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RESEARCH ARTICLE

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Climatic regionalization of wine grapes in the Hengduan Mountain region of China

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Abstract

The Hengduan Mountain region of China is one of the world's highest altitude and lowest latitude wine grape cultivation areas. This study screened the existing regional indexes; the active accumulated temperature (AAT) for grapes in the growing season was chosen as the heat index, and the dryness index (DI) in the growing season was chosen as the water index for climatic regionalization. An analysis of 90-meter resolution digital elevation model (DEM) data and the corresponding slope degree and direction for the Hengduan Mountain region in the range of 97°E-103°E, 27°N-33°N, as well as daily meteorological data over 30 years (1981-2010) from 53 stations in the study region, were used to establish the AAT and DI models for the northern area of the Hengduan Mountains. According to the multiple stepwise regression method, the interaction terms among different geographical and topographic factors were considered. In addition, the residual errors were interpolated and corrected based on the modeling, and this approach further improved the simulation accuracy of meteorological factors. A regional climatic map of wine grapes was produced according to these results. The model was used to calculate the suitable altitude range for wine grape cultivation in different regions of the Hengduan Mountains. The study shows that the distribution of suitable wine grape cultivation areas in the northern part of the mountain range generally mimics distribution of dry warm and dry hot valleys. The accuracy of the results was confirmed based on the existing locations of vineyards in the Hengduan Mountain region.

Additional keywords: active accumulated temperature; dryness index; digital elevation model; multiple regression.

Abbreviations used: AAT (Active accumulated temperature); DEM (Digital Elevation Model); DI (Dryness Index); FFP (Frost-free period); HI (Classical Heliothermal Index of Huglin); OLS (Ordinary least square).

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Introduction

The Hengduan Mountain region is located in the southeastern Tibetan Plateau, and it incorporates a series of the north-south trending mountains west of Sichuan and Yunnan provinces and east of the Tibet Autonomous Region. This region represents the longest, widest and most typical unique geographical unit composed of a series of north-south trending mountains and is the only region that contains water from both the Pacific and Indian oceans. This region includes low-latitude and high-altitude areas, and the plateau surfaces and mountaintop surfaces can be connected into a unified "cardinal plane", with mountains above and river valleys and basins below. The Nu River, Lancang River, Jinsha River, Yalong River, Dadu River and Minjiang River are interspersed within the region (Gan, 2007), which is traversed by ravines and gullies. Thus, the topography and physiognomy are extremely complex. The incline of the terrain is stepped from the northwest to the southeast, and a great disparity in elevation is observed. The stereoclimate of the region includes multiple climate types and an uneven spatial distribution, with the low-latitude and low-altitude areas and the high-latitude and high-altitude areas combined, which contributes to climate fluctuations over the entire region. The combination of these fluctuations with the effects of the two different terrains in the east and west and the superposition of mountain vertical changes promotes the formation of multiple climate zones from south to north, such as the north tropical zone, south subtropical zone, middle subtropical zone, north subtropical zone, warm temperate zone, temperate zone and cold temperate zone (Xu, 1991; Xu & Zhang, 2008).

The presence of multiple climate zones enables crops that belong to different climate zones to find suitable planting areas at the same time in this mountain range, and this includes suitable cultivation areas for wine grapes. In the 1980s, people in this region began to explore the cultivation of wine grapes, and the mountain range gradually developed into one of the most important wine grape producing areas of China. According to scientific theory, local economic and natural conditions are important in guiding the development of regional wine grape cultivation and the wine industry, determining the production direction and best breeds, and developing the production potential of wine grape resources to obtain high-quality products. Previous research has shown that climate has a predominant effect on grapevine physiology (Keller, 2010), and climatic factors are the main drivers of vineyard yield and wine quality (Orduna, 2010; Santos *et al.*, 2011; Bock *et al.*, 2013; Helder *et al.*, 2016; Joao *et al.*, 2017). The climate of the Hengduan Mountain region considerably differs from the climate types of other wine-producing areas of the world; therefore, the traditional regional indexes of wine-producing areas are not applicable in this area (Zhang & Shao, 2012; Li *et al.*, 2015). In view of this problem, this study screened the existing regional indexes and ultimately chose the appropriate indexes for exploring suitable grape cultivation areas in the study region. The climate of the Hengduan Mountain region is complicated, and a number of different climatic zones can be observed within a few kilometers. These variations can lead to vastly different temperatures and precipitations between adjacent vineyards. Thus, accurately assessing the suitability of viticulture areas remains a major challenge.

With the rapid development of the regional wine grape industry, domestic research institutions have begun researching the climatic regionalization of wine grapes in the Hengduan Mountain region (Li, 1987; Li *et al.*, 2011; Ma *et al.*, 2011; Zhang & Shao, 2012; Liu *et al.*, 2015). Li & Huo (2006b) examined the wine grape regionalization of China using the frost-free period (FFP) as a first grade index and the dryness index (DI) as the secondary grade index, and their results indicated that the Hengduan Mountain area has a wide range of suitable planting areas for wine grapes, although their mapping method was based on interpolation and did not consider differences in elevation. Thus, the regionalization results were planar and could not identify the exact position of suitable wine grape cultivation areas in the Hengduan Mountains. Zhang & Shao (2012) considered the active accumulated temperature (AAT) as the index in their regionalization work and divided the Yunnan Province into a subtropical zone, a tropical zone, a warm temperate zone, and a temperate zone, although the results only indicated the rough position of each district and its development direction. Ma *et al.* (2011) summarized the present situation of the grape growing regions in Yunnan Province and described the conditions of the cultivation region; Li *et al.* (2011) used indexes, such as accumulated temperature, precipitation, and FFP, to compare Aba Prefecture with other producing regions at home and abroad and compared the economic characteristics of wine grapes in different regions and indicated the range of suitable wine grape cultivation areas in the Aba Prefecture; Liu *et al.* (2015) adopted a fuzzy comprehensive evaluation method for analyzing the wine grape ecological suitability in three valleys in Western Sichuan Province, and they found that the suitable comprehensive index for cultivation was the highest in Danba County, which was located in the Dadu River Valley. These studies were summarized or verified mainly from small regions that have planted wine grapes; thus, the effects can only be generalized within the small regions, and the reference value is limited for other regions in the Hengduan Mountain area.

This research screened the existing regional indexes, provides regional results with high accuracy and explores the suitable cultivation locations for wine grape in a potential wine-producing region with extremely complex climate types. The initial spatial estimation of continuous surface meteorological elements should be conducted for climatic regionalization.

Material and methods

Study area

The generalized geographic range of the Hengduan Mountains is between 22 to 33° N latitude and 97 to 103° E longitude and starts from the Bayankala

Mountains in the north, to the Gaoligong Mountains in the south, and from the Qionglai Mountains in the east, to the Boshula Mountain ridge in the west, which represents the steering extension of the Nyainqentanglha and Tanggula mountains (Gan, 2007). Because of the considerable disparity in climate in the southern and northern sections of the Hengduan Mountains, we partitioned this region and modeled the sections separately to ensure the model's accuracy. In this paper, we only discuss the results of climatic regionalization in a range from 27 to 33° N latitude and 97 to 103° E longitude in the northern area of the Hengduan Mountains (only within the boundaries of China).

Data

This paper was based on the daily data of 53 meteorological stations in the range of 27 to 33° N latitude and 97 to 103° E longitude during 30 years (1981-2010). The data are provided by the China National Climate Center and include longitude and latitude, altitude, maximum and minimum air temperature, precipitation, wind speed, relative humidity and sunlight hours. The data processing program was written in C++, and the average Frost-free period (FFP, the number of days from the last frost day to the first frost day each year), dryness index (DI) (Huo, 2006), the accumulated active temperature (AAT, the sum of daily average temperatures higher than 10ºC) in the growth season, and the classical Heliothermal Index of Huglin (HI) (Huglin, 1978) of each station during 30 years (from 1981 to 2010) were calculated. The terrain data, including the digital elevation model (DEM), slope degree and slope direction, 90 meter resolution data, were provided by the Chinese Academy of Sciences, Computer Network Information Center and an international scientific data mirror website (http://www.gscloud.cn). The latitude and longitude grid data were formed by interpolating ASCII code data.

Regional index selection

The climate indicators used to determine whether grapes (*Vitis vinifera* L.) can be planted in a region are radiation, temperature, moisture and extreme climate event potential. The area of the Hengduan Mountains is in a low-latitude and high-altitude zone, the air transparency is high, and the radiation is sufficient; however, the natural conditions are not a limiting factor for the cultivation of wine grapes. In this study, we selected the wine grape regionalization index based on the two indicators heat and moisture, and the potential for climate disasters was further assessed.

Heat index

Grape growth has a high heat demand. In addition to the AAT in the growing season, certain temperatures are required to ensure that the grape plants go through every phenological period. There are several temperature indexes used for the climatic regionalization of grapes (Table 1) in many parts of the Hengduan Mountains (Li *et al.*, 2015), and although the growing season is sufficient, it is influenced by the high-altitude mountain climate. Thus, the spring and autumn climates are mild, the summer climate is cool, and the average temperature in the growing season is

Table 1. Heat index of selected meteorological stations in the Hengduan Mountain region.

Station	Altitude (m)	FFP* (d)	HI*	AAT (°C)$\sum Ta$	EAT (°C)$\sum Ta1$	AT (°C)	< -15°C Days (d)
Batang	2589	229	2235.4	3238.4	1435.4	19.7	0
Yajiang	2601	212	1931.2	2850.5	1095.5	17.9	0
Jinchuan	2169	245	2228.0	3213.6	1401.9	19.9	0
Dege	3184	150	1093.1	1876.8	503.1	14.8	54
Xinlong	3275	155	1325.7	2099.0	615.0	15.2	79
Daofu	2957	164	1388.6	2278.0	723.4	16.1	33
Jiulong	2925	185	1266.8	2266.9	677.5	15.3	1
Xiangcheng	2842	203	1724.1	2797.2	1068.5	17.7	0
Maerkang	2664	172	1512.2	2344.2	749.8	16.4	5
Baiyu	3260	156	1419.1	2221.0	694.7	16.0	48
Heishui	2400	192	1541.8	2503.3	854.3	17.3	0
Qamdo	3306	165	1360.0	2203.8	712.8	16.3	63
Deqin	3319	179	684.1	1545.1	320.8	16.4	0

FFP: Frost-free period; HI: Classical Heliothermal Index of Huglin; AAT: Active accumulated temperature; EAT: Effective accumulated temperature in the growing season; AT: Average temperature of the hottest month; < -15°C Days: Days with minimum temperatures of < -15°C, based on 30-year climate data.

low. For this reason, the temperature conditions cannot meet the needs of the very early ripening grape varieties or ensure that these varieties will experience a smooth phenological period (Huglin, 1978; Huo, 2006); therefore, grape cultivation is not profitable in these areas. A comparison of the main heat index (Amerine & Winkler, 1944; Huglin, 1978; Coombe, 1982) for typical stations showed that the regionalization results of suitable and unsuitable regions according to the AAT in the growing season, the effective accumulated temperature (EAT) in the growing season, the HI and the average temperature (AT) of the hottest month were generally consistent (Table 1). To ensure that the fruit matures well in most years, Zhang & Shao (2012) and Li *et al.* (2015) considered that an AAT of 2500°C in the growing season was the minimum temperature suitable for grape growth. For calculation convenience, the Chinese meteorological stations commonly record AAT as land surface climatic data, and these data are used widely in the study of Chinese grapes. Therefore, we selected the AAT in the growing season as the heat index for the climatic regionalization of grapes in the Hengduan Mountain region.

According to the actual production data and the research of Dave Thaya (He, 1999), Huo (2006) and Li *et al.* (2015), we adopted the division criteria for AAT for grape varieties with different maturation characteristics (Li *et al.*, 2015).

Water index

The commonly used wine grape climatic regionalization indexes include the following: hydrothermal coefficient, water-heat value, precipitation in the maturation period, and DI in the growing period (Huo, 2006). Li & Huo (2006a) compared and analyzed the above indexes and determined that the DI in the growing season is appropriate for measuring whether the local precipitation can meet the needs of wine grape growth and particularly suitable for China's climate, where rain and heat occur in the same season. The discrepancy in elevations throughout the Hengduan Mountain region is great, and during the study period, the precipitation varied significantly with elevation, which promoted the formation of a vertical mountain climate. However, the overall area was affected by westerly circulation in the high altitudes, and because of the monsoon circulation of the Indian Ocean and the Pacific Ocean, summers were rainy and winters were dry as observed in most areas of China, thereby supporting the suitability of the DI in the growing season as the climatic regionalization index of wine grapes in the Hengduan Mountains.

The DI represents the ratio between evapotranspiration (rate of evapotranspiration by grape crops, ET_C) and precipitation in the growing season of wine grapes (Huo, 2006). The expression of the DI is as follows:

$$DI = ET_C/P$$

$$ET_C = K_C \times ET_O$$

where DI is the DI in the growth season of the grape, ET_C is the amount of evapotranspiration in the growth season, P is the precipitation in the growth season; K_C is the crop coefficient, and ET_O is the reference crop evapotranspiration, which is calculated according to Penman-Monteith method (Allen *et al.*, 1998).

The K_C values of wine grapes for various regions of China have not been reported thus far; however we selected a maximum crop coefficient value of 0.8 in the growth season in this study based on the recommended values of the FAO (Allen *et al.*, 1998) and the methods of Huo (2006) and by considering the climate characteristics and actual conditions of cultivation in the Hengduan Mountains. We found that the land in this area has a slight slope and the drainage and ventilation were in good condition, and based on field research, we adopted a DI value of 0.75 as the appropriate boundary between the suitable cultivation area and non-suitable cultivation area for wine grapes.

Other indexes

Protecting grapes from the cold is an issue in other parts of China, and if the temperature is -15°C or below in a region every 5 to 10 years, then the irrigation lines must be buried (Huo, 2006). Research indicated that for the stations in this region with an average AAT in the growing season over the past 30 years above 2500°C (Table 1), then the irrigation lines did not have to be buried for grape cultivation in the Hengduan Mountains and other cold-proof measures in the high-altitude area could be implemented.

Research methods

In this paper, the multiple stepwise regression method was adopted to analyze the influence of geographical and topographical conditions on the distribution of the AAT in the growing season and the DI in Hengduan Mountain region. The stepwise regression and multiple-factor regression equations were established according to the ordinary least square (OLS) theory, the factors that did not have an influence or that had only a minimal influence on the dependent variable were eliminated with the stepwise regression method, the significant factors were identified, and then the optimal regression model was obtained. However, whether the optimal model can produce appropriate forecasts depends on the actual situation and hypothesis testing.

Modeling the AAT in the growing season

Temperature in a certain area with geography and terrain changes showed a certain regularity. According to the existing weather station data, we could find the AAT changes with geography, terrain factors model, thus inferring AAT data elsewhere in the region. The temperature in mountainous regions is affected by many factors, including longitude, latitude, altitude, mountain trends, climate background conditions, slope direction, slope degree and underlying surface properties (Weng & Luo, 1990; Fo, 1992). The macro factors, such as longitude, latitude and climate background conditions, will affect the measured values when the temperature is obtained. Overall, the influence of terrain factors, such as altitude and slope direction, is significant on a small regional scale, whereas the climate background is more important on a larger scale.

The simulated AAT values can be decomposed into trends and residuals. The trends can reflect the overall climate characteristics on a regional scale and are affected by macroscopic and systemic factors, such as longitude, latitude, altitude and local small terrain factors over a wide range. The residuals reflect changes in the local climate and are affected by certain random factors.

Therefore, the spatial distribution of AAT can be expressed as: AAT = A $(\phi,\lambda,h,\alpha,\beta,\varepsilon)$, where ϕ and λ are the longitude and latitude, respectively, h is the terrain altitude, and α and β are the sine of the slope degree and the cosine of the slope direction, respectively (Wang *et al.*, 2005; Liu & Zou, 2006). The other factors that influence the AAT are expressed by ε in the regression analysis. Latitude, altitude and cosine value of slope direction are correlated linearly with temperature. The slope degree of the stations in this region was mostly below 30 degrees, and the correlation between the sinusoidal value of the lower slope and the air temperature was also basically linear. The functional relationship between longitude and temperature was unclear. Considering the above factors, the model for estimating the AAT as influenced by geography and topography is as follows.

$$\text{AAT}= a_0+a_1\varphi+a_2\lambda+a_3\text{h}+a_4\alpha+a_5\beta+\varepsilon$$

where a_0 is a constant term, and a_1 to a_7 are the coefficients of each item. The estimated horizontal resolution of the meteorological index is 90 m, which is the same as the resolution of the terrain altitude. The formula can be expressed as follows when only the trend term is considered:

$$\text{AAT}=a_0+a_1\varphi+a_2\lambda+a_3\text{h}+a_4\alpha+a_5\beta$$

The slope degree and slope direction of the meteorological stations were extracted from terrain data by the Analyst Spatial function of ArcGIS10 (ESRI, Redlands, CA, USA) using the sine for the slope degree and the cosine for the slope direction (Wang *et al.*, 2005; Liu & Zou, 2006). The shading degree is the ratio of the grid points with elevations larger than that of the center points (Luo *et al.*, 2007) within a radius of 1 km. A multiple stepwise regression analysis was conducted for the AAT data, and an AAT trend model was established with the help of DPS software:

$$\text{AAT} = 14508.460 - 95.833\varphi - 64.800\lambda - 1.002\text{h}$$

The correlation coefficient R value was 0.9556, the F value was 231.2678, and significance was established at the 0.000 level. This model has an ideal fitting effect on the AAT data as determined by cross validation.

Because of the special ladder-shaped incline of the terrain from the northwest to the southeast and the low-latitude and low-altitude and high-latitude and high-altitude combinations, multiple correlations were observed between the variables. Table 2 shows the regression coefficients and t-test values of 5 geographical terrain factors and the AAT of the growing season in the Hengduan Mountains. Table 2 shows that factors α and β did not pass the t-test. Based on

Table 2. Coefficient and *t*-test of the regression modeling of active accumulated temperature (AAT) based on ordinary least squares (OLS). SE: standard error.

Variable	Standard coefficient	Partial correlation coefficient	SE	t value	*p* value
φ	-0.1767	-0.4254	25.9718	-3.7306	0.0004
λ	-0.1053	-0.2389	31.4695	-1.9530	0.0553
h	-0.9281	-0.8896	0.0065	-15.4625	0.0001
α	0.0174	0.0533	202.4611	0.4239	0.6731
β	0.0175	0.0559	63.4485	0.4448	0.6580

the lack of significance of the correlation coefficient, the two factors were not sufficiently correlated with the dependent variables; therefore, they could be eliminated from the model. This result was consistent with that of the stepwise regression modeling method. Although there were multiple correlations among the independent variables such as longitude, latitude, altitude and slope in this region, the coefficients of each factor in the model were consistent with their actual effects. The results did not show defects of regression modeling based on OLS (Zhou *et al.*, 2006; Shu *et al.*, 2007).

The mean relative error of cross-validation for AAT was 2.61 and the mean absolute error 19.1, demonstrating that the method is suitable for AAT modeling in the Hengduan Mountain area.

In addition to the macrogeographical factors and microtopographical factors, additional random factors had an effect on the spatial distribution of AAT, and the characteristics and effects of these factors were not analyzed individually. These random factors are expressed in the form of the residual error of the comparison between the measured values and simulation values of the observation samples. The simulation values of the AAT were calculated according to the prediction model above and the geographical and topographical data of the meteorological stations. The difference between the actual value and the predictive value of the AAT was considered the residual value ($\varepsilon = AAT_{actual} - AAT_{predictive}$), which was spatially interpolated by the Kriging interpolation method (Shi *et al.*, 2011) to obtain the raster layer of the ε value. The AAT value of each grid was calculated by a grid calculator under the surface analysis module of ArcGIS according to the 90-meter DEM grid data of the Hengduan Mountains. The AAT grid layer can be obtained by overlaying the grid layer for the simulation value and the residual value (Fig. 1).

Modeling the DI of the growing season

The DI during the growing season of wine grapes was determined by two factors: water requirements and precipitation. Crop water requirements have great spatial variability (Weng & Luo, 1990; Yuan & Li, 1990; Wang *et al.*, 2005). Wang *et al.* (2005) conducted a regression analysis on the water requirements of winter wheat using the quadratic surface method, and the fitting effect was good.

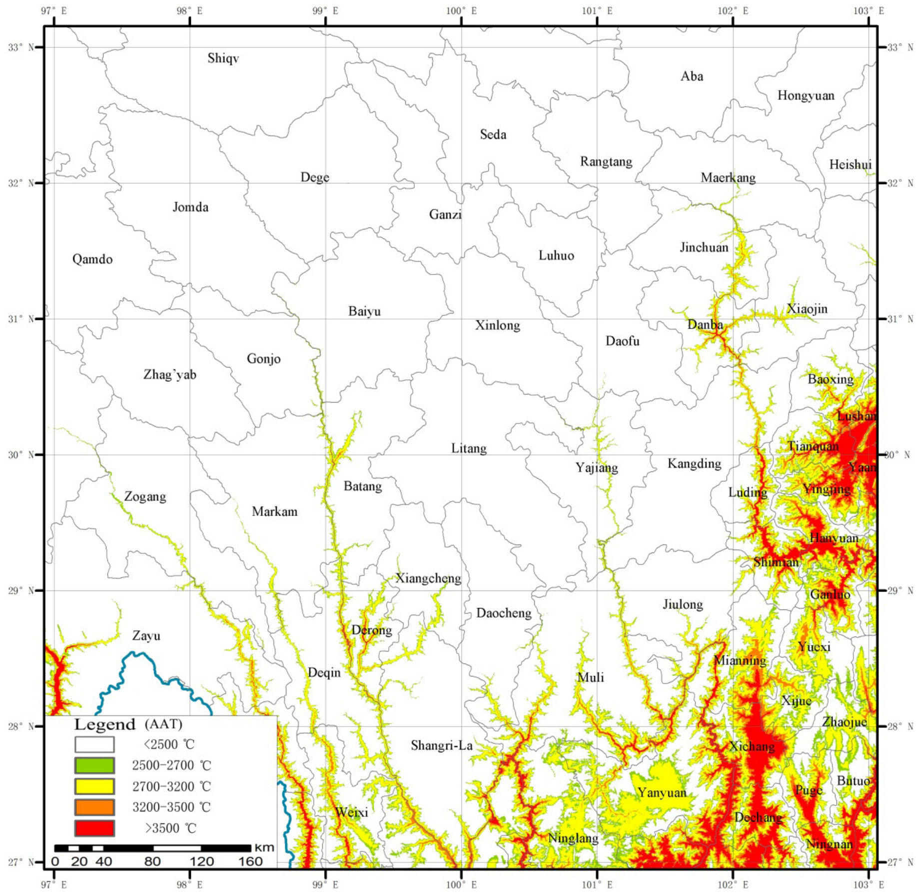

Figure 1. Active accumulated temperature (AAT) simulation map of the Hengduan Mountain region.

Previous studies (Ding *et al.*, 2001; Xu *et al.*, 2006; Kong & Tong, 2008) indicated that longitude, latitude, altitude, slope direction, slope degree and underlying surface were the principal factors that influence the spatial distribution of precipitation (Yang *et al.*, 2011). Shu *et al.* (2005) found that the degree of cover also had an obvious influence on precipitation. Considerable variation in annual precipitation was observed based on height variations of the mountain. The distribution of precipitation with elevation could be represented by a parabolic curve (Weng & Luo *et al.*, 1990). The precipitation in this region was influenced by two airflow streams from the southeast Pacific Ocean monsoon and the southwest Indian Ocean monsoon, and these streams are both blocked by the south-north direction of the mountains. Precipitation continued to diminish from the south to the north, leaving the driest area in the Hengduan Mountains in the middle; thus, the relationship between precipitation and longitude was not linear. Because of the extreme complexity of the topography and climate in the Hengduan Mountains, the influence of geographical terrain factors on precipitation is complex. Therefore, the interaction between these factors should be considered when establishing the model.

Therefore, the above factors and the interactions between them were considered, and the longitude, latitude, elevation, slope direction, slope degree and degree of shade were applied in the spatial distribution simulation of the DI. The DI distribution estimation could be expressed as a quadratic fitting polynomial:

$$DI=B_0+B_{\varphi(\lambda,\alpha,\beta,h,k)}+B_{\lambda(\alpha,\beta,h,k)}+B_{\alpha(\beta,h,k)}+B_{\beta(h,k)}+B_{h(k)}+B_k+\varepsilon$$

where B_0 is a constant term; $B_{\varphi(\lambda, \alpha, \beta, h, k)}$ represents the longitude and the interaction terms of the longitude and latitude, slope degree, slope direction, altitude and cover degree; $B_{\lambda(\alpha, \beta, h, k)}$ represents the latitude and the interaction terms of the latitude and slope degree, slope direction, altitude and cover degree; $B_{\alpha(\beta, h, k)}$ represents the slope degree and the interaction terms of the slope degree and slope direction, altitude and cover degree; $B_{\beta(h, k)}$ represents the slope direction and the interaction terms of the slope direction and altitude and cover degree; $B_{h(k)}$ represents the interaction terms of the altitude and cover degree; and B_k represents the cover degree.

$$DI=b_0+b_1\varphi+b_2\lambda+b_3h+b_4\alpha+b_5\beta+b_6k+b_7\varphi^2+b_8\lambda^2+b_9+ +h^2+b_{10}\alpha^2+b_{11}\beta^2+b_{12}k^2+b_{13}\varphi\lambda+b_{14}\varphi h+b_{15}\varphi\alpha+b_{16}\varphi\beta+b_{17}+ +\varphi k+b_{18}\lambda h+b_{19}\lambda\alpha+b_{20}\lambda\beta+b_{21}\lambda k+b_{22}h\alpha+b_{23}h\beta+b_{24}hk+ +b_{25}+\alpha\beta+b_{26}\alpha k+b_{27}\beta k+\varepsilon$$

where b_0 to b_{16} are the coefficients of each item, k is the cover degree, the meanings of φ, λ, α, β and h and the processing method for the data are the same as the above segment. The DI model of the Hengduan Mountain Region is obtained:

$$DI=-24.428+1.268\varphi+0.0085+0.00218\lambda^2-0.000000239h^2- -0.0119\varphi\lambda-0.0000736\lambda h-0.000170h\alpha+0.0000675hk- -0.166\alpha\beta$$

where R = 0.8285, F = 10.4619, and significance was established at the 0.000 level. The cross validation supported the good fitting effect of the above model on the DI.

Because the southwest section of this research area is located in India and Burma, relevant meteorological data were lacking; thus, considerable errors will be introduced into the DI simulation of the southwest of the region. Therefore, we corrected the residual error of certain stations in the southwest part of the region according to the meteorological data of Patiala and Dibrugarh in northern India (meteorological data were obtained from the world weather information service network: http://www.worldweather.cn/zh/home.html). The raster layer of the ε value was obtained by spatial interpolation using the inverse distance weighting method. The distribution map of the DI in the Hengduan Mountains was produced using the same method as above (Fig. 2).

Results and discussion

When the raster layers of the AAT and DI were overlaid, the areas with AAT above 2500°C and DIs above 0.75 were considered suitable areas; thus, the region was divided according to an AAT range for grapes with different maturation characteristics (Table 3) to obtain a spatial distribution map of suitable cultivation areas (Fig. 3).

Figure 3 indicates that the most suitable cultivation areas in the Hengduan Mountain area are scattered in separate river valleys over a wide range and account for a large total acreage; however, most of the separate areas are small. Based on variations in the results of this research and the distribution of dry and hot valleys in the Hengduan Mountain area (Fang, 2004; Sun *et al.*, 2005; Gao *et al.*, 2012), the distribution of the suitable cultivation areas for wine grape in the north of the Hengduan Mountain area is generally consistent with the distribution of dry hot and dry warm valleys in this region.

The accuracy of these results was confirmed by the existing locations of the vineyards in the Hengduan Mountain region (Fig. 3). The soils in climate-suitable areas identified in this research range were all suitable

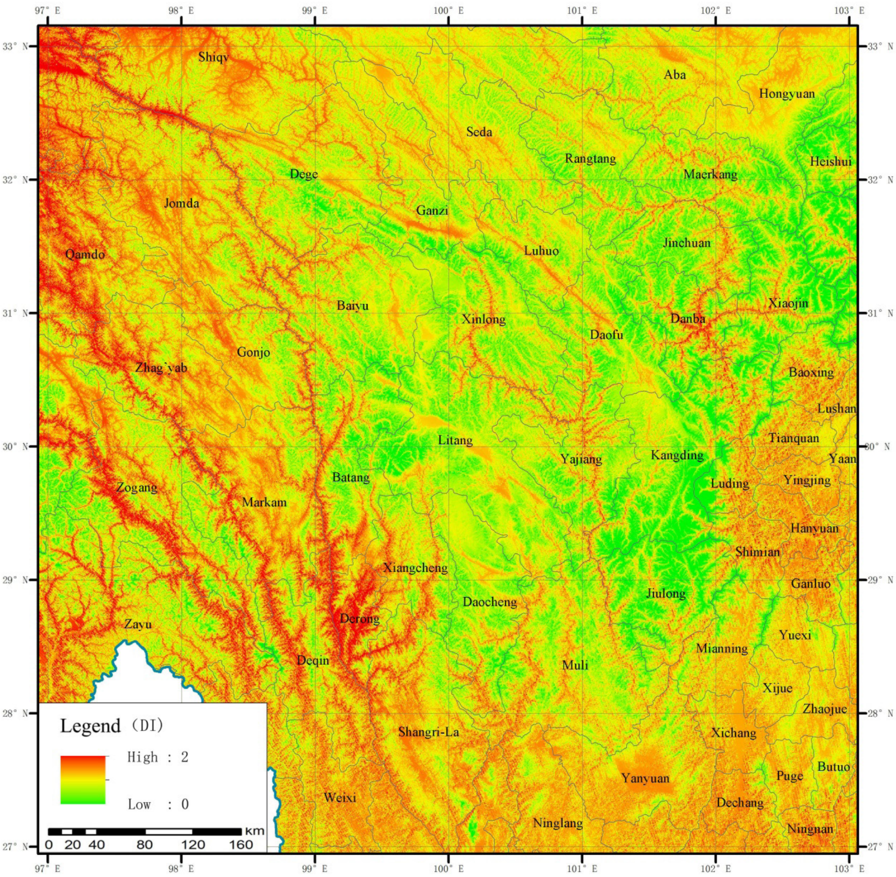

Figure 2. Simulation map of dryness index (DI) in the Hengduan Mountain region.

for viticulture; therefore, the suitability of soil factors was not assessed in this paper.

From the perspective of climatological significance, the effects of the geographical and topographical conditions on the distributions of meteorological elements, such as temperature, precipitation, and evaporation, can be considered relatively constant within a specific area. The temperature variation trend decreased overall as the altitude in the mountains increased, whereas limited differences were observed in the extent of the temperature variations in the different regions. Therefore, these regions should present a highest altitude threshold value, wherein values below the threshold present heat conditions that are sufficient for grape growth, and values above the threshold present heat conditions that are insufficient for grape growth.

Table 3. Division criteria of active accumulated temperature (AAT) in the growing season for grape varieties with different maturation characteristics (Li *et al.,* 2015).

Division criterion	AAT (°C)
Very early and early maturing	2500-2700
Middle maturing	2700-3200
Late maturing	3200-3500
Very late maturing	>3500

Precipitation variations in the region are complex, and the discrepancy between the precipitation levels in different regions is large, although the altitude range of a precipitation zone is generally constant within a specific area. Solar radiation and other meteorological factors do not vary greatly on a small scale, and altitude is the main factor that affects climate, thereby indicating that the presence of an arid zone as well as its range can be extrapolated according to the precipitation distribution characteristics of a region.

Because meteorological factors are closely related to altitude, this study attempts to convert the heat and moisture index for wine grape climatic regionalization into a corresponding altitude range to provide a better visual division of the suitable cultivation region of wine grapes in each small area. AAT has only three variables, and the highest elevation for a suitable AAT can be directly inferred from the longitude and latitude. Although the factors that affect the DI are numerous, the indicator for each specific station is fixed, and the elevation range with DI values above 0.75 can be

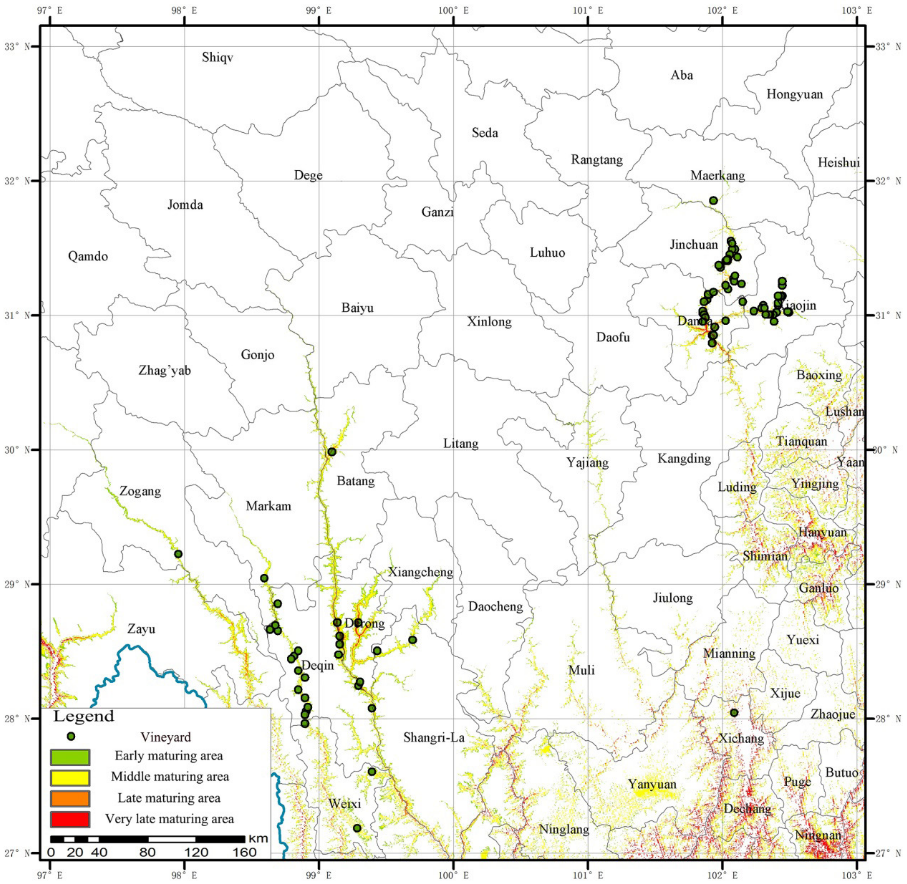

Figure 3. Climatic regionalization map for grapes and the existing locations of vineyards in the Hengduan Mountains.

determined. Combined with the above results and the regional climate characteristics, the suitable cultivation areas of wine grapes in the Hengduan Mountains can be divided into different areas suitable for grape varieties with different maturation characteristics, and an estimated altitude range can be derived for each suitable cultivation area.

— Yaan Mountain area. The suitable areas are mainly distributed in the regions under the jurisdiction of Yaan City and Ganluo County in the north of Liangshan Prefecture, and a small climatic area is observed with humid and high heat conditions. In this region, the altitude of suitable areas is mainly in the range of 1000-2000 m, although these areas are also sporadically distributed between 2300 and 2700 m asl.

— Dadu River and its tributary valley area. The suitable areas are mainly distributed in the basin in Jinchuan, Xiaojin, and Danba as well as in Kangding and Luding, and they present suitable heat and water conditions within an altitude range of approximately 1600-2700 m asl.

— Yalong River and its tributary valley area. The suitable areas are mainly distributed in Yajiang, Jiulong and Muli, and these small climatic regions present humid conditions within a suitable altitude range of approximately 2100-2700 m asl.

— Jinsha River and its tributary valley area. The suitable areas are mainly distributed in the river basin in Batang, and they present suitable heat and moisture conditions within an altitude range of approximately 1700-3000 m asl.

— Lancang River and its tributary valley area. The areas with suitable heat conditions are mainly distributed in the river basin south of Markam and north of the Deqin section and a small section of the Weixi territory; however, the water conditions are better in the north half, and the suitable altitude range is within approximately 1800-2800 m asl.

— Nujiang River and its tributary valley area. The suitable areas are mainly distributed in Tibet and present good heat and water conditions, and the suitable altitude range is within approximately 2000-3200 m asl.

— Chayu River and its tributary valley area. The suitable areas are mainly distributed in the Zayu River tributary-Sangqu River Valley region, although fragmented distributions are observed in the trunk stream; the suitable altitude range is within approximately 2000-3000 m asl.

— Lake and basin in plateau and arid valley in Liangshan Prefecture. The suitable areas are mainly distributed in the plateau lake and basin, river and valley south of Liangshan Prefecture, and the suitable altitude range is within approximately 1300-2600 m asl.

In summary, the grape producing areas in the Hengduan Mountain region are primarily distributed in valleys at altitudes between 1700 and 3000 m asl, thus representing the highest altitudes among the grape wine-producing areas in the world. These areas present advantages in wine production that many other producing districts cannot match. High altitude means more sunny, stronger ultraviolet rays, the hours of sunlight are long. In the studied areas the annual AT is high, and the range of temperatures is small within one year but large within in one day. however, the weather in the fruit maturation period is relatively cool or even cold, which is advantageous to the accumulation of aromatic substances and phenol substances. The extreme low temperature in winter is approximately -10°C to -12°C, which is within the safe winter temperature range for the Eurasian grape, meaning that the grapes do not have to be buried in winter.

Some suitable wine grape cultivation regions in this area are dry and experience serious shortages of water; therefore, the potential for irrigation should be the principle factor when considering whether to construct a vineyard. Most of the land in this region is sloped, although grape plants can develop roots in a relatively small space and are resistant to drought and barren soil; therefore, they are more suitable for cultivation on sloped land compared with other fruits. However, soil losses increase with increases in slope degree, which also increases the difficulty of vineyard soil management. Therefore, a gentle slope with a degree range below 20 to 25° should be given priority when planting grapes. Vineyards should be built according to the characteristics of the mountains because the types of soil and climate vary. The distribution of vineyards is scattered, which creates a natural block to the spread of diseases and insect pests. This approach will support different types of grape growth and increase the diversity in the types of wine produced.

Interpolations and regression analyses are two basic methods of estimating the spatial distribution and variation of meteorological elements (Ollinger *et al.*, 1995; Palomino & Martin, 1995). Because the Hengduan Mountain region has complex and diverse climates, apparent stereoclimates, strong spatial variability, and limited meteorological stations, interpolations could not fully consider the complex functional relationships between the spatial distribution of meteorological elements and a number of geographical elements; thus, the accuracy of the results was difficult to verify (Goodin *et al.*, 1979; Jarvis & Stuart, 2001). The use of regression analyses to establish equations between meteorological factors and spatial variables has the advantage of quantitatively reflecting the spatial distribution of elements in the real terrain (Shu *et al.*, 2007), and these advantages are apparent in corresponding research (Ollinger *et al.*, 1995; Kravchenko *et al.*, 1996; Bolstad *et al.*, 1998; Germann & Joss, 2000; Naoum & Tsanis, 2004; Shu *et al.*, 2007, 2009; Zhang *et al.*, 2008; Yang *et al.*, 2011). The multivariate statistical regression method has also been used to estimate the temperature, precipitation and other meteorological elements in this area and adjacent regions (Shu *et al.*, 2005, 2006; Zhang *et al.*, 2008; Ye, 2011). Shu *et al.* (2005) used the multivariate stepwise regression method to establish a spatial precipitation estimation model in Tibet with good results. Because of the large climate variations in the Hengduan Mountain area, the fitting degree of regression models may vary for different regions, and the residual error cannot be ignored.

This study used the multiple stepwise regression method to establish models for the AAT and the DI of the grape growing season in the northern region of Hengduan Mountain and correct for the residual error interpolation, considered the influence of macro factors, such as longitude, latitude and small climate, topographic factors, and it then constructed a climatic regionalization map of grapes in the northern Hengduan Mountain region. In addition, a 90 m DEM was adopted to improve the resolution of geographical factors, such as the slope degree, slope direction and cover degree, and this approach increased the simulation accuracy of the local terrain factors. All meteorological data from basic, benchmark and general sites in the study region were applied in this study, and the site density was increased by more than two times compared with other studies in this region. In water index modeling, the multivariate stepwise regression method, rather than the common multivariate regression method, was applied to analyze the formation regularity of precipitation. Additionally, this study applied the interaction terms among different geographical and topographic factors to improve the regional simulation accuracy by accounting for complex terrain and complex climate conditions. In addition, the residual errors were interpolated and corrected in this research based on the modeling results, which further improved the simulation accuracy of meteorological factors.

Comparison with the actual areas of grapevine growing and the climatic regionalization results (Fig. 3), we can find all the existing locations of vineyards in the suitable cultivation areas. Wine industry is developing rapidly in Hengduan mountain region, but many suitable areas are not distributed vineyards yet. This region has great potential for wine industry. The Hengduan Mountain region belongs to the Shangri-La region and has a wealth of cultural and tourism resources, which is suitable for producing different styles and characteristics of chateau wine. The Hengduan Mountain region has unique advantages, such as climate and cultural resources, and we believe that it will become one of the most significant wine-producing areas in the world. The complex topography and variable climate in this area produce multiple microclimates in certain regions; therefore, this study should only act as a reference when establishing vineyards, and the cultivation variety and management methods should be based on the actual conditions of the vineyard.

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