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# Spatial-temporal variation of marginal land suitable for energy plants from 1990 to 2010 in China

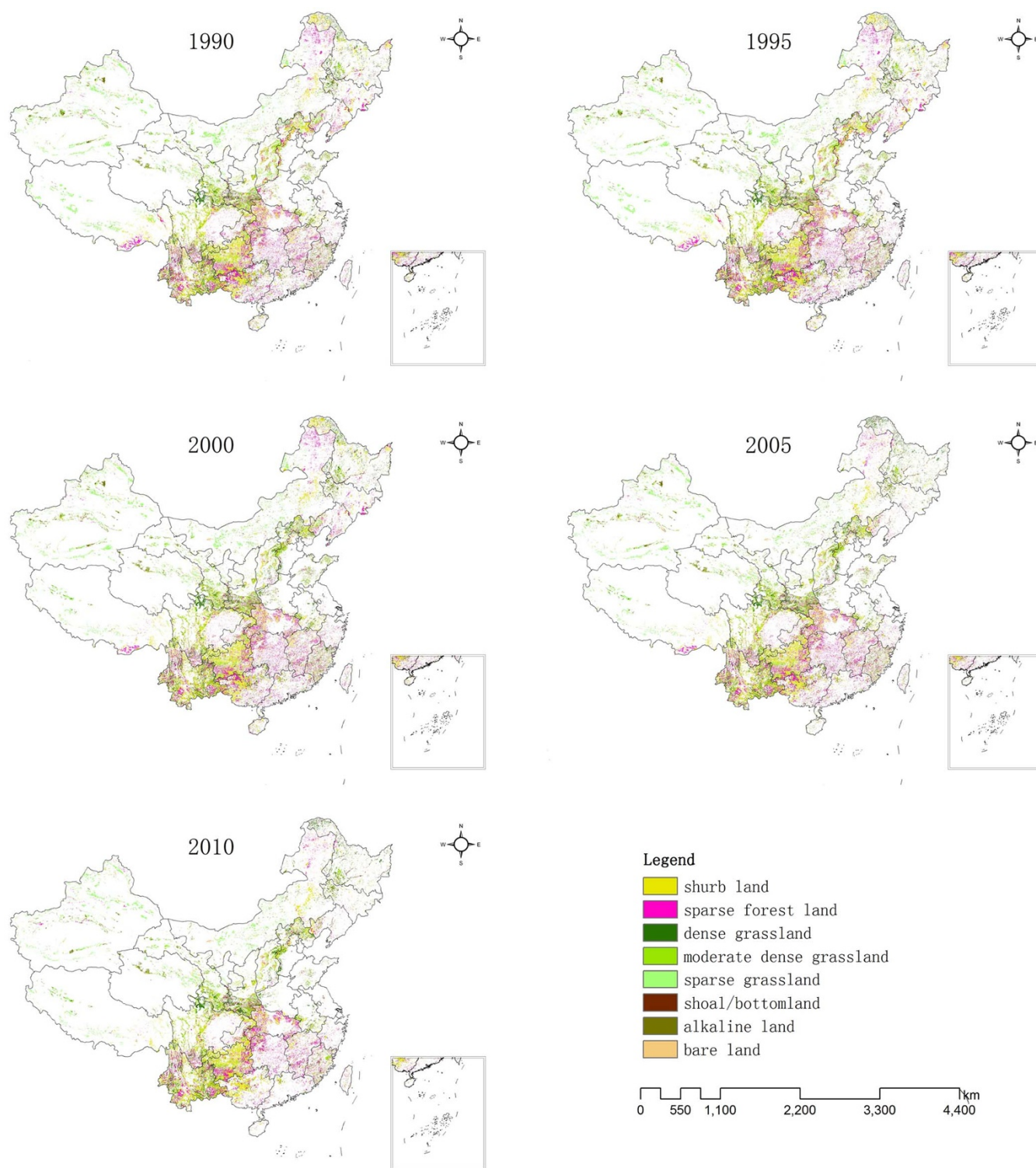
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Energy plants are the main source of bioenergy which will play an increasingly important role in future energy supplies. With limited cultivated land resources in China, the development of energy plants may primarily rely on the marginal land. In this study, based on the land use data from 1990 to 2010 (every 5 years is a period) and other auxiliary data, the distribution of marginal land suitable for energy plants was determined using multi-factors integrated assessment method. The variation of land use type and spatial distribution of marginal land suitable for energy plants of different decades were analyzed. The results indicate that the total amount of marginal land suitable for energy plants decreased from 136.501 million ha to 114.225 million ha from 1990 to 2010. The reduced land use types are primarily shrub land, sparse forest land, moderate dense grassland and sparse grassland, and large variation areas are located in Guangxi, Tibet, Heilongjiang, Xinjiang and Inner Mongolia. The results of this study will provide more effective data reference and decision making support for the long-term planning of bioenergy resources.

Energy is the lifeblood of the world economy and the force of social development; it is also the basis for the existence and development of modern society. The increasing global demand for energy has become a major challenge in the development of human society in the twenty-first century. The development of renewable energy is the most effective measure for solving the energy shortage. Recently, the energy arising from biomass resources has received significantly more attention, primarily to safeguard national energy security, reduce greenhouse gas emissions and meet the energy demand<sup>1–3</sup>. Energy plants are the main source of biomass energy. The literature on this topic has grown rapidly in recent years. For example, Liu L. et al. evaluated the biomass energy potentials and the environmental benefits of *Jatropha curcas* L. in southwest China<sup>4</sup>. Umar, M.S. et al. indicated that the palm oil biomass renewable energy industry should be strengthened in Malaysia<sup>5</sup>. Wang T. surveyed the woody plant resources for biomass fuel oil in China<sup>6</sup>. Hiloidhari M. and Baruah D.C. presented the spatial assessment of crop residue and its power potential at the village level in the Sonitpur District of Assam, India<sup>7</sup>. Yu H. et al. discussed the development and utilization of herbaceous energy plants<sup>8</sup>.

The availability of land to grow energy plants is the primary factor for bioenergy development. With limited cultivated land resources in China<sup>9</sup>, the development of energy plants must follow the idea “not using the grain intended for human consumption and not occupying the land intended for grain production”. There are many types of land in China, including marginal land, which is not suitable for food production. Making full use of marginal land resources is of great significance for biomass energy development<sup>10</sup>. Relevant studies have been presented on the distribution of marginal land in China that is suitable for certain energy plants on a regional scale. These studies include an analysis of the marginal land availability for developing *Pistacia chinensis*-based bioenergy in China<sup>11</sup>, the assessment of marginal land resources and bio-fuel potential in China using newly acquired data and Geographic Information System (GIS) techniques<sup>12</sup>, an evaluation of marginal land for energy plants in the Jiang Xi Province<sup>13</sup>, the plantation potential assessment of *Vernicia fordii* (Hemsl.) on marginal lands of the Sichuan Province<sup>14</sup> and a GIS-based assessment of the quality of the marginal land in Zhangzhou City in South China<sup>15</sup>.

Among the relevant studies, the evaluation of the marginal land suitable for energy plants was based on the data available at that time, which lacks a variation study over a longer time scale. An operational GIS-based approach was presented, taking into account a number of issues: land use type, elevation, climate, soil condition and

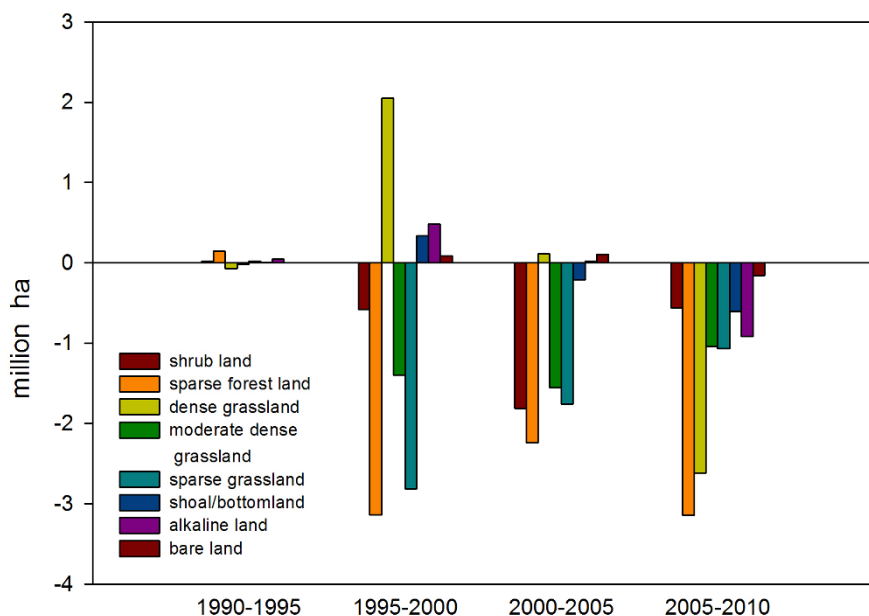


**Figure 1 | The spatial distribution of the marginal land suitable for energy plants in China from 1990–2010.** First, we used ‘select by attributes’ function in ArcGIS software which is a professional software for processing geospatial data to select the marginal land use types based on the land use data from 1990 to 2000. There are 6 land use types suitable as marginal land, include shrub land, sparse forest land, grassland (dense grassland, moderate dense grassland and sparse grassland), shoal/bottomland, alkaline land and bare land. Based on the marginal land data, the climate data, soil data, DEM data and slope data, considering constraint conditions for the growth of energy plants, using ‘con’ function in ArcGIS software, we obtained the spatial distribution of the marginal land suitable for energy plants.

conservation requirement. Total amount, spatial and temporal distribution of marginal land were achieved at national scale from 1990–2010. The result will provide more effective data reference and decision making support for the future long-term planning of bioenergy resources.

## Results

Based on the land use data from 1990 to 2010 (1 km; every 5 years is a period) and other data, using multi-factors integrated assessment, we obtained the spatial distribution of the marginal land suitable for energy plants from 1990 to 2010, as shown in Figure 1.



**Figure 2** | The land use types variation of marginal land suitable for energy plants from 1990 to 2010 in China. The part of greater than zero indicates that the amount of this land use type was increased, the opposite was decreased.

Figure 1 shows the marginal land suitable for energy plants is rich in China, but the land use type and spatial distribution of the marginal land suitable for energy plants have changed dramatically over the time scale. Therefore, we analyzed the change in the marginal land suitable for energy plants from the following two aspects: land use type and spatial distribution.

**The land use type variation analysis of marginal land suitable for energy plants.** Using ArcGIS software, we determined a classification statistic on marginal land suitable for energy plants (every five years is a period), obtaining the total amount of different land use types of marginal land suitable for energy plants from 1990 to 2010. The results are listed in Table 1.

Table 1 shows the total amount of China's marginal land suitable for energy plants is large, with an area of 136.501 million ha, 136.638 million ha, 131.672 million ha, 124.330 million ha and 114.225 million ha from 1990 to 2010 (every five years is a period), respectively. This land primarily consists of grassland, shrub land and sparse forest land. In 2010, shrub land, sparse forest land and grassland accounted for 29.62%, 20.85% and 44.67% of total amount of marginal land suitable for energy plants, respectively. Shoal/bottomland, alkaline land and bare land only accounted for 4.86% of total amount of marginal land suitable for energy plants. From figure 1 we can find that the marginal land suitable for energy plants was mainly distributed in Yunnan, Xinjiang, Sichuan and Inner Mongolia, besides, the mainly land use type was grassland in the northwest region and, the mainly land use types were shrub land and sparse forest land in the southern region.

From Table 1 and Figure 2 we can find that there was an observable change in the type of China's marginal land suitable for energy plants from 1990 to 2010. From 1990 to 1995, there is no significant change for each type, and the total area increased by only 0.137 million ha. After 1995, every land use type displayed a clear change. The total area of marginal land suitable for energy plants decreased by 4.966 million ha from 1995 to 2000, which was 3.63% of the 1995 value. The shrub land, sparse forest land, moderate dense grassland and sparse grassland were reduced by 0.576 million ha, 3.140 million ha, 1.397 million ha and 2.815 million ha, respectively, whereas dense grassland, shoal/bottomland, alkaline land and bare land increased by 2.053 million ha, 0.338 million ha, 0.484 million ha and 0.087 million ha, respectively. From 2000 to 2005, the total amount of marginal

land suitable for energy plants decreased by 7.342 million ha, which was 5.56% of the 2000 value. The shrub land, sparse forest land, moderate dense grassland, sparse grassland and shoal/bottomland decreased by 1.816 million ha, 2.242 million ha, 1.555 million ha, 1.760 million ha and 0.211 million ha, respectively, whereas the remaining land use types show a slight increase. From 2005 to 2010, the total amount of marginal land suitable for energy plants decreased by 10.105 million ha, which was 8.13% of the 2005 value. Each type of marginal land suitable for energy plants decreased in area, among which sparse forest land and dense grassland showed the greatest change, with a decrease of 3.141 million ha and 2.618 million ha, respectively, accounting for 31.08% and 25.91%, respectively, of the total decreased area.

In general, the national marginal land suitable for energy plants has continuously decreased at an increasing rate from 1995 to 2010. Most of the decreasing land use types are shrub land, sparse forest land and grassland.

Human activity is the main factor resulting in a decrease of marginal land suitable for energy plants, including the national macro strategy for land development, rapid economic growth and large-scale urbanization<sup>16</sup>, which lead to the increasing construction areas in urban and rural areas, causing a portion of the shrub land, sparse forest land and grassland to be occupied<sup>17,18</sup>.

The decrease of grassland areas mainly in Inner Mongolia, Heilongjiang, Tibet and Xinjiang etc where the marginal land suitable for energy crops mainly make up of grassland. In Mongolia and Heilongjiang, due to the profit-driven that farming income higher than animal husbandry income, coupled with no proper ecological and environmental protection policy, which resulted in the grassland was reclaimed for arable land. In the northwest, including Xinjiang, in addition to the grassland into arable land, control soil erosion and ecological restoration construction make the grassland into forest land. Besides, grassland desertification is also one of the reasons for its reduction<sup>19</sup>.

The reduction of shrub land and sparse forest land is the most significant form of human activity effect in nature. People expanded land area to increase food production, making part of shrub land and sparse forest land into arable land; Under the influence of natural driving factors, different forest types would be transformed between internal, such as shrub land and sparse forest land into forest land or


**Table 1 | The amount of marginal land suitable for energy plants from 1990 to 2010 in China (million ha)**

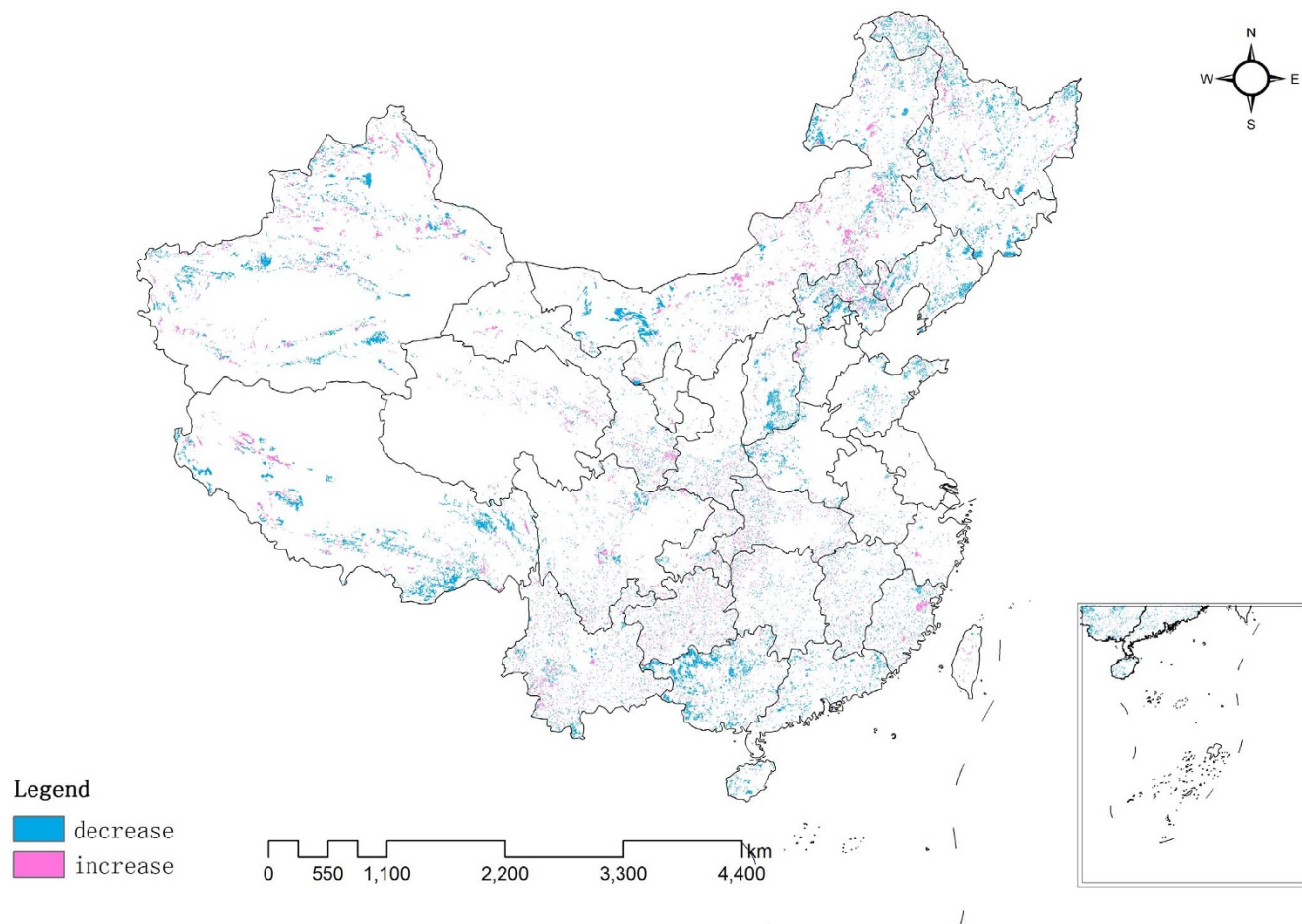
	Shrub land	Sparse forest land	Dense grassland	Moderate dense grassland	Sparse grassland	Shoal/bottomland	Alkaline land	Bare land	Sum
1990	36.766	32.197	19.511	19.771	21.895	1.812	3.983	0.565	136.501
1995	36.783	32.344	19.439	19.752	21.913	1.819	4.027	0.562	136.638
2000	36.207	29.204	21.492	18.354	19.098	2.157	4.511	0.650	131.672
2005	34.390	26.962	21.607	16.800	17.338	1.947	4.531	0.757	124.330
2010	33.831	23.821	18.989	15.761	16.270	1.341	3.613	0.600	114.225

other forest land type, this is also a factor in shrub land and sparse forest land decreased<sup>20</sup>.

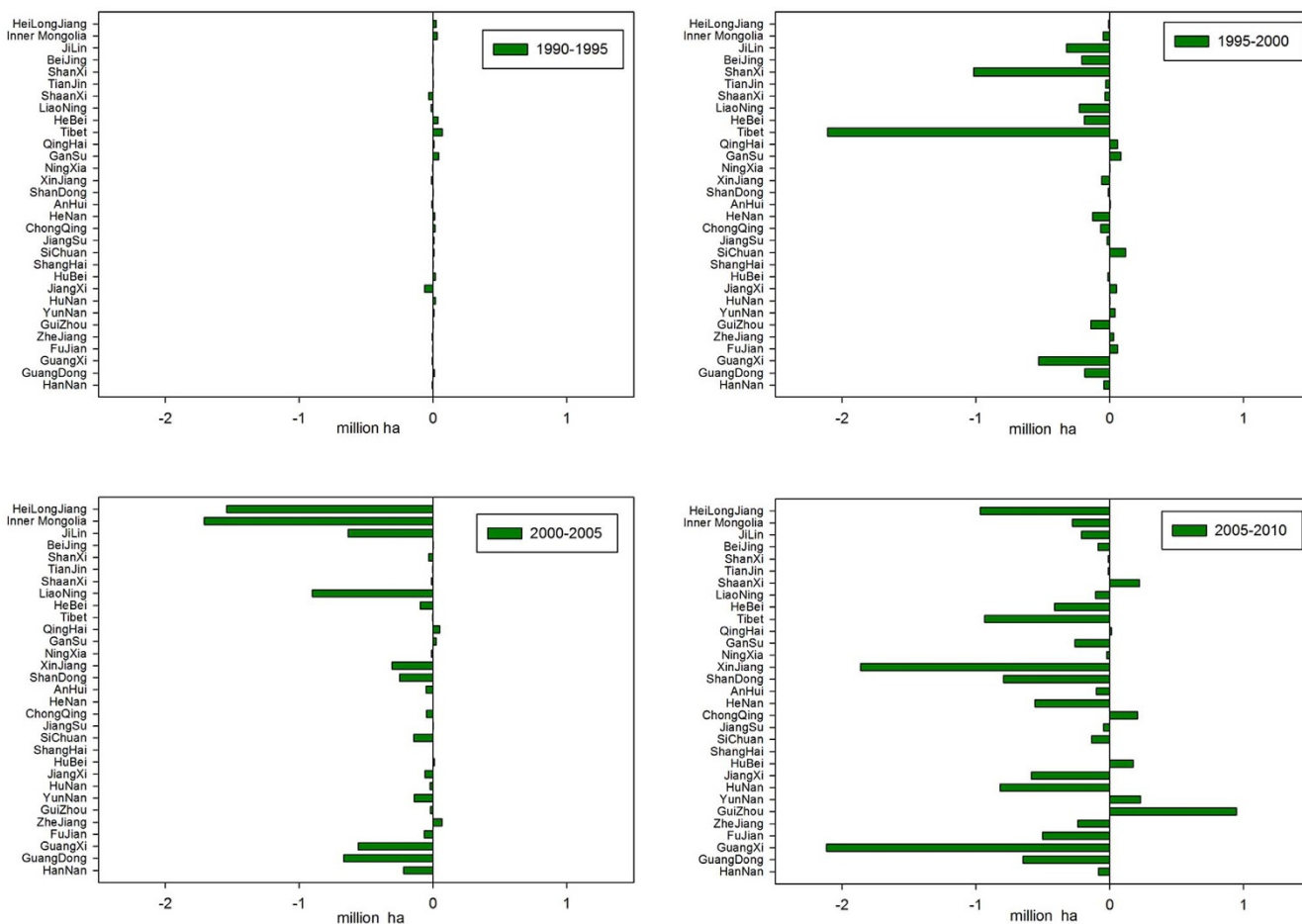
From 1990–2010, the variation of the alkaline land was salient, and before 2000, the area of the alkaline land increased continuously, from 2000 to 2005, the area of the alkaline land was unchanged, whereas the area decreased from 2005 to 2010. The decreasing trend is primarily attributable to the soil salinization and the secondary salinization of the arable land, which resulted in an increasing area of the alkaline land. Currently, the soil salinization pace has been effectively controlled because of national policy and improved technology in land desalination, and the area of alkaline land has been

reduced<sup>21,22</sup>. The other land use type variations of marginal land suitable for energy plants are not obvious.

**The spatial distribution variation analysis of marginal land suitable for energy plants.** The variation of the marginal land suitable for energy plants has salient regional characteristics in China. This study aims to analyze the data based on the province from 1990 to 2010 using ArcGIS software and to attain the variation diagram of the spatial distribution of the national marginal land suitable for energy plants over the past 20 years. The results are showing in Figure 3.



**Figure 3 | The spatial variation of the marginal land suitable for energy plants in China from 1990 to 2010.** First, the spatial of marginal land suitable for energy plants in 1990 and 2010 were reset the value of attribute using ArcGIS software. We set the attribute of region that without marginal land suitable for energy plants a value of 0 and set the attribute of region that with marginal land suitable for energy plants a value of 1. Then, we can obtain the spatial variation of the marginal land suitable for energy plants from 1990 to 2010 through subtracting the reset data in 1990 from the reset data in 2010 using ‘raster calculation’ function in ArcGIS software. The result indicated that the value 0 of the region means that the amount of marginal land suitable for energy plants unchanged, the value 1 of the region means that the amount of marginal land suitable for energy plants decreased, the value  $-1$  of the region means that the amount of marginal land suitable for energy plants increased, the value  $1$  of the region means that the amount of marginal land suitable for energy plants decreased. We use red to show the increased region of marginal land suitable for energy plants while blue shows the decreased region of marginal land suitable for energy plants using ArcGIS software, so that we could find the macroscopic variation of marginal land suitable for energy plants over past twenty years.



**Figure 4 |** The variation of each province’s marginal land suitable for energy plants in China from 1990 to 2010. The province of greater than zero indicates that the amount of marginal land suitable for energy plants was increased in this province, the opposite was decreased.

Figure 3 shows the area of marginal land suitable for energy plants in most regions has decreased in those that are closely grouped, whereas the few regions in which the land area has increased are scattered. A general declining trend was observed in China’s marginal land area suitable for energy plants. The suitable land area in Guangxi, Tibet, Heilongjiang, Xinjiang and Inner Mongolia declined on a large scale by 3.205 million ha, 3.046 million ha, 2.520 million ha, 2.233 million ha and 2.041 million ha, respectively, accounting for 38.1%,51.6%,38.1%,22.6% and 21.6%, respectively, of each province’s total area of marginal land suitable for energy plants in 1990.

We calculated and analyzed each province’s marginal land suitable for energy plants to obtain the variations during each five-year period, and the results are listed in Figure 4.

Figure 4 shows there is a clear variation in the spatial distribution of the national marginal land suitable for energy plants on the time scale. From 1990 to 1995, the variation of each province is not salient, and from 1995 to 2000, the variation in most of the provinces is not apparent. The areas of marginal land suitable for energy plants in Tibet, Shanxi, Guangxi and Jilin decreased by 2.11 million ha, 1.02

million ha, 0.53 million ha and 0.32 million ha, respectively, accounting for 35.3%, 23.5%, 6.3% and 13.2%, respectively, of each province’s total marginal land suitable for energy plants in 1995. The primary areas of decline were shrub land, sparse forest land and grassland. From 2000 to 2005, the suitable land areas in Guangxi and Jilin have declined by 0.56 million ha and 0.63 million ha, respectively. In addition to Guangxi and Jilin, the suitable land areas in Inner Mongolia, Heilongjiang and Liaoning Provinces have also declined on a large scale by 1.71 million ha, 1.54 million ha and 0.90 million ha, respectively, accounting for 18.2%, 23.3% and 40.2%, respectively, of each province’s total area of marginal land suitable for energy plants in 2000. For the Inner Mongolia and Liaoning Provinces, most of the decreased areas were sparse forest land and grassland. However, for Heilongjiang, most of the declined areas were shrub land and sparse forest land. From 2005 to 2010, the areas of marginal land suitable for energy plants in most regions significantly declined, and the declining areas in Guangxi, Xinjiang, Tibet and Heilongjiang Province exceeded 0.9 million ha, 2.12 million ha, 1.86 million ha, 0.94 million ha and 0.97 million ha, respectively,

Table 2   the criteria for obtaining the marginal land and the data introduction					
Factors	Criteria parameters	Scale	Format	Time	Data sources
Land use	Land use type	1 km	Grid	1990–2010	RESDC
Elevation	DEM Slope	1 : 250,000	Grid	—	SRTM for the globe Version 4
Climate	Precipitation Temperature	1 km	Grid	1971–2000	CMA(China Meteorological Administration)
Soil	Organic matter Effective depth	1 km	Grid	—	RESDC
Nature reserve	State policies	1 : 100,000	Shape file	2000	RESDC



**Table 3 | The constraints of the marginal land suitable for the energy plants in China**

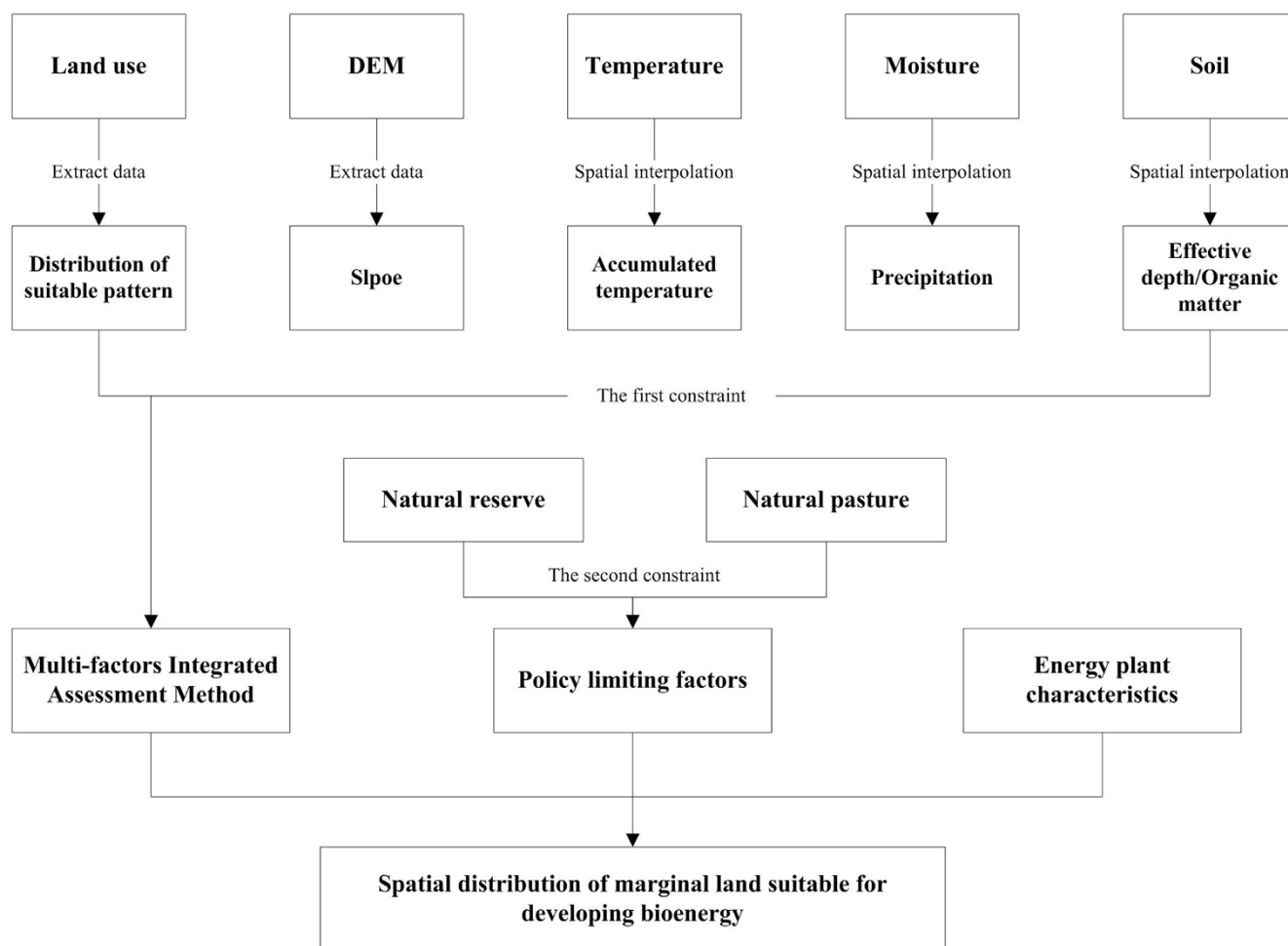
Factors	threshold
Slope	$<25^\circ$
Soil organic matter content/%	$>1.5$
Soil effective depth/cm	$\geq 20$
moisture/mm	annual precipitation $\geq 160$
temperature/ $^\circ\text{C}$	Accumulated temperature greater than or $10^\circ\text{C}/^\circ\text{C}\cdot\text{d} \geq 2000$

accounting for 28.9%, 19.6%, 24.2% and 19.0%, respectively, of each province's total area of marginal land suitable for energy plants in 2005. The reasons for this decline in various regions are different. For Guangxi, the decreasing areas were mostly sparse forest land and grassland; for Xinjiang, the decreasing areas were mostly grassland, alkaline land and shrub land; for Tibet, the decreasing areas were mostly shrub land and sparse forest land; and for the Heilongjiang Province, the decreasing areas were mostly shrub land and grassland. However, for the Guizhou and Yunnan Provinces, the areas of marginal land suitable for energy plants increased from 2005 to 2010, showing the dynamics of the spatial variation of the marginal land suitable for energy plants. The suitable area in the Guizhou Province increased the most, with a 0.95 million ha increase, accounting for 10.0% of Guizhou's total area of marginal land suitable for energy plants in 2005, and the most increased land use types were shrub land and sparse forest land.

## Discussion

Marginal land has various meanings in different disciplines and, therefore, the spatial coverage of marginal land differs<sup>23</sup>. However, the accuracy of statistical result is influenced by the accuracy of data resources, the assessment system of marginal land suitable for energy plants growing and other relevant constrain conditions, such as natural reserves. The data we used in this paper were obtained from authorities and were relatively reliable. Energy plants growth process is very complex. The requirements for environment are different in several stages of growth. The purpose in this study is to obtain the most potential marginal land areas suitable for energy plants growth. Therefore, we adopt the relative loose evaluation system and minimum limits of necessary constraints for energy plants growth.

From the results we can see that the total amount and type of China's national marginal land suitable for energy plants displayed an obvious change from 1990 to 2010: the total areas decreased by -0.137million ha, 4.966 million ha, 7.342 million ha, and 10.105 million ha, accounting for 0.10%, 3.63%, 5.56% and 8.13% of the total areas of marginal land suitable for energy plants in 1990, 1995, 2000 and 2005, respectively, whereas these decreases in marginal land suitable for energy plants are not obvious from 1990 to 1995. The amount of China's marginal land suitable for energy plants decreased over the past 20 years with a simultaneous increase in the rate of its reduction. The marginal land suitable for energy plants is decreased under human activities and natural factors. Land development strategy, urbanization, reclaiming wasteland to arable land and internal transformations among different types of forest land are the main factors that may lead to the increase of marginal land suitable



**Figure 5 | Workflow of the spatial distribution of the marginal land suitable for energy plants.** First of all, we should process the data using the ArcGIS software in order to get the needed data. We can obtain the distribution of marginal land suitable for energy plants through the constraint using ArcGIS.



for growing energy plants. China is undergoing a critical period of urbanization and industrialization, the demand for land has increased dramatically<sup>24</sup>. We can predict that the marginal land suitable for energy plants will continue to decline in future combining with the results of the analysis. China attaches great importance to energy plants and marginal land suitable for energy plants gradually in recent years<sup>24</sup>, we can inference that the speed of marginal land suitable for energy plants decrease will be slow. Therefore, land variation factors should be considered in the evaluation of biomass energy resources and industrial layouts.

## Method

**The criteria for assessment on the marginal land suitable for energy plants.** Multi-factors integrated assessment method is used in this paper to obtain the distribution of marginal land suitable for energy plants due to its high flexibility, powerful adaptability and other advantages<sup>25</sup>. First of all, we need to determine the criteria for assessment on the marginal land suitable for energy plants. The Ministry of Agriculture of China has presented the criteria for assessment on the marginal land<sup>26</sup>, but energy crops must meet certain conditions to grow at the same time, including soil conditions and climate conditions. The soil organic matter and the soil effective depth are important indices which can measure the soil fertility and crop growth<sup>27</sup>. Moisture, temperature and terrain conditions are also indispensable factors for energy plants growth. In order to guarantee the accuracy of the results, we set up an evaluation criteria system, including land use, elevation, climate, soil and other factors in consideration of marginal land evaluation standard put forward by the ministry of agriculture, the necessary conditions for energy plants growth, relevant national policies and previous literature<sup>4,11,12,23</sup>. According to the evaluation criteria system, the input data include land use type, DEM, slope, precipitation, temperature, soil organic matter, soil effective depth and nature reserve. The criteria and the data we used are listed in table 2:

Land use: The land use data, a very important factor, is the basis in obtaining the marginal land use type. The land use data of longer time scale is the foundation of studying marginal land change, while that change can provide effective data reference and decision making support for the long-term development of biomass energy. In this study, the land use data (1 km) included five periods (1990, 1995, 2000, 2005 and 2010) which were developed by experts in the Data Center for Resources and Environmental Sciences (RESDC) of the Chinese Academy of Sciences. The primary data sources for the land use data were Landsat MSS/TM/ETM CCD digital images. CBERS (the China-Brazil Earth Resources Satellite) and HJ-1 (a small satellite constellation for environmental and disaster monitoring) images were used as a supplement for the areas not covered by Landsat. Land use types divided into 6 categories and 25 sub-categories, including cultivated land, woodland, grassland, water, urban, rural settlements and barren land. A set of land data from field surveys was selected to guarantee the accuracy of land-use classification. It is the newest land use data at this scale in China and used as the most fundamental data for identification of marginal land which could be potentially used for the development of sustainable biomass energy<sup>12,28</sup>.

Elevation: Elevation is a factor limiting the growth of energy crops. According to China's environmental protection policy, it will lead to serious water loss and soil erosion, not suitable for planting energy crops, when the elevation is greater than 25°. therefore, the maximum elevation for energy crops is 25°. The elevation data sources in this paper come from SRTM for the globe gradient of Version 4, in the scale of 1:250 000, processed by GIS software, the average elevation information for 1 km grid was obtained.

Climate: Climate is also an important factor for the growth of energy crops, including temperature and precipitation. In this paper, the meteorological data are from the National Weather Service (CMA), wherein the temperature data includes some important factors for the growth of energy crops, such as  $\geq 10^{\circ}\text{C}$  accumulated temperature; moisture data mainly includes the national average annual rainfall distribution data.

Soil: Soil is the material basis for plant survival, and factors of soil effective depth and organic content decided plant growth. In this study, according to the soil profile recorded in the second national soil survey (1979–1994), we obtained the soil effective depth, soil organic matter content, soil texture, soil PH and other spatial information by the spatialization of soil profile using ArcGIS and in the method of Kring interpolation algorithm.

State policies: There are many other important factors to influence the development and utilization of land resources suitable to biomass energy crops, such as the relevant state policies, laws and regulations and other social economic factors. Therefore, not only the natural conditions, but also the Natural Forest Conservation Program (NFCP), Grain-to-Green program (GTGP), the overall planning of the protection and construction of grassland use and other related policies should also be considered.

To the same factors, different energy plants have different constraints<sup>29</sup>. To universalize the research findings, we selected the natural growth conditions of the typical energy plant *Jerusalem artichoke* as the constraint, which has the characteristics of a low environment, drought resistance, cold resistance and wide adaptability<sup>30</sup>. The detailed constraints are listed in Table 3.

**Multi-factors integrated assessment method.** Multi-factors Integrated Assessment Method which comprehensively considers various factors in the evaluation criteria system was used to obtain the distribution of marginal land suitable for energy plants<sup>31</sup>. The specific procedures are given in Figure 5.

According to the following steps, we can obtain the distribution of marginal land suitable for energy plants.

Step1: In compliance with the principle that bioenergy development should not occupy the land intended for grain production, we excluded cultivated land. We designated 6 land use types as suitable, including shrub land, sparse forest land, grassland (dense grassland, moderate dense grassland and sparse grassland), shoal/bottomland, alkaline land and bare land.

Step2: To avoid competition with ecologically protected land, all of the lands in the natural reserves are excluded. Considering the development of animal husbandry, native pasture (dense grassland and moderate dense grassland) in the five pastures (Qinghai, Xinjiang, Inner Mongolia, Tibet and Ningxia) are also excluded.

Step3: Considering the natural conditions for energy plant growth, we use the data in table 3 as the constraints. Through the ArcGIS software, we obtained the spatial distribution of the marginal land suitable for energy plants.

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## Author contributions

D.J. and J.-Y.F. contributed to all aspects of this work; M.-M.H. wrote the main manuscript text; D.-F.Z. and Y.-H.H. gave some useful comments and suggestions to this work. All authors reviewed the manuscript.

## Additional information

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