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Modeled spatial assessment of biomass productivity and technical potential of *Miscanthus × giganteus*, *Panicum virgatum* L., and *Jatropha* on marginal land in China

Bingquan Zhang[1] | **Astley Hastings**[2] | **John C. Clifton-Brown**[3] | **Dong Jiang**[4] | **André P. C. Faaij**[1]

[1]Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen, The Netherlands

[2]Institute of Biological and Environmental Science, University of Aberdeen, Aberdeen, UK

[3]Institute of Biological, Environmental and Rural Sciences (IBERS), Aberystwyth University, Aberystwyth, UK

[4]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

Correspondence
Bingquan Zhang, Energy and Sustainability Research Institute Groningen, University of Groningen, Nijenborgh 6, Groningen 9747AG, The Netherlands.
Email: bingquan.zhang@rug.nl

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Abstract

This article identifies marginal land technically available for the production of energy crops in China, compares three models of yield prediction for *Miscanthus × giganteus*, *Panicum virgatum* L. (switchgrass), and *Jatropha*, and estimates their spatially specific yields and technical potential for 2017. Geographic Information System (GIS) analysis of land use maps estimated that 185 Mha of marginal land was technically available for energy crops in China without using areas currently used for food production. Modeled yields were projected for *Miscanthus × giganteus*, a GIS-based Environmental Policy Integrated Climate model for switchgrass and Global Agro-Ecological Zone model for *Jatropha*. GIS analysis and MiscanFor estimated more than 120 Mha marginal land was technically available for *Miscanthus* with a total potential of 1,761 dry weight metric million tonne (DW Mt)/year. A total of 284 DW Mt/year of switchgrass could be obtained from 30 Mha marginal land, with an average yield of 9.5 DW t ha^{-1} year^{-1}. More than 35 Mha marginal land was technically available for *Jatropha*, delivering 9.7 Mt/year of *Jatropha* seed. The total technical potential from available marginal land was calculated as 31.7 EJ/year for *Miscanthus*, 5.1 EJ/year for switchgrass, and 0.13 EJ/year for *Jatropha*. A total technical bioenergy potential of 34.4 EJ/year was calculated by identifying best suited crop for each 1 km^2 grid cell based on the highest energy value among the three crops. The results indicate that the technical potential per hectare of *Jatropha* is unable to compete with that of the other two crops in each grid cell. This modeling study provides planners with spatial overviews that demonstrate the potential of these crops and where biomass production could be potentially distributed in China which needs field trials to test model assumptions and build experience necessary to translate into practicality.

KEYWORDS

biomass, energy crop, *Jatropha*, marginal land, *Miscanthus × giganteus*, switchgrass, technical potential, yield modeling

1 | INTRODUCTION

Renewable energy is stimulated by China to be more produced in order to protect the environment and increase energy security. China has overtaken the United States as the world's major greenhouse gas (GHG) emitter since 2007 (IEA, 2011), and has been the world's largest energy consumer since 2011 (Shi, 2013). China now expects to account for 50% of the increase in global CO_2 emissions by 2035 (IEA, 2011). This large consumption of fossil energy has caused a series of problems with respect to the environment and energy security, such as air pollution and GHG emissions contributing to global climate change, which are unsustainable. Therefore, to reduce this large consumption of fossil energy, China has set the goal to decrease China's carbon emissions per unit GDP by 40%–45% compared with 2005 by 2020 (Tian, Zhao, Meng, Sun, & Yan, 2009), and it is investigating possible options of renewable energy to accomplish this target, one of which is bioenergy.

According to the "13th Five-Year Plan for Renewable Energy Development" (NDRC, 2016), China has set ambitious goals for non-fossil energy of 15% and 20% of primary energy consumption by 2020 and 2030, respectively. Among the goals, 80 billion m^3 of biogas, 30 Mt of briquetted biofuels, 90 TWh of biomass electricity, and 6 Mt of liquid biofuels will be produced in 2020 in China. In recent years, increasing biomass as a feedstock has been used to generate electricity or produce biofuels. The amount of total bioenergy supply reached 2.4 EJ in China in 2017, accounting for 1.9% of the total primary energy supply of China in 2017, which was 117.8 EJ (NDRC/CNREC, 2018). In addition, several studies have addressed future bioenergy utilization under different scenarios in China. According to a report of the International Energy Agency (IEA), bioenergy could account for 7% of the total primary energy demand, with electricity production by bioenergy accounting for 4% of the total electricity generation of China in 2030 in a so-called Bridge Scenario (IEA, 2015). In addition to the IEA, a study conducted by Lucas et al. (2013) analyzed future bioenergy utilization in three global emission scenarios using the TIMER (Van Vuuren, van Ruijven, Hoogwijk, Isaac, & de Vries, 2006) model. It showed that biofuel production in China in 2035 was projected to be 6.3 EJ/year, 17.2 EJ/year, and 13.4 EJ/year, accounting for 3.4%, 11.8%, and 10% of the total primary energy supply for three scenarios: the reference, least-cost, and Copenhagen scenario that postpones ambitious mitigation action, starting from the Copenhagen Accord pledges (UNFCCC, 2009), respectively. Another study conducted by Zhang, Chen, and Huang (2016) simulated that biofuels will account for 6.0%–22.5% of the total transport energy consumption in 2050 in different scenarios depending on different levels of carbon emission tax by using the TIMES (The Integrated MARKAL-EFOM System, Loulou, Goldstein, & Noble, 2004) model. The most recent study found that bioenergy can share 5%–15% of the total primary energy consumption of China in 2030 in different scenarios for both different land occupations and efficiencies of conversion technologies (Zhao, 2018).

To produce more bioenergy, it is necessary to assess the potential of suitable land for growing energy crops in China. In 2007, China's government made a decision to change from food-based biofuel production to nonfood-based biofuel production without using arable land and considering the competition for food and arable land use caused by bioenergy production (Qiu, 2009). According to Tilman et al. (2009), bioenergy production might cause food shortages and loss of ecological and cultural diversity as croplands, cultural and nature reserves are used for the cultivation of energy crops. Taking into account the scarce arable land resources in China, bioenergy production should not occupy protected areas and arable land that are currently growing food crops. Therefore, it is necessary to locate and quantify where suitable spare land could be available for bioenergy production that would avoid land use conflicts with food production in China (Cassman & Liska, 2007; Elobeid & Hart, 2007; Gelfand et al., 2013; Lam, Tan, Lee, & Mohamed, 2009). Spare land is largely marginal land, which is poorly suited for conventional crops but suitable for energy crops or other functions according to edaphic, climatic, environmental, and economic criteria (Levis & Kelly, 2014).

To map the spatial distribution of potential biomass production, an increasing number of studies have applied some Geographic Information System (GIS)-based models to quantify and locate marginal land for energy crops in China. Some studies have focused on a specific region with one or more types of energy crops on marginal lands (He, 2008; Liu, Yan, Li, & Sang, 2012; Tian, Guo, & Liu, 2005; Tian et al., 2009; Wang & Shi, 2015; Wang, Su, Wang, & Li, 2013; Wu, Huang, & Deng, 2010; Yan, Zhang, Wang, & Hu, 2008; Yuan et al., 2008). Other studies have evaluated the potential of energy crops on marginal land on a national scale, while only one typical energy crop was considered. For instance, Xue, Lewandowski, Wang, and Yi (2016) estimated a yield potential of aboveground *Miscanthus* of 2.1–32.4 DW t ha^{-1} $year^{-1}$ and a total production potential of 135 DW Mt/year on 7.7 Mha of suitable marginal land in China by using a modified Monteith radiation yield model (Monteith, 1977) combined with GIS techniques. A study carried out by Zhang, Fu, Lin, Jiang, and Yan (2017) using the GEPIC model assessed that there is 59.4 Mha marginal land suitable for switchgrass production, which can achieve a yield potential of 6.8–18.5 DW t ha^{-1} $year^{-1}$. FAO and IIASA developed a generic crop model named GAEZ to estimate yield potentials for 49 types of crops, including some kinds of energy crops, in different climate scenarios on a global scale (IIASA/FAO, 2012). In addition, a study carried out by

Zhuang, Jiang, Liu, and Huang (2011), mapped the explicit spatial distribution of five kinds of energy plants growing on marginal lands on a national scale. However, which crops are best grown on which land is not known. Based on the review of different studies about assessments of marginal lands and bioenergy potential from marginal lands in China, it can be concluded that the majority of studies have a strong focus on a regional scale or on few types of energy crops, and they did not provide an optimally spatial yield distribution of multiple energy crops simultaneously cultivated on marginal land.

Therefore, herein, we aimed to compare different methods of yield modeling of *Miscanthus*, switchgrass, and *Jatropha* and to estimate the current (2017) spatially specific yield and technical potential, as defined in Section 2.3, of three types of energy crops cultivated on marginal land in China. These aims were accomplished by first identifying the area and spatial distribution of marginal land technically available for energy crops by using land use data and GIS analysis. Second, a crop-specific model MiscanFor (Hastings, Clifton-Brown, Wattenbach, Mitchell, & Smith, 2009) was applied to estimate the yields of *Miscanthus* × *giganteus*, and results extracted from the GAEZ model were further processed to show the productivity of *Miscanthus,* switchgrass, and *Jatropha* on marginal land in China. Next, the yields of *Miscanthus* calculated by MiscanFor were compared to the productivity of *Miscanthus* derived from GAEZ model. The yields of switchgrass extracted from the GEPIC model and GAEZ were also compared. Then, the combination of the first two steps' results was used to calculate the technical potential of bioenergy from marginal land in China. Finally, an optimal spatial distribution of the three energy crops simultaneously cultivated on marginal land was obtained by using overlay analysis.

2 | MATERIALS AND METHODS

2.1 | Identification of marginal land technically available for energy crop production

The term "marginal land" has been related to bioenergy because it is regarded as a potential land resource for bioenergy feedstock production. Definitions of marginal land differ in studies. The differences in the definitions of marginal land lead to dramatically different results of marginal land assessments (Cai, Zhang, & Wang, 2011; Lu, Jiang, Zhuang, & Huang, 2012; Milbrant & Overend, 2009; Schweers et al., 2011; Zhuang et al., 2011). There are two kinds of definitions of marginal land, including the general definition and the working definition (Levis & Kelly, 2014). General definitions are based on the purpose of marginal land utilization and are therefore relatively common in most studies related to bioenergy. For a typical example, Gelfand et al. (2013) defined marginal land as those land that are poorly suited for the cultivation of food crops due to their inherent edaphic, climatic or other environmental limitations or risks. In contrast, working definitions differ significantly between studies due to the different nations, target crops, input datasets, and methods used. Various criteria or filters have been implemented to identify marginal land across studies. For instance, Lu et al. (2012) and Zhuang et al. (2011) proposed different working definitions of marginal land. Both studies then implemented a set of criteria consisting of slope, climate, and soil constraints to identify marginal land suitable for energy crops.

The working definition of marginal land in this study consists of lands that are not in use as cropland, pastoral land, forest, eco-environmental reserves, urban, rural residential areas, and other constructed areas but that could be capable of growing energy crops. It should be noticed that the marginal land identified in this study is technically available but not practically available marginal land. The technically available marginal land was defined as the theoretical potential of marginal land that is identified based on the working definition of marginal land in this study. Because not all marginal land identified in this study could be practically used for energy crop production considering some areas are temporarily occupied for other purpose in reality, such as small-scale non-cereals crop production with low economic values for self-demand. The total amount and geographical distribution of marginal land was identified by utilizing the GIS analysis according to a land cover/use classification system formulated by the Chinese Academy of Sciences (CAS; Liu et al., 2003, 2005). This system classifies the land in China into six primary types, including arable land, forestland, grassland, water area, urban and construction areas, and unused land. They are further divided into 27 subcategories, which are shown in a raster layer of Chinese land use of 2015 with a grid-cell resolution of 1 km × 1 km. Although the land use from 2015 might have changed over time compared with the land use today, to date, these are still the most recent land use data in China on a national scale with the 1 km × 1 km resolution. According to the working definition of marginal land in this study, five filters as shown in Figure 1 were set to identify technically available marginal land for energy crops. Land used as cropland, forest, urban, and water areas was first excluded. Gobi Desert, bare rock land, and sand land were then excluded due to their poor geographic conditions that are not suitable for growing crops. As a result, only nine of 27 types of land were selected as a source for marginal land: (a) shrub land, (b) sparse forestland, (c) high coverage grassland, (d) moderate coverage grassland, (e) sparse grassland, (f) intertidal zone, (g) bottomland, (h) saline-alkali land, (i) bare land. The definitions

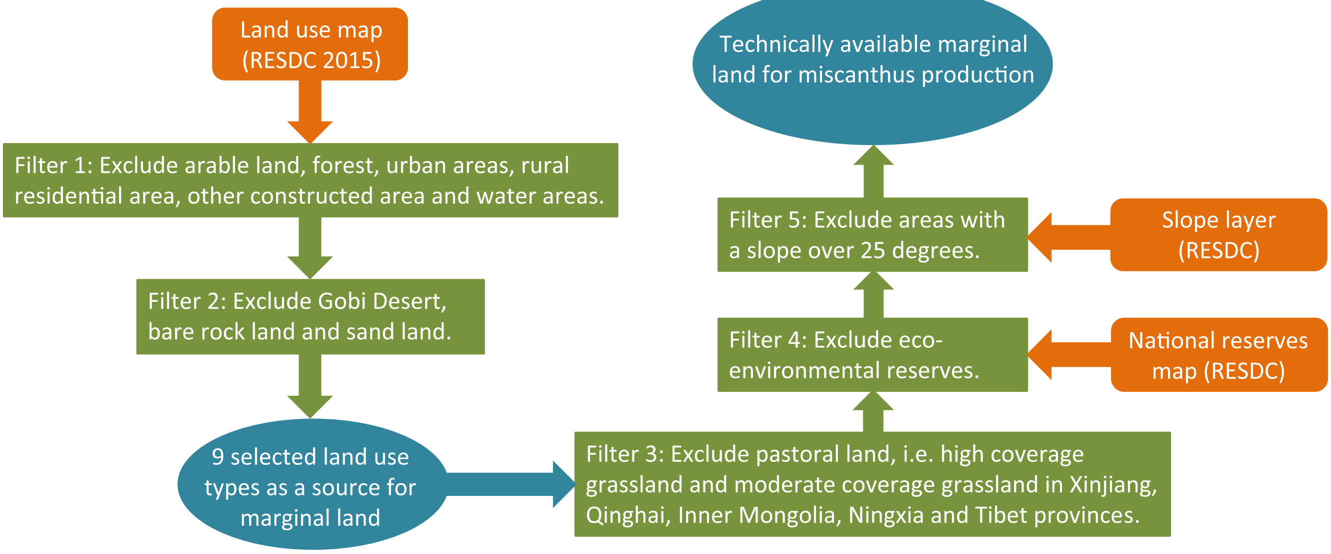

FIGURE 1 Flowchart for identification of technically available marginal land for energy crop production

of each land category are shown in Table S1. Furthermore, we defined the high coverage grassland and moderate coverage grassland distributed in the five pastoral provinces, including Xinjiang, Qinghai, Inner Mongolia, Ningxia, and Tibet, as pastoral land, as the pastoral land are not classified in this classification system. Then, the defined pastoral land was excluded from the land identified above. The eco-environmental reserves were then also excluded according to the data of national reserves. Finally, marginal lands with a slope over 25 degrees were excluded due to water runoff risks, soil erosion, and the difficulty of mechanical operations on this kind of land (Zhuang et al., 2011). According to the above principles, the marginal land technically available for energy crop cultivation was identified using GIS analysis technology.

2.2 | Yield of energy crop plantation on marginal land

2.2.1 | Species selection

Species of energy crops were selected for simulating biomass production on marginal land. Taking into account the hostile natural conditions of marginal land characterized by low water availability, poor chemical and physical soil characteristics, poor climatic conditions or excess slope, and the goal of Chinese government to change food-based to nonfood bioenergy production, few nonfood dedicated energy crops could be considered as the main feedstocks for bioenergy production on marginal land on a large scale in the mid- and long-term plan in China. Herbaceous dedicated energy crops, including *Miscanthus*, switchgrass, and sweet sorghum, and woody crops, including *Jatropha* and *Pistacia chinensis*, will play an important role in future sustainable bioenergy production in China. The comparison and selection of the energy crops are shown in Table 1. Given these information, two perennial herbaceous species (*Miscanthus* × *giganteus,* switchgrass) and one woody species (*Jatropha curcas* L.) were selected in this study. The *Jatropha* mentioned below is the seed of *Jatropha*.

2.2.2 | Model description and selection

The yield of crops could be estimated by various models, including crop-specific growth models and generic crop growth models. Three models were introduced and compared in this article. Some general characteristics of the three models are described in Table 2.

Crop-specific model

The crop-specific model enables crop simulation for only one species. In terms of the accuracy of modeling, the crop-specific model provides more accurate results than the generic crop model under the premise that same climate and soil input data with high spatial and temporal quality are implemented because it contains crop-specific process descriptions with more detailed crop-specific parameters for crop growth simulation. Therefore, the crop-specific growth model is preferred to calculate the crop yield. However, not all the crops in this study have a specific model. Only *Miscanthus* × *giganteus* has specific models, such as MiscanFor (Hastings et al., 2009) which is an updated genotype-specific version of MISCANMOD (Clifton-Brown, Neilson, Lewandowski, & Jones, 2000; Clifton-Brown, Stampfl, & Jones, 2004), and is the state-of-the-art model for *Miscanthus* developed in Europe. It

TABLE 1 Comparison and selection of energy crop species

	Advantages	Disadvantages	References
Selected crops			
Miscanthus and switchgrass	Have a lifetime of more than 20 years, lower inputs demands, higher biomass production, higher tolerance to poor eco-environmental conditions than annual crops.	—	Lewandowski, Scurlock, Lindvall, and Christou (2003); Mantineo, Agosta, Copani, Patanè, and Cosentinoa (2009); VanLoocke, Twineb, Zerid, and Bernacchic (2012); Emersona et al. (2014); Xue et al. (2016); Zhang et al. (2017)
Jatropha	High seed oil content and strong adaptability to drought.	—	Lim, Shamsudin, Baharudin, and Yunus (2015); Zhuang et al. (2011)
Unselected crops			
Sweet sorghum	High water-usage efficiency, tolerant to drought, cold and salinity.	Needs higher annual management practices, which increase production costs compared with perennial herbaceous crops.	Hu, Wu, Persson, Peng, and Feng (2017); Lee et al. (2018); Heaton et al. (2008)
Pistacia chinensis	Native to western and central China, strong tolerance to cold, high seed oil content.	Rare studies on it.	Zhuang et al. (2011)

can provide the spatial variability of the yield for each year. Given the reasons above, MiscanFor was selected herein to estimate the yield of *Miscanthus* × *giganteus*.

*MiscanFor (*Miscanthus × giganteus*).* MiscanFor is a process-based spatial crop simulation model for specific species of *Miscanthus*. It uses genotype-specific process descriptions for *Miscanthus* simulation, including phenological stages, leaf area dynamics, light interception and photosynthesis, soil water content and drought stress, frost and drought kill events, day matter repartition, and nitrogen stress. To run this model, monthly mean meteorological and soil data are required as the input data in the model. Table 2 shows the input variables for the model. Photosynthetically active radiation and potential evapotranspiration must be estimated from the meteorological variables (Hastings et al., 2009). The yields for each year are then estimated and subsequently calculated as average yields of each year over this time series. Field trial data for two spots in China were applied to validate the output results, and then the layer of technically available marginal land was used as a mask to extract the yields from the marginal land. Finally, we determined the spatial distribution of mean yields of *Miscanthus* from technically available marginal land in China. The flowchart of yield estimation on marginal land by MiscanFor is depicted in Figure 2.

Generic crop model

The generic crop model is able to simulate different kinds of crops. The GEPIC and GAEZ models were introduced and compared in this study.

GEPIC model (switchgrass). The GEPIC model is a GIS-based version of the EPIC model that enables simulations for more than 100 types of crops, including both herbaceous and woody crops and both agricultural and bioenergy crops, by using a unified approach (Liu, Williams, Zehnder, & Yang, 2007; Williams, Jones, & Dyke, 1984). The EPIC model has been widely applied to estimate yields of multiple crops, such as wheat, maize, soybean, and rice, among others, under various weather, soil, and management conditions in many countries (Liu et al., 2007). It uses a general species-based routine to simulate crop growth based on crop parameters, radiation interception, leaf area index, radiation-use efficiency, temperature, water and nutrient stress, and the harvest index. Beer's law equation (Monsi & Saeki, 1953) and Monteith's (1977) approaches were used to calculate the photosynthetic active radiation intercepted by crops and the daily production of biomass, respectively.

An example of the utilization of GEPIC is the study carried out by Zhang et al. (2017), which estimated the productivity potential of switchgrass from marginal land in China. The results of yield projection for switchgrass from Zhang's study were used in this research.

*GAEZ model (*Miscanthus*, switchgrass, and* Jatropha*).* The GAEZ model was developed by the International Institute for Applied Systems Analysis and the Food and Agriculture Organization of the United Nations (IIASA/FAO, 2012) by applying the Agro-Ecological Zone (AEZ) approach, which is based on land evaluation methodologies (FAO, 1976, 1984). It is a GIS-based global biophysical modeling framework that utilizes land evaluation approaches with socioeconomic and

TABLE 2 General characteristics of the three models

Models	Type	Crops covered	Crops used in this study	Input data required	Resolution and sources of spatial data in this study	Whether to verify with field trial data in this study
MiscanFor	Crop genotype specific, GIS based	*Miscanthus* × *giganteus, Miscanthus* × *sinensis*	*Miscanthus* × *giganteus*	Historical climatic data: daily or monthly mean, maximum and minimum temperature, precipitation, monthly average cloud cover, monthly maximum and minimum vapor pressure deficit, solar radiation. Soil data: soil water holding capacity, clay content, wilting point, field capacity, and bulk density. Other parameters: radiation use efficiency, leaf expansion index and base temperature, length of growing season for photosynthesis expressed in degree days.	Historical climatic data: 30 arc-minute grid cell from CRU 4.1 TS. Soil data: 30 arc-second from HWSD.	Yes
GEPIC	Generic, GIS based	More than 100 types of herbaceous and woody crops including *Miscanthus* and *Switchgrass*	*Switchgrass*	Historical climatic data: annually mean minimum and maximum temperature, precipitation, solar radiation. Soil data: soil organic, soil type, soil PH. Slope data. Other parameters: optimal and minimum temperature for plant growth, maximum leaf area index, maximum rooting depth, maximum crop height, heat units to germination and maturity, base temperature, radiation use efficiency, harvest index, influence rate of the CO_2 concentrations on plants, and crop management practices.	Historical climatic data: 1 km × 1 km grid cell from CMA. Soil data: 1:1,000,000 from RESDC. Slope data: 90 m grid cell from SRTM.	Yes
GAEZ	Generic, GIS based	49 types of herbaceous and woody crops including *Miscanthus, Switchgrass,* and *Jatropha*	*Miscanthus, Switchgrass,* and *Jatropha*	Historical climatic data: monthly average temperature, diurnal temperature range, precipitation, sunshine fraction, wind speed at 10m height, relative humidity, wet-day frequency. Climate Scenarios from 2020 to 2100: HadCM3, ECHAM4, CSIRO, CGCM2. Slope data. Soil data: soil profile attributes, soil drainage, soil phases.	Historical climatic data: 10 arc-minute grid cell from CRU 2.0 Cl and 30 arc-minute grid cell from CRU 1.0 TS. Climate scenarios: 5 arc-minute grid cell from GCM. Soil data: 1:1,000,000 from the ISSCAS. Slope data: 3 arc-second grid cell from SRTM.	No

Abbreviations: CMA, China Meteorological Administration; CRU, Climate Research Unit (CRU) at the University of East Anglia; GCM, General Circulation Models; ISSCAS, Institute of Soil Science, Chinese Academy of Sciences; RESDC, Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences; SRTM, Shuttle Radar Topographic Mission.

multicriteria analysis to assess the biophysical limitations and production potentials of land. It evaluates potential attainable yields under assumed management scenarios and input levels (low, intermediate, and high), both for rain-fed and irrigated conditions, for 49 major crops including wheat, corn, rice, soybean, *Miscanthus*, switchgrass, and *Jatropha*. These estimations are carried out with simple and robust crop models with crop-specific parameters. The currently used GAEZ is

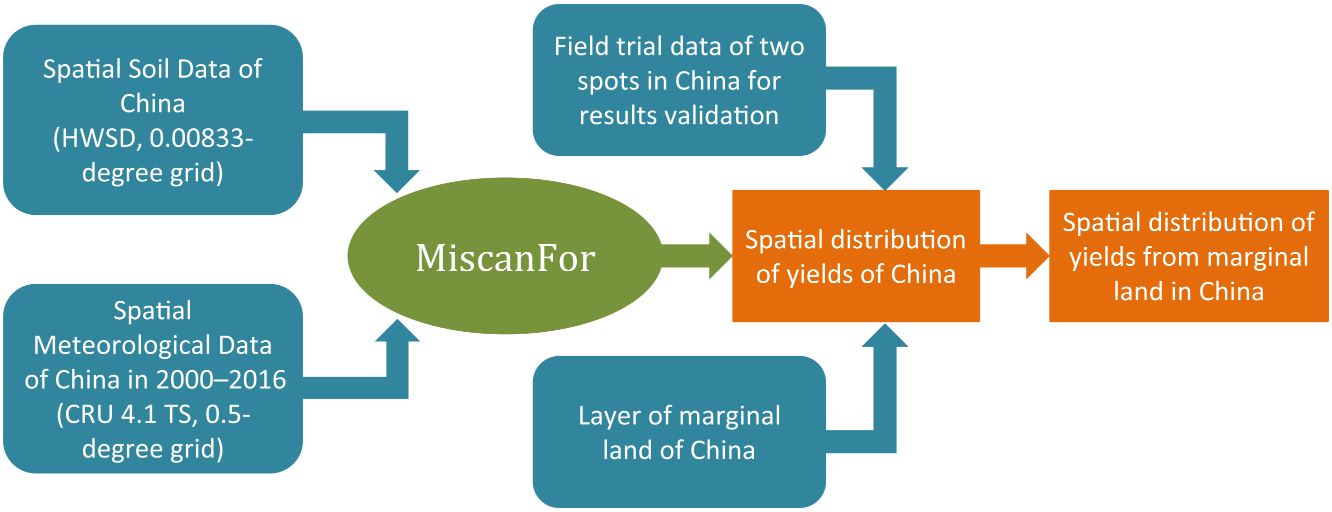

FIGURE 2 Flowchart of yield estimation on marginal land by MiscanFor

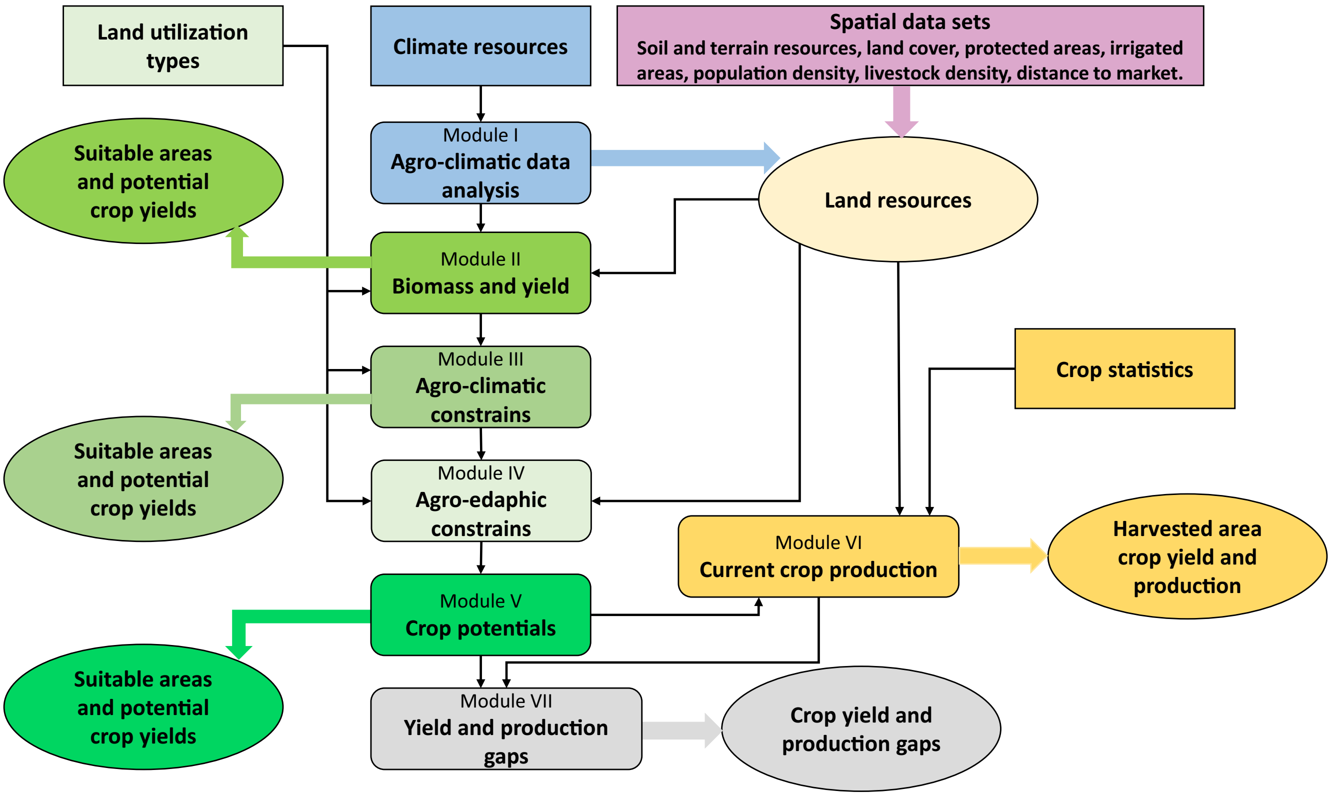

FIGURE 3 Overall scheme of model structure and data integration of GAEZ v 3.0 (IIASA/FAO, 2012)

GAEZ v 3.0, which was updated from the 2002 version of GAEZ (Fischer, Velthuizen, Shah, & Nachtergaele, 2002) by updating the data and expanding the methodology. The overall scheme of the model structure and data integration are shown in Figure 3. The core parts of the GAEZ model are module II–module IV. All results from GAEZ were integrated into a grid-cell-based database that forms a data portal named GAEZ Data Portal V3.0 (IIASA/FAO, 2012).

For switchgrass and *Jatropha*, there is no specific crop growth model. Nevertheless, the GAEZ Data Portal V3.0 provides the productivity results for these two energy crops and *Miscanthus*. The productivity of *Miscanthus*, switchgrass, and *Jatropha* is presented for three input levels (high, intermediate, and low), one water supply system type (rain-fed) for baseline climate (1961–1990), and future climate conditions. This study only considers the baseline climate.

The descriptions of the input levels are shown in Table S2 (FAO/IIASA, 2011–2012). This study ignores the low input level result taking into account that it no longer fits into the current farming system situation in China. The intermediate input level was considered as farming system in 2017 in China. Besides, the high input level could be regarded as farming system in the future in China. The results of the climate and agro-climatic analysis were based on mean climatic data for the 1961–1990 period.

2.3 | Technical potential of energy crop production on marginal land

The yield of each energy crop was converted into the corresponding technical biomass production potential. The technical potential was defined as the theoretically available energy content potential provided by the biomass production per grid cell. It was calculated per grid cell by multiplying the yield by the higher heating value (HHV) of each crop. The HHV of *Miscanthus* and switchgrass in this study was assumed to be 18 GJ DW/t harvested dry matter (Sims, Hastings, Schlamadinger, Taylor, & Smith, 2006). The oil content of *Jatropha* seeds was set to 34.3% on average (Achten et al., 2008). The HHV of *Jatropha* oil was assumed to be 39 GJ DW/t in this study (Wanignon, 2012). It should be noted that processing of *Jatropha* seed produces a main product of vegetable oil and coproducts of seedcake and husks. The coproducts could be used as an alternative wood or charcoal in boilers and as a fertilizer (Van Eijck, Romijn, Balkema, & Faaij, 2014). We only considered the vegetable oil as this is 55% of the energy in the calculation of the technical potential of *Jatropha* in this study.

An optimal crop zonation map of *Miscanthus*, switchgrass, and *Jatropha* on marginal land was determined by overlapping these layers of three crops and picking the highest value for their technical potential in each grid cell. Finally, the spatial opportunities for biomass production on marginal land were mapped.

3 | DATA INPUT

3.1 | Spatial data for the identification of marginal land

The land use data for 2015, slope data, and nationally protected areas in China (with a grid-cell spatial resolution of 1 km × 1 km) were from the Data Centre for Resources and Environmental Sciences of the CAS. All the obtained data were converted to a grid-cell spatial resolution of 1 km × 1 km.

3.2 | Yield of energy crop cultivation on marginal land

3.2.1 | Data required for MiscanFor

Spatial soil data and meteorological data

The soil data for marginal land in China from the Harmonized World Soil Database (HWSD; FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) on a 30 arc-second (approximately 1 km) grid were extracted using the marginal land layer of China. The monthly spatial meteorological data for China were derived from a gridded time series CRU 4.1 TS dataset (University of East Anglia Climatic Research Unit, Harris, & Jones, 2017), covering the period of 2000–2016 with a 30 arc-minute (approximately 50 km) grid resolution. All needed spatial data sources are shown in Table 3.

Field trial data for validation of the results

The data obtained in the multilocation field experiments for *Miscanthus'* yields in China in the 2009–2010 time series were provided by Tao Sang, an expert on *Miscanthus* breeding at the Institute of Botany of CAS. These data were used to validate the modeling results.

3.2.2 | Results from GAEZ and GEPIC for *Miscanthus*, switchgrass, and *Jatropha*

*GAEZ (*Miscanthus*, switchgrass, and* Jatropha*)*

The productivity maps of rain-fed *Miscanthus*, switchgrass, and *Jatropha* in China for two input levels (intermediate and high) with a resolution of 5 arc-minutes (approximately 10 km) are shown in Figure S1. The maps were downloaded from the GAEZ v 3.0 Data Portal, and the entirety of China was extracted from the originally global maps by ArcGIS 10.3. Maps showing the productivity of three rain-fed energy crops on marginal land in China were then extracted by masks of the layer of marginal land.

TABLE 3 Spatial data sources needed

Item	Source	Scale or Res.	Date
Land use satellite imagery	RESDC	Raster: 1 km	2015
Nationally protected area satellite imagery	RESDC	Raster: 1 km	Unknown
Soil data	HWSD	Raster: 1 km	2000–2016
Slope data	RESDC	Raster: 1 km	Unknown
Meteorological data	CRU 4.1 TS	Raster: 50 km	2000–2016

GEPIC (switchgrass)

In a study carried out by Zhang et al. (2017), the potential for switchgrass production on marginal land in China was estimated using the GEPIC model. The results are shown in Figure S2 and were applied to this study. These data were further processed by removing the national nature reserves from the original map and then used to calculate the technical potential of switchgrass.

4 | RESULTS

4.1 | Marginal land technically available for energy crop production

The distribution map (with a resolution of 1 km × 1 km) of technically available marginal land for energy crop cultivation is displayed in Figure 4. The results showed that a large amount of marginal land (184.9 Mha) was technically available for energy crops' cultivation, accounting for 19.19% of the total land area in China. The proportion of marginal land in China is higher than the proportion of arable land, which accounts for 11.26% of the total land area and has a huge potential for bioenergy production. However, approximately half of the marginal land is distributed in the western and northwestern regions of China with extreme climate conditions, including low temperature and limited precipitation of under 300 mm/year, limiting the growth of many crops.

Table 4 shows the areas and proportions for each type of marginal land in China. The largest area in the marginal land is sparse grassland, which is mainly distributed in the western and northwestern parts of China (i.e., Xinjiang, Xizang, Qinghai, Gansu, Ningxia, and Inner Mongolia Provinces), areas that are extremely prone to water. These findings indicate that many crops are unsuitable for growth on this sparse grassland without irrigation. However, this sparse grassland could be suitable for the growth of Crassulacean Acid Metabolism plants (Herrera, 2008). Sparse grassland is followed by shrub land, which is mainly distributed in southwestern China, especially in the provinces of Yunnan, Guizhou, and Guangxi, located in the subtropical temperature zone with an annual precipitation range from 1,000 to 2,000 mm and is suitable to energy crop growth. Additionally, there are three types of marginal land, including high coverage grassland, moderate coverage grassland, and sparse forestland dispersed in the southeastern half of China. The areas of different types of marginal land by provinces are presented in Table S3. As shown in Figure 4, Sichuan, Yunnan, Gansu, Guangxi, and Guizhou are the top five provinces with high-density and concentrated distributions of marginal land while not considering Xinjiang, Tibet, and Qinghai because of their unsuitability for crop growth. The former areas have great potential to develop bioenergy production due to the considerable resources and suitability of available marginal land.

TABLE 4 Areas and proportions for each type of marginal land in China

Land use type	Area (Mha)	Proportion (%)
Sparse grassland	68.5	37.0
Shrub land	34.3	18.5
Sparse forest land	24.7	13.4
Moderate coverage grassland	20.8	11.3
High coverage grassland	19.6	10.6
Saline-alkali land	11.2	6.1
Bottomland	3.2	1.7
Bare land	2.5	1.3
Intertidal zone	<0.1	<0.1
Total	184.9	100.00

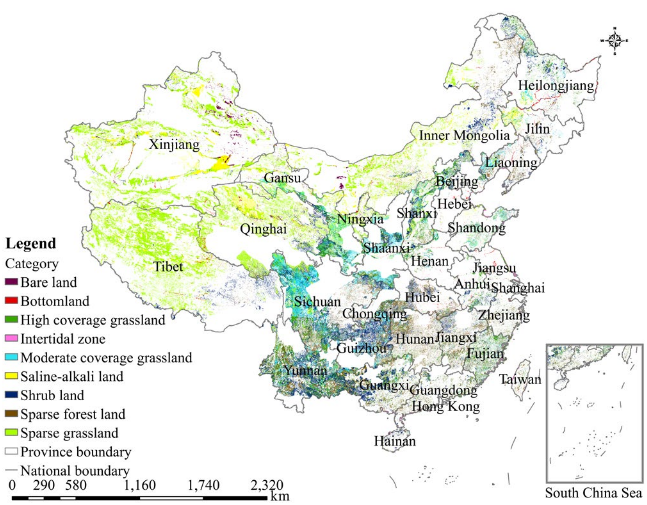

FIGURE 4 Marginal land technically available for energy crops cultivation in China

4.2 | Yields of energy crop cultivation on marginal land

4.2.1 | MiscanFor (*Miscanthus*)

The spatial distributions of simulated yields of *Miscanthus* in China with a grid-cell resolution of 30 arc-minutes gradually increase from northwest to southeast China (Figure 5a). It shows yield ranges from 1 to 31 DW t ha^{-1} year^{-1} in 2017. The yield differences could be explained primarily by precipitation.

The standard deviation of the yield for the interval from 2000 to 2016 is shown in Figure 5b. It indicates the extent of interannual variations in yields on each grid cell from 2000 to 2016. As shown in the figure, the areas with higher standard deviation values are those with a higher yield because the climatic conditions in low-yield areas are not suitable for crop

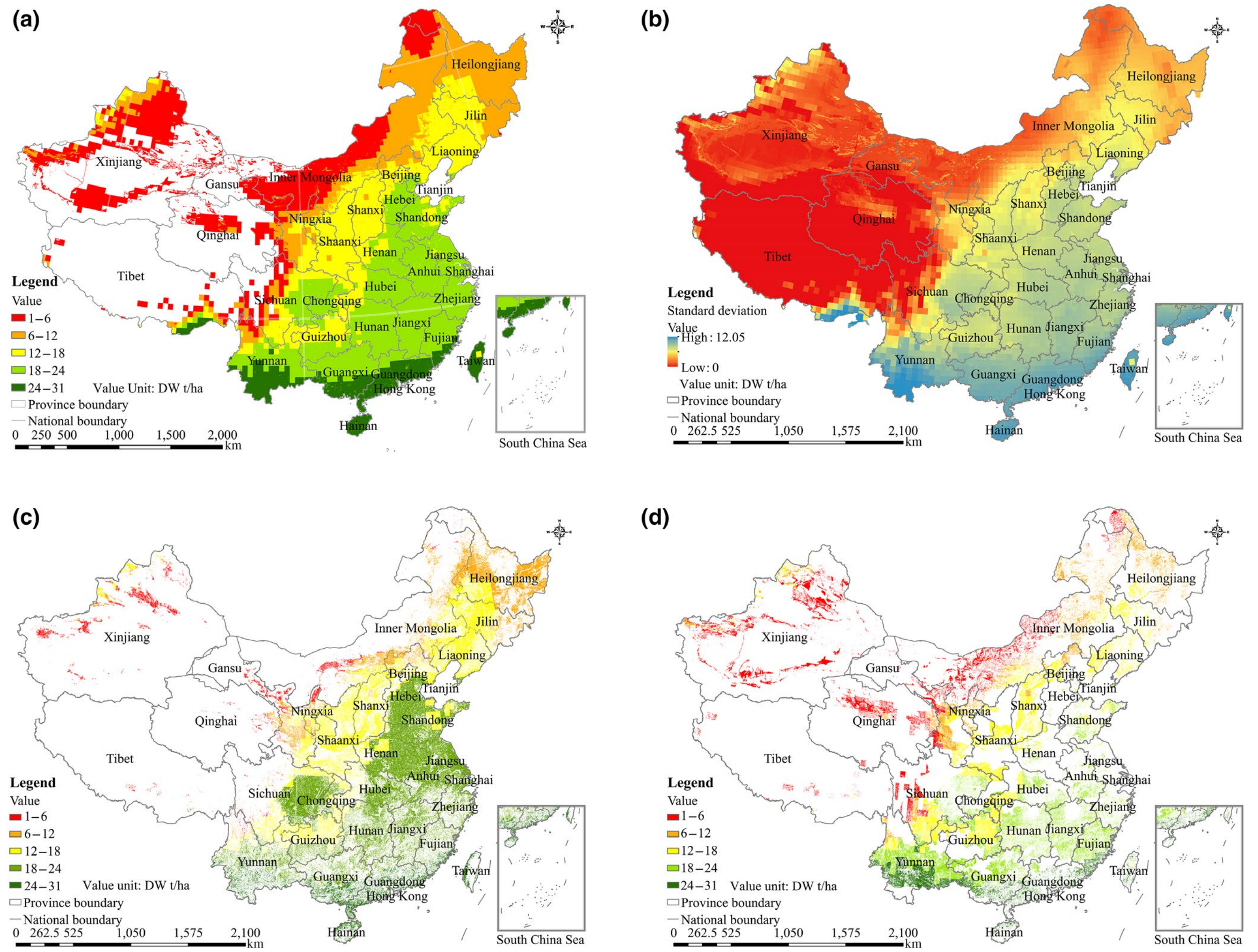

FIGURE 5 Productivity of *Miscanthus* in China by MiscanFor in 2017. (a) all land; (b) standard deviation of yield of the interval 2000–2016; (c) arable land; (d) available marginal land

growth; even if the climatic conditions worsen, the yield will not be greatly reduced.

Figure 5c demonstrates the productivity of *Miscanthus* on arable land in 2017. The total production of *Miscanthus* modeled by MiscanFor was calculated as 2,768.5 DW Mt/year from 165.8 Mha of arable land in China. The average yields of *Miscanthus* from the arable land in China were estimated as 16.7 DW t ha^{-1} $year^{-1}$.

Figure 5d shows the yield distribution maps of *Miscanthus* on marginal land in 2017. Table 5 describes statistics for the yield simulation by some provinces. Statistics for all provinces are shown in Figure S3. More than 120.3 Mha marginal land was technically available for *Miscanthus*, which delivered a total potential of 1,761.1 DW Mt/year, with a maximum yield of 31 DW t ha^{-1} $year^{-1}$ and an average yield of 14.6 DW t ha^{-1} $year^{-1}$. Compared with arable land, the marginal land has 12.6% lower productivity of *Miscanthus*. Yunnan Province has the highest production, sharing 21.9% of the total production in China with the most marginal land, while Guangdong Province has the highest average yield.

4.2.2 | GEPIC (switchgrass)

The spatial yield distribution map of switchgrass on marginal land in China in 2017 is shown in Figure 6. The map shows that most of the switchgrass are distributed in the southern half of China. Table 5 presents the statistics by some provinces with a production of switchgrass greater than 1 DW Mt/year. Statistics for all provinces are shown in Table S4. As shown in the Table 5, a total of 284.2 DW Mt/year of switchgrass could have been obtained from 29.9 Mha marginal land in China, with a maximum yield of 18.3 DW t ha^{-1} $year^{-1}$ and an average yield of 9.5 DW t ha^{-1} $year^{-1}$. It is found that 68.8% of the total production of switchgrass is distributed in the top five provinces: Yunnan, Guizhou, Sichuan, Guangxi, and Hubei. Therefore, this area had great potential for switchgrass production on marginal land. The modeled results were verified by field trial data from other reports (Hu, Gong, & Jiang, 2008; Wu et al., 2014; Xie, 2011; Xie, Guo, Wang, Ding, & Lin, 2007; Xie, Zhou, Zhao, & Lu, 2008) by Zhang et al. (2017).

TABLE 5 Statistics for yield modeling of *Miscanthus* and switchgrass by province from MiscanFor and GEPIC, respectively

Crop	Province	Area of marginal land (K ha)	Total production (DW Mt/year)	Average yield (DW t ha^{-1} year^{-1})
Miscanthus	Yunnan	16,818	385.4	22.9
	Guangxi	6,400	150.2	23.5
	Sichuan	9,592	127.0	13.2
	Guizhou	5,951	111.3	18.7
	Fujian	3,736	85.3	22.8
	Inner Mongolia	12,707	84.3	6.6
	Jiangxi	3,041	65.4	21.5
	Guangdong	1,913	48.4	25.3
	China in total	120,311	1,761.1	14.6
Switchgrass	Yunnan	8,463	75.7	8.9
	Guizhou	3,430	33.6	9.8
	Sichuan	3,615	29.7	8.2
	Guangxi	2,532	29.7	11.7
	Hubei	2,604	26.8	10.3
	Anhui	555	6.8	12.2
	Guangdong	349	3.7	10.6
	Jiangsu	104	1.3	12.5
	China in total	29,936	284.2	9.5

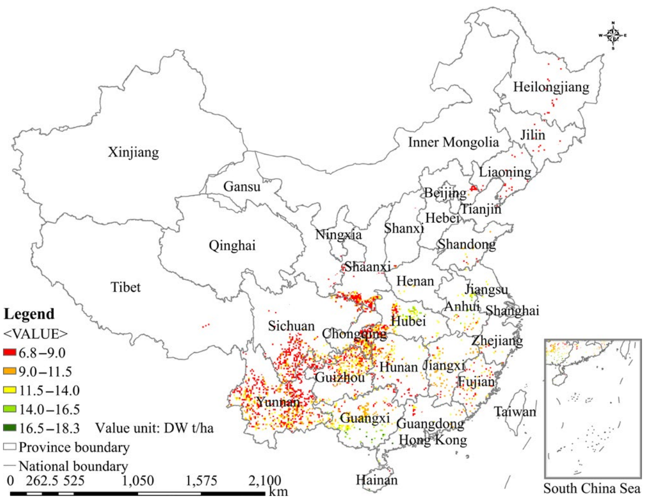

FIGURE 6 Spatial distributions of switchgrass yields on available marginal land in China by GEPIC in 2017

4.2.3 | GAEZ (*Miscanthus*, switchgrass, and *Jatropha*)

Miscanthus *and switchgrass*

The yield distribution maps of *Miscanthus* and switchgrass on marginal land for the intermediate input level modeled by GAEZ are shown in Table S5. The productions of *Miscanthus* and switchgrass on marginal land are mainly distributed in the southeastern half part of China. Table 6 shows the marginal land area, production, and yields of each type of energy crop for the intermediate input level. As shown in the table, the average yields of *Miscanthus* and switchgrass modeled by GAEZ are much lower than the results obtained from MiscanFor and GEPIC. Additionally, the results from GAEZ were not validated by field trial data, and the yields were significantly underestimated. Therefore, these results should not be applied in further studies.

Jatropha

The spatial distribution of *Jatropha* extracted from GAEZ for the intermediate input level on marginal land is demonstrated in Figure 7. The projected cultivation of *Jatropha* is distributed in the south of the Yangtze River in China. More than 35 Mha marginal land could be used for *Jatropha* cultivation, with a total production of 9.7 DW Mt/year for intermediate input level. According to a survey conducted by Dong et al. (2017), the yields of *Jatropha* seed vary significantly from 0.07 to 3 t ha^{-1} year^{-1}, with an average yield of 0.14 t ha^{-1} year^{-1} due to differences in varieties, growing conditions, and cultivation management. The actual yield of *Jatropha* is far below the expected yield, which should be 3–4 t ha^{-1} year^{-1}. As shown in Table 6, the yields of *Jatropha* seed modeled by GAEZ are within the range of actual yields in the survey and reflect the real situation of *Jatropha* production in China. In addition, the intermediate input level is defined as situations in 2017.

TABLE 6 Statistics for energy crops modeled by GAEZ for intermediate input level

Crop	Marginal land area (Mha)	Total production (DW Mt)	Average yield (DW kg ha^{-1} year^{-1})	Maximum yield (DW kg ha^{-1} year^{-1})
Miscanthus	86.0	27.4	318	1,313
Switchgrass	67.0	40.4	603	1,828
Jatropha seed	35.0	9.7	276	1,633

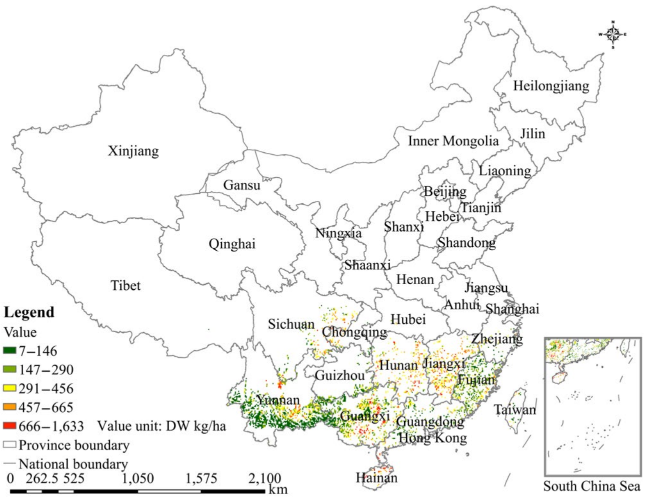

FIGURE 7 Productivity for rain-fed *Jatropha* on marginal land in China for intermediate input level

4.3 | Technical potential of energy crop plantation on marginal land

The spatial distributions of the technical potential of *Miscanthus*, switchgrass, and *Jatropha* in 2017 are consistent with their respective yield distributions. Table 7 describes the total and average technical potential of each crop from marginal land in China in 2017. The total national technical potential of energy crops on available marginal land was calculated as 31.7 EJ/year, 5.1 EJ/year, and 0.13 EJ/year in the case of planting only *Miscanthus*, switchgrass, or *Jatropha*, respectively. The average national technical potential on available marginal land was calculated as 263.5 GJ ha^{-1} year^{-1}, 170.9 GJ ha^{-1} year^{-1}, and 3.7 GJ ha^{-1} year^{-1} for *Miscanthus*, switchgrass, and *Jatropha*, respectively. The average technical potential of *Miscanthus* is 70 times that of *Jatropha*. Additionally, the highest technical potential of *Jatropha* is still lower than the minimum technical potential of switchgrass. Therefore, the technical potential from *Jatropha* is unable to compete with that of the other two crops in each grid cell in the case that three crops are simultaneously cultivated on marginal land. Table 8 shows the technical potential of *Jatropha* by province with a potential higher than 10 PJ/year in 2017. The highest total technical potential was found in Guangxi Province, while the highest average technical potential was found in Hainan Province. However, the technical potential is too low to develop *Jatropha* production in comparison to *Miscanthus* and switchgrass based on current knowledge.

TABLE 7 Technical potentials of energy crops from marginal land in China in 2017

Crop	Total technical potential (EJ/year)	Average technical potential (GJ ha^{-1} year^{-1})
Miscanthus	31.7	263.5
Switchgrass	5.1	170.9
Jatropha	0.13	3.7
Miscanthus & Switchgrass	34.0	254.5

TABLE 8 The breakdown of the technical potential of *Jatropha* by provinces in 2017

Province	Average technical potential (GJ ha^{-1} year^{-1})	Total technical potential (PJ/year)
Guangxi	4.0	30.6
Yunnan	2.3	23.5
Jiangxi	6.1	19.5
Hunan	6.3	15.1
Fujian	3.0	12.9
Sichuan	4.5	9.0
Guangdong	3.2	6.9
Hainan	9.6	3.7
Guizhou	2.4	3.6
Chongqing	4.9	2.3
Zhejiang	3.5	1.5
China in total	3.7	129.6

In the case of planting *Miscanthus*, switchgrass, and *Jatropha* simultaneously on the same marginal land, a total technical potential of 34.4 EJ/year in 2017 was calculated by overlapping the layers of *Miscanthus*, switchgrass, and *Jatropha* and determining the highest value of technical potential from each grid cell (Table 9). The results showed that the technical potential of *Jatropha* is unable to compete with that of the other two crops in each grid cell. Therefore, we named this result "*Miscanthus* & Switchgrass Mode." The total technical potential from the *Miscanthus* & Switchgrass Mode accounts for approximately 26.3% of the current primary energy consumption of China in 2017, which is approximately 131 EJ. The optimal distribution of *Miscanthus* and switchgrass from the *Miscanthus* & Switchgrass Mode is shown in Figure 8a. The distribution of highest technical potential from *Miscanthus* & Switchgrass Mode is shown in Figure 8b. Breakdown of the technical potential by crop indicates that the highest technical potentials are determined for *Miscanthus* on more than 120.3 Mha marginal land with a total technical potential of 31.7 EJ/year in 2017. For switchgrass, the projected technical potential is highest on 13.5 Mha of marginal land, potentially producing 2.7 EJ/year switchgrass in 2017 (Table 9), because the yield of *Miscanthus* is higher than that of switchgrass on most grid cells, and the distribution area of *Miscanthus* is much larger than that of switchgrass according to the results from MiscanFor and GEPIC models. Table 10 shows the breakdown of the technical potential by land use type, and indicates that 30% of the potential is distributed on shrub land, and 25.9% of the potential is from sparse forestland. The least potential that is no more than 0.1% is found in the intertidal zone. This result can be explained by the proportion of different land use types of the marginal land. Although sparse grassland shares the largest proportion of marginal land (see Table 4), only 8.7% of the potential comes from sparse grassland due to the poor climatic

TABLE 9 The breakdown of the technical potential of *Miscanthus* & Switchgrass Mode by crops in 2017

Crop	Total technical potential (EJ/year)	Share of potential (%)	Land area occupied (Mha)	Share of land area (%)
Miscanthus	31.7	92.2	120.3	89.9
Switchgrass	2.7	7.8	13.5	10.1
Total	34.4	100	133.8	100

TABLE 10 The breakdown of the technical potential of *Miscanthus* & Switchgrass Mode by land use types and provinces in 2017

Land use type	Total technical potential (EJ/year)	Share (%)	Average technical potential (GJ ha^{-1} $year^{-1}$)
Shrub land	9.5	30.0	321.8
Sparse forest land	8.2	25.8	344.8
High coverage grassland	5.7	18.0	319.8
Moderate coverage grassland	4.3	13.5	279.4
Sparse grassland	2.7	8.7	112.7
Saline-alkali land	0.6	1.8	101.5
Bottomland	0.6	1.8	234.4
Bare land	0.1	0.3	67.5
Intertidal zone	<0.1	<0.1	414.4
Total	34.0	100	254.5
Province			
Yunnan	374.7	—	7.4
Guangxi	394.1	—	2.9
Sichuan	225.4	—	2.5
Guizhou	306.5	—	2.2
Fujian	381.2	—	1.6
Hunan	319.6	—	1.6
Jiangxi	351.1	—	1.3
Guangdong	428.9	—	0.9
China in total	254.5	—	34.0

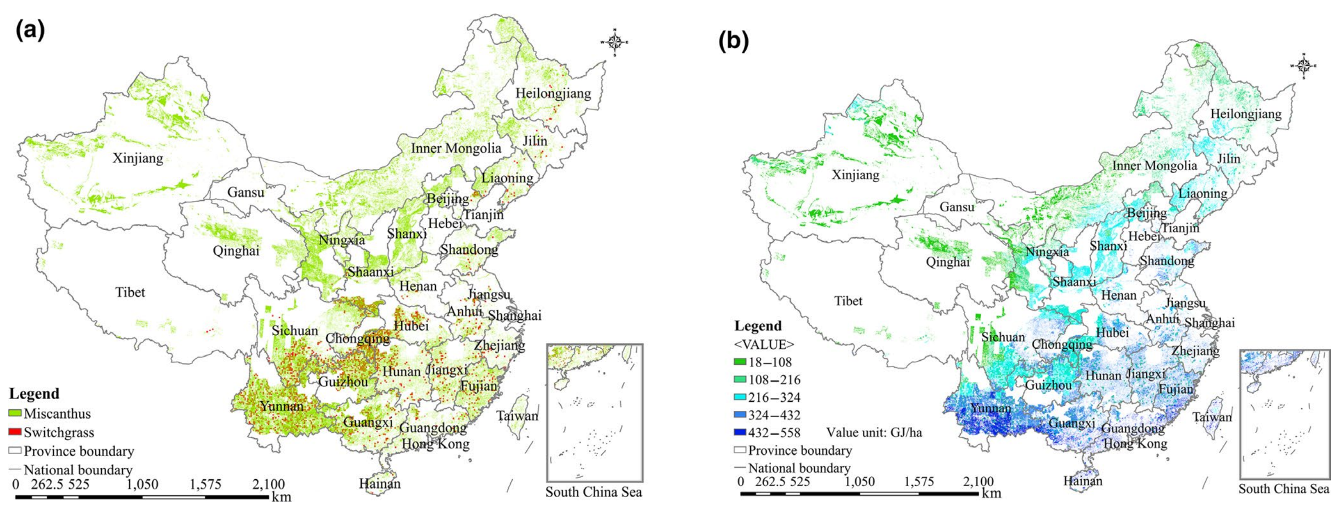

FIGURE 8 (a, b) Spatial distributions of *Miscanthus* & Switchgrass Mode on marginal land in China in 2017. (a) Optimal distribution; (b) the highest technical potential

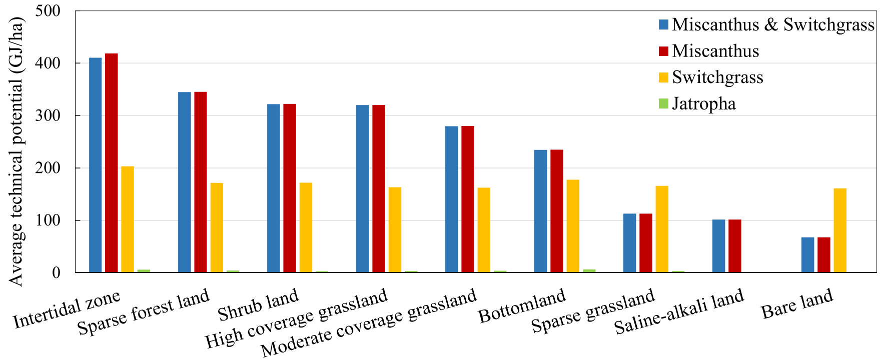

FIGURE 9 Average technical potential of four cultivation modes by different marginal land types in 2017

conditions on sparse grassland in the Tibet, Qinghai, and Xinjiang Provinces. The production in intertidal zone achieves the highest average technical potential (414.4 GJ ha^{-1} year^{-1}) while bare land has the lowest potential (67.5 GJ ha^{-1} year^{-1}). The breakdown of the technical potential of *Miscanthus* & Switchgrass Mode by some provinces is also shown in Table 10. Data for all provinces are shown in Table S6. The average technical potentials of *Miscanthus* & Switchgrass Mode production on marginal land in China were calculated as 254.5 GJ ha^{-1} year^{-1}. According to the higher total and average technical potential of these provinces, Yunnan, Guangxi, Guizhou, Fujian, Hunan, Hubei, Jiangxi, and Guangdong are the top eight provinces suitable for bioenergy production.

Figure 9 shows the average technical potential of four cultivation modes including *Miscanthus* & Switchgrass Mode, *Miscanthus* Mode, Switchgrass Mode, and *Jatropha* Mode on different marginal land types. It indicates that the productivity of *Miscanthus* decreases in line with the decline of land quality, whereas the performance of switchgrass is stable regardless of the land type change. The productivity of switchgrass is higher than that of *Miscanthus* on sparse grassland and bare land. The results indicate that switchgrass has a stronger tolerance to poor land than *Miscanthus*.

5 | DISCUSSION

5.1 | Comparison of yield prediction models for crops

The MiscanFor model could provide a more accurate result than crop-specific or generic models as genotype-specific process descriptions and parameters are embedded into the model. In comparison to MiscanFor, the GEPIC model uses species-specific process descriptions and parameters to predict crop yields. Species-specific parameters need to be multi-adjusted in actual use to achieve results close to field trial data. Unlike the direct simulation of the crop growth process of MiscanFor and GEPIC, the GAEZ uses an indirect method to predict crop yields by first evaluating the suitability of land and then calculating crop yields according to the land suitability ratings. Therefore, the model provides rougher results for crop yields compared with MiscanFor and GEPIC. Given all the above reasons, MiscanFor is the best option among GAEZ and MiscanFor for *Miscanthus* simulation. GEPIC is the most appropriate model for switchgrass between GAEZ and GEPIC, and GAEZ is the only suitable model for *Jatropha* among the selected three models.

5.2 | Identification of marginal land technically available for biomass production

Spatial analysis indicates a maximum of 185 Mha marginal land could be available for the three types of energy crop production in China. It should be pointed out that the technically available marginal land for energy crop production in this study is not all currently available for perennial energy crops. Sparse grassland accounts for the largest proportion (37%) of total marginal land, followed by shrub land (18.5%) and sparse forestland (13.4%). Before land use transition to perennial bioenergy crops can occur at a large scale, there are further actions that need to be taken including: (a) multi-year trials in different environments with year on year measurements of yield in commercial sized fields, (b) policies supporting industrial users that can pay an attractive price for the biomass, and (c) cultural/societal acceptability and impact on traditional regional livelihoods.

Food and industrial crop production needs to be integrated to maximize socio-economic and environmental benefits. Other analyses show that regional food production can continue to rise because perennial biomass crops can help improve soil health (when rotated back to food crops after ~15 years), minimizing leaching and providing erosion stabilization and flood mitigation (Wicke et al., 2011). Therefore, those quality improved land previously for biomass crop would be converted to arable land. This conversion of land use may reduce the availability of marginal land for biomass production. This study considered land with a high biodiversity as national reserve areas that were excluded from the total marginal land. However, no studies have evaluated biodiversity levels of marginal land on a national scale. This aspect and its impact on the sustainable development of biomass production on marginal land should be studied in detail in future research.

5.3 | Yields and technical potential estimation by models

More than 120 Mha marginal land was technically available for *Miscanthus* production, which has a total potential of 1,761 DW Mt/year, with an average yield of 14.6 DW t ha^{-1} year^{-1} and a yield range from 1 to 31 DW t ha^{-1} year^{-1} in 2017. This result is similar to those reported by Liu et al. (2012) and Xue et al. (2016), who estimated an average yield of 16.8 t ha^{-1} year^{-1} for marginal land in the Loess Plateau of China and a yield of 2.1–32.4 t ha^{-1} year^{-1} for marginal land in China by using empirical crop models based on the principles of radiation use efficiency (RUE) originally described by Monteith (1977). MiscanFor and GEPIC models have added parameters to adjust the RUE, water stress, and temperature stress to generate more accurate results. Xue et al. (2016) estimated a total production of 135 DW Mt/year on 7.7 Mha of suitable marginal land of China, which is much less than the value obtained in this study because of the difference in working definition of marginal land. A total of 284 DW Mt/year of switchgrass could be obtained from 30 Mha marginal land in China in 2017, with a yield range from 6.8 to 18.3 DW t ha^{-1} year^{-1} and an average yield of 9.5 DW t ha^{-1} year^{-1}. The results indicate that Yunnan Province has the greatest potential for large-scale production of *Miscanthus* and switchgrass on marginal land from the perspective of productivity. There is more than 35 Mha marginal land that could be used for *Jatropha* cultivation, with a total production of 9.7 DW Mt/year with a yield range from 0.001 to 1.8 DW t ha^{-1} year^{-1} in 2017. This result is in line with the survey conducted by Dong et al. (2017) investigating a yield range from 0.07 to 3 t ha^{-1} year^{-1}.

The total technical potential of energy crops on available marginal land was calculated as 32 EJ/year, 5.1 EJ/year, and 0.13 EJ/year from *Miscanthus*, switchgrass, and *Jatropha* in 2017, respectively. Most of the potential is distributed in the south and southeast of China, especially in Yunnan Province. The highest average potential is from the intertidal zone, followed by sparse forestland, shrub land, and high coverage grassland. However, the technical potential of *Jatropha* is unable to compete to that of the other two crops on each grid cell. Therefore, *Miscanthus* & Switchgrass Mode is the most productive method for biomass production. A total technical potential of 34.4 EJ/year could be obtained by the *Miscanthus* & Switchgrass Mode from marginal land in 2017.

In the future, the yields of energy crops are expected to increase due to improvements of breeding and agronomy in a world without climate change. In order to get an overview of the potential of increase, we also carried out a projection of the yield and technical potential of these energy crops for 2040. In this study, we assumed a yield increase rate of 0.8%/year for *Miscanthus* and 2.0%/year for switchgrass under the premise of no climate change in the future based on expert's observation and the estimation of Elbersen, Bakker, and Elbersen (2005). The high input level from GAEZ model was considered as farming systems for *Jatropha* in 2040 in China. Over the past decade, global warming is measurable, but it is very challenging to predict crop yields for 2040 because: (a) significant reductions of crop yields might be avoided under 1.5°C global warming by adaptations to increase resilience (Hoegh-Guldberg et al., 2018); (b) crop yields are affected by various climate variables, including temperature, precipitation, extremes, and non-climate variables including the concentration of atmospheric CO_2 and ozone. Given the above reasons, the future situation in this study was treated as a "no climate change" or "limited climate change" scenario. The results obtained for 2040 are still of reference value and showed in the Table S7–S12 and Figures S4–S7. However, in order to achieve reliable and comprehensive yield projections of energy crops for the future situations, more variables including climate change scenarios and land use change scenarios should be applied to the estimations in further studies.

It should be noted that the spatial distribution of *Miscanthus*' yield is more extensive than that of switchgrass in this study, even though switchgrass is more adaptable to the ecological environment than *Miscanthus*. This phenomenon is caused by the use of different approaches for yield estimation of *Miscanthus* and switchgrass. This study employed the results from the study carried out by Zhang et al. (2017), who estimated the yields of switchgrass in China using the GEPIC model. They first extracted marginal land suitable for switchgrass growth according to the requirements of agro-ecological conditions, such as temperature and precipitation, for switchgrass cultivation before inputting marginal land data into the GEPIC model. Consequently, some areas such as Tibet, Qinghai, and Xinjiang Provinces that are not eco-environmentally suitable for switchgrass cultivation or cannot obtain appropriate yields were excluded by this kind of preselection. However, this study did not perform preselection of marginal land during yield modeling of *Miscanthus*, but rather directly input the climatic and soil data for marginal land identified in the first step into the MiscanFor model. Therefore, there is some yield distribution of *Miscanthus* in some areas (e.g., Xinjiang and Tibet) that do not have yield distributions of switchgrass on marginal land; nevertheless, this does not indicate that switchgrass cannot grow in these areas, nor does it indicate a higher yield in this area of *Miscanthus* than switchgrass. In fact, the yield of *Miscanthus* in these areas is very low, and it is probably not economically viable to develop *Miscanthus* production in these areas. In the overlay analysis of the two layers of *Miscanthus* and switchgrass conducted in this study, we could only choose *Miscanthus* in the grid cells where there is no distribution of switchgrass due to the data availability of switchgrass, potentially leading to an underestimation of the total technical potentials of *Miscanthus* & Switchgrass Mode.

To ascertain the impact of water on yield calculations in models, only precipitation data were input into models without considering irrigation, groundwater, and lateral water transfer, which are all significant sources of water for crop growth. For trees, access to groundwater is more important than precipitation in semiarid or arid regions (Wicke et al., 2011). Consequently, this study was likely to underestimate the yields and potentials of biomass production on marginal land with groundwater within reach of the roots. In addition, to solve the problem of uneven water resource distribution and water shortage in some regions, there will be more water transfer projects such as the South-North Water Transfer Project in China. These projects will allow higher yields to be obtained in regions currently with low yields due to lack of water. Thus, more work on assessments of groundwater quantity and depth and water transfer projects on a national scale are required to evaluate the influence on yields and potentials.

The spatial resolution of the results from MiscanFor is limited by $0.5° \times 0.5°$ or the meteorological data. The resolution of the results depends on the lowest resolution of input data in the model. However, this is the highest resolution meteorological data available to date that meets the input data requirements for crop models. If new high-resolution meteorological data are made available, higher resolution results can be obtained in the future.

Because of large-scale biofuel production, only *Jatropha* oil was considered in this study. Valuable coproducts from the seedcake and seed husks could be sold for biofuel production or used as fertilizer in *Jatropha* production. The benefits from the coproducts could help offset the production costs of biofuel production from *Jatropha*. In addition, *Jatropha* oil is used for biodiesel which has valuable and specific applications. The economic aspect of biofuel production will be further analyzed in future research addressing optimization of the biomass supply chain.

Further studies regarding economic assessments of biomass production on marginal land and analysis of the biomass supply chain in China could be carried out based on the present study. Although this study is unable to reflect marginal land use in reality and practical potentials for three perennial biomass crops, these results provide an overview of the spatial potential distribution of biomass supply and provide a reference for policymakers to draw up plans for the bioenergy contribution to low carbon energy development in China. These maps will help guide the strategic positioning of future multilocation field trials needed to ground test potentially suitable varieties and develop the agronomies need to plant biomass crops on large scales.

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ORCID

Bingquan Zhang https://orcid.org/0000-0003-3129-1851
John C. Clifton-Brown https://orcid.org/0000-0001-6477-5452
Dong Jiang https://orcid.org/0000-0002-4154-5969

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SUPPORTING INFORMATION

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

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