

## ORIGINAL RESEARCH

# Evaluating the suitability of marginal land for a perennial energy crop on the Loess Plateau of China

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## Abstract

With a large marginal land area, the Loess Plateau in China holds great potential for biomass production and environmental improvement. Identifying suitable locations for biomass production on marginal land is important for decision-makers from the viewpoint of land-use planning. However, there is limited information on the suitability of marginal land within the Loess Plateau for biomass production. Therefore, this study aims to evaluate the suitability of the promising perennial energy crop switchgrass (*Panicum virgatum* L.) on marginal land across the Loess Plateau. A fuzzy logical model was developed and validated based on field trials on the Loess Plateau and applied to the marginal land of this region, owing to its ability of dealing with the continuous nature of soil, landscape variations, and uncertainties of the input data. This study identified that approximately 12.8–20.8 Mha of the Loess Plateau as available marginal land, of which 2.8–4.7 Mha is theoretically suitable for switchgrass cultivation. These parts of the total marginal land are mainly distributed in northeast and southwest of the Loess Plateau. The potential yield of switchgrass ranges between 44 and 77 Tg. This study showed that switchgrass can grow on a large proportion of the marginal land of the Loess Plateau and therefore offers great potential for biomass provision. The spatial suitability maps produced in this study provide information to farmers and policymakers to enable a more sustainable development of biomass production on the Loess Plateau. In addition, the fuzzy-theory-based model developed in this study provided a good framework for evaluating the suitability of marginal land.

## KEYWORDS

biomass production, fuzzy-theory-based models, land suitability, Loess Plateau, marginal land, perennial crops, switchgrass

## 1 | INTRODUCTION

To reduce the emission of greenhouse gases that cause global warming, it is urgent to look for alternative renewable and sustainable resources (Caspeta et al., 2013). As a renewable source for low-carbon energy carriers and materials, crop biomass is one of the key options for mitigating global CO<sub>2</sub> emissions (Ragauskas et al., 2006; Scarlet et al., 2015). However, the production of a large and sustainable supply of biomass is a great challenge because of the competition in terms of land used for food and feed production and that used for natural habitats (Lewandowski, 2015; Shortall, 2013; Tilman et al., 2009). One promising and feasible solution for these problems is to cultivate perennial bioenergy crops on marginal land, which would not only mitigate global warming but also improve the fragile ecological environment on marginal lands and bring local economic benefits (Gerwin et al., 2018; Smeets et al., 2009; Zhang et al., 2017).

The Loess Plateau is one of the regions most affected by erosion worldwide. About 60% of the land is subject to some degree of erosion, and about 1.64 billion tons of sediment are transported into the Yellow River each year (Jiang et al., 2013). The fragile eco-environment is the result of historically intensive agricultural activity, high erodibility of loess soil, and high-intensity rainfall concentrated during the summer (Cai, 2001; Wang et al., 2006). To restore degraded ecosystems, the Chinese government launched a revegetation policy in the late 1990s called the “Grain for Green Project” (GFGP), aimed at mitigating soil erosion and land deterioration as well as reducing local poverty by converting cropland to forestland and grassland (Bennett, 2008; Deng et al., 2014; Liu et al., 2014; Wang et al., 2007). After two decades, the GFGP has led to great achievements. Compared to the period 1998–2002, runoff and soil erosion during 2003–2007 were reduced by 18% and 45%, respectively (Deng et al., 2012). However, the agricultural land was shrunk dramatically as 56% of the total cropland was converted to afforestation during the 1999–2006. Therefore, the central government declared that no further cropland could be allocated to the project (Wang et al., 2013). As with popular research on energy crops plantation on the marginal land, researchers in China therefore turned their attention to the marginal land (Cheng & Zhu, 2012). It is estimated that Loess Plateau that has approximately 27.6–48.7 Mha of marginal land could be potentially used for biomass production (Liu et al., 2012, 2016; Liu & Sang, 2013). Researchers are trying to introduce the concept of planting perennial energy crops on the marginal land of the Loess Plateau as the continuation of the GFGP, with the intention of restoring the local ecology on the Loess Plateau, and at the same time reducing the greenhouse gas emission to reduce the contribution to the global warming (Cooney et al., 2017; Deng, 2014; Xue et al., 2016).

The perennial grass switchgrass (*Panicum virgatum* L.), with broad environment tolerance, high energy resource-use efficiency, and high biomass production, is demonstrated a promising candidate of energy crop on marginal land of the Loess Plateau (Alexopoulou et al., 2017; Cooney et al., 2017; David & Ragauskas, 2010). Since switchgrass was first introduced to China by Yi Qian from Utsunomiya University in the early 1980s (Ma yongqing, 2012), research has been conducted on switchgrass adaptability on the Loess Plateau, covering plant physiology, morphology, genetic resources screening, and agronomy management (Feng et al., 2016; Gao et al., 2015, 2017; Ichizen et al., 2005; Wang, 2016; Zhang et al., 2017). Research demonstrated that switchgrass could survive on the degraded land with limited irrigation and fertilizers and had a great potential to sequester carbon into soils with low N<sub>2</sub>O emissions and decreased the soil erosion while supplying significant quantities of biomass for biofuel synthesis on the Loess Plateau (Gao et al., 2015; Ichizen et al., 2005; Wang et al., 2015). This research provides valuable information for further study regarding switchgrass for biomass production on the Loess Plateau. However, there is a lack of information on the assessing of the marginal land suitability for switchgrass on the Loess Plateau. Despite the successful implementation of GFGP, one issue that should be noticed is that the inadequate assessment of the land suitability for selected plant species in some regions resulted in a low survival rate and even large areas of dead plants (Jiang et al., 2013; Wang et al., 2007; Yi & Wang, 2016). Therefore, the evaluation of the marginal land suitability for perennial energy crop switchgrass on a regional level is needed to fill this gap, which could provide the information to select the proper location for switchgrass plantation.

The current methods used to evaluate the land suitability have been developed and applied in the framework of geographic information system (GIS; Elaalem et al., 2011; Malczewski, 2004). Statistical methods and rule-based methods in the context of GIS are two classes of the most commonly used methods (Joss et al., 2008). The statistical methods, which are based on regression-based predictions, are usually criticized as unrealistic, inaccurate, and limited by a lack of empirical data or the data are qualitative (Joss et al., 2008). However, the rule-based fuzzy theory model is one of the popular methods and has been widely applied to evaluate the land suitability for agricultural land, urban land, forest, and recently been applied to marginal for energy crops (Jianfei & Weimin, 1992; Joss et al., 2008; Lewis et al., 2014; Maddahi et al., 2017; Malczewski, 2002; Reshmidevi et al., 2009). Because currently some of the biophysical data are depicted as discrete, homogeneous units in geographic space, and a single attribute value is assigned to each unit. These kinds of the data usually ignore the fact that in large-scale land, biophysical phenomena are spatially heterogeneous and biophysical data are naturally continuous (Malczewski, 2004).

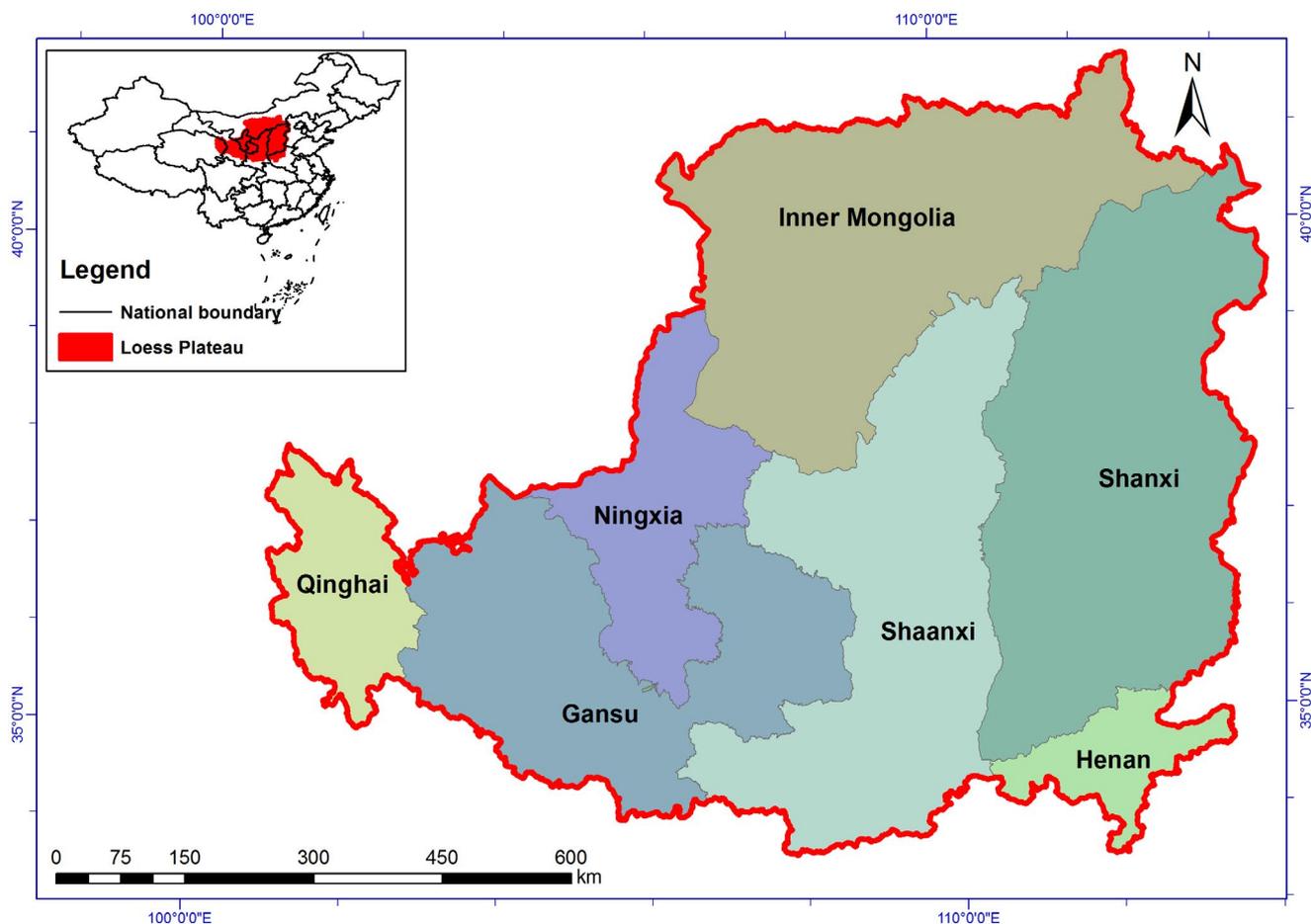
While the fuzzy-theory-based model is capable of dealing with the variability, imprecision, and uncertainty embedded in the input data by defining sets without clear boundaries or partial memberships of elements belonging to a given set (Joss et al., 2008; Malczewski, 2004; Zadeh, 1965).

Owing to the diversity of climate, soil, and topographic features, and uncertain biophysical data on the Loess Plateau area, we developed a fuzzy logical model and applied it to the Loess Plateau to evaluate both the crop yield and the marginal land suitability for switchgrass. The model was validated based on the dataset of the switchgrass field trials on the Loess Plateau. The marginal land suitability maps generated from the model provide land managers and farmers quantitative and spatial references to optimize the location plan on the Loess Plateau for future biomass production. The method in this study also provides a good framework to make land suitability evaluations in other research areas.

## 1.1 | Study region

The Loess Plateau, a region of more than 60 Mha, is located in the northern part of Central China ( $34^{\circ}41'–45^{\circ}5'N$ ,

$100^{\circ}52'–114^{\circ}33'E$ ). The region spans most or part of seven provinces, including Shanxi province, the central and eastern part of Gansu province, the north-central part of Shaanxi Province, northeastern Qinghai province, southern Ningxia Hui Autonomous Region, southern Ordos Plateau of Inner Mongolia, and the western hilly land of Henan province (Figure 1). The climate on the Loess Plateau is a semi-arid continental monsoon climate, with hot, rainy summers and cold, dry winters. The mean annual temperatures are  $6–10^{\circ}C$  and mean annual precipitation is between 300 and 600 mm. Both the temperature and precipitation decrease gradually from southeast toward northwest. Approximately 60%–70% of the precipitation is concentrated in July, August, and September, and the rainfall intensity is strong, which causes extreme soil erosion and sediment transport into the Yellow River (Shi & Shao, 2000). The three major topographical features of the Loess Plateau are stony mountains, valley plains, and plateau hills. Most of the Loess Plateau is covered with thick loess 50–80 m deep, reaching 158–180 m deep in some areas. The main soil types in the Loess Plateau are cinnamon, Lou, loessial, dark loessial, gray cinnamon, and sierozem (Jiang et al., 2013; Li et al., 2014).



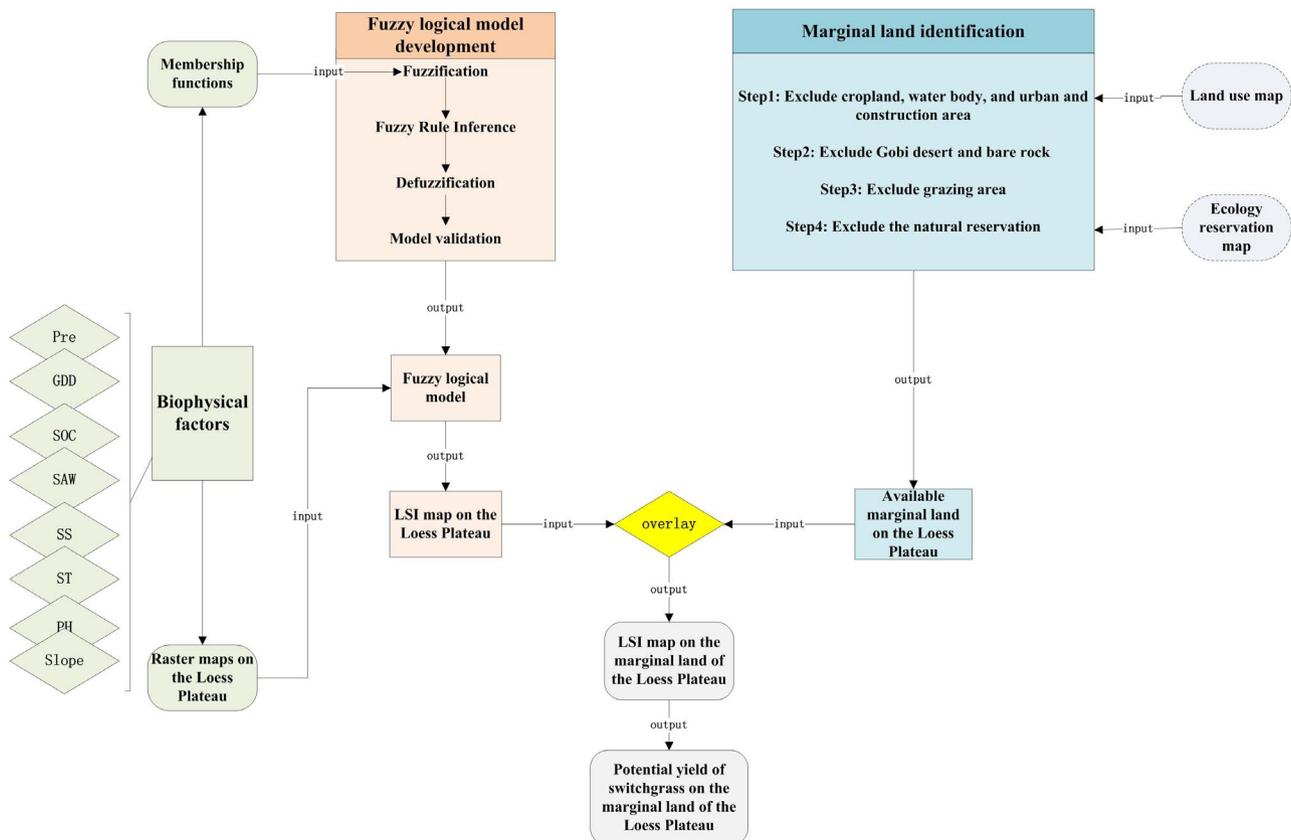
**FIGURE 1** The location of the Loess Plateau within China. Different provinces are demarcated

## 2 | MATERIALS AND METHODS

The flow chart in this study is shown in Figure 2. The processes to evaluate the suitability of the marginal land included following steps. First, identifying the available marginal land using spatial analysis. Second, determining the major factors that affect or limit the growth of the switchgrass according to the plant growth requirements and regional characteristics, and identifying threshold of each factor. Third, developing the fuzzy logical model for the switchgrass. The model was validated based on the field trial of the switchgrass on the Loess Plateau and then applied to the study region spatially, and output a land suitability index (LSI) spatial map. The suitable marginal land map was generated by overlying the available marginal land distribution map to the LSI map. Finally, biomass yield of switchgrass on the marginal land of the Loess Plateau was calculated. The total biomass production of the switchgrass was calculated by scaling the LSI map generated from Fuzzy logical model to the Loess Plateau with the regression function. The evaluation was conducted in each section of a 1 km grid. ArcGis10.5.1 was used to make spatial analysis. The algorithm of the fuzzy logical model was coded and run in MATLAB R2018b.

### 2.1 | Marginal land identification

The definition of the marginal land is different in various disciplines and for different research purposes (Gerwin et al., 2018; Shortall, 2013). The marginal land related to bioenergy is identified as the land which has poor natural conditions and the land currently is not used for other purposes (Cooney et al., 2017; Jianping et al., 2008; Tian et al., 2009). In this study, the available marginal land was identified by excluding agricultural land, grazing land, watersheds, urban and construction areas, and ecological reserves. It should be carefully checked that the marginal land defined in this study is technically available. Not all the defined marginal land could be practically used for energy crops production considering the dynamics of land-use change, short of detailed spatial distribution of grazing area as well as various local policy. The land-use map in this study is the land use in 2015, the latest national-scale map available while there may some changes in the land use since then. The land-use map is based on land used classification system of Chinese Academy Classifies (CAS). In CAS, land is classified into six primary classes which include cropland (sc.1), forest land (sc.2), grassland (sc.3), water body (sc4), urban and construction areas (sc5),



**FIGURE 2** Flow chart of methodology in this study. It mainly contains (1) Marginal land identification (blue module); (2) fuzzy logical model development and validation (pink module); and (3) Model application and output result. See Sections 2.1–2.3 for detailed descriptions of each part. GDD, growing degree-days; LSI, land suitability index; Pre, growing season precipitation; SAW, soil available water; SOC, soil organic carbon; SS, soil salinity; ST, soil texture

and unused land (sc6). Under each primary class, the land is then classified into 25 sub-classes of land-use types.

Loess Plateau is important for both agriculture and animal husbandry. Grazing is one of the main income sources for the farmers in this region especially in Inner Mongolia and Qinghai where there are large grasslands (Liu, 2017). While CAS does not distinguish the grazing area from the grassland, instead it classes the grassland into three sub-classes including high coverage grassland (sc. 31), moderate coverage grassland (sc. 32), and sparse grassland (sc. 33). According to CAS, high coverage grasslands generally have good hydrological conditions and lush grasses that are a good resource for grazing. The moderate coverage grassland has insufficient water and sparse grass that is only partially suitable for grazing. Sparse grasslands usually lack water and the grass is sparse which is in poor animal husbandry utilization conditions. Owing to the lack of detailed geographic information on the grazing area, in this study, we defined grazing grassland in two land-use scenarios to avoid the uncertainty that the biomass production may compete the land with the grazing areas. In scenario 1, the high coverage and moderate coverage grasslands were all reserved for grazing. In scenario 2, only the high coverage grassland was used for grazing. The marginal land was identified separately in these two land scenarios. In addition, there may be some provincial or county level land-use policies, which were not considered in this study. Based on the definition above, the identification of the marginal land in this study followed the steps below:

Step 1. Excluding the cropland land, water bodies, and urban and construction area from all the land.

Step 2. Excluding the Gobi desert, bare rock because the quality of these land is too poor for crops to withstand.

Step 3. Excluding grazing grassland defined in two land-use scenarios separately. So far, the marginal land here

included shrub land (sc. 22), spare forestland (sc. 23), moderate coverage grassland (sc. 32) (included in scenario 1 but not included in scenario 2), sparse grassland (sc. 33), bottomland (sc. 46), sand land (sc. 61), alkaline land (sc. 63), wetlands (sc. 64), bare land (sc. 65), and other unused land (sc. 67).

Step 4. To protect ecology and environment, the natural reserves and water conservation districts were excluded (Zhuang et al., 2011). This step was achieved by overlaying the ecology reservation map released by Chinese Academy of Science (Xue et al., 2016; Zhang et al., 2017; Zhuang et al., 2011). The information of the data source is shown in Table 2. To make it simple, the technically available marginal land in the following text is called available marginal land.

## 2.2 | Environmental factor selection and thresholds

Environmental factors affecting the growth of switchgrass and the corresponding thresholds were identified by combining literature reviews of crops' physiological, actual climate, soil, and topography condition of the Loess Plateau and the expert's opinions (Feng et al., 2017; Yi & Wang, 2016). In this study, only natural conditions that directly affected the growth of energy crops such as precipitation and growing degree-day (GDD) were considered. These included the soil conditions: soil pH, soil salinity, available soil water, soil organic carbon (SOC), and soil texture; climatic conditions: growing season precipitation and GDDs; and the terrain condition slope. The threshold values of the environmental factors for switchgrass were further used to develop the membership function in the fuzzy logical model, and the values are shown in Table 1.

No.	Switchgrass	HS	MS	NS
1	Growing season precipitation (mm)	>600	200–600	<200
2	GDD ( $T_B = 10^\circ\text{C}$ )	>1200	578–1200	578
3	Soil salinity ( $\text{ds m}^{-1}$ )	<4	4–15	>15
4	Soil texture (class) <sup>a</sup>	9,5,10	2,3,4,6,7,8,11,12,13	1
5	Soil pH	6–7.6	3.7–6, 6–8	>8, <3.7
6	Soil available water (class) <sup>b</sup>	1–2	3–6	7
7	Soil organic carbon ( $\text{g kg}^{-1}$ )	20	6–20	6
8	Slope ( $^\circ$ )	<4	4–25	>25

TABLE 1 Environmental factors and their threshold of switchgrass for Fuzzy Logical Model

<sup>a</sup>The number is the soil texture class code based on the USDA texture class: 1: clay (heavy); 2: silty clay; 3: clay; 4: silty clay loam; 5: clay loam; 6: silt; 7: silt loam; 8: sandy clay; 9: loam; 10: sandy clay loam; 11: sandy loam; 12: loamy sand; 13: sand (Nachtergaele et al., 2009).

<sup>b</sup>The number is the soil available water class ( $\text{mm m}^{-1}$ ) in HWSD: 1:125–150; 2:100–125; 3:75–100; 4:50–75; 5:15–50; 6:0–15; 7:0 (Nachtergaele et al., 2009).

## 2.2.1 | Precipitation

Precipitation is one of the major factors affecting plant development and biomass (Gunderson et al., 2008; Lee & Boe, 2005; Sanderson et al., 1999). In some regions of the Loess Plateau, such as loess hilly and gully regions, which are typical landforms, the only source of soil water for plant growth is precipitation (Yang et al., 2015). The precipitation of the Loess Plateau is seasonal and mainly concentrated in summer and the intense storms usually cause soil erosion (Shi & Shao, 2000). The highest biomass yield occurred with the greatest precipitation in growing season (April–September; Feng et al., 2017). It has been reported that switchgrass reaches the highest yields at approximately 600 mm of growing season precipitation, above which the yield is not limited by precipitation. It can achieve a high yield even in moderate or severe drought situations, but it fails to produce biomass under chronic extreme drought (Sanderson et al., 1999). The yield remains rather low when the growing season precipitation is below 200 mm (Feng et al., 2017).

## 2.2.2 | Temperature

The development rate of switchgrass in the vegetative period is mainly driven by temperature. Morphological development of switchgrass is closely related to cumulative degree-days and the base temperature is 10°C (Feng et al., 2017; Sanderson & Wolf, 1995; Van Esbroeck et al., 1997). It has been reported that switchgrass requires a minimum of 200 GDD and 378 GDD for leaf emergence and internode elongation, respectively (Sanderson & Wolf, 1995), and reaches maturity (peak biomass) at 1200 GDD (Trybula et al., 2015).

## 2.2.3 | Soil pH

Soil pH plays an important role in plant growth by controlling the chemical forms of the different nutrients and influencing the chemical reactions they undergo (Von Cossel et al., 2019). The optimal soil pH for seedling growth and yield of switchgrass is 6.3–8.1. Seedling growth reduced sharply at high pH values and seedlings can survive at pH 3.7–7.6. The germination speed and ratio remain high at pH 6.0–8.0 while the germination rate decreases when PH below 6 or above 8 (Heit, 2014; Zhang et al., 2015).

## 2.2.4 | Soil salinity

High soil salinity negatively affects seed germination, seedling emergence and growth, and it modifies a plant's physiological and biochemical processes (Kim et al., 2012; Sun

et al., 2018). There is a large area of land in the Loess Plateau that is plagued by soil salinity and sodium, and thus it is not suitable or not profitable for planting economic crops (Cooney et al., 2017). While switchgrass was moderately tolerant to soil salinity and it was reported to have produced high or moderate biomass in saline and alkaline land. Switchgrass is more sensitive to salinity at the seedling emergence stage than at any other stages. The germination and biomass decrease at 4 ds m<sup>-1</sup> of soil salinity, and it has a very low germination ratio when soil salinity is 14.9 ds m<sup>-1</sup> (Dkhili & Anderson, 1990).

## 2.2.5 | Soil available water

Soil available water is the amount of water that can be stored in a soil profile and is available for growing crops, and thus it has the most direct impact on the water use of plants. The soil available class was based on the available water storage capacity of the Harmonized World Soil Database (HWSD). Classes 1–2 are considered prime for plant growth, meaning sustained production of a wide range of cultivated crops. Classes 3–6 are generally marginal but capable for plant cultivation, and class 7 is unsuitable for plant growth.

## 2.2.6 | Soil organic carbon

Soil organic carbon is the basis of soil fertility and an index for assessing land quality. It releases nutrients for plant growth, promotes plant structure, and biological and physical health of the soil, and is a buffer against harmful substances (Blair et al., 1995). The classification for the SOC level for switchgrass was based on the second National Soil Census and related standards (Tang, 1989).

## 2.2.7 | Soil texture

Soil texture is a major control on the distribution of pore sizes in a volume of soil, which, in turn, largely determines both the water-holding capacity and the soil water potential for a given volumetric water content. Field capacity and wilting point are calculated from soil texture, geochemistry, and SOC in the Campbell method (Campbell, 1985). Switchgrass performs well in a wide variety of soil types (Lewandowski et al., 2003), but soil texture still has an impact on switchgrass productivity (Nasso et al., 2015). Switchgrass can adapt to sandy soil, clay loam, and other soil types, and it has a strong drought tolerance that it can grow well even in rocky soil (Nasso et al., 2015). In this study, we simplified the impact of the soil texture on the land suitability and classified the soil texture into three suitability levels. Switchgrass

performs well in a wide variety of soil types, only the class 1 heavy clay is not suitable for switchgrass at all and the classes 5 (clay loam), 9 (loam), and 10 (sandy clay loam) are very suitable for switchgrass. The soil classification system referred HWSD.

## 2.2.8 | Slope

The slope directly affects the distribution and concentration of water. The formation of surface runoff can easily lead to the loss of topsoil rich in organic matter, resulting in a decline of soil fertility, thus affecting species diversity and the primary productivity of plants (Jin & Du, 2007). Covered with loess in most areas of the Loess Plateau, the slope is more vulnerable to wind and water erosion. Therefore, the slope is an important factor to consider when establishing a plant. The slope gradient class values are based on the research of Wang et al. (2007).

## 2.3 | Fuzzy logical model development and land suitability evaluation

Fuzzy logical model comprise three steps: fuzzification, fuzzy inference, and defuzzification (Feng et al., 2017; Joss et al., 2008).

### 2.3.1 | Step 1. Fuzzification

Fuzzification converts conventional or oral expressions into fuzzy terms quantified by the fuzzy membership function. The result is a membership degree matrix of the evaluation factors to each suitability level. It includes three steps:

1. Defining fuzzy terms. Three terms representing different levels of suitability were defined for each environmental factor: highly suitable (HS), moderately suitable (MS), and not suitable (NS). The number of terms was limited

to three to avoid the complexity of fuzzy inference (Joss et al., 2008).

2. A membership function was established for each suitability level (HS, MS, and NS). The minimum and maximum values of the environmental factors used to develop the membership function for switchgrass are summarized in Table 1. Figure 3 displays an example of the membership function for environmental factors that have positive relationship with land suitability, such as growing season precipitation and GDDs. The HS, MS, and NS membership functions are given in Equations (1)–(3), respectively.

$$\text{Membership}_{\text{HS}}(f_i) = \begin{cases} 0, & f_i < a_i \\ \frac{x-a_i}{b_i-a_i}, & a_i < f_i \leq b_i \\ 1, & f_i > b_i, \end{cases} \quad (1)$$

$$\text{Membership}_{\text{MS}}(f_i) = \begin{cases} 0, & f_i < a_i \\ \frac{x-a_i}{(b_i+a_i)/2-a_i}, & a_i < f_i \leq \frac{b_i+a_i}{2} \\ \frac{-(x-b_i)}{b_i-(b_i+a_i)/2}, & \frac{b_i+a_i}{2} < f_i \leq b_i \\ 0, & f_i > b_i, \end{cases} \quad (2)$$

$$\text{Membership}_{\text{NS}}(f_i) = \begin{cases} 1, & f_i < a_i \\ \frac{-(x-b_i)}{b_i-a_i}, & a_i < f_i \leq b_i \\ 0, & f_i > b_i, \end{cases} \quad (3)$$

where  $i$  ( $i = 1, \dots, n$ ) represents the  $i$ th environmental factor,  $f_i$  is the value of the  $i$ th environmental factor,  $\text{Membership}_{\text{NS}}(f_i)$  is the  $i$ th membership value of not suitability,  $a_i$  is the minimum value of the  $i$ th environmental factor, and  $b_i$  is the maximum value of the  $i$ th environmental factor. The detailed membership function establishment procedures and the membership function for each factor are found in File S1.

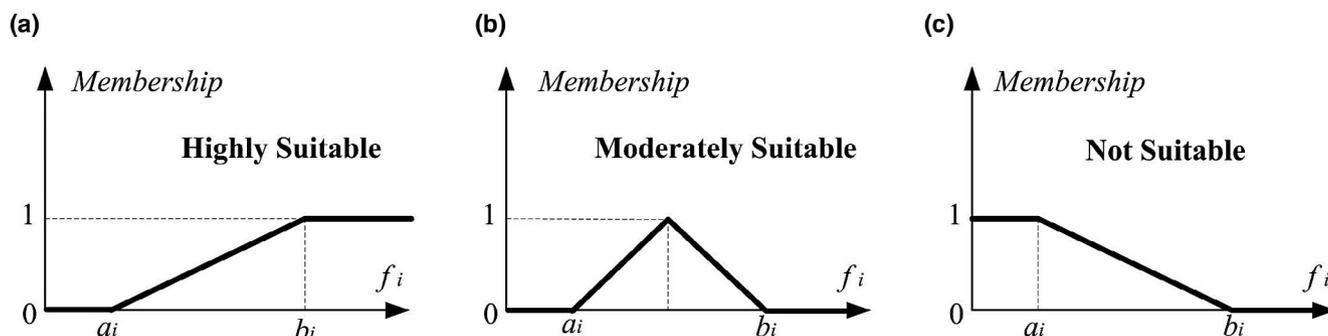


FIGURE 3 Fuzzy membership function graph. (a) HS; (b) MS; (c) NS

3. The membership function and membership value were obtained for the three suitable levels (HS, MS, and NS) of each environmental factor by converting the input empirical value to membership values ranging from 0 to 1.

### 2.3.2 | Step 2. Fuzzy rule inference: Aggregation and composition

In this step, the weight of the integrated land suitability was defined by generating rules that aggregated all environmental factors to determine the suitability level of the evaluated unit. The final comment set of the integrated suitability included five levels: integrated high suitable (iHS), integrated good suitable (iGS), integrated marginal suitable (iMS), integrated poor suitable (iPS), and integrated not suitable (iNS).

IF there is at least one factor belongs to NS, then the final comment will be Integrated Not Suitable (iNS).

IF all the factors are HS, then the final comment will be Integrated Highly Suitable (iHS).

IF there are 5–7 factors are HS, then the final comment will be Integrated Good Suitable (iGS).

IF there are 2–4 HS are HS, then final comment will be Integrated Marginal Suitable (iMS).

IF there are at most 1 factor is HS, then final comment will be Integrated Poor Suitable (iPS).

The “maximum–minimum” (MIN–MAX) fuzzy rule inference method was used to obtain the weight of the five integrating suitable levels. This means that we took the minimum value in each combination of the IF part and the maximum value in the aggregation of all the same integration suitability levels of the THEN part (Joss et al., 2008).

### 2.3.3 | Step 3. Defuzzification

In this step, the final LSI, which represents the overall suitability level of an evaluated land unit, was generated. We established a membership function representing the membership values of LSI for the five suitability levels (iHS, iGS, iMS, iPS, and iNS). The membership function is the same as the research of Feng et al. (2017). The center of maximum defuzzification method was used to calculate the LSI (Feng et al., 2017; Joss et al., 2008). The LSI was further reclassified into five classes: NS, poorly suitable (PS), MS, good suitability (GS), and HS. The definitions of these classes are the same as in previous studies (Feng et al., 2017; Reshmidevi et al., 2009).

### 2.3.4 | Step 4. Model accuracy verification

The fuzzy logical model was verified by comparing the LSI calculated from model with the actual harvest yield (Feng

et al., 2017). In this study, there were 10 samples based on the field trials on the Loess Plateau (detailed in the File S1). In each sample, with the climate, terrain and soil data as the inputs of the model, the model output the LSI and then compared with the actual measurement of the yield. The input meteorological data of the samples are based on daily measurements which were collected from the closest meteorological stations. The relationship between LSI and yield was presented in the form of linear regression in Excel. Goodness of fit ( $R^2$ ) was calculated to figure out the fitting degree of the regression line to the observed values. The root mean squared error (RMSE) was also calculated to measure the deviation of the modeled yield with actual measurement of the model.

## 2.4 | Model application and the land suitability evaluation

After verification, the model was applied to the whole Loess Plateau to evaluate the land. The evaluation conducted in each 1 km × 1 km grid and a map of LSI of all the land across the Loess Plateau was generated. The marginal land suitability map for switchgrass was extracted from all land suitability map by overlaying the available marginal distribution map. The yield potential of the switchgrass was then calculated with the scaling of the LSI based on the regression function. The information of input meteorological, soil, and the terrain data is shown in Table 2.

## 2.5 | Data and data sources

The geospatial datasets used in this study included the basic datasets to identify the marginal land and the input datasets for the fuzzy logical model. The detailed sources of the dataset are shown in Table 2. The most fundamental data for identifying marginal land was the land-use data of China from 2015 on a scale of 1:1000. The dataset was obtained using a Landsat 8 Thematic Mapper and CBERS-2 (China-Brazil Earth Resources satellite) satellite images and interpreted by experts in the Data Center for Resources and Environmental Sciences (RESDC), Chinese Academy of Sciences. It is the newest land-use dataset at this scale in China. The spatial range of the Loess Plateau and China's ecological reserve map were obtained from the website of the RESDC, Chinese Academy of Sciences (<http://www.geodata.cn>). The spatial analysis was operated in ArcGIS 10.5.1.

The input dataset for the models were raster maps of all the factors generated in ArcGIS 10.5.1 with the same resolution (1 km) and the same spatial coordination system. Precipitation was the average precipitation from 2004 to 2014. The GDD was calculated using Equation (4).

$$GDD = \sum \frac{T_{max} + T_{min}}{2} - T_{base}, \text{ if } \frac{(T_{max} + T_{min})}{2} - T_{base} < 0, \text{ then } GDD = 0, \quad (4)$$

TABLE 2 Basic information of geospatial datasets

Data	Data source	Resolution (m)
Land-use map of Loess Plateau	Derived from 2015 China land-use map. Data Center for Resources and Environmental Sciences (RESDC), Chinese Academy of Sciences (CAS)	1000
Ecology reservation map	Derived from China ecological function reserve zone. RESDC, CAS	1000
Growing season precipitation (mm)	2004–2014 monthly rainfall dataset on the Loess Plateau. The dataset was from the Loess Plateau Data Center, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China ( <a href="http://loess.geodata.cn">http://loess.geodata.cn</a> )	1000
Growing degree days (GDDs)	2010–2018 daily temperature of Meteorological stations. China meteorological data network	1000
Soil salinity ( $\text{dS m}^{-1}$ ), soil pH, soil texture (class), soil available water (class), soil organic carbon ( $\text{g kg}^{-1}$ ) and soil available water (class)	Harmonized World Soil Database (HWSD)	1000
Slope gradient ( $^{\circ}$ )	Derived from China DEM. RESDC, CAS	250

TABLE 3 The input and output for the models validation

	Growing precipitation (mm)	GDD10	Soil salinity ( $\text{dS m}^{-1}$ )	pH	Soil carbon ( $\text{g kg}^{-1}$ )	Soil available water (class)	Soil texture (class)	LSI	Yield ( $\text{t ha}^{-1}$ )
2012_Ansai	445.5	1847	0.1	6.2	0.79	3	11	0.38	7.1
2013_Ansai	888.0	1693	0.1	6.2	0.79	3	11	0.37	6.6
2014_Ansai	626.8	1492	0.1	6.2	0.79	3	11	0.37	5.3
2015_Ansai	221.7	1635	0.1	6.2	0.79	3	11	0.20	3.7
2016_Ansai	396.2	1725	0.1	6.2	0.79	3	11	0.38	4.2
2009_yangling	461.5	2185	0.3	7.8	1.15	1	9	0.55	17.1
2010_yangling	592.8	2200	0.3	7.8	1.15	1	9	0.56	39.1
2009_Dingbian	308.5	1593	0.1	6.0	0.50	3	13	0.31	1.0
2010_Dingbian	262.0	1585	0.1	6.0	0.50	3	13	0.28	5.0
2013_Dingbian	305.7	1733	0.1	6.0	0.50	3	13	0.31	10.0

Abbreviation: LSI, land suitability index.

where  $T_{\max}$  is the daily maximum,  $T_{\min}$  is the daily minimum, and  $T_{\text{base}}$  is the base temperature for crops. Here, the  $T_{\text{base}}$  temperature is  $10^{\circ}\text{C}$ . The GDD maps were generated by spatial interpolation using the 2010–2018 meteorological station data of the Loess Plateau in ArcGIS 10.5.1. The growing period is from April 1 to September 30. All the calculations were conducted in  $1 \text{ km}^2$  units.

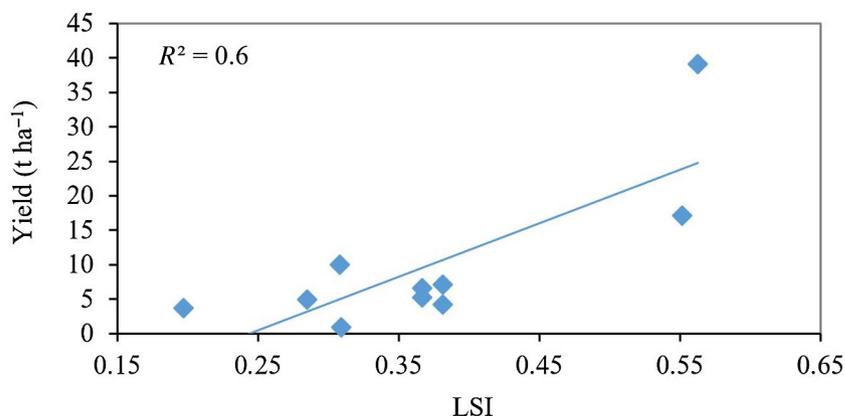
### 3 | RESULTS

#### 3.1 | Model validation

Table 3 shows the input and the output of model in the model validation samples based on the field trials of the switchgrass. Yangling has the advantages over other sites

in sufficient growing season precipitation and accumulated heat ( $\text{GDD}_{10}$ ), as well as high soil available water. As a result, Yangling has a higher yield than other sites. The actual measurement of the switchgrass yield in Yangling is  $17.10 \text{ t ha}^{-1}$  in the year 2009 and  $39.09 \text{ t ha}^{-1}$  in the year 2010. This is consistent with the model estimation that Yangling has higher LSI over other sites. Compared with the other years in Ansai, the yield of switchgrass in the year 2015 is lower ( $3.67 \text{ t ha}^{-1}$ ) than other years owing to the low growing season precipitation only 220 mm. Consistently, output of the LSI in Ansai in the year 2005 is also lower. In general, the estimation of the model is consistent with the real situation of the field trials. Figure 4 shows the regression line of the LSI and the actual measurement yield of the switchgrass based on the field trials on the Loess Plateau. The  $R^2$  (coefficient of determination) of the regression line

**FIGURE 4** The regression line for LSI and the actual harvest yield of switchgrass. LSI, land suitability index



is 0.6, the mean deviation is 4.7, and the RMSE is 6.56 which demonstrates that the fuzzy logical could explain the yield. In summary, the fuzzy logical model could reflect the suitability of the land well.

### 3.2 | Marginal land availability and distribution

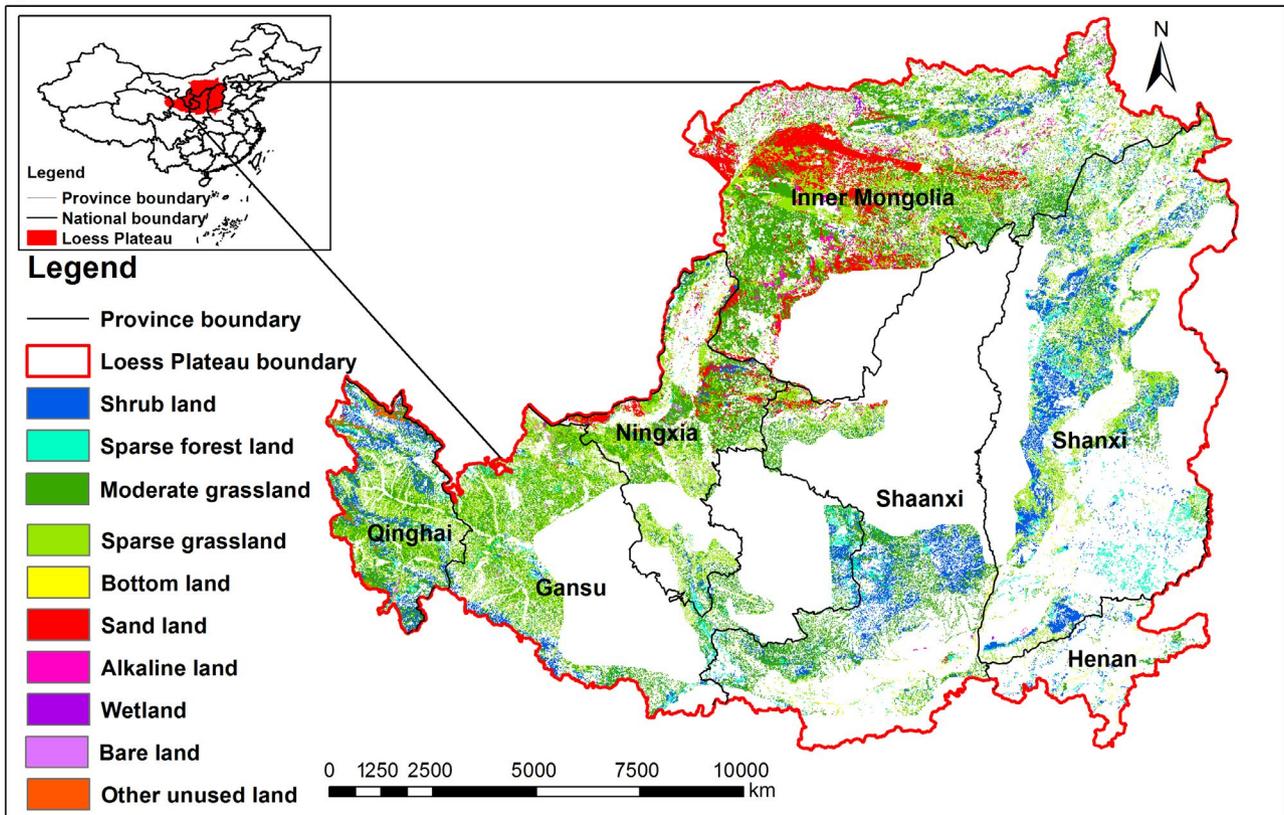
The available marginal land distribution map is displayed in Figure 5. In land-use scenario 1, approximately 20.8 Mha of marginal land is available for energy crop cultivation, which accounts for 32.5% of the total area of the Loess Plateau (Table 4). Moderate grassland is the largest marginal land type that account for 12.5% of the total Loess Plateau and it mainly distributes in Inner Mongolia (36.1%), Gansu (16.4%), and Shaanxi (14.4%) (Figure 6). The second largest available marginal land type is sparse grassland (8.9% of the Loess Plateau) and third is shrub land (4.7% of the Loess Plateau), which are mainly distributed in Inner Mongolia, Shaanxi, Shanxi, and Gansu. The available marginal land types sand land, alkaline land, and bare land all together only comprise 1.2% of the total area of the Loess Plateau, but the area is up to 2.3 Mha. The available bare land mainly distributes in Ningxia (40%) and Gansu (30%), and the unused land mainly distributes in Qinghai (78%) and Gansu (22%) (Figure 6). The wetland, bottom land, and unused land make only 2% of the total available marginal land. In land-use scenario 2, the moderate grassland is excluded, and the available marginal land decreased by 38.0%. The area is 12.8 Mha accounting for 20.0% of the total area of Loess Plateau. In both land-use scenarios, Inner Mongolia has the largest available marginal land, with an area of 4.3–7.2 Mha. Except the area of the Inner Mongolia in Loess Plateau per se is relatively large, there are big area of the moderate grassland and sparse grassland distribution. In addition, approximately 80% of the total area of the available sand land, alkaline land, and wetlands distributes in Inner Mongolia.

### 3.3 | Marginal land suitability evaluation for switchgrass

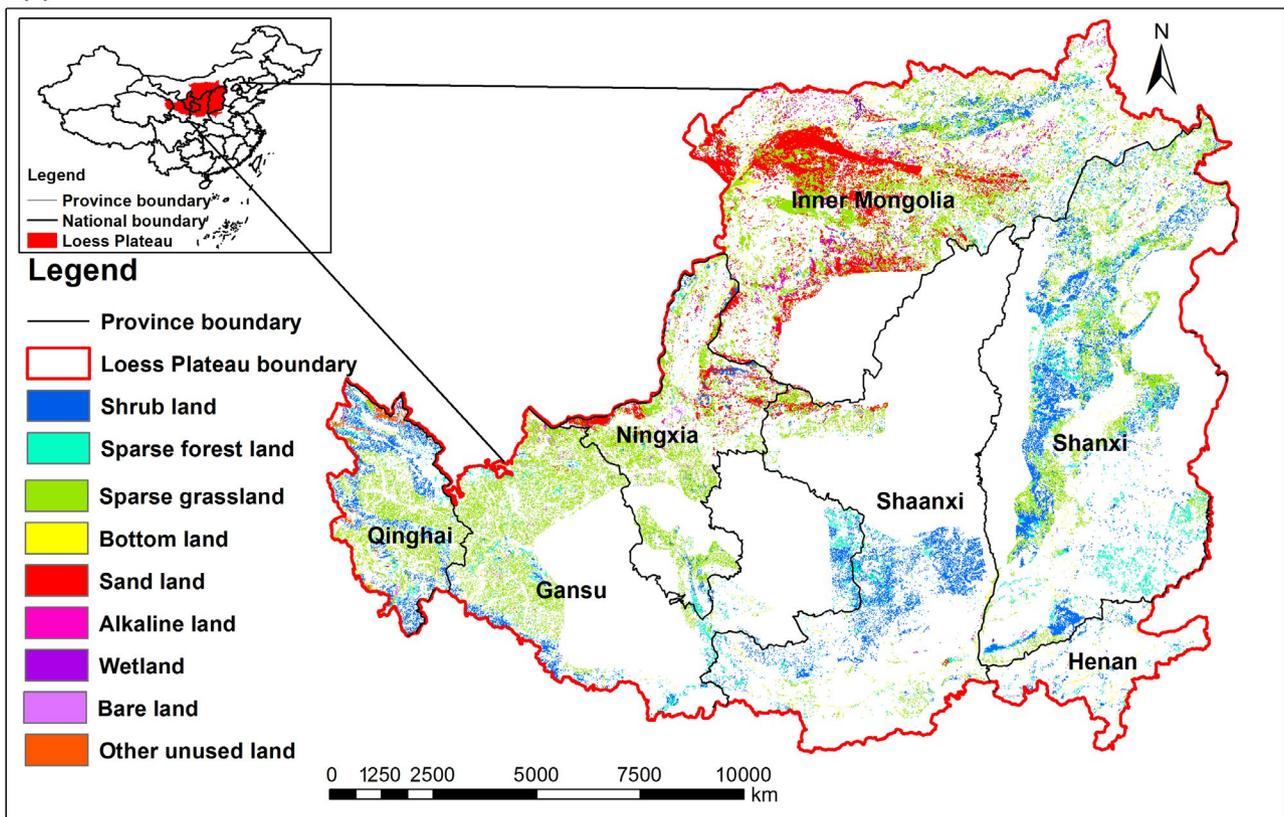
Figure 7 displays the distribution of the suitability classes of the available marginal land on the Loess Plateau. Most of the available marginal land is not suitable for switchgrass. In both land-use scenarios, the NS marginal land accounted for approximately 71% of all the available marginal land, whereas the HS marginal land only accounted for just 7.5% (Figure 8). The regression yield of NS and the PS marginal land is below 6 t ha<sup>-1</sup> in model validation which is very low productivity; therefore, the land units with HS, GS, and MS classes were defined as “suitable marginal land.” The suitable marginal land is mainly in the northeast and the southwest of the Loess Plateau (red circles in Figure 7). Figure 9 displays the area of the suitable marginal land-use types in each province in two land-use scenarios. The area of the suitable marginal land is about 4.7 Mha in land-use scenario 1 and it covers 7.3% of the Loess Plateau. The largest area of the suitable marginal land type is moderate grassland (1.8 Mha) and followed by shrub (1.1 Mha) land and sparse grassland (1.1 Mha) which totally makes up 88% of the total suitable marginal land in land-use scenario 1. When the moderate grassland is excluded, the suitable marginal land decreased by 43.5%. The suitable marginal land area in scenario 2 is 2.6 Mha, which covers 4.4% of the Loess Plateau (Figure 8).

The top 3 area rankings of the suitable marginal land in provinces in the Loess Plateau according to land-use scenario 1 is Qinghai (1.52 Mha)>Inner Mongolia (0.93 Mha)>Gansu (0.91 Mha), in land-use scenario 2 it is: Qinghai (0.86 Mha)>Shanxi (0.55)>Gansu (0.53 Mha). Inner Mongolia has the largest area of the available marginal land, whereas the largest area of the suitable marginal land distributes in Qinghai instead. Of all the available marginal land in Inner Mongolia, only averagely 12% is suitable for switchgrass. However, the rate in Qinghai is up to 71%, which is much higher than Inner Mongolia. One of the main reasons are the different component of land-use types of the available marginal land in provinces. As has mentioned in section 4.2

(a)



(b)



**FIGURE 5** Spatial distribution of available marginal land area for biomass across the Loess Plateau. (a) Land use scenario 1; (b) Land use scenario 2. The marginal land is composed of different land-use types, which are represented by different colors

that 80% of the sand land, alkali land, and bare land distributed in Inner Mongolia Inner; however, these lands are usually too poor to cultivate crops. Only about 2.3% of the sand land is suitable for switchgrass. The shrub land, forestland, and the grassland are usually more suitable for switchgrass that 20%–38% of these available land types are suitable for switchgrass (Figures 6 and 9).

**TABLE 4** Area and the proportion of the marginal on Loess Plateau

Land-use type	Area (Mha)	Proportion of Loess Plateau (%)
Shrub land	3.0	4.7
Sparse forest land	1.2	1.9
Moderate grass land	8.0	12.5
Sparse grassland	5.7	8.9
Bottomland	0.4	0.6
Sand land	1.9	2.9
Alkaline land	0.3	0.5
Wetland land	<0.1	0.1
Bare land	0.1	0.2
Unused land	0.1	0.2
Total (scenario 1)	20.8	32.5
Total (scenario 2)	12.8	20.0

### 3.4 | Yield potential of switchgrass on marginal land

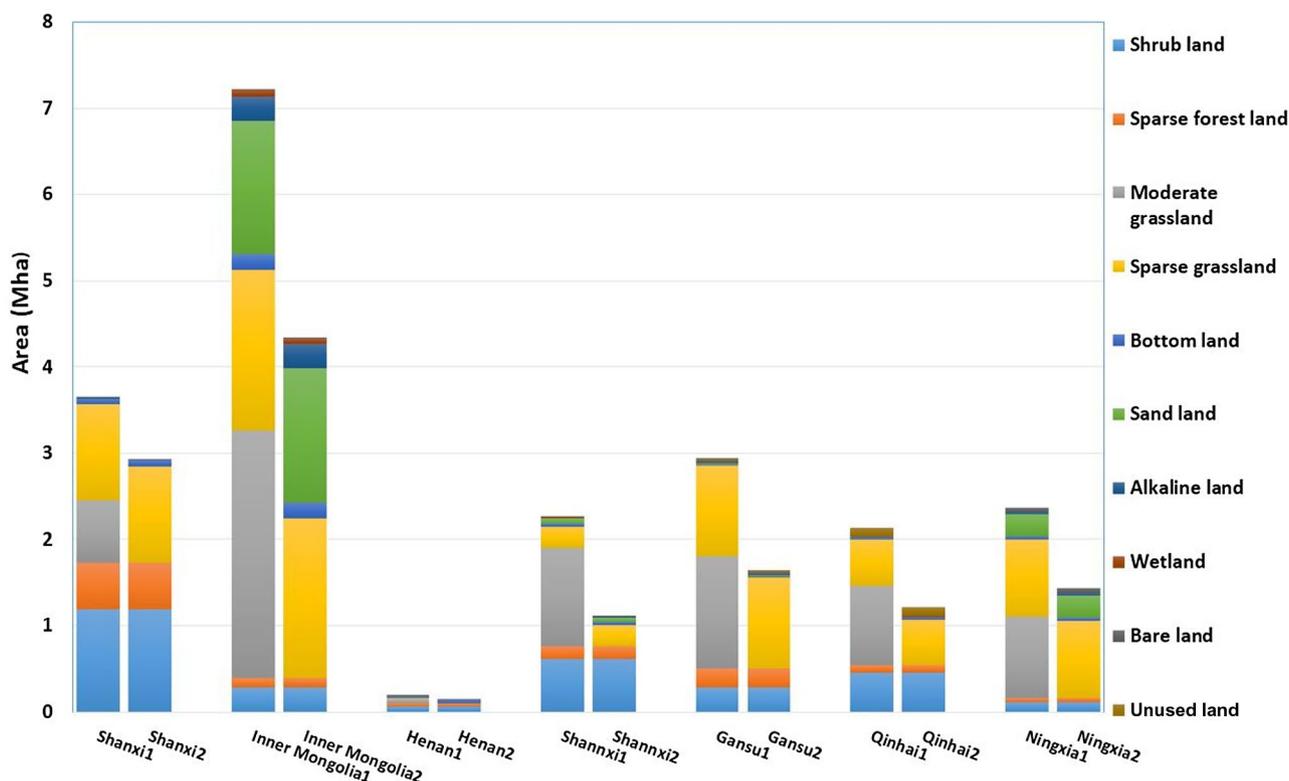
Table 5 shows the total potential yield and the average yield of switchgrass on the marginal land in each province of the Loess Plateau. The total yield of switchgrass on the marginal land of the Loess Plateau is 77 Tg in land-use scenario 1 and 44 Tg in land-use scenario 2. The average yield of the switchgrass on the Loess Plateau is 16 t ha<sup>-1</sup>. Consistent with the distribution of the suitable land, Qinghai has the highest yield and is followed by Gansu and Inner Mongolia. It demonstrates that these provinces have a large biomass production potential.

## 4 | DISCUSSION

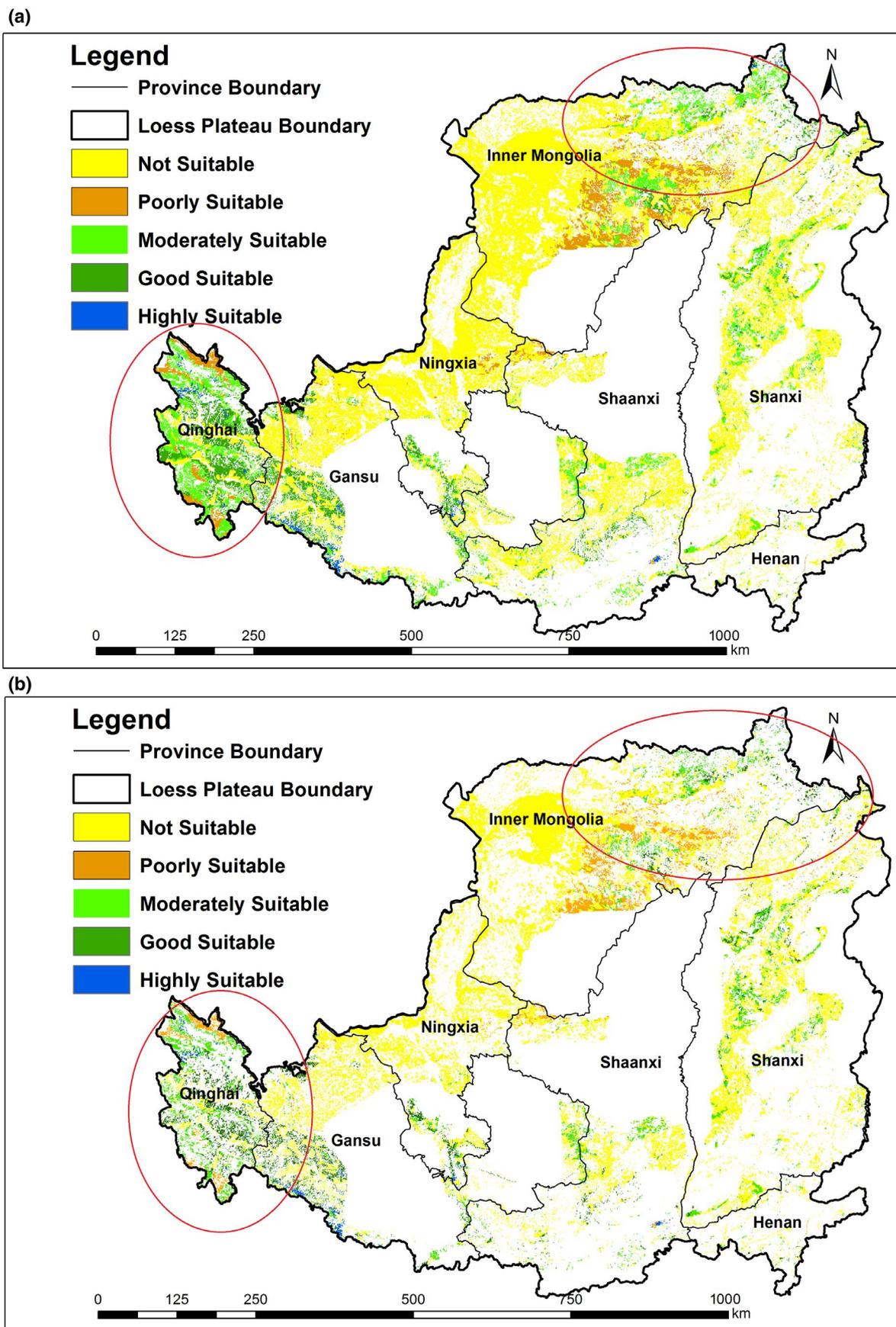
### 4.1 | Marginal land availability identification

It should be noted that the available marginal land in this study is theoretically available that not all the marginal land identified in this study could be used for biomass production practically.

Some of the land may temporarily occupied by other uses, while for other land detailed geographic information is

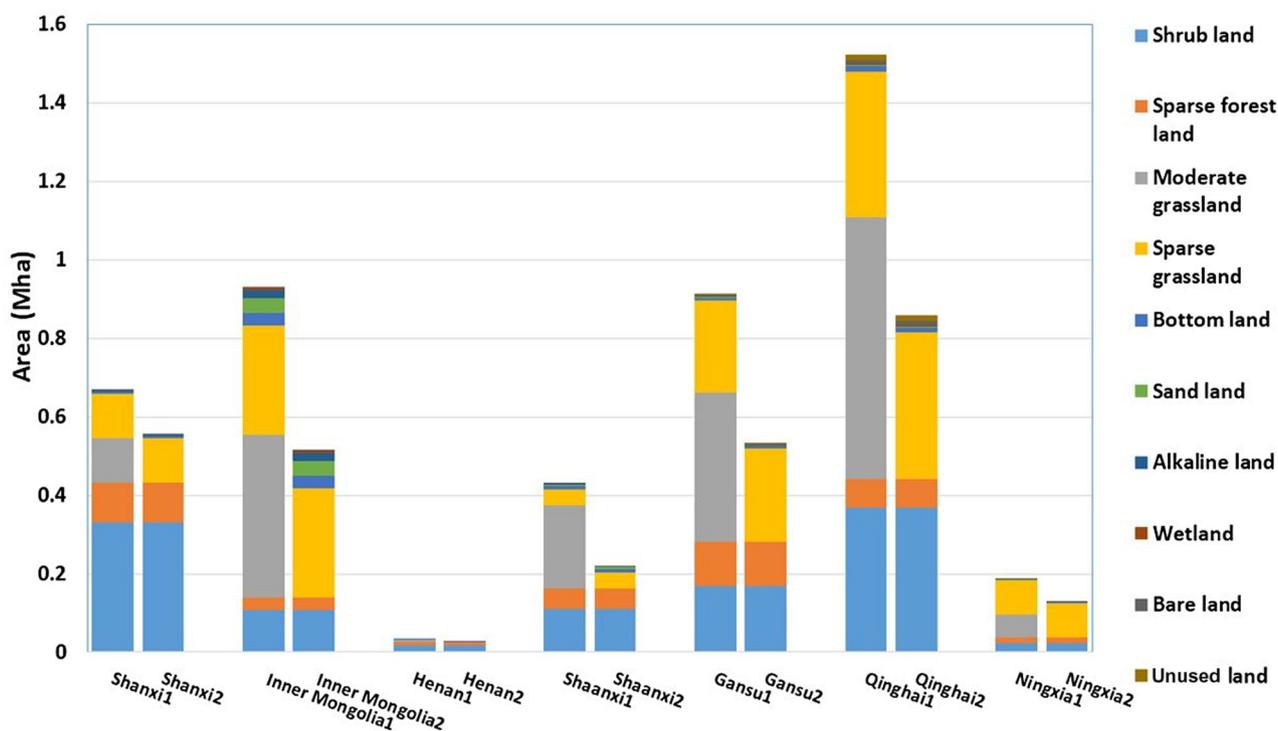
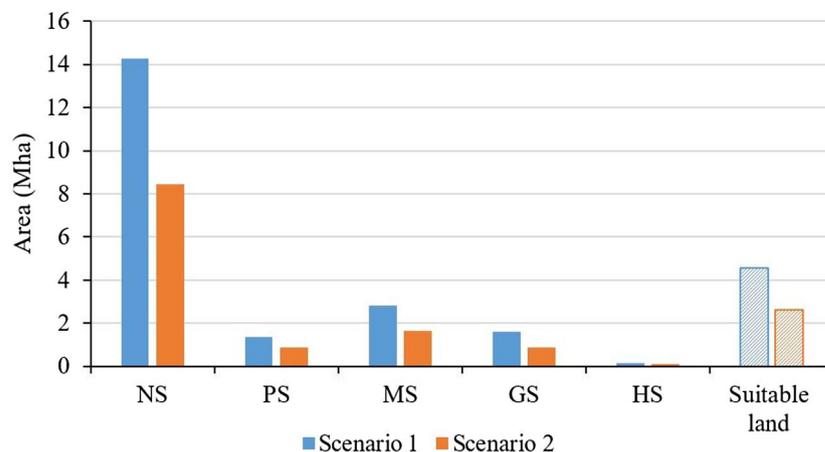


**FIGURE 6** The area of the marginal land use types. The numbers 1 and 2 within the names of the provinces represent land use scenarios 1 and 2



**FIGURE 7** Spatial distribution map of marginal land suitability classes generated from a fuzzy logical model for switchgrass in land use scenario 1 (a) and land use scenario 2 (b). The different suitability classes are represented by different colors. Red circles show concentrated areas of the suitable marginal land

**FIGURE 8** The proportion of the area of five suitability classes to the total area of the marginal land on the Loess Plateau for switchgrass. GS, good suitability; HS, highly suitable; MS, moderately suitable; NS, not suitability; PS, poor suitability



**FIGURE 9** The area of the suitable marginal land. The numbers 1 and 2 within the names of the provinces represent land use scenarios 1 and 2

**TABLE 5** The potential yield of switchgrass in each province

	Scenario 1		Scenario 2	
	Regional biomass (Tg)	Average regional biomass ( $t\ ha^{-1}$ )	Regional biomass (Tg)	Average regional biomass ( $t\ ha^{-1}$ )
Shanxi	8.7	13.1	7.1	12.7
Inner Mongolia	14.9	16.0	8.1	15.7
Henan	0.4	12.9	0.4	12.9
Shaanxi	6.5	15.1	3.0	13.7
Gansu	17.1	18.7	9.8	18.4
Qinghai	25.6	16.8	13.3	15.5
Ningxia	3.7	20.1	2.4	19.1
Total	77	16.5	44.0	15.5

missing. For example, the Loess Plateau is located in an ecotone of agriculture and animal husbandry, grassland is important resource for cattle grazing or other livestock systems by local people, especially in Inner Mongolia and Qinghai where a big area of the grassland is distributed. The data of the detailed geographic distribution of the grazing area are not currently available. In the definition of the marginal land in this study, high coverage grassland was totally reserved for grazing. The sparse grassland with low quality, which is low-quality grassland and unprofitable to grazing according to the definition of the CAS, was defined as marginal land. The use of the moderate grassland has some uncertainty that some of the land may currently be used as grazing area. With a big percentage of the marginal land is part of the moderate grassland, this would entail a large uncertainty overall because of the potential competition with other production systems. To avoid the uncertainty, we defined two land-use scenarios in this study. In land-use scenario 1, all the moderate grassland is available for biomass production with the assumption that the grassland required for grazing will be decreased significantly with the improvement of the grazing technology and the development of the intensive grazing. The spatial analysis indicates that a maximum of 20.8 Mha (land-use scenario 1) marginal land is available for biomass production on the Loess Plateau, of which the moderate grassland makes up 38% of the total marginal land with a big area of 8.0 Mha. In land-use scenario 2, the moderate grassland is absolutely prevented from being used for biomass production at all. In this case, there are still big areas of available marginal land up to 12.8 Mha on the Loess Plateau. The land use in this study is based on the land-use map of China of the year 2015 generated by CAS which is the latest land-use map with a resolution of 1km. The results of this study will be improved with the future release of the land-use map after 2020 and the availability of the geographic spatial distribution information of the grazing area.

The evaluation of the suitability of marginal land only considers physical factors in this study, with precipitation and GDD being the most relevant factors (Figure S4; File S1). The socio-economic factors such as the transportation infrastructures availability, mechanization levels, land ownership, and demographic conditions in the region where the marginal land located were not considered (Pancaldi & Trindade, 2020). The environmental factors such as impacts on the soil and water quality and quantity, and greenhouse gas emission were also not considered in this study (Von Cossel, Wagner, et al., 2019). These environmental and socio-economic factors are important to determine where to plant switchgrass, while this is outside the scope of the research in this study, and the relevant work will be conducted in my future work. With the overlay of all these factors in the future, a systemic evaluation will provide more realistic information where it is suitable to plant switchgrass.

## 4.2 | Land suitability model comparison

Currently, there are many methods developed to make land suitability evaluations and fuzzy-theory-based methods are widely applied. To choose the most suitable methods to apply in this study, we made a comparison of the two fuzzy-theory-based models beforehand. The fuzzy comprehensive model is another fuzzy-based model that has been widely applied in land suitability evaluations (Gang & Zhang, 2017; Hamzeh et al., 2014; Xu, 1992). We developed and validated the fuzzy logical model and fuzzy comprehensive model parallel using the same data source based on the field trials of the switchgrass on the Loess Plateau. Then we made a comparison between these two models. In the model validation process, the  $R^2$  of the regression the LSI with the yield of fuzzy logical model was 0.6 while the  $R^2$  of the fuzzy comprehensive model was 0.3 (Figure S2; File S2). In addition, RMSE of the fuzzy logical model (6.56) is less than fuzzy comprehensive model (11.20). It gives confidence that the fuzzy logical model is better than the fuzzy comprehensive model in terms of evaluating the marginal land suitability. The detailed description of fuzzy comprehensive model is included in File S2.

Zhang et al. (2017) estimated the switchgrass in the marginal land of China using the plant growth model GEPIC. We extracted the yield of switchgrass on Loess Plateau region from their national yield map by overlaying the Loess Plateau available marginal land map identified in our study. Their results demonstrated that switchgrass could not survive on the Loess Plateau at all. This is contrary to the results of our study that there are 2.6–4.6 Mha marginal land is suitable for switchgrass and achieved the yield of 44–77 Tg. The field trials on Yangling, Ansai, and Dingbian are strong evidence that switchgrass could not only survive but also have the capacity to achieve high yield on the Loess Plateau. The main reasons result to the difference in the two researches are that (1) the fuzzy logical model developed in this model is regional specific to the Loess Plateau and the model validated is based on the field trials on the Loess Plateau that could practically reflect the growth situation of the switchgrass on the Loess Plateau. While the GEPIC in Zhang's research is a national model and validated in the Guangxi Province of China (Zhang et al., 2017). The Guangxi is located in the southeast of China where the climate, soil, and terrain are significantly different with the Loess Plateau. (2) Because of the research-scale difference, the input data in this research are more accurate compared with the national-scale data in the GEPIC model. For example, the input data of  $GDD_{10}$  were calculated based on the 2010–2018 daily temperature of Meteorological stations on the Loess Plateau.

In summary, the fuzzy logical model developed in this study estimated the marginal land suitability for switchgrass on the Loess Plateau very well. It provides a good

framework to be adopted and applied to different land use and different crops. There are also some uncertainty in this study. (1) Currently available soil properties data on Loess Plateau are in county or watershed scale. The input soil properties data in this study were derived from HWSD. The soil properties of China included in the HWSD are provided by Institute of Soil Science, Chinese Academy of Sciences and the resolution of the geospatial soil maps is 1:1,000,000. Compared with other input maps in this study with high resolution of 1000, the soil properties maps are relatively rough. In particular, the soil available water is difficult to map. (2) There is a relatively large error of the LSI-based yield prediction model (with an rRMSE of 50%). One major reason is the lack of field trials with switchgrass on the Loess Plateau to validate the model. There are 10 datasets in three sites available, which is not representative for the Loess Plateau. Overall, the lack of high resolution of input soil properties and the lack of field trial data cause uncertainty in this study. Currently, most of the well-developed plant growth models of switchgrass and other perennial energy crops such as miscanthus, poplar, and willow were developed based on experimental data in Europe and the United States (Hastings et al., 2009; Kiniry et al., 2005). Fitting these models to the Loess Plateau region should be done by parameterizing and calibrating the models using the local field trial data. But the lack of field trial data on the Loess Plateau will always imply some uncertainty in the assessment (Liu & Sang, 2013). Consequently, we strongly recommend (1) to establish dedicated biomass crops (Von Cossel, Lewandowski, et al., 2019) on the Loess Plateau, especially in the marginal condition to provide systemic plant growth data; and (2) to improve the geographic data including soil properties and current land use on the Loess Plateau. With the improved data, the model could give a more accurate estimation.

## 5 | CONCLUSION

The marginal land of the Loess Plateau has a big potential for biomass production. There are approximately 12.8–20.8 Mha available marginal land on the Loess Plateau, of which 21% is suitable to plant switchgrass. The area of the suitable marginal land is 2.6–4.6 Mha with potential yield of 44–77 Tg. The fuzzy logical model developed in this study was proved to have better results than other models because the validation of the model was based on the field trials of the switchgrass on the Loess Plateau and with the more accurate input data compared with plant growth model. Therefore, the fuzzy logical model developed in this study also provide a good framework to evaluate the marginal land suitability.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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