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# Agricultural Land Suitability of Production Space in the Taihang Mountains, China

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**Abstract:** The contradiction between the shortage of land for agriculture due to rapid expansion of industrialization and urbanization and increasing population pressure is projected to impose great threats to future food security. Agricultural land suitability evaluation is an effective approach to improve the utilization of land resources for crop production and thus enhance the capacity of food provision. In this study, we evaluated the land suitability for agriculture of the production space in the Taihang Mountains by three steps: establishing indicator system, determining weights for indicators, and constructing a fuzzy matter-element model to assess the grades of suitability. Results showed that the land suitability had a significant linear correlation with potential crop yields, indicating our evaluation was effective to predict crop production. The spatial pattern of land suitability for crop production demonstrated that land with higher suitability was generally located in piedmont plains and basins, while land with lower suitability was mostly situated in mountainous areas. The area of highly, moderately, marginally suitable and unsuitable land for agriculture was 32.13%, 28.58%, 37.49% and 1.80% of the production space, respectively. However, the correlation degree analysis indicated that the requirements of these four suitability grades were currently not satisfied but could be potentially fulfilled. In terms of indicator weights, soil properties were much more important than topography and location conditions to influence the grades of suitability. Among all indicators, slope, soil organic matter, soil texture and soil depth were the most influential factors, so slope farming prevention and organic fertilization were most likely to improve land suitability for agriculture. Compared the outputs of our land suitability evaluation model with the distribution of the existing croplands, we found that about 66.52% of marginally suitable and 54.55% of unsuitable land for agriculture were currently used for croplands. Therefore, de-farming policy should be implemented in areas of these two suitability grades. In contrast, cropland expansion was encouraged in the land that was highly or moderately suitable for agriculture. Our evaluation of agricultural land suitability is beneficial for future land use planning and decision-making in the Taihang Mountains.

**Keywords:** agricultural land suitability; matter-element model; production space; the Taihang Mountains

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## 1 Introduction

The booming population is projected to pose threats to food security and evidence has revealed that global crop demand is going to increase double till the mid-21st century (Godfray et al., 2010; Tilman et al., 2011). In addition, increasing population immigration from mountainous areas to lowlands also imposes pressure on food production in lowlands. Thus, it is imperative to effectively use croplands in order to enhance the capability of food provision. To this end, crop production can be enhanced by agricultural land expansion, such as re-

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claiming more land for farming, or land intensification, i.e., improving yields per unit area (Tilman et al., 2011). However, the decline trend of arable land in both quantity and quality makes it difficult to further extend land for agriculture. For instance, the competing use of land for accelerating industrialization and urbanization has cut down land for crop production and excessive exploitation even resulted in land pollution and degradation, thereby causing farmland area reduction and conversion (Yang and Li, 2000; Chen, 2007). The scarcity of land resources for agriculture therefore requires utilization of land more intensively and efficiently, especially for mountainous areas with poor soil conditions.

Land suitability refers to the degree of appropriateness of land characteristics to support a specific land use (FAO, 1993). For the optimization of land use, land suitability evaluation is regarded as the prerequisite for land use planning and the fundament of sustainable land management (Kazemi and Akinci, 2018; Yu et al., 2018). Land suitability evaluation for agriculture is a complicated process to identify spatial land potential and limitations for crop production on the basis of multiple criteria such as soil properties, topography and location conditions (Zolekar and Bhagat, 2015; Mesgaran et al., 2017). Due to a large number of criteria involved in decision-making, the assessment of agricultural land suitability is initially considered as a multi-criteria evaluation problem (Zolekar and Bhagat, 2015; Kazemi and Akinci, 2018). Since these criteria usually have different units, it is essential to unify them into a common scale in order to eliminate the effects of dimension and magnitude, and then combine them together according to their degrees of importance in deciding the overall suitability for agriculture (Reshmidevi et al., 2009; Akıncı et al., 2013). Hence, the evaluation of agricultural land suitability is also a criteria aggregation problem. Additionally, agricultural land suitability evaluation aims to find out the most suitable land for agricultural production so that land can be utilized as croplands more reasonably, which contributes to environment benefits (Yu et al., 2018). Overall, agricultural land suitability evaluation can comprehensively detect the inherent capacity of land and provide assistance to appropriately allocate land resources for crop production with minimal environmental impacts.

Agricultural land suitability evaluation is a widely used method to determine the areas suitable for crop production and the evaluation procedure commonly includes four steps: identification of land for evaluation, establishment of indicator system, determination of indicator weights, and model construction to assess the grade of land suitability (Gong et al., 2012; Zolekar and Bhagat, 2015). First, the functional differentiation of land determines that not all land can be used for a particular purpose. For example, the land with important ecological function such as water bodies, dense forests and natural reserves should be excluded for agricultural land suitability evaluation in mountainous areas (Zolekar and Bhagat, 2015; Mesgaran et al., 2017). Second, a systematic selection of proper indicators for evaluation holds the key to the accuracy of outputs at the beginning. Comprehensiveness is not the only consideration in the establishment of the indicator system, yet the distinctiveness of a specific region should also be taken into account (Li and Li, 2014). For instance, other than soil, terrains and location conditions are also important factors that can not be ignored for agricultural lands in mountainous areas. Moreover, weights have to be assigned subjectively or objectively for all the indicators because they may be of different importance to a particular purpose of land use. Analytic Hierarchy Process (AHP), a technique of weight determination, provides a framework to combine human knowledge both qualitatively and quantitatively to solve complex decision making (Saaty, 1980). AHP has been also widely used in land suitability analysis, incorporating the participation of experts or decision makers (Hood et al., 2006; Kazemi and Akinci, 2018). Finally, land suitability can be evaluated via appropriate models. The weighted average models including weighted linear combination and weighted overlay analysis are generally used to assess agricultural land suitability for their advantages in trading off suitability and unsuitability between criteria and aggregating weighted criteria to solve complex spatial problems (Hood et al., 2006; Zolekar and Bhagat, 2015; Kazemi and Akinci, 2018; Yu et al., 2018). However, these traditional models can not detect the degree of suitability within a given suitability grade or the potential of land suitability for agriculture. Matter-element model, first introduced by Cai (1994), had been proved to be an effective method to resolve incompatible problems including risk assessment (He et al., 2011), health evaluation (Li and Li, 2014), sustainability appraisement (Wang et al., 2018), and suitability analysis (Gong et al., 2012). These problem solutions reveal that matter-element model and its extensions are able to produce more comprehensive outcomes and provide more variance information such as land suitability potential than other traditional methods. Therefore, the grade of land suitability for crop production can be derived accurately and reliably through the calculation of correlation degrees using the matter-element model.

As a mountain-plain transition zone in north China, the Taihang Mountains have a relatively large population with a considerable food demand. However, the land for crop production is scarce due to the increasing expansion of industrialization and urbanization. Furthermore, the improper utilization of land resources has made soil erosion the major environmental issue in this region (Cao et al., 2018). Several studies have attempted to assess agricultural land suitability in the Taihang Mountains. For example, Yu (2004) and Li (2012) evaluated the suitability of land resources for farming, forestry and animal husbandry and analyzed the agricultural production potential in the Taihang Mountains of Hebei Province, China. Xue (2006) and Bai (2012) also estimated the feasibility of arable land in Hebei Province. Nevertheless, all of these studies, usually based on a traditional weighted linear combination method, focused on the eastern part of the Taihang Mountains in Hebei Province. Furthermore, the accuracy of the results of suitability was seldom assessed. Since the shrinking space for croplands and the ubiquitous environmental problems caused by industrialization, urbanization and unreasonable land utilization become increasingly severe in the whole area of the Taihang Mountains, it is essential to improve the intensification of agricultural land based on a holistic evaluation of land potential for crop production. Matter-element model is regarded as a good tool to comprehensively assess land suitability for cultivation, so this study aims to: 1) evaluate and validate land suitability for agriculture with the matter-element model; 2) determine the most important influence factors of agricultural land suitability. The outcomes of this study will be of great value for appraising present status of land use and making future land planning decisions in the Taihang Mountains.

## 2 Materials and Methods

### 2.1 Study area

The Taihang Mountains are located along a geographical demarcation line between the North China Plain and the Loess Plateau with an area of ~136 500 km$^2$, stretching from 34°55′N to 40°83′N and from 110°21′E to 116°61′E (Fig. 1). As the intersection zone extending from Beijing City through Shanxi Province and Hebei Province to Henan Province, the study area has a semi-humid warm temperate continental monsoon climate, with an average annual precipitation of 547.8 mm and an annual average temperature of 10.3℃ from the year of 2001 to 2015. The topography is characterized by mountains, basins and piedmont plains with elevation ranging from sea level to about 3000 m. It contains 101 counties with a large population of more than 39 million, accounting for 2.93% of the total national population. The area is characterized by typical mountainous agroforestry ecosystems (Cao et al., 2018), with agriculture as an important livelihood for mountainous people. However, soil quality is generally in low to moderate level with thin soil depth and high gravel content (Geng et al., 2018). The frequent human activities and inappropriate land uses have caused a series of problems, such as land degradation, soil and water loss and tensions between human needs and land conservation (Liu et al., 2007).

Before the land suitability analysis, the available land for agricultural purpose was determined in advance. According to the function of land resources and the requirement for regional sustainable development, the land in the Taihang Mountains was classified into ecological space, production space and living space, with the major function of providing ecosystem services, producing industrial and agricultural products and guaranteeing human settlement, respectively (Geng et al., 2019). Considering the vital ecological shelter effects of the Taihang Mountains on North China Plain grain-production base and Beijing-Tianjin-Hebei urban agglomeration, the ecological space must be fully protected and the essential space for human living should also be comprehensively ensured. Therefore, the production space was used in this study for agricultural land suitability analysis (Fig. 1). The production space was mainly composed of croplands, low coverage grasslands and sparsely forested woodlands as well as some garden plots. The area of the production space is 59 750 km$^2$, accounting for 44.17% of the total land in the Taihang Mountains.

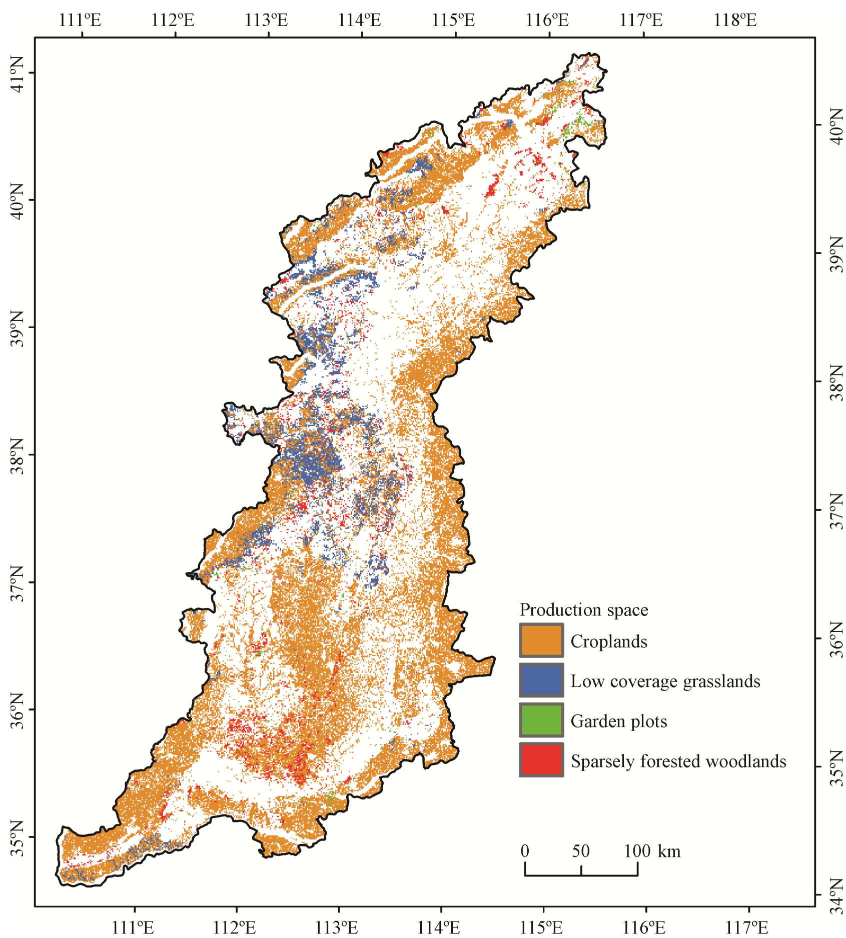


**Fig. 1** The location of the Taihang Mountains of China and the spatial distribution of its production space in 2015

## 2.2 Establishment of indicator system

In this study, the indicator system was established based on a comprehensive literature review and the real-world situation. We searched all the relevant references with the titles including 'land suitability' and 'agriculture' in Web of Science Core Collection for English academic journals and China National Knowledge Infrastructure (CNKI) databases for Chinese academic journals, and then counted the frequency of the indicators used in these references (Table 1). Then the indicators occurred more than three times in the literature review were selected and combined as our indicator system for agricultural land suitability evaluation. However, it must be noted that some indicators might be removed from or added to the indicator system according to the availability of data and the real-world situation. Specifically, we deleted the distance to the road, the irrigation condition and the soil water situation from the indicator system due to data unavailability. We also removed climatic indicators because various crops had different precipitation and temperature demands and there were no uniform climatic criteria for general agricultural land suitability evaluation. Available potassium content and base saturation were also eliminated due to their spatial homogeneity and non-limitation to crop growth. In addition, due to the poor transportation condition in the study area, the distance to residential area became very important so it was included in the indicator system. Finally, we established the indicator system for agricultural land suitability, including 18 indicators related to soil properties, topography and location conditions (Table 1). Soil and topography are closely related to crop productivity and they are frequently used for the evaluation of land suitability for crop production (Akıncı et al., 2013; Zolekar and Bhagat, 2015; Li et al., 2017). Soil physical properties such as soil texture, soil depth, drainage class, rock fragment and soil erosion play a vital role in provision of water and nutrients to plants and maintenance of soil structure, soil water holding capacity, soil hydraulic conductivity, soil porosity and soil infiltration. Soil organic matter and nutrients, for example, nitrogen and phosphorous, are essential for plant growth and productivity. Other soil chemical properties like potential of hydrogen, calcium carbonate, cation exchange capacity, and electrical conductivity influence the availability of nutrients, physiological processes and microbial activities. In addition, topography is an important factor that has to be considered in mountain areas (Zolekar and Bhagat, 2015). Slope affects many soil properties including soil thickness and soil erosion control, which have great impacts on agricultural production. Elevation and aspect determine the distribution of heat and sunlight for plants, particularly in highlands. Due to the poor transport and irrigation facilities in the mountains, distance to residential areas and rivers cannot be ignored for the feasibility of cultivation. Given the difficulty of land conversion, the original land use must also be considered in agricultural land suitability analysis (Bandyopadhyay et al., 2009). Overall, soil properties, topography and location conditions have close association with land suitability for agriculture, so it is rational to select them to establish the indicator system for agricultural land suitability evaluation in this study.

Data sources of the indicators in the indicator system were listed in Table 1. Data of soil texture were obtained from Harmonized World Soil Database (FAO et al., 2012). Other soil properties were mainly provided by the Soil Database of China for Land Surface Modeling (Shangguan et al., 2013) and the Global Soil Database for Earth System Modeling (Shangguan et al., 2014). Data of soil erosion and land use of the year of 2015 were procured from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn). The distance to river and residential area was calculated using Buffer and Distance tools on software ArcGIS 10.2. Elevation data were acquired from the NASA Shuttle Radar Topographic Mission (http://srtm.csi.cgiar.org) and slope and aspect were derived from the elevation data with software ArcGIS 10.2. All the spatial data used in this study were resampled to the same spatial resolution for subsequent analyses.

**Table 1** The indicator system and data source for agricultural land suitability evaluation

| Criterion | Indicator | Frequency | Abbreviation | Data source |
|---|---|---|---|---|
| Soil property | Soil texture | 18 | ST | FAO et al., 2012 |
| | Soil organic matter (g/100 g) | 16 | SOM | Shangguan et al., 2013 |
| | Soil depth (cm) | 14 | SD | Shangguan et al., 2013 |
| | Potential of hydrogen ($H_2O$) | 10 | pH | Shangguan et al., 2013 |
| | Drainage class | 8 | DC | Shangguan et al., 2014 |
| | Available phosphorous (mg/kg) | 7 | AP | Shangguan et al., 2013 |
| | Calcium carbonate (%) | 6 | CC | Shangguan et al., 2014 |
| | Cation exchange capacity (me/100 g) | 6 | CEC | Shangguan et al., 2013 |
| | Alkali-hydrolysable nitrogen (mg/kg) | 6 | AN | Shangguan et al., 2013 |
| | Electrical conductivity (dS/m) | 4 | EC | Shangguan et al., 2014 |
| | Rock fragment (g/100g) | 3 | RF | Shangguan et al., 2013 |
| | Soil erosion | 3 | SE | http://www.resdc.cn |
| Topography | Elevation (m) | 6 | EL | NASA Shuttle Radar Topographic Mission |
| | Slope (º) | 18 | SL | Derived from EL |
| | Aspect | 4 | AS | Derived from EL |
| Location condition | Distance to river (km) | 5 | DRI | http://www.resdc.cn |
| | Original land use | 4 | OLU | http://www.resdc.cn |
| | Distance to residential area (km) | 2 | DRA | http://www.resdc.cn |

### 2.3 Determination of indicator weights

The Analytical Hierarchy Process (AHP) developed by Saaty (1980) is one of the multi-criteria decision-making approaches to solve complex spatial problems. The AHP is very suitable to incorporate the knowledge of experts to determine the weights of a hierarchical structure of criteria, such as the indicator system of land suitability evaluation in this study. We organized the land suitability analysis for crop production into a hierarchical way consisting of the 'goal, criteria and alternative' structure. The goal was the land suitability evaluation for agriculture in the Taihang Mountains. The criteria were the indicator criterion in the indicator system including soil properties, topography and location conditions, and the alternative was the specific indicator within each criterion as listed in Table 1. After the organization of the hierarchical structure, the indicator weights were calculated by the AHP method with the opinions of experts.

### 2.4 Construction of fuzzy matter-element model

Matter-element model is an effective approach to evaluate the suitability of land for agriculture. In real world, the suitability of some indicators (e.g., soil texture) for crop production is ambiguous and it is difficult to objectively and quantitatively estimate the performance of these indicators. In order to solve this problem, the fuzzy theory can be applied to use a certain number between 0 and 100 to measure the degree of suitability of the indicators for agriculture. Therefore, the combination of matter-element model with fuzzy math is especially efficient to settle vague and incompatible problems (Li and Li, 2014), such as land suitability analysis. The detailed procedures of matter-element analyses are as follows.

#### *2.4.1 Determination of matter-element to be evaluated*

In the matter-element theory, a system is comprised of a set of matter-elements, with each matter-element consisting of objects ($N$), characteristics ($c$) and values ($v$). For each $N$, the characteristic $c$ is valued as $v$, then the orderly ternary group $R$ = ($N$, $c$, $v$), namely matter-element, is used to describe the system. For the land suitability in this study, it usually has various characteristics. Suppose the land suitability $N$ can be depicted by $n$ indicators $c_1$, $c_2$, …, $c_n$ and the corresponding values $v_1$, $v_2$, …, $v_n$, then the matter-element for land suitability can be expressed as:

$$R=(N,c,v)=\begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \tag{1}$$

where $R$ is the $n$-dimensional matter-element of land suitability for agriculture; $N$ is the minimum spatial unit of land suitability; $c$ is the indicators to evaluate land suitability; and $v$ is the value of each indicator.

#### *2.4.2 Classical domain and segmented domain*

The indicators of agricultural land suitability normally have different grades to describe the degree of their suitability for crop production. The classical domain ($R_j$) refers to the range of values for indicator $i$ at grade $j$.

$$R_j=(N_j,c_i,v_{ji})=\begin{bmatrix} N_j & c_1 & v_{j1} \\ & c_2 & v_{j2} \\ & \vdots & \vdots \\ & c_n & v_{jn} \end{bmatrix}=\begin{bmatrix} N_j & c_1 & (a_{j1},b_{j1}) \\ & c_2 & (a_{j2},b_{j2}) \\ & \vdots & \vdots \\ & c_n & (a_{jn},b_{jn}) \end{bmatrix} \tag{2}$$

where $N_j$ is the land suitability belongs to grade $j$; $c_1$, $c_2$, …, $c_n$ are $n$ different indicators of $N_j$; and $v_{j1}$, $v_{j2}$, …, $v_{jn}$ are the value ranges for each $c_i$ of $N_j$, of which $a_{ji}$ and $b_{ji}$ are the upper and lower limits for each $c_i$ of $N_j$, respectively.

The segmented domain ($R_p$) is an aggregation of classical domains and it can be defined as the range of values of the indicator $i$ at all grades.

$$R_p=(p,c_i,v_{pi})=\begin{bmatrix} p & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix}=\begin{bmatrix} p & c_1 & (a_{p1},b_{p1}) \\ & c_2 & (a_{p2},b_{p2}) \\ & \vdots & \vdots \\ & c_n & (a_{pn},b_{pn}) \end{bmatrix} \tag{3}$$

where $p$ is the land suitability at all grades; $v_{p1}$, $v_{p2}$, …, $v_{pn}$ are the value ranges for $c_1$, $c_2$, …, $c_n$; and $a_{pi}$ and $b_{pi}$ represent the minimum and maximum values for the range of each $c_i$, respectively.

On the basis of Food and Agriculture Organization (FAO) suitability classes (FAO, 1976), we classified the land suitability for agriculture into four grades: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (NS). For each indicator, the range of all the four grades was thoughtfully determined by collecting information from literatures and databases, and referring to the Second Nationwide General Soil Survey (National Soil Census Office, 1998) and the Regulation for Gradation on Agricultural Land Quality (Standardization Adiministration of the People's Republic of China, 2012) (Table 2). In this process, the classical domain and segmented domain for land suitability evaluation were established simultaneously.

### *2.4.3 Normalization of indicators*

All the quantitative indicators ($x_{ij}$) were normalized for each suitability grade ($S$) with the efficacy coefficient method before land suitability evaluation. Positive effective indicators were normalized between 0 and 100 for all four grades according to Equation (4), and negative effective indicators were also normalized similarly according to Equation (5).

$$S_{(xij)} = S_{\mathrm{MIN}} + \frac{x_{ij} - \min_{(xij)}}{\max_{(xij)} - \min_{(xij)}} \times (S_{\mathrm{MAX}} - S_{\mathrm{MIN}}) \tag{4}$$

$$S_{(xij)} = S_{\mathrm{MIN}} + \frac{\max_{(xij)} - x_{ij}}{\max_{(xij)} - \min_{(xij)}} \times (S_{\mathrm{MAX}} - S_{\mathrm{MIN}}) \tag{5}$$

where $S_{(xij)}$ is the normalized value of $x_{ij}$ with a range from 0 to 100; $S_{\mathrm{MAX}}$ and $S_{\mathrm{MIN}}$ are the maximum and minimum standardized values of a specific grade that $x_{ij}$ is subject to; and $\max_{(xij)}$ and $\min_{(xij)}$ are the measured values of the maximum and minimum of all the matter-elements for the same grade, respectively.

**Table 2** Range of grades for indicators of agricultural land suitability

| Criterion | Indicator[1] | Range of grades for agricultural land suitability[2] | | | | Grade reference |
|---|---|---|---|---|---|---|
| | | S1 | S2 | S3 | NS | |
| Soil property | ST | Loam; Sandy loam | Clay loam; Silt loam | Clay; Loamy sand | Sand | Standardization Adiministration of the People's Republic of China, 2012; Li et al., 2017 |
| | SOM | ≥4.0 | [2.0, 4.0) | [0.6, 2.0) | <0.6 | National Soil Census Office, 1998; Standardization Adiministration of the People's Republic of China, 2012 |
| | SD | ≥150 | [100, 150) | [30–100) | <30 | Standardization Adiministration of the People's Republic of China, 2012 |
| | pH | [6.0, 7.0); [7.0, 7.9] | [5.5, 6.0); (7.9, 8.5] | (8.5, 9.0] | >9.0 | Standardization Adiministration of the People's Republic of China, 2012 |
| | DC | Well; Moderately well | Imperfectly | Poorly | Very poorly | Standardization Adiministration of the People's Republic of China, 2012 |
| | AP | ≥40 | [10, 40) | [3, 10] | <3 | National Soil Census Office, 1998 |
| | CC | ≤1 | (1, 5] | (5, 15) | >15 | Mesgaran et al., 2017 |
| | CEC | ≥16 | [10, 16) | [6, 10] | <6 | Li et al., 2017 |
| | AN | ≥150 | [90, 150) | [30, 90] | <30 | National Soil Census Office, 1998 |
| | EC | ≤0.5 | (0.5, 2.0] | (2.0, 4.0] | >4.0 | Yu et al., 2011; Mesgaran et al., 2017 |
| | RF | ≤5 | (5, 15] | (15, 35) | >35 | Elsheikh et al., 2013; Mesgaran et al., 2017 |
| | SE | Mildly | Slightly; Moderately | Strongly | Extremely; Severely | Li et al., 2017 |
| Topography | SL | ≤2 | (2, 8] | (8, 25) | >25 | Standardization Adiministration of the People's Republic of China, 2012 |
| | EL | ≤200 | (200, 800] | (800, 1200] | >1200 | Yu, 2004; Guan et al., 2010 |
| | AS | Flat; South | East; Southeast; Southwest | Northeast; West; Northwest | North | Wei and Hua, 2012; Yao et al., 2015 |
| Location condition | DRI | ≤1 | (1, 2] | (2, 3) | >3 | Yu et al., 2011 |
| | OLU | Croplands | Grasslands | Garden plots | Woodlands | Bandyopadhyay et al., 2009; Fang et al., 2017 |
| | DRA | ≤1.0 | (1.0, 1.5] | (1.5, 2.0] | >2.0 | Dong et al., 2011; Fang et al., 2017 |

Notes: [1] See Table 1 for abbreviations of the indicators; [2] S1, S2, S3, and NS refer to the grade of highly suitable, moderately suitable, marginally suitable, and not suitable

For the qualitative indicators, a certain value ranging from 0 to 100 was allocated to each suitability grade objectively for further calculations. For example, loams, sandy loams, clay loams, silt loams, clay, loamy sands and sands in the soil texture were given the value of 100, 80, 70, 60, 40, 30 and 20, respectively. Similarly, the quantization of drainage class (well (100), moderately well (90), imperfectly (50), poorly (30), very poorly (10)), soil erosion (no erosion (100), mildly (90), slightly (70), moderately (50), strongly (30), extremely (10), severely (0)), aspect (flat (100), south (100), east (70), southeast (70), southwest (70), northeast (40), west (40), northwest (40), north (10)) and the original land use (croplands (100), grasslands (70), garden plots (40), woodlands (10)) was also determined.

***2.4.4 Establishment of the correlation function***

The correlation function was established to quantify the degree of land suitability for every indicator $i$ to each grade $j$. The correlation degree for all matter-elements was calculated with the following functions:

$$K_j(v_i)=\begin{cases}\dfrac{-\rho(v_i,v_{ji})}{|v_{ji}|}, v_i \in v_{ji} \\ \dfrac{\rho(v_i,v_{ji})}{\rho(v_i,v_{pi})-\rho(v_i,v_{ji})}, v_i \notin v_{ji}\end{cases} \quad (6)$$

where $K_j(v_i)$ is the correlation degree of indicator $i$ to grade $j$ and $v_i$ is the value of the matter-element measured; $v_{ji}$ and $v_{pi}$ are the classical domain of indicator $i$ at grade $j$ and the segmented domain of indicator $i$, respectively; $\rho(v_i, v_{ji})$ and $\rho(v_i, v_{pi})$ represent the distance of the evaluated matter-element of indicator $i$ to the classical domain and the segmented domain, and the distance can be calculated by Equation (7) and (8).

$$\rho(v_i,v_{ji})=\left|v_i-\frac{1}{2}(a_{ji}+b_{ji})\right|-\frac{1}{2}(b_{ji}-a_{ji}) \quad (7)$$

$$\rho(v_i,v_{pi})=\left|v_i-\frac{1}{2}(a_{pi}+b_{pi})\right|-\frac{1}{2}(b_{pi}-a_{pi}) \quad (8)$$

***2.4.5 Calculation of the integrated correlation degree***

The calculation of integrated correlation degree is the final step to determine the grade of agricultural land suitability for each matter-element. Based on the correlation degree ($K_j(v_i)$) of all the indicators and their weights ($w_i$), the integrated correlation degree can be calculated as below:

$$K_j(R)=\sum_{i=1}^{n} w_i K_j(v_i) \quad (9)$$

where $K_j(R)$ is the integrated correlation degree of grade $j$ for the evaluated matter-element $R$; $w_i$ is the weight of indicator $i$, and $K_j(v_i)$ is the correlation degree of indicator $i$ to grade $j$. If

$$K_j(R)=\max(K_j(R)) \quad (10)$$

then the matter-element $R$ belongs to the land suitability grade $j$ for agriculture. The value range of the integrated correlation degree can be $(-\infty, +\infty)$, rather than the closed interval [0, 1] in traditional fuzzy method, thereby providing more information and details for the variance (Tang et al., 2009; Gong et al., 2012). If $K_j(R)$ is larger than 0, the matter-element to be evaluated can meet the criteria of a given grade standard, and a larger value denotes greater suitability. If $K_j(R)$ is between −1 to 0, the matter-element to be evaluated cannot satisfy the criteria of a given grade standard, but has the potential to be transformed into that grade, with a larger value indicating greater potential of transformation. If $K_j(R)$ is smaller than −1, the matter-element to be evaluated cannot meet the criteria of a given grade standard and do not have the potential to transform to the given grade.

### 2.5 Accuracy assessment

In order to estimate the model accuracy, we compared our results of agricultural land suitability evaluation to the reference data of potential crop yield (Liu et al., 2015). Considering that the outputs of land suitability were categorical variables in this study, a numeric range from 0 to 100 was given to the grade of suitability, of which the interquartile range was given to the four suitability grades with larger values indicating higher suitability. Then the midpoints of each grade were used to explore the correlation between land suitability and potential crop yield. An accurate evaluation outcome is capable of investigating the rationality of current agricultural land distribution.

## 3 Results

### 3.1 Agricultural land suitability assessment

The outputs of the fuzzy matter-element model were illustrated as classification maps of land suitability for agriculture (Fig. 2). The spatial distribution of suitable land for crop production varied largely. Highly suitable and moderately suitable grades of land were predominately located in the piedmont plains along the eastern margin and the basins along the western margin of the Taihang Mountains, surrounding the marginally suitable and not suitable land mainly situated in the central mountainous zones. Statistics showed that the area of highly, moderately, marginally and not suitable land accounted for 32.13%, 28.58%, 37.49% and 1.80% of the production space, respectively. In the county-level analysis, the area proportion of highly suitable land combined with moderately suitable land was calculated to reveal the potential of land for crop production in each county. Similar to the spatial pattern of land suitability, the counties with higher suitability to develop agriculture primarily lied in the lowland zones with an average elevation of 531 m, among which the counties with the area ratio larger than 75% were mainly in the eastern side and the counties with the area ratio between 50% and 75% were largely in the western side. In contrast, the counties with the area ratio lower than 50% were concentrated in highlands with a mean elevation of 1042 m.

The highly and moderately suitable grades of land, covering an area of 36.27 thousand km$^2$, were optimum for agriculture with minor to moderate limitations, accounting for 60.71% of the production space in the Taihang Mountains. Most of the these areas were located in the Taihang Piedmont Plain, Datong Basin, Taiyuan Basin, Linfen Basin, Yuncheng Basin and Changzhi Basin. For the administrative areas, almost all counties in the Taihang Piedmont Plain, Datong Basin and Yuncheng Basin had more than 75% of their production space as moderately to highly suitable for agriculture. By comparison, the counties in Taiyuan Basin, Linfen Basin and Changzhi Basin had a lower area proportion of 50%–75%.

Only 1.80% of the production space was classified into the grade of not suitable for agriculture, indicating that a considerable amount of land was regarded as suitable for crop production. However, the quality of suitability was not high because the land within the grade of marginally suitable had the largest ratio with major limitations for agriculture. An area of 22.40 thousand km$^2$ in the production space was occupied by the marginally suitable land where poor soil quality, terrain and stand conditions were observed, especially in mountainous counties such as Mentougou, Xiyang, Heshun, Zuoquan, Pingshun, Gu, Anze and Qinshui.

### 3.2 Model validation

Mean potential crop yields were estimated for land within each of the four suitability grades to assess the model accuracy by examining the relationship between land suitability and the potential crop yield. Linear regression analysis showed that the potential crop yield was significantly correlated with agricultural land suitability with a high correlation coefficient ($R^2$) of 0.94 (Fig. 3). Thus, potential crop yields would increase proportionally with the improvement of land suitability, indicating that our evaluation of land suitability for agriculture was highly effective to predict crop production.

### 3.3 Ranges of land suitability grades

The range of integrated correlation degree was −0.85 to 0.05 for the grade highly suitable, −0.98 to 0.17 for moderately suitable, −0.98 to 0.18 for marginally suitable, and −0.75 to 0.01 for not suitable, respectively (Table 3). The sub-ranges separated by 0 were able to detect the degree of matter-elements to meet the criteria of a given grade standard, with positive values referring to the matter-element to be evaluated already within the given grade and negative values indicating the matter-element was currently not subject to but had the potential to be transformed into the given grade. Results showed that almost all the matter-elements did not satisfy the requirement of each grade but have the potential to be developed to the corresponding grade. For example, in the grade highly suitable, only 0.02% of the matter-elements were in line with the grade, while the rest (99.98%) of matter-elements was presently not affiliated to the grade but could be converted into the grade. In terms of the total area, the corresponding percentage of the former was 0.01% and the latter 32.12%. Similarly, the percentages of the matter-elements with potential to transform into grade moderately suitable, marginally suitable and not suitaoble were 99.58%, 98.94% and 100.00% of the grade, and 28.46%, 37.09% and 1.80% of the total area, respectively.

### 3.4 Influence factors of agricultural land suitability

The results of AHP indicated that the indicators showed distinctive importance to evaluate the suitability of land

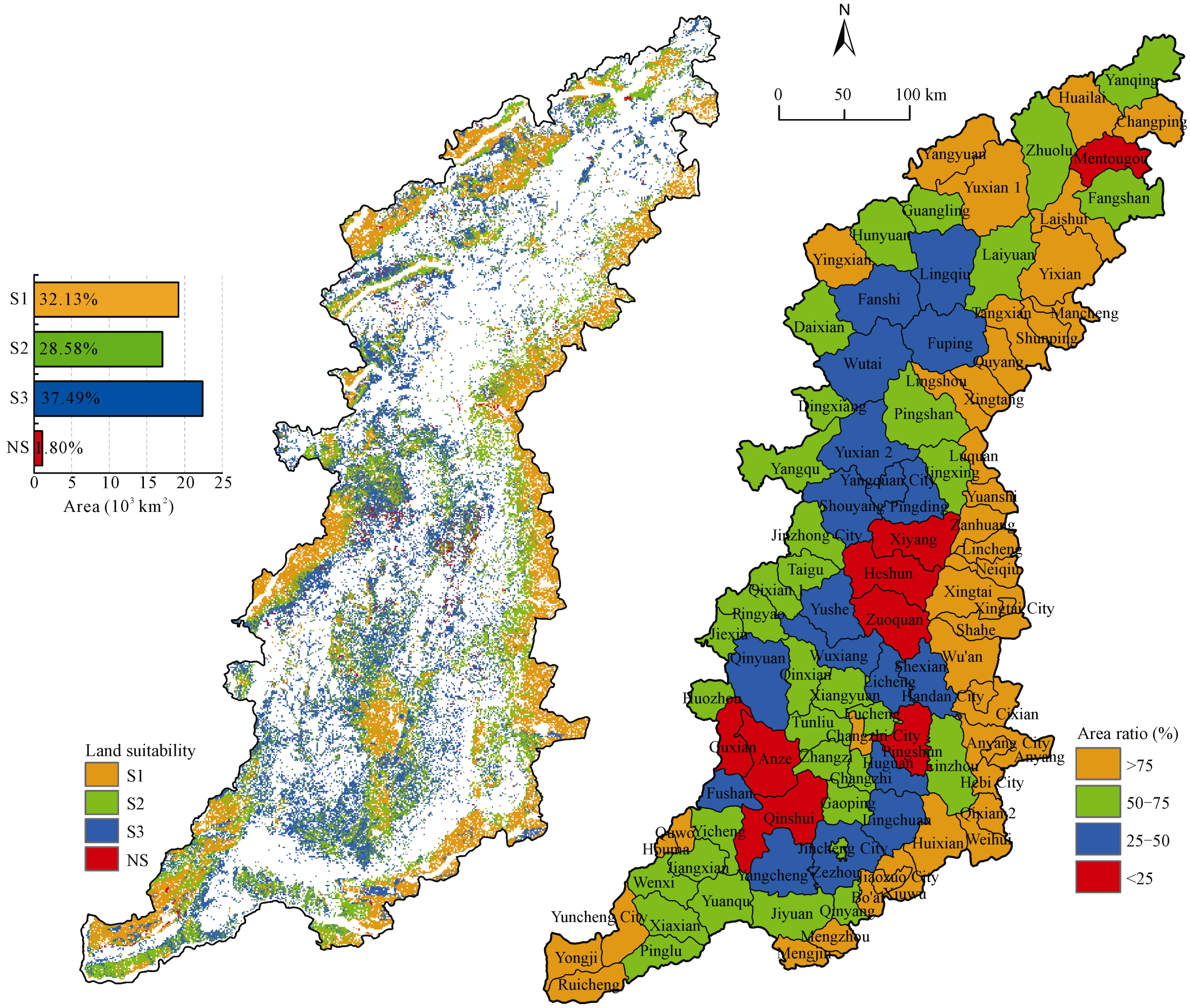


**Fig. 2** Spatial pattern with area statistics of agricultural land suitability (left) and county-level area ratios of land suitable (S1+S2) for agriculture (right). S1-highly suitable; S2-moderately suitable; S3-marginally suitable; NS-not suitable. Yuxian 1 and Yuxian 2 are two different counties with the same pronunciation which could be distinguished by number and location in the figure. The same for Qixian 1 and Qixian 2.

**Table 3** Ranges of different land suitability grades and their percentages of sub-ranges in production space of the Taihang Mountains in 2015

| Suitability grade[1] | Correlation degree | Percentage of the grade (%) | | Percentage of the total area (%) | |
|---|---|---|---|---|---|
| | | ≤0 | >0 | ≤0 | >0 |
| S1 | −0.85 to 0.05 | 99.98 | 0.02 | 32.12 | 0.01 |
| S2 | −0.98 to 0.17 | 99.58 | 0.42 | 28.46 | 0.12 |
| S3 | −0.98 to 0.18 | 98.94 | 1.06 | 37.09 | 0.40 |
| NS | −0.75 to 0.01 | 100.00 | 0.00 | 1.80 | 0.00 |

Notes: [1] S1, S2, S3, and NS refer to the grade of highly suitable, moderately suitable, marginally suitable, and not suitable

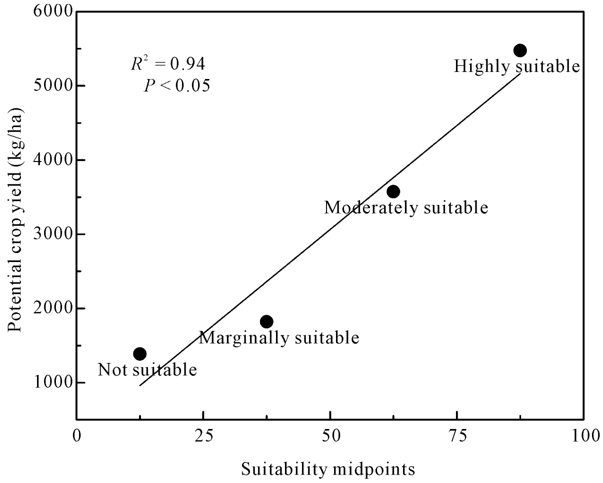


**Fig. 3** Correlation analysis of land suitability and potential crop yields in production space of the Taihang Mountains in 2015

for agriculture (Table 4). In the criteria hierarchy of AHP, the soil property was much more important than the topography and the location condition, with the weight of 0.66, 0.29 and 0.05, respectively. Among the soil properties, soil texture (ST), soil organic matter (SOM) and soil depth (SD) played the most vital role in determining the land suitability with the same weight of 0.12, followed by nutrient elements (e.g., available phosphorous, AP and alkali-hydrolysable nitrogen, AN) and pH values with the weight of 0.06. In contrast, calcium carbonate (CC) had the smallest impact with the weight of only 0.01. The influence of topography on the suitability was primarily determined by slope (SL) with the weight of 0.17, while elevation (EL) and aspect (AS) had an equivalent but much smaller weight of 0.06. Among the indicators in location conditions, distance from rivers (DRI) was more crucial compared to distance to residential area (DRA) and original land use (OLU). In general, the land suitability for agriculture relied heavily on SL, ST, SOM and SD, and their importance surpassed that of the rest 14 indicators.

### 3.5 Land suitability of existing croplands

The analysis of the distribution of existing croplands indicated that there were approximately 48.36 thousand $km^2$ of cropland in the Taihang Mountains and the percent of land used for cropping increased linearly with land suitability for crop production (Table 5). More croplands were distributed in the high and moderate suitability grade with the percentage of 95.83% and 84.80%, respectively. The corresponding percentage for the rest of two suitability grades, i.e., marginally suitable and not suitable dropped quickly to 66.52% and

**Table 4** The indicator weights determined by AHP in production space of the Taihang Mountains in 2015

| Goal hierarchy | Criteria hierarchy | Weight | Alternative hierarchy[1] | Weight |
|---|---|---|---|---|
| Land suitability for agriculture | Soil property | 0.66 | ST | 0.12 |
| | | | SOM | 0.12 |
| | | | SD | 0.12 |
| | | | pH | 0.06 |
| | | | DC | 0.02 |
| | | | AP | 0.06 |
| | | | CC | 0.01 |
| | | | CEC | 0.02 |
| | | | AN | 0.06 |
| | | | EC | 0.02 |
| | | | RF | 0.02 |
| | | | SE | 0.02 |
| | Topography | 0.29 | SL | 0.17 |
| | | | EL | 0.06 |
| | | | AS | 0.06 |
| | Location condition | 0.05 | DRI | 0.04 |
| | | | OLU | 0.01 |
| | | | DRA | 0.01 |

Notes: [1] See Table 1 for abbreviations of the indicators

**Table 5** The area of existing croplands within suitability grades and the corresponding percentages to the area of each suitability grade and the total cropland area

| Suitability grade[1] | Area of suitability grade ($10^4$ km$^2$) | Area of cropland ($10^4$ km$^2$) | S (%)[2] | C (%)[3] |
|---|---|---|---|---|
| S1 | 1.92 | 1.84 | 95.83 | 38.02 |
| S2 | 1.71 | 1.45 | 84.80 | 29.96 |
| S3 | 2.24 | 1.49 | 66.52 | 30.79 |
| NS | 0.11 | 0.06 | 54.55 | 1.24 |
| Total | 5.98 | 4.84 | – | 100.00 |

Notes: [1] S1, S2, S3, and NS refer to the grade of highly suitable, moderately suitable, marginally suitable, and not suitable; [2] S (%) means the percentage of land used for agriculture within each suitability grade; [3] C (%) means the percentage of cropland area of each suitability grade to the total cropland area.

54.55%. For the relative proportion of cropland distribution amongst the suitability grades to the total area of croplands (Table 5), more than 32% of the croplands were located in land with marginal or lower suitability for crop production. The moderately suitable land accounted for 29.96% of the total croplands, a very equivalent proportion to that of marginally suitable land at 30.79%. Regions with high suitability had the largest area, taking up 38.02% of the total area of croplands.

## 4 Discussion

### 4.1 Spatial pattern of agricultural land suitability

Land suitability for agriculture in the Taihang Mountains is generally in moderate to high level with more than 60% of the production space at moderately or highly suitable for crop production. The spatial pattern of land suitability is largely in accordance with landforms. Specifically, the suitability of piedmont plains and basins with smaller slope and lower elevation is higher than that of mountainous areas with larger slope and higher elevation, in line with previous studies (Yu, 2004; Bai, 2012). In addition, the actual and potential production analysis (Li, 2012) and the planting area suitability assessment (Zheng, 2015) of the dominant grain and oil crops in the study area indicated that the limitations for maize, wheat, millet, sweet potato, peanut and soybean decreased gradually from mountains to hills and then to basins and plains, a strong support of our findings. In comparison with traditional land suitability evaluation methods such as weighted linear combination or weighted overlay analysis, matter-element model is able to identify how close the land to be evaluated is to reach the standard of a given suitability grade. In this study, the ranges of land suitability grades that derived from integrated correlation degrees showed that the requirements of nearly all the grades were currently not satisfied but could be potentially fulfilled by the corresponding matter-elements under proper field management. This may be due to the low soil quality in the study area (Geng et al., 2018). As soil properties are the most important criterion with a much larger weight (0.66) than topography (0.29) and location conditions (0.05), soil will have more influences on the output of the suitability evaluation and thus poor soil quality is ought to reduce the potential of land for crop production. Therefore, soil fertility improvements are most likely to actualize land potential for agriculture. In conclusion, our classification of agricultural land suitability in the production space of the Taihang Mountains is rational and powerful to provide guidance for land management and tillage practices in mountainous areas.

### 4.2 Implications for land use planning scenarios

As a precondition of agricultural land planning, land suitability evaluation for crop production can provide suggestions for making decisions (Hood et al., 2006; Li et al., 2017; Kazemi and Akinci, 2018). First, weight determination method such as AHP can recognize the relative important factors to have vital influences on the suitability grades and these factors are usually the limiting factors for crop growth, so improvements can be introduced explicitly for them during practical production. For example, slope and soil quality especially soil organic matter and soil texture are the most limiting factors for cropland establishment in this study, so slope faming should be avoided to control soil erosion (Deng et al., 2012) and organic fertilization should be encouraged to ameliorate soil structure (Huang et al., 2010). Moreover, land suitability analysis can distinguish the potential land for agriculture. Although the percentage of land used for crop production within highly and moderately suitability grades are relatively high, there is still room for cropland expansion in these two grades, especially under the tendency of significant population emigration in the Taihang Mountains over the past decades (Li and Tan, 2018). In addition, the land suitability map can be guidance for the orientation of development. The county-level area ratio of the highly and moderately suitable land for agriculture indicates that counties with the ratio higher than 50% is appropriate to continuously develop agriculture because of their relatively good conditions for crop production, but the rest of counties with poor agricultural conditions may need to converse agriculture to other industries according to their local features to improve soil quality and compensate the economic loss of farmers, such as orchards or timberlands (Wang et al., 2013; Song et al., 2014).

Since the model used in this study is able to effectively and accurately assess the potential of land for crop production, the outcomes of land suitability evaluation can gain insights into the rationality of the present distribution of croplands. Although there is only 1.80% of the total production space and 1.24% of the current croplands found to be not suitable for crop cultivation, more than half (54.55%) of the land in the suitability grade of not suitable is currently occupied by croplands. Even a higher proportion of nearly two-thirds (66.52%) can be observed for the grade of marginally suitable, which has the largest area among all four suitability grades. These croplands in the marginally or lower suitability grade are generally located in areas with low soil quality, poor transportation, large slope and unpleasant crop yields, where soil erosion and land degradation are prone to occur under tillage (Islam and Weil, 2000). Hence, it is essential to reduce the percentage of croplands in these areas for the sake of ecological benefits. Actually, the government has launched a series of projects, i.e., the Grain for Green Program in the Taihang Mountains to prevent soil and water loss by removing slope farmlands (Liu et al., 2010; Deng et al., 2012). Furthermore, this program was reported to have beneficial effects on runoff decrease and soil erosion control (Deng et al., 2012). Therefore, de-farming policy should be implemented continuously to mitigate the severe soil erosion problem in the study area.

## 5 Conclusions

This study used an AHP-based fuzzy matter-element model to evaluate the agricultural land suitability of the production space in the Taihang Mountains. The model outputs were verified by potential crop yields, indicating that our assessment of the suitability of land for agriculture was able to accurately predict crop production. Results demonstrated that the spatial pattern of the evaluated land suitability varied largely along with landforms, i.e., higher suitability in piedmont plains and basins and lower suitability in mountainous areas. Land resources for agriculture were relatively rich with more than 60% of the land was moderately and highly suitable for crop production and only 1.80% was not suitable. However, the quality of suitability was not high because the marginally suitable land had the largest area, accounting for 37.49% of the production space. Slope, soil organic matter, soil texture and soil depth were the most important indicators to influence the suitability grade, so slope farming avoidance and organic fertilization are more likely to improve land potential for agriculture. Compared the agricultural land suitability with the distribution of the current croplands, de-farming was suggested to croplands in marginally and lower suitability grades, while expansion was encouraged for croplands in moderately and highly suitability grades.

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