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The influence of recent climate variability on viticultural zoning and variety regionalisation of *Vitis vinifera* in China

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ABSTRACT

The objective of this work was to estimate the influence of climate variability on viticultural zoning and variety regionalisation in China in the past 50 years. A multicriteria climatic indices system, which includes Frost-Free Season (FFS), Dryness Index (DI), and Extreme Low Temperature (ELT), was used to define climatic suitable areas and classify different climate zones for wine grape-growing in China. The Accumulated Effective Temperature (AET) was used as an index of variety regionalisation. Indices were calculated based on daily climatic observations from national ground weather stations throughout China from between 1967 and 2016. The variation trends were analysed by Sen's slope and Mann-Kendall non-parametric tests in 13 representative wine growing sites. Based on the studied criteria, the suitable viticultural zone exhibited a continuous northward expansion with an average increase of 0.204 million km^2/decade, largely due to increasing FFS. A significant increase of FFS was detected in most representative sites, with almost no detectable change of DI during the growing season. The analysis also revealed that the North East Region, Inner Mongolia Region, and Xinjiang Region are the three most profitable wine regions. Movement of the soil-burying line was limited to Shandong and Hebei provinces. Although the suitable viticultural zone increased, the data also revealed a decrease in the area for high quality wine production when considering varietal suitability. These results have important implications for understanding both new opportunities and challenges under changing climate and the latter's effects on viticultural viability in China. They can also help guide stakeholders to develop adaptive strategies for maintaining the profitability of currently used regions and for developing new regions for viticulture.

KEYWORDS

climate variability, dryness index, frost-free season, soil-burying line, suitable viticultural zone, varietal suitability

Supplementary data can be downloaded through: https://oeno-one.eu/article/view/2971

INTRODUCTION

There are wide concerns about climate change and its potential impacts on different aspects of human life, especially agriculture, which is extremely vulnerable to climate variations (Howden *et al.*, 2007; Nelson *et al.*, 2009; Piao *et al.*, 2010). *Vitis vinifera* is the most important grape species to be specifically used for wine making and is of high commercial value. This species is highly sensitive to climate conditions, and is thus distributed in a relatively narrow climate niche, which is traditionally located between the latitude of 30-50 °N and 30-40 °S (Schultz and Jones, 2010). As a perennial crop, wine grapes may be more susceptible to the effects of a changing climate.

Studies on both climate change and viticulture mainly started in the 1990s, and an increasing number of papers expressing concerns about climate change are being published (Marx *et al.*, 2017). From 1950 to 1999, the growing season mean temperature in many famous wine regions worldwide exhibited an average increase of 1.26 °C, with a stronger increase in the northern hemisphere compared to that in the southern hemisphere (Jones *et al.*, 2005). The Okanagan Valley wine region, which is located in British Columbia, Canada, experienced a rapid increase in average temperature of 7.0 ± 1.3 °C/century in the growing season over the post-1980 period and an increase of 7.3 ± 1.9 °C/century in the dormant season over the post-1970 period (Rayne and Forest, 2016). Strong, positive, and statistically significant trends of active temperatures and growing degree days have been observed in the transboundary region of Poland, Germany and the Czech Republic over the 1971–2010 period (Kryza *et al.*, 2015). Additionally, several studies have reported shifts of climate patterns in several wine regions based on different climatic variables and key bio-climatic indices (Briche *et al.*, 2014; Fraga *et al.*, 2016; Hall and Jones, 2009; Hannah *et al.*, 2013; Lereboullet *et al.*, 2014; Ramos *et al.*, 2008; Schultze *et al.*, 2014).

Rising temperature associated with climate change has already affected wine regions around the world. Advanced timing of plant phenological stages has been associated with climate change (Bock *et al.*, 2011; Duchêne and Schneider, 2005; García de Cortázar-Atauri *et al.*, 2017; Jones and Davis, 2000; Webb *et al.*, 2007). Early budburst may increase the risk of spring frost (Mosedale *et al.*, 2015; Sgubin *et al.*, 2018). Both increased temperature and advanced timing of phenology make grapevines mature during a warmer period, which directly leads to higher sugar, lower acidity, and a decrease in total anthocyanins (Gouot *et al.*, 2018; Sweetman *et al.*, 2014). Such changes will make management challenging (Neethling *et al.*, 2017; van Leeuwen and Destrac-Irvine, 2017).

Some cool wine regions that are on the climatic margins of commercial viticulture (like those in Canada (Jones, 2012; Shaw, 2017), the UK (Nesbitt *et al.*, 2016), Hungary (Kovacs *et al.*, 2017), and the Poland-Germany-Czech area (Kryza *et al.*, 2015) may benefit from global warming by becoming suitable for the cultivation of more grape varieties. Conversely, some regions which already have ideal conditions for producing wines (such as in western USA (Jones and Goodrich, 2008; White *et al.*, 2006), Romania (Irimia *et al.*, 2018), Slovenia (Pulko, 2014), and Roussillon in France (Lereboullet *et al.*, 2014) may become too hot to continuously produce high quality wines or maintain existing varieties, or they may be at increased risk of damage by extreme events.

China has become a super power of the grape and wine industry with the second largest vineyard surface area, the largest grape production, the seventh largest wine production, and the fifth largest wine consumption in the world (OIV, 2018). However, to our knowledge, the impacts of climate change on viticulture in China have not been well studied, as it is difficult to collect long-term data concerning phenology, production, quality, or related parameters. Thus, the impact of climate change on the suitability of wine growing is typically indirectly studied on a climate level by studying different wine regions worldwide (Fraga *et al.*, 2016; Jones *et al.*, 2005; Kryza *et al.*, 2015; Rayne and Forest, 2016).

In this context, the objective of this study was to explore the impacts of recent climate variability on the decadal (1967-1976, 1977-1986, 1987-1996, 1997-2006, and 2007-2016) evolution of: (1) Frost-Free Season suitable zone and Dryness Index suitable zone; (2) suitable viticultural zone; (3) soil-burying line; (4) and variety regionalisation in China. This was done by using a long time series of climate data from ground weather stations all over China.

MATERIAL AND METHODS

1. Meteorological data

The daily dataset V 3.0 of basic meteorological parameters from 2474 national ground weather stations during the period 1967 to 2016 was utilised in this study. This dataset was provided

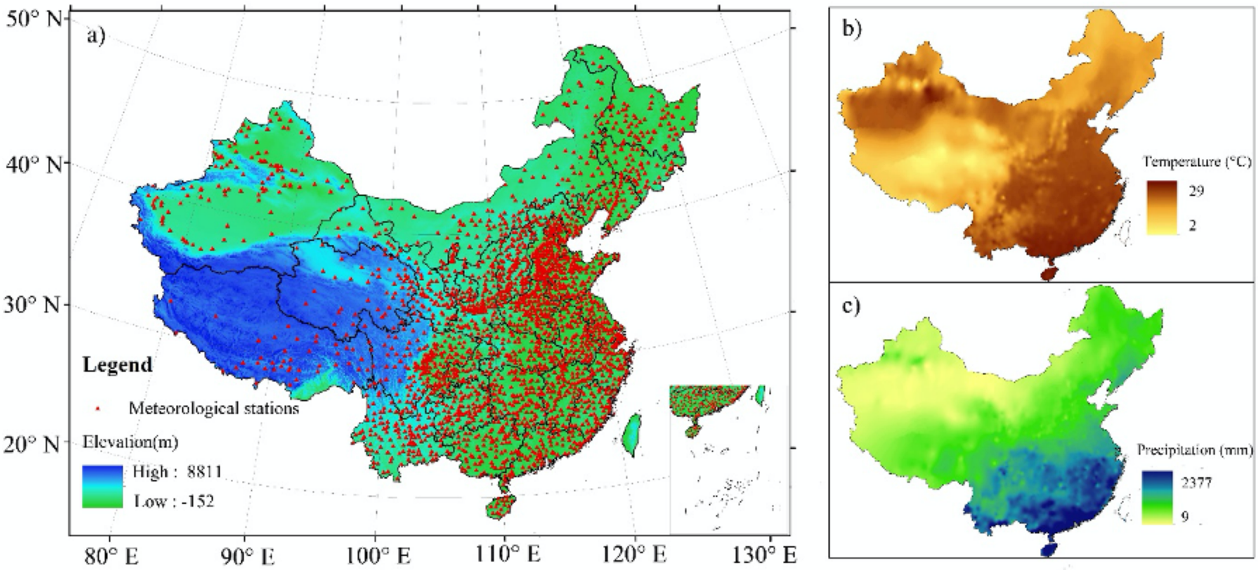


FIGURE 1. The distribution of meteorological stations and the climate pattern in China.
a) meteorological stations, b) mean temperature in growing season (April-September), c) total precipitation in growing season (April-September). The inset map in a) represents the South China Sea Islands

by the National Climatic Centre of the China Meteorological Administration and was subjected to strict quality control with artificial verification and correction of suspicious or incorrect data. It includes daily observations of temperature (mean, maximum, and minimum), precipitation, wind speed at 10 m height, relative humidity, sunshine duration, and geographical information of longitude, latitude, and altitude. Data from any station missing successive observations of more than three days during the calculation period was removed from the study. There is a relatively serious data gap between 1967 and1976, with data from only about 1800 stations that could be used; however, in other periods, data from more than 2000 stations could be used. illustrates the distribution of these weather stations and the climate pattern in China. Taiwan was not included in this study because of the lack of meteorological data for this area.

2. Digital Elevation Model

Shuttle Radar Terrain Mission (SRTM) Digital Elevation Model V 4.1 was used in this study, with a resolution of 3 arc-seconds, which corresponds to 90 m resolution at the equator. All elevations are in metres and referenced to the WGS84/EGM96 geoid. The SRTM has a horizontal and vertical accuracy of nearly 20 m and 16 m respectively. The original no-data holes within the SRTM data were filled by The International Center for Tropical Agriculture (CIAT). The dataset was provided by the Geospatial Data Cloud site, from the Computer Network Information Center of the Chinese Academy of Sciences (http://www.gscloud.cn). The distribution of elevation in China is shown in Figure 1. To facilitate the study, spatial resampling was conducted. A spatial resolution of 1000 m was selected as a compromise between computational efficiency and relatively high spatial resolution.

3. Representative sites

To assess the influence of climate variability on viticulture in China, 13 representative wine growing sites from ten main wine regions were studied, as shown in the following distribution maps. These sites are economically viable locations for *Vitis vinifera* cultivation, and many have produced excellent wines with international awards (http://awards.decanter.com). Information regarding these sites is presented in Table 1.

4. Climatic indices

4.1 Viticultural zoning

The multicriteria climatic indices system proposed by Li *et al.* (2011) was applied in this study. This system included three agro-climatic indices:

- Frost-Free season (FFS)
- Dryness Index (DI)
- Extreme Low Temperature (ELT)

FFS is defined as the number of days between the LFD in spring and the FFD in autumn. The threshold used to determine the frost day is a minimum temperature of 0 °C or less.

TABLE 1. The information of representative wine growing sites

Representative site	Abbreviation	Wine Region	Latitude (° N)	Longitude (° E)	Altitude (m)
Tsitsihar	TH	North East	47.38	123.92	147.1
Shihezi	SHZ	Xinjiang (North)	44.32	86.05	442.9
Yanqi	YQ	Xinjiang (South)	42.08	86.57	1055.3
Changli	CH	Jing-Jin-Ji (Costal)	39.72	119.17	17.6
Huailai	HL	Jing-Jin-Ji (Inland)	40.40	115.50	570.9
Wuhai	WH	Inner Mongolia	39.80	106.80	1105.6
Yinchuan	YC	Helan Mountain East	38.47	106.20	1110.9
Wuwei	WW	Hexi corridor	37.92	102.67	1531.5
Penglai	PL	Shandong	37.80	120.77	60.7
Jingyang	JY	Loess Plateau (Shaanxi)	34.55	108.82	428.1
Xiaxian	XX	Loess Plateau (Shanxi)	35.17	111.23	402.9
Minquan	MQ	Ancient Yellow River	34.65	115.15	60.6
Derong	DR	Southwest Mountain	28.72	99.28	2422.9

This was used as a thermal index in this study to assess if there was sufficient heat for grape growth in a given region. Insufficient FFS is not considered a problem for viticulture in southern China, but is a key restrictive factor in the Qinghai-Tibet Plateau and part of northern China. Thus, FFS was used to determine the northern boundary of the zone suitable for wine grape cultivation in China. The date of LFD and FFD were expressed as day of year (DOY).

DI is used to estimate the moisture regime of a given place for wine grape cultivation. As excessive rainfall is the main restriction factor of grape-growing in southern China, this index strongly determines the southern boundary of the zone suitable for wine grape cultivation in China. DI is calculated during the growing season (from 1st April to 30th September) as follows:

$$DI = ET_C/P$$

$$ET_C = K_C \times ET_O$$

where ET_C is the evapotranspiration of grape during the growing season [mm], P is the precipitation during the growing season [mm], K_C is the crop coefficient using a constant value of 0.8 here (Huo, 2006), and ET_O is the reference crop evapotranspiration [mm day^{-1}], as calculated by the Penman-Monteith method (Allen *et al.*, 1998), which is the most widely used method for ET_O estimation.

The calculation of ET_O can be expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where Rn is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [°C], u_2 is the wind speed at 2 m height [m s^{-1}], e_s is the saturation vapour pressure [kPa], e_a is the actual vapour pressure [kPa], e_s - e_a is the saturation vapour pressure deficit [kPa], Δ is the slope vapour pressure curve [kPa °C^{-1}], and γ is the psychrometric constant [kPa °C^{-1}]. These parameters can be directly obtained from the dataset or calculated from the data using the recommended method by Allen *et al.* (1998).

ELT refers to the minimal value of daily minimum temperature throughout a year. ELT is an index to assess whether soil burying is needed in a given region. Grapevines cultivated in areas with ELT lower than -15 °C need to be covered with soil during the winter to avoid roots and trunk/cane injuries (Li *et al.*, 2011). The -15 °C isotherm of ELT is considered the soil-burying line, which is the boundary of the soil-burying area and the non-soil-burying area.

Table 2 summarises the classification of suitable viticultural zones and the corresponding limits based on this system of multicriteria climatic

TABLE 2. The classification of suitable viticultural zones based on the multicriteria climatic indices system of frost-free season (FFS), dryness index (DI) and extreme low temperature (ELT).

	Semi-humid (I) 1<DI≤1.6	Semi-arid (II) 1.6<DI≤3.5	Arid (III) DI>3.5
Cold (A) 160d≤FFS≤180d	A I	A II	A III
Temperate (B) 180d<FFS≤200d	B I	B II	B III
Warm © 200d<FFS≤220d	C I	C II	C III
Hot (D) 220d<FFS	D I	D II	D III
Soil-burying		ELT ≤ -15°C	

Note that the accumulated active temperature (AAT)≥2500 °C is added as the supplementary requirement for each zone

indices (Li and Wang, 2015). In order to simply illustrate different sub-climate zones, a combination of letter and roman numerals were used here to represent 12 different climate types (Table 2). The zone with FFS>160 d is considered as frost-free season suitable zone. The zone with DI>1 is considered as dryness index suitable zone. An area is considered as a suitable viticultural zone only when FFS and DI are suitable at the same time (FFS>160 d and DI>1). However, there are some areas - mainly located in the Tibetan Plateau and its margins, or other high-altitude mountainous areas in the west of China - which have an appropriately long FFS, but a quite low temperature during the growing season and thus insufficient heat for wine grape cultivation. In order to exclude these regions, an accumulated active temperature (AAT, based on 10 °C) of at least 2500 °C in growing season was introduced as a supplementary requirement based on a previous analysis of several stations and actual viticultural viability in this high-altitude area (Li and Wang, 2015).

4.2 Variety regionalisation

Variety regionalisation was conducted based on accumulated effective temperature (AET) for the suitable viticultural zone. This index was adapted from the Winkler Index (Winkler, 1962). In China, the grapes are usually mature in September rather than in October, thus the calculation of AET is performed throughout September. Accordingly, as shown in Table 3, the classification limits of each zone have been slightly modified to match Chinese conditions, and some local varieties were added (Huo, 2006). The zone with AET of 1290-1560 °C and the zone with AET of 1560-1840 °C are both suitable for white wine and red wine. But white wine and red wine (a) is usually characterised by fresh flavor, medium alcohol and medium body, while white wine and red wine (b) is mainly characterised by the style of strong flavor, high alcohol and full body.

AET is calculated as follows:

$$AET = \sum_{1^{st}April}^{30^{th}Sept} (T_{mean} - 10) \qquad (T_{mean} \geq 10°C)$$

where T_{mean} is the daily mean temperature.

5. Methodology

The spatial interpolation of these agro-climatic indices was conducted using ANUSPLIN (Australian National University's Thin Plate Smoothing Spline) software 4.37 (Hutchinson, 2007). ANUSPLIN is software for interpolation using thin plate smoothing splines to allow transparent analysis and the effective interpolation of noisy multi-variate data. The degree of smoothness of the fitted function can be calculated automatically from the data by minimising the predictive error of the fitted surface, as defined by the generalised cross validation (GCV). Three independent spline variables of latitude, longitude, and elevation, were selected for analysis, each with three orders of spline, providing the best calculation model for accurate interpolation of these climatic indices. The decadal mean values (1967-1976, 1977-1986, 1987-1996, 1997-2006, and 2007-2016) of a single climatic index with altitude and longitude from all stations, as well as the SRTM digital elevation data, must be transformed into ASCII format and used as input data. The output data of ANUASPLIN 4.37 were further processed by ArcGIS 10.2. As the ET_O and P need to be spatialised separately, the interpolation of DI was achieved by calculating these two indices using the map algebra method. Sen's slope (Sen, 1968) and the rank-based non-

TABLE 3. The classification of different wine types and recommended varieties based on accumulated effective temperature (AET) during growing season (1st April - 30th September)

Limits of AET (°C)	Wine type	Recommended varieties
<1290	Sparkling wine and white wine	Muller-Thurgau, Pinot Blanc, Pinot Gris, Chasselas, Silvaner, Riesling, Chardonnay, Gewürztraminer, Pinot noir
1290-1560	White wine and red wine (a)	Riesling, Chardonnay, Colombard, Pinot Noir, French Blue, Syrah, Sangiovese
1560-1840	White wine and red wine (b)	Sauvignon Blanc, Italian Riesling, Chenin Blanc, Ugni Blanc, Rkatsiteli, Semillon Cabernet Sauvignon, Cabernet Franc, Merlot, Malbec, Syrah, Grenache, Canepabn
1840-2120	Red wine and sweet wine	Grenache, Muscat Blanc, Longyan, Ruby, Carignane, Zinfandel, Nebbiolo, Cinsault
> 2120		Table grapes

parametric Mann–Kendall (MK) trend analysis developed by Mann (1945) and Kendall (1975) were used to assess the inter-annual variation and the significance of the climate indices for each of the representative wine growing sites. The inter-annual variation multiplies 10 represents the change tendency over 10 years.

RESULTS

1. The decadal evolution of suitable frost-free season zone

As shown in , there has been a continuous northward enlargement of the suitable FFS zone in recent decades. This trend is more noticeable in North East Region (Heilongjiang, Jilin, and Liaoning), Inner Mongolia, and Xinjiang.

In the northern part of North East Region, the FFS is insufficient for wine grape cultivation from 1967 to 1986. In the next decade, the edge of the suitable FFS zone approached Tsitsihar. In the most recent two decades, the suitable FFS zone expanded further north than Tsitsihar. In Inner Mongolia, expansion mainly occurred in the southwestern and southeastern areas, and there was a slight transformation of classification. Initially, there was only a small cold zone, but in the following two decades this zone gradually expanded. In the fourth decade, some of the cold zone started to be replaced by temperate zone, and in the most recent decade, the temperate climate occupied a larger part of this region. In Xinjiang, the changing climate has not only continuously expanded the suitable FFS zone northwards, but has also notably altered the FFS classification of most areas. In the first decade, temperate and warm zones made up a large percentage of the area. In the following decades, the warm zone gradually expanded eastwards, and the temperate zone gradually moved northwards. The warm zone was gradually replaced by hot zone in the western part. Until the most recent decade, Xinjiang was dominated by a warm climate. In other regions, there was also an extension of the FFS, with a gradual increase of area and change of classification of suitable FFS zone. Most cold areas in Gansu, Ningxia, Shaanxi, and Shanxi gradually transformed into temperate type. Most warm areas in Jing-Jin-Ji (Beijing, Tianjin, and Hebei) and Shandong were gradually replaced by hot climate.

According to the trend analysis of the 13 representative wine growing sites, an extremely significant increasing trend of FFS was detected for most sites (Table 4). Jingyang showed the highest increasing change rate of 8.3 d/10 years, and Minquan was the second highest, with a change rate of 8.0 d/10 years. Half of the representative wine growing sites experienced a change of FFS classification based on the change in the decadal value (Table S1). Additionally, there was a significant delay in FFD in half of the representative wine growing sites, and a significant advance of LFD in more than half of these sites, with a higher variation rate.

2. The decadal evolution of suitable Dryness Index zone

Compared with FFS, the DI distribution exhibited a typical gradient with a stepped increase from southeast to northwest and almost no obvious movement of the suitable DI zone (Figure 3). Changes were only observed in some local regions, showing an irregularity of geographical distribution. The most distinguished changes were observed in North East Region and Southwest Mountain Region (Tibet, Sichuan, and Yunnan).

In the southwest and northeast part of North East Region, the area of suitable DI zone decreased in the first three decades, especially in 1987-1996, and slowly increased in the following two decades.

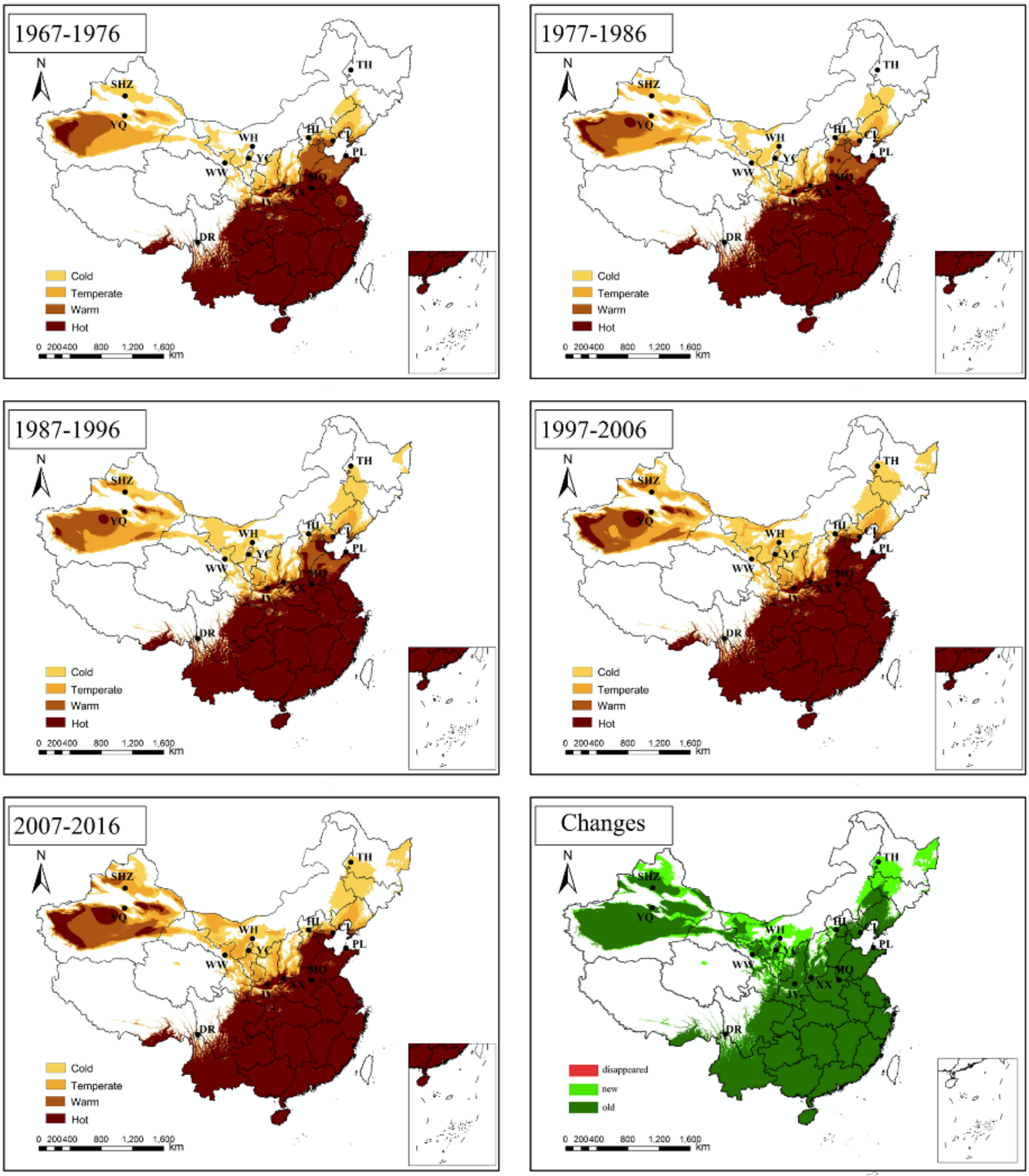


FIGURE 2. The decadal evolution of suitable frost-free season (FFS) zone during the period from 1967 to 2016, and the changes of suitable FFS zone between current (2007-2016) and past (1967-1976) time periods.

The black dots represent 13 representative wine growing sites.

The type of suitable DI zone in southeastern Inner Mongolia and the western North East Region also changed, with an early contraction of the semi-arid zone and an expansion of semi-humid zone, and then the reverse trend in the following two decades. In Southwest Mountain Region, the continuous enlargement of a small suitable DI zone was observed. This zone is mainly located in the eastern part of Tibet with a small part located at the junction of Tibet, Sichuan, and Yunnan. According to the trend analysis of the 13 representative wine growing sites, both increasing and decreasing trends were observed for DI, but most variations were not significant (Table 5).

TABLE 4. The mean value and variation rate of frost-free season (FFS), the first frost day (FFD) and the last frost day (LFD) from 1967 to 2016 in representative wine growing sites.

Representative site	FFS			FFD			LFD		
	Mean (d)[a]	Rate (d/10 years)	Sig[b]	Mean (DOY)	Rate (d/10 years)	Sig	Mean (DOY)	Rate (d/10 years)	Sig
Tsitsihar	157.4±12.5	3.9	***	279.0±7.6	1.5	+	120.6±8.3	-2.7	***
Wuwei	171.0±16.0	5.7	***	286.9±10.3	1.5	NS	114.9±12.6	-4.8	***
Shihezi	178.8±15.8	5.2	***	284.6±10.2	2.9	**	104.8±11.2	-2.3	*
Yinchuan	181.3±17.0	6.7	***	291.5±9.7	2.3	*	109.2±11.7	-4.5	***
Wuhai	182.6±11.3	1.7	+	290.2±9.1	1.1	NS	106.7±9.2	0.0	NS
Yanqi	184.1±12.3	2.5	*	289.6±8.6	1.3	NS	104.5±10.3	-1.5	+
Huailai	194.8±15.0	7.4	***	295.2±8.8	3.3	***	99.5±10.2	-3.2	***
Xiaxian	207.5±11.9	1.5	NS	302.5±10.4	0.8	NS	94.0±9.5	-0.7	NS
Changli	212.6±11.0	1.4	NS	305.5±8.1	0.4	NS	91.9±6.8	-1.0	NS
Jingyang	230.5±16.8	8.3	***	311.8±11.1	3.3	***	80.7±12.2	-4.4	**
Minquan	233.4±18.3	8.0	***	315.3±10.6	3.3	**	80.9±12.0	-5.4	***
Penglai	236.1±13.2	4.1	***	325.0±9.0	1.9	*	87.9±9.0	-2.5	**
Derong	278.9±16.7	4.8	*	332.4±10.2	1.9	NS	52.5±10.3	-2.5	*

[a] indicated by mean value ± standard deviation

[b] Significance: *** for $p < 0.001$, ** for $p < 0.01$, * for $p < 0.05$, + for $p <0.1$, NS for $p \geq 0.1$

There was almost no change in DI classification in these wine growing sites; a change may have been apparent in one decade, but it was restored in the following decade (Table S2). Changli started with DI<1, but a higher DI suitable for viticulture was exhibited in the two most recent decades. Minquan fluctuated between unsuitable and semi-humid. Both increasing and decreasing trends were found for P and ET_O, with almost no significance found for P. Four sites showed significant increasing trends and two showed significant decreasing trends in ET_O.

3. The decadal evolution of suitable viticultural zones

A region with both FFS suitability and DI suitability is considered to be a suitable viticultural zone. As shown in Figure 4, there was a continuous northward expansion of the viticultural suitability zone, with an average increase of 0.204 million km^2/decade. The most dramatic increase in this zone was observed in 1997-2006, with an increase of 0.309 million km^2. Figure 4 also shows that the suitable viticultural zone in Xinjiang, northwestern Gansu, northern Ningxia, and western Inner Mongolia are mainly classified as arid climate, while the suitable viticultural zone in east Gansu, Shaanxi, Shanxi, Hebei, Beijing, Tianjin, Shandong, and the northeast three provinces are dominated by semi-humid climate. Only the suitable viticultural zones in central and east Inner Mongolia, central Ningxia, central Gansu, and some areas in southwest China are considered as semi-arid climate.

The decadal variation in area of each climate zone is further shown in Figure S1. The arid climate always makes up the largest area, with A III, B III, and C III as the three main sub-climate types, but the area of D III in Xinjiang obviously increased in the two most recent decades. The semi-arid climate makes up the smallest area for all decades, with B II, C II, and D II as the three smallest sub-climate zones. In each dryness climate type (I, II, and III), cold climate always plays a leading role, and an increasing trend is observed in A I and A II. Except for C I, D II, and A III, the sub-climate zones show an obvious increase in area in the most recent two or three decades.

When comparing the distribution of FFS (Figure 2), DI (Figure 3), and suitable viticultural zones (Figure 5) in 1967-1976 with the distribution of those zones in 2006-2016, it was revealed that the increase in suitable viticultural zone is very closely matched to the expansion of the suitable FFS zone. Some existing wine regions are located in this novel suitable viticultural zone. A large novel zone appeared in the north, and a few areas are located at the edge of the semi-humid zone, with decreased viticultural suitability due to the DI decrease. The North East Region, Inner Mongolia Region, and Xinjiang Region are the three most profitable wine regions.

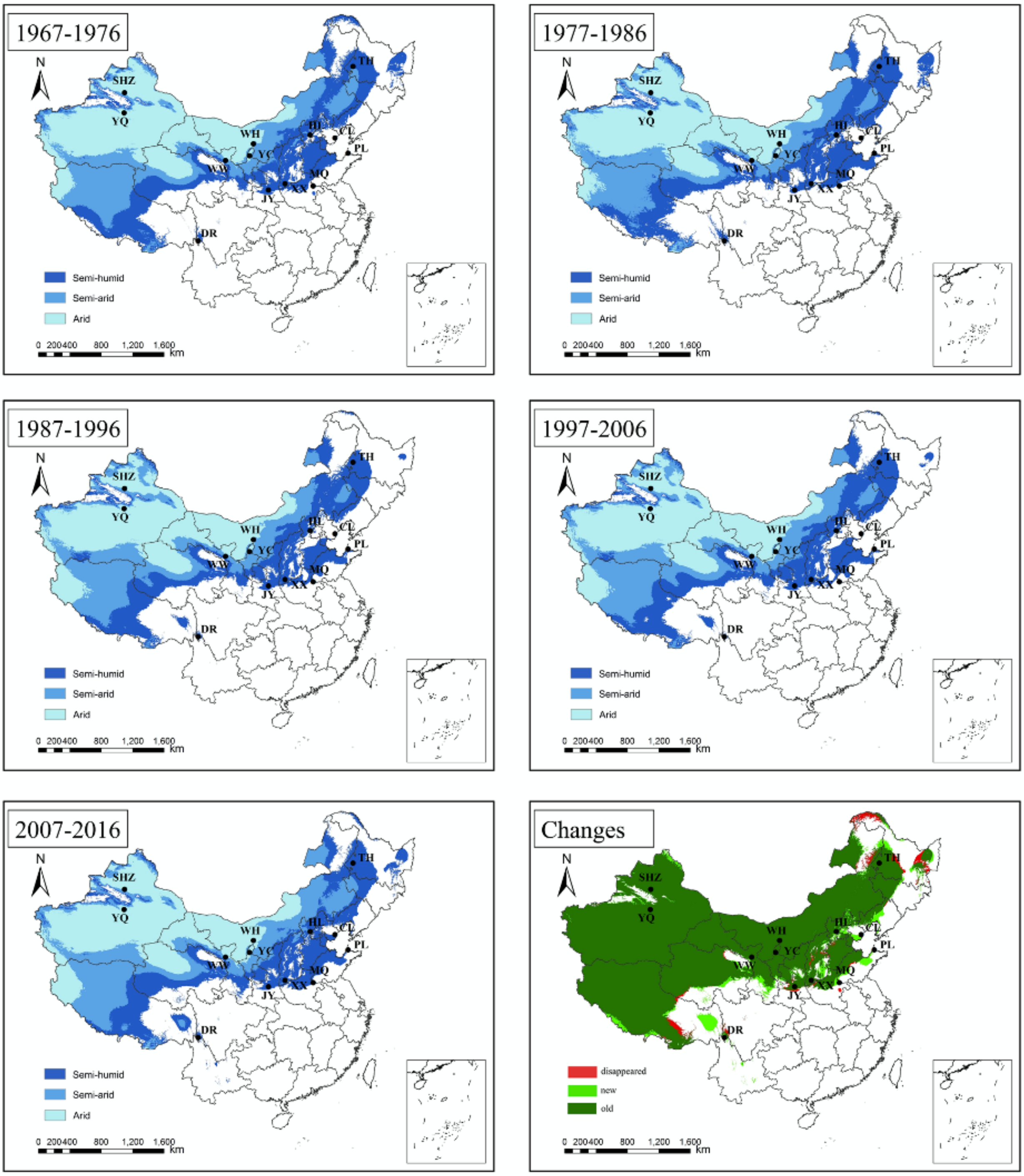


FIGURE 3. The decadal evolution of suitable Dryness Index (DI) zone during the period 1967 to 2016 and the changes in suitable DI zone between current (2007-2016) and past (1967-1976) periods.

The black dots represent 13 representative wine growing sites

4. Decadal moving of the soil-burying line

As shown in Figure 6, the displacement of the soil-burying line occurred only in part of the Jing-Jin-Ji and Shandong. Between 1967-1976 and 1977-1986, there was no obvious movement of the soil-burying line. However, in the following decade, a significant displacement of the soil-burying line was observed, which moved to north of the Shandong Region. During the period 1997-2006, a small section of the soil-burying line moved back to Shandong. In the most recent decade, the soil-burying line moved northwards again, but was still to the south of the line in

TABLE 5. The mean value and variation rate of dryness index (DI), precipitation (P) and reference crop evapotranspiration (ET_O) during the growing season (1st April - 30th September) from 1967 to 2016 in representative wine growing sites.

Representative site	DI			P			ET_O		
	Mean[a]	Rate (1/10 years)	Sig[b]	Mean (mm)	Rate (mm/10 years)	Sig	Mean (mm)	Rate (mm/10 years)	Sig
Changli	1.0±0.4	0.1	**	675.6±228.7	-66.2	*	764.4±47.3	10.0	*
Minquan	1.0±0.3	0.0	NS	612.7±178.7	-19.6	NS	728.2±63.0	-31.8	***
Penglai	1.3±0.5	0.0	NS	578.7±176.9	3.6	NS	807.9±49.2	-0.9	NS
Xiaxian	1.4±0.4	0.0	NS	457.3±112.2	-9.7	NS	770.6±40.6	-0.5	NS
Tsitsihar	1.5±0.4	-0.0	NS	428.3±91.9	2.4	NS	739.6±461	-5.5	NS
Jingyang	1.5±0.5	0.0	NS	416.3±118.1	-11.4	NS	711.6±59.0	9.6	NS
Huailai	1.8±0.5	0.0	NS	387.7±93.3	-2.8	NS	825.1±35.3	-4.1	NS
Derong	1.8±0.7	-0.0	NS	369.6±86.4	4.9	NS	776.0±47.2	-9.4	+
Wuwei	3.9±1.3	0.1	NS	177.6±58.4	0.3	NS	768.3±41.3	12.7	**
Yinchuan	3.9±1.6	0.0	NS	186.7±59.2	1.4	NS	807.8±37.7	12.8	***
Shihezi	4.7±1.5	-0.0	NS	151.9±44.6	2.6	NS	811.0±40.5	12.4	***
Wuhai	5.9±2.7	0.4	NS	164.1±57.8	-9.7	+	1019.5±51.5	-8.4	NS
Yanqi	12.5±9.0	-0.7	NS	75.7±38.5	4.1	NS	847.2±50.2	-12.3	*

[a] indicated by mean value ± standard deviation

[b] Significance: *** for $p<0.001$, ** for $p<0.01$, * for $p<0.05$, + for $p<0.1$, NS for $p\geq0.1$

1987-1996. Table S3 lists the ELT variation trends in the 13 representative wine growing sites. A significant increasing trend ($p<0.05$) was observed for half of the sites.

5. Decadal evolution of variety regionalisation

The decadal distribution of variety regionalisation is illustrated in Figure 7, with more details provided in Figure S2. In terms of accumulated effective temperature, the zone with AET>2120 °C makes up the biggest area, with an expansion in the most recent three decades. This expansion led to a decrease in the zone with an AET of 1840-2120 °C, which are the conditions recommended for late wine grapes in Xinjiang, Shandong, Henan, Jing-Jin-Ji, southern Tibet, and western Inner Mongolia. The zone with AET<1290 °C - making up the smallest area – is suitable for early grapes, which can be used to produce sparkling wine or fresh white wine. The decadal area changed with fluctuation, and was mainly distributed throughout east Qinghai, central and southeast Gansu, south Ningxia, and the boundary area of Sichuan, Yunnan, and Tibet. The zone with AET of 1560-1840 °C is suitable for the growth of most international grape varieties, which are used to produce both white and red wines with strong and full style. A continuous expansion of this region was observed, with especially notable changes in North East Region and southern Inner Mongolia; this zone was the biggest zone for cultivation of wine grapes in the recent two decades, although there was a slight decrease in the last decade. The zone with AET of 1290-1560 °C is suitable for both white and red wine grapes with earlier maturity and it also changed with fluctuation, with new areas in North East Region and Inner Mongolia, as well as areas that gradually transformed into a zone with higher AET. A jump of the total area of zones for wine only (excludes the zone with AET>2120 °C) occurred in the third decade, but this was followed by little change in the most recent two decades. What's more, the percentage of wine grapes shows the same trend in the first three decades, but a decreasing trend was observed in the two recent decades.

Compared with the above-mentioned climatic indices, AET exhibits a significant increasing trend ($p<0.05$) in almost all these representative wine growing sites except Minquan and Derong

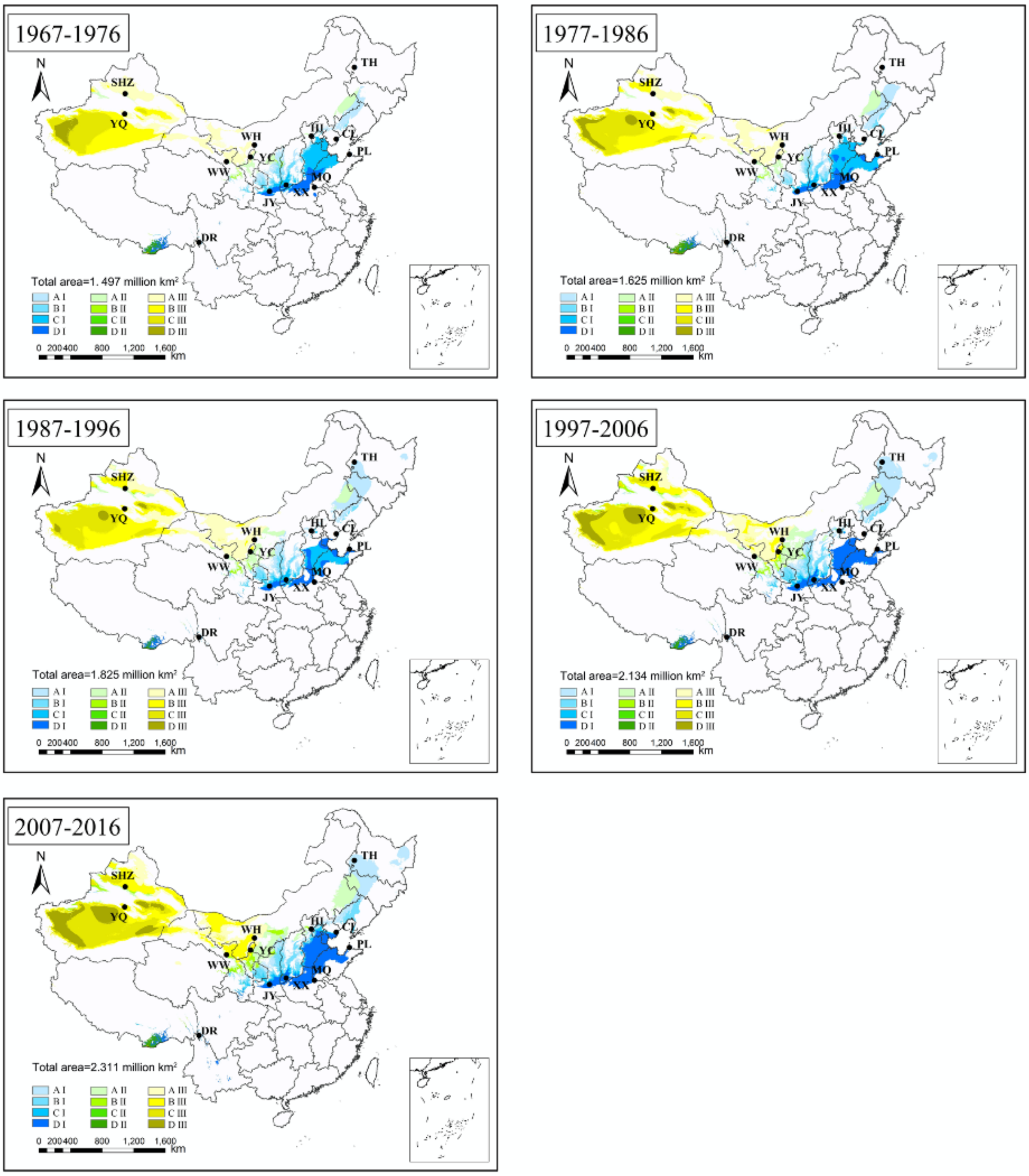


FIGURE 4. The decadal evolution of suitable viticultural zones during the period 1967 to 2016. The black dots represent 13 representative wine growing sites. Detailed definitions of 12 zones are given in Table 2

(shown in Table S4). Additionally, there was significant change in the decadal distribution of AET classification.

DISCUSSION

1. The climatic indices used in this study

Many agro-climatic indices have been proposed by researchers worldwide, like the Winkler index (Amerine and Winkler, 1944; Winkler, 1962), the Huglin index (Huglin, 1978), the Branás heliothermic index (Branás, 1974), the growing season mean temperature (Hall and Jones, 2009), and the latitude-temperature index (Jackson and Cherry, 1988). However, unlike many worldwide wine regions that benefit from an oceanic climate or Mediterranean climate types, China has a typical continental monsoon climate with hot, rainy summers and cold, dry winters, and sharp changes in temperature in spring and autumn.

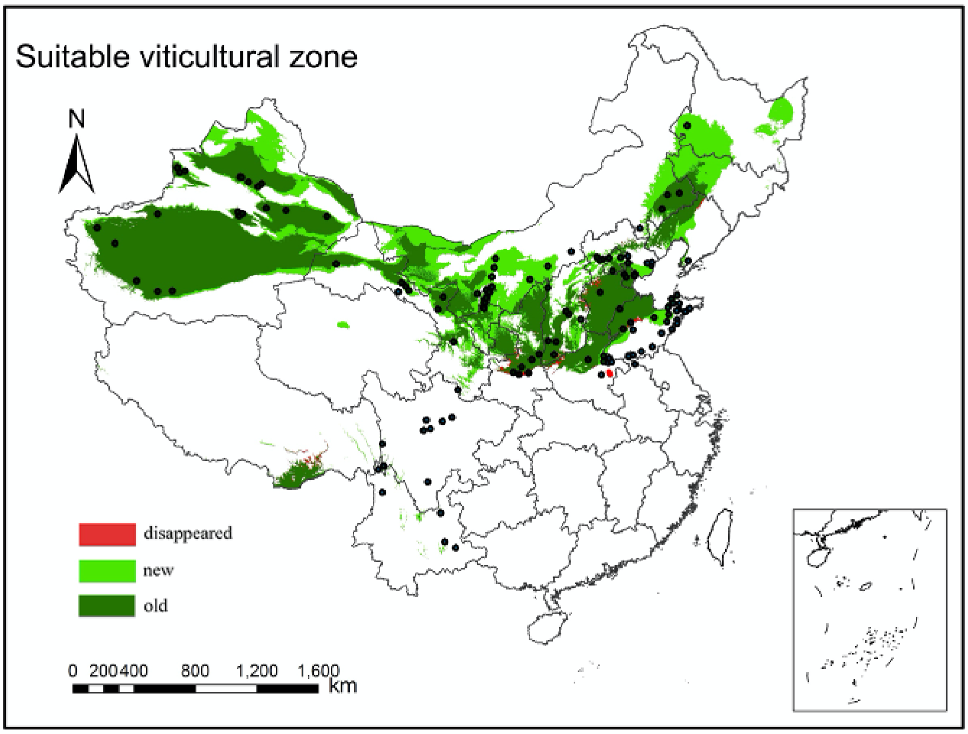


FIGURE 5. The displacement of suitable viticultural zones between current (2007-2016) and past (1967-1976) time periods.

The zone in dark green represents the situation in 1967-1976. The zone in red and in light green represent the disappeared and new zones respectively in 2007-2016. The black dots represent most of the existing wine grape growing sites in China (Wang *et al.*, 2018).

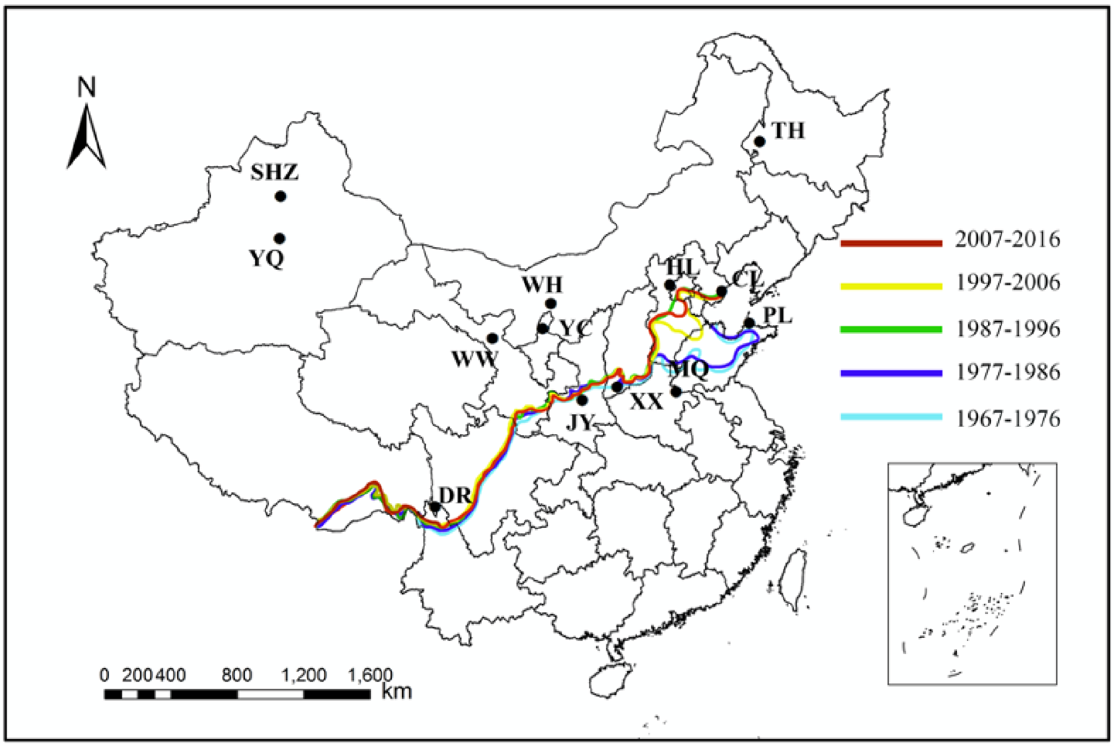
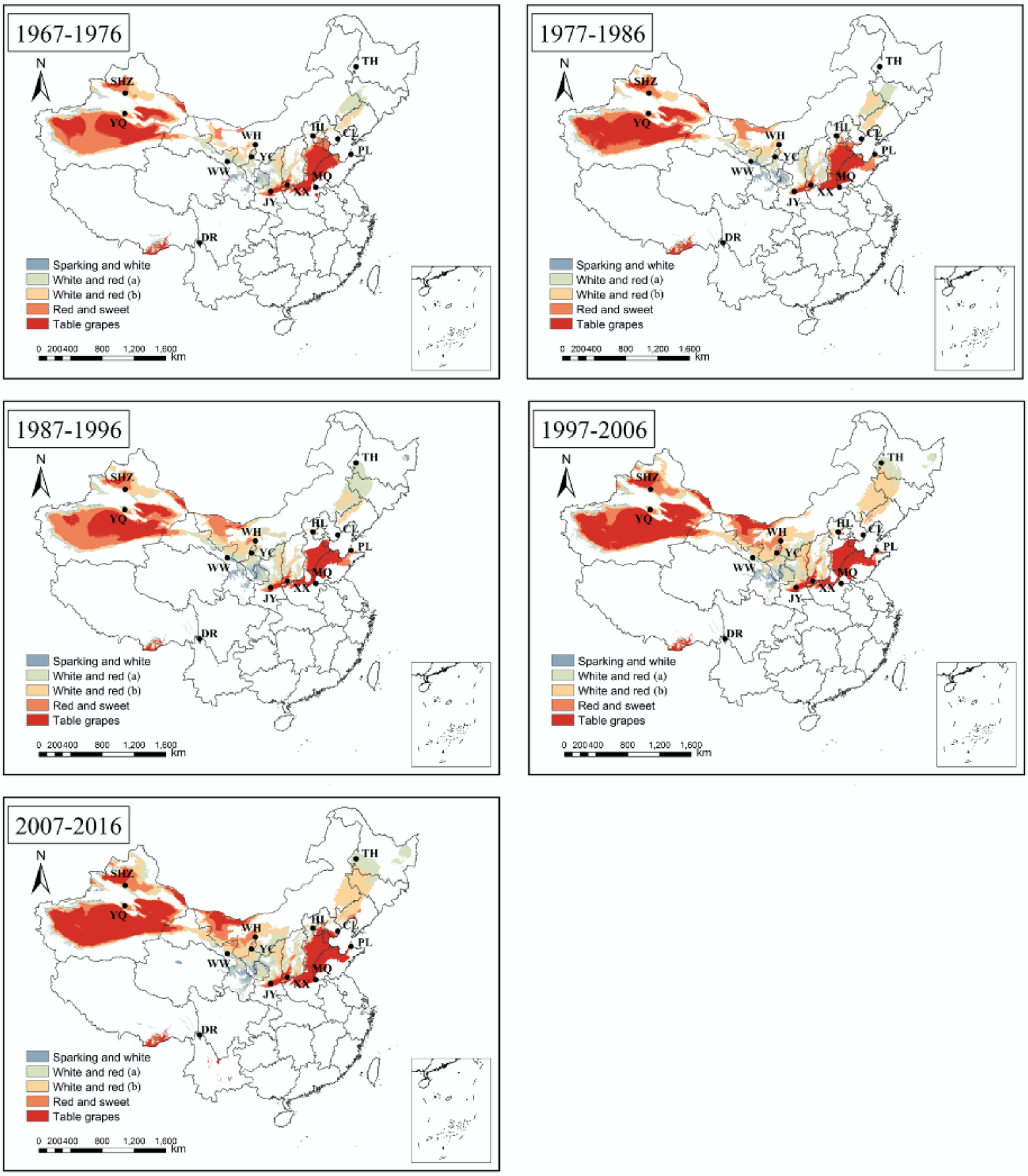


FIGURE 6. The decadal moving of soil-burying line during the period 1967 to 2016.

The black dots represent 13 representative wine growing sites.


1967-1976

1977-1986

1987-1996

1997-2006

2007-2016

FIGURE 7. The decadal evolution of variety regionalisation during the period from 1967 to 2016.
The black dots represent 13 representative wine growing sites.

These indices may therefore not be very applicable to China. For example, the adequate accumulative temperature of a region in China may largely be due to high temperature in summer, which will obscure the fact that the short period of FFS makes grapevine growing challenging. Different from the warm winter in many other wine countries that benefit from an oceanic or Mediterranean climate, most Chinese wine regions undergo severe winters with drought, which is a big issue for wine grape survival. Thus, soil-burying, which can provide an effective protection to the aerial portions of the vine by insulating them from the extreme cold air, is a necessary practice in 90 % wine regions in China (Li and Wang, 2015). This practice requires additional labour and expense, and can also contribute to environmental issues, such as soil erosion (Xue *et al.*, 2019). ELT is an important contributor, and a -15 °C isotherm of ELT can be applied to effectively identify soil-burying areas and non-soil-burying areas. After comparison and analysis, the climatic indices system, which includes indices of FFS, DI, and ELT was selected as the most appropriate indices system to reliably assess Chinese viticultural suitability (Huo, 2006, Li *et al.*, 2011, Wang *et al.*, 2018).

Different varieties of grapes have different heat requirements, and a variety will exhibit its best performance only if the heat requirement is well matched to the actual condition (van Leeuwen *et al.*, 2008). Here, the index of AET which is derived from the Winkler Index (Winkler, 1962), was selected for variety regionalisation with the calculation period from 1st April to 30th September. The LFD for many representative sites are later than, or very close to 1st April, except in Derong (Table 4), while many regions harvest in September. Thus, the calculation during this period can generally represent the thermal condition from budburst to maturity with a base temperature of 10 °C.

2. Implications

There are many reports about the benefits of recent climate change on agriculture, such as yield and cultivation boundaries of some crops in China (Chen *et al.*, 2011; Chen *et al.*, 2012). The same goes for grapevine cultivation in China. Wine grapes have been widely cultivated in 179 counties of China, with a total area of 1, 632 km^2 (Wang *et al.*, 2018). Some of these counties are located in the novel viticultural zone of emerging wine growing regions (Figure 5).

Although the suitable viticultural zone has expanded, most of the new suitable viticultural zone is dominated by a cold climate (Figure 4). Taking Tsitsihar as an example, the decadal average FFS is only a little more than 160 d (Table S1), indicating a potential risk of frost damage. Therefore, site selection, variety selection, cultural practices and frost protection technologies must be taken into account to protect grapevines from low temperature injuries (Evans, 2000). These areas are mainly classified as arid climate type (Figure 4), and water shortage is a key constraint on wine grape cultivation, as well as on other crops in northern China (Meng *et al.*, 2016; Mo *et al.*, 2017; Yang *et al.*, 2015). Irrigation is necessary in these areas, which directly stresses water conservation and food security (Dalin *et al.*, 2015). Thus, the development of adaptation strategies to both reduce the water footprint and maintain good grape quality is of tremendous importance for sustainability (Hannah *et al.*, 2013). Here, scientific irrigation approaches like partial root irrigation (Romero *et al.*, 2015), wastewater irrigation (Hirzel *et al.*, 2017), and precision irrigation (Rojo *et al.*, 2016) should be considered for more efficient and sustainable development. The semi-humid zone is also relatively wide ranging (Figure 4), and the potential risk of diseases and pests should be considered for this zone; this is especially true in a hot climate, which exhibited a sharp expansion in area in Shandong, Henan, Hebei, Beijing, Tianjin, and the southern part of Shaanxi in the two most recent decades.

As the shift of the soil-burying line has occurred exclusively in Shandong and Jing-Jin-Ji with fluctuation, there is still a need for vine burying in most areas under climate change. Other studies have also confirmed greater increases in minimum temperature in winter in northern and northeast China (Xu *et al.*, 2011), and some of this change has been attributed to rapid urbanisation after 1980 (Li *et al.*, 2014). Thus, soil burying remains a principal environmental constraint on Chinese grapevine cultivation. We suggest the selection and breeding of cold-tolerant varieties in soil-burying line boundaries to help reduce manpower and cost. Additionally, the use of biodegradable liquid film and other protection materials can be considered as alternative methods to reduce the cost of protecting the vines (Xue *et al.*, 2019).

With the increasing changes in area of suitable viticultural zones, the spectrum and distribution of varieties has also changed. In cool regions, like the North East Region, the changes in the zone allow the successful ripening of more varieties, while in some regions under warm or hot climate, especially in Hebei, Henan, Shandong, and Xinjiang, rising temperature poses a significant threat. This does not mean these regions have already lost their suitability for wine grapes, because the required thermal is empirically estimated and cannot strictly define the actual upper thermal value (van Leeuwen *et al.*, 2013); however, the high temperature effects will need to be considered in the near future. Variety selection is critical for taking advantage of regional characteristics and ensuring sustainable development. Compared with many appellation regions worldwide which have an established particular regional style (Neethling *et al.*, 2017; Ollat *et al.*, 2016), China has more opportunities to grow different varieties. In addition to international recognised varieties, a long-term goal would be to breed some specific varieties to cope with future climate change (Ollat *et al.*, 2017).

3. Limitations and expectations

Our approach still cannot satisfy the needs of some local regions, especially in the Southwest Mountain Region, where the topography is extremely complex with sharp changes in altitude, and where the wine grapes only grow under certain microclimate conditions. These areas are not clearly presented on the distribution map in this study due to a limited number of weather stations and the limited precision of the Digital Elevation Model.

For some regions, fixing the calculation period from April to September does not fit the actual growing season. For example, in Southwest Mountain Region, because of high altitude and low latitude, grapes usually sprout earlier than those in other regions. Similarly, in some hot regions with higher temperature, grape phenological timing is accordingly advanced, which leads to a change of growing season in the time period (Jarvis *et al.*, 2017). For example, in Xinjiang, Cabernet Sauvignon fully ripens in the middle of August (Zhang *et al.*, 2019), thus the calculation of accumulated temperature from April to September may show an overestimation. Rather than a fixed time period, the climate conditions should be evaluated regularly, especially for some key pheno-phases. This would allow a better estimation based on heat-defined growth intervals, rather than calendar dates, to be made (Caubel *et al.*, 2015; Holzkämper *et al.*, 2011; Real *et al.*, 2015).

Similarly, using the same criteria may not be appropriate for all regions. For example, vineyards distributed in Southwest Mountain Region have a certain slope, with higher evapotranspiration rates (Hofmann *et al.*, 2014). There is a lack of precise crop coefficient (Kc) values across China, and in order to simplify the calculation, a constant value used in previous studies (Huo, 2006; Li *et al.*, 2011; Li and Wang, 2015; Wang *et al.*, 2018) was also adopted here. However, this value changes during the whole crop cycle and differs with location. The FAO has provided the recommended value for different stages, but this should be adjusted according to local climate conditions (Allen *et al.*, 1998).

Climate change not only modifies the average climate characteristics, but also increases the frequency, time duration and intensity of some extreme weather events (Li and Bardají, 2017). These events (such as heatwaves, extreme drought, or spring frost, hail, and floods) can sometimes be fatal or may severely destroy vineyards in a short time (Gouot *et al.*, 2018; Marangon *et al.*, 2016; Rodó and Comín, 2000; Sgubin *et al.*, 2018; Webb *et al.*, 2010). The detrimental effects of these extreme events should be taken into account in further studies.

Taking into consideration all the above-mentioned situations, region-specific research combined with a variant period is strongly recommended in further studies. Of course, in addition to climate, there are still other environmental factors (such as soil type) that should be taken into account in order to accurately estimate viticultural suitability (van Leeuwen *et al.*, 2004).

CONCLUSION

We assessed the impact of recent climate change on Chinese viticulture by analysing the inter-decadal variation of the distribution of the suitable FFS zone, the suitable DI zone, suitable viticultural zone, soil-burying line and variety regionalisation. The recent climate change of the past 50 years has resulted in an obvious northward movement of the suitable viticultural zone. This has directly increased the opportunity for wine growing in North East Region, Inner Mongolia Region, and Xinjiang Region, with many newly established wine growing sites. These novel regions benefit most from the northward expansion of the suitable FFS zone. More than half of the representative sites showed a significant increase in the length of the FFS, as well as a significantly advanced LFD. The movement of the soil-burying line was only noticeable in Shandong and Jing-Jin-Ji; thus soil-burying for grapevine overwintering is still required in most regions. Besides, although the suitable viticultural zones showed no impact by the water regime, most suitable zones are classified as semi-arid or arid climate that are already showing a high demand of water use. The significant increase of AET in the growing season threatens varietal suitability in Xinjiang, Shandong, and Hebei. The results provide an insight into both the challenges and the opportunities arising from the recent climate variability on wine growing, and this analysis can be used to adjust vineyard management strategy and variety selection to facilitate the long-term and sustainable development of Chinese wine growing under a changing climate. We also encourage region-specific studies that utilise more precision methodologies.

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