Spatial distribution of usable biomass feedstock and technical bioenergy potential in China

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Funding information
National Key R&D Program of China, Grant/Award Number: 2017YFA0603602; National Natural Science Foundation of China, Grant/Award Number: 71773061, 71673165 and 51711520318; Headquarters of the Science and Technology Project of National Electric Net, Ltd. of China, Grant/Award Number: 5202011600U8

Abstract
Bioenergy will play an intimate and critical role in energy supply and carbon mitigation in the future. In recent years, “customizing the development of bioenergy to local conditions” and “prioritizing distributed utilization” have been the two key principles that have been released by the Chinese government to promote the national- and provincial-level development of bioenergy. While many recognize the importance of bioenergy in achieving low-carbon transition, little is known about the high-resolution distribution of usable biomass feedstock and technical bioenergy potential in China, which brings about uncertainties and additional challenges for creating localized utilization plans. We propose a new assessment framework that integrates crop growth models, a land suitability assessment, and the geographic information systems to address these knowledge gaps. Distributions of 11 types of usable biomass feedstock and three kinds of technical bioenergy potential are mapped out through specific transformation technologies at 1 km resolution. At the national level, the final technical biogas potential is 1.91 EJ. The technical bioethanol potential (0.04–0.96 EJ) from the energy crop can supply 0.13–3.12 times the bioethanol demand for the consumption of E10 gasoline in 2015. The technical heat potential (1.06 EJ) can meet 20% of the demand for heating in all provinces (5.38 EJ). Most of the 2020 bioenergy goals can be achieved, excluding that for bioethanol, which will
1 | INTRODUCTION

Bioenergy plays a critical role in energy supply and carbon mitigation at a time in which an emphasis on energy security and climate change has been on the rise (Slade, Bauen, & Gross, 2014). In recent years, a series of policies and plans, such as the 13th Five-Year Plan (2016–2021) of bioenergy (National Energy Administration, 2016), the Guidance for Promoting the Development of Bioenergy Heating (National Energy Administration, 2017a), and the Plan of Clean Heating (2017–2021) in Northern China (National Energy Administration, 2017b), have been released by the Chinese government to promote the development of bioenergy. In these documents, “customizing the development of bioenergy to local conditions” and “prioritizing distributed utilization” are the two key principles for the determination of national- and provincial-level plans. However, there exists little information about the high-resolution distribution and availability of usable biomass feedstock and technical bioenergy potential in China (Field et al., 2018; Somerville, Youngs, Taylor, Davis, & Long, 2010).

Bioenergy can be produced from a variety of biomass feedstocks, including woodland, grassland, and agricultural residues, and energy crops, animal manure, and the organic components of municipal solid waste (MSW) and municipal sewage sludge (Woods & Hall, 1994). These biomass feedstocks can be transformed into bioenergy such as electricity, heat, biogas, and bioethanol through a variety of processes and conversion technologies. However, not all biomass feedstocks have lower life cycle GHG emissions compared to fossil fuels; only stumps and branches from trees, leftover stalks from food and commodity agricultural crops, energy crops grown on low-carbon land that would not have been put into agricultural use (Gerssen-Gondelach, Wicke, & Faaij, 2017; Qin, Zhuang, Zhu, Cai, & Zhang, 2011), and wastes should be used in the production of bioenergy. Besides, the harvest level of biomass feedstock should seek a trade-off between GHG emission reduction, biodiversity protection (Qin et al., 2018; Snäll et al., 2017), soil carbon balance (Repo, Böttcher, Kindermann, & Liski, 2015), and economic use (Jiang, Zhuang, Fu, Huang, & Wen, 2012). Bioenergy projects also usually rely on local biomass supply availability (Raven, 2008), and the differences in biomass feedstock, conversion technology, and bioenergy will bring about substantial uncertainties and additional challenges for creating localized bioenergy utilization plans. Policymakers, therefore, are very careful when supporting particular feedstocks for bioenergy production.

Therefore, this research is intended to provide support for making decisions about the implementation and utilization of bioenergy at the local level in China. The research addresses the following two research questions: What is the spatial distribution of usable biomass feedstock and the technical bioenergy potential at 1 km resolution? What is the current status of provincial and national technical potential and demand for bioenergy under certain specific policy scenarios and assumptions? In this research, the usable biomass feedstock is defined as the amount of biomass that can be used for energy production within natural restrictions (such as soil and water) and economic constraints (including biomass for animal feeding, paper making, fiber production, etc.). Technical bioenergy potential is defined as the amount of bioenergy converted from usable biomass feedstock using current technological conversions (Batidzirai, Smeets, & Faaij, 2012). This research will not only reflect the spatial distribution of biomass feedstock types and the density of technical bioenergy potential at 1 km resolution but will also provide support for decisions about the implementation and utilization of bioenergy at the local level in China.

In recent years, there has been a considerable increase in the number of published studies of biomass feedstock and bioenergy potential. Table S1 provides information on existing studies, which can be divided into two main categories according to the research methods used: the statistical method (Kluts,
Wicke, Leemans, & Faaij, 2017; Namsaraev, Gotovtsev, Komova, & Vasilov, 2018; Wang, Ouyang, Hao, & Liu, 2017; Wang, Zuo, Wang, & Bi, 2017) and the remote sensing (RS)-geographic information system (GIS) method (Batidzirai et al., 2012; Brosowski; et al., 2016; Long, Li, Wang, & Jia, 2013; Xue, Lewandowski, Wang, & Yi, 2016). Figure 1 illustrates the statistical and RS-GIS methodologies adopted in these studies to assess bioenergy potential. Many studies have utilized the statistical method to assess the potential at the administrative division level, including the global level (Yamamoto, Fujino, & Yamaji, 2001; Yamamoto, Yamaji, & Fujino, 2000), the country level (De Wit & Faaij, 2010; Deng, Koper, Haigh, & Dornburg, 2015; Hoefnagels, Resch, Junginger, & Faaij, 2014), the provincial level (Chang, Wu, Zhou, Shi, & Yang, 2014; Chen, Xing, & Han, 2009; Ji, 2015; Jiang et al., 2017; Shane et al., 2016), and the county level (Brosowski et al., 2016; Muth, Bryden, & Nelson, 2013). This approach has been used frequently in the assessment of bioenergy potential because the calculation is simple, easy to implement and reproduce, and data are easily acquired from the National Bureau of Statistics. Estimations are calculated by considering a specific biomass feedstock or all types of biomass (residues, waste, or energy crops; Chen et al., 2009; De Wit & Faaij, 2010; Junfeng & Runqing, 2003; Yamamoto et al., 2001). A major disadvantage of the statistical method is that it cannot provide high-resolution results about land availability.

The second category of studies estimates biomass and bioenergy potential by evaluating biomass resources that are based on the RS-GIS method and land-use. The resolution of most of these studies is 1 km (Ji, 2015; Qiu, Sun, Xu, Cai, & Bai, 2014; Shi et al., 2008; Xu, Li, Fu, & Zhuang, 2013; Xue et al., 2016; Zhang, Xie, Li, Ge, & He, 2010; Zunkehr & Campbell, 2013) or even 0.1 km (Jiang et al., 2012). This method can help guide the intensive and efficient distributed utilization of bioenergy and the site selection of biorefineries, and contributes to the rational planning, scientific utilization, and effective management of the bioenergy industry. However, the RS-GIS method is usually applied to energy crops, forest residue, and agricultural residue based on the measurement of vegetation biomass (Long et al., 2013). The distributions and residue-to-product ratios of agricultural crops differ greatly; few researchers have distinguished these differences when calculating usable agricultural biomass. Ignoring the differences between distributions and residue-to-product ratios of agricultural crops usually lead to deviations between calculated agricultural residues and the actual distribution (Monforti, Bódis, Scarlat, & Dallemand, 2013). If the differences between the primary agricultural crops were subdivided, the information on agricultural residues would be more precise and valuable for the use of biomass feedstock in bioenergy. In addition, as the main source of newly added bioenergy in the coming years (Koçar & Civaş, 2013), energy crops will play an important role in bioenergy development. However, there is currently a lack of representative yield production data. The simulation of yield production, which must consider land-use and environmental constraints, including temperature, precipitation, and soil texture, can solve this problem (Jiang, Hao, Fu, Liu, & Yan, 2019; Nie et al., 2019). Because the utilization of bioenergy is becoming increasingly more industrialized and commercialized, the evaluation of the spatial distribution of all types of biomass feedstocks and the technical bioenergy potential at 1 km resolution is necessary.

In this research, we propose an assessment framework integrated with methodologies including the crop growth models, the RS-GIS method, and statistical downscaling to more comprehensively assess the spatial distribution of all biomass feedstocks and the technical bioenergy potential at 1 km resolution in China for the first time, but also provides a clear understanding of the energy allocation of technical bioenergy potential on a national scale.

2 | MATERIALS AND METHODS

The materials and methods in this study consist of four components: a generic model for estimating usable biomass, data.
sources and scenarios, the calculation of usable biomass at 1 km resolution, and the conversion from biomass to available bioenergy and assumptions.

2.1 A generic model for estimating usable biomass

Not all biologically available biomass can be used for bioenergy production due to a series of restrictions, such as soil carbon maintenance and economical use, including foraging and papermaking (National Bureau of Forest, 2013, 2014). A generic model is used to estimate the amount of biomass that is usable for bioenergy production in a specific grid (Shi et al., 2008):

$$B = \frac{N \times \alpha}{\beta},$$

where $B$ is the biologically available biomass and $N$ is the net biomass. As can be seen in Table 1, for agricultural residues, $N$ is derived from the production of rice on paddy land or the other 16 crops on dry land. For woodland residues, $N$ is derived from the total woodland residues. For grassland residues, $N$ is derived from the annual net primary productivity (NPP). For waste, $N$ is derived from statistical data of MSW, municipal sewage sludge, and animal manure. For energy crops, $N$ refers to the modeled total biomass of sweet sorghum, and is simulated by the Environmental Policy Integrated Climate GIS-based (GEPIC) model (Jiang et al., 2019) and the AquaCrop model (Nie et al., 2019). The data sources of $N$ are presented in the dataset column in Table 2.

The parameter $\alpha$ is the proportion of usable biomass in the total biomass, and $\beta$ is the carbon concentration in dry biomass. For residues and sweet sorghum, $\alpha$ refers to the proportion of the aboveground biomass and the total biomass (Bonin & Lal, 2013; Shi et al., 2008). For waste, we assume that both $\alpha$ and $\beta$ are 1.

$$P = B \times r \times (1 - c - e - l),$$

where $P$ is the potential of usable biomass for energy production. The parameter $r$ is the fraction of residues in $B$. For agricultural residues, the value of $r$ is different, and the value is sourced from the related literature listed in Table S2. For woodland residues, $N$ is the statistical data of the total woodland residues, so the value of $r$ can be regarded as 1. Because all aboveground grass can be used as grass residues, the value of $r$ for grass can be regarded as 1. For waste and sweet sorghum that are dedicated to energy production, $r$ is equal to 1.

Fraction $c$ is the proportion of the biomass that should be returned to the field to maintain soil quality. Fraction $e$ is the proportion of the biomass used for economic purposes such as animal feed, industry materials, and organic fertilizer. Fraction $l$ represents the loss during the entire process. All the parameters, including $N$, $\alpha$, $\beta$, $r$, $c$, $e$, and $l$, are exhibited in Table 1.

| Biomass type         | Land-use type       | $N$            | $\alpha$ | $\beta$ | $r$      | $c$  | $e$  | $l$ |
|----------------------|--------------------|---------------|----------|---------|---------|-----|-----|-----|
| Agricultural residues| Paddy land         | Production of rice | 0.5      | 0.5     | Table S2 | 0.313$^a$ | 0.499$^a$ | 0.05 |
| Agricultural residues| Dry land           | Production of other 16 crops | 0.5      | 0.5     | Table S2 | 0.313$^a$ | 0.499$^a$ | 0.05 |
| Woodland residues    | Orchard            | Orchard residues | 0.5      | 0.5     | 1       | 0.3$^b$ | 0.318$^b$ | 0.05 |
| Woodland residues    | Forest             | Forestry residues | 0.5      | 0.5     | 1       | 0.3$^b$ | 0.318$^b$ | 0.05 |
| Woodland residues    | Shrubbery          | Shrubbery residues | 0.5      | 0.5     | 1       | 0.3$^b$ | 0.318$^b$ | 0.05 |
| Grass residues       | Grassland          | NPP            | 0.2$^c$  | 0.5     | 1       | 0.3$^b$ | 0.447$^e$ | 0.05 |
| Waste                | Urban land         | Municipal solid waste | 1        | 1      | 1       | 0   | 0   | 0.05 |
| Waste                | Industrial land    | Municipal sewage sludge | 1        | 1      | 1       | 0   | 0   | 0.05 |
| Waste                | Residential land   | Animal manure   | 1        | 1      | 1       | 0   | 0.5$^f$ | 0.05 |
| Energy crop          | Marginal land      | Simulated data | 0.5      | 0.5     | 1       | 0$^g$ | 0    | 0.05 |

$^a$Sourced from Jiang et al. (2012).
$^b$Sourced from Sitch et al. (2003) and Foley (1995).
$^c$Calculated from the statistical data of wood particleboard and fiberboard, which are comprised of the woodland residues in the 2016 China Forestry Development Report, and the total woodland residues from Wang, Ouyang, et al. (2017).
$^d$Sourced from Shen, Zhu, and Zhao (2016).
$^e$Calculated from the statistical data of hay for animal husbandry in the National Planning for the Development of Herbivorous Animal Husbandry (2016–2020) and the total woodland residues from net primary productivity (NPP).
$^f$Sourced from Li and Zhang (2007) and indicates that half of animal manure is used as organic fertilizer.
$^g$The yield per hectare of sweet sorghum in this research is the stalk and grain yield, with the assumption that all leaves and roots have been put back into the soil. The fraction $c$ of the energy crop can be regarded as 0. The other parameter values in Table 2 are sourced from Shi et al. (2008).
2.2 | Data sources and scenarios

Due to the limited availability of data at 1 km resolution, all the datasets and related information used in this study are from the year 2015. As can be seen in Table 2, four main data sources are used for this research. The first type of data is utilized for the estimation of residues, and includes a land-use dataset provided by the Data Centre for Resources and Environmental Sciences, the Chinese Academy of Sciences (RESDC; http://www.resdc.cn), the Global Spatially-Disaggregated Crop Production Statistics Data from Harvard Dataverse, and the area and production of 17 main crops from the 2015 China Statistical Yearbook. The 17 main crops include rice, wheat, maize, other cereals, soybean, other beans, tubers, peanut, rapeseed, sesame seed, other oil crops, cotton, fiber, sugarcane, sugar beet, tobacco, and vegetables which are listed in Table S2. Woodland residues include tree cutting residue, wood processing residue, bamboo cutting and processing residues, tree tending and thinning residues, and wasted wood. All the woodland residues are the waste of wood growth and commodity manufacturing, the data on which are obtained from Wang, Zuo, et al. (2017) and Wang, Ouyang, et al. (2017) and are based on statistical data from 2013. The second type of data is used for waste estimation and statistical downscaling. Statistical downscaling is a method originally used to obtain high-resolution climate change information from relatively coarse-resolution global climate models (Khan, Coulibaly, & Dibike, 2006). Because the only statistical data on waste are from provincial and municipal levels, gross domestic product (GDP), demographic data, and land-use data are used to distribute the statistical data of waste to a finer resolution. GDP and demographic data, and urban land and rural land data at 1 km resolution, are provided by RESDC. MSW data are sourced from the statistical data in the 2015 China Urban Statistical Yearbook. Municipal sewage sludge data are sourced from the statistical data of the 2015 China Environmental Statistics Yearbook. Animal manure data are sourced from the statistical data of the 2015 China Statistical Yearbook. The third type of data is utilized for energy crop simulation based on marginal land data, meteorological data, soil data, slope data, and harvest information sourced from Nie et al. (2019). The environmental performance of energy crops heavily depends on the land-use types on which they are grown (Baldino, Pavlenko, Searle, & Christensen, 2018). The Chinese government has declared that the development of energy crops should not compete with agricultural land and threaten food security (Qiu, Sun, Huang, & Rozelle, 2012). Therefore, in this research, marginal land is defined as unused land and includes tidal-flat land, sand land, saline-alkali soil land, swampland, bare land as defined by the RESDC. Energy crops will be grown on marginal land without replacing agricultural land and woodland, and the cultivation will not compete with that of food crops. Finally,
the fourth type of data consists of conversion coefficients that are sourced from Hu et al., (2011) and the China Energy Statistics Yearbook. The details of conversion coefficients are exhibited in Table 3.

Sweet sorghum has been chosen as the representative energy crop in this paper because it is one of the most promising energy crops with advantages and characteristics including high biomass yield, drought, cold and flood resistance, wide adaptability, and high sugar content (Jiang et al., 2019; Nie et al., 2019; Zhang et al., 2010). Because sweet sorghum has not been extensively planted in China, two scenarios of sweet sorghum planting in this research, including the sustainable scenario and the optimal environmental conditions scenario, are established on the marginal land. The sustainable scenario reflects the minimum environmental performance of sweet sorghum cultivation, and indicates that sweet sorghum cultivation depends solely on rainfall without increasing the local water pressure on the marginal land. The yield per hectare of sweet sorghum in the suitable scenario is obtained from the rainfed value modeled by Jiang et al. (2019). The optimal environmental conditions scenario reflects the maximum possibilities of sweet sorghum cultivation, and refers to the sweet sorghum being planted with full irrigation and other optimal environmental conditions. We have simulated the fully irrigated yield per hectare of sweet sorghum in the optimal environmental conditions scenario according to Nie et al. (2019).

In addition, biomass and biomass feedstock are interchangeable and general terms for residues, waste, and energy crops in this research. Residues consist of agricultural residues, woodland residues (forestry residues, orchard residues, and shrubbery residues), and grassland residues. The waste consists of MSW, municipal sewage sludge, and animal manure.

### Calculation of usable biomass at 1 km resolution

Figure 2 presents the general methodology and detailed methods of usable biomass feedstocks and technical bioenergy potential estimation in this research. Figure 2a is the general methodology used in this research. Figure 2b–d describe the detailed methods for residues estimation, waste estimation, and sweet sorghum simulation at 1 km resolution, respectively.

#### Estimation of residues

In this section, 17 main agricultural crops are chosen from the 2015 China Statistical Yearbook (National Bureau of Statistics, 2016a). The spatial distributions of these crops are derived from the Global Spatially-Disaggregated Crop Production Statistics Data. The agricultural residue of each crop is calculated from the crop production and the residue-to-product ratios provided in Table S2. The usable agricultural residue at 1 km resolution is calculated based on the information of the distribution and agricultural residue production of each crop, as illustrated in Figure 2b. The usable woodland residues and grassland residues at 1 km resolution are also calculated based on the corresponding land distribution and parameter values in Table 2.

#### Estimation and statistical downscaling of waste

Some of the existing literature has indicated that waste production has a strong positive correlation with economic
development and population density at a 0.1 km resolution at the municipal and provincial levels (Mazzanti, Montini, & Zoboli, 2008; Mazzanti & Zoboli, 2008; Shu, Wang, & Sun, 2012; Xu, Yan, & Cui, 2013). In this research, the statistical downscaling method is used to spatialize waste based on the dataset of GDP, land-use, and the population at 1 km resolution (Li, Zhang, & Yang, 2014; Wilby et al., 1998, 2004; Zhu, Yang, & Zhao, 2011). Statistical data on MSW...
and municipal sewage sludge can be found in the Chinese Statistical Yearbook (National Bureau of Statistics, 2016c). The amount of animal manure is the product of the quantity of animals, the manure amount per animal per day, and the breeding period (Liu & Shen, 2007). The details of waste estimation and statistical downscaling can be seen in Figure 2c. The equations of this method and calibration can be found in SI.3 of the Supporting Information.

2.3.3 | Energy crop simulation

In this research, the energy crop simulation consists of two parts: the marginal land definition and yield per hectare simulation (Jiang et al., 2019; Nie et al., 2019). First, a multifactor integrated assessment (Lu, Jiang, Zhuang, & Huang, 2012) has been used to assess the land suitability for the planting of sweet sorghum on the marginal land. In this research, the land suitability assessment is based on the natural environmental conditions and the characteristics of the plant itself. Second, the sweet sorghum yield is simulated under both rainfed and fully irrigated conditions, and under the constraints of soil, temperature, slope, precipitation, and management habits. In this research, the rainfed yield per hectare of sweet sorghum in the sustainable scenario is derived from Jiang et al. (2019) with a crop growth model called the GEPI model. The fully irrigated yield per hectare of sweet sorghum in the optimal environmental conditions scenario is modeled by a newly developed Food and Agriculture Organization growth model called the AquaCrop model. The methods and equations used in these simulations are provided in Figure 2d and SI.4 of the Supporting Information. The details of the yield per hectare simulation can also be found in the research by Jiang et al. (2019) and Nie et al. (2019).

2.4 | Conversion from biomass to bioenergy and assumptions

The energy contained in the biomass and the conversion coefficients are two key factors that affect the energy potential in the conversion of biomass feedstock to bioenergy. Lower heating value (LHV) is one of the most common indicators used for calculating energy potential in biomass (IPCC, 2014; Ou, Zhang, & Chang, 2010). The LHVs in this research are sourced from IPCC (IPCC, 2014) and the China Energy Statistics Yearbook (National Bureau of Statistics & National Development & Reform Commission, 2016). There are different kinds of conversion technologies used for converting biomass feedstock into bioenergy, which would change in the future. Because the energy conversion coefficients of conversion technologies are different and there are no mature and fixed modes of bioenergy utilization throughout China, the actual bioenergy technical potential will vary with different conversion technologies. We pay more attention to biomass feedstock availability than actual bioenergy technical potential and make the analysis of the supply and demand of bioenergy an open discussion in this research.

Although the conversion technology and energy conversion coefficients would change heavily in the future, some assumptions are made based on the conversion technology trends and the actual utilization at present as follows: (a) electricity and heat, biogas, and bioethanol are three kinds of final bioenergy in this research. (b) According to the public preferences and climate benefit research of energy recovery from wastes and biomass residues (Liu & Rajagopal, 2019; Zhao, Cai, Li, & Ma, 2018), thermal combustion through biomass-assisted heat and power plants is the optimal pathway for woodland and agricultural residues, and thermal combustion is therefore adopted for all the residues in this research. (c) According to the actual utilization of waste at present (National Bureau of Statistics, 2016a; ), all the municipal sewage sludge and animal manure are used for biogas production via anaerobic digestion while considering the process of cleaning and compression, half of the municipal waste is converted into biogas via anaerobic digestion, and the rest of the municipal waste is used for thermal combustion. (d) According to the current utilization of sweet sorghum, the saccharification and fermentation process is the optimal pathway for bioethanol production. All the LHVs of biomass feedstocks and coefficients are presented in Table 3.

The bioenergy potential can be calculated by Equation (3), in which \( C \) refers to the energy conversion coefficient in Table 3.

\[
E = P \times C \times \text{LHV}. \tag{3}
\]

3 | RESULTS

3.1 | Usable biomass distribution at 1 km resolution

Figure 3 is the 1 km distribution of each type of usable biomass feedstock. From Figure 3, it is evident that: (a) there are significant differences in the spatial distributions of different biomass feedstocks. Forestry residue is primarily distributed in the Northeast, Southwest, and Southeast parts of China, and the usable biomass is greater in the Southwest and Southeast than in the Northeast. Shrubbery residue is mostly distributed in the Southwest. Grassland residue is located mostly in Inner Mongolia and Tibet. Additionally, usable agricultural residue in dry land is prominent in Henan and Shandong. (b) The usable biomass potentials range from the forest, shrubbery, grassland, and orchard residues, and are less than 1,372, 1,373, 1,515, and 1,633 tonnes, respectively, in a 1 km grid. The usable range of agricultural residue in dry land and paddy land is less than 3,136 and 1,720 tonnes, respectively, in a 1 km grid. The usable biomass of sweet sorghum in the sustainable scenario is primarily concentrated in Jilin and Heilongjiang (Figure 3j), and the usable biomass of sweet sorghum is much higher, and the spatial
FIGURE 3  The distribution of usable biomass feedstocks at 1 km resolution in China: (a) forestry residue; (b) shrubbery residue; (c) grassland residue; (d) orchard residues; (e) dry land agricultural residue; (f) paddy land agricultural residue; (g) animal manure; (h) municipal sewage sludge; (i) municipal solid waste; (j) sweet sorghum in sustainable scenario; (k) sweet sorghum in optimal environmental conditions scenario. All the base maps of China in this research are referred from Map number: GS(2019)1682
distribution is more widespread, in the scenario of optimal environmental conditions (Figure 3k). (c) Municipal sewage sludge and MSW are largely located in the industrialized and urbanized provinces and cities, including Guangdong, Shandong, Beijing, Tianjin, Shanghai, and Chongqing. Animal manure is mainly concentrated in the provinces of Shandong (141.5 million tonnes), Henan (146.2 million tonnes), Sichuan (131.7 million tonnes), and Inner Mongolia (74.5 million tonnes) where animal husbandry or stockbreeding is well developed. (d) From the perspective of the entire country, we can see that the southern region has abundant forestry bioenergy, the central region has plentiful agricultural residues, and the northeast region is rich in both forestry bioenergy and agricultural residues.

3.2 Technical bioenergy potential and distribution

According to the assumptions and the coefficients used for converting biomass feedstocks into bioenergy (Table 3), we calculated the spatial distribution of technical bioenergy potential at 1 km resolution in China (Figure 4). The spatial distributions of electricity and heat, biogas, and bioethanol vary greatly. Electricity and heat generated from biomass are widely distributed in most provinces in China as shown in Figure 4a. Biogas exhibits a primarily centralized distribution in urban and rural areas (Figure 4b). Jilin and Heilongjiang are the most suitable areas for bioethanol in the sustainable scenario (Figure 4c). Xinjiang and Inner Mongolia account for most of the suitable land for bioethanol production in the optimal environmental conditions scenario (Figure 4d). However, if we compare the energy density of each type of bioenergy, we can see that: (a) Although the available heat and electricity from biomass are widely distributed, most of the energy densities are less than 16 TJ/km². (b) Most of the energy densities of the available biogas potential are greater than 16 TJ/km². (c) Most of the energy densities of bioethanol range from 2 to 8 TJ/km² in the sustainable scenario, and from 4 to 16 TJ/km² in the optimal environmental conditions scenario.

**FIGURE 4** Bioenergy potential and distribution at 1 km resolution in China: (a) electricity and heat potential; (b) biogas potential from waste; (c) bioethanol potential in sustainable scenario; (d) bioethanol potential in optimal environmental conditions scenario
3.3 | Energy flow analysis of “land-biomass-bioenergy”

Based on the results of land-use, biomass, and bioenergy in this study, Figure 5 illustrates the energy flow of “land-biomass-bioenergy” from the national perspective (Chong, Ma, Li, Ni, & Song, 2015a; Chong, Ni, Ma, Liu, & Li, 2015b; Ma et al., 2018). The proportion of land-use types, in order from the highest to the lowest are grassland, woodland, marginal land, agricultural land, rural land, and urban land. The available biomass on these lands are 380, 310, 20, 990, 1,630, and 220 million tonnes, respectively. The energy contents of the biomass from the agricultural and forestry residues, the energy crops in the sustainable scenario, and waste that can be used are 24.78 EJ ($10^{18}$ J), 0.32, and 23.01 EJ, respectively. The final technical energy potentials of heat, bioethanol, and biogas are 1.06 EJ (equivalent to the usable heat generated by the combustion of approximately 170 million tonnes of standard coal), 0.04 EJ (approximately 1.49 million tonnes of bioethanol), and 1.91 EJ (approximately 86 billion cubic meters of biomethane), respectively, after returning to soil, total loss, and other economic uses are considered. The total technical heat potential can cover approximately 20% of the heat demand (5.38 EJ) of all the northern provinces. The total technical bioethanol potential from sweet sorghum in the sustainable scenario can supply 13% of the bioethanol in E10 gasoline in 2015 (113.68 million tonnes of gasoline consumption in total). The total technical bioethanol potential (0.96 EJ, approximate 35.76 million tonnes of bioethanol) from sweet sorghum in the optimal environmental conditions scenario can supply 3.12 times the bioethanol in E10 gasoline in 2015.

Under the assumption that all the usable biomass feedstocks are combusted for heat, the total technical potential of heat is 3.24 EJ (approximately 520 million tonnes of standard coal) and can cover approximately 60% of the heat demand by all the northern provinces. Under the assumption that all the usable sweet sorghum in the sustainable scenario and residues are anaerobically fermented for bioethanol, the total technical bioethanol potential is 0.65 EJ (approximately 24.05 million tonnes of bioethanol) and can supply 2.12 times the bioethanol in E10 gasoline in 2015.

The Chinese government has formulated the development goal of bioenergy in 2020, which includes 90 billion kWh of electricity (approximately 0.324 EJ), 8 billion cubic meters of biogas, 6 million tonnes of bioethanol, and 30 million tonnes of biomass molding fuel (equivalent to 58 million tonnes of standard coal in total), as outlined in the 13th Five-Year Plan (2016–2021) of bioenergy (National Energy Administration, 2016). Compared with the results in this research, the technical potential of residues and waste can meet the development goals of biogas, electricity, and biomass molding fuel. However, the technical potential of bioethanol only from sweet sorghum in the sustainable scenario (approximately 1.49 million
tonnes of bioethanol) would fail to meet the development goals of bioethanol (6 million tonnes). There are two ways that the 2020 bioethanol goal can be achieved. The first is to develop cellulosic ethanol technology so that more residues can be converted into bioethanol. The second is to increase water supply so that more energy crops can be planted on the marginal land, which may increase the local water pressure.

In summary, the energy flow analysis of “land-biomass-bioenergy” can help policymakers better understand biomass feedstocks availability and technical bioenergy potential at the national level. As the conversion technology and energy conversion coefficients could change in the future, policymakers should pay more attention to biomass feedstocks availability than on technical bioenergy potential when making bioenergy development plans.

4 | DISCUSSION

4.1 | Can bioethanol supplied by biomass meet the demand for transportation at a provincial level?

Because the bioethanol potential in the sustainable scenario is much lower than the total demand for bioethanol, we discuss the possibility of supplying the demand of bioethanol in the optimal environmental conditions scenario at a provincial level. The bioethanol potential in the optimal environmental conditions scenario at a provincial level (Figure 6a) is derived from the bioethanol potential from the energy crop at 1 km resolution (Figure 4d). Xinjiang and Inner Mongolia are the foremost two provinces. The Chinese government has set forth the goal of using E10 gasoline throughout the entire country by 2020 in its plan for expanding bioethanol production and promoting the use of ethanol gasoline for motor vehicles. In the context of this policy scenario, we calculated the requirement of E10 gasoline at a provincial level based on the gasoline consumption in China in 2015 (Figure 6b). Guangdong, Jiangsu, and Sichuan rank as the top three provinces in terms of bioethanol demand, and Tibet and Qinghai are the provinces with the least bioethanol demand. The demand of nearly half of the provinces is beyond 10 PJ (approximately 0.38 million tonnes of bioethanol). Under the assumption that there is no bioethanol trade across provinces, Figure 6c provides the comparative analysis results of bioethanol potential and demand in China at a provincial level. Xinjiang, Tibet, Inner Mongolia, Ningxia, Qinghai, Gansu, Shaanxi, Heilongjiang, and Jilin can meet the demand of bioethanol in 2015. There are different levels of bioethanol shortage in the other provinces. Guangdong, Zhejiang, and Jiangsu have relatively serious shortages with gaps beyond 20 PJ (approximately 0.75 million tonnes of bioethanol), which indicates that these provinces must either produce more bioethanol from other biomass resources or import more bioethanol from outside the province.

4.2 | Can heat supplied by biomass meet the demand for urban heating?

Figure 7a presents the heat potential on a provincial level. Northern provinces, such as Inner Mongolia and Heilongjiang, exhibit abundant heating potential, as do the southern provinces, including Sichuan, Yunnan, Guangdong, and Guizhou. Figure 7b is the urban heat demand at a provincial level estimated according to urban heating days and hot water supply power in each province in 2015. There is a high heat demand in the provinces of Liaoning, Shandong, Xinjiang, Inner Mongolia, Jilin, Beijing, and Heilongjiang, and no data are available for Tibet. Heat supplies from biomass in the provinces of Qinghai, Henan, Anhui, and Hubei can meet the demand for heat, as shown in Figure 7c. Xinjiang, Shandong, Beijing, Tianjin, Liaoning, Heilongjiang, and Jilin fall short in their ability to meet the urban heating demand (beyond 200 PJ), which indicates that these provinces must either continue to use fossil fuel sources or choose another alternative energy source. Figure 10d is the proportion of heat supply to heat demand at a provincial level in China. Although the heat supply cannot

FIGURE 6  Bioethanol potential in the optimal environmental conditions scenario and the demand at a provincial level in China: (a) bioethanol potential; (b) bioethanol demand; (c) supply–demand analysis of bioethanol
meet the heat demand in Gansu, Inner Mongolia, Shaanxi, Shandong, or Hebei, these provinces can seriously consider obtaining heat from biomass, as their proportions of heat supply to heat demand are all beyond 0.4.

4.3 | Comparison with other studies

Using the NPP dataset to calculate agricultural residues is a common method in spatially explicit analyses. However, there are large deviations in estimating the bioenergy potential of a single grid and the distribution as determined by the NPP method. In this research, we calculated the agricultural residues via the “residue-to-product ratio” method, which takes into consideration the 1 km resolution distribution and the residue-to-product ratio of each agricultural crop. We then compared the results derived from NPP (Figure S1) with the results found using this method (Figure 3e,f). The main findings are as follows: (a) The usable biomass feedstock potential ranges are different. The ranges of agricultural residue determined by NPP in dry land and paddy land are 0–1,839 and 0–2,328 tonnes, respectively, in a 1 km grid, while those derived from the “residue-to-product ratio” method are 0–3,136 and 0–1,719 tonnes, respectively. (b) The total amounts of biomass feedstocks are different. Using data from the 2015 China Statistical Yearbook, the total amount of agricultural residues calculated by the NPP method is 780 million tonnes, and the total amount calculated by the “residue-to-product ratio” method is 990 million tonnes. This discrepancy is part of the reason for the difference in usable biomass feedstock potential ranges; the other reason is that the “residue-to-product ratio” method has both a higher resolution and better accuracy of crop distribution. (c) The provinces with the highest usable biomass feedstock ranges of dry land are also different. It can be seen in Figure S1 that the provinces with the highest usable biomass feedstock ranges of dry land.
land are Sichuan and Yunnan, but Figure 3e indicates that these provinces are Henan, Shandong, and Hebei.

The available value of woodland residues utilized in this study is 0.31 billion tonnes, and was derived from statistical data. The China Forest Biomass Energy Development Potential Research Group (2006) roughly estimated that China’s woodland residues are 0.6 billion tonnes, while the National Forestry Biomass Energy Development Plan (National Bureau of Forest, 2013) claimed this number to be between 0.35 and 18 billion. Zhang Weidong (Zhang & Lu, 2008; Zhang, Zhang, & Zhang, 2015) calculated the potential of China’s woodland residues to be 0.92 billion tonnes based on statistical data and the coefficients of different forestry residues.

This research found the available value of grassland residue to be 0.38 billion tonnes. This value is slightly higher than the value of 0.32 billion tonnes that is proposed in the 2015 National Grassland Monitoring Report by the Grassland Supervision Centre of the Ministry of Agriculture (2014) and Rural Affairs of China.

The total amount of waste is determined to be the same as the data provided in the 2015 China Statistical Yearbook. There exists little literature about the waste at 1 km resolution, and this study has made a bold preliminary attempt to downscale the statistical data to 1 km grid data.

Under strict environmental constraints, our results find that the final bioethanol production of the energy crop on marginal land is 0.04 EJ (approximately 1.49 million tonnes of bioethanol) in the sustainable scenario, while Jiang et al. (2019) determined this value to be approximately 0.115 EJ. In ideal environmental conditions, our results indicate that the energy equivalent of sweet sorghum for bioethanol production is 15.44 EJ, and the final bioethanol production on marginal land is 0.96 EJ (approximately 35.76 million tonnes of bioethanol). In contrast, other studies (Li & Chan-Halbrendt, 2009; Lu, Zhu, Hu, & Wu, 2010) that have focused on energy crops on marginal land have reported the range of the potential production to be between 16.10 and 19.40 EJ. The China Automotive Energy Outlook (China Automotive Energy Research Center, Tsinghua University, 2012) has evaluated the energy equivalent of energy crops in China to be 17.29 EJ. The primary reasons for the discrepancies between our study and other published results are as follows: (a) Different datasets were used. The dataset used in this study includes simulated yield per hectare data from the AquaCrop model, as well as terrain data, soil texture data, and meteorological data, to assess land suitability. (b) Different definitions and assumptions were used. The definition of marginal land in this study is unused land including tidal-flat land, sand land, saline-alkali soil land, swampland, bare land, etc., while the marginal land used in the research by Jiang et al. is greater, and is defined as wasteland including land under consideration, natural grassland, sparse forestland, scrubland, and unused land. This is the primary reason why the final bioethanol production as determined by Jiang et al. (2019) is greater than that in this research. (c) Different limitations were considered. This study not only accounted for the loss during conversion but also considered the loss between energy crop collection and the section returned to the soil, and other economic uses. This is the reason why the energy equivalent of the energy crop in this study is lower than that in other studies.

4.4 | Research uncertainties and limitations

The uncertainties are due to parameter uncertainty (the values chosen for simulations can be arbitrary), model uncertainty (the model for usable biomass feedstock calculation and models for sweet sorghum yield per hectare simulation), and conversion uncertainty (the conversion pathway from biomass feedstock to bioenergy). There are several uncertainties for the four different types of biomass feedstock in this research. The first uncertainty is for agricultural residues; the uncertainties of agricultural residues can be attributed to the different datasets and methods that are discussed in Section 4.3. The second uncertainty is for waste; the primary uncertainty results from the statistical downscaling based on GDP and population data. The third uncertainty is for woodland and grassland residues; the uncertainties arise from the different datasets, different methods, and different types of residues adopted in residues estimation. The fourth uncertainty is for the energy crop. The uncertainty is fourfold: different production data of energy crops are used, different marginal lands are defined, different types of energy crops are adopted, and different conversion coefficients are used.

There are two major limitations of this study that could be addressed in future research. First, there is no large-scale and widespread utilization of bioenergy in China; therefore, this study focused on the technical potential of biomass and bioenergy without fully accounting for economic factors. Second, due to the uncertainty of conversion technology and the lack of transportation data, the conversions from biomass feedstock to bioenergy are simplified to three pathways: thermal combustion for electricity and heat, anaerobic digestion for biogas, and saccharification and fermentation for bioethanol. The collection, transportation, and conversion of biomass, and the distribution of bioenergy, occur in the grid at 1 km resolution, and are all represented by one certain conversion coefficient in Table 3. Therefore, the results of the technical bioenergy potential are higher than those of economic bioenergy potential. Based on this study, the economic bioenergy potential could be evaluated with the consideration of economic factors in further research. These limitations can be solved in future research with economic, technical, and traffic data related to biomass feedstock and bioenergy available.

Despite these limitations, the spatial distribution of usable biomass feedstocks and technical bioenergy potential
at 1 km resolution are still meaningful for bioenergy development according to the principles of “customizing the development of bioenergy to local conditions” and “prioritizing distributed utilization” in China. This research can provide additional supporting information for the implementation of the 13th Five-Year Plan (2016–2021) of bioenergy and the Plan of Clean Heating (2017–2021) in northern China.

ACKNOWLEDGEMENTS

This study has been financially supported by the National Key R&D Program of China (2017YFA0603602), the National Natural Science Foundation of China (71773061, 71673165 and 51711520318), and the Headquarters of the Science and Technology Project of National Electric Net, Ltd. of China (5202011600U8). The authors thank Mukul Sanwal and Jinghao Zhang for their generous help with this paper.

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REFERENCES

Baldino, C., Pavlenko, N., Searle, S., & Christensen, A. (2018). The potential for low-carbon renewable methane in heating, power, and transport in the European Union. The International Council on Clean Transportation. Retrieved from https://www.theicct.org/publications/sustainability-challenges-lignocellulosic-bioenergy-crops

Batidzirai, B., Smeets, E. M. W., & Faaij, A. P. C. (2012). Harmonising bioenergy resource potentials – Methodological lessons from review of state of the art bioenergy potential assessments. Renewable and Sustainable Energy Reviews, 16, 6598–6630. https://doi.org/10.1016/j.rser.2012.09.002

Bonin, C. L., & Lal, R. (2013). Aboveground productivity and soil carbon storage of biofuel crops in Ohio. Global Change Biology Bioenergy, 6, 67–75. https://doi.org/10.1111/gcbb.12041

Brosowski, A., Thran, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P., … Blanke, C. (2016). A review of biomass potential and current utilisation — Status quo for 93 biogenic wastes and residues in Germany. Biomass and Bioenergy, 95, 257–272. https://doi.org/10.1016/j.biombioe.2016.10.017

Chang, I. S., Wu, J., Zhou, C. B., Shi, M. M., & Yang, Y. X. (2014). A time-geographical approach to biogas potential analysis of China. Renewable and Sustainable Energy Reviews, 37, 318–333. https://doi.org/10.1016/j.rser.2014.05.033

Chen, L. J., Xing, L., & Han, L. J. (2009). Renewable energy from agro-residues in China: Solid biofuels and biomass briquetting technology. Renewable and Sustainable Energy Reviews, 13, 2689–2695. https://doi.org/10.1016/j.rser.2009.06.025

China Automotive Energy Research Center, Tsinghua University. (2012). Prospects for China’s vehicle energy. Beijing, China: Science Press.

Chong, C. H., Ma, L. W., Li, Z., Ni, W. D., & Song, S. Z. (2015a). Logarithmic mean Divisia index (LMDI) decomposition of coal consumption in China based on the energy allocation diagram of coal flows. Energy, 85, 366–378. https://doi.org/10.1016/j.energy.2015.03.100

Chong, C. H., Ni, W. D., Ma, L. W., Liu, P., & Li, Z. (2015b). The use of energy in Malaysia: Tracing energy flows from primary source to end use. Energies, 8, 2828–2866. https://doi.org/10.3390/en8042828

De Wit, M., & Faaij, A. (2010). European biomass resource potential and costs. Biomass and Bioenergy, 34, 188–202. https://doi.org/10.1016/j.biombioe.2009.07.011

Deng, Y. Y., Koper, M., Haigh, M., & Dornburg, V. (2015). Country-level assessment of long-term global bioenergy potential. Biomass and Bioenergy, 74, 253–267. https://doi.org/10.1016/j.biombioe.2014.12.003

Field, J. L., Evans, S. G., Marx, E., Easter, M., Adler, P. R., Dinh, T., … Paustian, K. (2018). High-resolution techno-ecological modelling of a bioenergy landscape to identify climate mitigation opportunities in cellulosic ethanol production. Nature Energy, 3, 211–219. https://doi.org/10.1038/s41560-018-0088-1

Foley, J. A. (1995). An equilibrium model of the terrestrial carbon budget. Tellus B: Chemical and Physical Meteorology, 47, 310–319. https://doi.org/10.3402/tellusb.v47i3.16050

Gerssen-Gondelach, S. J., Wicke, B., & Faaij, A. P. (2017). GHG emissions and other environmental impacts of indirect land-use change mitigation. GCB Bioenergy, 9, 725–742. https://doi.org/10.1111/gcbb.12394

Grassland Supervision Centre of the Ministry of Agriculture. (2014). Forage production in China Grassland Development Report (2011). China Animal Husbandry, 1, 76.

Hoefnagels, R., Resch, G., Junginger, M., & Faaij, A. (2014). International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union. Applied Energy, 131, 139–157. https://doi.org/10.1016/j.apenergy.2014.05.065

Hu, R. Q., Qin, S. P., & Fan, J. C. (2011). Research on China biomass energy technology roadmap. Beijing, China: China Environmental Science Press.

Intergovernmental Panel on Climate Change. (2014). Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. p. 1454.

Ji, L. Q. (2015). An assessment of agricultural residue resources for liquid biofuel production in China. Renewable and Sustainable Energy Reviews, 44, 561–575. https://doi.org/10.1016/j.rser.2015.01.011

Jiang, D., Hao, M., Fu, J., Liu, K., & Yan, X. (2019). Potential bioethanol production from sweet sorghum on marginal land in China. Journal of Cleaner Production, 220, 225–234. https://doi.org/10.1016/j.jclepro.2019.01.294

Jiang, D., Zhuang, D. F., Fu, J. Y., Huang, Y. H., & Wen, K. G. (2012). Bioenergy potential from crop residues in China: Availability and distribution. Renewable and Sustainable Energy Reviews, 16, 1377–1382. https://doi.org/10.1016/j.rser.2011.12.012

Jiang, Z. X., Dai, Y. H., Luo, X. X., Liu, G. C., Wang, H. F., Zheng, H., & Wang, Z. Y. (2017). Assessment of bioenergy development potential and its environmental impact for rural household energy consumption: A case study in Shandong, China. Renewable and Sustainable Energy Reviews, 67, 1153–1161. https://doi.org/10.1016/j.rser.2016.09.085
Raven, R. (2008). Strategic niche management for biomass: A comparative study on the experimental introduction of bioenergy technologies in the Netherlands and Denmark. Saarbrücken, Germany: VDM Publishing.

Repo, A., Böttcher, H., Kindermann, G., & Liski, J. (2015). Sustainability of forest bioenergy in Europe: Land-use-related carbon dioxide emissions of forest harvest residues. GCB Bioenergy, 7, 877–887. https://doi.org/10.1111/gcbb.12179

Research Group on the Development Potential of Forest Biomass Energy in China. (2006). Survey on cultivation and development potential of forest biomass energy resources in China. China Forestry Industry, 1, 12–21.

Shane, A., Gheewala, S. H., Fungtammasan, B., Silalerverukta, T., Bonnet, S., & Phiri, S. (2016). Bioenergy resource assessment for Zambia. Renewable and Sustainable Energy Reviews, 53, 93–104. https://doi.org/10.1016/j.rser.2015.08.045

Shen, H. H., Zhu, Y. K., & Zhao, X. Y. (2016). Analysis of the current situation of grassland resources in China. Chinese Science Bulletin, 2, 139–154.

Shi, X., Elmore, A., Li, X., Gorence, N. J., Jin, H. M., Zhang, X. H., & Wang, F. (2008). Using spatial information technologies to select sites for biomass power plants: A case study in Guangdong Province, China. Biomass and Bioenergy, 32, 35–43. https://doi.org/10.1016/j.biombioe.2007.06.008

Shu, S. Y., Wang, R., & Sun, Y. W. (2012). Spatial downscaling simulation of urban kitchen waste production. Environmental Science and Technology, 46, 458–463.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., ... Venevsky, S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology, 9, 161–185. https://doi.org/10.1046/j.1365-2486.2003.00569.x

Slade, R., Bauen, A., & Gross, R. (2014). Global bioenergy resources. Nature Climate Change, 4, 99–105. https://doi.org/10.1038/nclimate2097

Smäll, T., Johansson, V., Jönsson, M., Ortiz, C., Hammar, T., Caruso, A., ... Stendahl, J. (2017). Transient trade-off between climate benefit and biodiversity loss of harvesting stumps for bioenergy. GCB Bioenergy, 9, 1751–1763. https://doi.org/10.1111/gcbb.12467

Somerville, C., Youngs, H., Taylor, C., Davis, S. C., & Long, S. P. (2010). Feedstocks for lignocellulosic biofuels. Science, 329, 790–792. https://doi.org/10.1126/science.1189268

Viovy, N. (2016). CRUNCEP data set. Retrieved from http://dods.extra.cea.fr/data/p529viov/cruncep/readme.htm

Wang, W. Y., Ouyang, W., Hao, F. H., & Liu, G. Y. (2017). Temporal-spatial variation analysis of agricultural biomass and its policy implication as an alternative energy in northeastern China. Energy Policy, 109, 337–349. https://doi.org/10.1016/j. enpol.2017.06.068

Wang, H., Zuo, X., Wang, D., & Bi, Y. (2017). The estimation of forest residue resources in China. Journal of Central South University of Forestry & Technology, 37(2), 29–38.

Wilby, R. L., Charles, S., Zorita, E., Timbal, B., Whetton, P., & Mearns, L. (2004). Guidelines for use of climate scenarios developed from statistical downscaling methods. In IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA). Geneva, Switzerland: IPCC.

Wilby, R. L., Wigley, T. M. L., Conway, D., Jones, P. D., Hewitson, B. C., Main, J., & Wilks, D. S. (1998). Statistical downscaling of general circulation model output: A comparison of methods. Water Resources Research, 34, 2995–3008. https://doi.org/10.1029/98WR02577

Woods, J., & Hall, D. (1994). Bioenergy for development – Technical and environmental dimensions: FAO environment and energy paper 13. Rome, Italy: Food and Agriculture Organization of the United Nations.

Xu, L. L., Yan, W., & Cui, S. H. (2013). Path analysis of factors affecting urban domestic waste production – Taking Xiamen City as an example. Journal of Environmental Science, 33(4), 1180–1185.

Xu, X. L., Li, S., Fu, Y., & Zhuang, D. F. (2013). An analysis of the geographic distribution of energy crops and their potential for bioenergy production. Biomass and Bioenergy, 39, 325–335. https://doi.org/10.1016/j.biombioe.2013.08.036

Xue, S., Lewandowski, I., Wang, X. Y., & Yi, Z. L. (2016). Assessment of the production potentials of Miscanthus on marginal land in China. Renewable and Sustainable Energy Reviews, 54, 932–943. https://doi.org/10.1016/j.rser.2015.10.040

Yamamoto, H., Fujino, J., & Yamaji, K. (2001). Evaluation of bioenergy potential with a multi-regional global land-use-and-energy model. Biomass and Bioenergy, 21, 185–203. https://doi.org/10.1016/S0961-9534(01)00025-3

Yamamoto, H., Yamaji, K., & Fujino, J. (2000). Scenario analysis of bioenergy resources and CO2 emissions with a global land-use and energy model. Applied Energy, 66, 325–337. https://doi.org/10.1016/S0306-2619(00)00199-2

Zhang, C. X., Xie, G. D., Li, S. M., Ge, L. Q., & He, T. T. (2010). The productive potentials of sweet sorghum ethanol in China. Applied Energy, 87, 2360–2368. https://doi.org/10.1016/j.apenergy.2009.12.017

Zhang, W. D., Zhang, L., & Zhang, C. H. (2015). Classification and total estimation of forest biomass energy resources in China. Journal of Beijing Forestry University, 14(2), 52–55.

Zhang, X. L., & Lu, W. (2008). China forest energy. Beijing, China: China Agriculture Press.

Zhao, X., Cai, Q., Li, S., & Ma, C. (2018). Public preferences for biomass electricity in China. Renewable and Sustainable Energy Reviews, 95, 242–253. https://doi.org/10.1016/j.rser.2018.07.017

Zhu, H. W., Yang, S., & Zhao, X. Y. (2011). Progress in statistical downscaling of regional climate change. Chinese Journal of Ecology, 31(9), 2602–2609.

Zumkehr, A., & Campbell, J. E. (2013). Historical US cropland areas and the potential for bioenergy production on abandoned croplands. Environmental Science & Technology, 47, 3840–3847. https://doi.org/10.1021/es3033132

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**How to cite this article:** Nie Y, Chang S, Cai W, et al. Spatial distribution of usable biomass feedstock and technical bioenergy potential in China. *GCB Bioenergy*. 2020;12:54–70. https://doi.org/10.1111/gcbb.12651