Drought Analysis During the Growth Stages of Grape in the Main Grape-Growing Regions in China

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Abstract

In China, grape is one of the top five fruit crops for both bearing acreage and production. Recently, national grape production has been stalling because of an increase in drought events. In order to combat the adverse effects of drought on grape production, it is imperative to understand the historical drought trend and frequency during the growing season. In this study, we focused on agricultural drought during the four growth periods of grape: bud break-flowering, flowering-veraison, veraison-berry maturation, and berry maturation-leaf fall. Based on the weather data from 429 meteorological stations, we computed the Crop Water Deficit Index (CWDI) in the five main grape-growing regions of China: Northeast China, North China, Northwest China, Southwest China, and Southeast China. Then we evaluated the CWDI-based drought distribution and trend in the study regions, as well as the frequency of different degrees of drought. The results showed that exceptional drought was occurring frequently in Xinjiang Uyghur Autonomous Region, northern Gansu province, and northern Ningxia Hui Autonomous Region. Among the four study growth periods of grape, exceptional drought was the most expansive during bud break-flowering. What's more, exceptional drought coverage during bud break-flowering in the study regions was increasing from 1981 to 2016. Analysis of butterfly structure showed that the occurrence of drought was continuous and persistent in northern China. Our study results could serve as guideposts to highlight Chinese grape production industry's vulnerability to agricultural drought against the background of climate change.

1. Introduction

Grape (*Vitis vinifera L.*) is the most economically important fruit species in the world (Parmar and Rupasinghe, 2014, Villette *et al.*, 2020). The current world vineyard surface area is approximately 7.4 million ha (Organisation Internationale de la Vigne et du vin, 2019), with more than 76% found in five countries (India, Iran, China, Turkey, and USA). China has more than 2000 years of history of grape cultivation. China ranks first for total grape production and second for vineyard surface area in the world. In 2018, grape cultivation area reached 0.88 million ha and grape yield reached 11.7 million tons (9.5 million tons are table grape yield) in China (OIV, 2019). The grapevine originated in Central Asia. China is one of the origins of table grape, and table grape is a main horticultural crop in China (Du *et al.*, 2008, Nasim *et al.*, 2019). Table grape production accounts for nearly half of the world's total grape production, and China is the largest global producer of table grapes (Liu *et al.*, 2020, Xie *et al.*, 2020). Compared to other fruit trees, grapevines have a relatively short growth cycle (from planting to initial fruit set) but high yield and profit. In addition, grapevines are highly adaptive to a wide range of environmental, soil, and water conditions (Jin *et al.*, 2020). Nowadays, grape is widely planted in all major geographic regions of China (Dubos, 2018, Liang *et al.*, 2019).

Changes in temperature, precipitation, and the frequency and intensity of extreme weather can have significant impacts on crop production (IPCC, 2014). For example, erratic precipitation patterns and increased temperatures will likely make drought events more frequent in many regions, creating major challenges for agriculture (Gambetta *et al.*, 2020). Increasing temperatures have resulted in higher reference evapotranspiration and more frequent years with low rainfall, and will continue to induce more intense and frequent drought conditions for vineyards around the world (Leeuwen *et al.*, 2019). Water is also one of the most limiting factors for global grape production (Costa *et al.*, 2007, Carolin *et al.*, 2019). It is expected that climate change will generally have a negative impact on grape production. In the near-future, worsening extreme heat and water stress may threaten the production of grapes (Fraga, 2019).

Studies indicate that climate change will exacerbate drought events in many traditional grape-growing regions around the world (Intergovernmental Panel on Climate Change, 2014). The grape community will undoubtedly have to face a greater challenge of drought in the future. Climate has generally become warmer and drier in most grape-growing regions, and the impact of drought on grape production has become a hot topic among international scholars. In Europe, the central-south region will have a relatively high risk of summer drought (IPCC) due to increasing temperatures and decreasing precipitation. For example, in the most renowned wine region in Portugal (a southern European country), the projected synergistic effect of heat stress and water deficit in the future could jeopardize the grape production particularly in the south-innermost areas (Fraga *et al.*, 2018). Consequently, the suitable growing areas for grape in Europe will move towards the central-north region (Moriondo *et al.*, 2011, Fraga *et al.*, 2016, Fraga *et al.*, 2016). In China, drought coverage, frequency, and intensity as measured by the crop water deficit index substantially varied among Ningxia Hui Autonomous Region (in northwestern China), Gansu province (in northwestern China) and Yunnan province (in southwestern China) (Li *et al.*, 2014, 2015, 2016).

Studies on the physiology of drought stress in grapevine revealed that a water deficit would increase the accumulation of phenolic contents in grapes, which is detrimental to yield production (Egea *et al.*, 2010, Santesteban *et al.*, 2011, García *et al.*, 2012, Wang *et al.*, 2019). Drought stress could lead to stomatal closure, which negatively affects the gas exchange in plants and the metabolism of plants (Jones *et al.*, 1991, Chen *et al.*, 2011). The gas exchange in plants takes place through stomata, and the process is crucial for grapevine to respond to drought and maintain water use efficiency (Martorell *et al.*, 2015, Bota *et al.*, 2016). When 30% of the maximum soil available water capacity was replenished via irrigation at 55 BBCH-scale, though photosynthesis parameters were not impaired by water restriction, drought was negatively related to stomatal conductance and leaf area growth of the grapevines (Briglia *et al.*, 2020). In addition, drought stress could lead to low flowering, berry-set flower abortion, cluster abscission (Hardie and Considine, 1976, Düring, 1986), and limited photosynthesis in the grapevine (Kofidis *et al.*, 2004, Patakas *et al.*, 2005).

Increasing drought events have been affecting grape production in all main grape-growing regions of China, though knowledge about the regional drought coverage, frequency, and trend during the growth cycle of grape is still very limited. In order to adapt to climate change in the near future, it is essential to fill in the knowledge deficit so that the grape community can take appropriate preventative measures to achieve high yield and quality production . Therefore, we conducted this multi-regional study in China for two purposes: 1) to identify the areas and growth stages where and when the grapevine is the most susceptible to agricultural drought, and 2) to evaluate drought frequency and intensity within the growth cycle of grapevine in those drought-prone areas. Our study results provide scientific evidence for local farmers to take effective measures in order to mitigate drought during the growth cycle in the main grape-growing regions of China.

2. Materials And Methods

2.1. Study regions and data

Grape cultivation area has been expanding constantly in China. In this study, we focused on the grape-growing provinces that contribute to more than 1% of the national grape yield on average (Fig. 1) in the following five geographic regions: Northeast China (including Jilin and Liaoning provinces), North China (including Shanxi and Hebei provinces), Northwest China (including Xinjiang Uygur Autonomous Region, Gansu province, Ningxia Hui Autonomous Region, and Shaanxi province), Southwest China (including Sichuan, Guizhou, and Yunnan provinces), and Southeast China (including Jiangsu, Shandong, Zhejiang, Anhui, Fujian, He'nan, Hubei, Hu'nan provinces, and Guangxi Zhuang Autonomous Region). In these study regions, we obtained historical daily weather data (including maximum, minimum, and average temperatures, precipitation, sunshine hours, wind speed, and average relative humidity) during the period of 1981–2016 from 429 meteorological stations through the China Meteorological Administration Climate Data-Sharing Service System (http://cdc.cma.gov.cn). The dataset was routinely quality controlled by the staff at China Meteorological Administration. We estimated daily solar radiation with the calibrated Ångström formula based on the measured radiation income and observed number of sunshine hours at the study sites (Black et al., 1954, Jones, 1992). We collected grape phenology data (include the bud break, flowering, veraison, berry maturation, and leaf fall dates) from a series of previously published related papers (Table A.1).

2.2. Crop Water Deficit Index

In this study, we chose the commonly used crop water deficit index (CWDI, Eqs. (1) and (2)) (Li *et al.*, 2014, Dong, 2015) to evaluate drought during the growth cycle of grape. We computed CWDI during the four growth periods of grape: bud break-flowering, flowering-veraison, veraison-berry maturation, and berry maturation-leaf fall. We referred to the bud break-flowering and flowering-veraison growth periods as critical for grapevines because they are relatively sensitive to water supply during these two growth periods (Chen *et al.*, 2010, Li *et al.*, 2011). Based on the corresponding CWDI during the critical and non-critical growth periods, we categorized drought intensity scale in five levels: abnormally dry, moderate drought, severe drought, extreme drought, and exceptional drought (Li *et al.*, 2014) (Table 1).

$$CWDI = a \times CWDI_i + b \times CWDI_{i-1} + c \times CWDI_{i-2} + d \times CWDI_{i-3} + e \times CWDI_{i-4} \quad (1)$$

Where *CWDI* is the ten-day cumulative crop water deficit index during the growth stages of grape, $CWDI_i$, $CWDI_{i-1}$, $CWDI_{i-2}$, $CWDI_{i-3}$, and $CWDI_{i-4}$ are the water deficit index for current day, previous 1 day, previous 2 days, previous 3 days, and previous 4 days, respectively, *a, b, c, d,* and *e* are the cumulative weight coefficients of the ten-day period, in this study, *a* is 0.3, *b* is 0.25, *c* is 0.2, *d* is 0.15, and *e* is 0.1.

$$CWDI_i = \begin{cases} \frac{(ETc - P_i)}{ETc} \times 100\% & \text{ETc} > P_i \\ 0 & ETc \le P_i \end{cases} \quad (2)$$

Where $CWDI_i$ is the crop water deficit index during a certain period of time, *ETc* is the crop water requirement during a certain period of time, and P_i is the cumulative precipitation during a certain period of time.

Table 1. The range of CWDI for drought classification during the critical (i.e., bud break-flowering and flowering-veraison) and non-critical (i.e., veraison-berry maturation and berry maturation-leaf fall) growth periods of grape in the study regions.

Category	Description	Critical growth periods	Non-critical growth periods
D0	Abnormally Dry	0< ≤25%	0< ≤30%
D1	Moderate Drought	25%< ≤35%	30%< ≤45%
D2	Severe Drought	35%< ≤45%	45%< ≤60%
D3	Extreme Drought	45%< ≤55%	60%< ≤75%
D4	Exceptional Drought	>55%	>75%

2.3. Drought analysis

In this study, we calculated the drought frequency (Eq. (3)) and percentage of stations showing drought (Eq. (4)) during the four growth periods of grape in the five study regions. In a given area, the percentage of stations showing drought somewhat indicates the drought coverage (Huang *et al.*, 2010，Ma *et al.*, 2020). In addition, we used a “butterfly analysis” to model the probable recurrence feature of drought (Yan *et al.*, 2017). All the incidents were arranged horizontally in an order, and the butterfly diagram shows curves of the annual incidents that reoccur (Jin *et al.*, 2014). The pattern of the butterfly diagram reveals the recurrence probability of the annual incidents (Fig. 2) (Yan *et al.*, 2013, Wang *et al.*, 2018). In order to improve the accuracy of the modeled probability, we determined the lower threshold in the butterfly diagram based on the number of years in the time series (Table 2) (Peng *et al.*, 2019).

$$f = \frac{1}{n}\sum_{i=1}^{n} N_i \quad (3)$$

Where *f* is the drought frequency, *n* is the total number of years for the study period, and   is the number of drought events during a certain growth period of grape.

$$P = n/N \times 100\% \qquad (4)$$

Where *P* is the percentage of stations showing drought, *n* is the number of stations that had a certain level of drought, and   is the total number of stations in a given study area.

Table 2. Reference standards for the lower threshold of the butterfly diagram structure.

Disaster year	Same interval group
N≤5	≥2
6≤N≤10	≥3
11≤N≤15	≥4
16≤N≤20	≥5
N≥21	≥6

3. Results

3.1. Drought intensity and frequency

In the main grape-growing regions of China, CWDI-based drought intensity during bud break-flowering showed a gradual decrease from the north to the south and from the west to the east from 1981 to 2016. Exceptional drought (D4) during bud break-flowering mainly occurred in Xinjiang Uygur Autonomous Region, northern Gansu province, Ningxia Hui Autonomous Region, Hebei province, western Jilin province, northwestern Shandong province, northwestern Yunnan province, and southwestern Sichuan province. Abnormally dry (D0) was mostly in the Southeast China (Fig. 3(a)). During the 36-year study period, drought intensity during flowering-veraison showed a gradual decrease from the north to the south of the study regions. Exceptional drought (D4) during flowering-veraison mostly occurred in Xinjiang Uygur Autonomous Region, northern Gansu province, Ningxia Hui Autonomous Region, and central-south Hebei province (Fig. 3(b)). Drought intensity during the later study growth stages (i.e., veraison-berry maturation and berry maturation-leaf fall) was generally at lower levels than drought intensity during the earlier growth stages of grape (i.e., bud break-flowering and flowering-veraison). During the growth stages of veraison-berry maturation and berry maturation-leaf fall, most of the study regions experienced abnormal dryness (D0) or moderate drought (D1), and exceptional drought (D4) was focused in Xinjiang Uygur Autonomous Region and Gansu province (Fig. 3(c) and (d)).

During all four study growth periods of grape in the study regions, the subtotal frequency of abnormally dry (D0) and exceptional drought (D4) was generally higher than the subtotal frequency of moderate, severe, and extreme droughts (D1, D2, and D3) from 1981 to 2016. Overall, abnormally dry (D0) during the study growth periods of grape occurred in more than 60% of the study years (local farmers referred to it as ‘three times per five years’) in southern China. The areas where exceptional drought (D4) existed in more than 60% of the study years differed from growth period to growth period. During bud break-flowering, exceptional drought (D4) existed in more than 60% of study years in Xinjiang Uygur Autonomous Region, northern Gansu province, Ningxia Hui Autonomous Region, Hebei province, northwestern Shandong province, western Jilin province, southwestern Sichuan province, and Yunnan province. During flowering-veraison, exceptional drought (D4) existed in more than 60% of study years in Xinjiang Uygur Autonomous Region, northern Gansu province, Ningxia Hui Autonomous Region, and southern Hebei province. During veraison-berry maturation and berry maturation-leaf fall, exceptional drought (D4) existed in more than 60% of study years in Xinjiang Uygur Autonomous Region and northern Gansu province. During all four study growth periods of grape, extreme drought (D3) existed in fewer than 10% of the study years in most of the study regions. Meanwhile, severe drought (D2) existed in 20%–30% of the study years in North China and the western part of Northeast China. During veraison-berry maturation and berry maturation-leaf fall, moderate drought (D1) existed in 20%–30% of the study years in North China, Northeast China, and Southeast China regions (Fig. 4).

3.2. Drought coverage and trend

The annual percentages of stations indicate the drought coverage in a certain area. During the 36-year study period, more than 33% of the study stations showed exceptional drought during bud break-flowering in 20 of the study years, more than 25% of the study stations showed exceptional drought during flowering-beraison in 21 of the study years. During veraison-berry maturation (berry maturation-leaf fall), 10%–25% of the study stations showed moderate drought in 35 (31) of the study years. Overall, drought was more spread out and intense during bud break-flowering and flowering-veraison stages than other study growth stages (Fig. 5).

From 1981 to 2016, the annual percentage of stations showing moderate drought during all four study growth periods of grape unanimously displayed an increasing trend. During bud break-flowering, the annual percentage of stations showing severe drought displayed a decreasing trend while the annual percentage of stations showing exceptional drought displayed an increasing trend. During the other three growth periods of grape, the annual percentage of stations showing severe drought displayed an increasing trend but the annual percentage of stations showing exceptional drought displayed a decreasing trend. During berry maturation-leaf fall, the annual percentage of stations showing extreme drought displayed a decreasing trend. By contrast, during bud break-flowering, flowering-veraison, and veraison-berry maturation, the annual percentage of stations showing extreme drought all displayed an increasing trend (Fig. 5).

3.3. Drought recurrence feature

According to the drought butterfly structure diagram, exceptional drought (D4) recurred every 1yr. during both bud break-flowering and flowering-veraison from 1981 to 2016 in Northwest China. During veraison-berry maturation, exceptional drought (D4) showed recurrences of every 1yr. and 2yr., though the recurrence of 1yr. was more evident, extreme drought (D3) showed recurrences of every 1yr., 2yr., 4yr., and 9yr., with the recurrence of every 9yr. being the most manifest. During berry maturation-leaf fall, exceptional drought (D4) showed recurrences of every 2yr., 7yr., 9yr., and 11yr., with the dominant recurrence being every 7yr., extreme drought (D3) showed recurrences of every 1yr., 2yr., 4yr., 5yr., 6yr., and 7yr., with the relatively more apparent recurrences of every 1yr., 2yr., and 7yr. (Figs. A.2-A.6). Overall, drought was more frequent during the study grape growth stages in northern China (including Northwest China, North China, and Northeast China) than in southern China (including Southwest China and Southeast China). In northern China, different levels of drought (i.e., D1, D2, D3, and D4) showed the recurrence of every 1yr. during various growth stages of grape from 1981 to 2016. In addition, drought recurrence of every 7yr. was dominant during the growth stages of grape in northern China (Table 3).

Table 3. Recurrence features of moderate, severe, extreme, and exceptional droughts (D1, D2, D3, and D4) during the four study growth periods of grape (i.e., bud break-flowering, flowering-veraison, veraison-berry maturation, and berry maturation-leaf fall) in the main grape-growing regions of China (i.e., Northwest China, North China, Northeast China, Southwest China, and Southeast China). The more evident recurrence features are set in bold.

Region	Intensity	Growth period			
		Bud break-flowering	Flowering-veraison	Veraison-berry maturation	Berry maturation-leaf fall
Northwest China	D1	–	–	–	—
	D2	–	–	–	—
	D3	–	–	1yr., 2yr., 4yr., **9yr.**	**1yr.**, **2yr.**, 4yr., 5yr., 6yr., **7yr.**
	D4	1yr.	1yr.	**1yr.**, 2yr.	2yr., **7yr.**, 9yr., 11yr.
North China	D1	–	–	**1yr.**, 5yr.	**1yr.**, 2yr., 3yr., 6yr., **7yr.**
	D2	–	3yr., 7yr.	–	–
	D3	–	**1yr.**, 3yr.	–	–
	D4	**1yr.**, 3yr., **4yr.**, 5yr., **7yr.**, 12yr.	**1yr.**, 2yr., 4yr.	–	–
Northeast China	D1	–	**1yr.**, 2yr., 3yr.	1yr., 7yr.	1yr., 2yr., **7yr.**, 8yr.
	D2	**1yr.**, 4yr., **7yr.**, 8yr., 11yr., 12yr., 20yr.	**1yr.**, **3yr.**, 4yr., 5yr., 6yr., **7yr.**	–	–
	D3	1yr., 5yr., 6yr., 7yr., **11yr.**	–	–	–
	D4	–	–	–	–
Southwest China	D1	5yr., 8yr.	**1yr.**, 2yr., **3yr.**, 5yr., **6yr.**, 7yr., 8yr., **9yr.**, 12yr., 15yr.	–	–
	D2	2yr., 3yr., 5yr., **7yr.**, 8yr.	1yr., 11yr.	–	–
	D3	4yr., 8yr., 12yr., 16yr.	–	–	–
	D4	–	–	–	–
Southeast China	D1	15yr.	–	–	3yr., **4yr.**, **7yr.**, 11yr., 12yr., 15yr.
	D2	–	–	–	–
	D3	–	–	–	–

	D4	–	–	–	–

Note: “–”means no recurrence feature was detected in the butterfly analysis.

4. Discussion

Grapevine growth is mainly driven by meteorological factors (Keller, 2015), and climate change will influence the growth cycle of grape (Costa *et al.*, 2019) by advancing phenology dates with increasing temperatures (Parker *et al.*, 2011). In China, most grape-related studies are on smaller spatial scales like province, city, or county, and national scale grape studies have rarely been reported. By referring to extensive published literature, we summarized the grape growth periods’ data (i.e., Jufeng and Redearth) from all available locales and processed them by using the phenological law method (Gong and Jian, 1983). Based on the processed phenology data, we analyzed drought intensity, frequency, coverage, and recurrence feature during the four growth periods of grape in the main grape-growing regions of China.

CWDI is a commonly used index in regional agricultural drought analysis for crops, including spring maize (Huang *et al.*, 2009) and winter wheat (Wang *et al.*, 2015). It has also been used to investigate the drought characteristics for grape in Gansu and Yunnan (Li et al., 2015a, 2016a) and table grape in Bohai Rim Region (Xiao, 2020a). Our study showed that grape was more prone to drought during the early growth period in the main grape-growing regions in China. Our multi-regional CWDI-based drought analysis in the main grape-growing regions of China could be used to plan early-growth period drought prevention for local grape production.

Butterfly diagram and wavelet analysis have commonly been used to identify the probable recurrence features of agrometeorological disasters. Wavelet analysis is good for detecting periodic oscillations in historical time series and showing the possible evolution trend that will most likely to happen in the future (Yang *et al.*, 2016). Therefore, it has been adopted in local (Xu *et al.*, 2015a) and regional drought analysis studies (Huang *et al.*, 2020, Cheng *et al.*, 2020). In the 1980s, Weng brought up the commensurability theory based on the periodic feature of nature (Weng, 1981, 1984). Butterfly structure diagrams can illustrate the temporal symmetry of disaster occurrence and highlight the commensurable trend year(s) that are more likely to have disasters (Yan *et al.*, 2017). The combination of butterfly structure diagrams and commensurability forecasting techniques could improve the accuracy of disaster prediction, for example, the occurrence of earthquakes (Li and Yan, 2017, Meng *et al.*, 2018). Butterfly structure diagrams together with commensurability forecasting techniques have also been used to analyze the recurrence features of disasters (Li *et al.*, 2020). As compared with wavelet analysis, the butterfly structure diagram can better detect the periodic rules of disasters. Therefore, we chose the butterfly analysis to detect the recurrence features of four different levels of droughts (D1, D2, D3, and D4) during the growth periods of grape in the study regions. Our results showed that continuous drought was more pronounced during the early growth periods of grape in the study regions. Hence, it is essential to take preventive measures before or during the early growth periods of grape in order to combat the worsening impacts of drought on grape production.

In addition to precipitation, most of the grapevines in the main grape-growing regions of China are irrigated. As a matter of fact, irrigation is an essential component of crop production in many areas of the world, including most parts in China. International studies have shown that irrigation can effectively improve crop yield (Saab *et al.*, 2020, Zhang *et al.*, 2020). A three-year experiment conducted in central and southern Italy proved that irrigation treatment increased grape yield by 18%–33% as compared to rainfed grape (Silvestroni *et al*. 2020a). In China, the amount of irrigation greatly affects the grape yield (Cao *et al.*, 2021), especially in Gansu province where drought tends to be more intense. In the eastern foot of Helan Mountain, proper irrigation could substantially increase the yields of table grape and wine grape (Li *et al.*, 2016, Yang *et al.*, 2020). Meteorological drought is a prerequisite for other types of drought (Zhou, 2015). When precipitation decreases remarkably, the balance between precipitation and evapotranspiration will be disrupted. In this study, we did not factor in irrigation when evaluating drought conditions during the growth periods of grape. In essence, agricultural drought is the result of meteorological drought influence, and it usually occurs after meteorological drought. In the study regions, our results could be used to estimate the probability of drought recurrence for local farmers to take preventive measures to minimize the adverse effects of agricultural drought on grape production.

Previous regional studies pointed out that the risk of drought was higher during the early stage of grape, and the high-level drought-prone area was concentrated in northwestern Hebei province, northwestern Gansu province, and northern Ningxia Hui Autonomous Region (Li, *et al.*, 2014, 2015, Xiao, 2020). These findings are consistent with what we detected in the study regions. Our study helps to fill the knowledge gap in the regional drought intensity, frequency, coverage, trend, and recurrence feature for grape production in China.

In sum, we suggest analyzing drought conditions at province-scale and adjusting the drought index range based on local grape-growing experiments. By doing so, the results would be a) more comparable between different locations and b) more useful for local farmers. Irrigation is one of the most important and direct means to relieve drought. It is possible that our study might have overestimated the effects of drought on grapes. Hence we strongly urge future studies to take irrigation into consideration, including the amount and timing of irrigation.

5. Conclusions

Against the background of climate change, grapevines are experiencing worsening warmer and drier growing conditions (Leeuwen *et al.*, 2019). In the main grape-growing regions of China, from 1981 to 2016, grapevines experienced relatively more frequent drought during the earlier growth periods, especially during bud break-flowering. Among the five levels of drought, exceptional drought (D4) showed the highest coverage in general, in particular, the exceptional drought coverage during bud break-flowering showed an increasing trend during the 36-year study period. Exceptional drought during the growth periods of grape was most frequent in Northwest China, mainly focusing in Xinjiang Uygur Autonomous Region, northern Gansu province, and northern Ningxia Hui Autonomous Region. According to the drought recurrence features in the butterfly analysis, drought was consistently spread out during the growth stages of grape in northern China. In Northwest China, North China, and Northeast China, drought was relatively more frequent and the drought recurrence feature was relatively more apparent.

Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare.

Authors' contributions

Conceptualization: Xue Cheng, Xiaoguang Yang, and Shuang Sun. Methodology: Xue Cheng, Shuang Sun, and Zhijuan Liu. Data curation, funding acquisition, and supervision: Xiaoguang Yang. writing – original draft preparation: Xue Cheng. All authors read and approved the final manuscript.

Availability of data and material

All data in this study are from the China Meteorological Administration (http://cdc.cma.gov.cn/).

Code availability

We are willing to share our data and methods upon request.

Ethics approval

The article does not involve ethical issues

Consent to participate

The authors consent to participate

Consent for publication

The authors consent for publication

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Figures

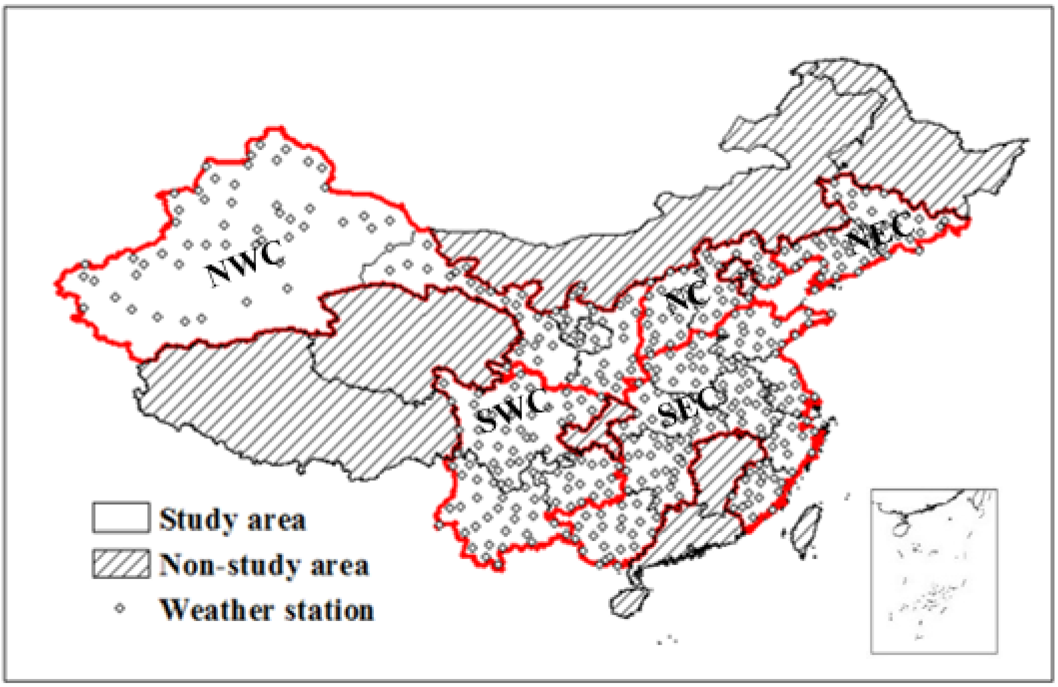

Figure 1

Locations of the 429 meteorological stations in the five main grape-growing regions of China: Northeast China (NEC), North China (NC), Northwest China (NWC), Southwest China (SWC), and Southeast China (SEC).

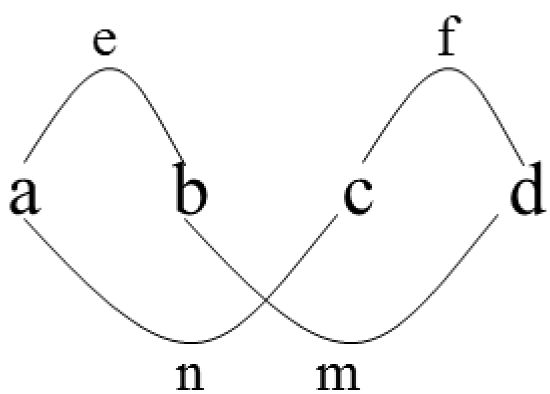

Figure 2

Illustration of the butterfly diagram pattern: a, b, c, and d are dry years, e, f, n, and m are the drought years with different intervals.

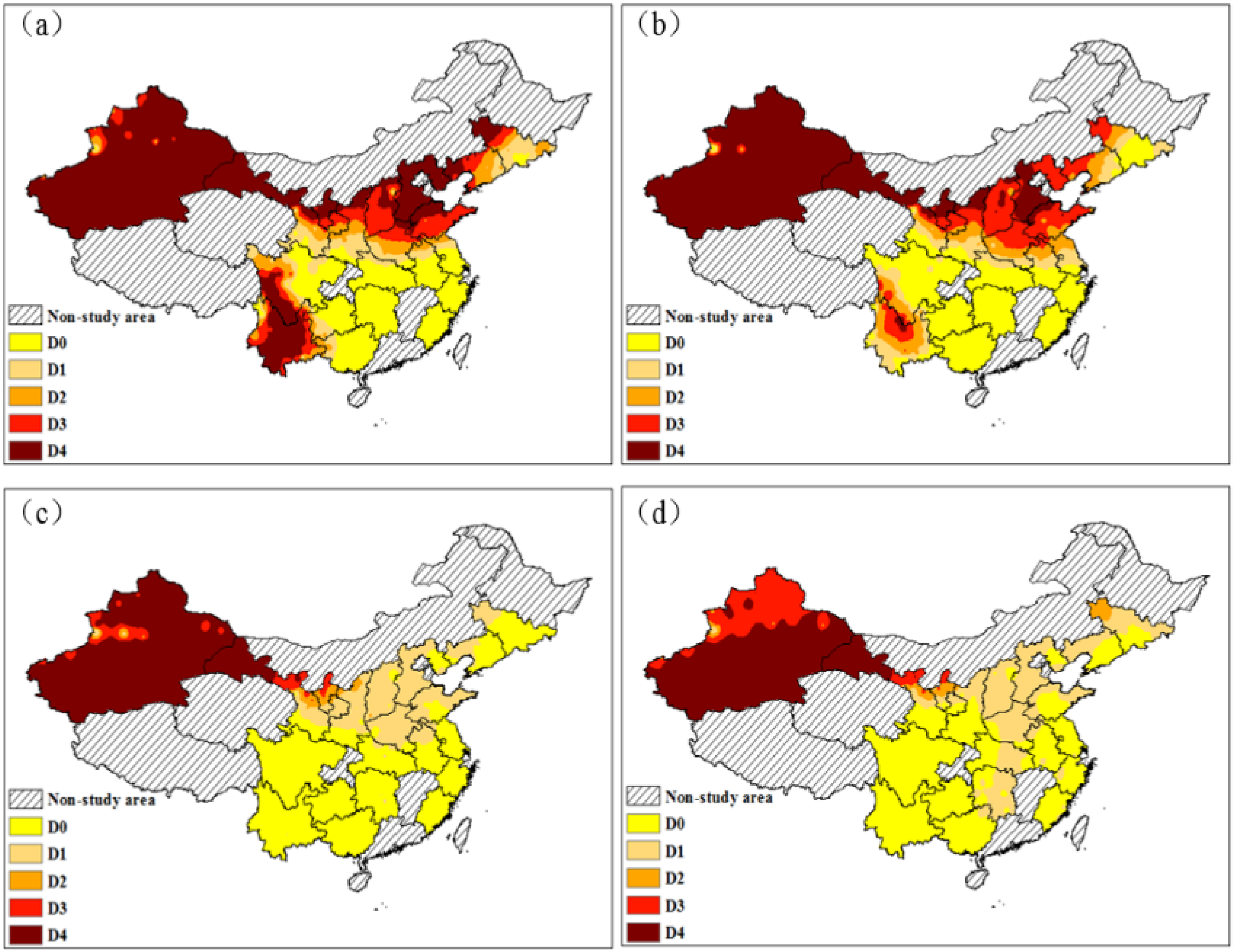

Figure 3

Geographical distribution of CWDI-based drought intensity (D0: abnormally dry, D1: moderate drought, D2: severe drought, D3: extreme drought, and D4: exceptional drought) during the four study growth stages of grape from 1981 to 2016 in the study regions. (a) Bud break-flowering. (b) Flowering-veraison. (c) Veraison-berry maturation. (d) Berry maturation-leaf fall.

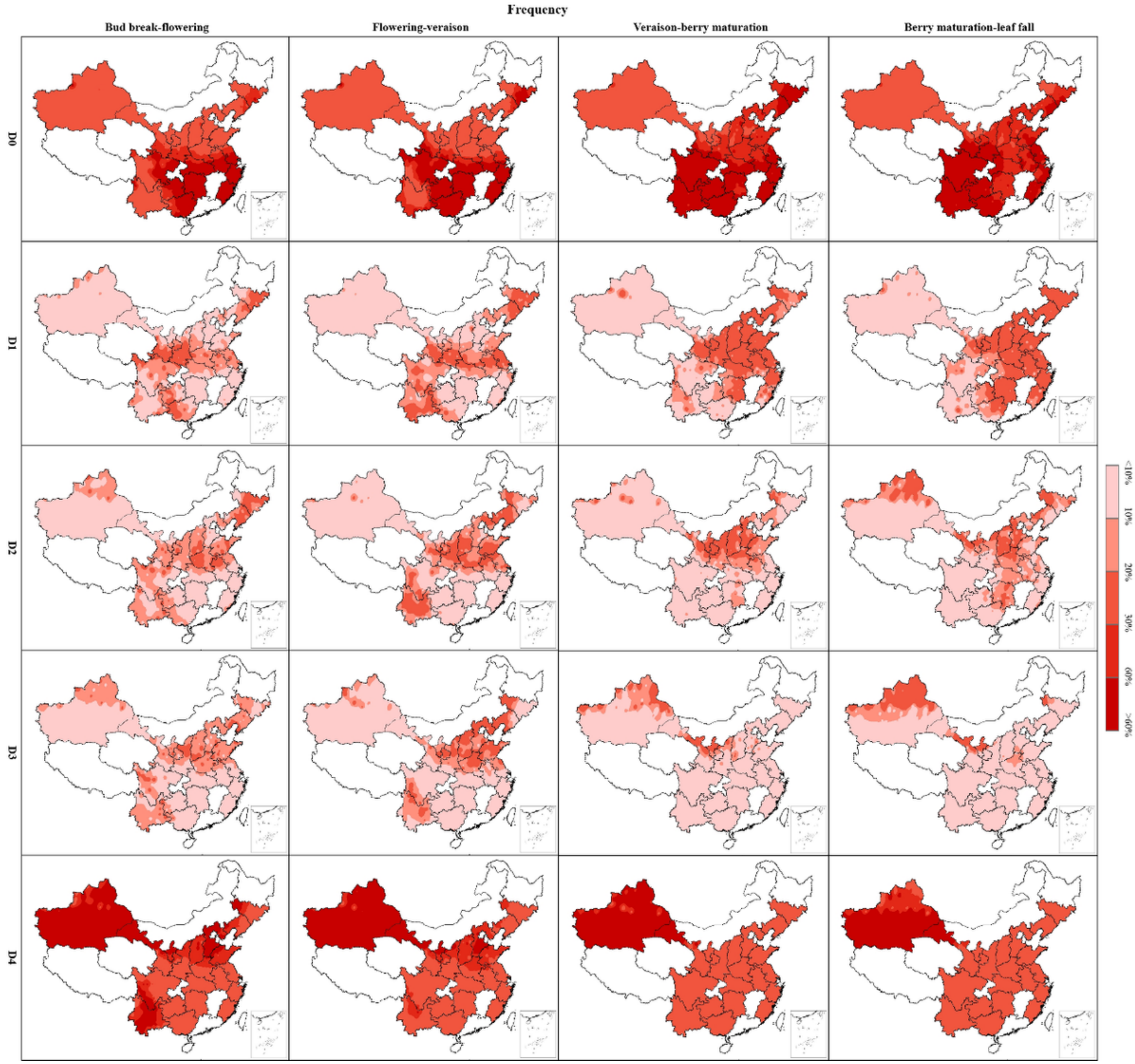

Figure 4

Geographical distribution of the frequency of abnormal dryness (D0), moderate drought (D1), severe drought (D2), extreme drought (D3), and exceptional drought (D4) during bud break-flowering, flowering-veraison, veraison-berry maturation, and berry maturation-leaf fall from 1981 to 2016 in the study regions.

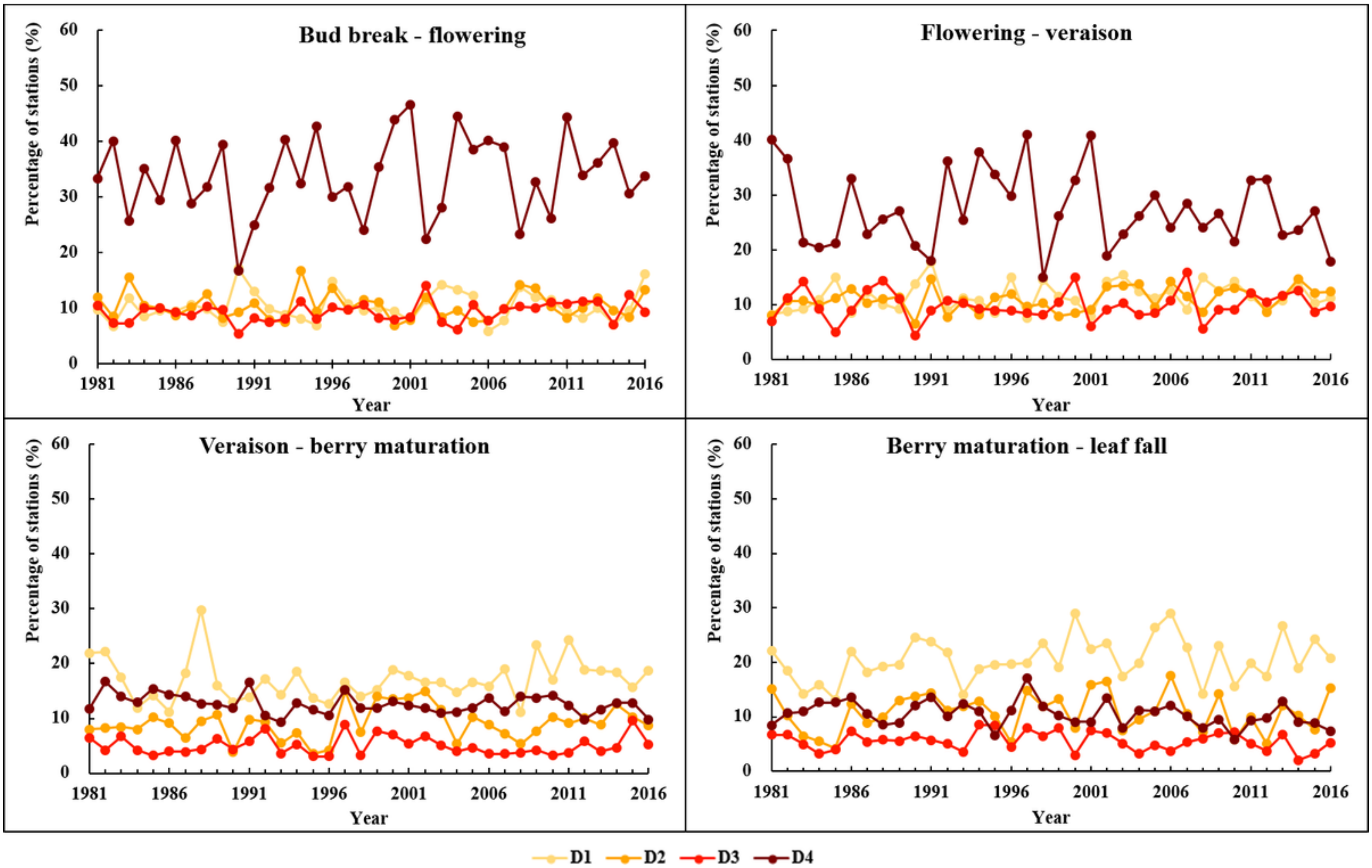

Figure 5

Time series of the percentages of stations showing moderate, severe, extreme, and exceptional droughts (D1, D2, D3, and D4) during the four study growth periods of grape in the study regions. (a) Bud break-flowering. (b) Flowering-veraison. (c) Veraison-berry maturation. (d) Berry maturation-leaf fall.

Supplementary Files

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