large scales for a GS, where P_{GS} is the total growing season precipitation:

$$WBd_{GS} = P_{GS} - WR_{GS} \tag{7}$$

Neglecting the water storage in the root zones in the vineyard water balance, difficult to consider in large-scale analyses, positive WBd values are a quantification of vineyard water excess, while the negative ones are related to the vineyard water deficiencies.

The WR_{GS} together with P_{GS} values allowed the development and application of the water balance ratio (WBr) indicator:

$$WBr_{GS} = \frac{P_{GS}}{WR_{GS}} \tag{8}$$

WBr takes into account the thermohydrological conditions, and it is a measure of the water availability in the vineyard root zone. When it is around 1.00, imply the feasibility for rain-fed wine grape, while those much higher should indicate moisture excess problems, independently of the absence or not of irrigation. Low WBr values mean possibility of natural water deficiencies and the degree of irrigation needs according to the pruning dates.

3. Results and discussion

Figure 3 shows the T_{GS} maps, for different wine grape pruning dates along the year, considering a mean 4-month GS, and the 10-year period from 2003 to 2012.

The coldest and the hottest growing seasons (GS) are those for pruning dates between April and July and from September to December, respectively. Considering the standard deviation (SD) values, there are low thermal spatial variations, due to the proximity of the counties to the equator. The lowest air temperatures for a growing season (T_{GS}) occur at the winter

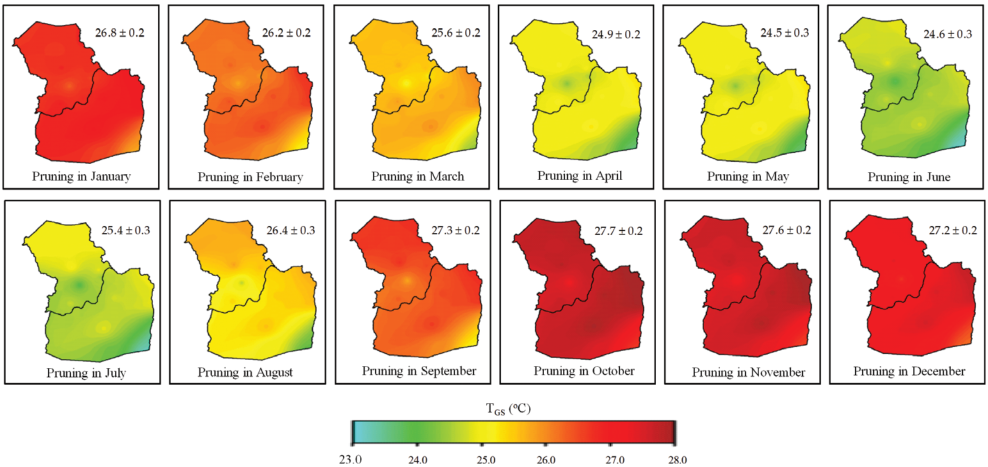

Figure 3. Spatial averages of mean air temperature values for a 4-month wine grape-growing season (T_{GS}), and a 10-year period (2003–2012), simulating different pruning dates, in the Petrolina (PE) and Juazeiro (BA) counties, Northeast Brazil. The mean pixel values and standard deviations are also indicated.

solstice time in the Southern hemisphere, while the highest ones are when the Sun is around the zenith position over the Brazilian tropical wine grape growing region. For pruning done during the coldest periods, several pixels present T_{GS} values lower than 24°C, while one can see all the areas with T_{GS} higher than 26°C, for pruning in the hottest months.

There are no thermal limitations for wine grape crop in the Brazilian semiarid region, with pruning dates in the middle of the year. On the one hand, for all pruning periods, T_{GS} pixels are below 30°C, which conditions around or above this value should increase suspended solid concentrations [15]. On the other hand, T_{GS} values are not below the threshold of 10°C, which could introduce a dormancy stage in temperate climates [3]. The T_{GS} values in the study area are between 23°C and 28°C, inside the optimum thermal range pointed by Gouveia et al. [9].

However, when the pruning is done from September to December, many areas with T_{GS} above 27°C often occur and could affect negatively the wine quality. These latter conditions will contribute to high sugar content in grapes but wines with increasing levels of alcohol, low acidity, and large pH values. These effects together will promote a wine unbalance with instability for the phenolic and aromatic composition [2, 3, 10–12].

Figure 4 shows the P_{GS} maps, for different wine grape pruning dates along the year, considering a mean 4-month GS, and the 10-year period from 2003 to 2012.

The pruning dates with the highest P_{GS} are those from December to February, with several pixel values larger than 300 mm GS^{-1} in the Petrolina County. During this period, the largest moisture spatial variation is also verified according to the SD values. The lowest P_{GS} are for pruning between May and July. High pixel values occur in the northwestern side of Petrolina (PE), while the lowest ones occur in the southwestern area of Juazeiro (BA).

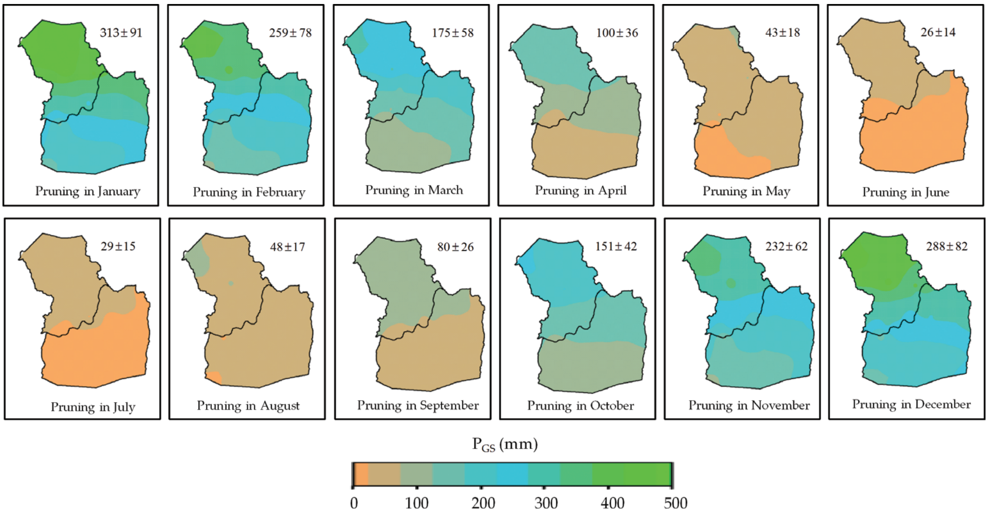

Figure 4. Spatial averages of total precipitation for a 4-month wine grape-growing season (P_{GS}), and a 10-year period (2003–2012), simulating different pruning dates, in the Petrolina (PE) and Juazeiro (BA) counties, Northeast Brazil. The mean pixel values and standard deviations are also indicated.

Taking into account all pruning dates, the rainfall amounts in Petrolina (PE) are 61% larger than in Juazeiro (BA). Thus, in the first county, there are more possibilities of matching the vineyard water requirements with rainfall together with supplementary irrigations, whenever irrigation water is available. However, as a first guess, risks of pest and diseases and other problems related to wine quality and to the balance between its chemical components are higher for pruning done from December to February [4, 9, 19–21].

Considering the cv. *Syrah* as reference for wine grapes in the growing regions of Petrolina (PE) and Juazeiro (BA), and the long-term weather conditions (2003–2012), the WR_{GS} spatial values for a 4-month mean GS are presented in **Figure 5**.

The pruning dates with the highest WR_{GS} are from August to October, with average pixel values larger than 420 mm GS^{-1}, when, according to the SD values, there are also the highest spatial variations. Pruning done from March to May will promote the lowest water consumptions, with mean WR_{GS} below 350 mm GS^{-1}, and the smallest SD values, below 25 mm in March and April. Large WR_{GS} occur in the northwestern side of Petrolina (PE), what might correspond to good grape yield and wine quality if water is available together with techniques to avoid natural water excesses in the root zones [4, 12]. However, special attention should be given under water scarcity conditions, when there is ample room for water productivity improvements in situations of lower atmospheric demands [21].

Taking into account all pruning dates along a year, the water demands in the Petrolina (PE) county are 10% larger, when comparing with those for Juazeiro (BA) one. Daily average WR values in the study region were between 2.7 and 3.6 mm day^{-1}, being similar to the ET rates

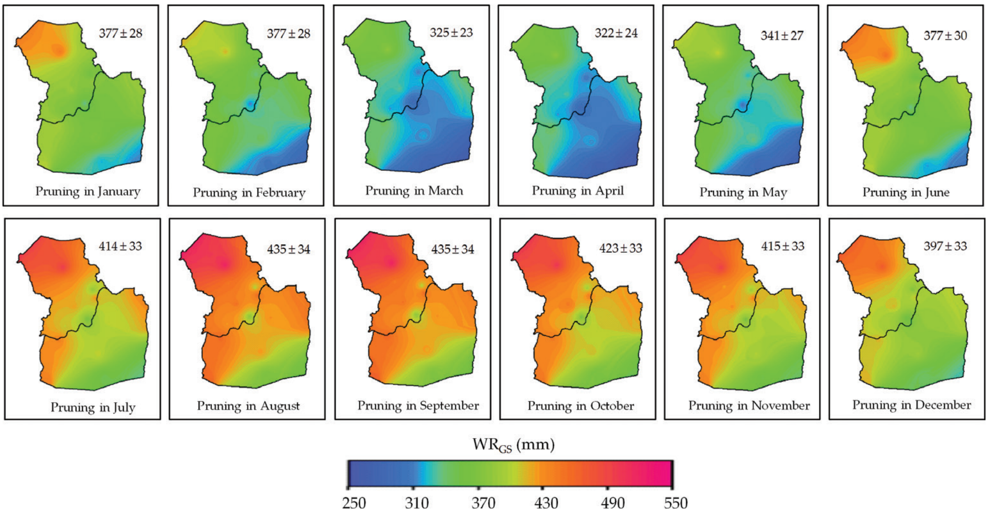

Figure 5. Spatial averages of the water requirements for a 4-month wine grape-growing season (WR_{GS}), and 10-year period (2003–2012), simulating different pruning dates, in the Petrolina (PE) and Juazeiro (BA) counties, Northeast Brazil. The mean pixel values and standard deviations are also indicated.

http://dx.doi.org/10.5772/intechopen.72751

found throughout field experiments in different wine grapes growing regions of the world [27, 30, 31], bringing confidence to the upscaling techniques applied in the current case study.

Table 1 resumes the averages and SD values of the vineyard water balance indices for each 4-month pruning date per county, for the wine grape, cv. *Syrah* considering the period of weather data from 2003 to 2012 in the growing region of Petrolina – Pet (PE) e Juazeiro – Jua (BA), in the semiarid region of Northeast Brazil.

No significant differences arise among the T_{GS} mean values from Petrolina (PE) and those from Juazeiro (BA) with average for all pruning periods of 26°C GS^{-1} for both counties; however, the second one presents larger spatial thermal variation, according to the SD values.

In case of P_{GS}, the values for Juazeiro (BA) are lower those for Petrolina (PE), indicating higher possibility of rainfall water use by the vineyards in the second county. As the vineyard thermal conditions between them did not differ so much, the WR_{GS} values for Juazeiro (BA) were, in average, 90% of those for Petrolina (PE). These differences could be attributed to the effect of relative humidity (RH) in the ET0 calculations, as lower P_{GS} reduce RH in Juazeiro (BA) when comparing with Petrolina (PE).

Keeping in mind that the wine quality depends on both thermal and water conditions, these conditions were analyzed throughout the mean pixel values and standard deviations (SD)

Pruning date	T_{GS} (°C)		P_{GS} (mm GS^{-1})		WR_{GS} (mm GS^{-1})	
	Pet	Jua	Pet	Jua	Pet	Jua
January	26.7 ± 0.1	26.8 ± 0.3	396 ± 65	253 ± 52	398 ± 23	362 ± 20
February	26.2 ± 0.1	26.3 ± 0.3	329 ± 57	209 ± 47	372 ± 22	337 ± 18
March	25.6 ± 0.1	25.6 ± 0.3	224 ± 47	139 ± 35	342 ± 19	313 ± 18
April	25.0 ± 0.1	24.9 ± 0.3	130 ± 28	78 ± 22	340 ± 19	310 ± 19
May	24.6 ± 0.2	24.4 ± 0.3	58 ± 14	32 ± 11	361 ± 22	327 ± 20
June	24.8 ± 0.2	24.5 ± 0.3	40 ± 10	17 ± 7	399 ± 25	360 ± 22
July	25.5 ± 0.2	25.3 ± 0.3	44 ± 8	18 ± 7	439 ± 28	396 ± 24
August	26.5 ± 0.2	26.3 ± 0.3	65 ± 11	37 ± 7	461 ± 29	416 ± 24
September	27.3 ± 0.2	27.2 ± 0.3	105 ± 17	62 ± 12	461 ± 29	417 ± 23
October	27.7 ± 0.1	27.7 ± 0.3	191 ± 28	121 ± 21	448 ± 27	404 ± 22
November	27.6 ± 0.1	27.6 ± 0.3	292 ± 40	189 ± 33	441 ± 26	396 ± 22
December	27.2 ± 0.1	27.3 ± 0.3	365 ± 57	233 ± 45	420 ± 24	368 ± 21
Mean	26.1 ± 0.1	26.2 ± 0.3	187 ± 32	116 ± 25	407 ± 24	367 ± 21

Air temperature (T_{GS}); Precipitation (P_{GS}); and Water requirements (WR_{GS}).

Table 1. Mean values and standard deviations (SD) of the vineyard water balance indices for the wine grape, cv. *Syrah*, considering a 4-month average growing season (GS) and a 10-year period (2003–2012), in the Petrolina—Pet (PE) and Juazeiro—Jua (BA) counties, Northeast Brazil.

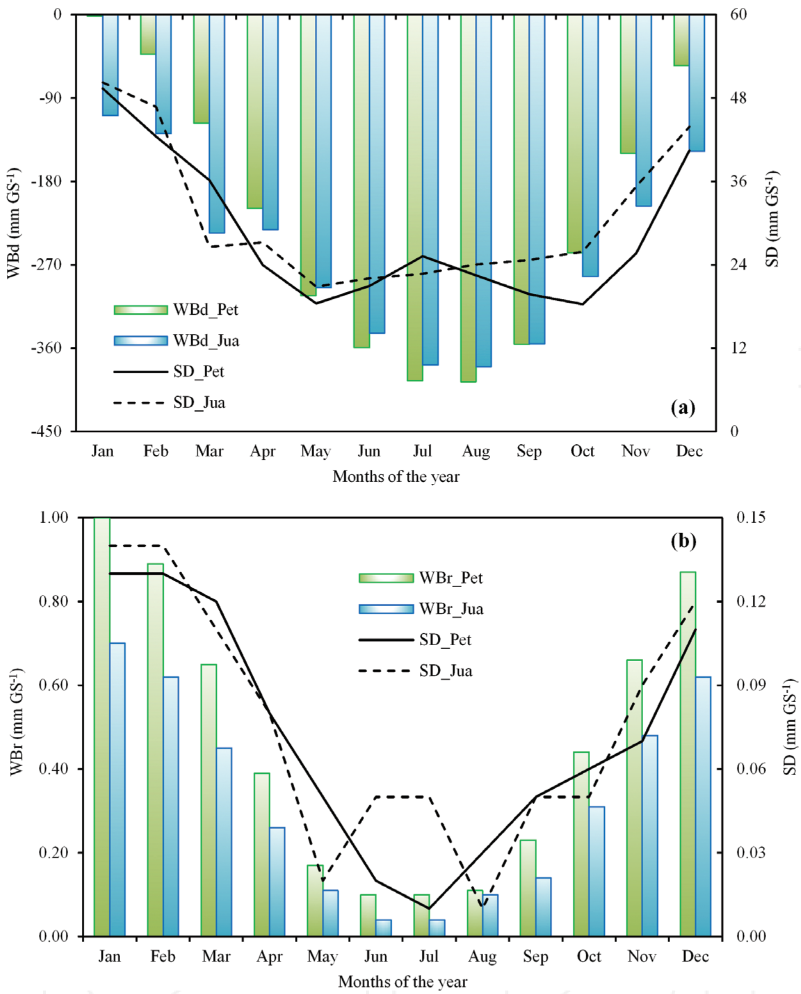

Figure 6. Mean pixel values and standard deviations (SD) for the water balance indices, considering a 10-year period (2003–2012) and an average 4-month wine grape-growing season, cv. *Syrah* according to the simulated pruning dates, in the Petrolina—Pet (PE) and Juazeiro—Jua (BA) counties, Northeast Brazil: (a) water balance difference (WBd) and (b) water balance ratio (WBr).

of WBd and WBr for a 4-month average growing season and according to the pruning dates considering the 10-year period of weather data (2003–2012) (**Figure 6**).

According to **Figure 6a**, there are no positive WBd mean values, meaning that considering the whole area and the average conditions; in general, there is absence of vineyard water excesses for any pruning dates. Disregarding the water storage in the root zones in the vineyard water balance, the pruning periods with the highest water deficiencies (the most negative WBd) are from June to September, when both counties presented average WBd pixel values lower than −340 mm GS^{-1} and also the lowest SD, around 23 mm GS^{-1}. The less negative WBd values obtained for pruning dates are from December to February, when the average was above −150 mm GS^{-1}. These last thermohydrological conditions indicated the feasibility of rain-fed wine grape with supplementary irrigation. Natural water deficiency in Petrolina is 87% of that for Juazeiro, with better chances of success for rain-fed wine grapes, once rainfall-water storage techniques are applied.

As, in average, P_{GS} in Petrolina is 61% higher than that for Juazeiro, but WR_{GS} is only 11% larger (**Table 1**), the differences regarding rainfall amounts will affect more the water balance than the different evapotranspiration rates between the counties. Similarly to the WBd index, pruning dates from December to February present the highest $WBr_{,}$ with averages ranging from 0.60 to 1.00, meaning that rainfall amounts met from 60 to 100% of the vineyard water demands during these pruning periods; however, SD values for both of them are around 0.10 (**Figure 6b**).

Although rainy conditions having the beneficial aspect of natural water availability, increasing soil moisture may reduce the ripening capacity of grapes, and the difficulty of water stress management is unfavorable for the organoleptic wine quality. In this sense, care should be also taken for improving drainage for both irrigated and rain-fed vineyards during the periods of high WBr.

The natural climate dryness conditions occur when the pruning is done from May to August. Under these circumstances, the WBr values are around 0.10 with almost no spatial variation, favoring more the irrigated vineyards. These conditions avoid plant diseases, root respiration problems, and direct damage to the berries promoted by excess of precipitation, favoring the quality of must and wine [3, 4, 9, 12, 20, 21].

4. Conclusions

Water balance indices are successfully developed and applied, allowing the large-scale analyses of the thermohydrological conditions for wine grape production under the semiarid conditions of the Brazilian Northeast, considering different pruning dates along the year.

On the one hand, under irrigation conditions, the best wine grape pruning dates in the Brazilian Northeast are from May to August, with the thermohydrological conditions favoring a better tropical wine quality. On the other hand, the most problematic pruning periods for irrigated crops are from December to February because the joint effects of higher air temperatures and precipitations. Considering the possibility of rainfed crops, this last period should be considered in situations with the possibility of supplementary irrigation applying rainfall water storage techniques.

The spatial delimitations carried out in the current research, joined with other environmental characteristics, are important for the success of the commercial tropical wine production expansion, considering also the sustainability of the activity in the Brazilian semiarid region, where the land use and climate changes are happening together with water competition during the last decades.

Acknowledgements

The authors acknowledge the National Council for Scientific and Technological Development – CNPq (Processe 404229/2013-1), for the financial support to a project. The research deals with agricultural water productivity in hydrological basins with land use changes in Brazil.

Author details

Antônio Heriberto de Castro Teixeira[1]*, Jorge Tonietto[2] and Janice F. Leivas[3]

*Address all correspondence to: heriberto.teixeira@embrapa.br

1 Embrapa Coastal Tablelands, Aracaju-SE, Brazil

2 Embrapa Grape and Wine, Bento Gonçalves, Rio Grande do Sul, Brazil

3 Embrapa Satellite Monitoring, Campinas, São Paulo, Brazil

References

[1] Jones GV, Webb LB. Climate change, viticulture, and wine: Challenges and opportunities. Journal of Wine Research. 2010;**21**:03-106. DOI: 10.1080/09571264.2010.530091

[2] Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA. An overview of climate change impacts on European viticulture. Food and Energy Security. 2012;**1**:94-110. DOI: 10.1002/fes3.14

[3] Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JÁ. Climate factors driving wine production in Portuguese Minho region. Agricultural and Forest Meteorology. 2014;**185**:26-36. DOI: 10.1016/j.agrformet.2013.11.003

[4] Lorenzo MN, Ramos AM, Brands S. Present and future climate conditions for winegrowing in Spain. Regional Environmental Change. 2016;**16**:617-627. DOI: 10.1007/s10113-015-0883-1

[5] Malheiro AC, Santos JA, Fraga H, Pinto JG. Climate change scenarios applied to viticultural zoning in Europe. Climate Research. 2010;**43**:163-177. DOI: 10.3354/cr00918

[6] Neethling E, Petitjean T, Quénol H, Barbeau G. Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change. Mitigation Adaptation Strategy for Global Change. 2017;**22**:777-803. DOI: 10.1007/s11027-015-9698-0

[7] Dunn MR, Lindesay JA, Howden M. Spatial and temporal scales of future climate information for climate change adaptation in viticulture: A case study of user needs in the Australian winegrape sector. Australian Journal of Grape and Wine Research. 2015;**21**:226-239. DOI: 10.1111/ajgw.12138

[8] Tóth JP, Végvári Z. Future of winegrape growing regions in Europe. Australian Journal of Grape and Wine Research. 2016;**22**:64-72. DOI: 10.1111/ajgw.12303, 10.1111/ajgw.12138

[9] Golveia C, Liberato MLR, DaCamara CC, Trigo RM, Ramos AM. Modelling past and future wine production in the Portuguese Douro Valley. Climate Research. 2011;**48**:349-362. DOI: 10.3354/cr01006

[10] Tarara JM, Lee J, Spayd SE, Scajel CF. Berry temperature and solar radiation alter acylation, proportion, and concentration of anthocyanin in merlot grapes. American Journal of Enology and Viticulture. 2008;**59**:235-247. DOI: 10.5344/ajev.2016.15106. ISSN 0002-9254

[11] Orduña RM. Climate change associated effects on grape and wine quality and production. Food Research International. 2010;**43**:1844-1845. DOI: 10.1016/j.foodres.2010.05.001

[12] Maxwell JT, Ficklin DL, Harley GL, Jones GV. Projecting future winegrape yields using a combination of *Vitis vinifera* L. growth rings and soil moisture simulations, northern California, UAS. Australian Journal of Grape and Wine Research. 2016;**22**:73-80. DOI: 10.1111/ajgw.12138

[13] Centeno A, Baeza P, Lissarrague JR. Relationship between soil and plant water status in wine grapes under various water deficits regimes. HortTechnology. 2010;**20**:585-593. ISSN: 1063-0918

[14] Caffarra A, Rinaldi MF, Eccel E, Rossi V, Pertot I. Modelling the impact of climate change on the interaction between grapevine and its pests and pathogens: European grapevine moth and powdery mildew. Agriculture Ecosystems and Environments. 2012;**148**:89-101. DOI: 10.1016/j.agee.2011.11.017

[15] Keller M. Managing grapevines to optimize fruit development in a challenging environment: A climate change primer for viticulturists. Australian Journal of Grape and Wine Research. 2010;**16**:56-69. DOI: 10.1111/j.1755-0238.2009.00077.x

[16] Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR. Earlier winegrape ripening driven by climatic warming and drying and management practices. Nature Climate Change. 2012;**2**:259-264. DOI: 10.1038/nclimate1417

[17] Anderson K, Findlay C, Fuentes S, Tyerman S. Garmaute Climate Change Review: Viticulture, Wine and Climate Change. Adelaide: University of Adelaide; 2008

[18] Teixeira AH de C, Hernandez FBT, Lopes HL. Up scaling table grape water requirements in the low-middle São Francisco River basin. Acta Horticulturae. 2014;**1038**:655-662. DOI: 10.17660/ActaHortic.2014.1038.83

[19] Teixeira AH de C. Water Productivity Assessments from Field to Large Scale: A Case Study in the Brazilian Semi-Arid Region. Saarbrücken: LAP Lambert Academic Publishing; 2009. 226 p. ISBN: 978-3838327785

[20] Santos JA, Grätsch SD, Karremann MK, Jones GV, Pinto JG. Ensemble projections for wine production in the Douro Valley of Portugal. Climate Change. 2013;**117**:211-225. DOI: 10.1007/s10584-012-0538-x

[21] Teixeira AH de C, Hernandez FBT, Scherer-Warren M, Andtrade RG, Victoria D de C, Bolfe EL, Thenkabail PS, Franco RAM. Water productivity studies from earth observation data: Characterization, modeling, and mapping water use and water productivity. In: Prasad ST, editor. Remote Sensing of Water Resources, Disasters, and Urban Studies. Vol. III. 1st ed. Boca Raton: Taylor and Francis; 2015. pp. 101-126. ISBN: 9781482217919

[22] Tonietto J, Carbonneau A. A multicriteria climatic classification system for grape-growing regions worldwide. Agricultural and Forest Meteorology. 2004;**124**:81-97. DOI: 10.1016/j.agrformet.2003.06.001

[23] Blanco-Ward D, García Queijeiro JM, Jones GV. Spatial climate variability and viticulture in the Miño River Valley of Spain. Vitis. 2007;**46**:63-70. ISSN: 0042-7500

[24] Ferrer M, Pedocchi R, Michelazzo M, Gonzalez-Neves G, Carbonneau A. Delimitación y descripción de regiones vitícolas del Uruguay en base al método de clasificación climática multicriterio utilizando índices bioclimáticos adaptados a las condiciones del cultivo. Agrociencia. 2007;**11**:47-56. ISSN: 1405-3195

[25] Montes C, Perez-Quezada JF, Peña-Neira A, Tonietto J. Climatic potential for viticulture in Central Chile. Australian Journal of Grape and Wine Research. 2012;**18**:20-28. DOI: 10.1111/j.1755-0238.2011.00165.x

[26] Teixeira AH de C, Bastiaanssen WGM, Bassoi LH. Crop water parameters of irrigated wine and table grapes to support water productivity analysis in Sao Francisco River basin, Brazil. Agricultural Water Management. 2007;**94**:31-42. DOI: 10.1016/j.agwat.2007.08.001

[27] Azevedo PV, Soares JM, Silva V de P, Silva BB, Nascimento T. Evapotranspiration of "superior" grapevines under intermitente irrigation. Agricultural Water Management. 2008;**95**:301-308. DOI: 10.1016/j.agwat.2007.10.011

[28] Teixeira AH de C, Scherer-Warren M, Hernandez FBT, Andrade RG, Leivas JF. Large-scale water productivity assessments with MODIS images in a changing semi-arid environment: A Brazilian case study. Remote Sensing. 2013;**5**:5783-5804. DOI: 10.3390/rs5115783

[29] Allen RG, Pereira LS, Raes D, Smith M. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Rome: Food and Agriculture Organization of the United Nations; 1998. 300 p

[30] Williams LE, Ayars JE. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. Agricultural and Forest Meteorology. 2005;**132**:201-211. DOI: 10.1016/j.agrformet.2005.07.010

[31] Ortega-Farias S, Carrasco M, Olioso A, Acevedo C, Poblete C. Latent heat flux over Cabernet Sauvignon vineyard using the Shuttleworth and Wallace model. Irrigation Science. 2007;**25**:161-170. DOI: 10.1007/s00271-006-0047-7