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Spatial and temporal characteristics of dryness/wetness for grapevine in the Northeast of China between 1981-2020

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Summary

The Northeast of China has a marked continental monsoon climate characterized by dry and wet hazards that have destructive impacts on wine grape yields and quality. The purpose of this study was to analyze the spatiotemporal characteristics of dryness/wetness of grapevines in the wine region of northeast China from 1981 to 2020. The Crop Water Surplus and Deficit Index (CWSDI) was used to characterize the dryness/wetness using meteorological data collected at 15 meteorological stations located in or near the wine region of northeast China from 1981–2020. Results showed that the multi-year average precipitation could satisfy the water requirement of grapevine with the average CWSDI of 43% (Bud burst), 35% (Shoot growth), 40% (Flowering), 73% (Berry development), 24% (Maturation) and 56% (Full growing stage) respectively for grapevine. Most growing stages experienced a wetting trend and varied discontinuously with the abrupt change in years. The drought-stricken areas were smaller than wet-stricken areas for each growing stage, especially for berry development and full growing stages. The drought and wet characteristics were stage-specific during the grapevine growth period. The precipitation, CWSDI, wet frequency, and wet risk increased from northwest to southeast for each growing stage, while crop evapotranspiration (ETc), drought frequency and drought risk showed the opposite characteristics. The drought risk was lower than wet risk in the Northeast wine region. These results can be used to develop strategies for mitigating and adapting dryness/wetness events in the wine regions of northeast China.

Key words

Northeast China, grapevine, wine region, dryness, wetness

Introduction

Anthropogenic influence has warmed the atmosphere, ocean and land at an unprecedented rate. The global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99°C [0.84-1.10°C] higher than 1850-1900 and it will continue to increase by 1.5°C and 2°C during the 21st century unless significant reductions in CO_2 and other greenhouse gas emissions occur in the coming decades (IPCC, 2021). Continued global warming has led to increasingly frequent extreme weather events and has caused greater challenges of human survival and sustainable development of the social economy. The third National Climate Change Assessment Report has shown that the disasters caused by extreme weather and climate events account for more than 70% of the natural disasters in China (Qin *et al.*, 2015). China is a major contributor of the global grape and wine industry with the second largest vineyard surface area, the seventh largest wine production, and the fifth largest wine consumption in the world (OIV, 2016). There are eleven wine regions, which are primarily delimited according to meteorological geographic divisions and administrative divisions (Wang *et al.*, 2018a). In the Northeast wine region, which is the world's largest ice grape production region dominated by cold climate, cold-resistant species are widely distributed in this area (Wang *et al.*, 2018a). The climatic conditions are very important and can explain 24.1% of the wine variances (Blotevogel *et al.*, 2019). Northeast China has a marked continental monsoonal climate characterized by dry and wet risk affected by global climate change (Wang *et al.*, 2018a). Drought has disastrous impact on viticulture around the world (Ma *et al.*, 2012; Krasensky and Jonak, 2012), and unfavorable abundant rainfall during ripening could lead to severe disease outbreaks and epidemics causing losses that may range from 40 to 90% (Du *et al.*, 2015; Meng *et al.*, 2012). Reductions in fruit quality and

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yield cause significant economic losses to the grape industry. Therefore, there is a need to fully assess the spatiotemporal risk of dryness and wetness in the Northeast wine region of China.

Natural disaster risk assessment is defined as the assessment of both the occurrence probability and degree of damage caused by natural disasters (Zhang *et al.*, 2002). Some studies took the frequency of disasters as the factor of hazards, but did not consider the intensity of disasters (Wang *et al.*, 2018a; Zhang, 2004; Hu *et al.*, 2014). Some studies divided disasters into multiple intensity levels and assigned different weights while ignoring the distribution of disaster intensity (Chen and Yang, 2013; Kim *et al.*, 2015; He *et al.*, 2011). Probability density function (PDF) is an improved method which can reflect the distribution of the disaster intensities and assess the risk more accurately (Mishra *et al.*, 2009). Therefore, the PDF method was chosen in the present study to explore drought and wet risk in the Northeast wine region.

Climatic indicators (such as precipitation, temperature and others) and indices, commonly known as variables and parameters, are numerically computed values from meteorological or hydrological inputs and have always been used to assess disaster risk. Numerous climatic indices have been used to characterize and monitor drought and wet conditions, such as the percentage of precipitation anomaly (Pa) (Van Rooy, 1965), aridity index (Budyko, 1974; Arora, 2002; Erinç, 1965), China composite index (China Meteorological Administration, 2006), Standardized Precipitation Index (SPI) (Mckee *et al.*, 1993), standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano *et al.*, 2010) and crop water surplus and deficit index (CWSDI). Each index has its own adaptability, advantages, and limitations. These indices can be generally classified as non-standardized, standardized, or combination indices. The non-standardized indices are always simple to compute using some available data, but their range for classifying drought level are different. The standardized indices are complicated in computation but their drought level classifications are similar and comparable. The index that only considers precipitation prevents reflecting drought conditions caused by warming, while an index that considered both precipitation and evapotranspiration is suitable for studying the effects of global warming on drought severity (Beguería *et al.*, 2014). CWSDI was a non-standardized index, which considered both the precipitation and evapotranspiration, and has been used to define hazards and assessment of the current extent and severity of hazards over a region. Liu *et al.* (2017) used CWSDI to assess the spatial and temporal behavior of drought during the potential growth period of maize in northeast China (NEC) for 1961–2010, and the result showed that the drought increased from east to west gradually during 1978–1984 and sharply during 2000–2010. Wang *et al.* (2018a) also used CWSDI to analyze the spatio-temporal characteristics of dryness and wetness at different maize growing stages in the Jilin province of China. The result showed that drought increased from the west to the central region and wetness decreased from the west to the central region. The CWSDI proved to be applicable for spatio-temporal characterization of both crop dryness and wetness.

However, most studies used the CWSDI to evaluate the effects of dry and wet changes on food crops. Whether the index can be applied to perennial cash crops needs further study. Therefore, the CWSDI was used to characterize the dryness/wetness of grapevine using meteorological data collected at 15 meteorological stations located in or near the wine region of northeast China from 1981–2020.

(1) To detect the temporal variation of water demand, supply and CWSDI of grapevine during the growing season; (2) to assess the spatiotemporal variations of water demand, supply and CWSDI of grapevine; (3) to explore the dryness/wetness risk of grapevine in the wine region of northeast China. The findings of this study are promising to provide some valuable scientific reference for drought/wet risk mitigation in the wine region of northeast China.

Study area and data analysis

Study area

The study area is located in northeast China (118°53′-135°05′E and 38°43′-53°33′N) and includes Heilongjiang, Jilin and Liaoning provinces (Fig. 1). The annual precipitation is 400-1000 mm, and 80% of the precipitation falls between May and September. The mean annual air temperature ranges from -4.3 to 10.8 °C, and the frost period typically begins on October 2 and ends on March 28 of the following year (Chen *et al.*, 2011). The frost-free season shows similar features of precipitation in terms of its spatial distribution. The annual total sunshine hours are in the range of 2212-2955 h (Liu *et al.*, 2009).

Climatic data

15 weather stations located in or near the northeast wine region were selected to analyze dry and wet conditions (Fig. 1). The observed weather variables, including daily precipitation (P), relative humidity (RH), minimum temperature (T_{min}), mean temperature (T_{mean}) and maximum temperatures (T_{max}), wind speed (U_2), and sunshine hours (n) recorded over the 1981–2020 period were collected from the Meteorological

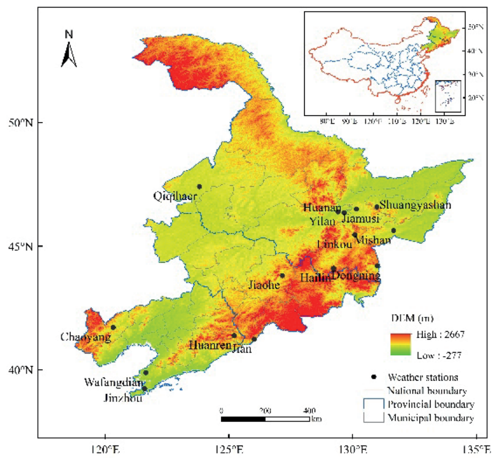

Fig. 1: The study area, weather stations and DEM (Digital Elevation Model) in the Northeast wine region.

Data Sharing Service Network in China following strict quality control. The quality and reliability of the data were cross-examined using nonparametric tests, including the Kendall autocorrelation test and Mann-Whitney homogeneity test (Helsel and Hirsch, 1992).

Crop Water Surplus and Deficit Index (CWSDI) calculation

The CWSDI index was used to quantify the dryness and wetness of grapevine in the Northeast wine region. The grapevine CWSDI was defined as the percentage of the difference between water supply and demand divided by crop water demand, as follows:

$$CWSDI_j = \frac{P_j - ETc_j}{ETc_j} \times 100\% \tag{1}$$

where P_j is the precipitation during a given period (mm), which approximates the grapevine water supply, and ETc_j is the crop evapotranspiration of a given period (mm), which approximates the grapevine water demand.

ETc was determined using the crop coefficient-reference evapotranspiration procedure. The reference evapotranspiration (ET_0) was multiplied by the crop coefficient (K_c) to estimate crop evapotranspiration (*ETc*) as follows:

$$ET_c = k_c \times ET_0 \tag{2}$$

The division of grapevine growth stage and the crop coefficients are shown in the Table in the supplemental materials. The values of *Kc* for the months of May, June, July, August, September, and October are 0.35, 0.52, 0.76, 0.70, 0.60, and 0.45, respectively (Allen *et al.*, 1998; Li *et al.*, 2015). ET_0 was estimated using the FAO-56 Penman-Monteith equation (Allen *et al.*, 1998).

Trend test

The modified non-parametric Mann-Kendall (MMK) method (Hamed and Rao, 1998), after adding a correction factor to the original variance computation based on the effective or Equivalent Sample Size (ESS) to avoid the effect of the temporal data auto-correlation (Kendall, 1975; Mann, 1945), was applied to analyze the tendency of the dryness/wetness indices.

The modified MMK statistic Z^* was calculated by the following equations:

$$Z^* = \frac{Z}{\sqrt{n^s}} \tag{3}$$

$$n^s = 1 + \frac{2}{n(n-1)(n-2)} \sum_{j=1}^{n-1} (n-j)(n-j-1)(n-j-2) r_j \tag{4}$$

where n^s is the calibration factor; *j* is the lag number; and r_j is the autocorrelation function of the time series.

A positive value of Z^* indicates an increasing trend, and a negative value of Z^* indicates a decreasing trend, while a zero value of Z^* indicates no trend. At the 1% significance level, the null hypothesis of no trend was rejected if $|Z^*|>2.576$; at the 5% significance level, the null hypothesis of no trend was rejected if $|Z^*|>1.96$; at the 10% significance level, the null hypothesis of no trend was rejected if $|Z^*|>1.645$.

Extent and frequency of drought and wetness

Drought is defined as CWSDI ≤ -30% at each growing stage; Wetness is defined as CWSDI ≥ 30% at each growing stage (China Meteorological Administration, 2006). The drought/wetness extent (PSSD/PSSW) has been defined as the percentage of stations suffering from drought/wetness out of the total 15 stations, calculated by:

$$PSSD = NS_d / 15 \times 100\% \tag{5}$$

$$PSSW = NS_w / 15 \times 100\% \tag{6}$$

where NS_d is the number of stations suffering from drought, NS_w is the number of stations suffering from wetness.

The drought/wetness frequency (DF/WF) has been defined as the percentage of years suffering from drought/wetness out of the total 40 years (1980-2020), calculated by:

$$DF = N_d / 40 \times 100\% \tag{7}$$

$$WF = N_w / 40 \times 100\% \tag{8}$$

where N_d is the number of years suffering from drought; N_w is the number of years suffering from wetness.

Drought/wetness hazard index calculation

Drought/Weness hazard is defined as the frequency and intensity of drought/wetness events. Frequent drought/wetness with high levels of intensity could result in severe hazardous effects. CWSDI was used to identify drought/wetness events and their intensities during the periods of 1981-2020. The following function was used to calculate the drought/wetness hazard:

$$Drought\ hazard = \int_{-\infty}^{-0.3} CWSDI \times f(CWSDI) d(CWSDI) \tag{9}$$

$$Wet\ hazard = \int_{0.3}^{+\infty} CWSDI \times f(CWSDI) d(CWSDI) \tag{10}$$

where the value of CWSDI reflected the intensity of drought/wetness and *f*(CWSDI) was the frequency of CWSDI.

Results

Temporal variation of water demand, supply and CWSDI of grapevine during the growing season

The temporal variation of water demand, supply and CWSDI for different growth stages of grapevine in the Northeast wine region of China from 1981–2020 has been shown in Fig. 2. For bud burst, shoot growth, flowering, berry development, maturation and full growth stages, the average precipitation was 18 mm, 39 mm, 27 mm, 375 mm, 55 mm, and 524 mm, respectively. The average ETc was 13 mm, 30 mm, 22 mm, 219 mm, 46 mm, and 336 mm, respectively, and the average CWSDI was 43%, 35%, 40%, 73%, 24%, and 56%, respectively. These results implied that the multi-year average precipitation could

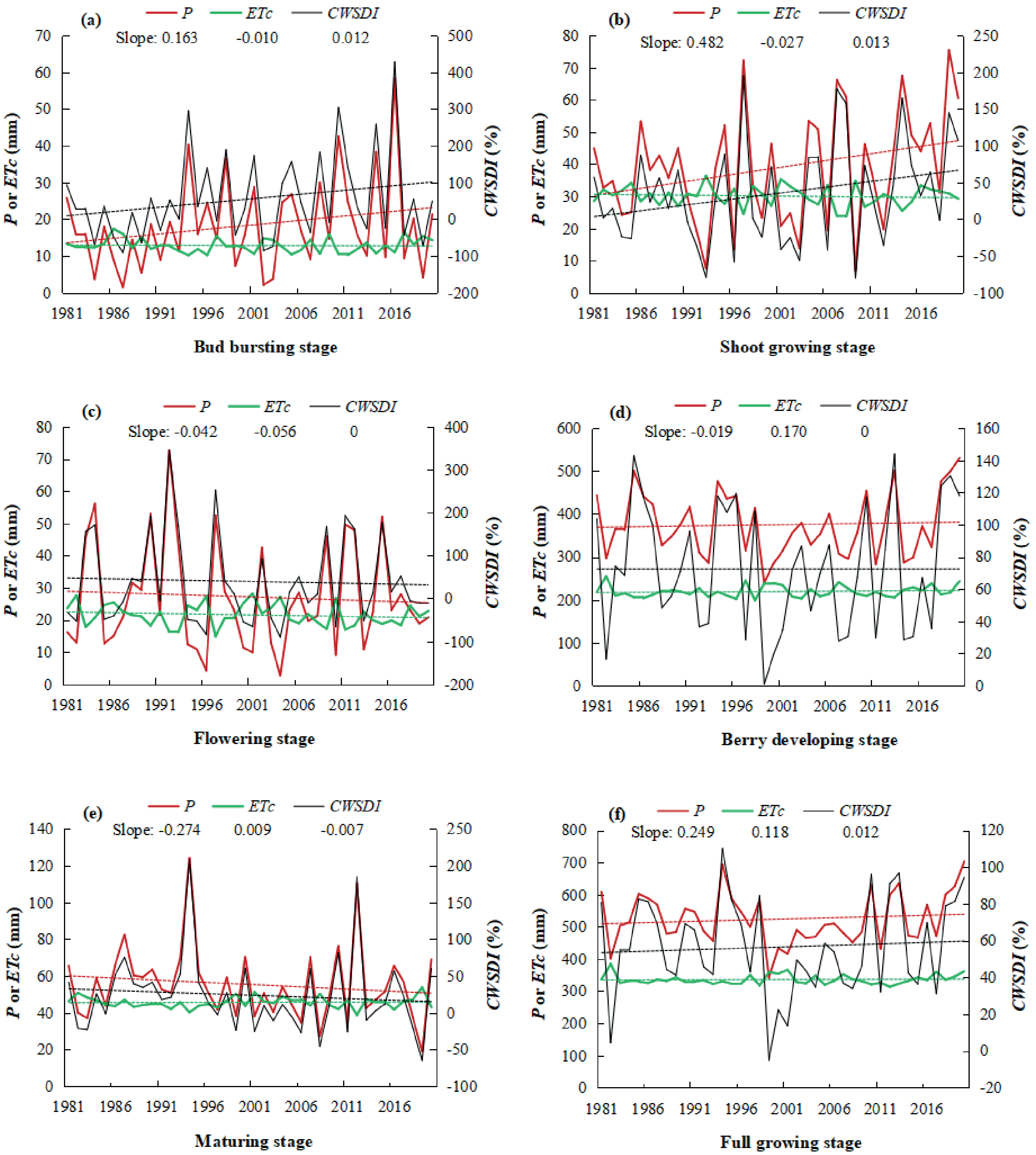

Fig. 2: Temporal variations of the precipitation, evapotranspiration (ETc) and CWSDI for different growth stages of grapevine in the Northeast wine region of China between 1981-2020.

satisfy the water requirement of grapevines for every growth stage. For each year, the precipitation could satisfy the water requirement of the grapevine for the full growth stage, except for 1999. The precipitation, ETc, and CWSDI showed different, insignificant trends for each growth stage from 1981 to 2020. The Sen's slope values of precipitation were 0.163 mm year^{-1}, 0.482 mm year^{-1}, and 0.249 mm year^{-1} for bud burst, shoot growth and full growth stages, respectively, which indicated an increasing trend of precipitation from 1981 to 2020. The Sen's slope values of precipitation were -0.042 mm year^{-1}, -0.019 mm year^{-1} and -0.274 mm year^{-1} for flowering, berry development and maturation stages, respectively, which indicated a decreasing trend of precipitation from 1981 to 2020. The variation of CWSDI was similar to that of precipitation in each growth stage. The Sen's slope values of ETc were -0.01 mm year^{-1}, -0.027 mm year^{-1} and -0.056 mm year^{-1} for bud burst, shoot growth and flowering stages, respectively, which indicated a decreasing trend of ETc from 1981 to 2020. The Sen's slope values of ETc were 0.170 mm year^{-1}, 0.009 mm year^{-1} and 0.118 mm year^{-1} for berry development, maturation and full-growth stages, respectively, which indicated an increasing trend of ETc from 1981 to 2020.

The precipitation, ETc, and CWSDI varied discontinuously (Fig. S1). For bud burst, shoot growth and full growth stages, the points of abrupt change for precipitation occurred in 1993, 2014, and 2020 respectively. They showed a decreasing trend before the year of abrupt change and an increase after that year. For flowering, berry-development, and maturation stages, the points of abrupt change for precipitation occurred in 1994, 1986, and 1998 respectively. They showed an increasing trend before the year of abrupt change and a decreasing trend after that year. The year of abrupt change and variation trends of CWSDI were similar to those of precipitation in each growth stage. For bud burst, shoot growth and flowering stages, the points of abrupt change for ETc occurred in 1987, 1987, and 1988; they showed an increasing trend before the year of abrupt change and a decreasing trend after that year. For berry development stage, the points of abrupt change for ETc occurred in 1982; from 1983 to 1989 it showed a decreasing trend; and a significant trend was shown in 1986. From the 1990s onwards, the ETc increased and decreased alternatively. For the maturation and full growth stage, the points of abrupt change for ETc occurred in 2003 and 2020, and they showed a decreasing trend before the year of abrupt change and a increasing trend after that year.

Temporal variation of PSSD and PSSW of grapevine during the growing season

For bud burst, shoot growth, flowering, berry development, maturation and full growth stage, approximately 40%, 29%, 42%, 5%, 26%, and 3% of stations suffered from drought and 45%, 44%, 41%, 72%, 42% and 69% of stations suffered from wetness respectively. These results indicate that the drought-stricken areas were smaller than wetness-stricken areas for each growth stage, especially for berry development and full growth stages. The PSSD and PSSW showed different insignificant trends for each growth stage from 1981 to 2020 (Fig. S2). The decreasing trends of PSSD were observed in bud burst, shoot growth and flowering stage with a slope value of -0.137%, -0.300%, and -0.119%, respectively. The increasing trends of PSSD were observed in berry development and maturation stage with the slope value of 0.099% and 0.456%, respectively. In the full growth stage, almost no trend for PSSD was observed. The trends of PSSW were opposite to that of PSSD in each growth stage, there were increasing trends in bud burst, shoot growth and flowering stage with slope values of 0.241%, 0.665% and 0.043%, respectively. Decreasing trends of PSSW were observed in berry development and maturation stage with slope values of -0.146% and -0.557%, respectively. In the full growth stage, PSSW increased with a slope value of 0.122%. In general, the trends of PSSW were consistent with CWSDI and PSSD were opposite to CWSDI for each growth stage.

Spatial variation of water demand, supply and CWSDI of grapevine during the growing season

The precipitation increased from northwest to southeast for each growth stage (Fig. S3). The maximum precipitation was in Ji'an, and the minimum precipitation was in Qiqihar during most growth stages. For bud burst, shoot growth, maturing and full growth stage, the maximum precipitation was 27 mm, 53 mm, 73 mm, and 759 mm in Ji'an and the min-

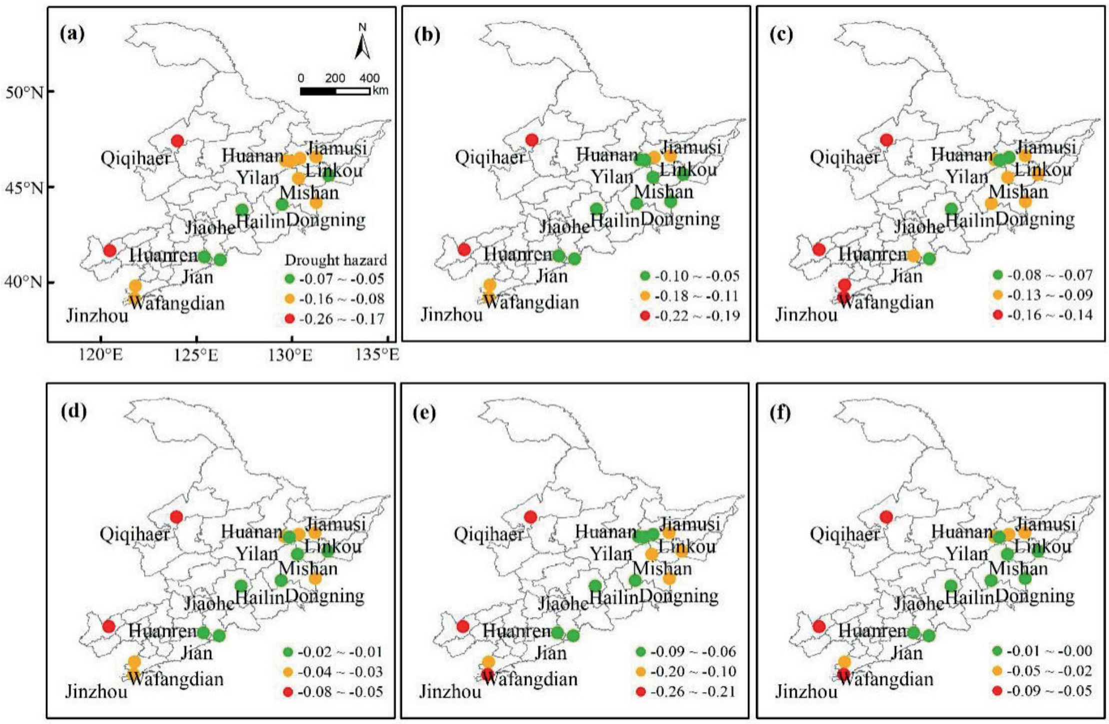

Fig. 3 Spatial distribution of drought hazard for different growth stages of grapevine in the Northeast wine region of China between 1981–2020 (a) bud burst; (b) shoot growth; (c) flowering; (d) berry development, (e) maturation; (f) full growth.

imum precipitation was 7 mm, 27 mm, 39 and 415 mm in Qiqihar, respectively. For the flowering stage, the maximum precipitation was 34 mm in Jiaohe and the minimum precipitation was 18 mm in Jinzhou. For the berry growth stage, the maximum precipitation was in Ji'an as well, it was 554 mm, and the minimum precipitation was 304 mm in Chaoyang.

The ETc decreased from northwest to southeast for each growth stage, and it was higher in Chaoyang, Qiqihar, Jinzhou, and Wafangdian and was lower in Ji'an, Huanren, and Hailin generally (Fig. S4). For bud burst to berry development and the full growth stage, the maximum ETc were in Chaoyang with 17 mm, 39 mm 22 mm, 257 mm and 407 mm, respectively. For the maturation stage, the maximum ETc was in Jinzhou with 59 mm, and Chaoyang had the second highest with 58 mm. The minimum ETc for bud burst and maturation was in Hailin with 11 mm and 39 mm, respectively. For shoot growth and full growth stage, the minimum ETc was in Ji'an with 27 mm and 315 mm, respectively. For the flowering and berry development stage, the minimum ETc was in Dongning and Huanren, with 19 mm and 205 mm, respectively. The difference between these areas was quite small, though the minimum ETc for each growth stage is not in the same area.

The spatial distribution of CWSDI was similar as that of precipitation (Fig. S5). The CWSDI increased from northwest to southeast at each stage. The maximum CWSDI was in Ji'an, and the minimum precipitation was in Qiqihar and Chaoyang during the most growth stages. For the berry development stage, the maximum CWSDI was in Huanren with 169%. For the rest of the growth stages, the maximum CWSDI was in Ji'an, which were 120%, 96%, 67%, 75% and 140% from the bud burst to full growth stage, respectively. The minimum CWSDI was in Chaoyang with -51%, -24% and -21%, respectively from the bud burst to flowering stage, and it was in Qiqihar with 18%, -28% and 2%, respectively from the berry development to full growth stage.

Spatial variation of drought and wet frequency of grapevine during the growing season

Frequent droughts have happened in the bud burst and flowering stage, and less droughts happened in berry development and full growth stages (Fig. S6). The drought frequency decreased from northwest to southeast for each growth stage. The higher drought frequency was in Qiqihar and Chaoyang, and the lower drought frequency was in Ji'an in most growth stages. For the bud burst stage, the maximum drought frequency was in Qiqihar with 70%, for the shoot growth stage, the maximum drought frequency was in Qiqihar and Chaoyang with 58%, for the flowering stage, the maximum drought frequency was in Jinzhou with 58%. For the berry development, maturation and full growth stage, the maximum drought frequency was in Chaoyang, which were 18%, 60% and 20%, respectively. The minimum drought frequency in the bud burst, shoot growth and maturation stage was in Ji'an with 18%, 5% and 10%, respectively. For the flowering stage, the minimum drought frequency was in Mishan with 28%, and Ji'an had the second minimum drought frequency of 33%. For the berry development and full growth stage, the frequency of drought was less in most study areas.

The characteristic of wetness frequency was opposite to the drought frequency in most aspects (Fig. S7). More wetness events happened in berry development and full growth stages. The wetness frequency increased from northwest to southeast for each growth stage. The higher wetness frequency was in Ji'an and Huanren, and the lower wetness

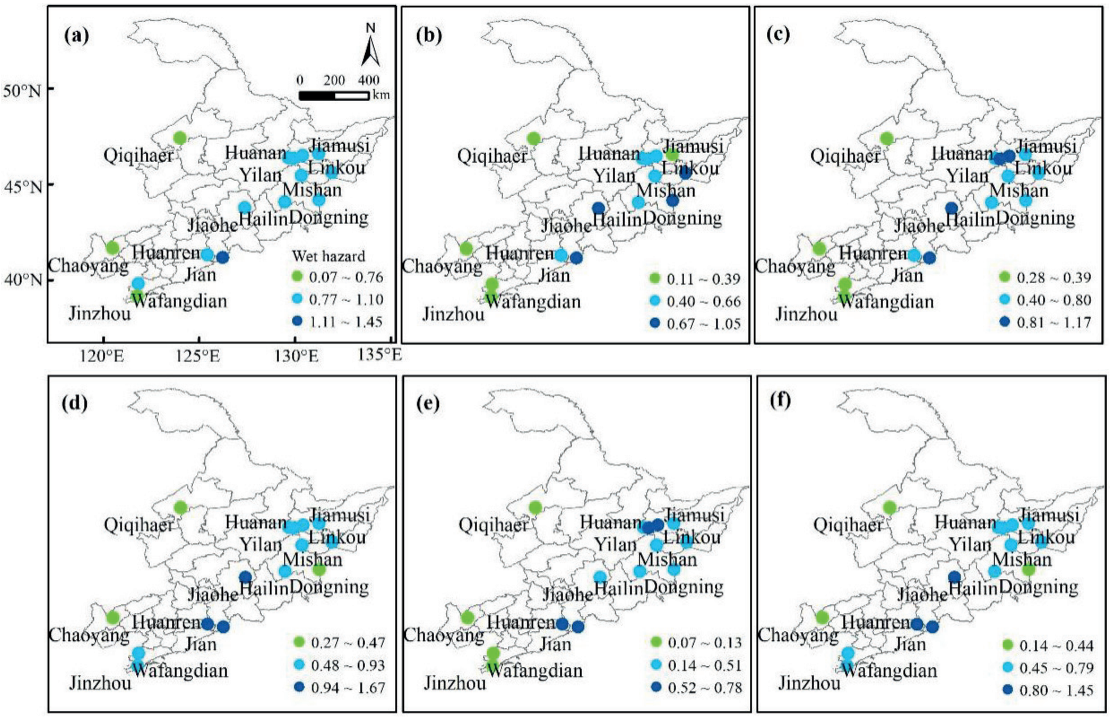

Fig. 4 Spatial distribution of wet hazard for different growth stages of grapevine in the Northeast wine region of China between 1981–2020 (a) bud burst; (b) shoot growth; (c) flowering; (d) berry development; (e) maturation; (f) full growth.

frequency was in Qiqihar and Chaoyang during most growth stages. For bud burst, shoot growth and maturation stage, the maximum wetness frequency was in Ji'an, which was 68% respectively. For the berry development and full growth stage, the maximum wetness frequency was in Huanren with 100%, Ji'an had the second highest wetness frequency with 95%. For the flowering stage, the maximum wetness frequency was in Jiaohe and Jiamusi with 50%. The minimum wetness frequency was in Qiqihar with 20% and 30% for the bud burst and flowering stage, respectively. For shoot growth, berry development, maturation and full growth stage, the minimum wetness frequency was in Chaoyang, with 23%, 40%, 10% and 28% respectively, and Qiqihar had the second lowest wetness frequency.

Spatial variation of drought and wetness hazard of grapevine during the growing season

The spatial distribution of drought risk during different growth stages of grapevine in the Northeast wine region of China over 1981-2020 has been shown in Fig. 3. Drought risk was found to be lower in the berry development stage and the full growth stage. The average drought risk was -0.10, -0.11, -0.11, -0.03, -0.12 and -0.02 for bud burst, shoot growth, flowering, berry development, maturation and full growth stage. Spatially, the drought risk decreased from northwest to southeast for each growth stage, and it was higher in Qiqihar and Chaoyang, and lower in Ji'an and Jiaohe during most growth stages. The maximum drought risk was in Chaoyang from the shoot growth to full growth stage with -0.22, -0.16, -0.08, -0.26 and -0.09, respectively. For the bud burst stage, the maximum drought risk was in Qiqihar with -0.25, and Chaoyang had the second highest drought risk with -0.17. The minimum drought risk was in Ji'an with -0.05, -0.05, and -0.01 for the bud burst, shoot growth and berry development stage, respectively and Jiaohe had the second lowest drought risk. For the maturation stage, Jiaohe had the lowest drought risk, and Ji'an had the second lowest. For the flowering stage, the minimum drought risk was in Jiamusi with -0.07, and Jiaohe and Ji'an had the second lowest drought risk. For the full growth stage, the drought risk was very low, nearly no drought risk existed in the western part.

The spatial distribution of wetness risk at different growth stages of grapevine in the Northeast wine region of China over 1981-2020 has been shown in Fig. 4. The wetness risk was lower during the maturity stage. The average wetness risk was 0.83, 0.57, 0.71, 0.76, 0.40 and 0.59 for bud burst, shoot growth, flowering, berry development, maturation and the full growth stage. The wetness risk increased from northwest to southeast at each growth stage. A higher wetness risk was in Ji'an, and a lower one in Chaoyang and Qiqihar during most growth stages. The maximum wetness risk was in Ji'an with 1.45, 1.05, 1.67, 0.78 and 1.45 from bud burst to full growth stage, respectively except the flowering stage. For the flowering stage, the maximum wetness risk was in Jiamusi with 1.17, and Ji'an had the second highest wetness risk with 1.03. The lowest wetness risk was in Chaoyang from shoot growth to full growth stage with 0.11, 0.28, 0.27, 0.07 and 0.14, respectively and Qiqihar had the second lowest. For bud burst, the minimum wetness risk was in Qiqihar with 0.07, and Chaoyang had the second lowest with 0.26.

Discussion

The multi-year average precipitation could meet the water demand of grapevine, and the risk of wetness was higher than that of drought

The reference crop evapotranspiration (ET_0) is a key parameter of crop water requirement and can be used to represent the water demand (Allen *et al.*, 1998). Generally, rainfall indicates the natural water supply and irrigation water denotes the artificial water supply. Under natural water supply conditions, rainfall and ET_0 are two related random hydrologic variables of the weather system with relevance for irrigation management and planning (Zhang *et al.*, 2017). Many related studies have indicated that the spatio-temporal characteristics of rainfall and ET_0 can explain the changes of the natural water supply and demand in the irrigation district (Katerji and Rana, 2006; Paulo and Pereira, 2007, 2008; Tabrizi *et al.*, 2010; Vangelis *et al.*, 2011). The multi-year average precipitation could satisfy the water requirement of grapevine for every growth stage in the Northeast wine region; these results were consistent with the water situation of grapevine in northeast China reported by Wang *et al.* (2018a). It was also reported that the precipitation could satisfy the water requirement of grapevine for every growth stage in the Ningxia wine region and part of the growth stages in the Yunnan wine region (Li *et al.*, 2014; Li *et al.*, 2016). The precipitation could satisfy the water requirement of grapevine for the full growth stage from 1981 to 2020 in the Northeast wine region except 1999, which was recorded as one of the most spatially extensive drought episode years in China's Meteorological Disaster Encyclopedia (Wen and Ding, 2008). However, the drought and wetness happened in each growth stage of grapevine from 1981 to 2020, like maize, soybean in northeast China (Liu *et al.*, 2017; Yang *et al.*, 2017; Wang *et al.*, 2018b). Although there was basically no shortage of water in the Northeast wine region, it was more likely to have excessive precipitation on the whole, the CWSDI showed a wetting trend for the full growth stage, and the drought-stricken areas were smaller than wetness-stricken areas for each growth stage, especially for berry development and full growth stages. This implied that the risk of wetness was higher than that of drought in the Northeast wine regions. Therefore, drainage and waterproofing were suggested as the important disaster prevention and relief task in the Northeast wine region.

The drought and wet of grapevine exhibited growth stage-specific characteristic

The temporal variation of water demand, supply, CWSDI, PSSD and PSSW of grapevine during the growth season exhibited growth stage-specific. There were increasing trends of precipitation from 1981 to 2020 for the bud burst, shoot growth and the full growth stage, respectively, and decreasing trend for flowering, berry development, and maturation stage. Meanwhile, The ETc decreased from 1981 to 2020 for the bud burst, shoot growth and flowering stage, respectively, and increased for the berry development, maturation and full growth stage respectively. The growth stage- specific of drought for grapevine was observed in Yunnan, Ningxia, and Gansu as well. The CWDI (Crop Water Deficit Index) for grapevine in Ningxia and Gansu initially exhibits an overall upward trend, followed by a subsequent decline and a subsequent rise again (Li *et al.*, 2014; Li *et al.*, 2015). In Yunnan, the CWDI show an upward trend in the later growth stages, with most other stages experiencing a downward trend. However, the majority of these trends are not statistically significant. The frequency of severe drought is higher during the early stages of growth, whereas the frequency of drought at different levels during the middle and later stages is comparatively low (Li *et al.*, 2016). The variations at different stages has also been reported by Guo *et al.*, 2018 that there were significant differences in the rate of change and amplitude of temperature and precipitation for each growth stage of maize in the midwest of Jilin province from 1960 to 2014 (Guo *et al.*, 2018). The different trends of drought characteristics in different maize growth stages in northeast China were found as well, the weakening trends in the early growth stage of maize for most stations, but in the late growth stage, which determines the maize yield, trends are increasing and the extent of drought is expanding (Guo *et al.*, 2017). Different conclusions have been obtained in publications concerning precipitation and evaporation trend in northeast China, and most researches have indicated general increasing of precipitation and decreasing of evaporation over the last several decades in northeast China (Liu *et al.*, 2016; Ma *et al.*, 2017; Yao *et al.*, 2018; Cui and Yin, 2021; Li and Lü, 2022). The reasons for these inconsistent findings may be due to the geographical position (e.g., distance from the ocean, the altitude variations), research period and area, and the fact that some studies on climate change utilize divergent climatic parameters. The relative humidity had a negative effect on the ET_0 which is one of the parameters of CWSDI, and air temperature, wind speed, and sunshine hours had a positive effect (Xu *et al.*, 2006; Liang *et al.*, 2008). It was shown that most weather stations in northeast China experienced decreasing trends in humidity, wind speed and sunshine hours, and increasing trends in air temperature from 1961 to 2013 (Yao *et al.*, 2018). These climate factors can act on the ET_0 at different time scales, resulting in the variation of the ETc, CWSDI, PSSD and PSSW of grapevine during the growing season. The decreasing trends of PSSD were observed in the bud burst, shoot growth and flowering stage respectively. The increasing trends of PSSD were observed in berry development and maturation stage. At the full growth stage, almost no trend of PSSD was observed. The trends of PSSW were opposite to that of PSSD in each growth stage. Thus, the growth stage-specific drought and wet should be taken specific consideration in order to avoid ignoring the disasters hided by the full growth water situation.

The drought of grapevine decreased and the wet of grapevine increased from the northwest to the southeast

The precipitation, CWSDI, wet frequency, and wet risk increased from northwest to southeast for each growth stage. While the ETc, drought frequency and drought risk decreased from northwest to southeast for each growth stage. It was consistent with the finding that the frequency of drought increases gradually from southeast to northwest in Songliao Plain which is around 25% area of the Northeast (Zhang, 2004). Guo *et al.*, 2017 also reported that drought-prone regions exhibit a higher positive correlation, whereas excess precipitation regions have negative correlations with drought indicators in most maize growth stages in northeast China (Guo *et al.*, 2017). It could be inferred from Equation (1) that CWSDI has a negative correlation with ETc and a positive correlation with precipitation. The features of spatial distribution of frequency of drought occurrence and risk are mainly results from the above-mentioned features of precipitation and ETc during the growing season. Precipitation has been reported as the dominant variable that influenced the soybean drought in northeast China (Yang *et al.*, 2017). The precipitation distribution in northeast China is uneven in space, which is mostly related to the northward extension of the East Asian monsoon and topographic distribution. The East Asian summer monsoon plays an important role in precipitation in northeast China, especially in the northward transport of water vapor and heat. The precipitation center in northeast China is located on the windward slope of the Changbai Mountains, and the monsoon flow is relatively easy to reach. The southern half of the sub-maximum rain belt is mainly fed by the monsoon flow, while the northern half is the joint action of the northern boundary of the monsoon flow and the uplift of the Greater Khingan Mountains and Zhangguangcai Mountains, which receive less precipitation on the lee slope due to the descending air flow. The spatial characteristics of drought and wetness of grapevine indicated that the measures of disaster prevention and mitigation, such as rain shelter cultivation, grass growth between rows, integration of water and fertilizer, reasonable frame (bird frame, Y-shaped frame), flower management, deficit adjustment irrigation, simple pruning and so on should be applied more in the northwest for the dryness and southeast for the wetness of grapevine.

Conclusion

This study established the drought/wetness hazard assessment index relative to the aspects of drought intensity and frequency to assess the grapevine growing season drought/wetness hazard during 1981-2020. The Crop Water Surplus and Deficit Index (CWSDI) was used to characterize dryness/wetness using meteorological data collected at 15 meteorological stations located in or near the wine regions from 1981-2020. The main conclusions were as follows:

The multi-year average precipitation could satisfy the water requirement of grapevine for each growth stage. The precipitation showed increasing trend for bud burst, shoot growth and the full growth stage and decreasing trend for other stages. The variation of CWSDI was similar with that of participation in each growth stage. The ETc showed decreasing trend for bud burst, shoot growth and flowering stage and an increasing trend for other stages. The drought-stricken area and wet-stricken areas showed the opposite trends in each growth stage. The decreasing trends of drought-stricken areas were observed during bud burst, shoot growth and flowering stage, while the increasing trends of drought-stricken area were observed in berry development and maturation stage. The drought-stricken area was smaller than wet-stricken areas for each growth stage, especially during berry development and full growth stages. The precipitation, CWSDI, wetness frequency, and wetness risk increased from northwest to southeast for each growth stage, while ETc, drought frequency, and drought risk showed the opposite characteristics. The drought risk was lower than wetness risk.

These results can help policymakers and grapevine stakeholders at various levels (e.g. farmer and industry) to develop mitigating and adapting strategies for dry/wet disasters in the Northeast wine regions of China. It is crucial to carefully consider stage-specific drought and wetness conditions to prevent overlooking potential disasters concealed by the seemingly favorable full growth water situation. Furthermore, heightened attention and disaster management efforts should be directed towards wetness hazards and regions with higher risks, as wetness risk surpasses that of drought and the characteristics in spatial distribution of dryness/wetness for grapevines designates a higher risk region. The approach used in this study incorporates a combination of climatic data and plant physiology parameters to evaluate the dryness/wetness levels. These factors are universal in wine production, and their assessment is essential for vine health, grape quality, and ultimately, wine characteristics. By customizing the specific input data for different regions, the proposed approach can be adapted to various climates found worldwide. However, there are some deficiencies in the research: factors other than climatic index impact the disaster hazard, including social and economic components. For further study, the drought/wetness hazard could be regarded as a multiple system with vulnerability, exposure and emergency response and recovery capability, which is quite valuable for management and mitigation of the drought/wetness hazard.

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Conflicts of interest

The authors declare that they do not have any conflicts of interest.

Supplementary material

Supplementary material to this article can be found in the Supplementary material file at: DOI: 10.5073/vitis.2024.63.02.

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