Journal of Agricultural Science and Technology A 9 (2019) 278-293
doi: 10.17265/2161-6256/2019.05.002

Terroir Suitability Zoning for the Six Prevailing Wine Grape Varieties in Ningxia Hui Autonomous Region (with a Focus on the Helan Mountain East) of China

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Abstract: Terroir plays an important role in wine grape production and good wine making. Among all the aspects of terroir in a given region, climate, soil and variety are the most important ones. The goal of this study was to evaluate these three aspects of terroir in Ningxia Hui Autonomous Region of China, with a focus on the Helan Mountain East. Based on historical weather data during the period 1981 to 2016 from 22 meteorological stations in the research area, the climatic indices were derived, with which the growable zone for wine grape cultivation in the research area was identified. By synthesizing the climatic indices and soil type data, stepwise and optimization methods were used to divide the growable zone into optimal, suitable, near-suitable and unsuitable zones for the six prevailing wine grape varieties. In the analysis, the six prevailing wine grape varieties include two white wine grape varieties of "Chardonnay" and "Riesling" and four red wine grape varieties of "Cabernet Sauvignon", "Merlot", "Pinot Noir" and "Grenache Noir". With the Geographic Information System (ArcGIS) software, the geographical distributions of these terroir suitability zonings were mapped in the research area according to a small grid simulation model. The results showed that the growable zone for wine grapes was mainly focused in most of the northern and central parts of Ningxia Hui Autonomous Region. This particular zone was suitable for the typical red wine varieties like late-maturing "Grenache Noir", medium-to-late maturing "Cabernet Sauvignon", medium-maturing "Merlot" and early-maturing "Pinot Noir". In particular, the optimal zone for these four red wine varieties was centered in Xixia county of Yinchuan city, Pigeon Hill of Qingtongxia city and Baima Township of Zhongning County. For the two early-to-medium maturing white wine varieties of "Riesling" and "Chardonnay", the optimal and suitable zones were in the cool area of the central arid zone and the Qingshui River tributary.

Key words: Wine grape, terroir, Helan Mountain East, China.

1. Introduction

Terroir is a French term based on the idea that food and drink from a certain place possess unique tastes. A gathering under the auspices United Nations Educational, Scientific and Cultural Organization (UNESCO) [1] had emphasized that it is extremely difficult to translate terroir into other languages, but French winemakers have long used this term to refer to the complex interaction between all of the physical aspects of geology, soils, climate, geomorphology and vegetation that combine to create a particular "place" where grapes are grown [2, 3]. It is said that climate has the greatest effect on wine grape production, followed by soil and cultivar [4].

Due to the complexity and unique nature of the terroir [5], it clearly shows difference of quality and style of the grape, especially on the wine, which makes all products have the characteristics of "terroir". The Old World wine countries like France and Italy have fully recognized the importance of terroir as early as the 1920s; the New World wine countries,

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including the United States, Australia and others, started to fully recognize the importance of terroir since the 1970s [2, 4, 6]. Based on terroir conditions, domestic grape-growing regions were divided into several small producing sub-regions, and some were even refined to the field level. Varieties, viticulture, brewing methods and wine types were all legally defined in each of the terroir areas [7-9].

Grape terroir was generated mainly by establishing a zoning index system based on climatic conditions and soil types in order to address the comprehensive effects of climate and soil on the growth and quality formation of wine grapes [10-12]. For example, Australian researchers divided the viticultural area with average air temperature of the hottest month, French scholars developed a photo-thermal index and a photo-thermal coefficient based on the sunlight and air temperature, and New Zealand scientists developed a dimension-temperature index [13]. In China, Li and Huo [14] were inspired by foreign studies and created a set of indices that could finely represent local development of wine grapes and climate conditions. This set of domestic indices includes annual frost-free period (an air temperature indicator) as the first-level index, dryness during the growing season (an agro-hydrologic indicator) as the second-level index, and annual extreme average air temperature (-15 °C) as the third-level index. Another domestic scholar integrated the factors of soil, climate, topography and others into the ecological zoning of wine grapes in Northern China and proposed a detailed development plan (e.g., growable environment, maturity varieties and wine characteristics) for all involved wine grape-growing sub regions [15].

Compared to other wine grape-growing countries, China started studying grape terroir relatively late. But after a long period of development, a high-quality wine grape raw material base was fully developed in China. Thus, there are 10 famous grape-growing and wine-producing regions in China. They are North East, Jing-Jin-Ji, Shangdong, Ancient Yellow River, Loess Plateau, Inner Mongolia, Helan Mountain East, Hexi Corridor, Xinjiang and Southwest Mountain. Yantai city in Shandong province (1987) and Helan Mountain East (2012) in Ningxia Hui Autonomous region were nominated as observers by the International Organization of Vine and Wine (OIV) [16]. In each of the grape-growing and wine-producing regions, the ecological and geographical conditions are diverse yet uniquely. Recently, more domestic scholars have started to focus their regional research on the development of grapevines and quality characteristics of wine [17, 18].

Studies have pointed out that terroir of wine grapes has been mostly centered on the regionalization of climate. Results of terroir studies could be used to optimize wine grape production by taking advantage of beneficial climate conditions while combating the negative effects climatic disasters have on the growth and development of grapevines. For example, information about terroir could be used to guide local wine grape communities to avoid expanding grape production in areas that are barren for wine grapes. However, the effects of soil and varieties (two other main aspects of terroir) on the distribution of vineyard are not well documented. Focusing on three aspects of terroir, including climate, soil and variety, this study was intended to evaluate the suitability of wine grape production for the six prevailing varieties in Helan Mountain East (one of the major grape-growing and wine-producing regions) in Ningxia Hui Autonomous Region of China.

2. Materials and Methods

2.1 Research Area

In this study, the Ningxia Hui Autonomous Region was chosen as a research area, with a focus on the Helan Mountain East (a vast stretch of alluvial fan and plain, 37°43′-39°23′ N and 105°45′-106°47′ E) which is the main grape-growing and wine-producing region in China (Fig. 1). In Helan Mountain East, the major wine grape-growing counties/cities include Dawukou,

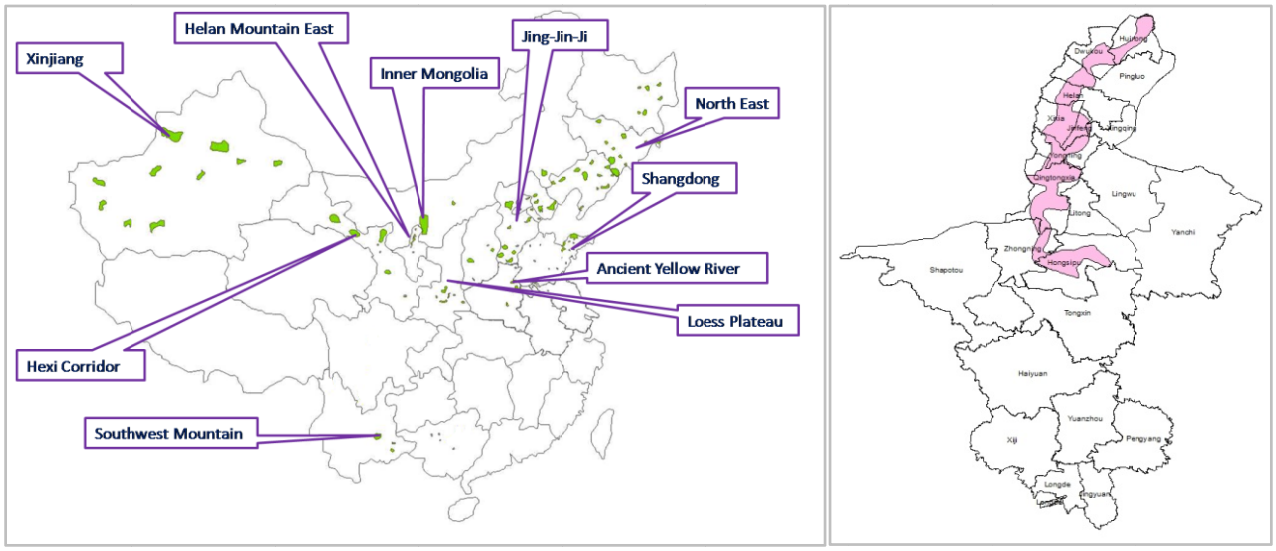

Fig. 1 The main grape-growing and wine-producing regions in China (left) and the Helan Mountain East in Ningxia Hui Autonomous Region of China (right), purple area is "The protected wine grape region of origin in the Helan Mountain East".

Huinong, Pingluo, Yinchuan, Helan, Yongning, Qingtongxia and Hongsipu [19]. After the Changli county in Jing-Jin-Ji region and Yantai city in Shangdong region, Helan Mountain East was certified as the third protected wine grape region of origin by the China Geographical Indications Committee in 2003.

Helan Mountain East has a typical continental climate, with abundant sunlight, significant annual variation in temperature, high diurnal temperature range and little rainfall (frequent drought) [20]. A study that was conducted in North China pointed out that, when average annual minimum temperature is below -15 °C, it is necessary to adopt the soil-burying method to prevent grapevines from the damage of extreme low temperatures in winter; as a result, approximately 90% of the current vineyards in China would need to use the soil-burying method [21]. In Helan Mountain East, during the wine grape growing season (from April to September), average air temperature ranges from 18.9 °C to 19.3 °C and total sunshine duration ranges from 1,451 h to 1,797 h. During the year, active average accumulated temperature above 10 °C is 3,501.4 °C·d (with the minimum of 3,485.4 °C·d in Yongning area and the maximum of 3,536.2 °C·d in Hongsipu area), average frost-free period ranges between 174.1 d and 186.4 d, and annual extreme minimum temperature ranges from -20.4 °C to -19.5 °C [22]. In addition, average annual precipitation in Helan Mountain East is only 188 mm, and most of the local wine grape growth and development heavily relies on groundwater irrigation that originates from the Yellow River.

The parent material of the land in Helan Mountain East is mainly alluvial with sierozem soil and aeolian soil, which contains gravel and sand. Overall, the terrain is flat and the soil is barren, with low nutrient content and organic matter and poor water and fertilizer retention capacity [23]. In Ningxia Hui Autonomous Region, the three typical soil types are linked to the differences in the maturity and phenolic compounds of wine grape berries. In particular, wine grapes grown in Aeolian sandy soil mature early, with relatively higher fruit sugar and color content of the peel and relatively better formation of grape aroma; wine grapes grown in sierozems irrigated soil mature moderately, with relatively higher total phenol and tannin content in the grape berries; wine grapes grown in cumulated irrigated soil mature late, with relatively higher acidity content in the grape berries [24].

Due to the unique climate and excellent

environment, Helan Mountain East has attracted investments in wine grape production bases from world-renowned companies (e.g., Hennessy, Paul Liga and Ballyda) and Chinese wine industry tycoons (e.g., Zhang Yu, Wang Chao and Great Wall). Some famous locally-developed wine companies include Xixiawang, Gabelan, Yuma, Heyu and Hedong. Jessie Robinson, who is an international wine master and one of the world's three leading wine tasters, reported to *Financial Times* that Helan Mountain East was the most promising wine region. During "China's Excellent Wine 2012 Awards", held by the French magazine *Wine Review*, Helan Mountain East was crowned "Chinese star producing region". Thus far, Helan Mountain East has become a world-renowned wine region, and wine produced in this region has won many international awards [25].

2.2 Meteorological Data

In this study, historical daily weather data (including average air temperature, precipitation and sunshine duration) during the period 1981 to 2016 were from 22 meteorological stations in Ningxia Hui Autonomous Region. Based on the daily weather data, the study indices were obtained, including annual frost-free period, ≥ 10 °C active accumulated temperature and hydrothermal coefficient ($K = 10 \times P/T_a$, where P is precipitation and T_a is active accumulated temperature). In addition, the 1:25 million digital elevation data were acquired from the China Meteorological Administration's digital elevation model (DEM). Based on the 1:250,000 soil type map from Ningxia Agricultural Survey and Design Institute, vector processing was used to export the digital soil type map of Ningxia Hui Autonomous Region.

With the small grid estimation methods in Geographic Information System (ArcGIS) [26], the 22 station-level weather data were interpolated into the entire research area. Based on the three factors of longitude, dimension and elevation, statistical models were established for three of the climatic indices used in the analysis (Table 1). Then these climatic indices were spatialized to 1:25 raster maps with the spatial tools in ArcGIS 10.0. Based on the rasterized residuals of the corresponding statistical models, the grid maps (grid-level geographical distributions) of these climatic indices were corrected with the inverse distance weighting (IDW) method in ArcGIS. As to the annual extreme minimum temperature index, there were no statistically significant correlations with the three factors of longitude, dimension and elevation. Therefore, the station-level index values were directly interpolated to the entire research area with the IDW method to obtain the grid map.

2.3 Wine Grape Varieties

Cabernet Sauvignon is the most widely planted wine grape in China, with a national planting area of more than 20 ha. Other prevailing wine grape varieties in China include Chardonnay, Cabernet Franc, Syrah and Pinot [27]. In Helan Mountain East, the main wine grape varieties are Cabernet Sauvignon, Merlot, Cabernet Gernischt, Chardonnay and Riesling [19]. In this region, wine types are usually dry white or dry red, and grapevine maturing types often refer to early-maturing, medium-maturing, medium-to-late maturing, or even (though it is rare) late-maturing varieties [15].

Table 1 Statistical models for the three climatic indices based on longitude (λ), dimension (ψ) and elevation (h).

Climatic index	Statistical model	R^2
≥ 10 °C accumulated active temperature	$AT = 11{,}207.2214 - 75.0573\lambda + 48.8528\psi - 1.33903h + \varepsilon$	0.9589
Precipitation during the period with daily average temperature greater than or equal to10 °C	$P_{T10} = -26{,}120.1 + 406.0144\lambda - 424.879\psi + 0.767014h + \varepsilon$	0.9535
Precipitation in September	$P_{Sep} = -716.307 + 10.63702\lambda - 10.7547\psi + 0.021016h + \varepsilon$	0.8892

"ε" means the residual of the statistical model, and R^2 is the coefficient of determination.

According to the quality traits and environmental requirements of different varieties, this study chose Grenache Noir (a late-maturing variety), Cabernet Sauvignon (a medium-to-late maturing variety), Merlot (a medium-maturing variety), Riesling (an early-to-medium maturing variety) and Chardonnay and Pinot Noir (both are early-maturing varieties) (Table 2) to represent different maturing types and wine-color grape varieties in the research area. The required ≥ 10 °C thermal time ranged from 2,800 °C·d to 3,600 °C·d for these six prevailing wine grape varieties in Ningxia [15]. At present, about 90% of the grapevines grown in Helan Mountain are self-rooted seedlings [28]. As more studies focused on rootstocks [29-32], researchers in Ningxia began to conduct grafting cultivation studies in order to choose rootstocks that are suitable for local wine grape varieties. The main high-resistance rootstock varieties include S04, 5BB and 3309 [28]. In general, the focus of new varieties development should be on increasing the resistance to adverse environments such as drought and cold. And the ultimate goal of developing new varieties is to improve grape production and the fruit quality, as stated in the trend of the development of Chinese grape industry rootstocks [33].

2.4 Indices and Methods

Studies on the effects of terroir (i.e., climate, soil and wine grape variety) on wine production in Ningxia Hui Autonomous Region pointed out that local viticulture was not limited by precipitation or sunshine [34, 35], but by annual frost-free period and ≥ 10 °C accumulated temperature from April to September [36]. Nevertheless, rainfall events during the fruit ripening phase could reduce the fruit quality by causing fruit cracking or even deteriorating diseases [37]. In addition, soil types and conditions significantly affect the wine grape maturity and phenolic compounds of wine grape berries, and ultimately the wine characteristics [23]. In Northern China, sub-regional variations in ecological environment were linked to different maturity types of wine grape varieties [38, 39]. Soil type also has been identified as an influential factor for wine quality [40].

In previous studies, a variety of factors were used to zone the terroir. Based on Fraga *et al*. [41], Zhang [15] and Li *et al*. [36], thermal condition, hydric condition and soil type are the three most important elements for grapevine yield and wine quality attributes [42, 43]. In this study, the indices for terroir zoning were formed by combining the traits of varieties to climate conditions (Table 2). Two temperature indices for zoning of wine grape cultivation (i.e., growable and non-growable zones) were adopted in Ningxia Hui Autonomous Region. In the growable zone for wine grapevines, a temperature index, a precipitation index and soil type (Table 3) were used to divide wine grape terroir for the six studied wine grape varieties. The wine grape terroir for each of the varieties was divided into optimal, suitable, near-suitable and unsuitable zones. In the optimal zones, thermal condition, hydric condition and soil type are all optimum for wine grapevines to grow and develop. No further agricultural management practices would be needed throughout the entire growing season [35]. In the suitable zones, the climate condition and soil type could be a good balance to grow grapevines for making high-quality wine without other stress factors. In the near-suitable zones, the thermal condition, hydric condition and soil type are all subpar, and additional agricultural management inputs would be required to ensure the grapevines grow and develop. In the unsuitable zones, the climatic condition and soil type are usually imbalanced for growing wine grapevines, and the marginal cost of introducing high-technology cultivation techniques and wine brewing methods would outweigh the marginal profit.

According to the stepwise, hierarchical and optimized zoning rules, spatial tools in ArcGIS were used to interpolate the corresponding indices for wine grape cultivation zoning and terroir zoning in the entire research area. Then terroir-suitability zoning maps

Table 2 Traits (including maturity type, wine color, quality trait and resistance trait), environmental requirements (including suitable soil type and required ≥ 10 °C thermal time), and maturity time of the six prevailing wine grape varieties (including Grenache Noir, Cabernet Sauvignon, Merlot, Riesling, Chardonnay and Pinot Noir) in Ningxia Hui Autonomous Region of China.

Varieties	Maturing type	Wine color	Quality trait	Resistance trait	Suitable soil type	Required ≥ 10 ℃ thermal time (°C·d)	Maturity time
Grenache Noir	Late	Red	High in sugar content, low in acid, rich in alcohol and full-bodied wine with ripe fruit	Strong adaptability and wind resistance	Barren and dry soil	3,400-3,600	Early October (1^{st} to 10^{th})
Cabernet Sauvignon	Medium-to-late	Red	Small fruit, thick and dark skin, high in sugar and acid, rich in tannins, strong wine skeleton, thick and dignified wine taste, and strong ability to hold	Diseases resistance, drought tolerance, late germination, anti-night cream, and strong adaptation to climate change	Calcareous loam	3,200-3,400	Late September (21^{st} to 30^{th})
Merlot	Medium	Red	High in sugar and low in acid, plays a supporting role in brewing red wine to make wine plump, bright and high in alcohol, with the complex taste of cherries, plums and spices	Sensitivity to severe cold and rot, with no resistance to late frost	Fertile sandy soil	3,100-3,300	Early September (1^{st} to 10^{th})
Riesling	Early-to-medium	White	Brewed wine is fine and has elegant aroma	The most cold-resistant variety, and resistant to diseases	Strong soil adaptability, growable in sunny slopes and sandy clay	3,000-3,200	Early September (1^{st} to 10^{th})
Chardonnay	Early	White	Typical high-sugar and high-acid variety, making fine wine with elegant aroma	Strong adaptation to climate change, early germination, no resistance to late frost, high yield and stability	High-calcium soil, optimal in limestone soil with marl	2,800-3,100	Late August (21^{st} to 31^{st})
Pinot Noir	Early	Red	Typical high-sugar and low-acid variety, the brewed wine has a delicate aroma, Pinot Noir grown in warm climate makes lighter wine with lighter aroma, Pinot Noir grown in acidic soil makes light and hairy wine [36]	Adaptable to cool climate	Calcareous hilly slopes	2,800-3,100	Late August (21^{st} to 31^{st})

Table 3 Climatic indices for wine grape cultivation zoning and climatic as well as soil indices for terroir suitability zoning for the six prevailing wine grape varieties in the research area.

Item	Variety	Zone	Climatic index			Soil type
			≥ 10 °C active accumulated temperature (°C·d)	Precipitation in September (mm)	Frost-free period (d)	
Cultivation	-	Growable	≥ 2,500	-	≥ 150	-
	-	Non-growable	< 2,500	-	< 150	-
Terroir	Cabernet Sauvignon	Optimal	3,200-3,400	< 10	-	Coarse soil, sierozem soil
		Suitable	3,100-3,400	10-20	-	Sierozem soil, aeolian soil
		Near-suitable	> 3,400	20-30	-	Cumulated irrigated soil, yellow loess soil
		Unsuitable	< 3,100	> 30	-	Saline, Chao soil, marsh soil
	Merlot	Optimal	3,100-3,300	< 10	-	Aeolian soil
		Suitable	3,100-3,300	10-20	-	Cumulated irrigated soil, yellow loess soil
		Near-suitable	> 3,300 or 3,000-3,100	20-30	-	Sierozem soil
		Unsuitable	< 3,000	> 30	-	Saline, Chao soil, marsh soil
	Pinot Noir	Optimal	2,800-3,100	< 10	-	Coarse soil, sierozem soil
		Suitable	2,800-3,200	10-20	-	Sierozem soil, aeolian soil
		Near-suitable	2,700-2,800 or > 3,200	20-30	-	Cumulated irrigated soil, yellow loess soil
		Unsuitable	< 2,700	> 30	-	Saline, Chao soil, marsh soil
	Chardonnay	Optimal	2,800-3,100	< 10	-	Coarse soil, sierozem soil
		Suitable	2,800-3,200	10-20	-	Sierozem soil, aeolian soil
		Near-suitable	2,700-2,800 or > 3,200	20-30	-	Cumulated irrigated soil, yellow loess soil
		Unsuitable	< 2,700	> 30	-	Saline, Chao soil, marsh soil
	Riesling	Optimal	3,000-3,200	< 10	-	Coarse soil, sierozem soil
		Suitable	2,900-3,200	10-20	-	Sierozem soil, aeolian soil
		Near-suitable	2,800-2,900 or > 3,200	20-30	-	Cumulated irrigated soil, yellow loess soil
		Unsuitable	< 2,800	> 30	-	Saline, Chao soil, marsh soil
	Grenache Noir	Optimal	3,400-3,600	< 10	-	Aeolian soil
		Suitable	3,300-3,600	10-20	-	Cumulated irrigated soil, yellow loess soil
		Near-suitable	3,300-3,400	20-30	-	Sierozem soil
		Unsuitable	< 3,300	> 30	-	Saline, Chao soil, marsh soil

for the six study wine grape varieties were exported with the method that was used in ecological zoning for wine grape production in Northern China [15].

3. Results

3.1 Wine Grape Cultivation Zoning

In Ningxia Hui Autonomous Region, based on the two indices of ≥ 10 °C active accumulated temperature and annual frost-free period, wine grapevines are growable in most of the central northern parts (where air temperatures met the required amounts for wine grape growth and development). Meanwhile, the non-growable zone (where air temperature did not meet the required amounts for wine grape growth and development) was focused on Xingren, Tongxin, Weizhou and Mahuangshan, as well as the areas with more than 1,300 m altitude in Helan Mountain, Luoshan Mountain and Xiangshan Mountain (Fig. 2). In addition, meteorological disasters occurred frequently in the non-growable zone for wine grapevines, such as drought, hail and frost [44].

3.2 Terroir Suitability Zoning for Cabernet Sauvignon

The optimal zone for growing Cabernet Sauvignon was scattered in Xixia district of Yinchuan city, Dove Mountain and Miaoshan Lake area in Qingtongxia city and Baima township in Zhongning county (Fig. 3). The sub total area for growing Cabernet Sauvignon was 0.9 million hectares. In the optimal zone for Cabernet Sauvignon, soil layer was deep with coarse soil in the upper layer and ash-calcium soil in the lower layer, which was ideal for producing high-quality Cabernet Sauvignon. The suitable zone for growing Cabernet Sauvignon was mainly distributed around the Yellow River irrigation district of Ningxia plain. In particular, part of the origin protected wine grape region of Helan Mountain East, including Yinchuan city, Yongning county and Qingtong city (with a lower than 1,200 m elevation and a subtotal area of 404,600 ha), was categorized as suitable for growing Cabernet Sauvignon. The suitable zone for growing Cabernet Sauvignon had abundant sunlight, moderate air temperature, large diurnal temperature range and little precipitation. In addition, soil was mostly ash-calcium soil which is rich in stones and has deeper layers. All of these above-mentioned climatic and soil characteristics are beneficial for grapevine roots to grow deep in the soil to as much as 10 m below the ground. This could be translated into the high quality and elegant aroma of Cabernet Sauvignon [45]. By contrast, most of the central arid region was considered unsuitable for growing Cabernet Sauvignon. The main limiting factor was that air temperature did not meet the required amount for growing Cabernet Sauvignon. Though Cabernet Sauvignon was growable in most of the central arid region of the research area, the grapevines may not mature normally during the cool/cold years.

3.3 Terroir Suitability Zoning for Merlot

In the research area, the suitable zone for growing Merlot was concentrated in the southern part of the Yellow River irrigation region and the southern part of Helan Moutain East (e.g., Qingtongxia city area) (Fig. 4). In the suitable zone for growing Merlot, the dominant soil type was ash-calcium soil with deep layers and rich stones, which is beneficial for grapevine roots to grow deep. In some fields, the grapevine roots could reach a level 10 m below the ground. Usually, Merlot that is made of grape berries in this particular zone is high-quality and has elegant aroma [45]. In addition, Merlot was suitable to be grown in areas with sandy soil like Qingshui River basin, Zhongning county, and Zhongwei and Lingwu cities (with a sub total area of 655,800 ha). The optimal zone for growing Merlot was concentrated in Xixia district of Yinchuan city, Pigeon Mountain area of Qingtongxia city, Baima township of Zhongning county and Shikong area in Hongsipu district of Wuzhong city (with a sub total area of 27,100 ha).

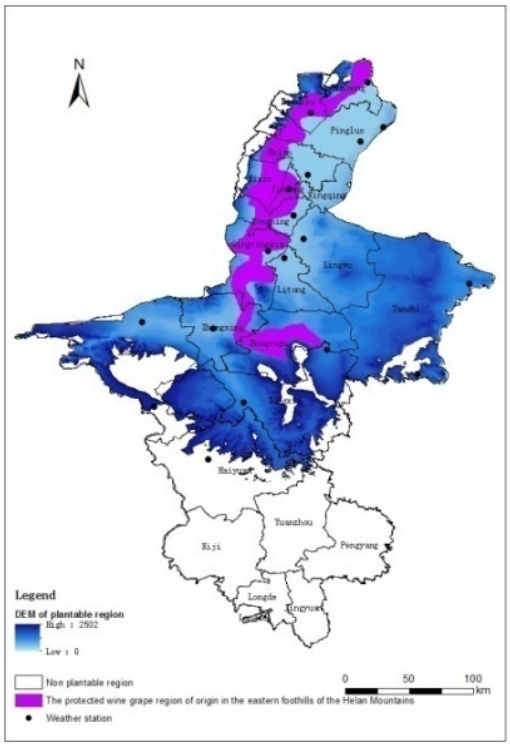

Fig. 2 Wine grape cultivation zoning in Ningxia Hui Autonomous Region of China.

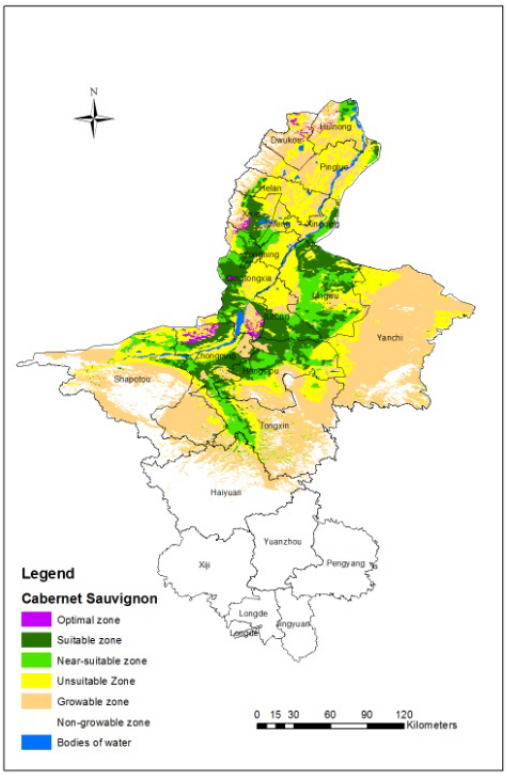

Fig. 3 Terroir suitability zoning for Cabernet Sauvignon in the research area.

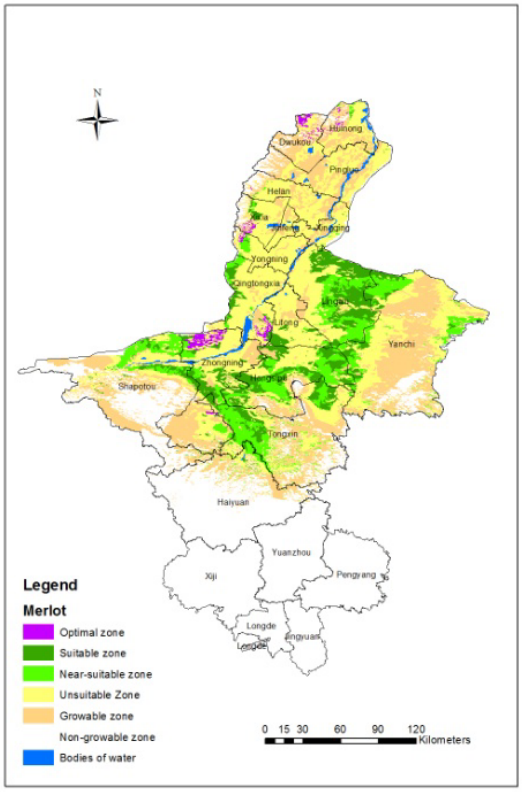

Fig. 4 Terroir suitability zoning for Merlot in the research area.

3.4 Terroir Suitability Zoning for Pinot Noir

In the research area, the suitable zone for growing Pinot Noir was scattered in cool areas such as Lingwu city in Southern Ningxia plain, the southern part of Litong district in Wuzhong city, the north of Hongsipu district in Wuzhong city, Qingshui River and the high-altitude area of Helan Mountain. In addition, the sandy-soil areas in Zhongning county of Zhongwei city and Lingwu city were suitable for growing Pinot Noir (Fig. 5). The subtotal area of suitable zone for Pinot Noir was 890,600 ha. The optimal zone for growing Pinot Noir was in Baima township and Shikong area of Zhongning county, with a subtotal area of 49,300 ha.

3.5 Terroir Suitability Zoning for Chardonnay

In the research area, the suitable zone for growing Chardonnay had a subtotal area of 913,700 ha. It was mainly distributed in Yanchi county of Wuzhong city, Qingshuihe valley, and the northern parts of Hongsipu district in Wuzhong city and Shapotou districtin Zhongwei city (Fig. 6). The optimal zone for growing Chardonnay was scattered in Pigeon Mountain of Qingtongxia city and Jiji valley as well as Baima township of Zhongning county in Zohngwei city, with a subtotal area of 43,300 ha. In the optimal zone for growing the early-maturing Chardonnay, the climate was cold (though with high diurnal temperature range) and dry (low precipitation), and the soil was mostly ash-calcium soil and aeolian sandy soil. In Ningxia plain, air temperature during the ripening phase for Chardonnay was too high to form rich aromas and other essential characteristics of wine grape berries. Therefore, Ningxia plain was rated as near-suitable for growing Chardonnay.

3.6 Terroir Suitability Zoning for Riesling

In the research area, the suitable zone for growing Riesling was scattered in the southeast of Lingwu city, the west of Yanchi county in Wuzhong city, Qingshui River, the north of Hongsipu district in Wuzhong city,

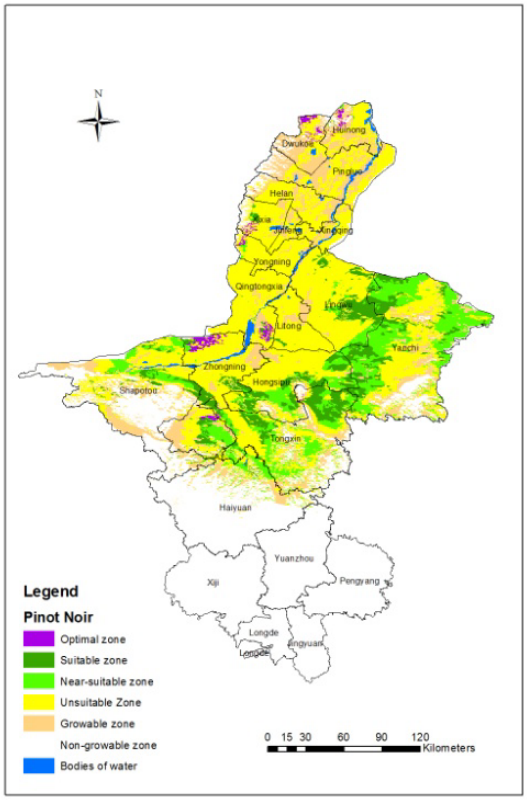

Fig. 5 Terroir suitability zoning for Pinot Noir in the research area.

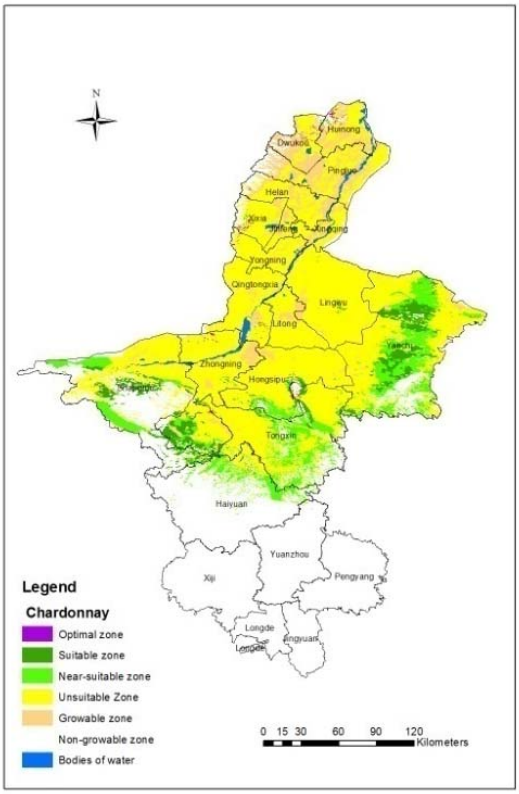

Fig. 6 Terroir suitability zoning for Chardonnay in the research area.

and the cool/cold areas along the Helan Mountain East (Fig. 7). The suitable zone for Riesling had a subtotal area of 92.81 million hectares. Overall, the suitable zone was flat, the main soil types were ash-calcium and aeolian sandy soils (both are deep soils), and the climate was cool or cold (ideal for the cold-hardy Riesling).

3.7 Terroir Suitability Zoning for Grenache Noir

In the research area, the suitable zone for growing Grenache Noir was scattered in Yinchuan city (particularly in Yongning and Helan counties), Dawukou district of Shizuishan city and the alluvial (flood) areas of Huinong along the northern part of Helan Mountain East (Fig. 8). The subtotal area of suitable zone for Grenache Noir was only 91,000 ha, which was less than that for other varieties. This was because the cool climate in most of the research area was not ideal for growing the late-maturing Grenache Noir. In the suitable zone for growing Grenache Noir, ≥ 10 °C active accumulated temperature was more than 3,400 °C·d (with large diurnal temperature variation), annual precipitation was less than 183 mm (with mild drought), and sunshine duration was just enough. All of these climatic characteristics were suitable for growing the late-maturing variety of Grenache Noir. The near-suitable zone for growing Grenache Noir was concentrated in the Yellow River irrigation areas, including the northern part of Yinchuan city, Helan county of Yinchuan city and Pingluo county of Shizuishan city.

4. Discussion

As the major elements of terroir, climatic conditions (e.g., insolation, air temperature and precipitation) can influence the grape quality, and soil (mineral supply) may influence the development of grapevines and ripening of grape berries [4, 24, 43]. Although different maturing type grape varieties could

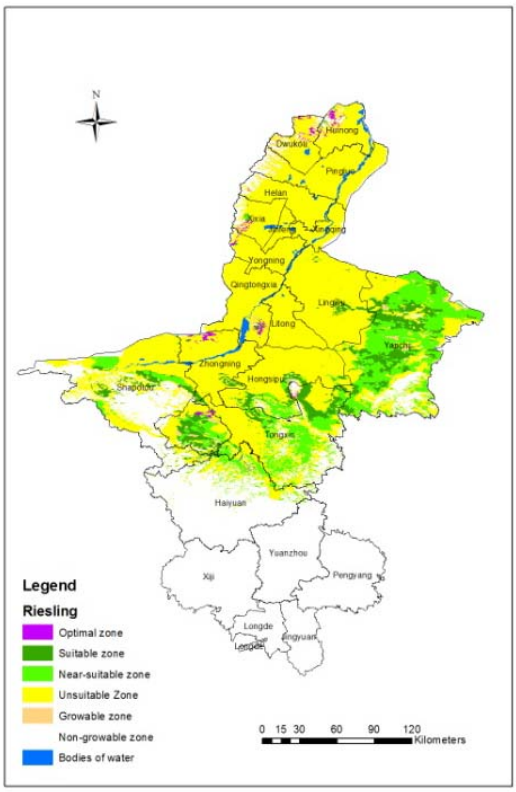

Fig. 7 Terroir suitability zoning for Riesling in the research area.

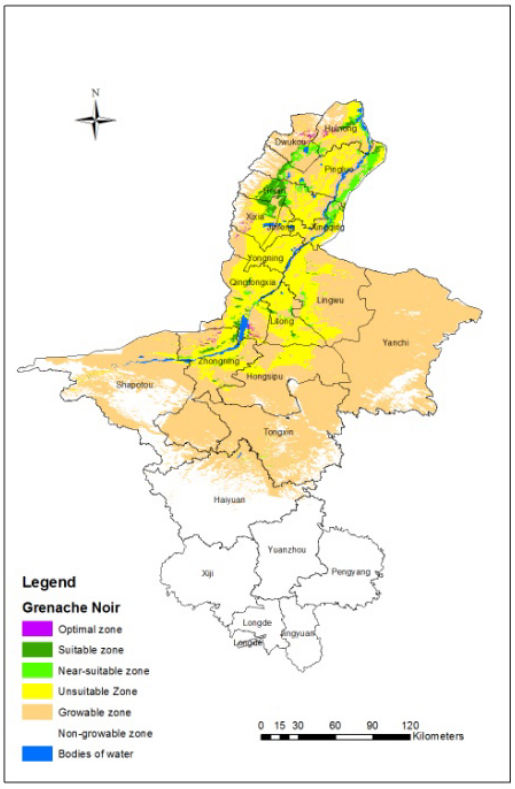

Fig. 8 Terroir suitability zoning for Grenache Noir in the research area.

be grown in most parts of Central and Northern Ningxia [22], the best quality grape berries for wine making can only be produced where the growing season climate and other environmental conditions are ideally synced [17]. In the wine grape-growing region of Ningxia Hui Autonomous Region, the extreme minimum temperature in the coldest month was generally lower than -25 °C. Even in the suitable zone (according to the three main aspects of terroir), it is best to bury the grapevines in late fall in order to protect them from the freezing cold temperatures in the winter [36]. In April, frost disasters occur frequently in the research area; therefore, wine grape growers should be extra-cautious when choosing varieties like Pinot Noir and Chardonnay that have low frost tolerance. In those areas that actually grow such varieties, more attention should be paid to frost damage in late spring. Wine grapevines usually have good tolerance to drought, yet they require about 600-800 mm of annual precipitation in the growing areas. In Ningxia Hui Autonomous Region, annual precipitation in the suitable zone for growing wine grapes is generally less than 300 mm, so supplemental irrigation is absolutely needed [34].

Against the background of global warming, air temperatures have significantly increased in Northern China, which could potentially affect the wine grape cultivation in Ningxia Hui Autonomous Region where climate is usually cool with cold winter [16, 27]. On the other hand, global warming could cause negative effects on wine grape production by increasing the incidence of grapevine diseases and floods (e.g., extreme rainstorm events). When the wine stakeholders make decisions about building new grape-growing and wine-producing bases, it is critical to factor in the potential effects (both positive and negative) of local climate change [16, 19].

5. Conclusions

In Ningxia Hui Autonomous Region, the suitable zone for growing the typical wine grape varieties showed a clear spatial pattern. For all six studied wine

grape varieties, the total area of optimal zones was 50,000 ha. The suitable zones for growing the main wine grape varieties were significantly beyond the scope of the origin protected wine grape region of Helan Mountain East (certified by the China Geographical Indications Committee in 2003). This indicates that these newly-discovered suitable areas have high potential to become grape-growing and wine-producing bases for the prevailing varieties in Ningxia.

The results of this study could be used to help the local wine grape community adjust their cultivation practices and brewing techniques, for the sake of improving production efficiency. In addition, this study provides scientific evidence for regional agricultural policy makers to plan the distributions of different wine grape varieties in order to optimize the climatic and soil resources.

Acknowledgments

This research was funded by the Ningxia Hui Autonomous Region Key Research and Development Program No. 2018BFH03012 (Terroir) and National Natural Science Fund China Scholarship Council Project No. 41675114 (Grapevine Frost/Freeze Damage).

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