



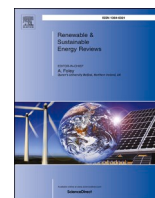
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Bioenergy in China: Evaluation of domestic biomass resources and the associated greenhouse gas mitigation potentials

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ABSTRACT

As bioenergy produces neutral or even negative carbon emissions, the assessment of biomass resources and associated emissions mitigation is a key step toward a low carbon future. However, relevant comprehensive estimates lack in China. Here, we measure the energy potential of China's domestic biomass resources (including crop residues, forest residues, animal manure, municipal solid waste and sewage sludge) from 2000 to 2016 and draw the spatial-temporal variation trajectories at provincial resolution. Scenario analysis and life cycle assessment are also applied to discuss the greenhouse gas mitigation potentials. Results show that the collectable potential of domestic biomass resources increased from 18.31 EJ in 2000 to 22.67 EJ in 2016 with overall uncertainties fluctuating between (−26.6%, 39.7%) and (−27.6%, 39.5%). Taking energy crops into account, the total potential in 2016 (32.69 EJ) was equivalent to 27.6% of China's energy consumption. If this potential can be realized in a planned way to displace fossil fuels during the period 2020–2050, cumulative greenhouse gas emissions mitigation would be in the range of 1652.73–5859.56 Mt CO₂-equivalent, in which the negative greenhouse gas emissions due to the introduction of bioenergy with carbon capture and storage would account for 923.78–1344.13 Mt CO₂-equivalent. Contrary to increasing bioenergy potentials in most provinces, there are declining trends in Tibet, Beijing, Shanghai and Zhejiang. In addition, Yunnan, Sichuan and Inner Mongolia would have the highest associated greenhouse gas mitigation potentials. This study can provide valuable guidance on the exploitation of China's untapped biomass resources for the mitigation of global climate change.

1. Introduction

Bioenergy has been the fourth-largest energy source in the world after coal, oil and natural gas, accounting for 9.5% of global primary energy supply and 69.5% of global renewables supply in 2016 [1]. A recent study indicated that the global potential of biomass resources would be approximately 100–600 EJ by 2050 [2], which is equivalent to 15–65% of primary energy demand, according to the estimates of the International Energy Agency [3]. Besides its dominant role in the renewable energy mix, bioenergy, as the only renewable carbon source, is considered as the most promising alternative for fossil energy with a

potential to abate greenhouse gases (GHG) emissions. Generally, the carbon in bioenergy derives from the atmospheric carbon dioxide (CO₂) which is sequestered by photosynthesis during biomass growth [4]. Thus, bioenergy utilization could result in neutral or even negative carbon emissions if coupled with carbon capture and storage (CCS). Toward a low carbon future, the assessments of biomass resources availability and associated GHG mitigation potentials constitute the foundation for bioenergy chains planning.

China is actively promoting the development of renewable energy to achieve a low carbon transition and the sustainable development goals. Currently, hydropower is responsible for the highest share of renewable energy generation, but it has negative impacts on river ecosystems

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Abbreviations

GHG	greenhouse gas
CCS	carbon capture and storage
BECCS	bioenergy with carbon capture and storage
GIS	geographic information system
IAM	integrated assessment model
LCA	life cycle assessment
CR	crop residues
FR	forest residues
AM	animal manure
MSW	municipal solid waste
SS	sewage sludge
EC	energy crops
RPR	residue to product ratio
LHV	COD lower heating value chemical oxygen demand
EJ	exajoule (10^{18} J)
PJ	petajoule (10^{15} J)
ha	hectare
Mtce	million tons of coal equivalent
CO ₂ e	CO ₂ -equivalent

[5–7]. Whilst China has been the world's top carbon emitter since 2007, considering the huge pressure posed by both environment preservation and climate change, biomass resources represented by energy crops (EC) have attracted much attention in China. Bioenergy is the domestic third-largest energy source after coal and oil, contributing to 15% of energy consumption in 2017 [8]. Moreover, while the Chinese government made a voluntary mitigation commitment with a peak of CO₂ emission by 2030, there is a growing interest in bioenergy as it is a low, neutral and even negative emissions technology. In this context, it is imperative to evaluate the biomass resources with spatial-temporal distribution and their potential to reduce GHG emissions in China.

A large body of work has studied the bioenergy potential worldwide using two main approaches: geographic information system (GIS) and statistical analysis. GIS technique, especially when coupled with remote sensing, can estimate the regionalized and aggregated potentials of biomass resources [9–11]. However, it is solely applicable to few biomass categories. Statistical analysis is the most widely used method on both regional and national scales since the primary data is comprehensive and easily accessible. Accordingly, the theoretical potential of biomass residues can be directly assessed [12,13]. Collectable potential and utilizable potential could then be quantified, considering significant technical and economic-environmental constraints [14–19]. For China, Yang et al. [20] analyzed the energy potential of predominant biomass resources, which amounted to 887 Mtce in 2007. Zhou et al. [21] evaluated that the collectable potential of China's major biomass resources in 2008 was about 18.8 EJ. However, these studies were performed based on outdated data and a coarse classification of biomass resources. On the other hand, since different values of key parameters were used for the quantitative appraisal, the results were diverse.

The explicit bioenergy availability is a premise for assessing its associated GHG emission reduction potentials. GHG emissions analysis, focusing on the sustainability concerns of biomass resources for possible energy use, has been emphasized in previous studies [22–25]. The climate change abatement potential is mainly identified through two methods: integrated assessment model (IAM) and life cycle assessment (LCA). IAM is carried out estimating GHG mitigation potentials at a global-level with idealized assumptions and it is generally used to explore climate strategies and scenarios on the macro level [26]. However, the narrow boundaries of its environmental impact assessment make it unable to reflect life cycle effects on the micro scale [27,28]. In contrast, cradle-to-grave LCA, typically includes process-based LCA

(bottom-up method), input-output-based LCA (top-down method applied to economic data) and hybrid LCA (combining the first two methods), has higher precision and completeness for certain regions and technologies [29]. For instance, Wu et al. [30,31] assessed the carbon emissions and water footprint of coal-fired generation systems in China, integrating process-based LCA and input-output analysis. Lu et al. [32] calculated life cycle GHG emissions of coal-biomass gasification systems in China.

Bioenergy with CCS (BECCS), as a negative emissions technology, is becoming increasingly important under the pressure of global warming. Despite that its large-scale deployment is yet to come, the stricter 1.5 °C goal issued by 2015 Paris Agreement makes this technology inevitable [33]. Meanwhile, a whole-system analysis of the BECCS value chain concludes that BECCS is a reliable option for permanent CO₂ removal [34]. Some studies have analyzed the deployment potential of BECCS related to individual bioenergy carriers [35–38]. In China, Pang et al. [39] took a typical biomass power plant with CCS as an example to evaluate the life-cycle carbon reduction benefits. Nevertheless, to the extent of our knowledge, no work to date has quantified the GHG emissions reduction of large-scale BECCS deployment at high spatial resolution in China.

On the whole, there are still knowledge gaps concerning biomass resources with spatial-temporal distribution and the associated GHG mitigation potentials in China. The aim of this study has therefore been to trace changes in the potential of all possible domestic biomass resources on a provincial level and to investigate their uncertainty range. On top of that, it is estimated for the first time the GHG mitigation potential of bioenergy utilization in China by mid-century, with special attention on BECCS. The steps of the assessment are as follows. First, based on the statistical data, we provide the spatial-temporal changes of domestic biomass resources, including crop residues, forest residues, animal manure, municipal solid waste and sewage sludge, and draw the evolution trajectories during the period 2000–2016. Then, the energy potential of total biomass resources (including EC) in 2016 is elaborated to assess the bioenergy production of twelve representative feedstock-to-final conversion pathways from 2020 to 2050. Furthermore, scenario analysis and LCA are applied to calculate GHG emissions reduction of Bioenergy with and without CCS to displace fossil fuels. Finally, we conduct the uncertainty analysis of bioenergy potential using the Monte Carlo simulation. These outcomes could provide decision-makers with the geographically targeted information on the exploitation of China's bioenergy resources for the mitigation of global climate change.

2. Methodology

The flowchart of the methodology applied in this study is shown in Fig. 1. To draw the evolution trajectories of biomass resources potential and then compare it with the existing literature, the first 16 years from the beginning of this century were selected as the time series for resources assessment. Moreover, the associated GHG mitigation potentials have been predicted until mid-century to quantitatively measure the contribution of China's biomass resources to domestic and global emission reduction goals.

2.1. Bioenergy potential estimation

In the present study, we assess the following biomass resources in China from 2000 to 2016: (i) crop residues, (ii) forest residues, (iii) animal manure, (iv) municipal solid waste, and (v) sewage sludge. The potential assessment of EC is based on previous research by Zhang [40]. Three categories of the potential availability of every possible biomass resource are evaluated, which are theoretical potential, collectable potential and utilizable potential; following the approach of Long et al. [41]. Here we give a definition of the three considered potentials:

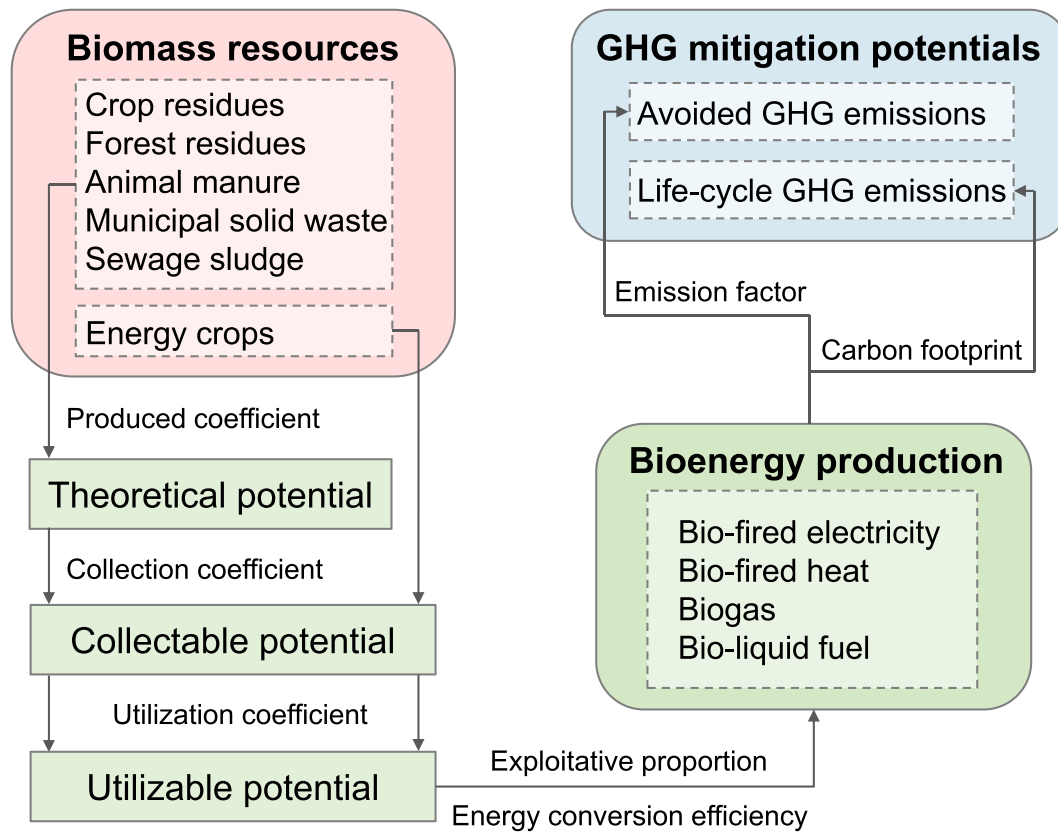


Fig. 1. The framework for evaluating biomass resources and associated GHG mitigation potentials in China.

- Theoretical potential: upper limit of biomass resources obtained in a chosen area.
- Collectable potential: a certain amount of theoretical potential that can be obtained under the technical and logistics restrictions.
- Utilizable potential: a certain amount of collectable potential used as energy, excluding other competing uses such as fertilizer, livestock feed and industrial raw material.

In line with the quantitative appraisal, the potentials above are finally converted into bioenergy potential expressed in terms of joule, by using conversion factors.

2.1.1. Crop residues (CR)

The CR discussed in this study come from food crops (rice, wheat, corn, millet, sorghum, other grains, beans and tubers) and cash crops (oil crops, cotton, hemp, sugar crops, tobacco and melons). During the period 2000–2016, the theoretical potential of CR is calculated by multiplying grain production for the residue to product ratio (RPR). RPR is the ratio of residues (such as straw, stalk, leaves, etc.) to the crops, and we adopt the mean value from related articles, as shown in Table 1. Crop production is derived from China Rural Statistical Yearbook (2001–2017). Then, the collectable potential of CR (CP_{CR}) can be estimated using the following equation:

$$CP_{CR} = \sum_{i=1}^n P_i \times RPR_i \times C_i \times LHV_{CR} \tag{1}$$

where P_i is the production of i th crop, kg; C_i is the collection coefficient of i th crop; LHV_{CR} is the lower heating value (i.e., conversion factor) of residue from i th crop, kJ/kg.

2.1.2. Forest residues (FR)

Three main types of FR are forest tending residues, forest harvesting

Table 1
Parameters for the bioenergy potential estimation of crop residues.

		RPR ^a	Collection coefficient [42]	LHV (kJ/kg) [42]	
Food crops	Rice	0.95	0.83	14059	
	Wheat	1.21	0.65	14766	
	Corn	1.40	0.9	14356	
	Millet	1.44	0.85	14569	
	Sorghum	1.65	0.9	15105	
	Other grains	1.39	0.86	14384	
	Beans	1.48	0.56	14789	
	Tubers	0.63	0.73	14126	
	Cash crops	Oil crops	2.03	0.78	14775
		Cotton	3.32	0.86	14979
Hemp		2.29	0.87	15491	
Sugar crops		0.24	0.7	13816	
Tobacco		1.03	0.95	11300	
Melons		0.10	0.5	13498	

^a All references are listed in Table A1 in Supplementary material.

residues and orchard residues. The evaluation parameters of FR are listed in Table 2 and Eq. (2) is used to evaluate the collectable potential of FR (CP_{FR}). The primary data of woody mass and orchard area are from China Forestry Statistical Yearbook (2000–2016). Other area data for FR are collected from the 6th to 8th National Forest Resources Survey [43]. Since the data of the 9th National Forest Survey has not yet been published, we use the 8th National Forest Survey (2009–2013) to calculate FR potential during the period 2014–2016 instead.

$$CP_{FR} = \sum_{i=1}^n A_i \times Y_i \times U_i \times LHV_{FR} \tag{2}$$

where A_i is the area of i th FR, ha; Y_i is the product yield of i th FR, kg/ha; U_i is the collection coefficient of i th FR; LHV_{FR} is the lower heating value

Table 2
Parameters for the bioenergy potential estimation of forest residues [42,44].

		Product yield (kg/ha)	Collection coefficient	LHV (kJ/kg)
Forest tending residues	Timber forest	3750	0.50	18600
	Protection forest	3750	0.20	18600
	Firewood forest	3750	1.00	16747
	Special-use forest	1875	0.10	18600
	Economic forest	1875	0.10	18600
	Sparse forest	1875	0.50	18600
	Shrubbery	938	0.50	18600
	Sipang forest	2 (kg/each plant)	0.50	18600
Forest harvesting residues	Bamboo forest	1875	0.10	17672
	Wood	900 (kg/m ³)	0.344	19500
Orchard residues	Orchard	1875	0.10	18600

of *i*th FR, kJ/kg.

2.1.3. Animal manure (AM)

Humans, cows, horses, donkeys, mule, sheep, pigs and chickens are included in our study. The animal numbers are derived from China Rural Statistic Yearbook (2001–2017), where pigs and chickens are considered as the slaughter capacity while cows, horses, donkeys, mule and sheep are regarded as the year-end stock. The collectable potential of AM (CP_{AM}) in the accounting period is estimated using Eq. (3). Daily excretion coefficients of the animals are represented by the mean values taken from relevant literature, as presented in Table 3.

$$CP_{AM} = \sum_{i=1}^n B_i \times N_i \times E_i \times D_i \times R_i \times LHV_{AM} \quad (3)$$

where B_i is the breeding cycle of animal *i*, day; N_i is the number of animals in *i*th category, head; E_i is the excretion coefficient of *i*th animal category, kg/day; D_i is the dry matter content of manure from *i*th animal category, %; R_i is the collection coefficient of manure from *i*th animal category; LHV_{AM} is the lower heating value of manure from *i*th animal category, kJ/kg.

2.1.4. Municipal solid waste (MSW) and sewage sludge (SS)

MSW and SS are the urban wastes, whose organic fraction is the main feedstock for waste-to-energy processes. Original data for the bioenergy potential estimation of MSW and SS is from China Statistical Yearbook on Environment (2001–2017). Equations of the collectable potential of MSW (CP_{MSW}) and SS (CP_{SS}) are as follows:

$$CP_{MSW} = Q \times LHV_{MSW} \quad (4)$$

Table 3
Parameters for the bioenergy potential estimation of animal manure.

	Breeding cycle (day) [45]	Daily excretion coefficient ^a (kg/d)	Dry matter content (%) [46]	Collection coefficient [46]	LHV (kJ/ kg) [47]
Humans	365	0.55	0.15	1.00	18817
Cows	365	25.93	0.19	0.60	13799
Horses	365	13.16	0.25	0.55	15472
Donkeys	365	10.03	0.25	0.55	15472
Mule	365	9.26	0.25	0.55	15472
Sheep	365	2.10	0.50	0.60	15472
Pigs	199	3.12	0.20	0.90	12545
Chickens	210	0.12	0.50	0.60	18817

^a All references are listed in Table A2 in Supplementary material.

where Q is the harmless disposed quantity of MSW, kg; LHV_{MSW} is the average lower heating value of MSW, 4200 kJ/kg [48].

$$CP_{SS} = CE \times LHV_{COD} \quad (5)$$

where CE is the chemical oxygen demand (COD) emissions of sewage, kg; LHV_{COD} is the lower heating value of COD, 14000 kJ/kg [20].

2.2. GHG mitigation potentials estimation

2.2.1. Avoided GHG emissions

China's 13th five-year plan for renewable energy development [49] emphasizes that biomass resources for energy use in China would reach large-scale commercialization in 2020. Therefore, based on the collectable potential of biomass resources obtained above, we can project their utilizable potential (see section 4.1) during the period 2020–2050 for the scenario analysis of associated GHG mitigation potentials. Twelve feedstock-to-final bioenergy conversion pathways are proposed to fully replace fossil fuels, and their utilization structure is reckoned according to China Bioenergy Development Roadmap 2050 (hereafter referred to as CBDR2050) [50]. AM and SS could only be converted into biogas by anaerobic digestion. Power generation from waste incineration and sanitary landfills management are considered to be two ways for MSW treatment. Given the vigorous forecasted development of waste incineration power plants in the future, we assume that up to 50% and 80% of the disposed quantity of harmless MSW are used in incineration power production during the period 2020–2030 and 2040–2050, respectively [50]. CR, FR and EC would be fully converted by the remaining nine pathways, whose exploitative proportion are listed in Table B2 in Supplementary material. The avoided emissions ($MP_{avoided}$), which refer to GHG emissions from bioenergy by offsetting fossil fuels-derived energy carriers, are defined by Eq. (6).

$$MP_{avoided} = UP(j) \times P(j) \times EE(j) \times EF_{fossil}(j) \quad (6)$$

where $UP(j)$ is the utilizable potential of biomass resources via conversion pathway *j*, MJ; $P(j)$ is the exploitative proportion of conversion pathway *j* (100% for AM and SS anaerobic fermentation); $EE(j)$ is the energy conversion efficiency of pathway *j*; $EF_{fossil}(j)$ is the emission factor of fossil fuels, which would be replaced with bioenergy production of pathway *j*, kg CO₂e/MJ_{feedstock}.

2.2.2. Life-cycle GHG emissions

Eq. (7) is used to calculate life-cycle GHG emissions (MP_{LC}), in which we assume that $EE(j)$, $CF_{biomass}(j)$, as well as $EF_{fossil}(j)$ will remain constant in the first half of this century due to the absence of forecasts. Data collection and collation of these can be found in section C of Supplementary material, and the results are listed in Table 4.

$$MP_{LC} = UP(j) \times P(j) \times EE(j) \times CF_{biomass}(j) \quad (7)$$

where the definition of $UP(j)$, $P(j)$ and $EE(j)$ are consistent with Eq. (6); $CF_{biomass}(j)$ is the life-cycle carbon footprint of bioenergy pathway *j* coupled with and without CCS, kg CO₂e/MJ_{feedstock}.

Eventually, GHG mitigation potentials (MP) are determined by the difference between the avoided emissions and life-cycle emissions [51]:

$$MP = MP_{avoided} - MP_{LC} \quad (8)$$

3. Spatial-temporal variation of bioenergy potential

3.1. Temporal changes of domestic bioenergy potential

The collectable potential of China's domestic biomass resources increased from 18.31 EJ in 2000 to 22.67 EJ in 2016 (Fig. 2). The annual growth rate is about 1.34% during that period. MSW was the fastest-growing among five resources (at an annual growth rate of 6.4%), whereas SS presented a negative growth. Furthermore, two nadirs in

Table 4
Key parameters for GHG mitigation potentials estimation.

Final fossil carrier offset	Bioenergy carrier	Bioenergy conversion pathway	Energy conversion efficiency	Emission factor (kg CO ₂ e/MJ)		Carbon footprint (kg CO ₂ e/MJ)	
				Fossil fuels-derived	Without CCS	With CCS	
Coal-fired electricity	Bio-fired electricity	Direct-fired power	0.174	0.220	0.089	-0.126	
		Gasification power	0.176	0.220	0.137	-0.058	
		Co-fired power	0.296	0.220	0.189	0.012	
		Waste incineration	0.257	0.220	0.184	-0.001	
		Combined heat and power	0.160	0.220	0.010	-0.028	
Coal-fired heat	Bio-fired heat	Combined heat and power	0.083	0.128	0.001	-0.014	
		Densified biofuel	0.101	0.128	0.011	-0.035	
Natural gas	Biogas	Pyrolysis gas	0.584	0.089	0.086	-0.003	
		Livestock biogas	0.350 m ³ /kg AM	0.089	0.050	-0.003	
		Industrial biogas	0.907 m ³ /kg COD	0.089	0.086	-0.003	
			0.131 m ³ /kg MSW	0.089	0.086	-0.003	
Gasoline	Bio-liquid fuel	Bio-ethanol	0.380	0.087	0.048	0.011	
Diesel		Bio-diesel	0.402	0.095	0.073	-0.124	
Kerosene		Bio-jet fuel	0.462	0.204	0.022	-0.124	

Note: All references are listed in Supplementary material.

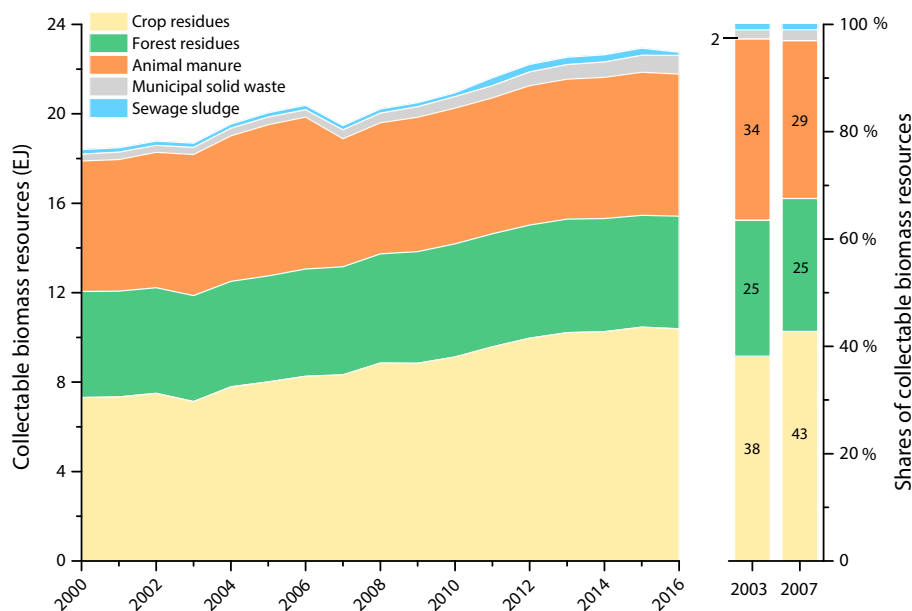


Fig. 2. Changes in China's domestic bioenergy potential.

2003 and 2007 can be identified in the period. In 2003, the outbreak of the severe acute respiratory syndromes (SARS) epidemic across China led to an abnormal fluctuation of crop yields. As a result, CR hit a minimum at 7.11 EJ in 2003, mainly due to the decrease of the rice and wheat straws. The increment trend of CR had recovered since 2004 and its collectable potential reached 10.39 EJ in 2016. Owing to the rising feed prices, AM showed an abrupt plunge in 2007 (5.64 EJ), especially

the cows and pigs manures. Afterwards, AM potential fluctuated between 5.78 EJ in 2008 and 6.27 EJ in 2016. In addition, FR exhibited a steady growth period from 2000, reaching the pinnacle at 5.08 EJ in 2013. It is reported that China leads in forest area increment around the world. Thanks to the forest conservation and expansion, China was responsible for 25% of the global net increase in leaf area from 2000 to 2017 [52].

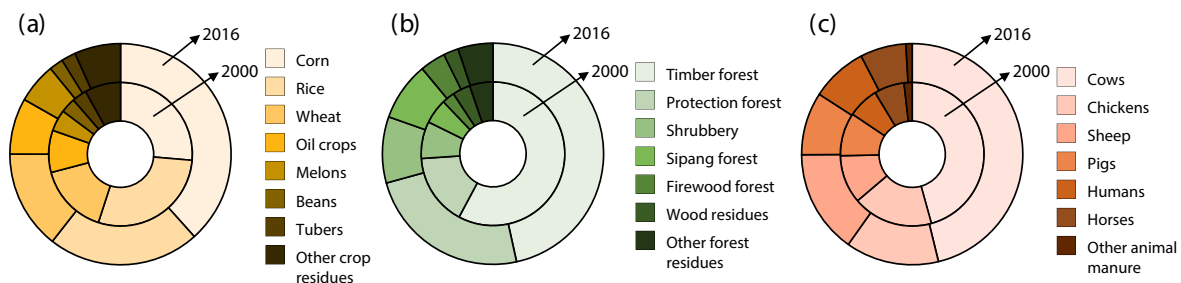


Fig. 3. Percentages of the sub-types of crop residues (a), forest residues (b) and animal manure (c). (The inner ring depicts the percentages in 2000 and the outer ring represents that in 2016).

Moreover, we summarize the temporal changes of the sub-types of the three major biomass resources above using the donut chart (Fig. 3), and their collectable potential from 2000 to 2016 are shown in Table D1–D3 of Supplementary material. The residues of corn, rice and wheat always dominated the CR potential, occupying 74.7% of the total in 2016. Among these, corn residue potential was the largest, and its proportion increased from 26.2% in 2000 to 38.2% in 2016. In fact, China has become the world’s second corn producer since 2011 [53]. Additionally, as a market-oriented agricultural product, cash crops have been of interest to the world for the socio-economic and ecological impacts [54–56]. The economic profit per hectare of melons could be three times higher than that of paddy fields [57]. Our results showed that the potential of melons stems was the fastest-growing resource, accounting for 5.8% of total CR in 2016.

For immature forests, tending and thinning is a management measure to cut down part of the trees regularly and repeatedly to promote the cultivation of reserve resources. The collectable potential of forest tending represented around 90% of FR. Specifically, timber forest, whose primary use is wood production, contributed half of FR potential. Protection and special-use forests for environmental services are aimed at maintain biological diversity or natural resources [58,59]. Along with the expansion of protection forest’s area, the proportion of their collectable potential increased from 16.1% in 2000 to 24.2% in 2016. The potential of wood residues was also growing fast, which can be explained by the fact that China’s harvested wood production and consumption has been at the forefront in the world [60].

The number of animals (heads) is the leading cause of the change in AM potential. China is the world’s largest animal excrement producer, and the livestock population tripled in the last three decades [61,62]. Excrement from cows, chickens, sheep and pigs made up the bulk of AM, and the collectable potential accounted for 25%, 28%, 17% and 15% of the total in 2016, respectively. Chickens’ manure was the fastest-growing resource among these eight kinds. It is worth noting that, since China is the most populous country in the world, humans’ excretion may be a promising resource. The collectable potential of that contributed to 12.5% of the total AM in 2016.

Table 5 shows the variation of the MSW potential from 2000 to 2016. According to the national data [47], Chinese urbanization level rose from 29% to 57% during the period 1995–2016. With the accelerating urbanization and economic growth, the amount of MSW experienced a substantial increase in recent years. Meanwhile, the rate of harmless disposal increased to 96.6% in 2016 due to the improvement of MSW disposal in waste management options [63]. At present, organic wastes such as paper, textiles and leather account for 25%–30% of total MSW in China, and their moisture content is higher than that in European countries [64].

As presented in Table 6, wastewater discharge kept an ever-increasing trend from 2000 to 2016, while the collectable potential of SS exhibited two jumps during that period. In China, domestic sewage is a major source of wastewater. Wastewater discharge is growing with rapid urbanization and industrialization. Yet, COD emissions caused by the organic matter of wastewater, generally embody the energy potential of SS [20]. Evidently, the collectable potential of SS stepped into a peak at 35 EJ in 2011. The main reason is the expansion of the urban population and the widespread use of agricultural fertilizers. Since 2015, there has been a transition in wastewater treatment plants and wastewater pollution management [65]. Thus, SS potential dropped sharply to 0.15 EJ in 2016, which was even lower than the potential in

Table 5
The collectable potential of municipal solid waste in China.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Volume of disposal/Mt	118	135	137	149	155	156	148	152	154	157	158	164	171	172	179	191	204
Harmless disposal/Mt	73	78	74	75	81	81	79	94	403	112	123	131	145	154	164	180	197
Collectable potential/EJ	0.31	0.33	0.31	0.32	0.34	0.34	0.33	0.40	0.43	0.47	0.52	0.55	0.61	0.65	0.69	0.76	0.83

2000.

3.2. Spatial distribution of bioenergy potential

3.2.1. Provincial changes of biomass resources (except EC)

Fig. 4 depicts the structure of China’s provincial biomass resources (except EC) in the period concerned, ranked based on the collectable potential in 2000. The collectable potential of the sub-types CR, FR and AM classified on a provincial level can be found in Supplementary material Section E. Shandong, Henan, Sichuan and Heilongjiang were the top four provinces during the study period, whose collectable biomass resources potential accounted for around 27% of national potential. Heilongjiang took Sichuan’s place in 2016 (1491.18 PJ), mainly owing to the rapid increase of CR potential. Furthermore, the collectable potential of biomass resources in Tianjin, Shanghai, Ningxia, Beijing and Hainan was relatively low (<150 PJ). On the other hand, the bioenergy potential of each province was dominated by CR, FR and AM resources. CR in the northeast and central regions was rich. FR was clustered in southwest China. AM was the most evenly distributed of five biomass resources.

Compared with the increasing potential of biomass resources in most regions, Tibet, Beijing, Shanghai and Zhejiang showed a declining trend (Fig. 4d). The collective share of bioenergy potential in these four regions declined from 5.4% in 2000 to 4.1% in 2016. For the Tibet autonomous region, the reason was the reduction of FR resource. Its shrubs gradually disappeared and the ecological environment had a moderate degradation in recent years [66]. While for highly developed cities such as Beijing and Shanghai, CR and AM resources potentials presented a significant drop. According to the realistic positioning of these two cities, the proportion of the primary industry in the gross domestic product (GDP) decreases, while the proportion of the tertiary industry increases [67]. So the crops cultivation and livestock breeding reduced and MSW continued to rise. This situation was also similar to the declining bioenergy potential of Zhejiang province, even though its decline was slower. In terms of the increasing trends, northern China had a higher annual growth rate of bioenergy potential than southern China. Liaoning province had the biggest annual growth rate because it first launched the “Pig-biogas-crop-fruit” recycling biomass to achieve gas production and fertilizer products used in agriculture and breeding [68].

3.2.2. Provincial distribution of total biomass resources (including EC)

As EC grown on marginal land do not affect food security and the environment, they are playing an increasing role in biomass material supply [69–72]. EC are generally perennial herbaceous and woody plant species [73]. Currently, due to a lack of empirical data concerning the productivity, quantitative appraisal of EC is based on a specific category through GIS technique [11,74–78]. To assess the energy potential of China’s domestic biomass resources from a comprehensively and systematically perspective, we used the basic data of EC in 2016 [40]. These data indicated the total net primary productivity of the marginal land suitable for EC was 395 tera-gram of carbon (TgC) under loose screening conditions, which was equivalent to 345 Mtce (10.09 EJ) of EC potential. The solid grey circles in Fig. 5a represent the provincial EC potential in China. Yunnan and Inner Mongolia were the two highest production regions, whose collectable potential was 2844 PJ, accounting for 28.3% of the total bioenergy potential in China. The large agricultural provinces, Henan and Shandong showed a low degree of EC potential (<100

Table 6
The collectable potential of sewage sludge in China.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Wastewater discharge/Gt	41.5	43.3	44.0	45.9	48.2	52.5	53.7	55.7	57.2	58.9	61.7	65.9	68.5	69.5	71.6	73.5	71.1
COD emissions/Mt	14.5	14.0	13.7	13.3	13.4	14.1	14.3	13.8	13.2	12.8	12.4	25.0	24.2	23.5	22.9	22.2	10.5
Collectable potential/EJ	0.20	0.20	0.19	0.19	0.19	0.20	0.20	0.19	0.19	0.18	0.17	0.35	0.34	0.33	0.32	0.31	0.15

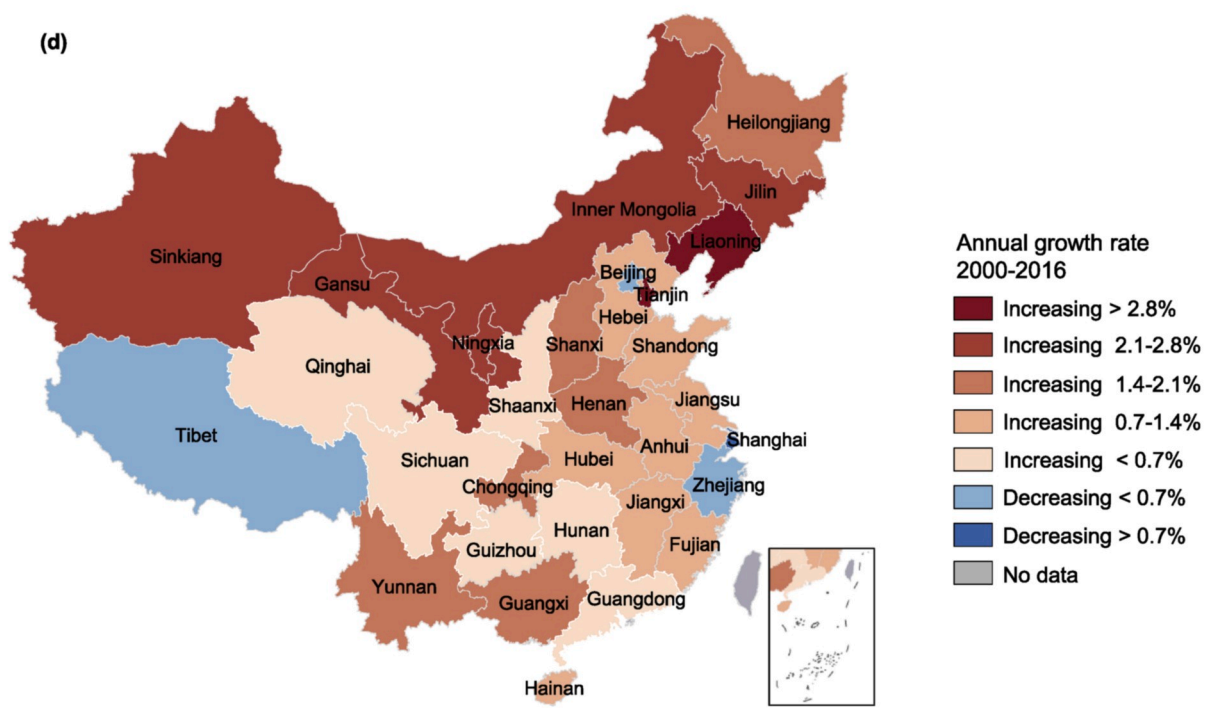
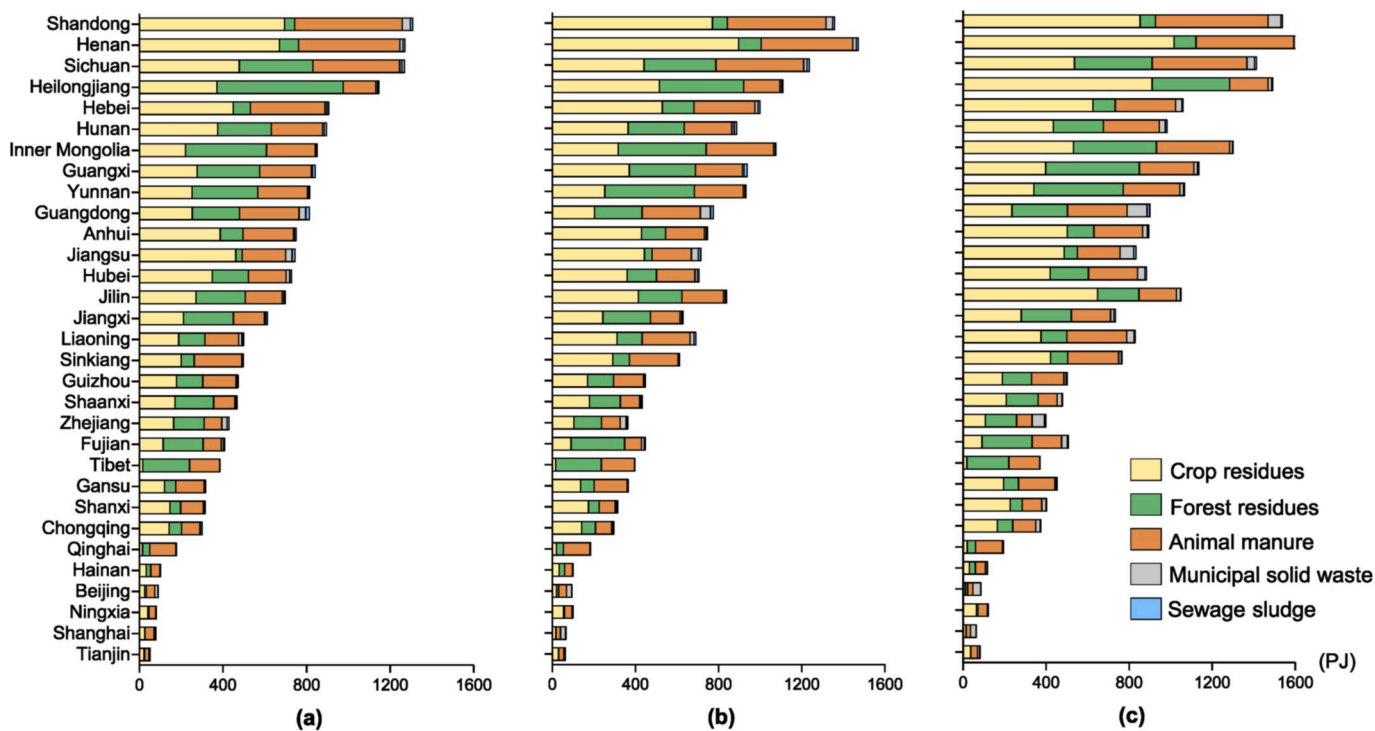


Fig. 4. China's provincial bioenergy potential in 2000 (a), 2007 (b) and 2016 (c), as well as the relative changes between 2000 and 2016 (d).

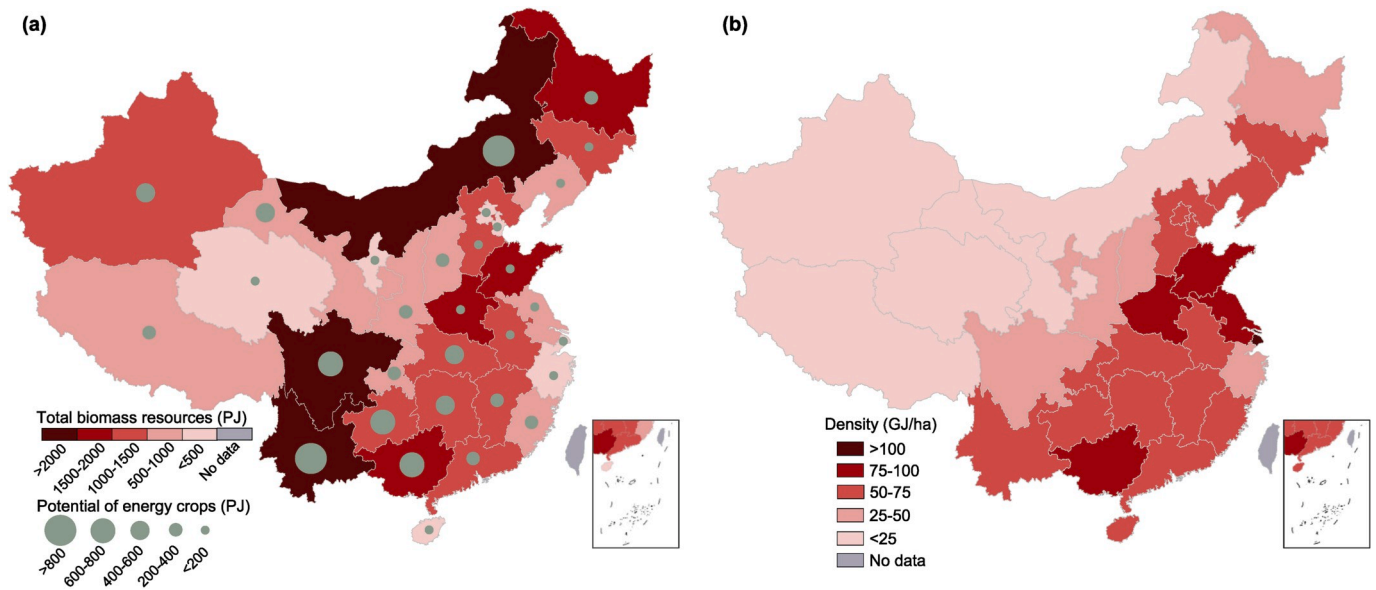


Fig. 5. The total potential of China’s biomass resources including energy crops (a) and their density (b) in 2016.

PJ).

For the spatial distribution of total biomass resources in 2016 (Fig. 5a), Yunnan, Inner Mongolia and Sichuan reached the top three positions, together accounting for 22.3% of the total. Henan, Heilongjiang and Shandong, which are rich in CR resources had a total biomass resources potential of more than 1500 PJ. On the contrary, Beijing, Tianjin, Ningxia, Qinghai Plateau and eastern coastal regions had lower resources potential (<math>< 500</math> PJ).

To further characterize the provincial disparities, we investigated the density of total biomass resources potential, as illustrated in Fig. 5b. Clearly, the total domestic biomass resources were dense in eastern China but sparse in western China. More specifically, the density of biomass resources in the Inner Mongolia autonomous region and northwest China was low (<math>< 25</math> GJ/ha) due to their vast territory. The resources density of Shanghai ranked the top among all the provinces, at 101.25 GJ/ha. Followed by Henan province (99.31 GJ/ha), Shandong province (99.08 GJ/ha), Jiangsu province (85.52 GJ/ha) and Guangxi province (79.75 GJ/ha). These four would be important regions for the development of the bioenergy industry.

4. GHG mitigation potentials

4.1. Trends in GHG mitigation potentials from 2020 to 2050

4.1.1. Bioenergy production of final carriers

Bioenergy potential would triple in the first half of this century in CBDR2050 due to the surge of EC, but the EC data used in this study were carried out under maximum loose conditions. So we make a simplifying assumption that the collectable potential of China’s domestic biomass resources will remain at the same level reached in 2016 during the period 2020–2050. Subsequently, to ensure that our assessments take sustainability concerns into account, we consider two types of utilizable potential of biomass resources to predict GHG mitigation in that period. Group “Planning potentials” is using energy utilization coefficients from CBDR2050 to obtain final bioenergy availability, which would be 13.25 EJ, 20.86 EJ, 23.73 EJ and 24.40 EJ in 2020, 2030, 2040 and 2050, respectively (Table B1 and Fig. B1 show the details). Whereas group “Maximum potentials” assumes that all the collectable biomass resources are completely utilized for bioenergy production (energy utilization coefficient is 1).

Concerning the “Planning potentials”, the bioenergy production of final carriers is listed in Table 7. The total bioenergy production for

Table 7

Bioenergy production of “Planning potentials” in China (PJ).

	2020	2030	2040	2050
Bio-fired electricity	1555.63	2076.95	1753.15	1644.05
Bio-fired heat	422.95	638.14	573.56	586.45
Biogas	1858.24	3390.78	3818.94	4095.59
Bio-liquid fuel	366.15	1005.98	2236.97	2872.81
Total	4202.97	7111.85	8382.62	9198.9

2020, 2030, 2040 and 2050 in China would be 4202.97 PJ, 7111.85 PJ, 8382.62 PJ and 9198.9 PJ, respectively. It is indicated that biogas would always be the most productive among the four bioenergy carriers. Its production would increase from 1858.24 PJ (71.69 Gm³) to 4095.59 PJ (158.01 Gm³) over the period. As a matter of fact, China has the largest number of operating digesters and is becoming a world leader in the development of anaerobic digestion [79]. Wherein the middle-to large-scale biogas projects have to fulfill a broader demand since energy production is separated from the highly consuming inhabitants’ region [80]. Besides, upgrading biogas to biomethane by separating CH₄ from CO₂ to achieve commercial methane purity has been used for several purposes, especially in the transport sectors [81].

Biomass liquid fuels would be the most promising final carriers. In 2020, their production would be the lowest among the four carriers at only 366.15 PJ, while the production would become the second-largest in 2050 (2872.81 PJ). At the beginning of this century, China has begun the large-scale demonstration production of bio-liquid fuels, including bio-ethanol and bio-diesel as transport vehicle fuel which is promoted by multiple policy incentives [82,83]. Moreover, the Chinese government prioritized the development of non-food EC biofuels, and the production could be more promising in the long-term period [84].

The output of electricity and heat energy would reach a peak of 638.14 PJ and 2076.95 PJ in China 2020, respectively, but they would present downward trends until 2050. Biomass power generation in 2050 would be 1644.05 PJ, accounting for only 17.87% of the total. Generally, biomass power has a higher energy consumption and environmental impact in comparison to wind power generation [85]. Furthermore, there are redundant subsidies for biomass power electricity, which may be a financial burden for the government [86,87]. Biomass heating includes biomass cogeneration heating and biomass boiler heating. The bio-fired heat carrier in 2050 would be equivalent to only 586.45 PJ. This result may be due to the fact that domestic investors

pay less attention to the application of biomass heating in recent years [88]. Biomass heating in urban areas can also be responsible for important particulate emissions, which will aggravate air pollution.

4.1.2. Scenario analysis of GHG mitigation potentials

In view of the bioenergy utilizable potential and large-scale deployment of BECCS technology in the future, there are four scenarios for the evaluation of GHG mitigation potentials in our study. As described in Table 8, the utilizable potentials are the two groups potentials assumed in the previous section. For bioenergy conversion technology, scenario 1 and scenario 3 are the biomass feedstock-to-final conversion pathways without CCS, scenario 2 and scenario 4 assume that all the technological pathways are coupled with CCS to minimize GHG emissions.

Fig. 6 illustrates the contribution of each bioenergy carrier to the GHG mitigation potentials from 2020 to 2050. Bio-liquid fuels have the greatest prospect on the GHG emissions reduction among four considered bioenergy carriers. Their proportion in scenario 4 would significantly increase from 7.58% in 2020 to 43.95% in 2050. As transportation fuels, biofuels have a great performance on reducing fossil energy consumption and carbon emissions in the transport sector, especially bio-diesel as an alternative to conventional diesel [89]. With the extensive application of biomass liquid fuels, their more sustainable problems such as biodiversity and ecosystem services have attracted more attention. In this case, third-generation biofuels derived from microalgal biomass which have a lower ecological footprint, will be a key technology in the future [90,91].

Despite the huge production of biogas, the mitigation benefit of biogas is not so satisfactory. For one reason, the primary environmental advantage of biogas production by anaerobic fermentation is linked with the decrease in chemical fertilizers use [92]. On the other hand, biogas is a mixture of CH₄ and CO₂. CH₄ is another greenhouse gas, however, whose global warming potential is 25 times higher than that of CO₂ [93]. For wastewater treatment, CH₄ emissions are yet large, although methane recovery has been started up in China [94]. Fortunately, China's national and local policies concerning MSW sanitary landfill have been promoted to reduce the CH₄ emissions of MSW treatment [95].

The dotted line and symbols in Fig. 6 represent the carbon mitigation targets of CBDR2050. It can be observed that the GHG mitigation potentials of scenario 1 could meet the target only in 2020, and couldn't do it after 2020. Scenario 3 shows that if all the collectable biomass resources are converted into energy utilization, this would greatly contribute to the achievement of the target. Furthermore, scenario 4 could always be at the high levels of mitigation potentials, substantially exceeding the planned targets. In other words, BECCS will play a strategic role in reducing GHG emissions in the future. In 2050, China's GHG emissions mitigation promoted by the bioenergy sector would reach 604.76–2063.66 Mt CO₂e. From an international perspective, this alone could contribute to 6.1–20.8% of the global carbon emissions reduction goal set by IPCC (medium 9900 Mt at the “lower 2 °C” scenario [96]).

4.2. Spatial distribution of cumulative GHG mitigation potentials

The avoided GHG emissions and life-cycle GHG emissions of bioenergy from 2020 to 2050 are depicted in Fig. 7. Clearly, the avoided GHG emissions from the bioenergy sector of scenario 3 and scenario 4

Table 8

Scenarios of GHG mitigation potentials estimation.

	Bioenergy utilizable potential	Bioenergy conversion technology
Scenario 1	Planning potentials	Without CCS
Scenario 2	Planning potentials	With CCS
Scenario 3	Maximum potentials	Without CCS
Scenario 4	Maximum potentials	With CCS

(under “Maximum potentials”) would remain approximately 1500 Mt CO₂e, higher than those of scenario 1 and scenario 2 (under “Planning potentials”). Concerning the life-cycle GHG emissions, compared with the positive emissions of bioenergy without CCS, the negative carbon emissions of BECCS would amount to 923.78–1344.13 Mt CO₂e in the period 2020–2050. Based on this, we calculated the total cumulative GHG mitigation potentials of China's bioenergy sector during that period, which would be in the range of 1652.73–5859.56 Mt CO₂e.

On a provincial level (Fig. 8), the overall distribution of cumulative GHG mitigation potentials during the period 2020–2050 is in line with that of bioenergy potential. The provinces with larger bioenergy potential (e.g., Yunnan, Sichuan and Inner Mongolia) would have higher associated GHG mitigation potentials. However, from the perspective of scenario analysis, the geographic distribution of cumulative GHG emission reduction potentials varies greatly from scenario to scenario. There are no provinces with bioenergy GHG emissions mitigation higher than 150 Mt CO₂e in scenario 1, but there are two, thirteen and twenty provinces in scenario 2, scenario 3 and scenario 4, respectively. Certainly, Shanghai, Tianjin, Beijing, Hainan and Ningxia would have a relatively low degree of cumulative GHG mitigation potentials in all four scenarios (<50 Mt CO₂e). In this case, the bioenergy potential of three provincial-level cities (i.e. Beijing, Tianjin and Shanghai) should be developed according to local conditions. Given the big availability of MSW, it should be a high priority for these cities to use MSW as the resource for BECCS technology. For the provinces with great GHG mitigation potential, the government should increase the investment to advance cleaner utilization of bioenergy and the large-scale deployment of BECCS.

5. Discussions

5.1. Uncertainty analysis

The energy potential of CR and AM are estimated using the mean values of RPR and animal daily excretion coefficients (see section 2), which are the source of the uncertainties of total bioenergy potential. Monte Carlo simulation, as a common method to quantify the error propagation of model parameters [97], tests the uncertainty ranges of bioenergy potential in this study. RPR and daily excretion coefficient are assumed to fit the log-normal distribution curve with a confidence degree of 95% [98]. Monte Carlo model then runs 5000 times to get the statistical distribution results of RPR and excretion parameters (for details see section A of Supplementary material), whose ranges are summarized by box-and-whisker plots (Fig. 9). In terms of RPR, cotton exhibited the highest interquartile range, which denoted the largest variability of cotton among CR. The values of cotton RPR are scattered due to the influence of the different growing environment. Following this, the uncertainty of corn RPR ranked the second, however, it was the main source of the uncertainty of CR since corn had the highest energy potential. For the uncertainty of AM, the excretion coefficient of the cow was the major contributor to uncertainty, owing to its highest interquartile range as well as the dominant role of cow manure in AM. Overall speaking, the uncertainty of AM was higher than CR.

Finally, parameters uncertainties were propagated to estimate the overall uncertainties of China's domestic biomass resources (except EC) through Eq. (1) and Eq. (3). As shown in Fig. 10, the propagated uncertainties varied from (–26.6%, 39.7%) in 2000 to (–27.6%, 39.5%) in 2016. Compared to the evaluations based on the average values, the uncertainty analysis provides policy-makers with more information to optimize the future planning of bioenergy. Given the higher resources uncertainties of cotton, corn and cow, more field tests and on-site investigations for them should be conducted to improve statistics further. Also, more attention should be paid to the provinces rich in these three resources (e.g. Heilongjiang, Henan and Sinkiang) to formulate subnational bioenergy policy. The efforts to reduce uncertainties will help to prioritize the development of the bioenergy industry more reasonably.

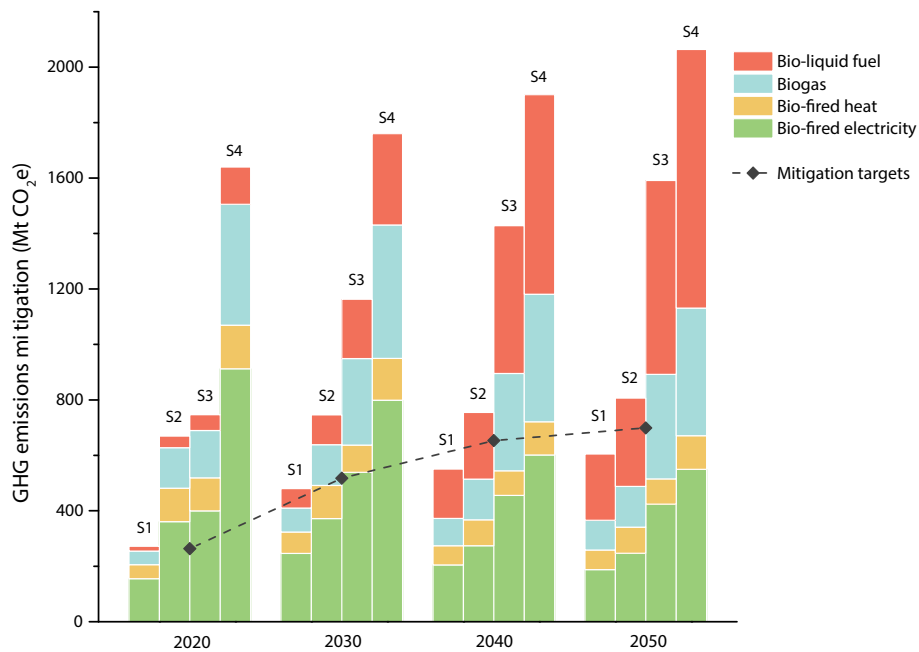


Fig. 6. GHG mitigation potentials of the bioenergy sector in China. (S1, S2, S3 and S4 represent scenario 1, scenario 2, scenario 3 and scenario 4, respectively).

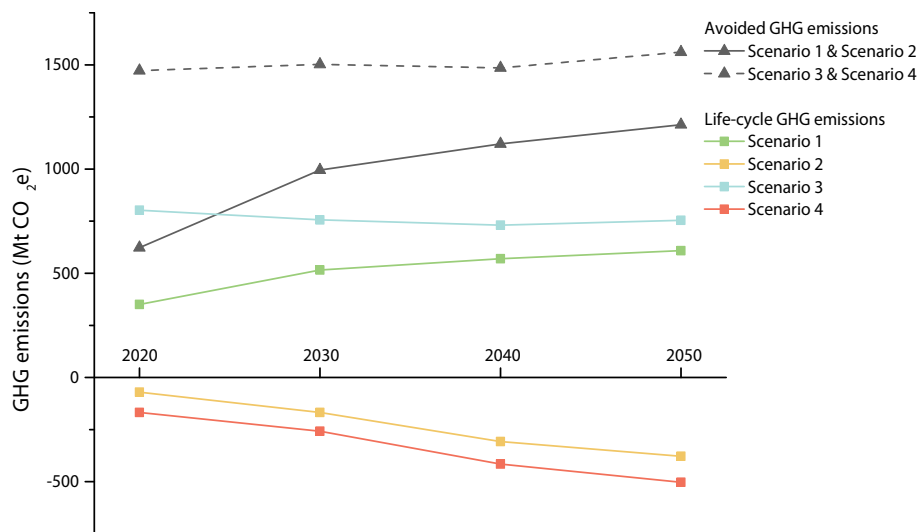


Fig. 7. Avoided GHG emissions and life-cycle GHG emissions of bioenergy in China.

5.2. Comparison with existing biomass resources assessment

Fig. 10 also compares our resource evaluation with existing studies that calculated the collectable potential of biomass resources for China. The collectable potentials of biomass resources estimated in other existing studies are quite different from that in this study throughout the accounting period. This difference is attributed to the diverse types of biomass resources and to the inconsistent values of their produced coefficients. To systematically evaluate the bioenergy potential in China, this study considered all kinds of possible biomass resources and their produced coefficients, which are average values from existing literature (Section 2.1). Liu et al. [44] did not assess the collectable potential of SS and used smaller RPR of CR and daily excretion coefficient of AM, which led to a significant difference compared to this study. Yang et al. [20] used less classifications for FR and adopted larger coefficients, resulting in the FR potential alone being 29% higher than that of this evaluation in 2007. The estimate in 2008 by Zhou et al. [21] was lower than that of

this study, mainly due to the fact that AM and SS were not included in their assessment. Because of the smallest difference of produced coefficients, the biomass resources potential estimated by Zhang [40] is only 2% lower than that of this study, and this small gap is mainly due to the fact that Zhang [40] did not include in the study human faeces. However, these four estimates are within the uncertainty range examined by the Monte Carlo model of the current study, which indicates that all the assessments are acceptable for strategy policies.

5.3. Limitations and future work

Some limitations existed in the current study. Future work will concentrate on these limitations to provide a more precise evaluation of China's bioenergy potential and GHG mitigation potentials. First, the data sources of the statistical method is responsible for part of the uncertainty of in results. In section 5.1, the uncertainty analysis of the resource potential that arises from produced coefficients acknowledged

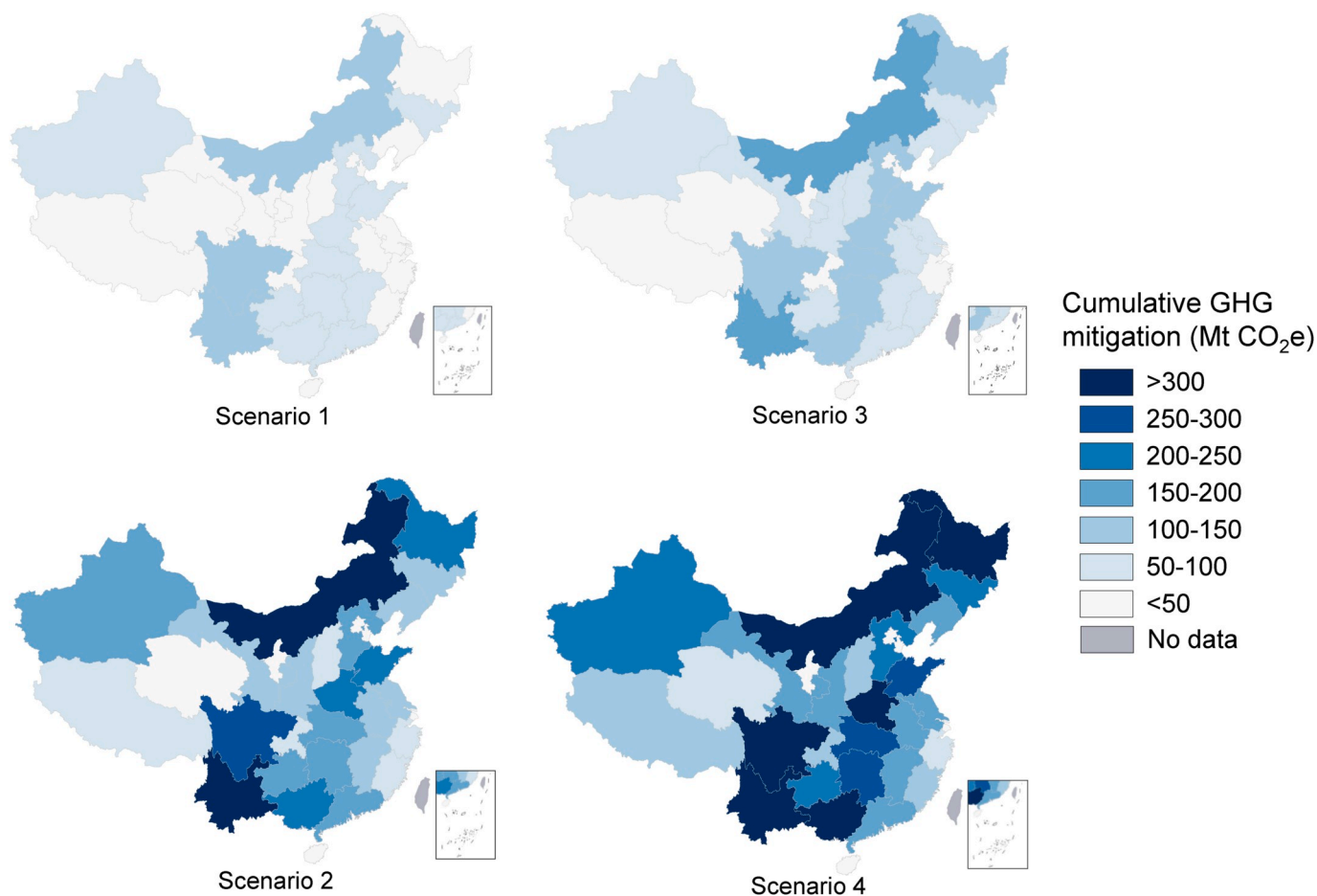


Fig. 8. China's provincial cumulative GHG mitigation potentials of bioenergy from 2020 to 2050 in the four scenarios.

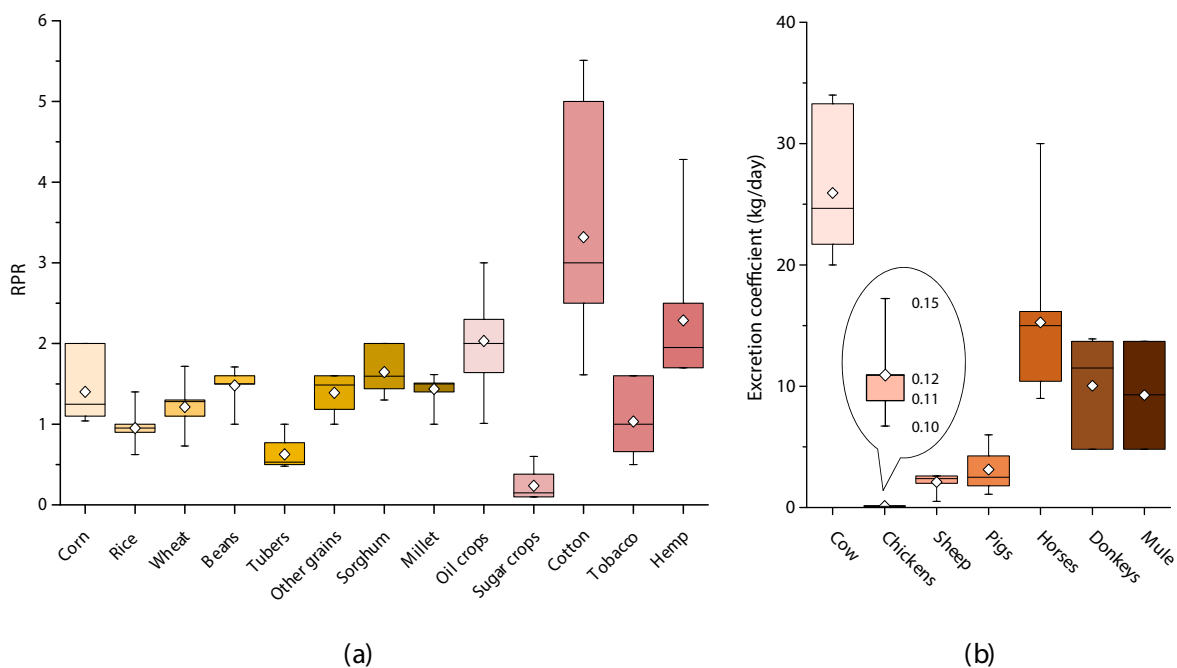


Fig. 9. Ranges of residue to product ratio (RPR) and animal excretion coefficient for each sub-type of crop residues (a) and animal manure (b). (Diamonds and centre lines represent mean values and 50th percentile, respectively. Boxes represent 25th to 75th percentiles, and bars represent 5th to 95th percentiles of 5000 Monte Carlo simulations).

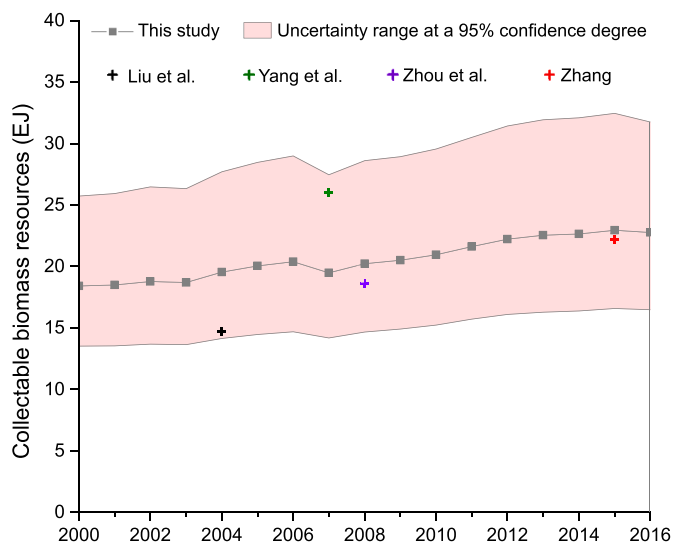


Fig. 10. Uncertainties of the collectable potential of China's domestic biomass resources in this study and comparisons with existing studies. Data sources are Liu et al. [44], Yang et al. [20], Zhou et al. [21], and Zhang [40].

this limitation and attempted to shed light on our assessment more accurately. Certainly, there are other uncertainties that are small and difficult to quantify, especially the EC potential. Due to data accessibility of the actual yield of EC on marginal land, we only assessed the potential of biomass resources including EC in 2016. In the future, to provide more reliable data to policy makers it is advisable to encourage experiments in the cultivation of various EC on marginal land. Meanwhile, future study will try to combine GIS system and land suitability assessment to calculate the time-series potential of EC. Second, we used the national unified planning of bioenergy exploitation to predict associated GHG emissions mitigation, without considering the scales of bioenergy utilization in different provinces. In the future, the distribution characteristics of biomass resources should be taken into account to select more targeted bioenergy conversion pathways. Further studies will specify related policies on a provincial level to achieve more precise assessment on GHG mitigation potentials. Third, the scope of this study was limited in terms of the ecological impacts of large-scale exploitation of bioenergy. This is an important issue for sustainable development of renewable energy sources. It is recommended that further works explore the potential impacts of large-scale bioenergy exploitation, and the relevant research experience developed for hydropower can offer significant background in this regard [5–7].

6. Conclusions

This study comprehensively evaluates the spatial-temporal variation of bioenergy potential in China from 2000 to 2016 and tests their propagated uncertainties using Monte Carlo analysis. The associated GHG mitigation potentials are also assessed, with special attention on BECCS, through a scenario analysis.

It is estimated that the collectable potential of the domestic biomass resources (including CR, FR, AM, MSW and SS) increased from 18.40 EJ in 2000 to 22.67 EJ in 2016, with overall uncertainties varying from (–26.6%, 39.7%) to (–27.6%, 39.5%). MSW was the fastest-growing resource at an annual growth rate of 6.4%. The potential of EC on marginal land reached 10.09 EJ in 2016. If EC is taken into account, the total potential of China's biomass resources reached 32.69 EJ in 2016, corresponding to 27.6% of domestic energy consumption. On a provincial level, except Tibet, Beijing, Shanghai and Zhejiang, the collectable potential of biomass resources in remaining regions was increasing during the accounting period. Southwest region and Inner Mongolia together contributed to 34% of the total biomass resources potential in

2016, and eastern coastal areas have the highest density of biomass resources.

Bioenergy production, based on twelve feedstock-to-final conversion pathways from 2020 to 2050 is discussed for GHG mitigation potentials estimation. Biomass liquid fuels have the greatest application prospect with the fastest growth rate (7.1%), which will dominate biomass utilization and GHG emissions mitigation in the medium- and long-term. During the period 2020–2050, cumulative GHG emissions mitigation of China's bioenergy would be in the range of 1652.73–5859.56 Mt CO₂e, in which the negative emissions of BECCS would amount to 923.78–1344.13 Mt CO₂e. In 2050, China's GHG mitigation potentials of bioenergy would reach 604.76–2063.66 Mt CO₂e, which could contribute to achieving 6.1–20.8% of the global carbon mitigation goal (medium 9900 Mt CO₂e). Spatially, Yunnan, Sichuan and Inner Mongolia would have higher associated GHG mitigation potentials. Definitely, the huge GHG mitigation potentials of the bioenergy sector will significantly contribute to meeting China's emission reduction commitment and alleviating global climate change.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Yating Kang: Investigation, Methodology, Writing - original draft, Writing - review & editing. **Qing Yang:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing. **Pietro Bartocci:** Supervision, Writing - review & editing. **Hongjian Wei:** Investigation, Methodology. **Sylvia Shuhan Liu:** Writing - review & editing. **Zhujuan Wu:** Methodology. **Hewen Zhou:** Writing - review & editing. **Haiping Yang:** Supervision. **Francesco Fantozzi:** Supervision. **Hanping Chen:** Supervision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2020.109842>.

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