

# The effect of terrain factors on rice production: A case study in Hunan Province

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**Abstract:** Rice (*Oryza sativa* L.) is the most important staple crop of China, and its production is related to both natural condition and human activities. It is fundamental to comprehensively assess the influence of terrain conditions on rice production to ensure a steady increase in rice production. Although many studies have focused on the impact of one or several specific factors on crop production, few studies have investigated the direct influence of terrain conditions on rice production. Therefore, we selected Hunan Province, one of the major rice-producing areas in China, which exhibits complex terrain conditions, as our study area. Based on remote sensing data and statistical data, we applied spatial statistical analysis to explore the effects of terrain factors on rice production in terms of the following three aspects: the spatial patterns of paddy fields, the rice production process and the final yield. We found that 1) terrain has a significant impact on the spatial distribution of paddy fields at both the regional scale and the county scale; 2) terrain controls the distribution of temperature, sunlight and soil, and these three environmental factors consequently directly impact rice growth; 3) compared with the patterns of paddy fields and the rice production process, the influences of terrain factors on the rice yield are not as evident, with the exception of elevation; and 4) the spatial distribution of paddy fields mismatched that of production resources due to terrain factors. Our results strongly suggest that managers should scientifically guide farmers to choose suitable varieties and planting systems and allocate rice production resources in the northern plain regions to ensure food security.

**Keywords:** rice production; terrain factor; spatial distribution; rice phenology

## 1 Introduction

Rice (*Oryza sativa* L.) is the most important stable crop of China and almost 60% of Chinese

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feed on rice. Faced with the challenge of climate change, water shortages, and rapid urbanization, as the world's largest producer and consumer of rice (Bao *et al.*, 2012), China is in urgent need of a comprehensive assessment of all natural factors that influence rice growth to ensure steady increase of rice production and food security.

Previous studies have discussed the influence of different factors on rice production in China at different spatial scales (Wang *et al.*, 2006; He *et al.*, 2007; Peng *et al.*, 2009; Yu *et al.*, 2009; Wang *et al.*, 2014; Zhang *et al.*, 2015), including those of climate, soil, agricultural management, policy and so on. Most of these human or natural factors are dynamic while few studies paid attention to the influence of those stable and changeless factors on rice production, such as the terrain. As one of the most important natural geographical factors, terrain not only determines the spatial pattern of farmland but also has an indirect impact on the rice growth process through the spatial redistribution of regional water, heat and nutrients. Compared to studies performed in North America and Europe (Ciha *et al.*, 1984; Kravchenko *et al.*, 2000; Persson *et al.*, 2005), studies focusing on the impact of terrain conditions on rice production in China have mostly focused on the following two aspects. Several researchers have focused on the impact of terrain factors on the spatial distribution of farmland and investigated their dynamic changes: Qiu *et al.* (2003) explored the relationship between changes in cultivated land and terrain features in a small watershed on the Loess Plateau; Sun *et al.* (2004) described the spatial features of farmland in Yanqing County based on the terrain distribution index; and Wei *et al.* (2008) analysed the influence of terrain factors on the dynamic changes of cultivated land in the mountainous areas in northern Guangdong. Other researchers have focused on the impact of terrain on those factors related to rice production, including sunlight, heat, soil nutrients and soil water, and agricultural machinery (Huang *et al.*, 2003; Yang, 2004; Wang *et al.*, 2007; Zhou *et al.*, 2013). However, there are still some deficiencies in these two types of studies: the first kind of study is essentially concerned with the impact of terrain conditions on regional land-use changes as well as the regional spatial distribution of land cover when farmland is just a type of land use; the second type of study focuses on the impact of terrain conditions on natural or human factors, which are associated with rice production, but they lack analyses of the impact of terrain on the factors that directly reflect rice growth conditions, such as the phenology of rice and rice yield. Considering that rice production is a type of agro-economic system, based on the classic economy theory of pattern to process, we attempted to analyse the impact of terrain on the spatial distribution of rice production, rice growth and the final yield. We aimed to provide a comprehensive assessment of the relationship between terrain conditions and rice production. This research can help us deepen our understanding of the association between terrain and agro-economic systems. Moreover, this study can also offer useful information to provide a comprehensive assessment of regional agricultural patterns and optimize the layout of crop planting.

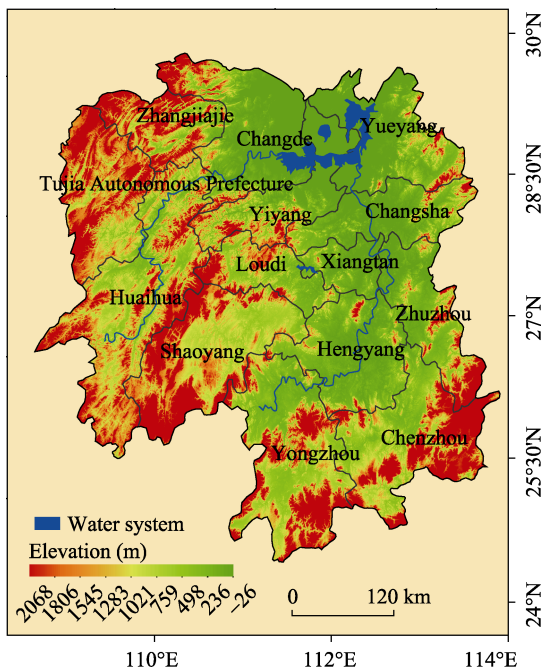
As one of the major rice-producing provinces in China, Hunan contributes more than 10% of the rice yield of China. Compared with another major rice production region, Northeast China, the terrain conditions are much more complex in Hunan Province; therefore, they are more closely associated with rice production. Thus, using multi-source data, we applied different methods to investigate the association between terrain conditions and rice production, including the impact of terrain factors on the spatial distributions of paddy fields, rice growth and final yields.

## 2 Study area and methodology

### 2.1 Study area

Hunan Province is located between 108°47'E–114°15'E and 24°38'N–30°08'N, and it contains 13 municipal administrative units (Figure 1). The terrain of Hunan Province is relatively complex: mountains surround the western, eastern and southern parts of this province, low hills are located in the central, while plains are found in the northern. Generally, the topographic terrain of Hunan is high in the west and south and low in the east and north, creating a horse-shoe-like pattern.

The climate of Hunan is subtropical. The temperature is sufficient for rice growth, and the humidity is moderate. In addition, the river network is dense, and water resources are also abundant. Therefore, Hunan is very suitable for rice cultivation, especially for double-cropping rice. According to a report of the National Bureau of Statistics, over the past 10 years, the double-cropping rice yield accounted for more than one-fifth of the national yield.



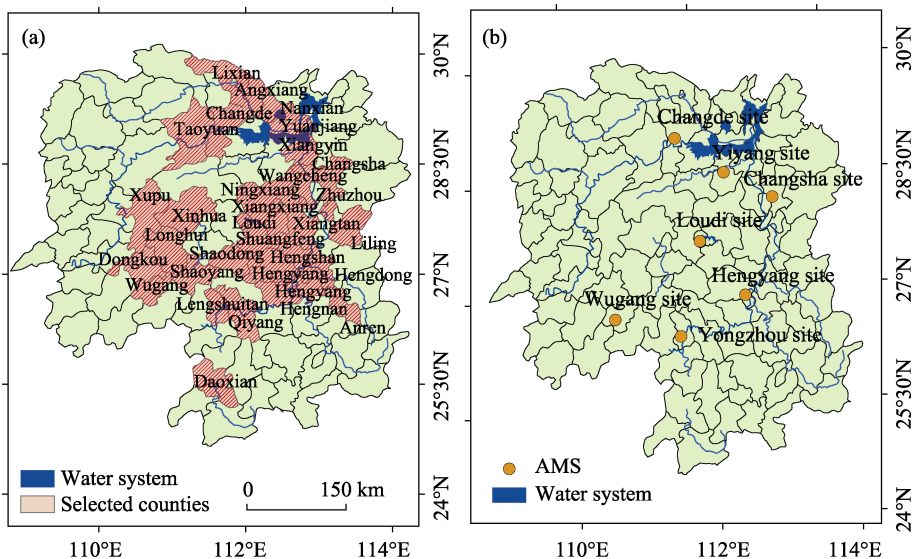
**Figure 1** The location of Hunan Province in China and its terrain

### 2.2 Datasets

In this study, the revised Advanced Space borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) Version 2 was used to extract various terrain factors. The spatial resolution of the GDEM is 30 metres. The paddy field raster of Hunan Province was extracted based on the 100-m resolution land use data of 2010 (Liu *et al.*, 2014). Moreover, to investigate the relationship between terrain factors and the environmental factors of rice growth, we obtained the spatial distribution of soils in Hunan Province based on the 1:1,000,000 soil map of China (NSSO, 1995), and we calculated the daily average temperature and sunlight from 2010–2012 based on the 0.25-degree daily meteorological grid data (Yuan *et al.*, 2015). Given that Hunan is an irrigated area, our research did not take rainfall into consideration.

There are 102 county-level administrative units in Hunan Province. We collected rice yield data for each county based on the website of China Planting Information (<http://202.127.42.157/moazzys/>) and the China Rural Statistical Yearbook of Hunan (Department of Rural Survey, NBS, 2011–2013). However, data at the county level were difficult to access; finally, only the yield data from 2011 to 2013 for 33 counties were available. The spatial distributions of the selected counties are shown in Figure 2a. During this process,

we obtained the yield of each county by calculating the average per unit area yield of three years. Information about rice phenology came from the agricultural meteorological sites (AMS) of the China Meteorological Administration National Meteorological Information Center. Considering that it represents the dominant style of rice production in Hunan, double-cropping rice was the only focus of this study. Figure 2b shows the spatial distribution of AMS.



**Figure 2** Spatial distribution of selected counties and agricultural meteorological stations in Hunan Province

The rice phenology recorded by the AMS included 10 stages: emerge, trefoil, transplant, green-up, tillering, jointing, booting, heading, milk-ripe and mature. Among these stages, transplanting, tillering, heading and mature are the four most important stages. Transplanting is the stage when rice is planted in the paddy fields; tillering is the most prosperous period of rice vegetative growth; heading is the stage when the rice transits from vegetative growth to reproductive growth; and mature is the stage of rice seeding and harvesting. Therefore, we focused on these four most important phenological stages of rice. Due to the different emergence dates of different areas in Hunan, in this study, the dates of transplanting, tillering, heading and mature stages are relative dates: we subtracted their corresponding emergence dates from these four actual dates. Moreover, to mitigate the adverse impact of differences in rice varieties, we used the record of indica hybrid rice data from 2010 to 2012 at each agricultural meteorological site. Meanwhile, to eliminate the impact of the use of different cropping systems on different rice varieties, we selected records from the same cropping system (i.e., all the early maturing varieties or medium maturing varieties in these three years) at each site and calculated their average value to reflect the phenological information for each site. Table 1 shows the phenological information of the double-cropping rice obtained at some sites.

**2.3 Methodology**

**2.3.1 Selection and extraction of terrain factors**

To effectively describe the terrain features, we used the factors of altitude, slope, slope as-

pect, surface relief degree, surface roughness and slope position. Altitude and slope are the two basic terrain factors that form the basic skeleton of the surface. The slope aspect has a direct impact on the sunlight that the crop receives.

**Table 1** Some records of double cropping rice phenological information in Hunan Province

Site	Cropping system	Transplant	Tillering	Heading	Mature	Tillering-transplant	Heading-tillering	Mature-heading
Changde	Early rice	33	52	103	133	15	51	30
	Late rice	31	44	86	121	13	42	34
Hengyang	Early rice	32	44	85	116	12	41	31
	Late rice	22	31	75	114	9	44	40
Wugang	Early rice	28	53	93	112	17	40	29
	Late rice	32	42	73	110	11	31	37

The degree of surface relief is the indicator that describes the regional relative elevation and influences the spatial distribution of surface nutrients. The formula of the surface relief degree is as follows:

$$RF_i = H_{\max} - H_{\min} \tag{1}$$

where  $RF_i$  represents the relative difference in elevation within the window where the  $i$ -th raster is the centre.  $H_{\max}$  and  $H_{\min}$  are the maximum and minimum values of altitude, respectively, within this window. According to previous studies and the terrain features of our study region (Zhang *et al.*, 2012), we selected 59\*59 as the size of the calculated window to obtain the surface relief degree.

Surface roughness is an indicator that reflects the complexity and erosion of the surface (Jia *et al.*, 2013; Tang *et al.*, 2006). It represents the degree of surface fragmentation and is calculated using the following formula:

$$M = 1 / \cos(\theta * \pi / 180) \tag{2}$$

where  $\theta$  represents the slope.

Slope position is an indicator that measures the location of a target point in the vertical profile of a given terrain. Additionally, the slope position can influence the spatial pattern of soil nutrients. We obtained the slope position based on the Topographic Position Index (TPI). The principle of the TPI is to calculate the difference between the altitude of a target point and that of its neighbour and then classify the slope position based on this difference. The formula of the TPI is as follows:

$$TPI = Z - Z^* \tag{3}$$

where  $Z$  represents the altitude of the target point, while  $Z^*$  represents the altitude of the neighbouring area. It can be observed that TPI is scale-dependent. Therefore, based on previous research, we chose 11\*11 as the size of the calculated window and obtained the TPI of Hunan. Based on the TPI and slope of the target point,

**Table 2** Classification criterion of slope position

Types	Classification criterion
Ridge	$TPI > 1 \text{ SD}$
Up-hill	$0.5 \text{ SD} < TPI \leq 1 \text{ SD}$
Mid-hill	$-0.5 \text{ SD} < TPI < 0.5 \text{ SD}$ , Slope $> 5^\circ$
Flat	$-0.5 \text{ SD} < TPI < 0.5 \text{ SD}$ , Slope $\leq 5^\circ$
Down-hill	$-1 \text{ SD} < TPI \leq -0.5 \text{ SD}$
Valley	$TPI < -1.0 \text{ SD}$

we obtained the slope position of Hunan. The classification criterion of slope position based on the TPI and slope is shown in Table 2 (Weiss, 2001; Gong, 2015).

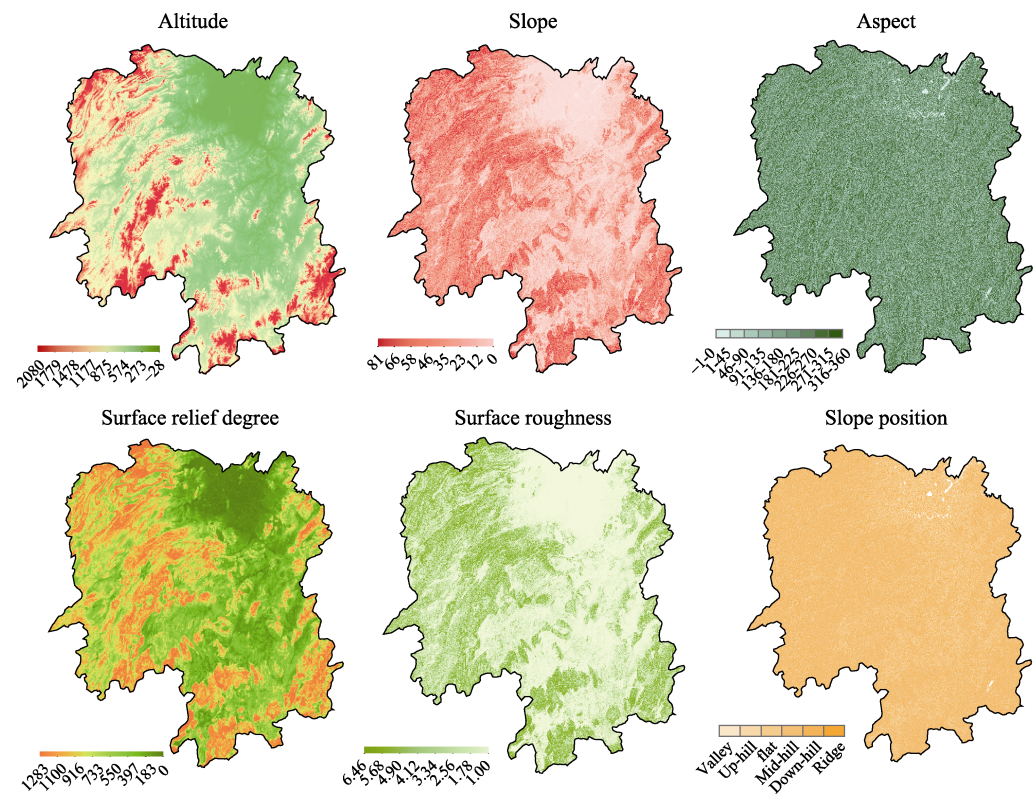


Figure 3 Terrain factors of Hunan Province

Figure 3 shows the 6 terrain factors of Hunan Province. Previous studies have demonstrated that the extraction of terrain factors is scale-dependent (Tang, 2014). It has been well acknowledged that the altitude and slope establish the framework of the surface and its landforms (Zhou and Liu, 2006). Meanwhile, the slope is relatively sensitive to changes in resolution (Tang *et al.*, 2003; Yang *et al.*, 2013). Thus, we selected 8 typical sample areas in Hunan Province, including all geomorphic types (plains, tablelands, hills and mountains), and we resampled the DEM with a 30 m resolution to 50 m, 70 m, 90 m and 110 m; then, we calculated the altitude and slope in those 8 sample areas. We performed this analysis to investigate whether the effect of scale can influence the extraction of terrain factors.

2.3.2 Research on the relationship between terrain factors and distribution of paddy fields

The spatial distribution of paddy fields is the basis of rice production; thus, we investigated the impact of terrain factors on the paddy fields at both county level and provincial level.

At the province scale, we used the terrain distribution index (TDI) to compare differences in the distribution of paddy fields at different terrain levels. The formula of the TDI is as follows (Sun *et al.*, 2004):

$$P = \left( \frac{S_{paddy\ e}}{S_{paddy}} \right) / \left( \frac{S_e}{S} \right) \tag{4}$$

where  $P$  represents the TDI, which is a standardized and dimensionless index;  $e$  represents a type of terrain factor, such as slope or the surface relief degree.  $S_{paddy\ e}$  represents the area of the paddy fields at a level of terrain factor  $e$ .  $S_{paddy}$  is the total area of paddy fields.  $S_e$  represents the total area of a terrain factor at a given level.  $S$  is the total area of the region. A  $P$  value of larger than 1 indicates that the distribution of paddy fields at a class of terrain factor  $e$  has an advantageous position. A larger  $P$  value means that more paddy fields are distributed at this terrain level. Based on previous studies (Liang *et al.*, 2010) and the characteristics of rice production in Hunan, we classified the altitude of Hunan into 13 levels; altitudes of higher than 1200 m and lower than 100 m are divided into two levels, respectively, and the altitudes ranging from 100 m to 1200 m are divided into a level every 100 metres. Similarly, we also divided the slope into 13 levels: one level comprises slopes of larger than 36 degrees, and slopes of less than 36 degrees are divided into a new level every 3 degrees. Because no studies have classified the surface relief degree and surface roughness, we applied quantile to classify the surface relief degree and surface roughness, which were also divided into 13 levels. In contrast to the four abovementioned terrain factors, we classified slope aspects into five levels (flat, ubac, semi-ubac, adret and semi-adret), and we classified slope positions into six levels (valley, uphill, flat, mid-hill, downhill and ridge). We argue that this classification can clearly describe the redistribution of radiation and soil nutrients, such as nitrogen.

At the county level, to compare the number of paddy fields in different counties, we used the ratio of paddy field areas in a county to the entire county area ( $R_{PF}$ ) as an indicator to evaluate the amount of paddy fields. We obtained the average values of terrain factors from 102 counties in Hunan Province and calculated the correlation coefficients between the  $R_{PF}$  values and different terrain factors. Then, we selected terrain factors with correlation coefficients of greater than 0.5 to perform spatial statistics. Notably, because the slope aspects and slope position cannot be quantified, only altitude, slope, surface relief degree and surface roughness were used in this analysis at the county level.

We used the classical Moran's  $I$  and Getis-Ord  $G_i^*$  (Getis *et al.*, 1992; Jin and Lu, 2009) to investigate the global spatial patterns of terrain factors and  $R_{PF}$ , and we also obtained hotspot maps. First, we calculated the Moran's  $I$  of terrain factors and  $R_{PF}$  to measure the spatial autocorrelation; then, we calculated the Getis-Ord  $G_i^*$  to map the hot and cold spots at different locations in Hunan.

### 2.3.3 Research on the relationship between terrain factors and rice growth

Investigating the relationship between terrain factors and rice growth can be divided into two steps. First, we explored the association between the terrain factors and environmental factors of rice growth. Based on the daily average temperature and duration of sunlight, we calculated the accumulated temperature ( $A_T$ ) and accumulated sunlight ( $A_S$ ) during the rice growth period (from April to the end of October) of each grid and then mapped the spatial distribution of the  $A_T$  and  $A_S$  values of Hunan Province. Moreover, we mapped the soil spatial distribution of Hunan Province based on the 1:1,000,000 soil dataset of China. Finally, we could analyse the impact of terrain factors on the environmental factors of rice growth by comparing the spatial distribution of the meteorological factors, soil, paddy fields and altitude of Hunan.

In the second step, we used the phenology of rice as a direct indicator to reflect the rice



growth process and investigated the impact of terrain factors on the length of the rice growth period. We performed a correlation analysis on the terrain information and phenological information of double-cropping rice at the site scale and then selected the significantly correlated terrain factors to perform a stepwise regression with the corresponding phenological information.

2.3.4 Research on the relationship between terrain factors and rice yield

Similar to the methods used in section 2.3.2, to analyse the relationship between terrain factors and paddy fields at the county level, we first applied the correlation analysis between the per unit rice yield and the mean values of terrain factors of each county and then calculated the Moran’s I and Getis-Ord Gi\* values of both the terrain factors and yield. Finally, we obtained the spatial patterns of the yield and terrain factors. Notably, when we established the relationship between terrain factors and yield, data from only 33 counties were included.

3 Results

3.1 Effect of scale on the extraction of terrain factors

Table 3 shows the average slope and average altitude extracted from the DEMs with different resolutions. The observed effect of scale on terrain factors differs between different regions: with decreasing resolution, the average slope and average altitude decrease significantly in plains and tablelands; in steep mountainous areas, this decrease is more obvious. This result is consistent with many previous studies (Niu, 2010; Gong, 2015). However, in hilly areas, such as Changning County and Yongxing County, the average slope increases with decreasing resolution. As the resolution becomes coarser, the slope value become lower. In addition, this made the steepest areas flat so that the average slope in those sub-steep areas increased. Chen *et al.* (2006) also observed a similar phenomenon where, with the

Table 3 Effect of different resolutions of DEM on the extraction of terrain factors

a. Average slope extracted from DEM with different resolutions								
DEM resolution	Plain		Tableland		Hill		Mountain	
	Xiangyin	Yuanjiang	Changsha	Zhuzhou	Changning	Yongxing	Dong'an	Shuangpai
30	2.14	1.29	5.83	7.35	10.15	11.38	13.85	22.79
50	2.13	1.29	5.83	7.34	10.15	11.37	13.85	22.79
70	2.13	1.29	5.82	7.33	10.16	11.37	13.86	22.79
90	2.09	1.27	5.81	7.33	10.20	11.38	13.83	21.09
110	2.03	1.19	5.76	7.28	10.24	11.39	13.82	18.73
b. Average altitude extracted from DEM with different resolutions								
DEM resolution	Plain		Tableland		Hill		Mountain	
	Xiangyin	Yuanjiang	Changsha	Zhuzhou	Changning	Yongxing	Dong'an	Shuangpai
30	32.71	29.14	77.52	94.25	195.60	245.63	549.14	389.59
50	32.70	29.14	77.51	94.22	195.01	245.56	549.09	389.76
70	32.70	29.14	77.50	94.13	195.00	245.46	548.91	390.20
90	32.70	29.14	77.52	94.09	194.26	245.46	548.74	390.76
110	32.70	29.14	77.51	94.10	194.24	245.50	548.70	390.53



decreasing resolution of DEM, areas with slopes ranging from 8 to 15 degrees also increased. Admittedly, different scales of DEM showed some impact on the slope and altitude, but it is also evident from Table 3 that the changes in both altitude and slope are not as obvious in the plains and tablelands, where paddy fields are more widespread. Thus, the GDEM with a resolution of 30 m used in this study is sufficiently accurate to ensure the reliability of the extraction of terrain factors.

3.2 The relationship between terrain factors and the spatial distribution of paddy fields

3.2.1 Spatial pattern of paddy field distribution at the provincial level

Figure 4 shows the terrain distribution index (TDI) values of paddy fields in Hunan Province at different levels. Figure 4a reveals that the distribution index (DI) of paddy fields is greater than 1 in areas with altitudes of less than 200 m and that the DI is close to 1 in areas with altitudes ranging from 200 m to 300 m. As the altitude increases, the DI decreases; in those areas above 900 m, the DI is close to zero. This change in DI reflects that most of the paddy fields are distributed below 300 m; at altitudes of greater than 900 m, there are few paddy fields in Hunan. When the altitude ranges from 300 m to 900 m, paddy fields are sparsely distributed. This spatial distribution of paddy fields is consistent with the distribution of farming activities in Hunan. Figure 4b shows the DI values of paddy fields with different slopes. It is clear that the DI is greater than 1 in areas where the slope is less than 9 degrees. As the slope increases, the DI tends to zero. No paddy fields appear to be distributed in areas

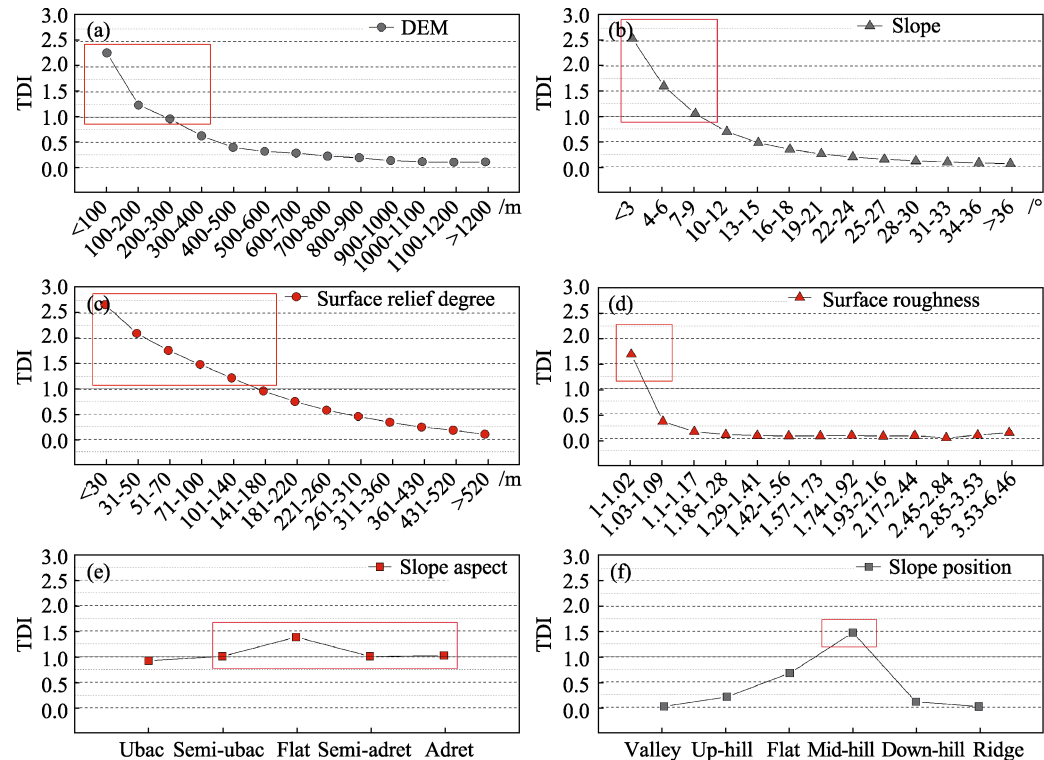


Figure 4 Terrain distribution index values of rice paddy fields in Hunan Province

with slopes of greater than 24 degrees. Figure 4c shows that the DI of a paddy field is greater than 1 if the surface relief degree is less than 140 m. Similar to the altitude and slope, with increasing surface relief, the DI decreases; if the surface relief degree is more than 400 m, the DI tends to zero. However, the DI seems to be sensitive to surface roughness: if the surface roughness is greater than 1.02, the areas of paddy fields decrease sharply, and if the surface roughness is greater than 1.1, the DI tends to zero. Surface roughness reflects complexity and erosion. The greater the surface roughness value, the more complex and eroded the surface is. Terrain factors have been viewed as the driving force of soil nutrients (Zhang *et al.*, 2010; Zhan, 2009). Too much roughness could lead to soil erosion in these areas, thus causing decreases in the soil nutrients in these paddy fields. Therefore, roughness is a considerable terrain factor that may limit the distribution of paddy fields. Figure 4e shows the DI values associated with different slope aspects. It can be observed that the paddy fields in flat areas are more widespread. Additionally, it is worth noting that the DI values of the other four types of slope aspects, such as adret slope, are all near 1.0; additionally, the DI values of flat areas tend to be 1.5, which indicates that the distribution of paddy fields is not sensitive to changes in slope aspects. Previous studies have also pointed out that the impact of slope aspects is not significant for the spatial distribution of soil nutrients (Zhang *et al.*, 2008), which adequately explains the low dependence of paddy fields on slope aspects. Figure 4f shows the relationship between the distribution of paddy fields and different slope positions. It can be observed that most paddy fields are distributed in mid-hill and flat regions due to their abundant water and heat resources, which can benefit rice production.

3.2.2 Effect of scale on the extraction of terrain factors

Table 4 shows the correlation coefficients between different terrain factors and the ratio of paddy fields to county areas ( $R_{PF}$ ). We observed clear negative correlations between the  $R_{PF}$  values and all four terrain factors.

**Table 4** Correlation between terrain factors and ratios of paddy field areas to entire county areas

	Terrain factors	Altitude	Slope	Relief degree	Surface roughness
$R_{PF}$	Pearson coefficient	−0.782	−0.85	−0.811	−0.783
	P-value	<0.01	<0.01	<0.01	<0.01

$R_{PF}$ : Ratio of paddy field areas in a county to whole county areas

It can be observed from Table 5 that the values of the Moran’s I of  $R_{PF}$  and the four terrain factors are all greater than 0 and their standard Z scores are greater than 2.58, which is the threshold value of the corresponding standard Z score (99% Confidence Interval). This reflects that both  $R_{PF}$  and the chosen four terrain factors of Hunan Province exhibit significant spatial autocorrelation, which means that the distribution patterns of all these factors represent spatial clusters.

**Table 5** Estimates of global Moran’s I and their tests for terrain factors and ratios of the paddy field area to total area at the county level

	$R_{PF}$	Altitude	Slope aspects	Relief degree	Surface roughness
Moran’ I	0.67	0.71	0.7	0.67	0.66
Z-score	10.64	11.27	10.94	10.47	10.39
P-value	<0.01	<0.01	<0.01	<0.01	<0.01
Z-score threshold	2.58	2.58	2.58	2.58	2.58

We mapped the spatial hotspots of the  $R_{PF}$  and four terrain factors at the county level (Figure 5). We found that the spatial distributions of the hotspots of all those terrain factors are almost the same and that they are consistent with the spatial distribution of cold spots of  $R_{PF}$ . In other words, there seemed to be a negative spatial relationship between the distribution of  $R_{PF}$  and terrain factors. There were evident hotspots of paddy fields in northern and central Hunan, which means that there were high  $R_{PF}$  values in these counties and their adjacent counties; cold spots were commonly located in west, southwest and southeast Hunan. The terrain condition exhibits the opposite spatial pattern: hotspots were aggregated in west, southwest and southeast Hunan, while cold spots were located in the northern and central parts. Additionally, although the hotspots of altitude are not as obvious in western Hunan, such as Sangzhi, Yongshun and Baojing counties, there are obvious hotspots of slope and relief in this area. This implies that the complexity of terrain conditions in west Hunan cannot be entirely ascribed to its high altitude. Similarly, although some counties in south Hunan, such as Dong'an County, have high altitudes, some paddy fields are located in these areas because the slope and degree of relief are not as high. Thus, even though the spatial distribution between paddy fields and terrain factors in Hunan Province showed a negative correlative tendency, there are still some abnormal areas in the mountainous areas of west and south Hunan.

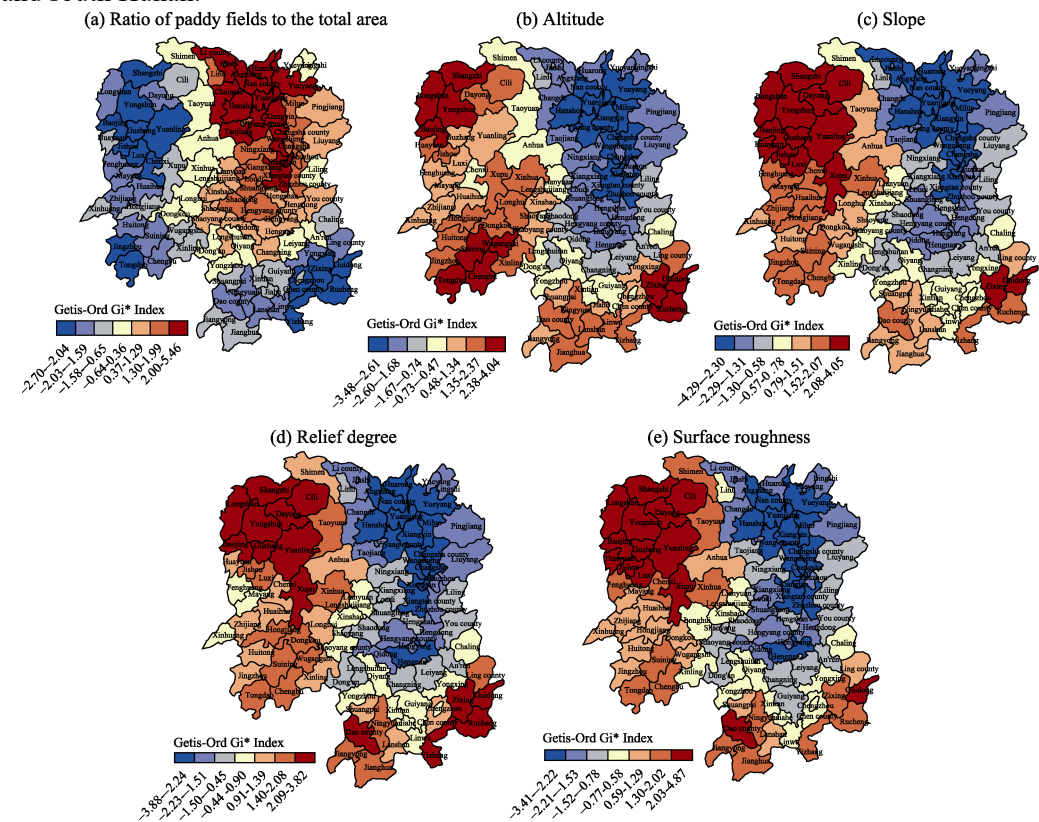
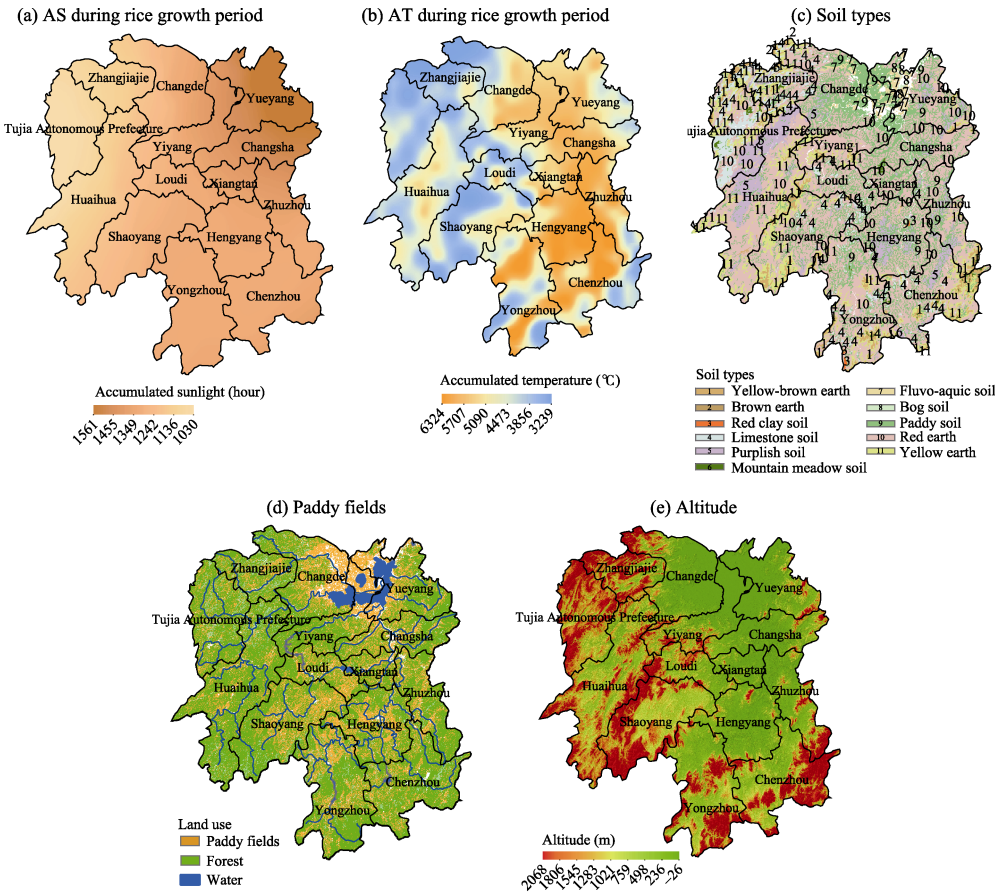


Figure 5 Hotspot map of ratio of paddy fields to total county area and of terrain factors

3.3 The relationship between terrain factors and rice growth process

3.3.1 Effect of terrain factors on environmental factors of rice growth

Based on the daily meteorological grid data and soil data, we mapped the spatial distribution of the environmental factors of rice growth. From Figure 6a, we found that the accumulated sunlight during the growing period ( $AS_g$ ) of rice decreased from the Dongting Lake plain to its surrounding areas, which was similar to the spatial distribution of altitude in Hunan. Comparison of Figure 6b with Figure 6c revealed that the spatial pattern of accumulated temperature during the growing period ( $AT_g$ ) is almost the same as its spatial distribution in the northern plain and southern hills. This demonstrates that the terrain condition can determine the spatial distribution of heat. Based on the information obtained from the spatial distribution of soil (Figure 6c) and paddy fields (Figure 6d) in Hunan Province, we found that fluvo-aquic soils and paddy soils are mainly distributed in the Dongting Lake plain in northern Hunan. In the central and southern parts, i.e., tableland areas, the soil types comprised red earth and paddy soil. Brown earth, yellow-brown earth, limestone soil and minor purplish soils are distributed in the hills of southern Hunan. In the mountainous areas of west Hunan, there are yellow earth, brown earth and limestone soil, but few paddy soils. Hence, terrain factors can influence the rice growth process through the spatial distribution of meteorological factors and soil types.



**Figure 6** Spatial distribution of environmental factors of rice growth and terrain factors in Hunan Province

### 3.3.2 Effect of terrain factors on rice phenology

According to the phenological information of double-cropping rice at the site level, we cal-

culated the correlation coefficients between phenology and the four terrain factors. The results of early rice are shown in Table 6. It was observed that the transplanting stage and altitude are negatively correlated, which means that the higher the altitude is, the shorter the transplanting stage. Moreover, there is also a negative correlation between the tillering stage and slope as well as surface roughness. In other words, the steeper the surface is, the shorter the tillering stage.

**Table 6** Correlation between terrain factors and early rice phenology

Stages of early rice phenology	Altitude	Slope	Relief degree	Surface roughness
Transplanting	−0.75**	−0.10	−0.31	−0.13
Tillering	0.00	−0.69**	−0.33	−0.64**
Heading	0.42	−0.67	0.30	−0.55
Mature	0.45	−0.35	0.43	−0.18
Tillering-transplanting	−0.05	−0.38	−0.25	−0.42
Heading-tillering	0.43	−0.08	0.58	0.00
Mature-heading	0.23	0.37	0.40	0.53

Note: In this table, symbol ‘\*\*\*’ represents the correlation coefficient that passes the 95% confidence interval test; symbol ‘\*\*’ represents the correlation coefficient that passes the 90% confidence interval test. Moreover, phenological stages such as transplanting, tillering and so on are a relative length of phenology: we used the date of this phenological stage to subtract the date of the emerge stage. The ‘Tillering-transplant’, ‘Heading-tillering’ and ‘Mature-heading’ represent the length between two phenology stages.

We modelled the relationship between the transplanting stage and latitude and the relationship between the tillering stage and slope and roughness using stepwise regression to investigate whether terrain factors can influence the change in early rice phenology. We obtained the following regression equation between the transplanting stage and altitude:

$$y_{transplant} = -0.023 * x_{altitude} + 36.835 \quad (1)$$

The R-square value of this equation is 0.57; in other words, altitude can account for almost 60% of the change in the transplanting stage of early rice. This equation also demonstrates that as the altitude decreases, the transplanting stage may be prolonged. However, the R-square of the equation of the tillering stage and slope or roughness was 0.39, which means that although the slope and roughness are correlated with the tillering of early rice, it is not substantial enough to explain this change.

Table 7 displays the correlation between terrain factors and late rice phenology. It can be

**Table 7** Correlation between terrain factors and late rice phenology

Stages of late rice phenology	Altitude	Slope	Relief degree	Surface roughness
Transplant	−0.15	0.07	−0.16	0.15
Tillering	−0.21	−0.04	−0.19	0.08
Heading	−0.64**	−0.09	−0.54	−0.13
Mature	−0.77**	0.05	−0.37	0.01
Tillering-transplant	−0.21	−0.23	−0.13	−0.10
Heading-tillering	−0.67**	−0.08	−0.55	−0.25
Mature-heading	−0.67**	0.24	0.03	0.22

Note: In this table, symbol ‘\*\*\*’ represents the correlation coefficient that passes the 95% confidence interval test; symbol ‘\*\*’ represents the correlation coefficient that passes the 90% confidence interval test. Moreover, phenological stages such as transplanting, tillering and so on are a relative length of phenology: we used the date of this phenological stage to subtract the date of the emerge stage. The ‘Tillering-transplanting’, ‘Heading-tillering’ and ‘Mature-heading’ represent the length between two phenological stages.

observed that only altitude is related to phenology, and it has a negative correlation with the heading stage and mature stage. Similarly, the length between heading and tillering as well as the length between mature and heading are also negatively correlated with altitude. This means that with increasing altitude, the heading stage and mature stage will shift to earlier dates, and both the length between heading and tillering and the length between mature and heading may decrease.

Based on the results of correlation analysis, we used two phenological stages and two stage gaps of early rice as dependent variables, and we used altitude as an independent variable to establish the regression equations. We found that it is hard for altitude to account for the change in the heading stage of late rice and the length between heading and tillering because the R-squares of these two regression equations were 0.398 and 0.342, respectively. However, the altitude can sufficiently explain the change in the mature stage and the length between the heading stage and mature stage using the following equations:

$$y_{mature} = -0.07 * x_{altitude} + 129.81 \tag{2}$$

$$y_{heading-mature} = -0.028 * x_{altitude} + 41.65 \tag{3}$$

The R-square values of these two equations are 0.59 and 0.55, respectively, which reflects that the altitude had an impact on the change from mature to late rice as well as the length of the gap between the mature and heading stages.

To sum up, the slope, surface roughness and altitude are all related to the phenology of rice; of these variables, altitude shows the closest relationship with the phenology. For early rice, the altitude affects the transplanting stage: with increasing altitude, the transplanting date will occur earlier. For the late rice, the altitude can influence the mature stage and the length of the gap between the mature date and the heading date: with increasing altitude, the mature date will occur earlier and the length between the heading and mature dates will shorten.

3.4 The relationship between terrain factors and rice yield

Based on the rice yield of 33 counties from 2010 to 2012 in Hunan Province, we calculated the correlations between terrain factors and the final yield. Table 8 shows that there is a significant negative correlation between yield and the altitude, relief degree and surface roughness, while the correlation between the yield and slope is not significant. In these three factors, the correlation coefficient is only strong between altitude and yield (−0.584 95% CI). In summary, compared with the relationship between terrain conditions and the distribution of paddy fields or rice growth, although there was a relationship between terrain factors and rice yield, it was relatively weaker.

Table 8 Correlation between terrain factors and rice yield

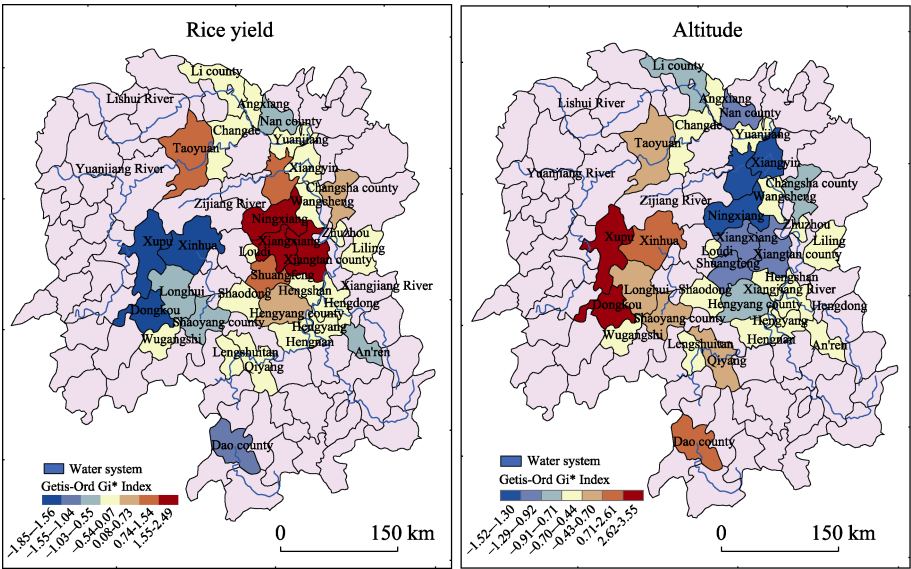
		Altitude	Slope	Relief degree	Surface roughness
Yield per unit area	Pearson coefficient	−0.584	−0.312	−0.381	−0.382
	P-value	<0.05	>0.1	<0.1	<0.1

Table 9 and Figure 7 reveal the characteristics of the spatial pattern of rice yield and terrain factors. It was observed that the Moran’s I of both altitude and yield was greater than zero, and their standard Z scores were above the threshold. This means that the rice yields of

33 counties and altitude exhibit spatial clustering. Figure 7 further shows the map of the spatial hotspots of the yield and altitude. Generally, the distribution of hotspots of yield matched the cold spots of altitude. However, this match is not as consistent. In the areas around Dongting Lake, such as Nanxian, Xiangyin and Yiyang counties, although the altitude is low, these areas also contain the cold spots of yield. Moreover, while Taoyuan County is located in an area of altitude hotspots, i.e., the transition zone between the hills of central Hunan and the mountains of west Hunan, it is also an area of yield hotspots. This phenomenon demonstrates that even though terrain factors can impact the spatial patterns of rice yield, the influences of other factors appear to be more important.

**Table 9** Estimates of global Moran's I and their tests for terrain factors and rice yield at the county level

	Rice yield	Altitude
Moran' I	0.54	0.83
Z-Score	2.27	3.37
P-value	<0.05	<0.01
Z-score threshold	1.96	2.58



**Figure 7** Hotspot map of rice yield at the county level and hotspot map of elevation

## 4 Discussion

### 4.1 Impact of terrain factors on the spatial pattern of paddy fields in Hunan Province

Terrain factors exhibit obvious impacts on the spatial distribution of paddy fields in Hunan Province at both the province scale and the county scale. At the provincial level, we found that most paddy fields were distributed in the northern plains and central hills, where the altitude is below 300 m, the slope is less than 9 degrees and the relief is less than 140 m. Additionally, most paddy fields are located in flat areas. Meanwhile, we found that the distribution of paddy fields is not sensitive to the slope position and roughness. Although some studies have shown that the vegetation in Hunan Province is influenced by the slope aspect (Wang *et al.*, 2004), our results demonstrated that rice production is not related to the slope aspect because the spatial anisotropy of soil nutrients resulting from slope aspects can be



reduced by agricultural management measures (Zhang *et al.*, 2015). At the county level,  $R_{PF}$  is negatively correlated with the altitude, slope, relief degree and surface roughness. Moreover, both the  $R_{PF}$  and these terrain factors exhibit spatial autocorrelation. The spatial pattern of  $R_{PF}$  also shows a negative relationship with the spatial patterns of these terrain factors.

#### **4.2 Impact of terrain factors on the environmental factors of rice growth in Hunan Province**

Rice is a short-day crop that prefers a warm and humid environment. Because transplanting is the main method of cultivation in rice production in Hunan, rice growth does not lack water; thus, temperature and sunlight are the two direct environmental factors affecting rice production. It can be observed that terrain conditions can directly influence the spatial distributions of temperature and sunlight: the spatial distributions of  $A_T$  and  $A_S$  are similar to the spatial pattern of altitude in Hunan Province. Although the flat Dongting Plain in northern Hunan is very suitable for rice cultivation, the temperature conditions are better in the central and eastern parts of Hunan, such as Changsha, Xiangtan, Zhuzhou and Hengyang. Previous studies have pointed out that the rice yields per unit in Xiangtan and Zhuzhou were higher than those in Changde and Yueyang of northern Hunan (Qing *et al.*, 2007). Meanwhile, some other environmental factors were also nonnegligible for rice production. For example, Huaihua, a city located in the hilly area of western Hunan, has the basic conditions for double-cropping rice growth, but there are few double-cropping rice areas distributed in this region, where the average altitude ranges from 400 m to 800 m and the  $A_T$  during the growth period is over 5000 degrees Celsius. This is because the basic soils in this area are purplish soil and yellow-brown earth. Compared to the red earth and paddy soil that are more beneficial to rice growth (Xi, 1994), the parent material of purplish soil is relatively loose, which indicates that terraced fields should be built to plant rice here. In summary, terrain factors can determine the spatial patterns of some environmental factors and thus indirectly influence rice growth.

#### **4.3 Impact of terrain factors on the phenology of rice in Hunan Province**

Compared with the environmental factors of rice growth, such as meteorological conditions and soil types, the phenology of rice can directly reflect the process of rice growth. Our results show that the altitude, slope and surface roughness are related to the phenology of double-cropping rice. Among these factors, altitude may influence the transplanting stage of early rice, mature stage of late rice and the interval between the heading and mature stages. For early rice in high-altitude areas, if the transplant date is late, it is difficult to harvest rice and to transplant late rice due to the limited heat. Thus, the higher the altitude is, the earlier the transplanting stage. Furthermore, altitude also impacts the mature stage of late rice. Because of the low temperature, the harvesting stage in hilly and mountainous areas are often earlier than that in plains. This can avoid a short interval between the heading stage and mature stage and insufficient grain-filling (Liu *et al.*, 2012), which also suggests that the per unit area rice yield is relatively lower in high-altitude areas.

#### **4.4 Impact of terrain factors on rice yield**

Compared with the impact of terrain factors on paddy field distribution and rice phenology,

the impact of terrain factors on the final yield is not as significant. Only altitude has a negative correlation with the rice yield. Similar to the spatial distribution of paddy fields, the spatial pattern of rice yield also shows a clustering feature and has a negative correlation with the spatial pattern of altitude. However, when we compared the spatial distribution of yield to the spatial pattern of altitude, we found some abnormal areas: the areas where the yield per unit area is the highest are often distributed in areas where paddy fields are the next-densest and the altitude is moderate (such as Ningxiang County, Xiangxiang County and Taoyuan County). This phenomenon can be ascribed to the better conditions of temperature and sunlight and agricultural management compared to the plains in northern Hunan (e.g., Dongting Lake Plain). Based on the spatial patterns of paddy fields and environmental factors of rice, we argued that the problem with rice production in Hunan Province is the spatial mismatch in the distribution of paddy fields and the per unit area rice yield: although paddy fields are distributed very densely in the northern plains of Hunan around Dongting Lake, the per unit area rice yield in this area is lower than that in eastern and central Hunan due to the spatial distribution of heat. This impedes efficient and scale rice production in Hunan Province. Hence, in the northern plains of Hunan, it is necessary to select spring-cold-tolerant early rice varieties as well as autumn-cold-tolerant late rice varieties and to implement more management measures to increase the per unit area yield, which can benefit the optimal configuration of rice production.

#### 4.5 Limitations

There are some limitations in our research. First, the yield data at the county level are still insufficient. When analysing the relationship between rice yield and terrain factors, we only collected yield data from 33 counties; in future research, we hope to collect data from the statistical yearbook of each county to expand data. Moreover, we did not take some non-environmental factors into consideration, such as the amounts of fertilizer and pesticide, the use of agricultural machinery and so on, which can influence the rice growth and final yield because these data are difficult to obtain at the county level. In the next step, we would like to cooperate with the agriculture departments of local governments to collect specific agricultural management data.

### 5 Conclusions

Based on the multi-source data obtained at both the site and regional scales, we applied the spatial analysis method to investigate the impact of terrain factors on the distribution of paddy fields, the rice growth process and the rice yield. Our research framework is consistent with the classic ecologic theory of process to pattern. The result shows that terrain factors have a direct impact on the spatial pattern of paddy fields. Similarly, terrain factors also influence the spatial patterns of those fundamental environmental factors, such as temperature, sunlight and soil types, which then affect rice growth. However, in this process, we found that terrain factors led to a spatial mismatch of rice production resources in Hunan: most paddy fields are distributed on the plains of northern Hunan, while the yield per unit area in this area is lower than that in the hilly areas of central Hunan because of the limited heat. This impedes the scale production of rice in northern Hunan. Thus, we suggest that the Hunan provincial government should implement useful measures based on regional charac-

teristics and help farmers select suitable planting varieties and crop systems to improve the efficiency of rice production in Hunan, especially in its northern parts.

## References

- Bao Y X, Liu W, Gao P *et al.*, 2012. Study on characteristics of rice heat damages in Jiangsu province under the background of climate warming and its influence on the rice yield. *Chinese Journal of Agrometeorology*, 33(2): 289–296. (in Chinese)
- Chen N, Tang G A, Zhu H C, 2006. The study on the uncertainty of slope information derived from DEM with different spatial. *Research of Soil and Water Conservation*, 13(3): 153–156. (in Chinese)
- Ciha A J, 1984. Slope position and grain yield of soft white winter wheat. *Agronomy Journal*, 76(2): 193–196.
- Department of Rural Survey, NBS, 2011. China Rural Statistical Yearbook (2011). Beijing: China Statistics Press. (in Chinese)
- Department of Rural Survey, NBS, 2012. China Rural Statistical Yearbook (2012). Beijing: China Statistics Press. (in Chinese)
- Department of Rural Survey, NBS, 2013. China Rural Statistical Yearbook (2013). Beijing: China Statistics Press. (in Chinese)
- Getis A, Ord J K, 1992. The analysis of spatial association by use of distance statistics. *Geographical Analysis*, 24(3): 189–206.
- Gong M, 2015. The uncertainty of topographic wetness index derived from DEM in the Loess Plateau of northern Shaanxi province [D]. Nanjing: Nanjing Normal University. (in Chinese)
- He F, Huang J L, Cui K H *et al.*, 2007. Effect of real-time and site-specific nitrogen management on rice yield and quality. *Scientia Agricultura Sinica*, 40(1): 123–132. (in Chinese)
- Huang Y L, Chen L D, Fu B J *et al.*, 2003. The influence of topography land use on soil moisture spatial-temporal pattern in the hilly area of Loess Plateau. *Quaternary Sciences*, 23(3): 334–342. (in Chinese)
- Jia T B, Wu F Q, Zhao L S *et al.*, 2013. Micro-relief slope surface complexity characteristics of sloping farm land under different tillage practices. *Journal of Soil and Water Conservation*, 27(4): 152–156. (in Chinese)
- Jin C, Lu Y Q, 2009. Evolvement of spatial pattern of economy in Jiangsu Province at county level. *Acta Geographica Sinica*, 64(6): 713–724. (in Chinese)
- Kravchenko A N, Bullock D G, 2000. Correlation of corn and soybean grain yield with topography and soil properties. *Semigroup Forum*, 92: 75–83.
- Liang F C, Liu L M, 2010. Analysis on distribution characteristics of land use types based on terrain gradient: A case of Liuyang City in Hunan Province. *Resources Science*, 32(11): 2138–2144. (in Chinese)
- Liu J Y, Kuang W H, Zhang Z X *et al.*, 2014. Spatiotemporal characteristics, patterns and causes of land use changes in China since the late 1980s. *Acta Geographica Sinica*, 69(1): 3–14. (in Chinese)
- Liu X F, Zhang Z, Shuai J B *et al.*, 2012. Effect of chilling injury on rice yield in Heilongjiang Province. *Acta Geographica Sinica*, 67(9): 1223–1232. (in Chinese)
- National Soil Survey Office (NSSO), 1995. 1:1,000,000 Soil Mapping of China. Xi'an: Geological Publishing House. (in Chinese)
- Niu L, 2010. Relationship between slope and resolution: A case study on hill zones in Loess Plateau [D]. Xi'an: Northwest University. (in Chinese)
- Peng S, Tang Q Y, Zou Y, 2009. Current status and challenges of rice production in China. *Plant Production Science*, 12(1): 3–8.
- Persson A, Pilesjö P, Eklundh L, 2005. Spatial influence of topographical factors on yield of potato (*Solanum tuberosum* L.) in central Sweden. *Precision Agriculture*, 6(4): 341–357.
- Qing X G, Ai Z Y, 2007. On regional distribution of rice cultivation in Hunan Province. *Research on Agricultural Modernization*, 28(6): 704–708. (in Chinese)
- Qiu Y, Fu B J, Wang J *et al.*, 2003. Spatio-temporal distribution of land use in relation to topography in a gully catchment of the Loess Plateau, China. *Journal of Natural Resources*, 18(1): 20–29. (in Chinese)

- Sun L, Chen H W, Pan J W, 2004. Analysis of the land use spatiotemporal variation based on DEM: Beijing Yan-qing County as an example. *Journal of Mountain Science*, 22(6): 762–766. (in Chinese)
- Tang G A, 2014. Progress of DEM and digital terrain analysis in China. *Acta Geographica Sinica*, 69(9): 1305–1325. (in Chinese)
- Tang G A, Liu X J, Lv G N, 2006. Digital Elevation Model and Principles and Methodology in Geographical Analysis. Beijing: Science Press. (in Chinese)
- Tang G A, Zhao M D, Li T W *et al.*, 2003. Modeling slope uncertainty derived from DEM in the Loess Plateau. *Acta Geographica Sinica*, 58(6): 824–830. (in Chinese)
- Wang C A, Wang B L, Zhang W X *et al.*, 2006. Effects of water stress of soil on rice yield and quality. *Acta Agronomica Sinica*, 32(1): 131–137. (in Chinese)
- Wang P, Zhang Z, Song X *et al.*, 2014. Temperature variations and rice yields in China: Historical contributions and future trends. *Climatic Change*, 124(4): 777–789.
- Wang Y Q, Zhang X C, Li S J *et al.*, 2007. Spatial variability and the relationships of soil mineral N and topographic factors in a small watershed. *Environmental Science*, 28(7): 1567–1572. (in Chinese)
- Wang Z N, Chen A P, Fang J Y, 2004. Richness of seed plants in relation with topography in Hunan Province. *Acta Geographica Sinica*, 59(6): 889–894. (in Chinese)
- Wei L Z, Deng N R, Wu Z F *et al.*, 2008. Effects of topography on distribution and change of farmland in mountainous area of north Guangdong Province, China. *Journal of Mountain Science*, 26(1): 76–83. (in Chinese)
- Weiss A, 2001. Topographic Position and Landforms Analysis. San Diego, CA: ESRI User Conference.
- Xi C F, 1994. Soil Taxonomy. Beijing: China Agricultural Press. (in Chinese)
- Yang C J, Zhao X L, Zhou Q L *et al.*, 2013. Analysis of scale effect characteristics of DEM and slope in hilly areas. *Journal of Geo-information Science*, 15(6): 814–818. (in Chinese)
- Yang X, 2004. DEM based simulation on solar radiation and temperature and its application in agriculture [D]. Xi'an: Northwest University. (in Chinese)
- Yu G P, Zhu H Y, 2009. Status analysis and development countermeasures of rice production in China. *Modern Agricultural Science and Technology*, (6): 122–126. (in Chinese)
- Yuan W P, Xu B, Chen Z Q *et al.*, 2015. Validation of China-wide interpolated daily climate variables from 1960 to 2011. *Theoretical & Applied Climatology*, 119(3/4): 689–700.
- Zhan L Q, 2009. Study on variability of paddy soil nutrients and evaluation of paddy soil fertility [D]. Chongqing: Southeast University. (in Chinese)
- Zhang J Z, Chai Y L, Feng L X *et al.*, 2008. GIS-based study on spatial variability of soil characteristics in north-west plateau of Hebei. *Journal of Agricultural University of Hebei*, 31(5): 24–28. (in Chinese)
- Zhang J, Yao F, Hao C *et al.*, 2015. Impacts of temperature on rice yields of different rice cultivation systems in southern China over the past 40 years. *Physics & Chemistry of the Earth*, 87: 153–159. (in Chinese)
- Zhang S M, Wang Z M, Zhang B *et al.*, 2010. Prediction of spatial distribution of soil nutrients using terrain attributes and remote sensing data. *Transactions of the CSAE*, 26(5): 188–194. (in Chinese)
- Zhang S P, Qiao J, Sun X Y *et al.*, 2015. Effects of slope aspect and slope position on spatial distribution of soil nutrients of *Paulownia fortunei* plantation. *Journal of Central South University of Forestry and Technology*, (1): 109–116. (in Chinese)
- Zhang W, Li A N, 2012. Study on the optimal scale for calculating the relief amplitude in china based on DEM. *Geography and Geo-Information Science*, 28(4): 8–12. (in Chinese)
- Zhou J, Chen Y P, Ruan D Y, 2013. Effect of terrain condition on regional imbalance development of agricultural mechanization. *Chinese Rural Economy*, (9): 63–77. (in Chinese)
- Zhou Q M, Liu X J, 2006. Digital Terrain Analysis. Beijing: Science Press. (in Chinese)