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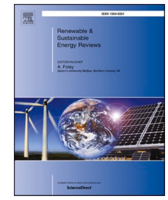

Biomass energy in China's terrestrial ecosystems: Insights into the nation's sustainable energy supply

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ABSTRACT

The energy stored in biomass, a key component of global sustainable energy, is essential for achieving the United Nations Sustainable Development Goals, especially for climate change mitigation and energy security. However, it remains unknown how much energy is stored in the vegetation biomass of China's terrestrial ecosystems. Furthermore, the shortage of biomass has limited the development of China's bioeconomy and bioenergy industry, requiring us to seek more multi-source and sustainable biomass supplies. In view of this, through comprehensive investigations and systematic data integration (including biomass data, calorific value data, land cover data, climate data, etc.), we explored the gross biomass energy (BE) reserves and their spatiotemporal pattern based on a total of 14 vegetation types that account for 76.24% of China's land area. The theoretical potential of gross BE in China was estimated as 535.91 EJ in 2010, which was equivalent to 18.29 Gt standard coal. BE showed a trend of continuous increase from 1980 to 2060 and is expected to peak in 2030. Importantly, BE (per land area or per capita) was significantly negatively correlated with provincial development levels in China. Our findings indicate that China has abundant BE reserves, which have potential as feedstocks for the production of different forms of energy in the context of sustainable development. Furthermore, more advanced low-cost technologies, such as coal and biomass co-gasification, are expected to promote the transformation and upgradation of energy systems in China in the future.

1. Introduction

China is the world's largest energy consumer; yet, bioenergy accounts for only 0.1% of the country's primary energy consumption, with the coal-led energy sector generating large quantities of greenhouse gas (GHG) emissions and contributing to serious environmental pollution [1,2]. Meanwhile, the Paris climate agreement aims to restrict global warming to below 2 °C and to "pursue efforts" to limit it to below 1.5 °C, relying heavily on renewable energy [3]. Proposed solutions to reduce environmental pollution and to achieve the climate goals include substitution with bioenergy. Bioenergy, as a green and renewable energy source, is important to realize emission reduction goals, especially for China to actively increase the proportion of bioenergy in the energy system [4,5].

However, as an important part of the global renewable energy strategy, the lack of bioenergy feedstock supply limits the development of the bio-economy and bioenergy industry [6]. In particular, limited land supply restricts the development of energy crops, whereas the competition for land between energy crops and food production further contributes to biodiversity loss [7,8]. Cropland residues are an important source of bioenergy, representing a potential solution to achieve climate targets without adversely affecting food security or the environment [9,10]. Similarly, BE from forests and grasslands offers the opportunities to reconcile biodiversity goals [11–14]. Meanwhile, some controlled experiments have demonstrated that grassland biomass plays

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Lists for abbreviations

BE	biomass energy (EJ)
BED	biomass energy density (TJ ha^{-1})
GHG	greenhouse gas
EJ	exajoule (10^{18} J)
TJ	terajoule (10^{12} J)
GJ	gigajoule (10^{9} J)
SCE	standard coal equivalent
HDI	human development index
EBF	evergreen broad-leaved forests
ENF	evergreen needle-leaf forests
DBF	deciduous broad-leaved forests
DNF	deciduous needle-leaf forests
NBF	needle-leaf and broadleaf mixed forests
SF	shrub forests
IFBB	integrated generation of solid fuel and biogas from biomass
CBECCS	coal-bioenergy gasification systems with carbon capture and storage
LIHD	Low-Input High-diversity
HIHD	High-Input High-diversity

important roles in the development of bioenergy [12,15]. Van Meerbeek et al. conducted a systematic and comprehensive calculation of the EU bioenergy feedstock, including the High-Input High-diversity (HIHD) system and the Low-Input High-diversity (LIHD) system among others [9,16–19]. Dale et al. also presented a positive outlook on the availability of biomass from forests [14] and even suggested that ecosystems should be considered for the provision of BE when designing landscapes [20]. As the concept of a bio-based economy spreads globally, biomass for bioenergy might be one of the "future ecosystem services" for protected natural ecosystems [21].

Meanwhile, some studies on BE have mainly focused on agricultural residues or forest residues [22–30] or the potential of marginal land production in China [31–34]. Unfortunately, none of these studies revealed how much BE, which is the basis of the bioenergy economy and industrial development, is stored in China's terrestrial ecosystems [26, 27]. Information on total BE reserves in China remains unclear, resulting in lags far behind the requirement for the bio-economy and bioenergy industry [35]. As China is the largest energy consumer globally, it is important to comprehensively assess the gross BE potential of China's terrestrial ecosystems to facilitate the diversified and sustainable supply of bioenergy feedstocks and to further promote the transformation and upgradation of energy systems [9,16,36].

The purpose of this research was to explore the theoretical potential of gross BE in China's terrestrial ecosystems (Fig. S1), revealing its spatial distribution characteristics and growth potential from 1980 to 2060 in the context of global change. Specifically, based on the biomass data and calorific value data of the national-scale field survey, and integrating a large amount of literature data, we used the geographic information system tools and models for the first time to systematically and thoroughly evaluate the gross BE of China's terrestrial ecosystem (forest, grassland, and cropland ecosystem). The results of this study are expected to provide a scientific basis for policy makers and would further promote China's energy transition toward a low-carbon economy and green development.

2. Methods

2.1. Data collection

To estimate BE in the vegetation biomass of China, we collected data comprehensively and systematically from multiple sources to construct biomass databases of forests and grasslands in the 2010s and 1980s as shown in Fig. S2.

1) Forest and grassland biomass data

First, we calculated biomass data, using a coefficient of 0.45 from the carbon storage data of vegetation in Chinese terrestrial ecosystems, which were recently published as part of a very intensive field survey in 2011 and 2012 [37]. Then, based on the partition coefficient of biomass between different plant organs in long-term monitoring data of CERN, we obtained biomass data at the organ level for the 2010s [38].

Furthermore, we derived the forest biomass for China from the data of Luo (1996) (http://www.geodata.cn/) [39,40]. Using this information, we built a database of forest biomass for the 1980s, containing basic information regarding latitude, longitude, and others [41]. Similarly, we collected data on the grassland resources of China surveyed during the 1980s [42]. We also collected other field data from the published literature in the Institute for Scientific Information (ISI) (http://apps.webofknowledge.com) and China National Knowledge Internet (http://www.cnki.net) to construct a grassland biomass dataset [43,44].

After integrating these data, there were a total of 54,392 plot scale records of biomass data. These records contained 29,761 and 11,232 plot scale records data for forests and grasslands in the 2010s, respectively, along with 6801 and 7138 plot data for forests and grasslands in the 1980s, respectively (Fig. S3; Fig. S4). Furthermore, we extracted global forest and grassland biomass data from Pan (2011) and Erb (2017) [45,46].

2) Data on calorific value among different plant organs

In a previous study, we constructed a calorific value parameter dataset at the organ level for plants in China, covering different forests and grassland types [47]. These data were obtained using our measured data and also integrated from these published papers in China National Knowledge Internet (http://www.cnki.net) and the ISI (http://apps.webofknowledge.com).

3) Data on climate and eco-regions

Mean annual temperature (MAT, °C) and mean annual precipitation (MAP, mm) were the two key parameters of the models used here [48]. To estimate future changes in MAT and MAP, it is necessary to provide emission scenarios for future GHG. In this study, we used three GHG emission scenarios: RCP 8.5, RCP 4.5, and RCP 2.6 [49], and downloaded relevant regional climate data from the National Climate Center (http://ncc.cma.gov.cn/cn/).

We explored the BE of terrestrial vegetation and its spatial distribution at the levels of province, eco-region, and nation. In practice, we partitioned China into eight eco-regions [47,50], which were designated as the cold humid region (I), temperate humid and semi-humid region (II), temperate arid and semi-arid region (III), warm temperate humid and sub humid region (IV), subtropical humid region (V), tropical humid region (VI), warm temperate arid region (VII), and Qinghai-Tibet Plateau cold temperate arid region (VIII) [47].

4) Data on vegetation area and social economy

Data on the vegetation area of China were extracted from the Chinese land cover classification systems from http://www.geodata.cn/ [51]. We extracted the area data of various vegetation types in 1980s and 2010s at the national, eco-regional, and provincial levels. We obtained information on a total area of 73,193,000 ha, accounting for 76.24% of the national land area (Fig. S1). Vegetation was divided into forests, grasslands, and cropland. Furthermore, forests were subdivided into evergreen broadleaf forest (EBF), deciduous broadleaf forest (DBF), evergreen needle-leaf forest (ENF), deciduous needle-leaf forest (DNF), needle-leaf and broadleaf mixed forest (NBF), and shrub forest (SF). Grasslands were sub-divided into meadow, steppe, tussock, herbal wetlands, and sparse grassland. Cropland was sub-divided into dry land and paddy fields. A total of 17 vegetation types, accounting for 76.24% of China's land area, accompanying was accompanied by BE reserves here. Excluding water systems and Taiwan, the terrestrial ecosystems of China cover an area of 9.26×10^8 ha.

Data on energy consumption, grain production, area, and population of each province were obtained from the China Statistical Yearbook and China Energy Statistical Yearbook (http://data.cnki.net/). In the early 1980s, the rural population of China accounted for more than 80% of the total population, and their energy supply was mainly cropland residuals and forest residuals, which are a traditional sources of non-commercial BE. Therefore, to calculate energy consumption in China during the 1980s, we used more comprehensive statistics, including non-commercial BE consumption in rural China [52].

5) Theoretical potential of forest residue

In China, the lawful logging of forests is strictly managed by the government based on a forest cutting quota. Therefore, we obtained these basic data on deforestation from the forest harvest quota files published by the State Council of China (http://www.gov.cn/index.htm). First, to convert the data of wood biomass volume into primary energy, we used a common value of 7.2 GJ m^{-3} [53–55], which was based on an average density of 0.45 m^{-3} t^{-1} and caloric value 16 GJ t^{-1} [52–56]. Second, forest residues usually include harvest losses, branches and stumps, which are important BE resources during forest harvesting and wood processing. To obtain the total amount of forest residue resources, we required the establishment of establish a coefficient of wood logging residue. According to previous studies at home and abroad, the general value range is from 30% to 60% [56–60], and the average was used as the coefficient of forest residue at 45%; here, we did not consider the differences among different forest types. Finally, the recovery factor, which is defined as the proportion of residue being actually harvested, was set as 0.5, despite ranging from 0.25 to 0.75 [61,62]. Due to technical limitations and environmental constraints, these values are often limited to some extent [63–66].

2.2. Data calculation

1) Biomass energy in the forest and grassland vegetation of China

The following calculations were used

$$BED = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(B_{ij} \times C_{ij} \times 10^{-3}\right) \quad (1)$$

$$BE = \sum_{r=1}^{k}\left(BED \times A_r\right) \quad (2)$$

$$BE_v = \frac{BED}{\Delta t} \quad (3)$$

where i represents different life forms, j represents different organs, r represents different vegetation types, B_{ij} is the biomass at the organ level (t ha^{-1}), C_{ij} is the calorific value at the organ level (KJ g^{-1}), and A_r is the area of the forest type (ha). *BED* is biomass energy density (TJ ha^{-1}), *BE* is biomass energy (EJ), and BE_v is the annual rate of change of biomass energy (GJ ha^{-1} yr^{-1}).

2) Biomass energy in the cropland residue of China

To obtain the basic data on cropland residue in China, we extracted data on 16 crop types in China from the published literature [67], including rice, wheat, corn, other grains, beans, potatoes, cotton, peanuts, rapeseed, sesame, other oil crops, jute and ambary hemp, other fiber crops, sugar cane, sugar beet, and tobacco. Then, we collected data on the calorific value of different straw types. Considering that food production has increased gradually in China, we adjusted the straw data in relation to the increasing rate of grain production over the last decade; see Equ.4 and 5, respectively.

$$BE_{crop} = \sum\left(P_{straw} \times C_r \times k_r \times 10^{-18}\right) \quad (4)$$

$$k_r = \frac{\Delta p_{straw}}{\Delta t} \quad (5)$$

where BE_{crop} represents biomass energy in straw (EJ), P_{straw} is the straw yield of $crop_r$ (Kg yr^{-1}), r represents the type of crop, C_r is the calorific value of crop r straw (KJ g^{-1}), and K_r is the increasing rate of $crop_r$ production over the last decade. Furthermore, the conversion unit of energy is 1 EJ = 10^{18} J, 1 TJ ha^{-1} = 10^{12} J ha^{-1}, and 1 GJ ha^{-1} yr^{-1} = 10^9 J ha^{-1} yr^{-1}; the standard coal calorific value is 29.31 MJ kg^{-1}.

3) Simulation for future change

To estimate the potential for changes in BE from 2010 to 2060, we used the FCS model, which was established by He using a large quantity of measured data in China (2017) [48]. Based on the 2010s forest biomass data (including forest age) combined with climate data for RCP 8.5, RCP 4.5, and RCP 2.6 scenarios, we calculated how the biomass of forests would change from 2010 to 2060 in China. Then, we used the Equ.1 and 2 to calculate the BE. To display the distribution of BE and its future potential in China's terrestrial vegetation visually, we adopted the classic Kriging interpolation method.

4) Global forest and grassland data

To calculate the BE of forests and grasslands globally, we obtained the carbon storage data of global forests from Pan et al. [45]. Then, biomass data were transferred using the carbon content constant (0.5, Eq. (6)). Furthermore, we obtained the biomass data of different organs according to the distribution ratio of biomass among different organs [38]. Similarly, grassland biomass data at the global level were derived from grassland carbon storage data published by Erb et al. [46].

Global forest biomass energy was calculated as:

$$BE = \sum\left(\frac{C_s}{0.5} \times k_i \times C_i \times 10^{-18}\right) \quad (6)$$

where k_i represents the partition coefficient of biomass among different organs, C_i is the calorific value at the organ level (KJ g^{-1}), and C_s represents carbon storage (Pg).

5) Statistical analysis

Spatial analysis (including Kriging interpolation, mask analysis, extraction analysis, raster calculation) and spatial maps were completed using ArcGIS (version 10.2, Redlands, California, ESRI Press). Other figure and data analyses were conducted using SigmaPlot 14 (Systat Software, San Jose, CA). We used the nonparametric statistical method "Spearman analysis" for correlation analyses. The significant difference was set at the 0.05 level.

3. Results and discussion

3.1. Biomass energy in the terrestrial vegetation of China in the 2010s

Assessments of climate change mitigation scenarios suggest that, in scenarios meeting the 1.5 °C target, bioenergy should exceed 20% of the final energy consumption by 2050, or 115–180 EJ_{Prim} yr^{-1} [36]. However, the shortage of bioenergy feedstocks has seriously hindered the achievement of this goal. Fortunately, terrestrial ecosystem vegetation is a vast pool of BE that could be used to meet the energy requirements of humans and to replace fossil fuels to reduce GHG emissions and environmental pollution to a large extent [68]. Vegetation BE in China was estimated as 535.91 EJ in the 2010s, which is the equivalent to 18.29 Gt standard coal (Fig. 1; Table 1). Per capita BE reserves were 396.37 GJ (Table S1). The estimated BE of forest, grassland, and cropland straw was 434.83, 87.48, and 13.60 EJ, respectively. For forest vegetation, ENF had the largest BE (173.59 ± 3.07 EJ), whereas DNF had the smallest (21.40 ± 0.71 EJ). For grassland vegetation, BE was largest in steppe (32.30 ± 0.66 EJ) and lowest in tussock (4.45 ± 0.14 EJ) (Table 1). For cropland, the straw of corn, rice, and wheat stored 4.35, 3.50, and 2.74 EJ, respectively (Table S2). Furthermore, BE varied apparently with respect to vegetation type, life form, and organ (Supplementary Text 1).

In 2018, China was the world's largest energy consumer at 131.55 EJ, with bioenergy only accounting for 0.1% of energy sources (Fig. 1; Fig. S5) [69,70]. The BE stored in forests and grasslands globally was estimated at 23029.44 EJ (Fig. 1). Thus, BE clearly has considerable potential, but there is a major gap between the rich BE and its extremely low utilization ratios, which needs to be resolved in the future to reduce our dependency on fossil fuels (Fig. 1; Fig. S5; Fig. S6). Furthermore, the forest is the largest storage source of BE, and its BE is much higher than that of other ecosystems (Table 1; Fig. 1). China is also the world's largest afforestation country [71], and thus, we should pay more attention on how to obtain biomass for bioenergy from forests on the premise of ensuring sustainability and without depressing forest carbon sequestration [72]. For example, increased investment in forest management, regular thinning to obtain biomass bioenergy, and a focus on the quality of afforestation rather than simple quantity should be the focus.

China's reform and opening, economic growth, accompanied by strong energy consumption, result in rapid expansion of the commercial energy supply. Bioenergy once played an important role in China's energy consumption, with a utilization rate of approximately 35% in the

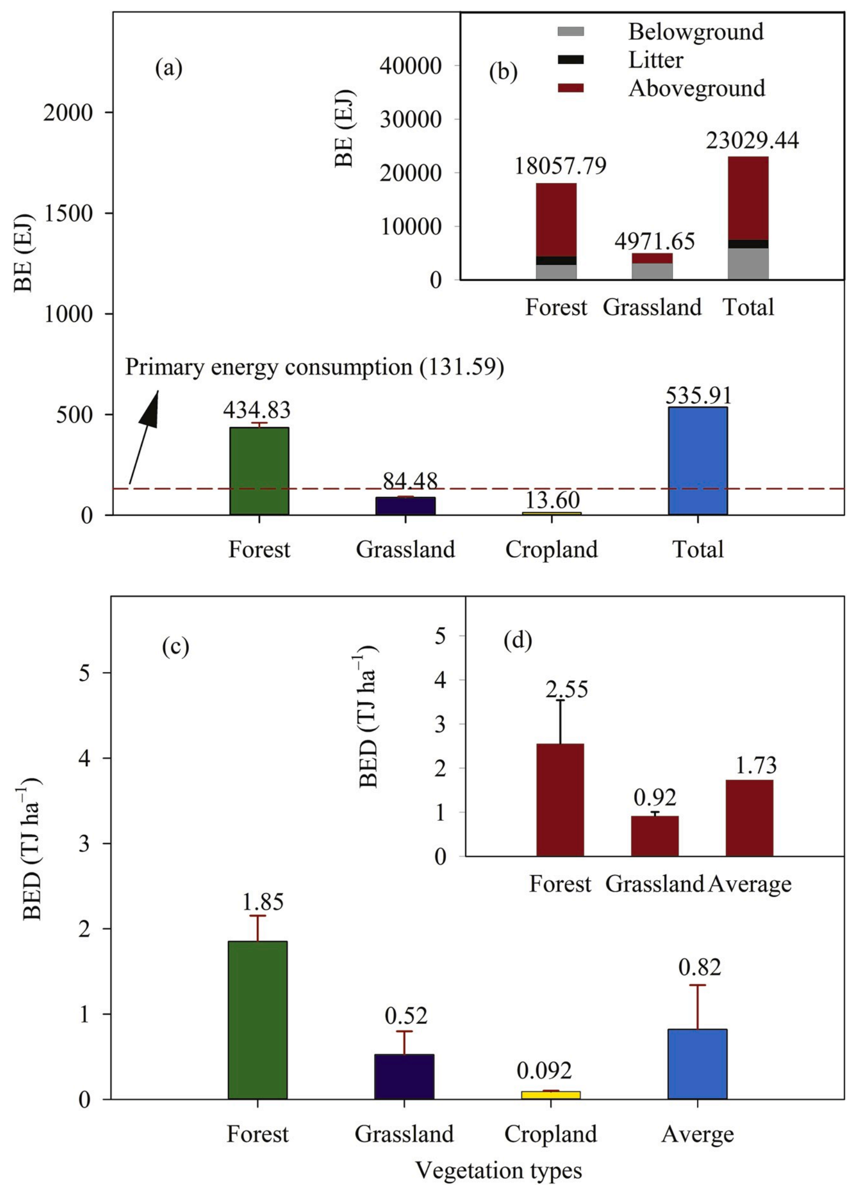

Fig. 1. Biomass energy (BE, EJ) and biomass energy density (BED, TJ ha^{-1}) of different vegetation types in China and globally. Panels (a) and (c) show the data for China, and (b) and (d) show the data globally for BE and BED, respectively. Primary energy consumption is represented by the total energy consumption in China in 2018.

Table 1
Estimation of biomass energy in the different terrestrial ecosystems of China.

	Vegetation types	Area (10^6 ha)	Biomass Energy (BE, EJ[c])	Density of biomass energy (BED, TJ ha^{-1})	Standard coal equivalent (SCE, Gt)	Percent (%)
Forest	EBF[a]	36.92	89.85 ± 3.20 [b]	2.43 ± 0.09	3.07	16.76
	ENF	77.46	173.59 ± 3.07	2.24 ± 0.04	5.92	32.38
	DBF	57.86	94.85 ± 2.82	1.64 ± 0.05	3.24	17.69
	DNF	10.90	21.40 ± 0.71	1.96 ± 0.07	0.73	3.99
	NBF	9.15	21.71 ± 0.74	2.37 ± 0.08	0.74	4.05
	SF	69.30	33.44 ± 1.64	0.45 ± 0.02	1.14	6.24
	Subtotal	261.60	434.83 ± 24.32	1.85 ± 0.30	14.84	81.13
Grassland	Meadow	41.26	16.16 ± 0.43	0.39 ± 0.01	0.55	3.02
	Steppe	125.61	32.30 ± 0.66	0.26 ± 0.01	1.10	6.02
	Tussock	17.54	4.45 ± 0.14	0.25 ± 0.01	0.15	0.83
	Herbal Wetlands	14.49	23.28	1.61	0.79	4.34
	Sparse grassland	99.30	11.29 ± 0.45	0.11 ± 0.01	0.39	2.11
	Subtotal	298.21	87.48 ± 4.81	0.52 ± 0.27	2.98	16.33
Cropland		172.12	13.60	0.09	0.46	2.54
Total		731.93	535.91	0.82	18.29	100

[a] EBF, Evergreen broadleaf forest; ENF, Evergreen needle-leaf forest; DBF, Deciduous broadleaf forest; DNF, Deciduous needle-leaf forest; NBF, Needle-leaf and broadleaf mixed forest; SF, Shrub forest.
[b] Uncertainty estimation were represented as standard error.
[c] 1 EJ = 10^{18} J, 1 TJ ha^{-1} = 10^{12} J ha^{-1}, 1 Gt = 10^9 t.

1980s, especially in rural areas (Fig. S6). However, energy supply in rural areas has increasingly transitioned from traditional BE to fossil fuel in the last decades. From 1980 to 2010, global primary energy consumption increased from 300 to 510 EJ $year^{-1}$, with more than 85% of energy from fossil fuels [73]. Moreover, the contribution of bioenergy was relatively stable, at approximately 10% [70], especially in developed regions where the industrial utilization of modern bioenergy has been realized. If China could upgrade its current energy system and move towards the modern industrial utilization of bioenergy to utilize multiple sources biomass for bioenergy maximally, these actions could

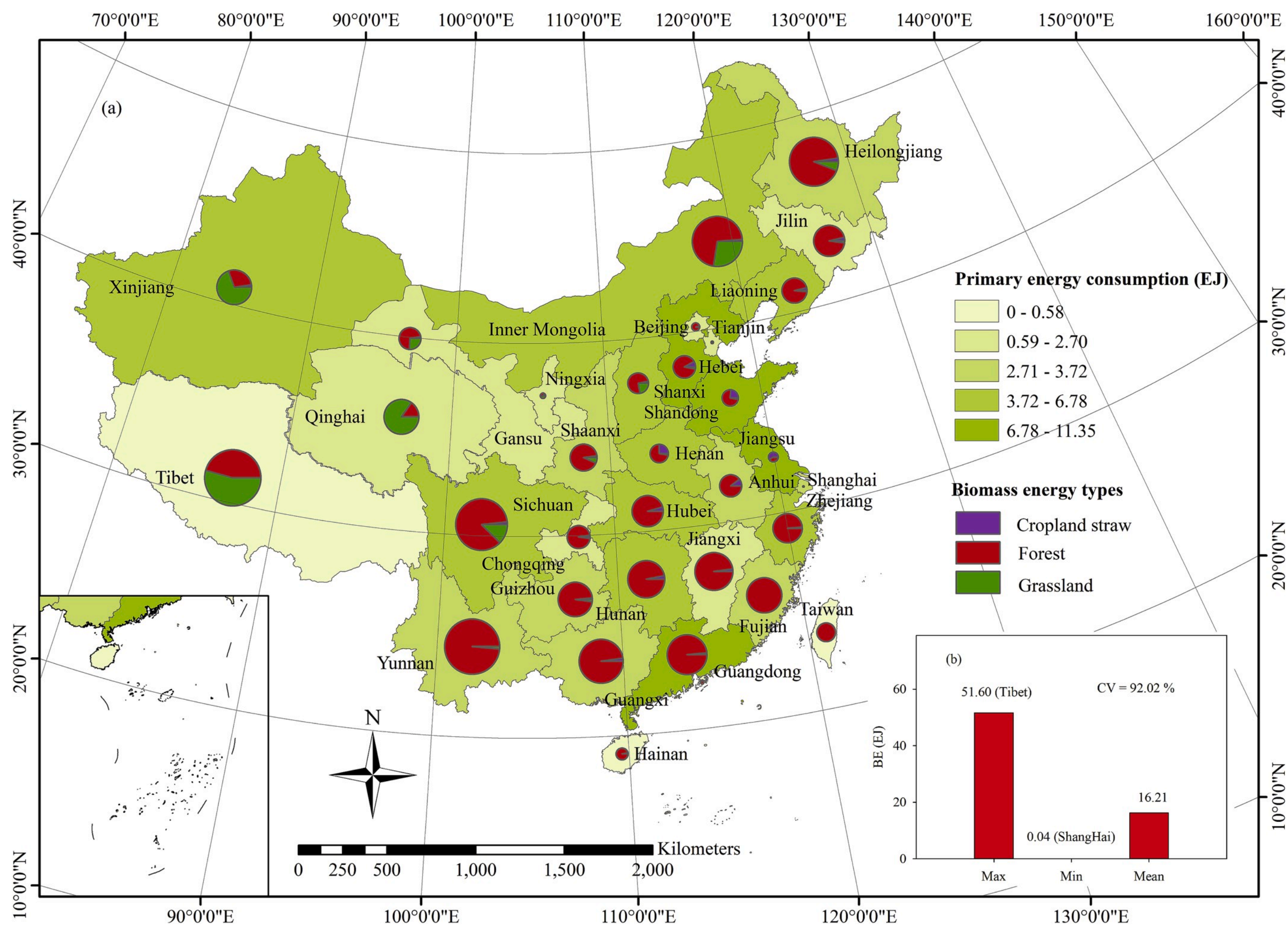

Fig. 2. Spatial distribution of biomass energy (BE, EJ) among different vegetation types in China (Forest, Grassland, and Cropland straw, respectively). Panel (a) shows the distribution of biomass energy in different provinces; panel (b) shows variation at the provincial level.

promote environmental protection and climate change mitigation.

3.2. Spatial distribution of biomass energy in China

Overall, BE was relatively higher in the northeast and southwest parts of China (Fig. 2). There was a significant difference in BE across provinces, with a coefficient of variation of 92.02% (Fig. 2; Text S2). The overall distribution of BE in terrestrial vegetation was strongly influenced by the spatial distribution of vegetation types, and the BED significantly differed among forests, grassland, and cropland straw (Table 1; Fig. 2; Fig. S7; Fig. S8). In some agriculture-dominated provinces (such as Henan, Shandong, and Hebei), cropland straw had a relatively high proportion of BE (Fig. 2; Fig. S9).

Previous studies have shown that the integrated generation of solid fuel and biogas from the biomass (IFBB) technology system for semi-natural grassland could save 4.6 t CO_2-eq per hectare [74]. Bioenergy production from biomass has received considerable attention as a management strategy for semi-natural areas [16]. Of course, selecting appropriate locations is extremely important for the development and utilization of biomass for bioenergy [75]. China's grassland area covers approximately 2.95 million km^2 and is highly concentrated in several provinces (Fig. S8). The use of biomass as bioenergy feedstock clearly offers rare opportunities to integrate bioenergy production into ecosystem multi-functionality or services. For example, the establishment of an IFBB technology system near the grasslands of Inner Mongolia could boost the green economic growth of this region and reduce GHG emissions by up to 27.05 Mt CO_2-eq (using only 10% grasslands in this region).

3.3. Significant negative correlation between biomass energy and provincial development levels

BE at the province level was significantly negatively correlated with provincial development levels in China ($P < 0.05$, $r = -0.59$; Fig. 3). According to the United Nations (UN) classification of the human development index (HDI), the average BE in extremely high development provinces (HDI > 0.80) was estimated as 1.41 ± 1.09 EJ. In comparison, the average BE in provinces with high development (0.80 > HDI > 0.70) was 16.52 ± 2.65 EJ, whereas that in medium development provinces (HDI < 0.70) was 29.56 ± 8.82 EJ (Fig. 3). Furthermore, per capita BE was significantly negatively correlated with provincial development levels (Fig. S10; Text S2).

Provinces with lower development levels tend to be more motivated to develop, with the increasing rate of energy demand being relatively stronger, resulting in higher CO_2 emissions [76]. Coincidentally, these provinces have higher BE in China. Of note, the sustainable intensification of highly diverse biomass for bioenergy could help achieve optimal bioenergy benefits [12]. In comparison, provinces with lower supplies of bioenergy feedstock face enormous challenges [77]. Therefore, it is important to utilize BE supplies from vegetation and establish a sustainable bioeconomy system in China (and even raise subsidies) to break this extremely unbalanced situation and depress GHG emissions from fossil fuels in the development processes of these lower-developing provinces.

At present, the theoretical feedstocks supply potential of agricultural and forestry residues (13.60 EJ yr^{-1} and 0.41 EJ yr^{-1}) is far from meeting the requirement of planned bioenergy in China (plan to meet 10% of the country's total energy consumption), and could seriously impact the drive of government agencies to develop bioenergy [1] (Table 1; Table S3). Consequently, it is necessary to incorporate the output targets of bioenergy feedstock into the management and maintenance of multifunctional ecosystems based on ecological principles, which could protect the eco-environment and enhance the economic income of local residents.

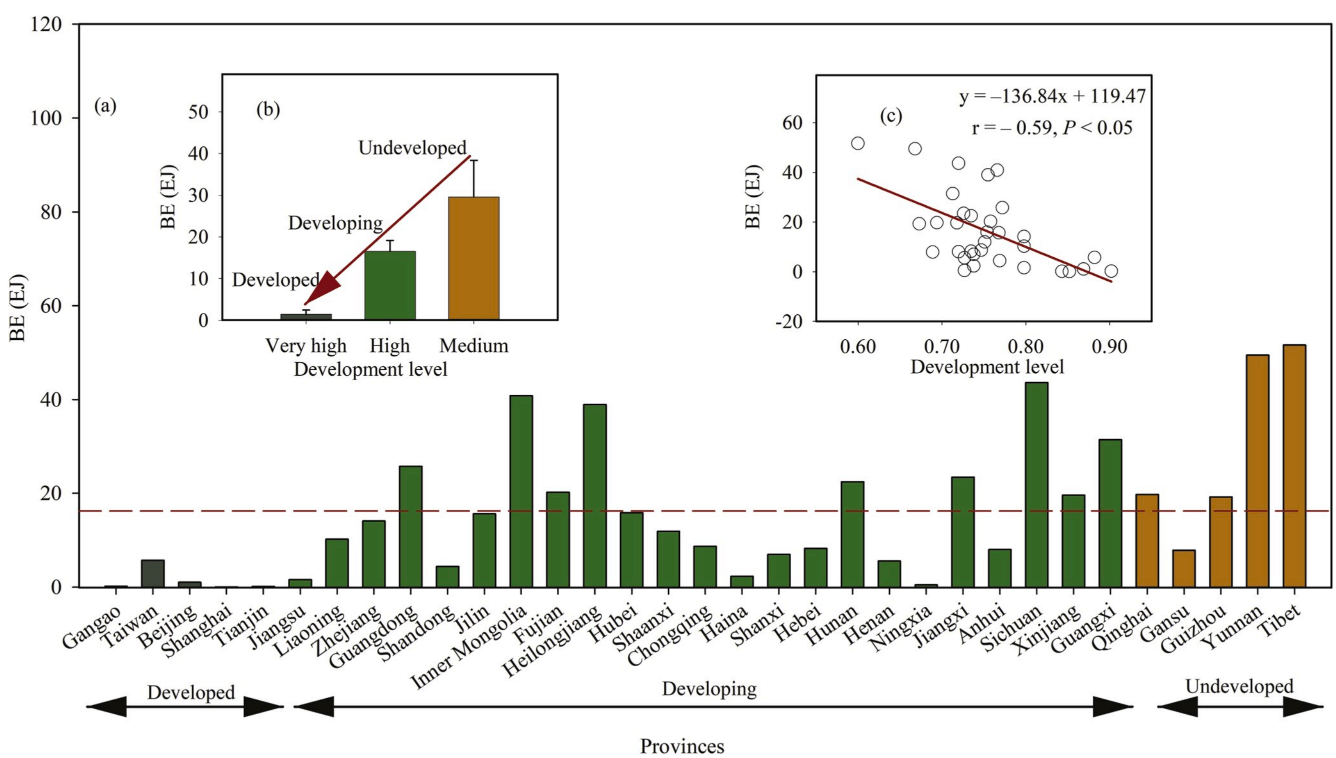

Fig. 3. Relationship between biomass energy (BE, EJ) and development level. The Human Development Index (HDI) indicates the level of development; HDI is a standard index used by the United Nations Development Programme since 1990 to depict the socio-economic development of specific countries and regions. This index is calculated using the average life expectancy at birth, the number of years of schooling, and the per capita gross income. The red line in Panel (a) indicates the average BE at the provincial level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Increasing biomass energy from 1980 to 2060 in China's terrestrial vegetation

Since the late 1970s, China has launched six national key restoration projects to restore degraded ecosystems. Such projects include "Three-North Shelter Forest Program," and "Returning Grazing Land to Grassland Project," among others [71]. As a result of implementing these projects, China's natural ecological environment has greatly improved, resulting in a significant increase in vegetation coverage [78]. Accordingly, we found that the BE of China's terrestrial vegetation increased by 114.61 EJ over the last three decades, mainly from forests (Fig. 4; Fig. 5). Because of the low average age of forests in China (33.97 years; Table S4), these forests show a huge potential to increase by 542.90 EJ between 2010 and 2060 (Fig. 4). Overall, BE has been steadily increasing since 1980 in China, with this trend predicted to continue until 2060, and might reach its peak in 2030 (Fig. 4; Fig. 5; Text S3).

Undoubtedly, conservation and restoration are crucial to maintaining a wide range of ecological functions and services in these ecologically vulnerable areas, but it is difficult to find a reasonable and resource-efficient management strategy without sacrificing ecological values. Fortunately, BE could be used to address this dilemma, based on a 2-year experiment in the USA, which successfully gained economic benefits from BE outputs, while eliminating invasive species [79]. The concepts of producing BE from other ecosystems have also been well proven [21,80,81]. Except for the factor of climate change, internal competition of forests could result in a certain degree of mortality with respect to forest vegetation, influencing the formation of carbon sinks [82]. Furthermore, young forests in China have the potential to provide significant amounts of feedstock for bioenergy production through thinning and other measures, which could help offset the desired reductions in fossil fuel use [72]. Last but not least, the potential of biomass for bioenergy could help to accomplish desired reductions in hazardous fuels that feed wildfires [83], providing an approach that creates suitable wildlife habitats that reduce the incidence of insects pests and disease [84].

3.5. Potential bioenergy feedstock repository

Access to high-quality energy resources is strongly linked to prosperity and human well-being [85,86]. Moreover, biomass for bioenergy has significant economic benefits [79] that could guarantee energy security and achieve climate goals [87], particularly with the development of technology. Such technology includes IFBB technology [74] and the latest integrated gasification cycle system combined with carbon capture and storage (CBECCS) technology [88]. Meanwhile, experiences in the European Union (EU) and USA have demonstrated that supportive policies play an important role in creating demand, stimulating production, and promoting the development and commercialization of biomass for bioenergy [89]. In 2009, the EU proposed to increase the proportion of renewable energy to 20% by 2020 and explicitly requested to increase forest biomass [90]. The US Energy Independence and Security Act (2007) explicitly required the replacement of 36 billion gallons of fossil fuel per year with biomass fuels [91]. Comparatively, China's progress is somewhat slow, even though the Chinese government has implemented some effective policies to improve the development of bioenergy, focusing on ethanol.

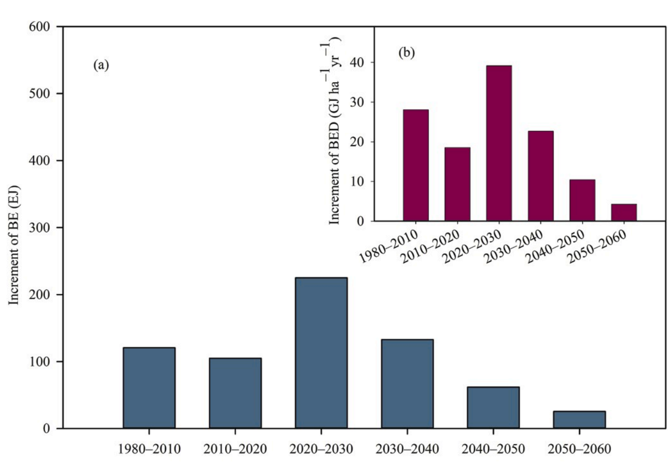

Fig. 4. Increase in biomass energy (BE, EJ) and biomass energy density (BED, TJ ha^{-1}) in China between 1980 and 2060. Panel (a) and panel (b) represent changes in BE and BED, respectively.

Even a 1% utilization of these available BE sources in China could meet approximately 4% of China's energy demand in the 2010s. At present, the energy system in China is still dominated by fossil fuel (Fig. S5). According to the latest paper on progress [92], a combination of coal and BE to produce electricity in China using a low-cost CBECCS technology system could help to reduce air pollutant emissions, contributing to China's short-term goal to improve air quality. Consequently, the large-scale deployment of BE for bioenergy could provide a low-cost and viable opportunity to retrofit existing energy systems, and particularly power generation systems. However, according to the annual forest harvesting quota of China from 2015 to 2020, the annual forest residue that could be provided is only 0.41 EJ (Table S3), which is far from meeting the actual demand. Hence, it is important to establish a balance between the resource system and the socio-economic system (Fig. S2). The ignored potential of BE provides us with an opportunity to achieve a win-win situation with respect to conserving resources and sustaining social development, especially for developing countries such as China (Fig. S2).

3.6. Challenges between biomass energy supply and climate change

The supply of BE for bioenergy could support the UN Sustainable Development Goals in terms of climate action (Goal 13) and sustainable energy supply (Goal 7) [93]. However, there are still some challenges between the supply of biomass for bioenergy and climate change mitigation. However, biomass is often seen as a key component of future renewable energy systems as it can be used for heat and electricity production, as a transport fuel, and a feedstock for chemicals [80]. In addition, it can be used in conjunction with carbon capture and storage to provide so-called "negative emissions" [88]. Seeking multi-source (from forest, grassland, and cropland) BE is a potentially effective solution for solving the shortage of biomass supply [17,21,80,94]. Importantly, forests, grasslands, and cropland are generally considered a huge carbon sink that can absorb carbon dioxide to mitigate climate change mitigation [95–97]. Some scientists have mainly argued that we need to protect forests from infringement in an almost extreme way, which also increases the difficulty of forest management [72]. However, some researchers suggest that even if humans do not disturb the forest, excluding climate change factors, the forest itself will die on a large scale and become a carbon source [82,98]. In addition, the use of forest biomass for bioenergy releases recently stored carbon into the atmosphere, but avoids the release of historic carbon owing to the burning of fossil fuels [99]. Together, there are some complexities in decision-making regarding the use of forest biomass, mainly resulting from current insufficient technologies [4,72].

Compared to that from forests, biomass from grasslands and cropland is much less controversial, and there have been far more studies in this field [17,80,81]. First, most carbon stored in grassland and cropland is distributed in the roots, and the utilization of aboveground biomass has little effect on the carbon storage of grassland or cropland ecosystems [100,101]. Second, the aboveground biomass of grasslands and croplands can generally be regenerated each year, without a substantial impact on its ecosystem carbon sink [100].

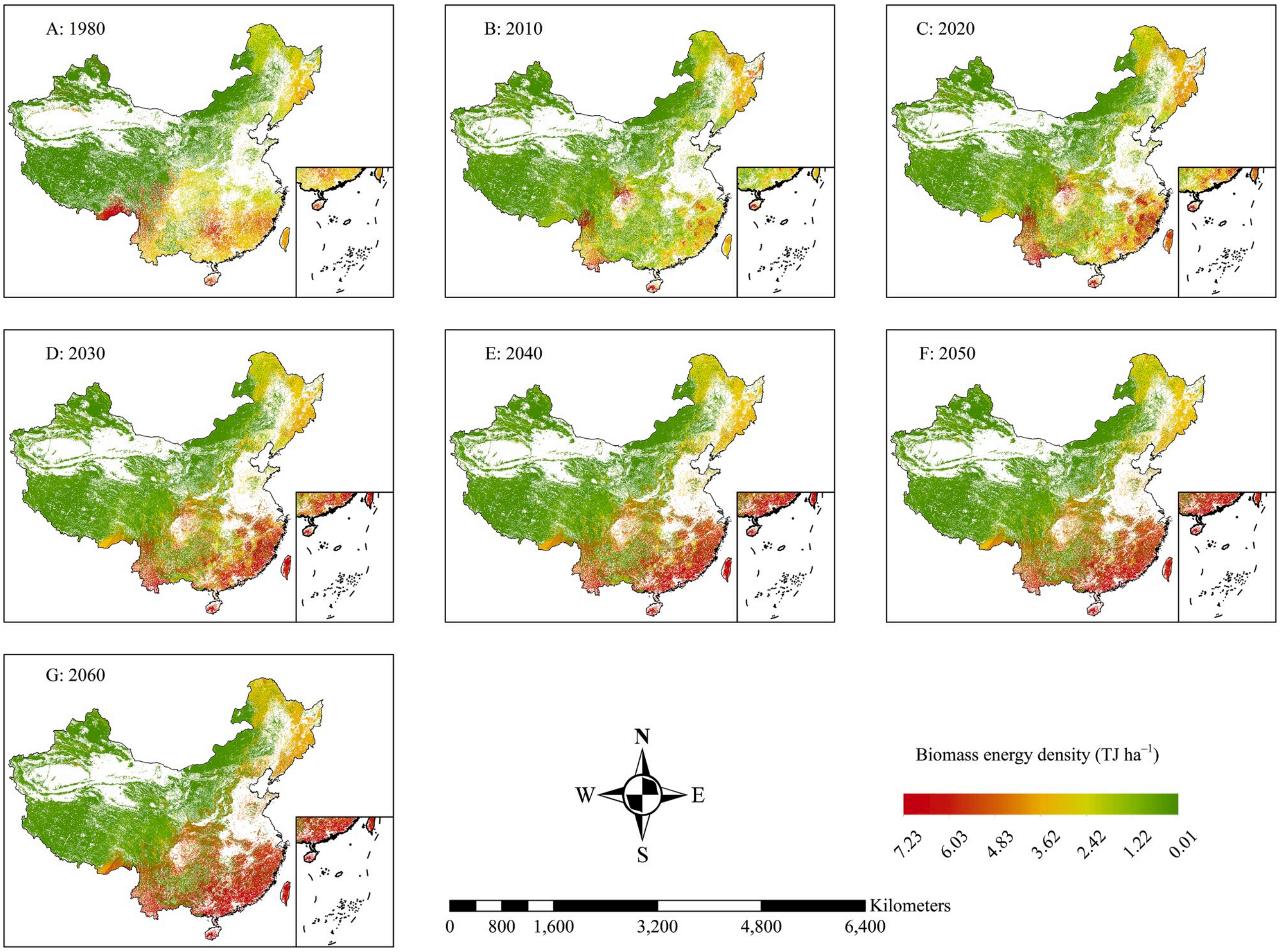

Fig. 5. Temporal and spatial variation of biomass energy density (BED, TJ ha^{-1}) in the forests and grasslands of China from 1980 to 2060.

4. Conclusion

This study first explored the gross BE and its spatiotemporal dynamics in China's terrestrial ecosystems from 1980 to 2060. The gross BE in China was estimated as 535.91 EJ, which is equivalent to 18.29 Gt standard coal. Further, BE shows a continuous increasing trend from 1980 to 2060 in China, and rate of increase might peak in 2030. Importantly, the spatial distribution of BE is uneven, such that BE (per land area or per capita) is significantly negatively correlated with provincial development levels in China. Our findings highlight the fact that China has abundant BE reserves and that ecological protection projects in the past three decades have achieved great progress. Policy makers should further stimulate the development of a green economy and support research on biomass for bioenergy conversion technologies, which might improve the utilization of biomass resources to reduce environmental impacts. Furthermore, cost and sustainability assessments of BE availability are necessary to further assess their potential with respect to technology and the economy in the future.

Declaration of competing interest

There are no conflicts of interest to declare.

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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.2020.109857.

Author contributions

N.H. designed the research. P.Y., C.X., L. X, N·H, and A.L. conducted the research (collected the datasets and analyzed the data). Y.P, C.X., L. X and A.L. wrote the manuscript. G.Y. and S.P. commented on the manuscript.

Data accessibility

The data and Python codes that support the findings of this study are available from the corresponding authors upon request.

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