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Determinants and identification of the northern boundary of China's tropical zone

XU Qian[1], *DONG Yuxiang[1,2], WANG Yuying[1], YANG Ren[1], XU Chengdong[3]

1. Guangdong Provincial Key Laboratory of Urbanization and Geo-simulation, School of Geography and Planning, Sun Yat-sen University, Guangzhou 510275, China;
2. Xinhua College of Sun Yat-sen University, Guangzhou 510275, China;
3. LREIS, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China

Abstract: The influence of monsoon climatic characteristics makes the tropics of China different from those of other parts of the world. Therefore, the location of the northern boundary of China's tropical zone has been one of the most controversial issues in the study of comprehensive physical regionalisation in China. This paper introduces developments in the study of the northern boundary of China's tropical zone, in which different scholars delimit the boundary with great differences based on different regionalisation objectives, indexes, and methods. The main divergence of opinion is found in different understandings of zonal vegetation, agricultural vegetation type, cropping systems, tropical soil type and tropical characteristics. In this study, we applied the GeoDetector model, which measures the spatial stratified heterogeneity, to validate the northern boundaries of the tropical zone delimited by six principal scholars. The results show that the mean *q*-statistic value of the higher latitude boundary delimited by Ren Mei'e is the largest (q=0.37), suggesting that, of the rival views, it best reflects the regional differences between China's tropical and subtropical zones, but it is not necessarily suitable for guiding the development of tropical agriculture. The mean values of the *q*-statistics of Zheng Du's line and Yu Xianfang's line around the Leizhou Peninsula at a lower latitude were smaller, at 0.10 and 0.08 respectively, indicating that the regional differences were smaller than those of Ren Mei'e's boundary. Against the background of global climate change, the climate itself is changing in fluctuation. It is, thus, worth our further research whether the northern boundary of the tropical zone should not be a fixed line but rather should fluctuate within a certain scope to reflect these changes.

Keywords: comprehensive physical regionalisation, the northern boundary of the tropical zone, China

1 Introduction

Comprehensive physical regionalisation employs the similarity of and differences in the natural surface as means to divide the natural region, the unit of division being the characteristics of natural complex systems and their laws of occurrence, development and distribution (Bailey, 1983; Bailey *et al*., 1985); the delimitation of the regionalisation boundary is based on the principle of maximum difference inter-region and maximum similarity intra-region (Fortin and Drapean, 1995). The delimitation of a certain boundary in

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Author: Xu Qian (1984–), PhD, specialized in exploitation and protection of land resources. E-mail: xuqian19840613@163.com
***Corresponding author:** Dong Yuxiang (1964–), Professor, specialized in integrated physical geography, coastal aeolian landforms, development and protection of land resources. E-mail: eesdyx@mail.sysu.edu.cn

the regionalisation process is often controversial, as there is no clear global definition of the tropical zone (Oliver, 1991). According to the astronomical division, the tropics range lies between the Tropic of Cancer and the Tropic of Capricorn, but the tropical zone cannot be delimited accurately. Supan (1879) first delimited the physiographic boundary of the temperature zone, proposing the isotherm of sea-level annual mean temperature 20°C as the boundary between the tropical and temperate zones. Subsequently, hundreds of schools of thought have contended and developed many tropical division methods based on climate, vegetation, soil, etc. Teriung and Louie (1972) summarised 169 tropical division methods with different climate indexes. The internationally popular division method of Köppen (1918, 1923, 1936), modified by Geiger and Pohl (1954), provided the world's first climatic regionalisation scheme based upon the influence of temperature and precipitation on regional crop growth, and mainly uses the isoline of the coldest monthly mean temperature of 18°C (initially set at 20°C) as the tropical boundary, this temperature being the minimum caloric requirement for coconut trees in the tropical zone. Pelzer *et al*. (1955) disagreed with Köppen's scheme: pointing out, for example, that the mean temperature of the coldest month in Hanoi, which should be in the tropical zone, is 16.7°C, they argued it would be more appropriate to use frost as a division standard. Troll and Paffen (1964) comprehensively analysed land cover and the restriction of the tropical zone to areas remaining above certain prescribed temperatures and precipitation levels, concluding that the restriction of daily temperature in the tropical zone is more important than the monthly mean temperature over the whole year. Alvin and Kozlowski (1977) considered that the monthly mean temperature over the whole year to range between 20°C and 30°C in the tropical zone. Holdridge (1987) proposed the 'life zone partition system', with the isoline of annual mean biological temperature of 24°C as the tropical boundary. Wissnann (1948) distinguished the tropical standard between marine climate and continental climate, and considered that the tropical standard in the marine region is a mean temperature of the coldest month of 18.3°C, while the standard in the continental region is being absolutely frost-free. Longman and Jenik (1974) and Golley (1983) divided the tropical zone according to the spatial distribution of tropical crops, and contended that there is no subtropical zone between the tropical zone and the temperate zone, as this is included in the tropical range. Bridges (1978) and Walter (1983) considered the relationship between climate and temperature zones according to vegetation and soil. Lauer (1974) proposed a regionalisation scheme that comprehensively considers the radiation condition and the number of humid months. Lauer and Frankenberg (1985, 1988) later adjusted Lauer's (1975) scheme by also considering azonal factors such as landform. Even applying the same index of each scholar, the tropical boundary is different when measured in different periods; thus, it can be seen that the tropical boundary is one in fluctuating change, its essence being a transitional zone evolving over time (Lockwood, 1978; Nieuwelt, 1977).

Scholars from various countries have conducted extensive research on the division of the tropical zone; the zoning index also tends to conduct diversified development from singleness. However, due to differences in regionalisation objectives and the selection of the index system, the views of different scholars are inconsistent, and the delineation of the global tropical boundary is not totally applicable to China's actual situation (Manfred, 2003). For example, based on the difference between the monsoon climate and continental climate, Wissmann (1939) points out that the Köppen scheme is not applicable to the monsoon climatic region in South China and, instead, divides the tropical boundary using the standard of the coldest monthly mean temperature of 13°C.

China is significantly affected by the relationship between land-sea differentiation, landform, terrain, etc.; the tropical monsoon climate is prevalent (Zhu and Wan, 1963) and the winter temperature is lower than other global regions with the same latitude; therefore, the terrestrial part of the northern boundary of China's tropical zone is not as regular as that of other countries, and its position lies further south. China's tropical zone has a wide range of land and sea, a short biological growth period, high natural productivity, and great potential for development; it is, therefore, important to determine the boundary of its spatial distribution for the purposes of physical regionalisation of China (He D Z and He D, 1988; Huang, 1959; Zhong *et al.*, 1990).

2 Different regionalisation schemes of the northern boundary of China's tropical zone

Comprehensive physical regionalisation has always been the focus and core of Chinese physical geography (Wu and Zheng, 2001; Zheng *et al.*, 2015): as early as the 5th century BC, the book 'Yugong Geography' recorded that China was divided into nine regions using the indexes of soil type and soil fertility. In the 1930s, Chu Kochen and other scholars began to research the modern physical regionalisation of China (Zhu, 1958, 1963, 1979). In the 1950s, the Chinese Academy of Sciences undertook the comprehensive physical regionlisation of China, highlighting the zonality law of physical geography. Regional planning work has since been comprehensively conducted in different fields (Wu and Zheng, 2003), but there remains significant controversy over some boundaries.

Due to the particularity of China's monsoon climate and the influence of the country's land-sea distribution, China's temperature zone is divided into three zones: the tropical, temperate and cold zones, according to international practice, the subtropical zone having been split between the tropical and temperate zones (Corlett, 2013). In other parts of the world with the same latitude, the subtropical zone usually forms a desert zone due to the subtropical high belt: for example, in the typical and subtropical climate zone, the Mediterranean climate is wet in winter and dry in summer (Qiu, 1993a), while China's subtropical zone, which lies within the monsoon climatic region, is a synchronisation of high temperatures and ample precipitation. The subtropical zone is located in the transitional zone between the tropical and temperate zones, showing obvious transitional properties in climate, soil and vegetation types. It has obvious seasonality compared with the tropical zone and is warmer than the temperate zone (Huang, 1992).

The subtropical zone is of great significance for China's physical regionalisation, in determining whether the northern boundary of the tropical zone is the boundary between the tropical and subtropical zones or between the tropical and temperate zones. Therefore, exploring the northern boundary of the tropical zone is of great significance to the development of the tropical regional system and coping with the global climate change.

2.1 Progress in research methods

The top-down division and bottom-up mergence are two basic methods in the study of comprehensive physical regionalisation. The method of top-down division is mainly used for the study of large-scale regionalisation, such as nationwide regionalisation: First, the higher units perform type regionalisation, based on regional differentiation regularity, then the lower units perform regional regionalisation. The method of bottom-up mergence is suitable for the study of mid-scale and small-scale regionalisation, the lower units being aggregated and merged into the higher units sequentially. However, the practical regional planning work of large-scale regionalisation often uses the two methods in conjunction: the method of top-down division serves as macroscopic guidance, while the method of bottom-up mergence, with higher accuracy, is added as a complement (Zheng *et al.*, 2015).

The early study of comprehensive physical regionalisation was limited by the data and technical conditions, mainly using qualitative and expert integration methods. The regionalisation boundary was confirmed by field investigation, soil and vegetation type distribution and expert experience. With the rise of quantitative geography in the 1970s and the development of '3S' (GIS, GPS and RS) technology in the mid-1990s, the research methods of comprehensive physical regionalisation became increasingly quantitative and comprehensive. The combination of the traditional regionalisation methods – such as the overlay metod, principal factor method, geographic correlation analysis method and land type graph method (Liu, 1994; Liu *et al.*, 2010) and the application of '3S' technologies and metrological methods – such as cluster analysis (Ding *et al.*, 2007), principal component analysis (Miao *et al.*, 1988), uncertainty reasoning method (Cong *et al.*, 2007), SOFM (self-organizing feature map) neural network analysis (Huang *et al.*, 2011), grid analysis method (Chai *et al.*, 2008) and fuzzy set theory (Kuang, 2006) – greatly improved the objectivity of the results of comprehensive physical regionalisation and the level of mathematical verification (Wu, 2010), but also improved the research level of comprehensive physical regionalisation and the accuracy of delimiting the regionalisation boundary.

2.2 Typical regionalisation schemes

In comprehensive physical regionalisation, because of the differences in regionalisation objectives and index selection, and the transitional character and complexity of natural zones, there is a significant controversy in the delimitation of the northern boundary of China's tropical zone (the southern boundary of the subtropical zone), especially in the middle segment of the tropical zone (He D Z and He D, 1988; Hou, 1988; Huang, 1992; Qiu, 1993b; Ren, 1962, 1991; Tang, 1964; Yu *et al.*, 1986; Zeng, 1962; Zhang, 1965; Zheng, 1999, 2008; Zhu, 1958). We will now introduce six kinds of regionalisation scheme with important influence (Figure 1):

(1) Ren's regionalisation scheme

Ren's regionalisation scheme (1991) suggests that vegetation and soil should be mainly considered as division indexes, as these can better reflect the regional bioclimatic conditions; to avoid the anthropogenic influence and subjective effect, it is not appropriate to rely too much on accumulated temperature. Ren Mei'e stressed the difference between zonal vegetation and azonal mountainous vegetation, positing the former as a more suitable indicator than the latter for delimiting the northern boundary of the tropical zone. Evidencing the tropical delimitation in his regionalisation scheme, he contended that tropical fruits such as litchi and longan cannot exceed the Nanling ridge, and referred to the elephants, peacocks, crocodiles and other large tropical animals distributed in the ancient Pearl River Delta and

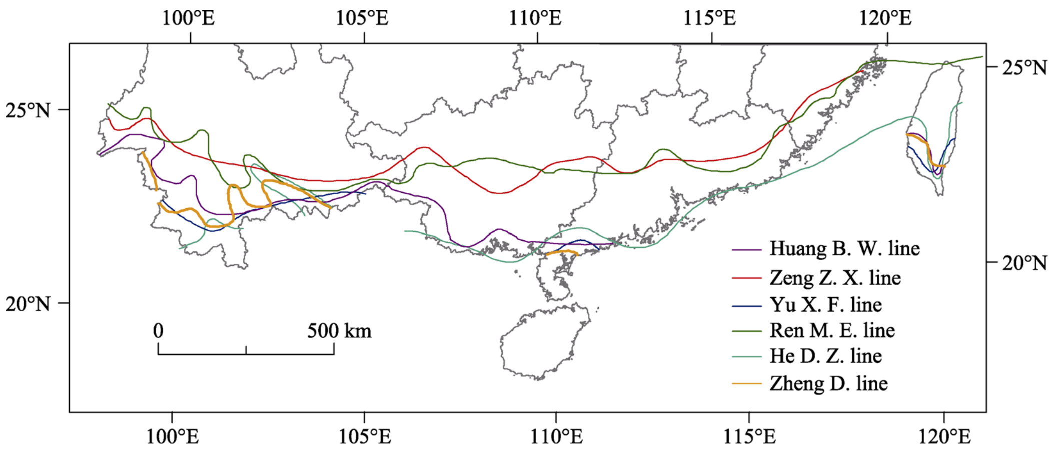

Figure 1 Different regionalisation schemes of the northern boundary of China's tropical zone

the southern Fujian Delta as further bases for his scheme. To explain the controversial issue of classifying Guangzhou within the tropical zone, Ren considered that the frost in Guangzhou is the result of the flatland wildwood destruction in the urban district; were it still covered by primeval forest, Guangzhou's flatland vegetation would not be affected by frost. The boundary of Ren's scheme mainly passes through the mid-northern Taiwan, south-eastern Fujian, southern mainland Guangxi and Guangdong.

(2) Huang's regionalisation scheme

Huang Bingwei (1959) stressed the physical geography zonality law. The main division index of Huang's scheme is active accumulated temperature greater than 8000°C, and the tropical zone should meet the mean temperature of the coldest month exceeding 12°C, the extreme lowest temperature of the annual average not being less than 5°C and the absolute minimum temperature recorded being not less than 0°C. The tropical zone of Huang's scheme includes two thermal zones, three regions or sub-regions, three zones and six provinces (Table 1).

Table 1 The tropical zone of Huang's regionalisation scheme

Thermal zone	Region/sub-region		Zone	Province
Tropical zone	Humid region	Eastern sub-region	Tropical monsoon forest and latosol zone	Plain of southern Taiwan and Kaohsiung
				Plain and hilly southern Guangdong
				Plain and hilly Hainan
				Mountains of Hainan
		Western sub-region	Tropical monsoon forest and latosol zone	Basin among mountains of southern Yunnan
Equatorial zone	Humid region		Equatorial rainforest zone	Nansha Islands

(3) Zeng's regionalisation scheme

Zeng Zhaoxuan (1980) considered the tropical zone as the area of high temperatures throughout the year, claiming it is more reasonable to delimit the northern boundary of the tropical zone with the 'snow-free line' instead of the 'frost-free line'. He stressed that south China belonging to the tropical region should not be denied by the radiation frost that follows a cold wave. The tropical boundary of Zeng's scheme lies mainly in the valley basin of south-western and southern Yunnan, Youjiang Valley, Xijiang Valley, the northern margin of

Pearl River Delta, coastal areas of eastern Guangdong, coastal areas of southern Fujian, Taiwan and the nearby islands.

(4) He's regionalisation scheme

This scheme selected more indexes than others, using the coldest monthly average temperature of 15°C, the annual average extreme lowest temperature of 3°C, absolute minimum temperature 0°C, the annual average of 1–2 frost days, and ⩾10°C accumulated temperature greater than 5000°C as the main indexes. The northern boundary of the tropical zone in He's scheme passes, in turn, through Gaozhou in western Guangdong, eastward coastal areas of western Guangdong, the Pearl River estuary, coastal areas of eastern Guangdong, coastal areas of middle-southern Taiwan, westward coastal areas of southern Guangxi and southern Xishuangbanna of southern Yunnan (He D Z and He D, 1988).

(5) Yu's regionalisation scheme

Yu Xianfang (1981) stressed that geographers should focus on the geographical domain of natural complex systems in the research of zonal differentiation and should not divide the tropical zone completely according to latitude lines. Instead, it should be divided with multiple indexes according to the influences of different aspects, with the region meeting three indexes to be classified as the tropical zone, comprising ⩾10°C accumulated temperature greater than 8200°C, 365 days with daily temperature ⩾10°C and the annual average extreme lowest temperature of 5°C.

Regarding the controversy over whether Guangzhou should be included in the tropical zone, Yu Xianfang considered that although the temperature difference between Guangzhou and Haikou is only 2–3°C, this small difference is critical in distinguishing Guangzhou's agricultural production since the region cannot provide the growth and development conditions of rubber and other tropical crops in winter; thus, Guangzhou should not be included in the tropical zone. The tropical zone of Yu's scheme included Hainan Island and the Leizhou Peninsula in north-eastern China's monsoon region, Xishuangbanna of Yunnan and the estuary area in western China's monsoon region.

(6) Zheng's regionalisation scheme

Zheng Du and others (Wu and Zheng, 2000; Zheng *et al.*, 2015) contend that the temperature conditions (especially the average temperature of the coldest month) should be considered as the main basis for dividing the tropical zone; they select ⩾10°C accumulated temperature (the guarantee of normal crop growth), the mean temperature of the coldest month and the extreme lowest daily mean temperature (the guarantee of tropical crops overwintering) as the main indexes, while vegetation and soil are chosen as the verification indexes.

Zheng proposed the concept of the tropical boundary, annual tropical boundary, real tropical boundary and tropical fluctuating zone based on the transitional properties between the tropical and subtropical zones. The boundary of the hottest year on record is called the annual tropical boundary, and that of the coolest year on record is called the real tropical boundary; furthermore, the area from the real tropical boundary to the annual tropical boundary is called the tropical fluctuating zone. The tropical range of Zheng's scheme comprises the tropical boundary ranging between 21°40′N and 22°10′N, the annual tropical boundary ranging between 23°N and 23°40′N, the real tropical boundary at 21°30′N and the tropical fluctuating zone ranging between 21°30′N and 24°40′N.

2.3 Differences in the soil and vegetation types in different schemes

According to the soil and vegetation types of the different schemes, the boundary in Ren Mei’e’s and Zeng Zhaoxuan’s schemes is basically delimited between lateritic red soil and red soil (Figure 2). As Xiong and Li (1981) observed, as ‘the properties of lateritic red soil are closer to latosol, the latosol is the suitable soil type for the tropical economic crops, and the lateritic red soil is a kind of soil type which is likely to be introduced and propagated in this kind of tropical crops’; thus, the soil clay minerals of lateritic red soil and latosol will generally be combined into one zone. Therefore, the northern boundary of China’s tropical zone basically corresponds to the boundary between the lateritic red soil and red soil.

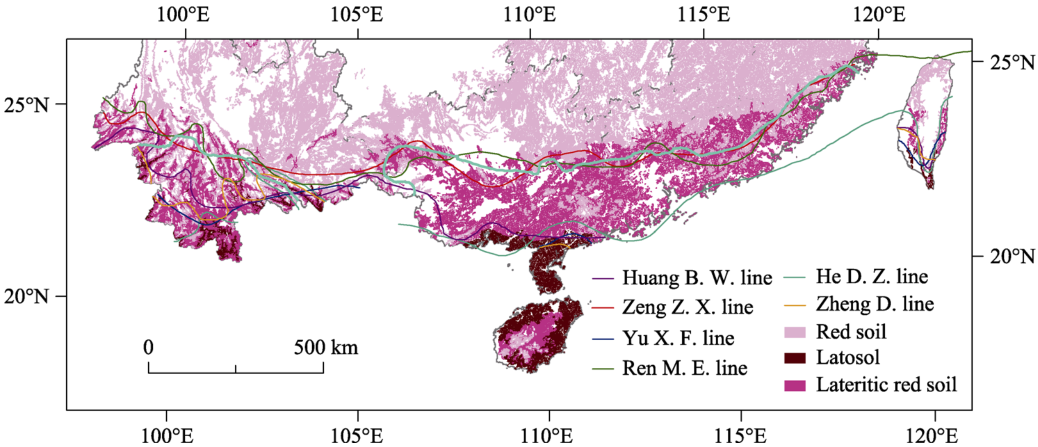

Figure 2 Map showing the northern boundary of China’s tropical zone with different regionalisation schemes and soil types

Regarding Hainan Island in the tropical zone, while the island’s periphery has latosol, the centre has lateritic red soil because of the terrain. However, this soil type differentiation cannot be used to determine that the island’s periphery with mainly latosol is in the tropical zone while the central area with lateritic red soil is mainly in the subtropical zone: the entire Hainan Island should belong to the tropical zone.

The northern boundary of the tropical zone coincides with the boundary between lateritic red soil and latosol based on Huang Bingwei’s scheme: the tropical area of Guangxi and Guangdong is mainly covered by latosol, but in southern Yunnan, due to the plateau terrain, the boundary between lateritic red soil and latosol is not clear; thus, the lateritic red soil and latosol are mixed in the tropical zone.

In terms of natural vegetation distribution, the focus of the controversy over the tropical zone’s northern boundary is different understandings of ‘zonal vegetation’. It is generally believed that flatland vegetation, the altitude of which is lower than 300–350 m, is zonal vegetation (Hou, 1988); the tropical rainforest, as zonal vegetation, is considered an important index in delimiting the tropical zone. However, in most parts of China, the original vegetation is almost non-existence due to human activities (Wu and Zheng, 2001); therefore, the division standards focus more on the crops, economic crop growth and the cropping system. In terms of the cropping system, the tropical zone of all the schemes belong to the category of double cropping rice or its continuous thermophile dry farming (Figure 3). However, according to the schemes of Ren Mei’e and Zeng Zhaoxuan, the boundary is basically consistent with the divide between double cropping rice or its continuous thermophile dry farming and single (double) cropping rice or its continuous chimonophilous dry farming, considering whether it is suitable for continuous cropping of winter crops after double cropping rice: for example, the flatland of central Guangdong and southern Fujian and the valley floor of Guangxi Youjiang, Xinjiang have generally implemented continuous cropping in winter of sweet potato after double cropping rice (Hou, 1988).

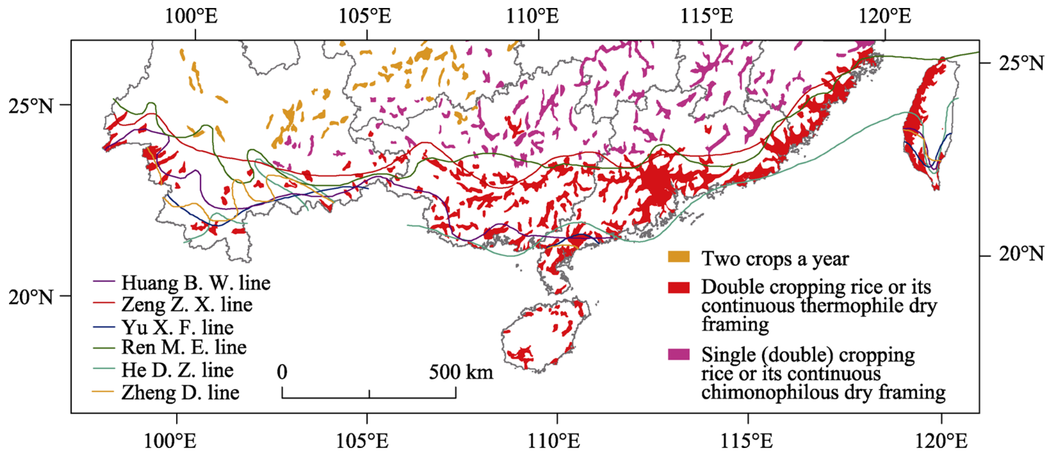

Figure 3 Map showing the northern boundary of China's tropical zone with different regionalisation schemes and cropping systems

In conclusion, the difference of opinion between experts over the northern boundary of China's tropical zone is mainly due to different understandings of 'zonal vegetation' and of regional agricultural cropping system and vegetation types. For example, Hou and Ren consider that an area in which there is continuous cropping of one winter crops after double cropping of rice can be considered tropical, but Huang Bingwei and Zhang Baokun strictly delimited the tropical zone to areas in which thermophilic crops grow all year round (Qiu, 1993a). Understanding of tropical characteristics is not consistent (Qiu, 1993b): for example, while some areas exhibit tropical signs due to fluctuant changes in the climate, these areas should not be classified within the tropical zone (Wu and Zheng, 2001).

In summary, the views of Chinese scholars on the northern boundary of China's tropical zone are mainly divided into two factions:

(1) Nanling area

The advocates of this position are, Hou Xueyu (1988) and Ren Mei'e (1962, 1991). The boundaries of Hou's and Ren's divisions are very close, the boundary of Ren's being further south than Hou's, but Qiu Baojian (1993b) argues 'division in Nanling area', contending that longan and litchi should belong to the South Asian tropical crops, and that whether tropical crops can be planted in part of Guangdong and Guangxi is affected by the azonality, such as Nanling and the horseshoe landform. Moreover, if 90% guarantee of tropical crops growing normally is used to delimit the tropical zone, rubber trees, needing 7–8 years post-planting to start producing rubber and only delivering economic value for 1–2 years in every 10 years, will be devastated by suffering damage through excessive cold even once every 10 years on average; therefore, the northern boundary of the tropical zone should be further south.

(2) Near the Leizhou Peninsula

The advocates of this position are Huang Bingwei, Zhong Gongfu and others (Chen, 1984;

Huang, 1959, 1992; Jing, 1962; Li and Wang, 1982; Pang, 1986; Qiu, 1993a; Sheng, 1987; Zhang B K, 1965; Zhang J M, 1991; Zhao, 1958; Zhong *et al*., 1990). Huang Bingwei believes that the tropical zone's northern boundary should be the north of the Leizhou Peninsula (Huang, 1959), which is further north than others contend. Zhong Gongfu sets the northern boundary at about 22°N (Zhong *et al.*, 1990), around the north end of the Leizhou Peninsula, dividing the tropical zone into four regions: Hainan and the Leizhou Peninsula, southern Taiwan, southern Yunnan and the South China Sea Islands. Zhang Baokun, Zhao Songqiao and others have a similar view, delimiting the northern boundary at the northern part of the Leizhou Peninsula: the main principle of division is that the tropical zone should be suitable for the growth of thermophilic crops all year round, and not affected seriously by the cold wave from China's strong winter monsoons (Zhang, 1965), and the soil type should be latosol. Overall, the division scheme of 'Nanling area' is more focused on differences in the regional comprehensive characteristics, while the division scheme of 'Near the Leizhou Peninsula' is more inclined to the guiding significance of tropical crops.

3 Discriminatory analysis of different regionalisation schemes of the northern boundary of China's tropical zone

The core of comprehensive physical regionalisation is spatial stratified heterogeneity, meaning minimum differences among the regions of the same regionalisation level and the biggest differences between different regions. Due to differences in understanding of the regional characteristics and the limits of traditional technology and methods, the northern boundary of the tropical zone is not quantification index; consequently, comparative analysis of different regionalisation schemes through quantitative methods was very difficult in previous studies. The GeoDetector model can quantify and objectively reflect geographical elements' effects on natural complex systems, and the spatial stratified heterogeneity was realised (Wang and Hu, 2012; Wang *et al*., 2013; Yang *et al*., 2015; Yang *et al*., 2016). Therefore, faced by the controversial research status of the northern boundary of China's tropical zone, and based on the GeoDetector model, this study conducted an empirical analysis aiming to detect and identify the different regionalisation schemes to achieve rich and clear cognition on this subject.

3.1 GeoDetector

Based on the law of regional similarity and difference, with regard to physical regionalisation, regions within the same natural area should share identity features, whereas different natural areas should have obvious regional differences (Fu *et al*., 2001). The GeoDetector model (Wang *et al*., 2010; Hu *et al*., 2011; Wang *et al*., 2016) (http://www.geodetector.org/) can measure the degree of spatial stratified heterogeneity and test its significance, through the within-strata variance less than the between strata variance. We now use the GeoDetector model to reveal spatial stratified heterogeneity through the process (q-statistic) of different climate indexes in the study area, aiming to assess different regionalisation schemes of the northern boundary of China's tropical zone. The formula of the q-statistic is as follows:

$$q = 1 - \frac{1}{N\sigma^2}\sum N_h \sigma_h^2 \tag{1}$$

The spatial stratified heterogeneity will be realised by the northern boundary of China's tropical zone, which is the major determinant of different climate indexes. We assessed spatial stratified heterogeneity between the tropical zone and subtropical zone by applying the q-statistic to the climate indexes. N is the number of all the samples in this study and σ^2 denotes the variance of indexes. The study area is stratified into L stratums, denoted by h= 1, 2, …, L. $q\in[0, 1]$. The q-statistic can be used to test the significance of stratification through the process (q-statistic). An increase in the q-statistic denotes an increase in stratified heterogeneity, and vice versa. When q = 0, there is no spatial stratified heterogeneity in the study area, whereas when q=1, the study area has perfect spatial stratified heterogeneity.

3.2 Assess different regionalisation schemes

This study aims to tackle the controversial research status of the northern boundary of China's tropical zone, using the GeoDetector model to assess its different regionalisation schemes. However, given the lack of climate data in Taiwan, we only assess China's different regionalisation schemes. We chose six kinds of regionalisation scheme with important influence (Huang, 1959; He D Z and He D, 1988; Ren and Zeng, 1991; Yu *et al*., 1986; Zeng, 1962; Zheng, 2008) (Figure 1). From among the main regionalisation indexes of all the regionalisation schemes, we chose eight of the most commonly used indexes that can reflect the characteristics of the study area. These regionalisation schemes use main climate elements, comprising the annual average monthly mean temperature, the mean temperature of the coldest month, the lowest daily mean temperature, the extreme lowest temperature, ≥10°C accumulated temperature, the days with a daily temperature ≥10°C, the days with a daily minimum temperature ≤0°C, and the days with a daily minimum temperature ≤2°C (Figure 4). Except for the extreme lowest temperature, taken as the minimum of the 30 years from 1981 to 2010, the rest of the indexes use average values from 1981 to 2010 inclusive. All the climate data were taken from China's 756 benchmark ground meteorological stations and automatic stations that recorded daily datasets from 1981 to 2010 (http://data.cma.cn). The point value data were interpolated using the Kriging interpolation method. All the raster data is at 250 m spatial resolution.

Based on the GeoDetector model, the quantitative q-statistics of the different regionalisation schemes were acquired. The spatial stratified heterogeneity can be assessed by q-statistics. The northern boundary of the tropical zone differs in different regionalisation schemes, so the area of the tropical and subtropical zones are different. Therefore, the q-statistics of different regionalisation schemes must be different, using the GeoDetector probe for a total of 45,201 samples in the study area. For example, ≥10°C accumulated temperature of 7500°C and the mean temperature of the coldest month of 15°C were also used in He Dazhang's and Yu Xianfang's regionalisation schemes, but tropical scope of the two regionalisation schemes were different; thus, the variance of ≥10°C accumulated temperature in the two regionalisation schemes are different, and the q-statistics of the same index in the two regionalisation schemes must also be different. From the q-statistics of the six regionalisation schemes, the test results are as follows (Table 2): the highest score was q=0.37 for Ren Mei'e's line, after which the other schemes scored as follows: Zeng Zhaoxuan (q=0.32) > He Dazhang (q=0.17) > Huang Bingwei (q=0.12) > Zheng Du (q=0.10) > Yu Xianfang (q=0.08). The maximum q-statistics of the eight indicators were all found

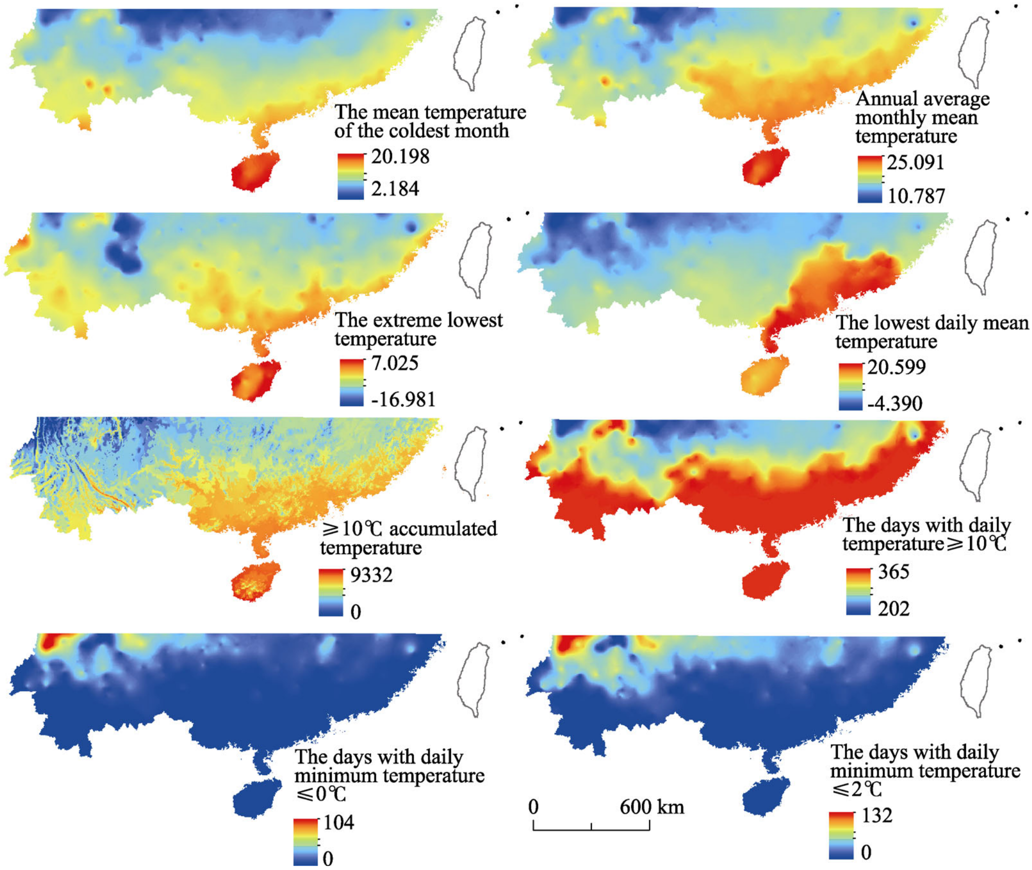

Figure 4 Annual average values of main climatic indexes in the northern boundary of China's tropical zone from 1981 to 2010

along Ren Mei'e's line and Zeng Zhaoxuan's line. In the categories of the extreme lowest temperature, the mean temperature of the coldest month, the days with daily temperature ≥10°C, the days with a daily minimum temperature ≤2°C and the days with a daily minimum temperature ≤0°C, Ren Mei'e's line has the highest q-statistics of the six regionalisation schemes, the values being 0.52, 0.52, 0.41, 0.30 and 0.20 respectively. In Zeng Zhaoxuan's scheme, the q-statistics of ≥10°C accumulated temperature, annual average monthly mean temperature and the lowest daily mean temperature are highest in their respective categories among the six schemes, with values of 0.37, 0.37 and 0.35 respectively. Therefore, from the perspective of the spatial stratified heterogeneity of the tropical zone and subtropical zone, Ren Mei'e's and Zeng Zhaoxuan's regionalisation schemes should be considered the most valuable. The schemes of Zheng Du, Yu Xianfang and others are relatively weak in their expression of spatial stratified heterogeneity. Using the GeoDetector to study of the northern boundary of China's tropical zone can satisfy the regionalisation principle regarding homogeneity of the within-strata value and maximum heterogeneity of the between-strata value. As the classification results are reasonably credible, the GeoDetector model can, thus, provide good technical support for comprehensive physical regionalisation.

Table 2 Detection results of the delimitation index of the northern boundary of China's tropical zone (q value)

Regionalisation scheme	Mean temperature of the coldest month	Extreme lowest temperature	≥10°C accumulated temperature	Annual average of monthly mean temperature	Days with daily temperature ≥10°C	Days with daily minimum temperature ≤2°C	Lowest daily mean temperature	Days with daily minimum temperature ≤0°C	Average of *q* value
Huang's	0.24	0.20	0.11	0.10	0.10	0.07	0.07	0.05	0.12
Zeng's	0.11	0.47	0.37	0.37	0.41	0.29	0.35	0.19	0.32
Yu's	0.05	0.15	0.10	0.09	0.07	0.05	0.09	0.03	0.08
He's	0.20	0.20	0.15	0.19	0.07	0.19	0.19	0.19	0.17
Ren's	0.52	0.52	0.34	0.35	0.41	0.30	0.32	0.20	0.37
Zheng's	0.23	0.16	0.09	0.09	0.07	0.05	0.07	0.03	0.10
Average	0.23	0.28	0.19	0.20	0.19	0.16	0.18	0.12	/
Maximum	0.52	0.52	0.37	0.37	0.41	0.30	0.35	0.20	/

4 Conclusion and discussion

Due to the uplift of the Qinghai-Tibet Plateau, China's climate near the Tropic of Cancer is characterised by monsoons, causing delimitation of the subtropical and tropical boundaries to be a contentious issue in the research of physical regionalisation. This article summarises the principal scholars' different viewpoints on the northern boundary of China's tropical zones and uses the GeoDetector model to reveal spatial stratified heterogeneity, detecting and identifying different regionalisation schemes. The results are as follows: (1) The focus of the dispute over the northern boundary of China's tropical zone has mainly been the middle segment of the tropical zone, concerning whether the regions from the north of the Leizhou Peninsula to the Tropic of Cancer belong to the tropical region. The boundary of Ren Mei'e's scheme is set further north than others', approximately in Nanling. However, the boundaries of Huang Bingwei's, Zheng Du's and others' schemes are set further south, near the Leizhou Peninsula. The focus of the debate lies mainly in different cognitions about zonal vegetation, agricultural vegetation types, cropping systems, tropical soil types and other tropical characteristics. The differences in the soil and cropping systems are mainly displayed by some boundaries, with Ren Mei'e's being the best representative, which divide the lateritic red soil and red soil, while the regionalisation schemes of Huang Binwei, Zhengdu and others set the dividing line nearly between lateritic red soil and latosol. Furthermore, the above boundaries, with Ren Mei'e's being the best representative, are near the dividing line between double cropping rice or its continuous thermophile dry farming and single (double) cropping rice or its continuous chimonophilous dry farming. By detecting and identifying using the GeoDetector, the average q-statistic of Ren Mei'e's scheme is the highest (q=0.37), followed by: Zeng Zhaoxuan (q=0.32) > He Dazhang (q=0.17) > Huang Bingwei (q=0.12) > Zheng Du (q=0.10) > Yu Xianfang (q=0.08). These findings show that, of the studied schemes, that of Ren Mei'e best expresses maximal within-strata homogeneity and between strata-variance between tropical and subtropical regions.

The problem of the northern boundary of China's tropical zone needs to be further discussed as follows. (1) Though soil, vegetation, cropping systems, etc. are affected and restricted by climate conditions, they cannot fully reflect the characteristics of climate and they have certain lags as regards climate change (Qiu, 1993a). In addition, with the improvement of scientific and technological levels, soil properties, vegetation species, cropping systems, etc. will also change, with the result that regionalisation might be error-prone if only soil, vegetation and cropping systems are chosen as regionalisation indicators. It would be more reasonable for soil, vegetation and cropping systems to be used as auxiliary indicators for reference. In studying comprehensive physical regionalisation, climate indexes should be adopted as the dominant factors. (2) The region between the tropical and subtropical regions has gradient features, and its climate has been undergoing dynamic changes, with indicators of climate characteristics also varying. Thus, as the climate index in different time scales also presents certain differences, division of the tropical zone's northern boundary through different methods produces different results, but the boundary must guarantee prominent regional characteristics. Furthermore, the northern boundary of the tropical zone should change dynamically, rather than being a fixed line (Yu, 1986). Therefore, changes in the boundary still need further analysis and research in the context of global climate change (Wu *et al*., 2015; Wu *et al*., 2016a; Wu *et al*., 2016b).

References

Alvin P D T, Kozlowski T T, 1977. Ecophysiology of Tropical Crops. New York: Academic Press.

Bailey R G, 1983. Delineation of ecosystem regions. *Environmental Management*, 7(4): 365–373.

Bailey R G, Zoltai S C, Wiken E B, 1985. Ecological regionalization in Canada and the United States. *Geoforum*, 16(3): 265–275.

Bridges E M, 1978. World Soils. Cambridge: Cambridge University Press.

Chai H X, Zhou C H, Chen X *et al*., 2008. The new methodology of geomorphologic zonalization in Xinjiang based on geographical grid. *Geographical Research*, 27(3): 481–492. (in Chinese)

Chen C J (Chinese Academy of Sciences "China's Physical Geography" Editorial Committee), 1984. China's Physical Geography (The Fascicule of Climate). Beijing: Science Press, 151–161. (in Chinese)

Cong W Q, Pan M, Li T F, 2007. Uncertainty reasoning and its application in the slope geological hazard zonation. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 43(2): 891–302. (in Chinese)

Corlett R T, 2013. Where are the subtropics? *Biotropica*, 45(3): 273–275.

Ding Y G, Zhang Y C, Liu J F, 2007. A new cluster method for climatic classification and compartment using the conjunction between CAST and REOF. *Chinese Journal of Atmospheric Sciences*, 31(1): 129–136. (in Chinese)

Fortin M, Drapean P, 1995. Delineation of ecological boundaries: Comparisons of approaches and significance tests. *Oikos*, 72(3): 323–332.

Fu B J, Liu G H, Chen L D, 2001. Scheme of ecological regionalization in China. *Acta Ecologica Sinica*, 21(1): 1–6. (in Chinese)

Geiger R, Pohl W, 1954. Eine neue weltkarte der klimaebiete der erde. *Erdkunde*, 8(1): 58–60.

Golley F, 1983. Tropical Rain Forest Ecosystems, Structure and Functions. Amsterdam: Elsevier.

He D Z, He D, 1988. North border of tropical climate of China. *Acta Geographica Sinica*, 43(2): 176–182. (in Chinese)

Holdridge L R, 1967. Life Zone Ecology. San Jose, Costa Rica: Tropical Science Center.

Hou X Y, 1988. Chinese Vegetation Geography. Beijing: Science Press, 183–185. (in Chinese)

Hu Y, Wang J F, Li X H *et al.*, 2011. Geographical detector-based risk assessment of the under-five mortality in the 2008 Wenchuan earthquake, China. *Plos One*, 6(6): e21427.

Huang B W, 1959. A preliminary study of China's comprehensive natural regionalization. *Science Bulletin*, 9(18): 594–602. (in Chinese)

Huang B W, 1992. Study on tropical limitation of China: I. Definitions of tropical and subtropical in the world. *Scientia Geographica Sinica*, 12(2): 97–104. (in Chinese)

Huang J, Gao Y, Zhao Z Q *et al.*, 2011. Comprehensive physiographic regionalization of China using GIS and SOFM neural network. *Geographical Research*, 30(9): 1648–1659. (in Chinese)

Jing G H, 1962. Several basic questions about trying to talk about natural divisions. *Acta Geographica Sinica*,

28(3): 241–249. (in Chinese)
Köppen W, 1918. Klassifikation der klimate nach temperatur, niederschlag, und jahreslauf. *Petermanns Mitteilungen*, 64(193): 193–203.
Köppen W, 1923. Die Climate der Erde. Grundriβ der Klimakunde. Berlin: Leipzig.
Köppen W, 1936. Das geographische system der klimate. In: Köppen W, Geiger R. Handbuch der Klimatologie. Vol. 1, Part C, Berlin.
Kuang L H, Liu B C, Yao J C, 2006. Research on regionalization of debris flow risk degree with fuzzy and extension method. *Journal of Catastrophology*, 21(1): 68–72. (in Chinese)
Lauer W, 1975. Vom wesen der tropen. Klimaökologische studien zum inhalt und zur abgrenzung eines irdischen landschaftsgürtels. Akademie der wissenschaften und der literature mainz, Abhand. *Math.–Naturwiss. Klasse, Wiesbaden*, 3: 359–365.
Lauer W, Frankenberg P, 1985. Versuch einer geoökologische klassifikation der klimate. *Geographische Rundschau*, 37: 359–365.
Lauer W, Frankenberg P, 1988. Klimaklassifikation der erde. *Geographische Rundschau*, 40: 55–59.
Li S K, Wang S L, 1982. The National Agricultural Climate Zones of the Preliminary Discussion. Beijing: China Meteorological Press, 1–8. (in Chinese)
Liu P L, Liu C L, Deng Y Y *et al*., 2010. Landscape division of traditional settlement and effect elements of landscape gene in China. *Acta Geographica Sinica*, 65(12): 1496–1506. (in Chinese)
Liu W D, 1994. Land type and comprehensive physical regionalization in Jianghan Plain. *Acta Geographica Sinica*, 49(1): 73–83. (in Chinese)
Lockwood J G, 1978. Tropical climatology. *Nature*, 272(5648): 104.
Longman K A, Jenik J, 1974. Tropical Forest and Its Environment. London: Longman.
Manfred D, 2003. Climatological characteristics of the tropics in China: Climate classification schemes between German scientists and Huang Bingwei. *Journal of Geographical Sciences*, 13(3): 271–285.
Miao Q L, Li Z Y, Dou Y Z, 1988. Analysis of the major components of the climate and its demarcation in Shaanxi Province. *Geographical Research*, 7(2): 87–93. (in Chinese)
Nieuwelt S, 1977. Tropical Climatology. London: John Wiley.
Oliver J E, 1991. The history, status and future of climatic classification. *Physical Geography*, 12(3): 242–246.
Pang Q T (The Agricultural Encyclopedia of China Editorial Committee), 1986. The Agricultural Encyclopedia of China (Agricultural Meteorology Volume). Beijing: Agriculture Press, 216–217, 332–333, 377–378. (in Chinese)
Pelzer K J, Gourou P, Laborde E D, 1955. The tropical world. *Pacific Affairs*, 28(4): 383
Qiu B J, 1993a. China's tropical, subtropical, and temperate. *Journal of Henan University* (*Natural Science Edition*), 23(4): 11–12. (in Chinese)
Qiu B J, 1993b. The northern border of tropical zone in China. *Scientia Geographica Sinica*, 13(4): 297–306. (in Chinese)
Ren M E, 1962. China's approximate tropical zone. *Journal of Nanjing University* (*Geography*), 29–34. (in Chinese)
Ren M E, Zeng Z X, 1991. The extent of tropical zone in China. *Scientia Geographica Sinica*, 11(2): 101–108. (in Chinese)
Ruddle K, Manshard W, 1981. Renewable Natural Resources and the Environment. Dublin: Tycooly.
Sheng C Y (The Encyclopedia of China Publishing House Newsroom), 1987. Encyclopedia of China Publishing House (Volumes of Atmosphere Science, Ocean Science, Hydrology Science). Beijing-Shanghai: Encyclopedia of China Publishing House, 845–847. (in Chinese)
Supan A, 1879. Die temperaturezonen der erde. *Petermanns Geog. Mitt.*, 2: 349.
Tang Y L, 1964. Basis and demarcation of tropical and subtropical of China in the view point of geo-flora. *Collection of Plant Ecology and Geo-flora*, 2(1): 135–143. (in Chinese)
Terjung W H, Louie S F, 1972. Energy input–output climates of the world: A preliminary attempt. *Theoretical & Applied Climatology*, 20(2): 129–166.
Troll C, Paffen K H, 1964. Karte der jahreszeitenklimate der erde. *Erdkunde*, 18: 5–28.
Walter H, Breckle S W, 1983. Ecological Systems of the Geobiosphere. Berlin: Springer.
Wang J F, Li X H, Christakos G *et al*., 2010. Geographical detectors-based health risk assessment and its applica-

tion in the neural tube defects study of the Heshun region, China. *International Journal of Geographical Information Science*, 24(1): 107–127.

Wang J F, Hu Y, 2012. Environmental health risk detection with GeogDetector. *Environmental Modelling & Software*, 33(10): 114–115.

Wang J F, Wang Y, Zhang J *et al*., 2013. Spatiotemporal transmission and determinants of typhoid and paratyphoid fever in Hongta District, China. *PLOS Neglected Tropical Diseases*, 7(3): e2112.

Wang J F, Zhang T L, Fu B J, 2016. A measure of spatial stratified heterogeneity. *Ecological Indicators*, 67: 250–256.

Wissmann H V, 1939. Die Klima-und Vegetationsgebiete Eurasiens. Berlin: Zeitschr Ges Erdk, 1–14.

Wissmann H V, 1948. Klimagebiete der erde. In: Bluethgen J. Aligemaine Klimageographie. Berlin: Walter de Gruyter.

Wu S H, Liu W Z, Pan T *et al*., 2016b. Amplitude and velocity of the shifts in the Chinese terrestrial surface regions from 1960 to 2011. *Chinese Science Bulletin*, 61(19): 2187–2197. (in Chinese)

Wu S H, Luo Y, Wang H *et al*., 2016a. Climate change impacts and adaptation in China: Current situation and future prospect. *Chinese Science Bulletin*, 61(10): 1042–1054. (in Chinese)

Wu S H, Yin Y H, Fan J *et al*., 2010. Retrospect and prospect of regionalization system of China. *Geographical Research*, 29(09): 1538–1545. (in Chinese)

Wu S H, Zhao Y, Tang Q H *et al*., 2015. Land surface pattern study under the framework of Future Earth. *Progress in Geography*, 34(1): 10–17. (in Chinese)

Wu S H, Zheng D, 2001. Delineation of boundary between tropical/subtropical in the middle section for eco-geographic system of South China. *Journal of Geographical Sciences*, 11(1): 80–86.

Wu S H, Zheng D, 2003. Delineation of eco-geographic regional system of China. *Journal of Geographical Sciences*, 13(3): 309–315.

Xiong Y, Li Q K, 1987. China's Soil. 2nd ed. Beijing: Science Press, 15. (in Chinese)

Yang R, Liu Y S, Long H L *et al.*, 2015. Spatio-temporal characteristics of rural settlements and land use in the Bohai Rim of China. *Journal of Geographical Sciences*, 25(5): 559–572.

Yang R, Xu Q, Long H L, 2016. Spatial distribution characteristics and optimized reconstruction analysis of China's rural settlements during the process of rapid urbanization. *Journal of Rural Studies*, 47: 413–424.

Yu X F, Huang Y L, Guo E H, 1986. China's Tropical Zone. Guangzhou, Guangdong People's Publishing House. (in Chinese)

Zeng Z X, 1962. China's tropical place. *Geographic Knowledge*, (1): 12–14. (in Chinese)

Zeng Z X, Liu N W, Li G Z *et al*., 1980. The issue of China's tropical boundary. *Acta Geographica Sinica*, 35(1): 87–92. (in Chinese)

Zhang B K, 1965. Climatic Regionalization of China. Beijing: National Commission on Atlas compiled, 197–201. (in Chinese)

Zhang J M (National Agricultural Climate Regionalization Committee), 1991. Agricultural Natural Resources and Agricultural Regionalization of China. Beijing: Agriculture Press, 14–17, 46–49, 114–117. (in Chinese)

Zhao S Q (Chinese Academy of Sciences, "China's Physical Geography" Editorial Committee), 1958. China's Physical Geography (The Fascicule of Pandect). Beijing: Science Press, 187–197. (in Chinese)

Zheng D, 2008. System Research of Ecological Geographic Area in China. Beijing: The Commercial Press, 132. (in Chinese)

Zheng D, Fu X F, 1999. A preliminary study on issues of integrated geographical regionalization. *Scientia Geographica Sinica*, 19(3): 2–6. (in Chinese)

Zheng D, Yang Q Y, Wu S H, 2015. Physical Geography Pandect in China. Beijing: Science Press, 339–347. (in Chinese)

Zhong G F, Huang Y L, Liang G Z, 1990. Characteristics and regional diversity of tropical China. *Acta Geographica Sinica*, 45(2): 245–252. (in Chinese)

Zhu K Z, 1958. Subtropical area of China. *Science Bulletin*, 8(17): 524–528. (in Chinese)

Zhu K Z, 1979. Zhu Kezhen Corpus. Beijing: Science Press, 350–356. (in Chinese)

Zhu K Z, Wan M Q, 1963. Phenology. Beijing: Popular Science Press, 21. (in Chinese)