Renewable and Sustainable Energy Reviews 16 (2012) 1377–1382

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Bioenergy potential from crop residues in China: Availability and distribution

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ARTICLE INFO

Article history:
Received 8 March 2011
Received in revised form
19 December 2011
Accepted 19 December 2011
Available online 18 January 2012

Keywords:
Bioenergy
Sustainable removal rate
Geographic Information System

ABSTRACT

The accurate estimate of the availability of crop residue resources is very important for the development of bioenergy in China, a large agricultural nation. Previous efforts to evaluate the bioenergy potential from converting straws to energy were mainly based on agricultural statistical data on the provincial/county level. Straw yield calculations generated by most of those works significantly overstate the amount of crop straws for ignoring environmental requirement and harvest constrain. The paper presents a GIS-based approach for the assessment of the availability and distribution of crop residues in China, taking into account a number of conservation issues: resources (total amount, spatial and temporal distribution), economy (transportation costs), environment, and technology. All data are converted into unified geographic unit (100 m × 100 m pixels), and integrated analysis is implemented with GIS software. The results indicate that considering conservation requirements, the production of net available crop residues is about 505.5 million tons per year. The bioenergy potential is about 253.7 million tons standard coal per year (7.4 EJ/year), which account for 8.27% of total energy consumption of the country in 2009. The results and dataset will present significant support for energy planning both at national and regional scale.

Contents

1. Introduction

Biomass energy occupies a significant status in the world's energy consumption and in the fight against climate change. Sustainable bioenergy production can reduce energy poverty, contribute to rural development and avoid the negative environmental impacts such as decreasing greenhouse gases emissions [1]. Although bioenergy accounts for only 10% of global energy consumption at present, the potential of bioenergy will be very great in the near future. A report from World Bioenergy Association (WBA) in 2010 stated that the reasonable and sustainable utilization of global biomass energy could meet global energy demand [2]. The U.S. Biomass Roadmap by the U.S. Department of Energy (USDOE) set forth a goal that, by the year 2030, biomass will supply energy approximately equivalent to 30% of current petroleum consumption [3]. Within Europe, the European Commission (EC) has set mandatory targets for an overall share of 20% renewable energy

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doi:10.1016/j.rser.2011.12.012

and a 10% share of renewable energy in transport in the EU's consumption in 2020 [4]. For Romania, the target set by the Renewable Energy Directive on the promotion of the use of energy from renewable sources for 2020 is a 24.0% share of energy in gross final consumption [5]. National estimates of the fraction of Australia's petrol usage that could be replaced by biofuels range from 10% to 140% [6].

Conversion of forest and agricultural residues to biomass feedstock for electricity generation and district heating is becoming a common form of bioenergy [4]. Rising energy price and emerging new technologies have renewed people's interest in conversing crop residues to energy products [7,8]. Crop residues such as the straws of cereal and corn, which can be converted into liquid or gaseous biofuels by thermo-chemical or biological techniques, are potential resources for the development of bioenergy [9]. Hence, crop residue is a viable option for energy production, especially for rural areas in developing countries. The accurate estimation of the amount of crop residues used for bioenergy purpose is very important for the sustainable supply of biomass. Increasing attention has been paid to quantification of bioenergy potentials of crop residues. John et al. provided an overview of the current status of bioenergy development globally, focusing on biomass energy and the potential contribution of agricultural biotechnologies in developing countries [10]. Gary et al. assessed the availability of straw biomass energy used as feedstock in the Northwest Pacific in U.S.A. [11]. Nicolae et al. assessed the utilization potentials of straws for bioenergy purpose in the European Union [8]. Idania et al. discussed the potentials of bioenergy resources used in agricultural activities in Mexico, while presenting the spatial distribution of different crops [7].

There is a growing recognition that the interrelations between agriculture, food, bioenergy, and climate change have to be better understood in order to derive more realistic estimates of future bioenergy potentials [12]. The increasing role of biomass in future energy supply requires the use of all available resources in a sustainable way, without causing directly or indirectly negative impacts [5]. Some recent researches indicated that excessive straw reaping might have adverse impact on soil, environment and crop yield. Thus reasonable reaping (removal) ratio is needed for sustainability purpose. For example, Susan et al. [13] discussed the effect of straw reaping on soil quality, pointing out that sustainable straw reaping rates vary depending on factors such as management, yield and soil types. The Conservation Technology Information Center (CTIC) of USA provides assessments of conservation tillage practices and pointed out that the non-conservation tillage (intensive/conventional and reduced tillage) leaves less than 30% crop residue cover (CRC), while conservation tillage leaves more than 30% CRC [14]. A study sponsored by the National Renewable Energy Laboratory (NREL) and the US Department of Energy (DOE) showed that the use of corn stover as a feedstock for ethanol production in Iowa, USA, could be done without adversely impacting soil health, while providing significant energy and greenhouse gas benefits [15,16].

China is one of the largest agricultural countries in the world. Since the 1980s, with the increase of crop yield, the total yield of straw increased rapidly [17]. In the past, the majority of these straws was used as fuels in rural areas or burned in the fields for the market available for straws was limited. During the recent 10 years, for the requirements of air quality protection, straw burnings have sharply reduced, and the rational utilization of the straws has been required [18]. A large number of studies have been conducted on the assessment of the amount and distribution of crop residues for biomass in China [19–22]. Previous efforts were mainly based on agricultural statistical data on the provincial level. The total amount of crop residues produced in China was estimated at 600–800 million tons per year. However, a detailed assessment of spatial distribution of crop residues for different regions is needed for regional bioenergy planning [23]. Moreover, not all straws are available for biomass use because some of them should be returned to the soil as residue to prevent erosion and enhance soil quality [24,25]. The previous methods remarkably overstated the crop residue yield since the part of cropland returning and reaping lose was not considered [25,26], and this part of straws should be left in the field to meet all the environmental and farming requirements [8,27,28].

This paper is focused on the assessment of availability of straws in China as an energy resource, based on Geographic Information System (GIS) approach and data from multiple sources. Total yield of straws from 2000 to 2009 was calculated first. Up-to-date 1:100,000-scale map of farmland distribution was used and the spatial distribution of straws was simulated at 100 m × 100 m pixel with a GIS-based method. The net straw availability for bioenergy purpose was estimated then, by well considering the requirements on soil conservation and transportation costs. Thus, the estimation on the potentials of bioenergy production from crop residues was discussed.

2. Methodology

In this paper, the yield of straws was calculated based on the crop yield and the corresponding crop-to-residue ratios. Availability of straws was thereby obtained based on the straw yield, environmental consideration and soil requirements.

(1) Calculation of total yield of crop residues

The 2000–2009 official agricultural statistics data of yield and planting area at the county level for each type of crops are accessible from China's Ministry of Agriculture, and the crop-to-residues ratios were mainly derived from this source [29]. The regional straw production could be calculated in terms of the yield of each crop and the corresponding crop-to-residue ratio of each species.

(2) Simulating the spatial distribution of crop residues

The map of farmland distribution was derived from a national data base of land-use at 1:100,000 scale, provided by Resources and Environmental Sciences Data Center (RESDC) and Chinese Academy of Sciences (Fig. 1). Based on this map and the planting information, the yield of straws for each geographic unit (100 m × 100 m pixel) was assigned according to proportion of farmland area to each pixel. Thus, analysis on net availability could be performed by combining this data with other data such as road data and soil type data, for further processing.

(3) Determining net availability of crop residues

Net available crop residue equals that the total crop residues yield minus the amount of crop residues returning to the fields for conservation purpose. The recommended amount of straws returning to fields depends on local climate conditions, soil corrodibility, nutrient demands, slopes of land, and governmental policies. A great deal of studies has presented estimates on the sustainable removal rate of straws vary between 30% and 70% [29–31]. Nicolae et al. [8] used the sustainable reaping rate of 40% for wheat, rye, barley, while 50% for maize, rice, and sunflower, during the estimate of available straws in the European Union. Gary et al. [11] employed Natural Resources Conservation Service Soil Condition Index worksheet recommended by USDA to calculate the total and available wheat, barley and oat straws in the Northwest Pacific. Yajing Wang et al. [32] pointed out that 18.52% of straws were returned to the fields in China in 2005, and the recommended average sustainable reaping rate of straws was about 65–71% in China. In this study, sustainable straw reaping rate is determined according to requirements of National Fertile Soil Project launched in 2005 by China's Ministry of Agriculture [29,33]. A pixel-by-pixel analysis is also performed to obtain sustainable straw reaping rate, and net available straws is then calculated based on soil-type map at 1:100,000 scale, crop-zoning map and information on crop types.

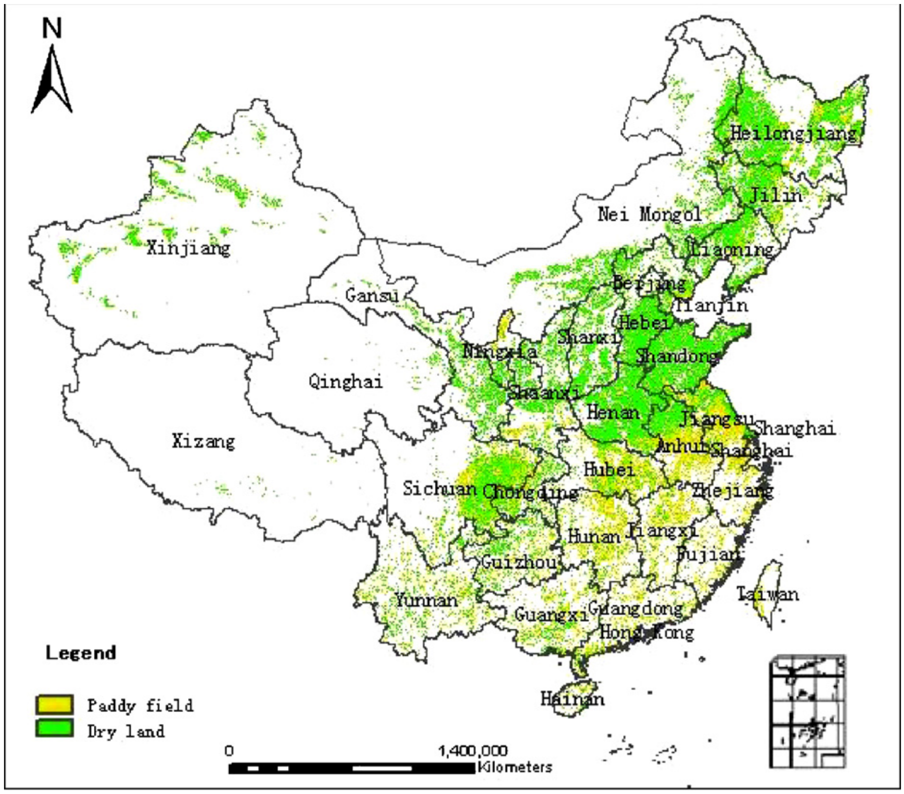

Fig. 1. The map of farmland distribution in China, 2008.

The cost of transportation, a major obstacle to the economic conversion of straws into energy, is also considered in this study. Some low-density straws distant away from road network are considered unavailable for energy use and are thus dismissed in further statistics. In this study, the above-mentioned straw data layer (in raster format) is overlaid with national road-network data layer (in vector format). Straws in pixels with a distance to main road greater than 15–20 km, according to the updated literatures, are excluded using Overlay and Buffering functions of ArcGIS software.

3. Results and analysis

3.1. Total yield of crop residues

The crops considered in this study include rice, wheat, maize, beans, tubers, oil-bearing crops (peanut, sesame), cotton, fiber crops, sugar crops (sugar cane, sugar-beet). Annual estimates of straws in China from 2000 to 2009 are calculated based on crop yield and the crop-to-residues index (CRI), defined as the ratio of the dry weight of residues produced to the total weight of crops produced. CRI for each type of crops in China are derived from recent literatures [34,35]. Annual crop residue yield and corresponding CRIs are listed in Table 1.

It is estimated that the total yield of crop residues in China in 2009 is about 806.9 million tons, and the average yield is 716.0 million tons in the past 10 years. The three principle straws are straws of maize, wheat and rice that accounted for 40.6%, 24.2% and 15.7%, respectively (Table 1). Fig. 2 shows temporal variation of crop yield and straws in China from 2000 to 2009. The annual total yield of straws increased successively from about 660 million tons to more than 800 million tons in the past 10 years at an average rate of 2.1%/year.

The provincial statistical results indicate that the majority of straw productions are concentrated in Henan, Shandong and

Table 1
Annual estimate of crop residues in China in 2009.

Crop	Yield (million ton)	CRI	Crop residue (million ton)	%
Rice	195.1	1.0	195.1	24.2
Wheat	115.1	1.1	126.6	15.7
Maize	163.7	2.0	327.4	40.6
Beans	19.3	1.7	30.0	4.1
Tubers	30.0	1.0	30.0	3.7
Oil-bearing crops	31.5	2.0	63.1	7.8
Cotton	6.4	3.0	19.1	2.4
Fiber crops	0.4	1.7	0.6	0.1
Sugar crops	121.7	0.1	12.2	1.5
Total	530.8	/	806.9	/

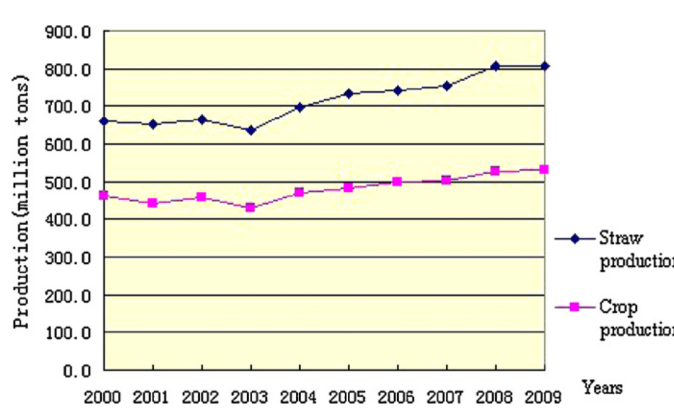

Fig. 2. Temporal variations of crop yield and straws in China from 2000 to 2009.

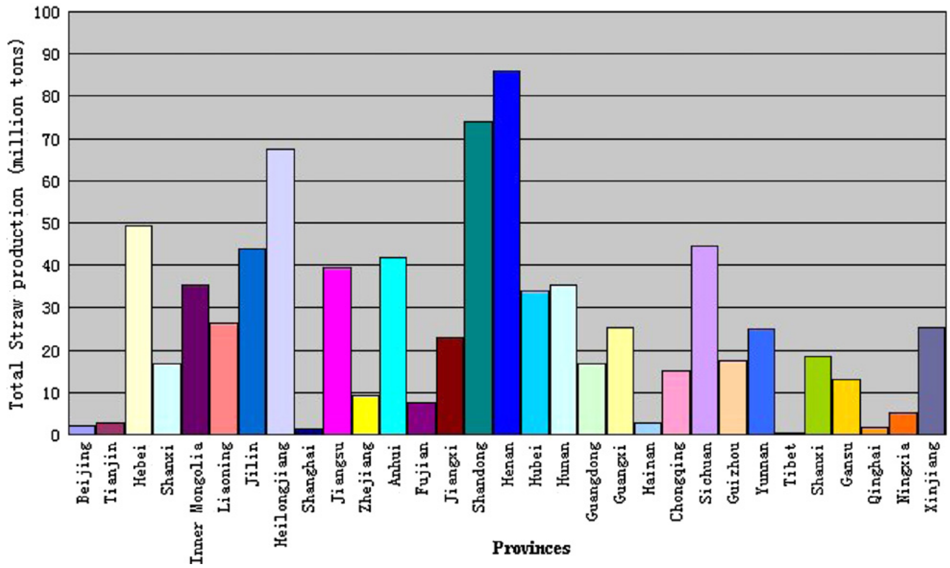

Fig. 3. Total yields of straws in each province in China, 2009.

Heilongjiang Province, with total straw yields of 8.61, 7.41 and 6.75 million tons in 2009, respectively (Fig. 3).

3.2. Availability of crop residues for bioenergy purpose

3.2.1. Net availability of crop residues and its spatial distribution

Based on the total yield of straws and the consideration of sustainability (sustainable reaping rate, cost analysis, etc.), net availability of straws for bioenergy purpose is then estimated. The estimates show that the amount of straws available for bioenergy production in China in 2009 is about 505.5 million tons, with the average of 451.3 million tons/year in the past 10 years. For the convenience of further processing and analysis, the results are spread onto 100 m × 100 m pixels, making its spatial distribution much clearer than the map based on statistical data at province or county level (Fig. 4).

Fig. 4 shows a significant regional unbalance of net availability of straws in China. The majority of crop residues are concentrated in the two principle grain-producing areas which are Huang-Huai-Hai region and Northeast Plain. Within Huang-Huai-Hai region, crop

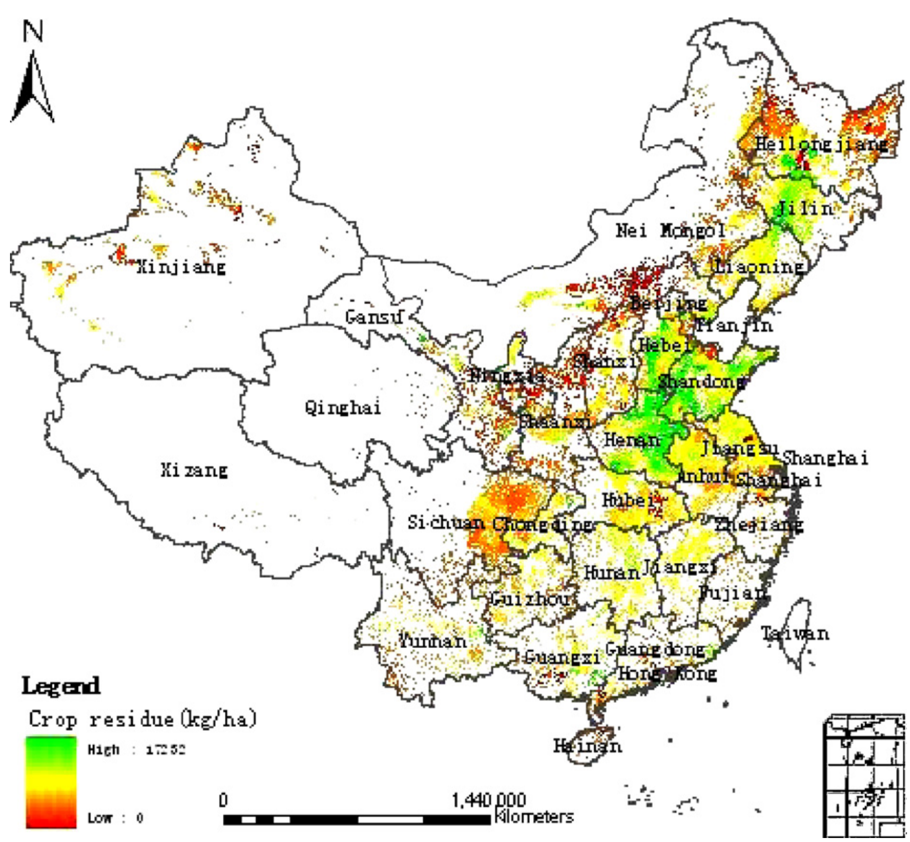

Fig. 4. Spatial distributions of net crop residues in China, 2009 (100 m × 100 m). (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

Table 2
Annual estimates of energy potentials of crop residues in China in 2009.

Crop	Crop residue (million ton)	Conversion ratio[a]	Equivalent standard coal (million ton)	Energy potential (EJ)[b]
Rice	103.8	0.429	44.5	1.303
Wheat	75.6	0.500	37.8	1.106
Maize	223.0	0.529	117.9	3.452
Beans	20.5	0.543	11.1	0.326
Tubers	19.2	0.486	9.3	0.274
Oil-bearing crops	41.1	0.529	21.7	0.636
Cotton	13.3	0.543	7.2	0.211
Fiber crops	0.4	0.521	0.2	0.006
Sugar crops	8.7	0.441	3.8	0.112
Total	505.5	/	253.7	7.426

[a] Conversion ratio stands for the ratio from each type of crop residue to equivalent standard coal [27].
[b] Lower heating value of standard coal is used for 29.27 MJ/kg [28].

residues are mainly distributed in the northern and the eastern part of Henan Province, western part of Shandong Province, and central belt region of Hebei Province (areas in the green color in Fig. 4). Huang-Huai-Hai region is the principle grain-producing area of China, where wheat straws and maize straws are main productions. In the northern part of Anhui and Jiangsu Province, which are adjacent to above-mentioned areas, the yield of straws is also relatively higher (areas in the yellow color in Fig. 4). The main crop residues are straws of winter wheat, maize and rice. In Northeast Plain, the regions with higher density of crop residues per unit area are located at the belt stretching from the north of Liaoning Province to the south of Heilongjiang Province, with main crop residues of straws of maize and rice. The crop residue resources are quite abundant in Sichuan Province and Hubei Province with a lower density of crop residues per unit area compared to above-mentioned regions.

3.2.2. Bioenergy potentials from crop residues in China

Currently, crop residues can be converted to energy productions by using techniques such as combustion (direct and co-firing) and non-combustion methods (thermo-chemical and biochemical). The conversion efficiencies of different types of techniques were obtained from existing literatures [36,37]. Based on net biomass yield from straws and conversion efficiency (thermal values of each type of straws), energy potential of crop residues of China could be estimated (Table 2).

The estimates indicate that the total bioenergy potential from straws in China reached 253.7 million tons standard coal (7.4 EJ) in 2009, which accounted for about 8.3% of total energy consumption of the country. According to the national mid- and long-term planning of renewable energy development, biomass energy is expected to account for about 4.0% of total energy consumption by 2020. In China, biomass energy resource mainly consists of crop residues, forest residues, grassland biomass, etc. Crop residues will play more and more important role in energy supply in the near future.

4. Discussion

The accurate estimate of the availability of crop residues for bioenergy purpose is very important for the sustainability of biomass supply. In this study, an operational GIS-based approach has been proposed for comprehensive assessment of the current amount of available crop residues. The estimates indicate that the average annual production of crop residues is more than 800 million tons after 2008. Considering the conservation requirements, the production of net available crop residues is about 505.5 million tons/year. The total yield of crop residues is apparently consistent with the existing estimates. However, the estimate of net availability of crop residues is much lower than results in previous literatures. The reasons for the significant variation lie in the following two aspects. First, in most of the previous studies the reaping

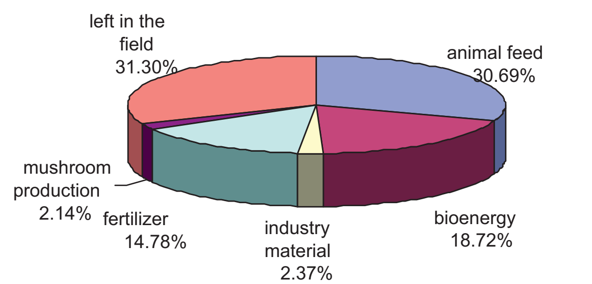

Fig. 5. Utilization of crop residues in China
Data source: China's Ministry of Agriculture

rates were set as a fixed value of about 19%, with reaping loss included. In fact, sustainable reaping rates vary depending on factors such as management mode, yield and soil types. Sustainable crop residues reaping rates adopted in the paper from about 55% to 72%, in accordance with the requirements of National Fertile Soil Project. Second, cost efficiency was also taken into consideration in this study. Low-density straws far away from the road network were excluded using road network data and GIS software.

The net crop residues are available for bioenergy purpose. However, this type of resources is used for several alternative purposes currently, such as animal feed, industry materials, fertilizer and mushroom production. The utilization of crop residue in China is illustrated in Fig. 5.

Fig. 5 shows that 31.30% of crop residues were left in the field in China in 2009, and 30.69% of crop residues were used as animal fodders. Only 18.72% of crop residues were used for bioenergy purpose. In recent years, the percentage of the straws burned directly in the fields has decreased dramatically in China. In general, crop residue resources have not been effectively exploited now. Residue resources play an increasingly significant role in sustainable development of agriculture and economy in rural areas, and the comprehensive utilization of crop residue resources is still a challenging task.

5. Conclusion

China is a large agricultural nation with abundant crop residues resources. In this study, the assessment of the current available crop residues has been conducted, by taking into account a number of issues: resources (total amount, spatial and temporal distribution), economy influence (transportation costs), environmental and technological conditions. All data were converted into unified geographic unit (100 m × 100 m pixels) and integrated analysis was achieved with GIS technique, which had been proved to be an efficient way for assessment of crop residue resources with multiple data sources [38–40].

This study indicates that the yield of residues is tremendously great in China, estimated at 806.9 tons in 2009, and 716.0 million tons per year averaged over the past 10 year (2000–2009). The results also reveal that enormous unbalance exists in the spatial distribution of crop residues. However, the annual fluctuation of crop residues is small, estimated at approximately 1.2% per year. Considering conservation requirements, the production of net available crop residues is about 505.5 million ton/year. The bioenergy potential is about 253.7 million tons standard coal/year (7.4 EJ/year), which account for 8.27% of total energy consumption of the country in 2009. The results and dataset will present significant support for energy planning both at national and regional scales. Much field survey and on-site investigation should be carried out for the verification of the estimates in the subsequent researches.

Acknowledgements

This research was supported and funded by State Key Lab of Resources and Environmental Information System of China; and Knowledge-innovation Project (Integrated assessment of mass culture of main bioenergy plants in China) of Chinese Academy of Sciences.

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