Small-Scale Evaluation of Tobacco Planting Suitability Based on Spatial Information Technology

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Fengrui Chen[1] , Guangxiong Peng[2,*], Wei Su[3], Yaochen Qin[1], and Xi Li[4]

[1] The College of Environment and Planning, Henan University, Kaifeng, China
[2] School of Geosciences and Info-Physics, Key Laboratory of Metallogenic Prediction of Nonferrous Metals, Ministry of Education,Central South University, Chansha, China.
[3] College of Information and Electric Engineering, China Agriculture University, Beijing,China
[4] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, WuhanUniversity, Wuhan, China
fruich@gmail.com, pgxcsu@csu.edu.cn

Abstract. Crop planting suitability evaluation is important for agricultural production. In this study, a comprehensive evaluation framework which combined geographical information system, remote sensing, global position system and geostatistics with other models was presented to evaluate the tobacco planting suitability on a small scale. Ten indicators from three respects of climate, terrain and soil nutrients were selected to build evaluation indicator system. The results show that 70% of study area is suitable for tobacco planting. However, the spatial distribution of current tobacco fields is some degree of irrationality, and 20% of fields are located in moderate or not suitable area. Through scale analysis of the arable land, the suitable fields are mainly distributed in the middle and southern parts of the study area, which is 6324.5 ha.

Keywords: Spatial Information Technology, Planting Suitability Evaluation, Tobacco, Scale Analysis.

1 Introduction

Developing precision agriculture is an inevitable direction in the world [1-4]. The key of actualizing precision agriculture is spatial information technology, which involves spatial data acquisition, processing and decision–making [5-7]. Tobacco is a special agriculture crop which products excellent tobacco leaves only in regional cultivated land. In order to improve the tobacco quality and have a high market competitiveness, it is meaningful to evaluate tobacco planting suitability based on spatial information technology, and on this basis, tobacco production is redistributed rationally.

Geographic information system (GIS) which provides powerful spatial data management and analysis functions has been widely used for manage spatial resource

* Corresponding author.

[8-11]. In recent years, tobacco planting suitability evaluation based on GIS has been presented [12-14]. Although they can guide tobacco production overall, the evaluation results can not meet the requirements of precision agriculture on small scale. For example, there is always a meteorological station per country[15] and several soil sampling points standing the whole area, which will be very rough for assessment. However, few studies have focused on small-scale tobacco planting suitability evaluation such as on the county and its below scale. Furthermore, modern tobacco agriculture demands that tobacco fields not only are distributed in suitable area, but also have a certain scale. All these pose challenges to the traditional evalution method.

The increasing needs of modern tobacco agriculture and the shortage of current evaluation method stimulate a need for sophisticated methods of suitability evaluation. In this study, according to the physiological characteristic of tobacco [16] and the study area condition, ten evaluation indicators from three factors of climatic, terrain and soil have been chosen to build the tobacco planting suitability evaluation indicator system on small scale. Then, in order to attain accuracy evaluation indicators, remote sensing data was used to retrieve surface parameters, and soil sampling data based on global position system (GPS) was used to attain soil nutrient information by geostatistical analysis. On the basis of analysis above, GIS combined with analytic hierarchy process (AHP) and membership function model were applied to comprehensive evaluation of tobacco planting suitability, which could provide scientific bases for sustainable development of tobacco production.

2 Materials and Method

2.1 Study Area

The research was conducted in one part of Huili County (E 102°13′-102°24′ and N 26°33′-26°48′), located in the southwest of Sichuan province, China (Fig.1). It is one of the main tobacco production regions of Sichuan province. The highest elevation of the study area is 2390 m and the lowest is 1680 m. There are many kinds of landform types such as mountain, hill, plain and basin, which results into redistribution of light, heat and water resources, arable land mainly distribute in plain and basin area. The local climate is classified as temperate continental with annual average rainfall of 1150 mm, annual mean temperature of 15.1℃, annual sunshine of 2398 h and annual frost-free days of 240. There is big different in temperature between day and night here, and is rich in water, heat and good natural conditions, therefore, it is very suitable for high-quality tobacco production.

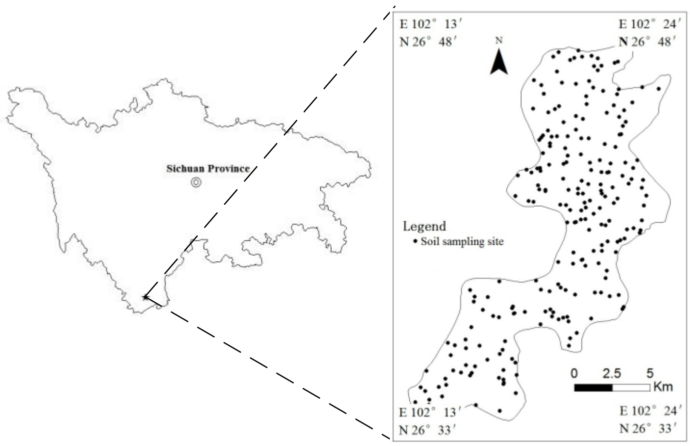

Fig. 1. The location of study area and the spatial distribution of soil sampling.

2.2 Data Source

Solar radiation is an important impact factor for crop growth. In order to attain high accuracy spatial distribution of solar radiation, a series of models and methods have been established and developed[17, 18]. In this paper, the model proposed by Fu and Rich[19] was used to calculate the solar radiation of the study area, which has been applied widely. The tobacco growing season is from May to July, so the mean solar radiation of this period was calculated (Fig.2).

Owing to the sparse distribution of meteorological station, about a station per country, so it is difficult to obtain high accuracy climate data from observation site at country or its below scale. Remote sensing is an effective method, which can acquire surface parameters with high spatial resolution in any region, and compensate for the loss caused by the absence of observation stations[20]. Moderate resolution imaging spectroradiometer (MODIS) which has high temporal and spectral resolution, moderate spatial resolution and abundant products was used to retrieve land surface parameters. MODIS products in May, June and July from the year of 2005 to 2010 were adopted, and these data were downloaded from the website of national aeronautics and space administration (NASA) of the United States.

Land surface temperature (LST) is obtained from MOD11 products of MODIS with the spatial resolution of 1 km. Its average error is smaller than 0.5 K [21, 22]. Fig.2 shows the mean LST from May to July in the study area.

Soil moisture is derived from temperature vegetation dryness index (TVDI) based on normalized difference vegetation index (NDVI) products and land surface temperature (LST, MOD11) products of MODIS [23]. It can effectively reflect the spatial distribution of relative value of soil moisture, and has high correlation with the soil moisture. The value of TVDI is from 0 to 1. The soil moisture increases with the decrease of TVDI. The spatial distribution of TVDI is shown in Fig.2.

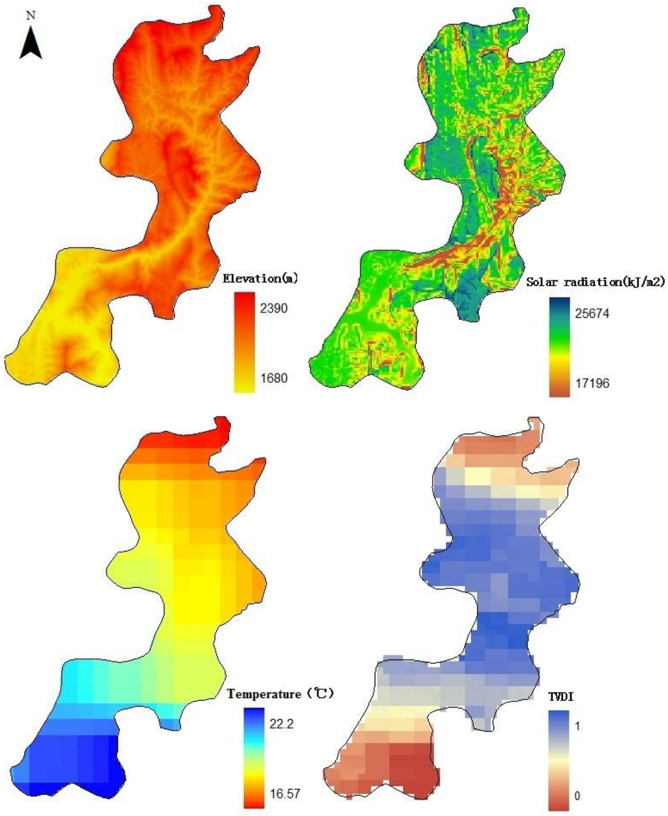

Fig. 2. The evaluation indicators of elevation, solar radiation, temperature and TVDI.

Soil sampling was carried out in April 2009, immediately after harvest of wheat and cole. In total 268 soil samples at the depth of 20 cm were taken and their precise locations were recorded by a GPS receiver (Fig.1). Before analysis, all soil samples were air-dried and passed through a 2-mm sieve prior to analysis. Soil pH value was determined by the method of electrical potential; organic matter (OM) content was measured by dilution heat method with potassium bichromate; and available nitrogen (AN), available phosphorus (AP) and available potassium (AK) were measured by alkaline hydrolysis diffusion, molybdenum stibium anti-color method and flare photometer, respectively.

In addition, elevation and slope indicators are derived from DEM data with the spatial resolution of 20 m. Arable land is derived from the digital of thematic map with the scale of 1:50000.

2.3 Geostatistics Method

Geostatistics was used to estimate and map soil nutrients in unsampled areas [24, 25]. Among the geostatistical techniques, kriging is a linear interpolation procedure that provides a best linear unbiased estimation for quantities, which varies in space. Kriging estimates are calculated as weighted sums of the adjacent sampled concentrations. That is, if data appear to be highly continuous in space, the points closer to those estimated receive higher weights than those farther away[26].

In geostatistical analysis, the semivariogram was calculated for each soil variable as follows:

$$r(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \quad \textbf{(1)}$$

where $z(x_i)$ is the value of the variable z at the sampled location x_i, h is the distance lag in meters and $N(h)$ is the number of pairs of sample points separated by h. For irregular sampling, it is rare for the distance between the sample pairs to be exactly equal to h. Therefore, h is often represented by a distance interval. For the distance lag h, the semivariance is $r(h)$.

The experimental semivariogram was then fitted with a suitable theoretical model: spherical, exponential or gaussian. The models provide information about the spatial structure as well as the input parameters for kriging interpolation. Kriging is considered as the optimal spatial interpolation for making best linear unbiased estimates of regionalized variables at unknown locations. The spatial prediction of the value of a soil variable z at an unknown point x_0 is calculated as a weighted average:

$$z^*(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \quad \textbf{(2)}$$

where $z^*(x_0)$ is the value to be estimated at the location x_0; $z(x_i)$ is the known value at the sampling site x_i and λ_i is the weight. There are n sites within the search neighbourhood around x_0 used for estimation, and the magnitude of n will depend on the size of the moving search window and on user's definition. Kriging differs from other methods, such as inverse distance weighted, in that the weight function λ_i is no longer arbitrary, and is calculated from the parameters of the fitted variogram model with unbiasedness and minimized estimation variance for interpolation.

2.4 Comprehensive Suitability Evaluation

According to the principles of locality, similarity, diversity, integration and practicality, an evaluation indicator system based on three factors including ten indicators was built. The flow chart and processes method of this study is as Fig.3 .

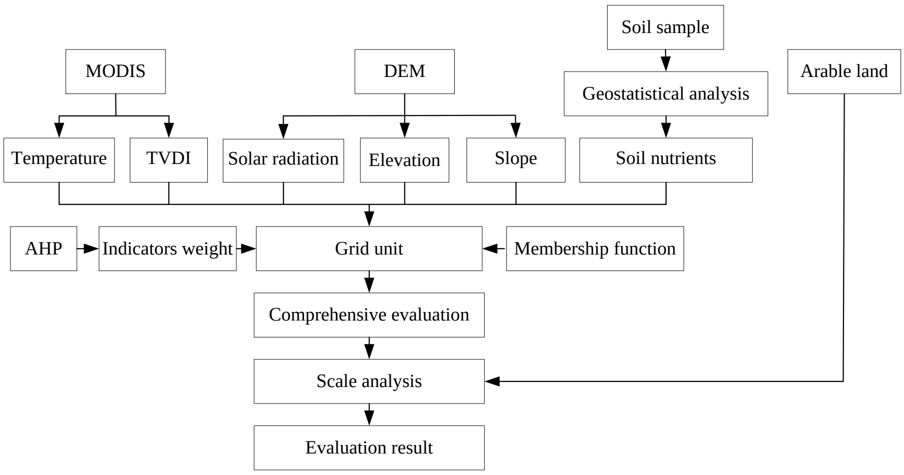

Fig. 3. The flow chart and processes method of this study.

2.4.1 Indicator Scoring

Table 1. Standard scoring functions and parameters for quantitative tobacco planting suitability evaluation indicators.

	FT	L	L1	U1	U	MF
Temperature(℃)	S-type	17	--	--	19	$f(x)=\begin{cases}1 & x\geq U\\ 0.9\times\frac{x-L}{U-L}+0.1 & U>x\geq L\\ 0.1 & x<L\end{cases}$
SR(kJ/m^2)	S-type	15000	--	--	23000	
AK(mg/kg)	S-type	80	--	--	180	
TVDI	Z-type	0	--	--	1	$f(x)=\begin{cases}1 & x\geq U\\ 0.9\times\frac{x-L}{U-L}+0.1 & U>x\geq L\\ 0.1 & x<L\end{cases}$
Elevation(m)	parabola-type	800	1400	1800	2400	$f(x)=\begin{cases}1 & L1\leq x<U1\\ 0.9\times\frac{x-L}{L1-L}+0.1 & L<x<L1\\ 0.9\times\frac{x-U1}{U-U1}+0.1 & U1<x<U\\ 0.1 & x\leq L, x\geq U\end{cases}$
Slope(°)	parabola-type	0	6	15	25	
pH	parabola-type	4.5	5.5	6.5	8.0	
OM(g/kg)	parabola-type	10	22	28	45	
AN(mg/kg)	parabola-type	40	80	100	150	
AP(mg/kg)	parabola-type	5	20	30	45	

FT means membership function type; L means lower limit; U means upper limit; L1 means lower optimal value; U1 means upper optimal value; MF means membership function.

Because of different indicator units, a standard scoring function was used to score suitability indicators. The scoring of evaluation indicators on growth suitability of tobacco can be described with the fuzzy methods. The interaction between growth and quality of tobacco was different. Referring to the existed research results [16, 27, 28] and the actual situation of the study area, different types of membership functions, including parabola-type, Z-type and S-type, were chosen to express their relations (Table 1). The membership degree which is between 0.1 and 1.0 can be calculated according to these membership functions, which reflects the degrees of membership.

The upper limit 1.0 is referred to as the best situation of indicators which is suitable for the growth of tobacco crops, while the lower limit 0.1 is referred to as such that there is a serious deficiency in that indicator.

2.4.2 Weight Assignment

The indicator weight is the contribution degree of the effects of evaluation indicators to tobacco growing. There are many methods to assign indicator weight for tobacco planting suitability, such as the Delphi, AHP, regression analytical method and principal components analysis. In order to weaken subjective influence, the application of the AHP method, developed by Saaty [29] for environmental assessment, has been used extensively[30, 31] and was used to derive the weights of indicators, which are shown in Fig.3.

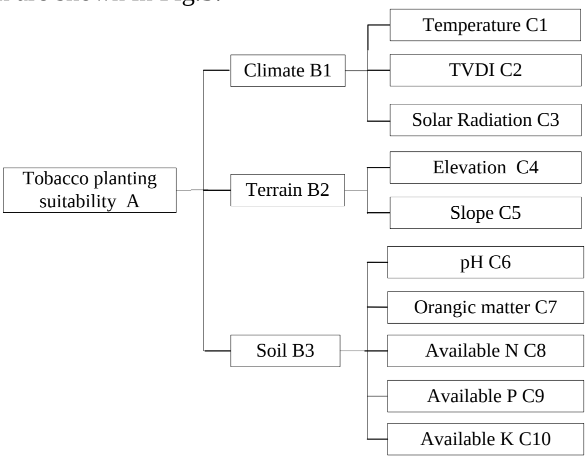

Fig. 4. Hierarchical structure for the indicator weight assignments.

Table 2. The weight of evaluation indicator for tobacco planting suitability

C	B1	B2	B3	Weights
	0.49	0.20	0.31	
Temperature C1	0.54	0	0	0.26
TVDI C2	0.16	0	0	0.08
Solar radiation C3	0.30	0	0	0.14
Elevation C4	0	0.75	0	0.15
Slope C5	0	0.25	0	0.05
pH C6	0	0	0.44	0.14
Organic matter C7	0	0	0.29	0.09
Available N C8	0	0	0.13	0.04
Available P C9	0	0	0.05	0.02
Available K C10	0	0	0.09	0.03

The results of AHP analysis are presented in Table 2. The consistency test for single and general hierarchy storing was conducted by calculating the average random consistency index (RI). The results indicated that all RIs for single and general hierarchy storing were lower than 0.1, which means all the matrixes in the hierarchy A, B and C were logically constructed. In addition, the maximum of the eigen value and its eigen vector should be calculated and verified by the coherence index-coherence ratio (CR). If the CR value is less than 0.1, it deems that the variance should be allowed. Or else, the matrix must be adjusted once again. In this study, CR value was 0.04, which was less than 0.1. Therefore, the analysis results were acceptable.

2.4.3 Calculation of Comprehensive Evaluation Values

According to the character of study area, the size of evaluation unit for tobacco planting suitability is 30 * 30 m. All the indicators should be resampled into grid unit with the spatial resolution of 30 m before comprehensive evaluation. After all indicators were scored and weighted, the integrated quality index (IQI)[32] model was used to calculate the tobacco planting suitability level in study area:

$$IQI = \sum_{i=1}^{n} W_i N_i \qquad (3)$$

Where W_i is the assigned weight of evaluation indicator, N_i is its score, and n is the number of evaluation indicators. The higher the IQI value is, the more suitable the unit is for tobacco planting.

3 Results

3. 1 Descriptive Analysis of Soil Nutrients

Table 3. Descriptive statistics of soil nutrients in the study area.

	Min	Max	Mean	Std	CV	Skewness
pH	4.9	8.1	6.3	0.72	0.11	0.19
OM(g/kg)	6.0	62.2	24.7	10.5	0.43	0.84
AN(mg/kg)	11.4	212.2	81.4	39.1	0.48	0.64
AP(mg/kg)	2.3	51.8	23.3	11.7	0.5	0.45
AK(mg/kg)	58.4	490.9	198.6	102.9	0.52	1.05

The descriptive statistics of soil pH, organic matter, AN, AP and AK for study area are shown in Table 3. In general, the soil was suitable for tobacco planting, and the means of pH, OM, AN and AP were in their optimal value ranges (Table 1). The CVs of OM, AN, AP and AK were similar, all exceeding 0.4, which indicated considerable spatial variability. However, the CV of pH was much smaller, only 0.11, which indicated significant spatial constant. The skewness of AK was more than 1, so it was necessary to transform its non-normally distributed raw data into data with an approximately normal distribution. We found that the log transformation of AK significantly improved their normality, therefore, log(AK) were used for the geostatistical analysis.

3.2 The Spatial Analysis of Soil Nutrients

The best-fit semivariogram models and parameters for pH, OM, AN, AP and log(AK) are listed in Table 4. We used variable distance lags to compute the experimental semivariogram to see how the semivariograms behave near the origin and when the distance lag increases. As listed in Table 4, the exponential model gave the best fit to the pH, AN, AP and log(AK) experimental semivariograms, except OM. For OM semivariogram, a gaussian model (C_0=29.1, C=29.57 and range = 1720 m) produced the best fit (Table 4).

Table 4 also indicates a distinctly different degree of spatially structured variations of the five nutrients. Spatial continuity for a regionalized variable can be characterized by its range. The longer the range is, the better spatial continuity becomes. Among the five nutrients, the range of log (AK) (2970 m) was the longest, so it had the best spatial continuity. In addition, spatial structured variation for a regionalized variable can be divided into three categories: strong, moderate and weak spatial dependence, corresponding to a nugget-to-sill ratio $C_0/(C+C_0)$ of < 0.25, 0.25~0.75 and > 0.75, respectively. In this study, all five variables demonstrated moderate spatial dependence, and AP had the strongest spatial dependence due to its lowest nugget-to-sill ratio (0.39). Although pH and log (AK) had similar nugget to sill ratios (0.5 and 0.52), their spatially structured variations appeared at different spatial scales as their ranges were significant different (1820 m for pH and 2970 m for log(AK)).

Table 4. Semivariogram models and their parameters for soil nutrients.

	Model	C_0	C	$C_0/(C+C_0)$	Range (m)
pH	Exponential	0.18	0.23	0.44	1820
OM	Gaussian	29.1	29.57	0.5	1720
AN	Exponential	721	624	0.54	2850
AP	Exponential	55	86	0.39	2474
log(AK)	Exponential	0.12	0.11	0.52	2970

Fig.5 shows the spatial patterns of the five soil nutrients generated from ordinary kriging analysis based on their semivariogram parameters (Table 4). Owing to the smooth effect of kriging, all predicted value ranges of five nutrients were smaller than the corresponding sampling data. Cross validation was carried out to evaluate the accuracy of the ordinary kriging interpolation. As a result several indices, mean prediction error (ME), mean absolute error (MAE), root mean squared error (RMSE) and correlation (r) between observed and predict value were adopted. Table 5 summarizes the cross validation of ordinary kriging interpolations for pH, OM, AN, AP and AK. The results indicted that AN and AK were slightly overestimated and OM and AP slightly underestimated. According to the correlation coefficients r, pH was predicted best (r = 0.77), then AP(r = 0.72), and the worst AK (r = 0.55). The relatively low r for AK may be due to its predicted value which was transformed from the predicted value of log (AK).

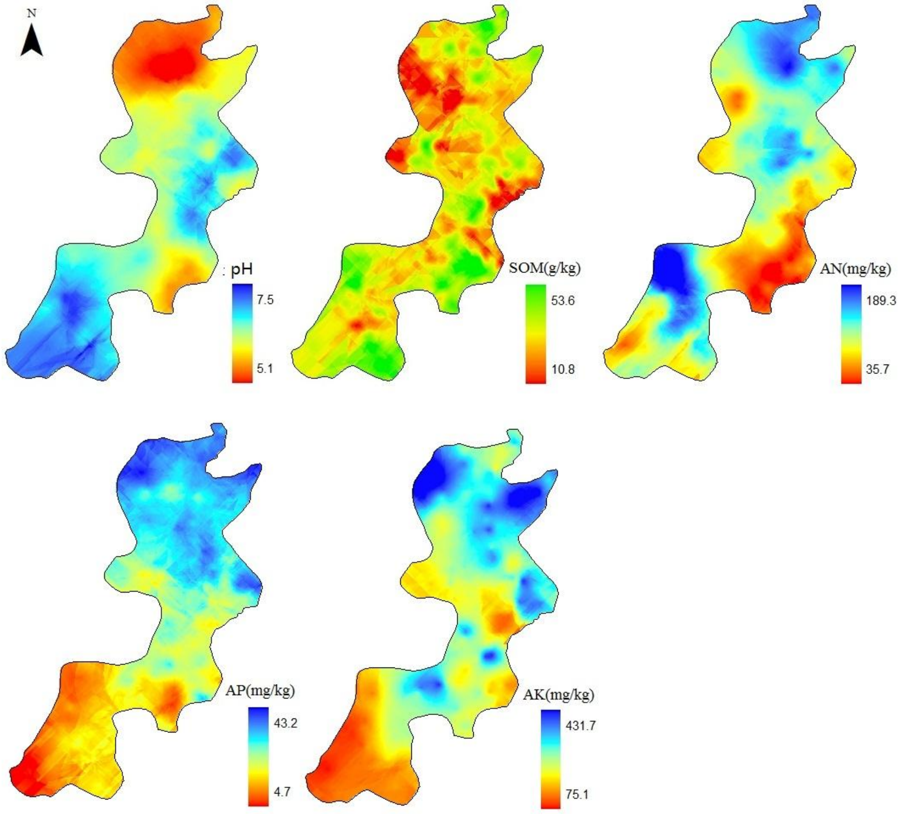

Fig. 5. The spatial distribution of soil nutrients.

Table 5. Summary of cross validation of ordinary kriging interpolation for soil nutrients

	pH	OM	AN	AP	AK
ME	0.0	-0.03	0.01	-0.02	0.05
MAE	0.13	3.61	3.63	3.13	5.3
RMSE	0.45	4.77	4.79	4.23	7.5
r	0.77	0.68	0.72	0.64	0.55

The spatial distribution of pH was characterized by an increasing trend from south to north, pH in most parts of the north is less than 6.0 while is more than 6.5 in most parts of the south. AP and AK have similar spatial distribution, in contrast with pH, they show decreasing trend from south to north. In addition, it is difficult to discern a trend in OM and AN. OM content in the north border is higher, and AN content is higher in the centre of study area.

3.3 Evaluation Result

Based on the method of AHP and fuzzy mathematics, the tobacco planting suitability of study area is classified into four grades. The high suitability of IQI ranges from 3.4 to 4, while the suitability of IQI ranges from 2.9 to 3.4, the moderate suitability of IQI ranges from 2.4 to 2.9, the not suitability of IQI ranges is less than 2.4. As shown in Fig.6, the high suitable tobacco planting parts are mainly distributed in the southern part of the study area, accounting for 26.1% of the whole investigated areas. The suitable parts are 53% of the whole areas, mainly distributed in the northern and middle parts of study area. In addition, the moderate and not suitable parts are mainly distributed in the northeast of the study area, which are of 16.4% and 4.5% of the whole area, respectively.

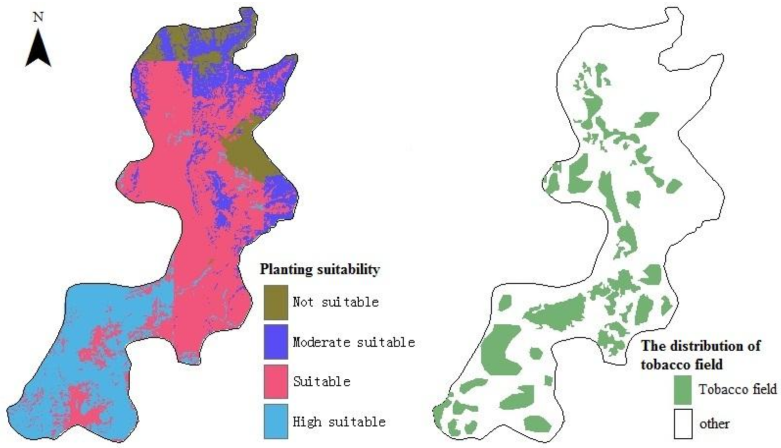

Fig. 6. The evaluation result of tobacco planting suitability and scale analysis.

Then, we analyzed the suitable condition of the current tobacco fields on the basis of the evaluation results above. In summary, most of the current tobacco fields were suitable for tobacco planting. 79.8% of which were located in suitable and higher suitable areas. However, there were more than 20% of tobacco fields which were not suitable for tobacco planting; these would result into the decline of tobacco quality. Beyond that, the size of 22.4% of tobacco fields were less than 6.7 ha, which didn't meet the demand of the large scale in modern tobacco agriculture. Therefore, it is necessary to reset the spatial distribution of tobacco planting in study area.

In modern tobacco agriculture, the tobacco fields not only are suitable for tobacco planting, but also have a certain scale, which can improve the quality and standardization of tobacco leaves. Considering the tobacco planting condition and arable land in study area, 6.7 ha was selected as the scale criterion of tobacco fields, the analysis chart and its result are shown in Fig.2 and Fig.6, respectively. There were 6324.5 ha of tobacco fields meeting the requirement of modern tobacco agriculture, which were mainly distributed in the middle and southern parts of the study area.

There are two main reasons for this. 1) The current layout of tobacco planting is based on the planning of the 1980s. Subject to conditions at the time, the suitability evaluation was performed at larger small, and the indicators selected were simple and parts of these were qualitative description. In addition, owing to the rapid development of China's economic, the environment conditions have changed a lot in past 30 years. 2) The tobacco planting is mainly based on family unit in this country, the family can planted tobacco according to the distribution of their field optionally; therefore, some tobacco was planted in a little field without considering the demand of scale production.

4 Discussion and Conclusion

The integration of GIS, RS and GPS provided a powerful tool for this study in terms of tobacco planting suitability evaluation. Ten indicators from three respects of climate, terrain and soil nutrients were selected to build evaluation indicator system. In order to measure the relation between indictors and tobacco planting accurately, the membership function and AHP method were adopted to determine the suitability of indicators and their weights. Then, tobacco planting suitability evaluation of study area was calculated by IQI model. The results show that most parts of study area were suitable for tobacco planting.

General, traditional suitability evaluation is on provincial level or state level, counties or townships are often used as the basic evaluation units. In China, most of suitable areas for tobacco planting are located in mountainous region, where the environment variables such as air temperature, precipitation, sunshine, soil nutrients and so on have significant difference in micro-region. Large-scale evaluation is very difficult to reflect these differences and not meet requirements of modern precision agriculture. While small-scale evaluation can solve these problems, it can reflect the differences of crop growth environment micro-region and makes the evaluation results more accurate.

The distribution density of meteorological stations is about 50*50 km per station in China, so it is difficult to attain the accuracy spatial distribution of meteorological data by observation station. Remote sensing can acquire surface parameters with high spatial resolution in any region, which can compensate for the loss caused by the absence of observation station.

In order to enhance market competitiveness of tobacco, it should be improve the quality of tobacco leaves. The current tobacco production is mainly based on family unit, and each family adopted his planting mode, which is difficult to attain this target. The scale planting is an effective way to deal with this problem. It can be conducive to mechanized production, improve farm management level, and save labor and reduce production costs, which will help to achieve standardization of tobacco production. However, the current evaluation method which only evaluates the suitable level of each location is powerless to do these. In this study, through integrating suitability evaluation and arable land, the scale analysis was developed by spatial analysis of GIS.

After analyzing the current tobacco fields, it was found that more than 20% of tobacco was planted in moderate and not suitable area, therefore, the spatial distribution of tobacco planting needed to be adjusted. Based on scale analysis for arable land, we found that the tobacco fields which were suitable for tobacco planting and had a certain scale mainly distributed the middle and southern parts of study area, accounting for 75.3% of arable land.

Acknowledgments: This research was financially supported by Natural Science Foundation of Hunan Province (No. 11JJ6029) and the Fundamental Research Funds for the Central Universities (No.2011QNZT006).

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