Process-based evaluation indicators of grape drought and risk characteristics in Bohai Rim Region (BRR), China

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Abstract

Drought stress is one of the major environmental limiting factors for grape growth in the Bohai Rim Region (BRR) in China. Investigation of process-based meteorological evaluation indicators is of particular interest to precisely understand the spatiotemporal characteristics of grape drought processes, providing substantial support for grape drought monitoring, prevention, and mitigation. In this study, a daily index grape drought index (GDI) was constructed based on the rolling calculation of water profit and deficit. Characteristics of GDI in historical drought disaster samples were analyzed, and drought evaluation level indicators were constructed, facilitating the assessment of process-based grape drought risk. The results showed that duration days with GDI<-0.4 identified can be used as drought level indicators, and the threshold of grape drought in germination-new shoot (P1), flowering-fruit setting (P2), fruit expansion (P3), and coloring-mature (P4) were 14, 13, 12, and 13 days with GDI<-0.4, respectively. Identification results calculated by grape drought indicators were basically consistent with historic occurrence levels of grape drought, with 76.9% of historical records completely consistent with the grape level assessment, and 15.4% within one level. The process-based grape drought risk gradually decreased with the advancement of grape growth process, with grape drought risk in the order of P1 > P2 > P3 > P4. Beijing, Tianjin, Hebei and west of Liaoning were detected with the higher drought risk.

1 Introduction

Drought is a major restricting condition on plant growth and production, with frequency and intensity exacerbated because of global warming (Zhou et al. 2017). Drought circumstances may change the physiological and morphological characteristics of plants in agricultural production, and fundamentally influence the plants' quality and output (Toivonen and Hodges 2011). China is a drought-prone country, with more than 60% (approximately 2–3 $*10^3$ km^2) of meteorological disaster was drought (Wang 2010). The frequency and magnitude of drought events has increased in recent decades, especially in North China (Wu et al. 2018; Yang et al., 2021).

Cereals (e.g., maize and wheat) (Wu et al., 2018; Li et al., 2022; Liu et al., 2022; Marat et al., 2022; Wan et al., 2022) and fruit trees (e.g., apple, grape) (Yang et al., 2020; Julio et al., 2016) have been shown to be vulnerable to drought. Physiological, morphological, yield, and quality changes of plants under artificial drought stresses (Prichard and Verdegaal, 2001; Cantore et al., 2016) have been investigated, to explore the mechanistic effects of drought on plants and the plants' response to this stressor. Drought stress can alter plant physiology, such as phenology development, blossoming, leaf growth, and reproduction, resulting in severe damage to leaves, flowers and young fruits, and ultimately leading to lessened productivity from reduced quality or yield (Rodrigo, 2010; Toivonen and Hodges 2011; Cantore et al., 2016), with different drought response characteristics and mechanisms between species. Many studies have focused on the drought characteristics and their negative influence in agriculture, fruit or vegetables at a regional scale in recent decades (Malheiroet al, 2010; Wu et al., 2018), based singly on drought index or combined drought indicators, such as seasonal, and yearly precipitation, evapotranspiration, SPEI, SPI, etc. (McKee et al. 1993; Vicenteserrano et al. 2010). Negative relationships between plant quality or productivity and drought have been explored based on such indexes or indicators, providing fundamental information about drought and its influence on plants under climate change.

However, plant drought is a disaster process with procedural and cumulative effects (Zhang et al., 2016; Esfahanian et al., 2017; Zhang et al., 2017). It is a dynamic process of gradual accumulation from the increase of water stress to the critical threshold that affects the normal growth of plants, leading to plant damage. Generally, drought tolerance varies between species. Appropriate drought stress is beneficial to plants; however, it might change to harmful to plants when drought accumulates beyond a certain magnitude, representing a drought disaster (Huo et al., 2003; Yang et al., 2021). So, two basic elements must be considered to trigger a plant drought disaster: the first is the drought weather conditions, including the duration (days or months), the magnitude, etc. The second is the drought resistance of the specific plant, which varies with the species and phenological phase (Yang et al., 2016; Yang et al., 2020 and 2021). Indicators of drought such as seasonal or yearly indexes show serious limitations for identifying a disaster weather process, and cannot be used in process-based identification of a plant drought event, which is crucial for predicting and monitoring such events. Nowadays, little index or indicators can reflect the daily changes of drought stress in the whole disaster processes, with starting day, ending day, duration days and magnitude of drought stress in each day undefined.

Grape is one of the world's major fruit crop varieties. China's grape industry has developed rapidly over the past 40 years, with the total grape production ranking first in the world, while the grape planting area ranks second (Liu et al., 2020). The area of grape cultivation reached 725,000 hectares, with 13.66 million tons of output by the end of 2018 (National Bureau of Statistics of China, 2020). The Bohai Rim Region (BRR), as the largest grape-producing area in China, accounts for about 36.2% of the country's total grape-growing area, and 44.0% of the country's total grape production (Mao et al., 2022; National Bureau of Statistics of China, 2020). However, the BRR spans the warm temperate zone and semi-humid monsoon climate zone. The rainfall is unevenly distributed temporally and spatially (Mao et al., 2022), which sets the stage for drought disasters in grapes. The reduction in grape quality and yield due to drought can be a significant problem for commercial fruit cultivators in the BRR.

Investigation of grape drought based on disaster processes is of particular interest for representing the potential consequences on grape production. In this study, grape drought in BRR in China is assessed, and the objectives include: 1) to represent historical grape drought processes and its characteristics based on daily index analysis, exploring the process-based evaluation indicators of grape drought in growth phases and thus identifying dry weather conditions that could potentially trigger grape damage, and 2) to propose an equation that would allow us to characterize the process-based drought risk for grapes in the Bohai Rim Region, China.

2 Materials And Methods

2.1 Study area

The Bohai Rim Region (113°04′–125°46′E and 34°23′–43°26′N) comprises the entire coastal area of the Bohai Sea and a portion of the coastal area of the Yellow Sea, including Beijing, Tianjin, Hebei, Shandong and Liaoning Provinces (Fig. 1a and 1b), In 2019, the grape planting area in the BRR was about 1.18×10^{2} thousand hectares, and the output was about 3.22×10^{6} tons (National Bureau of Statistics of China, www.stats.gov.cn). The grape vineyard area and yield from 1981 to 2019 are shown in Fig. 1c and 1d. This region is considered a warm temperate semi-humid monsoon region, with an annual average temperature of 8–12 ℃, and annual precipitation is approximately 800 mm, with approximately 80% of the annual precipitation concentrated in June to September.

2.2 Data

Meteorological, phenological data and disaster records were used in the study. Meteorological data, phenological data and disaster records were firstly combined to construct historical grape drought samples for the identification of drought evaluation levels in grape growth stages. Afterwards, meteorological data and average phenological of grape were integrated for the calculation of drought risk in grape growth phases.

Daily meteorological data at 303 weather stations from 1981 to 2020 across the BRR were obtained from the National Meteorological Information Center, China Meteorological Administration (NMIC, CMA). All data were quality- checked, and there were no missing meteorological records during the study period in the BRR.

Historical grape drought disaster records from 1981 to 2020, including, grape disasters surveys, county-based vineyards drought records, media reports about grape drought, and records acquired from the "*Yearbook of Meteorological Disasters in China*" (from 2004 to 2020), *Meteorological Disasters Book* (Hebei, Shandong, Beijing, Tianjin). The records described the onset date, location and the destruction of grape drought events.

Based on the difference in water requirements of grape growth periods, grape growth is divided into four phases, i.e., germination-new shoot (P1), flowering-fruit setting (P2), fruit expansion (P3), and coloring-mature (P4). Phenological data of grapes in BRR is derived from orchard investigation and reference literature (Li et al., 2006; Liu et al., 2006; Zhang et al., 2014; Xiao, 2020). Usually, grapes germinate in late April, and new shoots initiate in late May. June is the flowering-fruit setting period for grapes in the BRR, and fruit expansion occurs in July. Early August to early September is the major period for grape fruit expansion.

2.3 Development of Grape Drought Index (GDI)

Over the course of their evolution, plants have formed effective adaptive mechanisms to maintain their own survival in the face of stresses common to their local environment (Zia et al., 2020). The water deficit deviates from the average state, which is the direct factor leading to the occurrence of droughts (He, 2009; Mao et al., 2022). In order to eliminate the impacts of temporal and spacial variation in water monitoring to identify drought disasters, it is necessary to compare the amount of water available to plants to the amount that they typically require. So, daily crop water requirement (ET_c) was replaced as the average value of ET_c in the targeted day, in the construction of Water Budget of Grape (W_j), facilitating the construction of the Grape Drought Index (GDI).

Additionally, the aim of the GDI is to reflect the daily drought conditions of grapes, for the identification of total drought processes, facilitating timely monitoring and forecasting of grape drought disaster. Referring to the drought indexes of field crops (i.e., wheat, maize), GDI is designed as a daily index based on the rolling calculation of water profit and deficit in the past 50 days.

2.3.1 Crop Water requirement (ET_c)

The ET_c can be calculated referring to the "Reference Crop Evapotranspiration Multiplied by the Crop Coefficient Method" recommended by FAO, as follows:

$$ET_{ci} = ET_0 \times K_{ci}$$

1

Here, ET_{ci} is the water requirement of grape in the i-th development stage; ET_0 is plant evapotranspiration under standard conditions, as calculated with the Penman-Monteith formula (Allen et al., 1998); K_{ci} is the crop coefficient of grape at the i-th development stage. Coefficients of grape as determined by FAO-56 in 1998 (Allen et al., 1998) and related literature (Xiao, 2020), K_c are 0.35, 0.45, 0.52, 0.85, 0.8, 0.6 and 0.45, for each month from April to October.

2.3.2 Water Budget of Grape (Wj)

Water budgeting can be a highly effective technique that involves the local community in the understanding and monitoring of water resources, whereas auditing helps in identifying areas at risk for water loss, and how much water is used in different sectors (Arti et al., 2021). Considering that the water budget condition is suitable for drought condition evaluation at scales above 10 days, the W_j at 10 days was defined as:

$$W_j = \frac{P_j - ET_{cj}}{\overline{ET}_{cj}}$$

2

Here, P_j is the precipitation of a certain 10 days, in mm; ET_{cj} is the evapotranspiration of plants in a the same 10 days, in mm; $\overline{ET}_{cj}$ is the average value of ET_{cj} in the same period over the years in the calculated period, in mm.

2.3.3 Grape Drought Index

GDI is designed based on the water budget of the past 50 days (that is, 5 steps), cumulatively counted in 10d steps, and can be depicted as:

$$GDI = a * W_j + b * W_{j-1} + c * W_{j-2} + d * W_{j-3} + e * W_{j-4}$$

3

Here, GDI is the target daily drought index for grapes defined as the drought conditions over the most recent 50 days. W_j is the drought index corresponding to the nearest 10 days (including the target days); $W_{(j-1)}$ is the drought index corresponding to the 11th-20th days; $W_{(j-2)}$ is the drought index corresponding to the 21th-30th days; $M_{(j-3)}$ is the drought index corresponding to the 31th-40th days; $W_{(j-4)}$ is the drought index corresponding to the 41th-50th days. Referring to the agricultural drought grade index, the decreasing weights method (Yang et al., 2020, 2021) was used. The weights of a, b, c, d and e are defined as 0.3, 0.25, 0.2, 0.15 and 0.1, respectively.

2.4 Representation of historical grape drought

2.4.1 Classification of grape drought damage

The harmful effect of a drought process is considered to characterize its intensity. According to historical grape drought records in BRR, three evaluation levels (light, moderate, and severe) of drought damage to grape were identified, according to the damage descriptions. At the light level of grape drought, vineyards report detectable drought and grapes are noticeably affected. At the moderate level, drought destruction occurs, and grape flowers and fruit fall down partially. Severe drought causes grape fruit or plant body destruction and death.

2.4.2 Data coupling

According to the time and location of historical grape drought disaster records, historical grape drought processes were represented by coupling with grape growth stages, drought level, and historical daily GDI data. We take a drought in Chaoyang, Liaoning Province, from early March to late May 1984, as an example. According to the phenological data of grapes around the Bohai Sea, the grapes in this area are in the P1 stage. The records in the *Meteorological Disasters Book (Liaoning province)* described the drought as "severe drought in Chaoyang area from early March to the end of May, poor soil moisture and dry weather conditions lead to the death of fruit trees, including grape.” The evaluation grade is determined as severe. The meteorological data were derived from Chaoyang meteorological station, and daily GDI was calculated. According to the grape growth period, drought level and daily GDI series, the grape drought disaster data set is constructed as follows: P1, severe, GDI series (from early March to the end of May).

Finally, a database including 68 grape drought disaster examples was constructed in the context of grape growth stages (germination-new shoot, flowering-fruit setting, fruit expansion, coloring-mature), drought level (light, moderate, severe), and GDIs. We randomly selected 55 grape droughts in different growth periods and different levels of drought for the construction of evaluation indicators, while the remaining 13 disaster samples were reserved for validation.

2.5 Identification of grape evaluation indicators

Historical disaster events and records can basically provide knowledge on the mechanism of disaster processes (Ng et al., 2015; Yang et al., 2016). Damage documents and weather conditions can be integrated to investigate the magnitude of disaster weather conditions that can trigger a plant meteorological disaster (Ana et al., 2015; Wu et al., 2018; Yang et al., 2020). In this study, the daily GDI was firstly calculated and extracted according to the historical grape drought disaster records. Historical drought sample recognition rates (DRR) were calculated according to the magnitude of GDI, identifying ongoing dry weather conditions related to the drought events to serve as the threshold GDI. Afterwards, duration days below the threshold from 1981 to 2020 were calculated and represented by the down-cumulative distribution function. DRR were calculated at 5% steps of cumulative probability. The evaluation indicators of light, moderate and severe grape drought were identified based on the principle of the largest DRR in duration days.

2.5.1 Drought samples recognition rates (DRR)

The drought samples recognition rates (DRR) refer to the proportion of drought disaster samples that meet the conditions to the total number of disaster samples.

DRR = a/A*100% (4)

Here, a is judged as the correct number of samples; A is the total number of samples during a given growth period of the grape.

2.5.2 Down-cumulative distribution function

The down-accumulation distribution function means that the number of times a variable is greater than a certain value is proportional to the total number of samples (Huang et al., 2007; Cheng et al., 2020).

$$C_{FD} = \frac{G_i}{G_n} * 100\%$$

5

$$G_i = \sum_{i-1}^{n} g_i$$

6

Here, C_{FD} is the cumulative probability; n is the number of levels divided between the maximum and minimum values of the variable (here there are 3, namely light, moderate and severe); g_i is the number of variables within the corresponding level, and G_i is the number of variables greater than or equal to that level; G_n is the total number of samples.

2.6 Grape Drought Risk Index (GDRI)

Grape Drought Risk Index refers to the possibility of light, moderate and severe drought damage to grapes in a given geographical region within a certain period of time. Comprehensively considering the drought levels and their occurrence probability in different grape development stages, the GDRI was established as:

$$GDRI = \sum_{j=1}^{m} P_j * Q_j$$

7

Here, m is the number of drought levels (light, moderate, and severe). Q_j refers to the intensity of grape drought at the target level. P_j is the probability of occurrence of drought at the target level.

3 Results

3.1 Evaluation level of grape drought

According to the drought disaster process, which can be acquired from daily GDIs in the disaster samples constructed, DRR between 0, -0.1, -0.2, -0.3, -0.4, -0.5, and -0.6 of the drought processes are calculated. The DRR are 100% in the processes with GDIs between 0~0, -0.1～-0.1, -0.2～-0.2, -0.3～-0.3, and -0.4～-0.4, while it decreased gradually when the GDI decrease below -0.5, meaning that all the drought processes can be recognized with GDI more than and equal to -0.4 (Fig.2). To achieve the largest DRR and the lowest anti-DRR (that is misjudgment), GDIs of less than -0.4 were selected as the initial threshold of grape drought.

The cumulative probability distribution of duration days with GDI <-0.4 from 1981 to 2020 is plotted by the down-cumulative distribution function, with historical disaster samples plotted on the corresponding curve (Fig.3). Duration days to the cumulative probabilities with 5% step were calculated in each grape growth period, as shown in Table 1.

Taking the duration days with cumulative probability of 5% as the step, the DRR of light, moderate and severe drought samples in each growth stage of grape were calculated. DRR changes with different duration days GDI<-0.4 at 5% step in cumulative distributions, as showed in Fig.4. The RRD is gradually reduced with the increase of duration days with GDI <-0.4. To obtain the largest RRD while decreasing empty judgment for historical disaster samples, the largest duration days with RRD of 100% were selected as the optimum threshold for grape drought trigger at target disaster level. For P1, P2 and P3, RRD for light drought samples were 100% when the cumulative probability was 20%, 30% and 40%, respectively, and RRD decreased when the cumulative probability increased. The corresponding duration days were 14 days, 13 days and 12 days, respectively. Based on this, the light grape drought trigger thresholds for P1, P2 and P3 can be identified consecutively as 14 days, 13 days and 12 days with GDI<-0.4. Since there were no records of light drought at P4, the average of the light drought trigger thresholds of the former three periods was selected as the light drought trigger threshold of P4; that is, the light drought trigger threshold of P4 was 13 consecutive days with GDI<-0.4. Similarly, moderate and severe indicators of grape drought were identified, as listed in Table 2.

3.2 Evaluation level validation

Thirteen reserved grape drought samples in BRR were used for the validation of our validation. Table 3 shows the verification results of grape drought evaluation levels we constructed. The results are divided into three categories, that are, Complete correspond, mainly correspond and not correspond. Complete correspond means the calculated level is totally in agreement with the level in historical records, while mainly correspond and not correspond means the calculated level is one step and two steps different to the level in historical records, respectively. Evaluation levels calculated by grape drought indicators were largely in accordance with historic records of grape drought, with 76.9% complete correspond and 15.4% mainly correspond. Overall, these results suggest that the grape drought indicator constructed in this study accurately reflects the actual grape drought at regional scale.

3.3 Characteristics of grape drought risk

3.3.1 Characteristics of grape drought probability

The probability of grape drought disaster at 303 stations around the BRR in P1, P2, P3 and P4 was calculated based on the information diffusion method, and its spatial distribution is shown in Fig.5. The probability of drought disaster is the highest around the BRR in the period of P1, with more than 20% probability detected in most areas with light and moderated drought. Hebei is the most drought-prone province in the BRR, with more than 20% probability of severe drought detected in the last 40 years. The probability of light and moderate drought in P2 is 10 to 20% in most study areas. The probability of light and moderate drought in the earliest two growth periods (P1 and P2) are generally characterized by a decrease from West to East, whereas, the probability of severe drought increases in more northwestern regions. The drought probability in P3 and P4 is significantly lower than in the earlier two growth stages, with light, moderate and severe drought probability in most areas less than 10%.

3.3.2 Characteristics of grape drought risk index (GDRI)

Comprehensively considering the occurrence probability and disaster intensity of grape drought at different levels (light, moderate and severe), the grape drought risk index is calculated. The spatial distribution of grape drought risk index different grape growth stages around the BRR is shown in Fig.6. In general, the risk of grape drought gradually decreased with the advancement of grape growth process, with grape drought risk in P1>P2>P3>P4.

There is little rain in spring in the main grape-producing areas around the Bohai Sea, and the early growth and development of grapes are greatly affected by drought (that is, P1 and P2). The average risk index of grape drought in P1 is > 0.6. Beijing, Tianjin, Hebei, and west of Liaoning were detected with higher drought risk, with grape drought risk index more than 1.5 (Fig.6a). The regional average risk index was 0.95 in P2, and the high-risk areas are mainly in parts of central and Southern Hebei, with the risk index greater than 0.6 (Fig.6b). It is rainy in summer in BRR, and the rainfall is mainly concentrated from July to September, which is at P3 and P4, resulting in less impact of drought disaster in the later stages of grape growth and development. The regional average of DRI is 0.52 and 0.20 for P3 and P4, respectively. Except for the drought risk index in a small area of Southwest Hebei Province that is higher than 0.9, most of the study area is basically below 0.6 in P3 (Fig.6c). Only the northwest and south of Hebei were detected with GDRI more than 0.3 in P4 (Fig.6d).

4 Discussion

4.1 Rationality of theory and method

Grape cultivation is of high economic value to the agricultural and forest industry in China. Generally, 1200 mm water is needed for grape production (95% of water requirement is used for transpiration) (Ojeda et al., 2001; Zhang et al., 2017), with water requirements differing with local climate, irrigation management, plant methods, etc. Water requirements in the germination-new shoot (P1) stage is comparatively lower, while it increases after new shoots are produced, and water requirements gradually increase to a maximum in the coloring-mature period (P4) (Cheng et al., 2021). However, due to the seasonality and regional distribution imbalance of precipitation, as well as insufficient supplemental irrigation in vineyards, water deficit in grape orchards happen frequently. Appropriate water deficit can suppress shoot growth, increase the rate of fruit expansion, and improve water use efficiency without yield reduction (Wang et al., 2019). However, if the water deficit exceeds a reasonable range, drought occurs, restricting seed setting rate, causing fruit to shrivel, and even causing the fruit tree to dry up and die in extreme cases (Yang et al. 2021). The formation of drought is organized by interacting effects such as weather conditions, geography and topography, soil moisture, drought tolerance of the species, and field/orchard management (Bao et al., 2011; Song et al., 2020). Among these, weather conditions (mainly precipitation and evapotranspiration)-lead water deficit are the most important factor in triggering a drought event (Yang et al., 2016; 2021; Wu et al., 2021). The GDI constructed in this study can achieve daily rolling weather condition assessment, which is applicable for effective monitoring and early warning of grape drought.

GDI and dry weather duration days were adopted to demonstrate process-based grape drought, for GDI below − 0.4 can reflect the dry weather condition/drought intensity, while duration days of GDI below − 0.4

is a measure of accumulation of the drought process. Threshold identification methods, such as the cumulative distribution function, disaster samples recognition rates, etc. (Yang et al., 2016, 2020, 2021; Wu et al., 2018, 2021), have been used in the identification of grape drought, making the evaluation indicators regional applicability.

4.2 Utilization of the grape drought evaluation indicators

Plant drought due to unbalanced precipitation and excessive evapotranspiration is one of limiting circumstances for plant sustainability around the world, with negative impact not only on plant yield, but also on quality (Estaji and Niknam, 2020; Remi et al., 2021). Dry weather conditions, and plant tolerance to these conditions, is the most important trigger factor for determining a crop drought disaster. The evaluation indicators constructed in our study specified how mismatch of dry weather conditions and plant tolerance to drought stress for grape production may trigger grape drought at levels (light, moderate and severe) for regional evaluation. The results demonstrate that days with GDI below − 0.4 is useful for the identification of grape drought. The grape drought indicators can serve as a convenient meteorological method for the unique identification of grape drought or processes, including the drought beginning, duration, and ending. With real-time and/or weather-forecasting products, as well as real/predicted grape phenological phase observations and simulations, drought processes such as starting time, ending time, positions, and intensities, can be spatio- temporally targeted. Additionally, grape damage assessment can be assessed based on the grape drought evaluation level constructed, with comparability across regions and time.

4.3 Potential strategies to mitigate grape drought

Drought risk in plants has been shown to vary strongly by region due to interconnecting factors such as species characteristics, target growth stage, geographic differences, and field/orchard management. For example, agriculture droughts in China showed regional characteristics, with drought more concentrated in the Yellow River Basin and its northern areas (Guan et al., 2021). With the increased evapotranspiration and decreased precipitation modelled in future seniors, suitable areas and production for oil crops (such as olive in Andalusia) are exposure in potential decrease (Arenas-Castro et al., 2020). Drought was shown to be generally more damaging in the early stages of growth and development for grapes. Generally, the flowering-coloring growth stage requires more water, while the budding-flowering growth stage requires the less (Ojeda et al., 2001; Cheng et al., 2021). However, uneven precipitation makes drought more likely in earlier grape growth stages, rendering plants in the early stages comparatively more susceptible to drought in this region despite the plants’ lessened need for water at early stages.

Developing and applying practical strategies to alleviate the negative effects of drought on plants is a major goal for researchers. Supplementary irrigation during these high drought risk seasons is considered as the most efficient method to alleviate the harmful impact of drought. Irrigation volume and frequency — implemented based on the precipitation, ETc and process-based drought indicators, and soil moisture threshold defined according to detection and observations — make irrigation reasonable without affecting grape yield and quality (Pizarro et al., 2022). Additionally, drought leads to a reduction in photosynthetic activity and translocation rate of assimilates, which mainly is linked to the low leaf water potential, decreased stomatal opening, and an inhibition of chloroplast activity (Sokoto and Muhammad, 2014). Some exogenous protectants, such as phytohormones, antioxidants, signaling molecules, polyamines, and trace elements, have been applied to alleviate plant drought stress (Tuteja and Gill, 2014), maintaining or increasing plant productivity under limited water availability. For example, exogenous Si can alleviate the negative impacts of drought in tomato by improving hydraulic conductivity, light energy distribution and antioxidant defense capacity (Remi et al., 2021). Application of different exogenous protectants can be applied to alleviate drought damage to plants with less harmful effects, being a useful drought prevention measure for vineyards.

4.4. Uncertainties and limitations

Different results on plant drought disasters have been detected under the background of climate change, and plant species, geographical environment, phenological phase and artificial drought resistance measures can influence drought occurrence and characteristics (Wu et al., 2018, 2021; Yang et al., 2021). For example, supplementary irrigation and man-made disaster resistance, such as the use of water-retaining agents, can affect plant drought formation and development (Yang et al., 2021). In addition, other weather factors, can alleviate or aggravate drought impacts. For instance, a deficit in precipitation in hot days may lead to more severe drought than a similar deficit under cool weather (Teixeira et al., 2007; Iltis et al., 2020). Also, plants frequently exposed to adverse environments may develop adaptive mechanisms for survival (Shubha and Tyagı, 2007). Therefore, it is necessary to optimize and modify the grape drought indicators in specific areas, considering other factors such as soil, terrain, and vineyards management, as well as drought resistance abilities in different species and growth seasons.

5 Conclusion

A daily index GDI was constructed based on the rolling calculation of water profit and deficit, for the identification of total drought process to timely monitor and forecast grape drought disaster. Process-based evaluation of grape drought in the Bohai Rim Region (BRR), China, was investigated with $GDI<-0.4$ as a trigger threshold and duration days with $GDI<-0.4$ identified as drought level indicators, based on historical disaster representation and disaster process analysis. Grape drought gradually decreased with the advancement of grape growth stages. Beijing, Tianjin, Hebei and west of Liaoning were detected with higher drought risk.

Our study explicitly investigated the GDI characteristics by historical representation of grape droughts processes, providing fundamental knowledge of the relationship between the drought weather conditions and grape drought processes. In addition, the process-based risk characteristics could provide more robust information for adaptation measures and strategies, such as increased irrigation facilities in high-risk areas and seasons, as well as deficit irrigation according to drought trigger thresholds in order to save water and alleviate the water crisis. Additionally, information about soil, terrain, vineyards management, as well as drought resistance abilities should be considered, if related data are available, to optimize grape drought identification and risk analysis.

Declarations

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Conflict of interest

The authors declare that they have no conflict of interests.

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Availability of data and material

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable.

Ethics approval

Not applicable.

Consent to participate

The authors express their consent to participate for research and review.

Consent for publication

The authors express their consent for publication of research work.

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Tables

Table 1

Cumulative probability inverse value for duration days GDI < -0.4 with 5% step

Cumulative probability	Duration days with GDI <-0.4			
	P1	P2	P3	P4
5%	3	2	2	1
10%	7	4	3	2
15%	10	6	4	3
20%	14	8	5	4
25%	19	10	6	5
30%	25	13	8	5
35%	31	16	10	6
40%	34	18	12	8
45%	37	22	16	9
50%	40	26	19	11
55%	43	32	23	14
60%	48	38	28	16
65%	51	46	33	19
70%	54	59	41	24
75%	59	72	48	30
80%	67	80	56	38
85%	72	88	72	51
90%	72	94	103	64
95%	72	102	111	90

Table 2

The grape drought disaster level indicators during different growth stages

Growth stages	Drought level	Duration days with GDI<-0.4
P1	Light	14～39
	Moderate	40～66
	Severe	≥67
P2	Light	13～25
	Moderate	26～79
	Severe	≥80
P3	Light	12～22
	Moderate	23～55
	Severe	≥56
P4	Light	13～28
	Moderate	29～50
	Severe	≥51

Table 3

Validation of grape drought evaluation indicators

Time	Disaster sits in history records	History records and Disaster levels judged by records	Disaster levels calculated by indicators	Correspond
1989.4～5	Qixia/Shandong	The fruit trees die/Severe	Light	Not correspond
2000.2～5	Haiyang/ Shandong	Drought affect grape growth/Moderate	Moderate	Complete correspond
2000.5	Beijing	Widespread grape drought/Moderate	Moderate	Complete correspond
1984.3～5	Chaoyang/ Liaoning	Drought to grape tree died/ Severe	Severe	Complete correspond
1988.4～5	Dalian/ Liaoning	Severe shortage of water/ Severe	Severe	Complete correspond
2000.3～9	Pingdu/ Shandong	Drought disaster occurrence /Light	Light	Complete correspond
1981.4～7	Chaoyang/ Liaoning	The fallen petal rate 40%/Moderate	Moderate	Complete correspond
1982.6	Tianjin	Severs drought/Severe	Severe	Complete correspond
1986.4～6	Dalan/ Liaoning	The flowers have fallen down because of the drought/Moderate	Severe	Mainly correspond
1992.6～7	Chaoyang/ Liaoning	A large number of the fallen petal/Moderate	Moderate	Complete correspond
1992.7	Feixian/ Shandong	Drought happen/Light	Moderate	Mainly correspond
1997.6～7	Weifang/ Shandong	Some of the fruit fell /Moderate	Moderate	Complete correspond
1992.8	Yingkou/Liaoning	Drought affect grape growth/Moderate	Moderate	Complete correspond

Figures

Figure 1

Maps of study area- Bohai Rim Region (BRR), China. *Note*: **a** is the location of the BRR, **b** is the location of the meteorological stations; **c** and **d** are vineyard area and grape yield from 1981 to 2019 in each province.

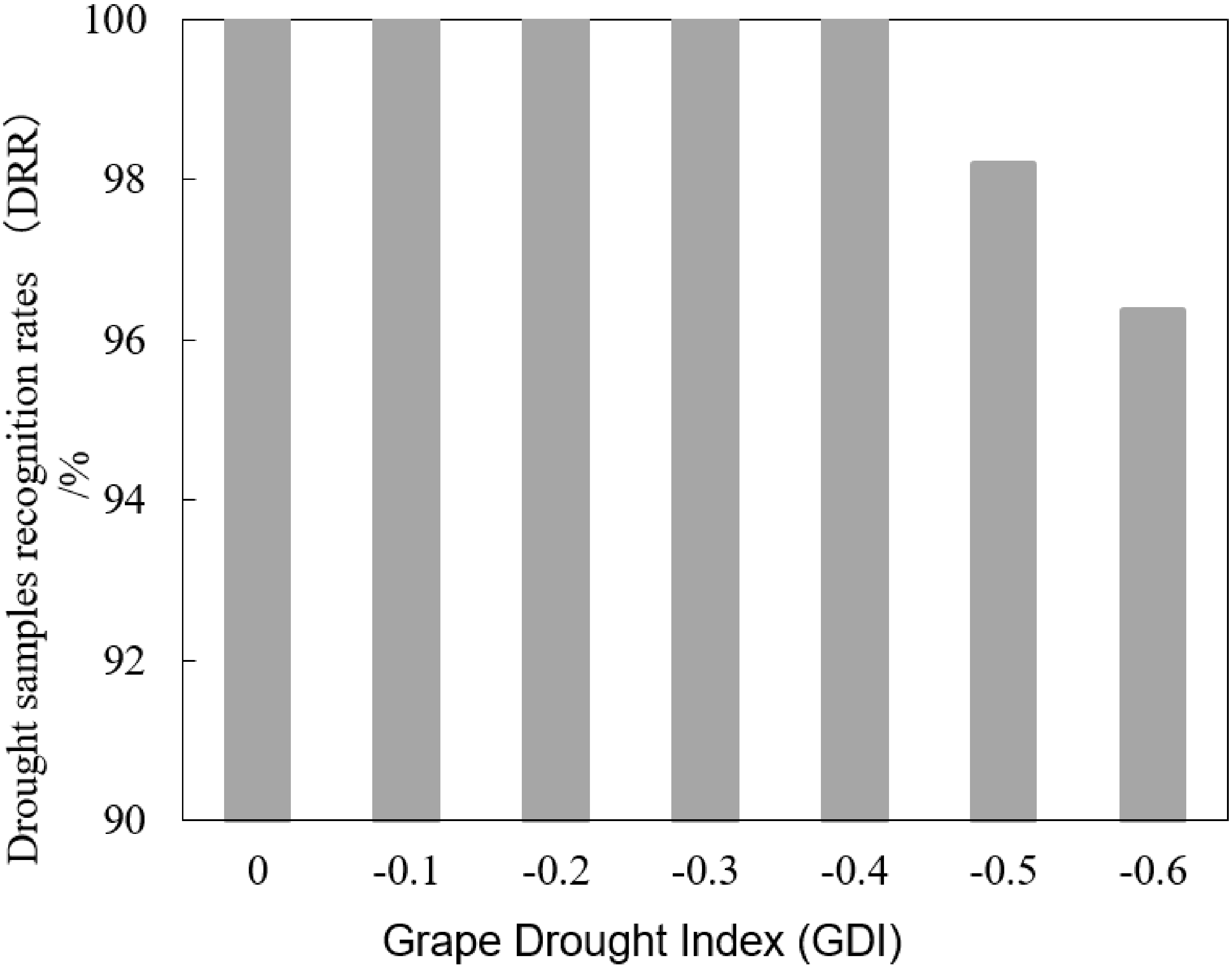

Figure 2

Drought samples recognition rates (DRR) changes with different threshold of Grape Drought Index (GDI).

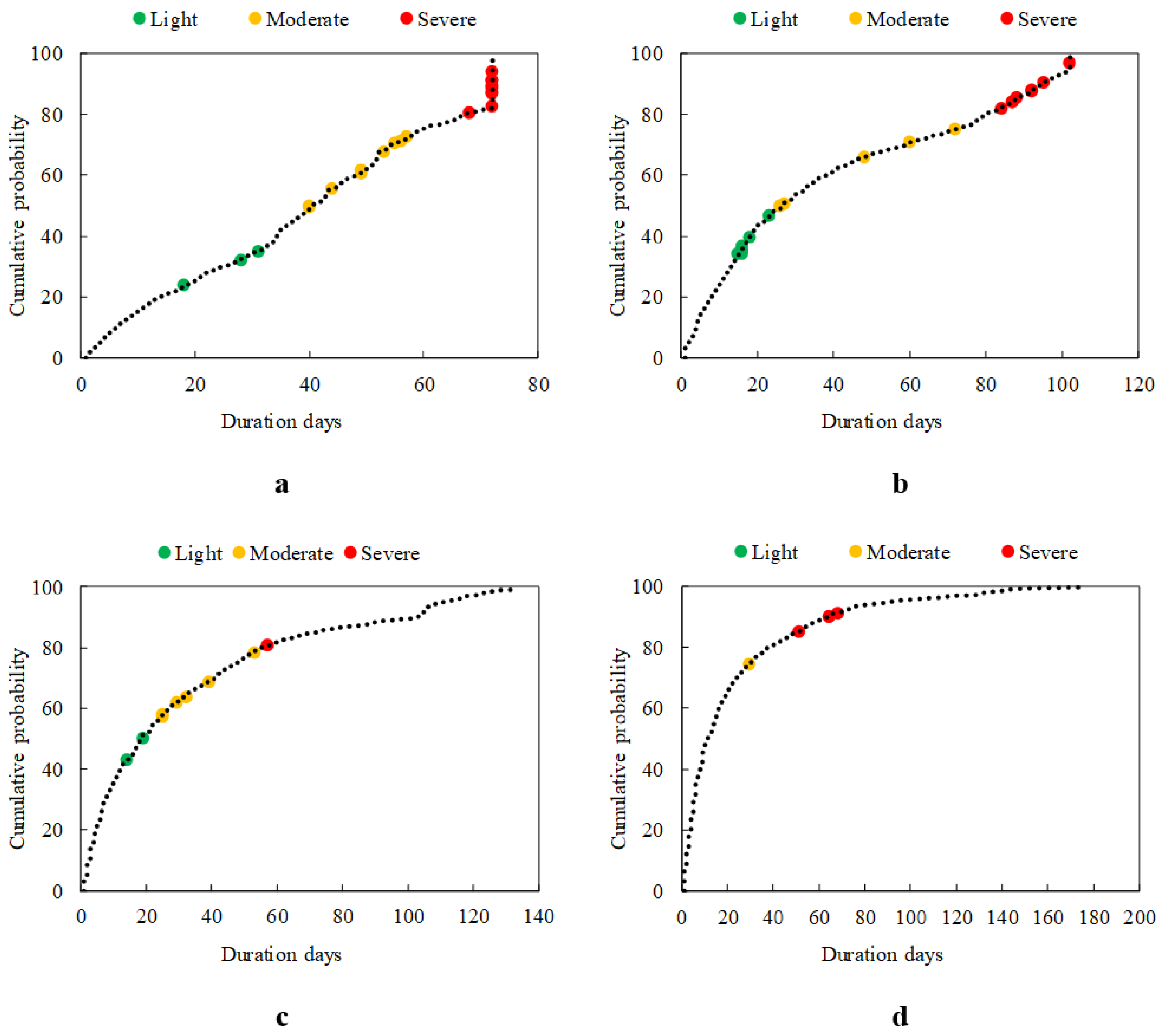

Figure 3

Cumulative distributions of duration days with GDI< -0.4 in different grape phenological phases. *Note*: **a** is germination-new shoot (P1), **b** is flowering-fruit setting (P2), **c** is fruit expansion (P3), and **d** is coloring-mature (P4).

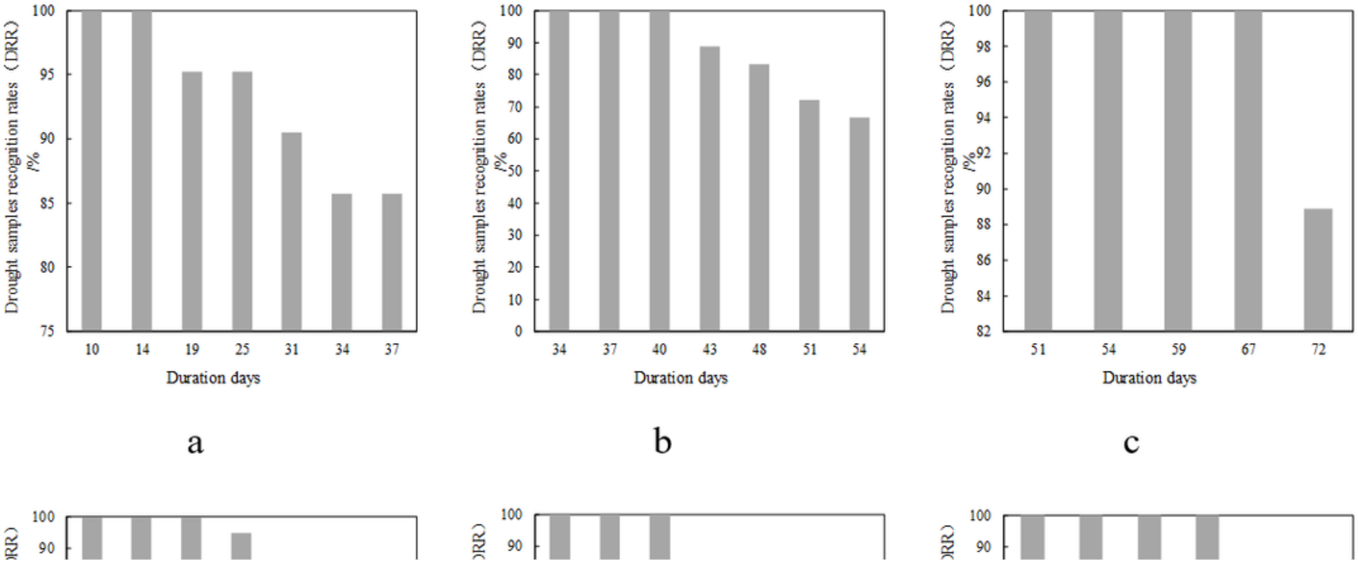

Figure 4

Drought samples recognition rates (DRR) changes with different duration days GDI<-0.4 at 5% step in cumulative distributions. *Note*: **a** is light in P1, **b** is moderate in P1, **c** is severe in P1, **d** is light in P2, **e** is moderate in P2, **f** is severe in P2, **g** is light in P3, **h** is moderate in P3, and **i** is severe in P4.

Figure 5

Probability Distribution of Grape Drought in different levels. *Note*: **a** is light in P1, **b** is moderate in P1, **c** is severe in P1, **d** is light in P2, **e** is moderate in P2, **f** is severe in P2, **g** is light in P3, **h** is moderate in P3, **i** is severe in P3, j is light in P4, k is moderate in P4 and l is severe in P4.

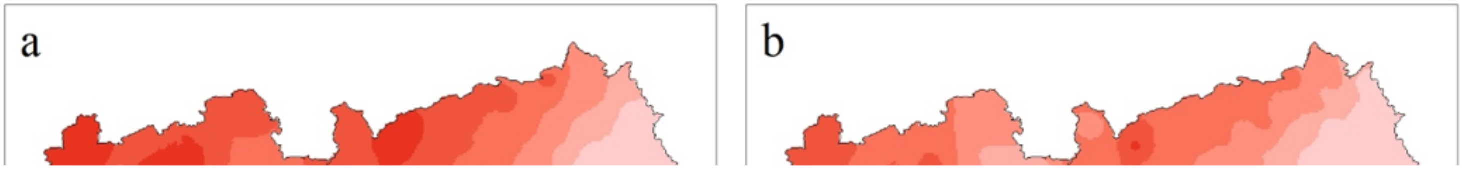

Figure 6

Spatial distribution of GDRI. *Note*: **a** is GDRI in P1, **b** is GDRI in P2, **c** is GDRI in P3, **d** is GDRI in P4.