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Quantitative assessment of bioenergy from crop stalk resources in Inner Mongolia, China

Jin Liu [a,b], Jianguo Wu [c,d,*], Fengqiao Liu [d], Xingguo Han [a,e]

[a] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, 20 Nanxincun, Xiangshan, Beijing 100093, China
[b] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[c] Sino-US Center for Conservation, Energy, and Sustainability Science, Inner Mongolia University, Hohhot 010021, China
[d] School of Life Sciences, Arizona State University, Tempe, AZ 85287, USA
[e] Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China

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ABSTRACT

Inner Mongolia Autonomous Region (IMAR) is one of China's strategic energy bases for the 21st century. While bioenergy in IMAR may play an important role in securing future energy supply, little research has been done so far, particularly for crop stalk resources as a potential source of bioenergy in this region. In this study we systematically analyzed the temporal and spatial patterns of crop stalk resources, evaluated the bioenergy potential of crop stalk resources, and explored possible pathways of developing stalk-based energy strategies in Inner Mongolia. Our results show that the total crop stalk yield in IMAR increased consistently from 1980 to 2008, with an average annual increase of 16.3%. Between 2004 and 2008, 26.14 million tons of crop stalks were produced each year in IMAR, 8.82 million tons of which could be used for biofuel production. Grain crops contributed most to the total amount of stalks for energy production, of which corn stalks were the largest contributor, accounting for 62% of the total crop stalk yield. Based on the current trend, crop stalk yields may continue to increase in the future. Geographically, the abundance of biofuelable crop stalk resources, either on a per capita or per unit of area basis, had a spatial pattern of "high on East and West and low in the middle". Our findings suggest that IMAR has the potential for developing stalk-based bioenergy to improve its current overwhelmingly coal-dominated energy structure. However, more detailed and comprehensive studies are needed to figure out how exactly such bioenergy development should be carried out in a way that would promote the regional sustainability of Inner Mongolia – i.e., simultaneously providing social, economic, and ecological benefits.

1. Introduction

The excessive use of fossil fuels has resulted in a number of environmental and socioeconomic problems worldwide, including ecosystem degradation, pollution, and global climate change. The establishment of a sustainable energy production, supply, and consumption system has now become a primary and imperative task for achieving a sustainable future [1,2]. Consequently, restructuring energy consumption and reducing fossil fuel dependency can no longer wait. Seeking new and alternative energy sources is an important way towards energy sustainability. At present, governments all over the world are committed to looking for new clean energies to power their future with strong sustainable supply capacity and low- or zero-carbon emissions.

Bioenergy has long been used by society, and has been increasingly recognized as part of the renewable energy development in recent decades. As an alternative to fossil energy, bioenergy has the potential to be carbon-negative because of its ability to sequester CO_2. The first generation biofuel, mainly bioethanol and biodiesel, is derived from raw materials that are rich in starch, sugar, and fat, such as corn, sugarcane, soybeans, and rape seeds. Its promotion has been met with controversies because energy crops often compete for land and water with food and forage production, increase soil erosion and decrease soil fertility, and exacerbate environmental pollution (due to the application of chemical fertilizers and pesticides) [3–6]. The Life-Cycle Analysis (LCA) of energy consumption and GHG emissions of China's current six biofuel pathways (including corn-, cassava-, and sweet sorghum-derived ethanol; and soybean-, jatropha fruit-, and waste cooking oil (WCO)-derived biodiesel), showed that the first generation biofuel pathways were not really meritorious in terms of energy-saving or GHG emission reduction [7]. Using a social metabolic approach, Haberal [8] found that the production of the first generation

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* Corresponding author at: School of Life Sciences, Arizona State University, Tempe, AZ 85287, USA. Tel.: +1 480 965 1063; fax: +1 480 965 6899.
E-mail address: Jingle.Wu@asu.edu (J. Wu).

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bioenergy could lead to a surge in human appropriation of net primary production (HANPP), the destruction of many valuable ecosystems, and accelerated losses of biodiversity worldwide [8]. Therefore, the production of the second generation biofuel should be based on multifunctional production systems, which can simultaneously provide raw materials as well as food and ecological services [9]. The process of switching biofuel from the first generation to the second ought to be guided by the general notion, which is increasingly supported by scientific research, that biofuel productions should not compete for food with humans, not compete for land with food production, not compete for fertility with land, and not compete for feed with livestock. This general guide is particularly relevant to China who has to feed more than 20% of the world's population with less than 9% of the world's farmland. Thus, if the second generation biofuels are to have a future in countries like China, utilization of crop stalk resources available for energy production, namely biofuelable crop stalk resources, must be considered.

For stalk resources to successfully play a positive role in future energy consumption, the reliable assessment of existing biomass resources and the viability of their utilization for power generation are key issues [10]. First, we must investigate its characteristics such as its production capacity and distribution patterns of the supply system [11]. Second, we must also evaluate different kinds of bioenergy crops and the appropriate scale of production so that food security and ecosystem services are not adversely affected [1]. A number of studies have examined stalk resources in China [12–16]. However, most of these studies cover the entire country with rather coarse spatial resolutions and over a short time span (1 year). While these studies are useful for understanding the crop stalk resource utilization pattern at the national scale, they do not provide adequate details needed by local governments for regional planning and policy implementation. For the few studies that paid attention to regional stalk resources, the methods for estimating the amount of biofuelable stalk were often oversimplified [17]. Furthermore, these studies lack comparability because they did not use unified or standard techniques for stalk resource investigation and evaluation [18], resulting in highly variable estimates of stalk resources [19].

The main purpose of this study was to estimate the total production potential and spatial distribution of crop stalks in the Inner Mongolia region. We systematically analyzed the annual yield of different kinds of crop stalk resources in IMAR from 1980 to 2008 at three administrative levels: the province (i.e., IMAR), the prefecture (i.e., league or regional city), and the country (i.e., banner or local city). Based on data from diverse sources, we quantified the amount, kind, and spatial distribution of biofuelable crop stalks for the entire region. Finally, we explored different strategies for developing bioenergy from stalk resources in the Inner Mongolia region.

2. Methods

2.1. Study area

Inner Mongolia Autonomous Region (IMAR) is China's third largest province in area (12.3% of China's total land area), covering 2400 km east to west and 1700 km south to north (Fig. 1). IMAR is known as the top energy-rich province in China as it has ample energy resources – especially coal, wind, and solar energy. By June 2007, the proven reserve size of coal in IMAR was estimated to be 685.3 billion tons, ranked number one among all provinces in China [20]. Wind energy resource that can be exploited in IMAR is 202 million kW, accounting for 40% of the country's total [21]. The total amount of solar radiation of IMAR per year is between 5000 and 7000 MJ/m^2, second only to Tibet [22]. About 26 million tons (dry weight) of stalk resources, more than 20 million tons (dry weight) of forest biomass [23], and more than 80 million tons (dry weight) of grass biomass [24] are produced each year in IMAR.

Although IMAR is rich in various energy resources and a strategic energy base of China for the 21st century, up to date its energy development has primarily focused on coal resources. IMAR's annual output of raw coal has increased exponentially since 1978, jumping from 58 to 316 million tons (standard coal equivalent) in only 8 years [25]. Concomitantly, GHG emissions and environmental pollutant discharges, such as SO_2, NO_x, fume and dust, soared as well.

2.2. Data acquisition and processing

Data on the annual yield and sown area of different crops of each banner from 1980 to 1993 and from 1995 to 2008 were derived from the following sources: (1) Statistical Yearbook on Agricultural and Livestock Production in Inner Mongolia from 1980 to 1986 [26]; (2) Statistical Yearbook on Rural Social Economy in Inner Mongolia from 1987 to 1991 [27]; (3) Statistical Yearbook on Rural and Pastoral Areas' Social Economy in Inner Mongolia from 1992 to 1993 and from 1999 to 2005 [28,29]; (4) Basic Data on Agriculture and Animal Husbandry Economy in Inner Mongolia from 1995 to 1997 [30]; and (5) Inner Mongolia Economy and Society Investigation Yearbook from 2006 to 2009 [31]. Information on annual yield and sown area of different kinds of crops of IMAR in 1994 was obtained from Inner Mongolia Statistical Yearbook 1995 [32]. Data on population, cultivated area, total power of machinery for faming and animal husbandry, irrigated land, chemical fertilizers, and energy consumption were derived from Inner Mongolia Statistical Yearbook from 1989 to 2009 [25]. Data on the coefficient of collectable stalks (the proportion of stalks that can be harvested) for different kinds of crops in IMAR were from The Yearbook of Agricultural Mechanization in China from 1991 to 2007 [33] and Cui et al. [18].

During the period of 1980–2008, the boundaries of some administrative units were altered due to reorganization. To make sure that the crop yield matched its corresponding area, we combined several municipal districts into one administrative unit when they fell within the jurisdiction of one city. Data analysis was performed using Microsoft Excel, SPSS, and ArcGIS. Since the temporal extent of the study spans over 29 years, it was different to get a complete statistical dataset for the whole period. We estimated the values of missing data points using the "missing value analysis" function in statistical software, SPSS. The confidence level of all estimated values was all above 95%.

Because IMAR is vast and spatially heterogeneous, we divided its 12 administrative areas (leagues or prefectures) into three sub-regions in order to facilitate within-region comparisons in our analysis. The three sub-regions were: East Inner Mongolia, Central Inner Mongolia, and West Inner Mongolia (Fig. 1).

2.3. Calculating the theoretical reserve of crop stalk resources

The theoretical reserve of crop stalk resources represents the maximum annual output of a region and is usually estimated by multiplying the total crop yield with the residue/crop product ratio [18]. We derived the residue/crop product ratios (Table 1) from data in Cui et al. [18], Jia [34], and Song et al. [23]. We selected the coefficients that were based on recent research and had information on the water content of stalks. According to Technical Code of Crop Straw Surveying and Evaluating, published by Ministry of Agriculture of the People's Republic of China in 2009 [35], we calculated the actual amount of biofuelable crop stalk resources following the flow chart shown in Fig. 2.

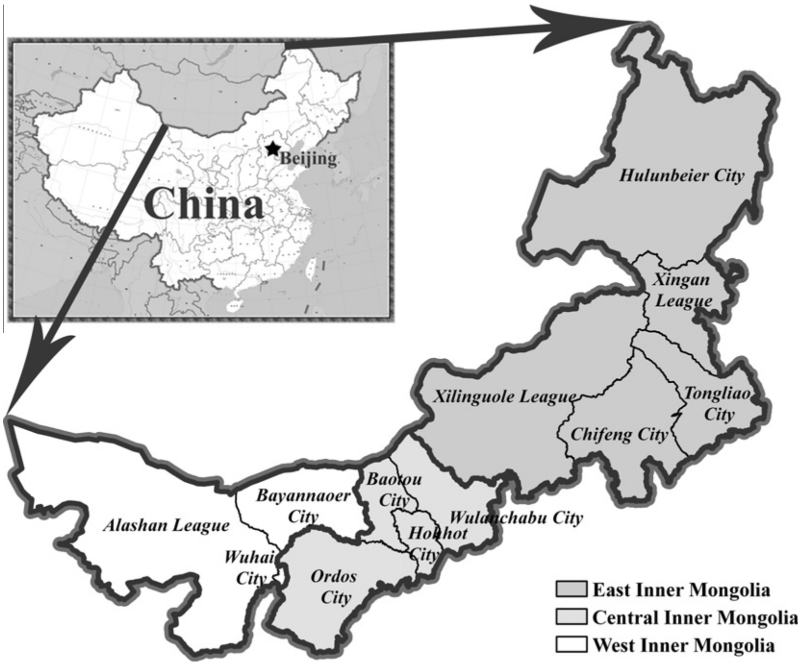

Fig. 1. The location of the study site, Inner Mongolia Autonomous Region (IMAR), China, with three sub-regions identified.

Table 1
Residue/crop product ratios of different crops in China (derived from Cui et al. [18], Jia [34], and Song et al. [23]).

Crops		Coefficient
Food crops	Rice	0.73
	Wheat	0.68
	Corn	1.25
	Other cereal crops	1.0
	Beans	1.5
	Tubers	1.2
Oil-bearing crops	Peanuts	2.0
	Rape	1.01
	Sunflower	3.0
	Others	2.0
Fiber crops	Hemp	1.7
	Flax	1.7
Other economic crops	Sugar beet	0.1
	Cotton	5.51

2.4. Estimating collectable reserve of crop stalk resources

The collectable crop stalk resource refers to the stalk that can be utilized after taking off the loss of harvest and transportation from the theoretical reserve [18]. It is determined by the theoretical stalk reserve in survey area and the collectable stalk coefficients of the crops. The formula to calculate collectable stalk coefficients is as follows (see Table 2 for detail):

$$\eta_i = [(1 - L_{i,jc}/L_i) \cdot J_i + (1 - L_{i,sc}/L_i) \cdot (1 - J_i)] \cdot (1 - Z_i)$$

where L_i is the average height of crop type i (cm), $L_{i,jc}$ is the average cutting height of crop type i by mechanical harvesting (cm), $L_{i,sc}$ is the average cutting height of crop type i by manual harvesting (cm), J_i is the proportion of crop type i harvested by machinery in the total harvested area, and Z_i is the loss rate of crop type i during harvesting and transportation.

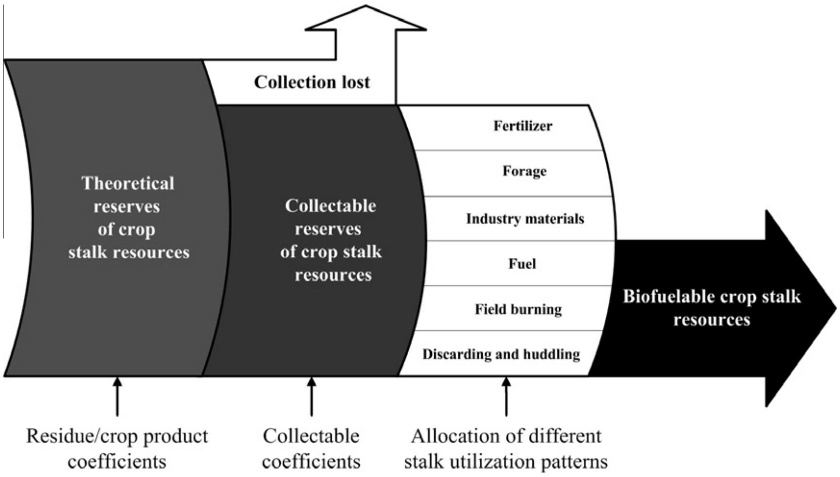

Fig. 2. A flowchart of the derivation of crop stalk resources available for energy utilization, illustrating how the three kinds of crop stalk resources are related to each other.

Table 2
Parameters used in calculating collectable stalk coefficients of different crops (harvesting area was obtained from [25]; mechanical harvesting area derived from [33]; reaping coefficient and lost coefficient were quoted from Cui et al. [18]).

Crops	Harvesting area (10^3 ha)	Mechanical harvesting			Artificial harvesting		Lost coefficient	Collectable coefficient
		Area (10^3 ha)	(%)	Reaping coefficient	(%)	Reaping coefficient		
Rice	91.472	29.33	32.06	0.66	67.94	0.90	0.05	0.7819
Wheat	483.567	450.70	93.20	0.77	6.80	0.90	0.05	0.7399
Corn	1915.587	73.96	3.86	1.00	96.14	1.00	0.05	0.9500
Beans	973.218	341.33	35.07	1.00	64.93	1.00	0.05	0.9500
Rape	229.794	188.45	82.01	0.85	17.99	0.95	0.05	0.8246
Cotton	1.987	–	–	–	100.00	0.94	0.05	0.8930
Others	1870.937	–	–	–	100.00	0.95	0.05	0.9025

Table 3
Different utilization proportions of stalk resources (Data were quoted from Gao et al. [36]).

Stalk types	Fertilizer	Forage	Industry materials	Biofuelable		
				Fuel	Field burning	Discarding and huddling
Rice	41.7	16.2	5.6	25.5	7.8	3.2
Wheat	40.2	14.3	8.3	20.3	9.0	7.9
Corn	32.2	27.1	1.8	24.7	5.4	8.8
Other cereal crops	11.5	67.8	2.8	10.5	1.0	6.4
Legumes	16.8	34.4	1.2	41.6	1.9	4.1
Tubers	20.9	47.1	0.0	13.6	5.6	12.8
Peanuts	26.0	41.5	1.0	23.0	0.7	7.8
Rape	34.1	20.4	1.0	26.6	12.5	5.4
Cotton	16.0	15.5	4.4	56.6	2.3	5.2
Others	47.6	27.5	1.1	14.6	3.7	5.5
Total[a]	29.2	33.2	2.2	23.3	4.6	7.6

[a] Values in last row are 29 years averages calculated by different crop stalk yield of each year in IMAR and its corresponding utilization proportion.

2.5. Estimating biofuelable crop stalk resources

With data of collectable crop stalk resources, the allocation of different stalk utilization patterns in IMAR was calculated based on the research by Gao et al. [36], which represented the proportions of six utilization patterns of different crops at the national level (Table 3). In our opinion, stalk which ends up as fuel material, field burning, or is discarded or huddled should be used as bioenergy stock with modern bioenergy conversion technology in the context of IMAR. We defined these categories of stalk as biofuelable crop stalk resources. Without field survey of stalk utilization patterns in IMAR or closely related literature, adoption of average national statistical data might result in higher estimation of stalk utilization for fertilizer and lower estimation for forage. By incorporating data of annual mechanized silage in IMAR, however, we reduced the deviations of estimations for fertilizer and forage utilization as a whole. Since the main purpose of our study was to determine the amount of biofuelable stalk resources, the estimation calculated according to the research of Gao et al. that 35.5% of theoretical crop stalk yield was available for biofuel production in IMAR every year was creditable.

After data of biofuelable crop stalk resources were obtained, two other evaluation indicators were calculated. One is per capita biofuelable stalk resources and it refers to the stalk resources that can be consumed as energy by each person in the region [18]. This indicator describes the relative abundance of biofuelable stalk resources. Since all banners in IMAR (not only agricultural areas) produced stalk resources, we used total population of each administrative district to calculate per capita biofuelable stalk resources. The other one biofuelable stalk resource yield per sown area refers to the stalk resources for energy utilization that is produced per unit sown area in some region [18]. The greater the value is, the higher concentration of biofuelable stalk resources is and the more beneficial it will be for large-scale resource exploitation and utilization economically. We chose sown area rather than administrative district or cultivated area because it was more meaningful when considering collecting cost, energy consumption, etc.

3. Results

3.1. Gross reserve of crop stalk resources in IMAR

The type, quantity, proportion, and production area of stalk resources in IMAR vary in space and time (Table 4). Six major kinds of stalk accounted for 94.0% of the total crop stalk resources, which were corn, sunflower, other cereal crops, wheat, beans and tubers in sequence according to their contribution. Among them five were grain crops and the sum of their percentages reached 83.4%, indicating that grain crops play a crucial role in the crop stalk resource production. Nationally, it was grain crops too that occupy absolute predominance in gross stalk resource production. But the top 3 kinds of stalk resources were rice, corn and wheat [15,19].

The standard deviations of the theoretical yield of stalk were all large (Table 4). It indicated that stalk yield had great variability among different years. From 1980 to 2008, total regional theoretical yields of crop stalk resources kept a trend of robust increase on the whole (Fig. 3), rising from around 5 million tons to nearly 30 million tons with an average annual increase of 16.3%.

The estimation of the gross stalk production in China was 795 million tons in 1998 by Zhong et al. [13], about 940 million tons in 1999 by Han et al. [12], 554 million tons in 2000 by Gao et al. [36], 622 million tons in 2002 by Zeng et al. [37], 490 million tons in 2003 by Liu [15], 728 million tons in 2004 by Liu

Table 4
Average theoretical stalk yield by crop categories (1980–2008) in Inner Mongolia (data are presented as means ± SD, $n = 29$. Values in brackets are 29 years average output proportions of leagues or prefectures).

Crops	Yield of crops (10^4 ton)	Theoretical yield of stalk (10^4 ton)	(%)	Central producing area[b]
Corn	576.1 ± 378.6	720.2 ± 473.2	48.5	TL (34.2%), CF (18.4%), XA (11.6%), BYNE (9.0%)
Sunflower	52.4 ± 17.0	157.1 ± 50.9	10.6	BYNE (52.0%), CF (9.5%), EEDS (8.9%)
Other cereal crops	143.2 ± 44.1	143.2 ± 44.1	9.6	CF (35.2%), TL (18.6%), WLCB (10.3%), XA (9.5%)
Wheat	194.3 ± 77.7	132.1 ± 52.8	8.9	BYNE (31.6%), HLBE (23.2%), CF (8.5%) WLCB (7.5%)
Beans	84.3 ± 53.0	126.5 ± 79.4	8.5	HLBE (55.2%), XA (14.7%), TL (13.3%), CF (9.4%)
Tubers	97.5 ± 61.0	117.0 ± 73.2	7.9	WLCB (40.1%), HLBE (13.1%), HHHT (12.0%), BT (7.3%)
Rice	38.4 ± 26.3	28.0 ± 19.2	1.9	TL (39.9%), CF (26.6%), XA (24.0%), HLBE (9.4%)
Sugar beet	190.2 ± 81.1	19.0 ± 8.1	1.3	BYNE (34.8%), TL (19.1%), CF (8.6%), WLCB (8.3%)
Oil flax	7.6 ± 2.6	15.2 ± 5.1	1.0	WLCB (45.9%), HHHT (18.8%), XLGL (13.5%)
Other oil-bearing crops	6.3 ± 2.8	12.6 ± 5.6	0.8	TL (69.5%), BT (7.1%)
Rape	11.3 ± 10.0	11.4 ± 10.1	0.8	HLBE (60.5%), WLCB (12.3%), HHHT (9.4%)
Fiber crops	0.8 ± 1.0	1.4 ± 1.7	0.1	HLBE (43.2%), XA (23.8%), CF (11.2%), WLCB (9.4%)
Peanuts	0.7 ± 1.0	1.3 ± 2.1	0.1	TL (81.1%), XA (16.4%)
Cotton	0.04 ± 0.07	0.2 ± 0.4	0.0	ALS (86.3%), TL (10.3%)
Total	1403.2 ± 549.9	1485.5 ± 680.6	100.0	

[b] HLBE, Hulunbeier City; XA, Xingan League; 0TL, Tongliao City; XLGL, Xilinguole League; WLCB, Wulanchabu City; HHHT, Hohhot City; BT, Baotou City; EEDS, Ordos City; BYNE, Bayannaoer City; WH, Wuhai City; ALS, Alashan League.

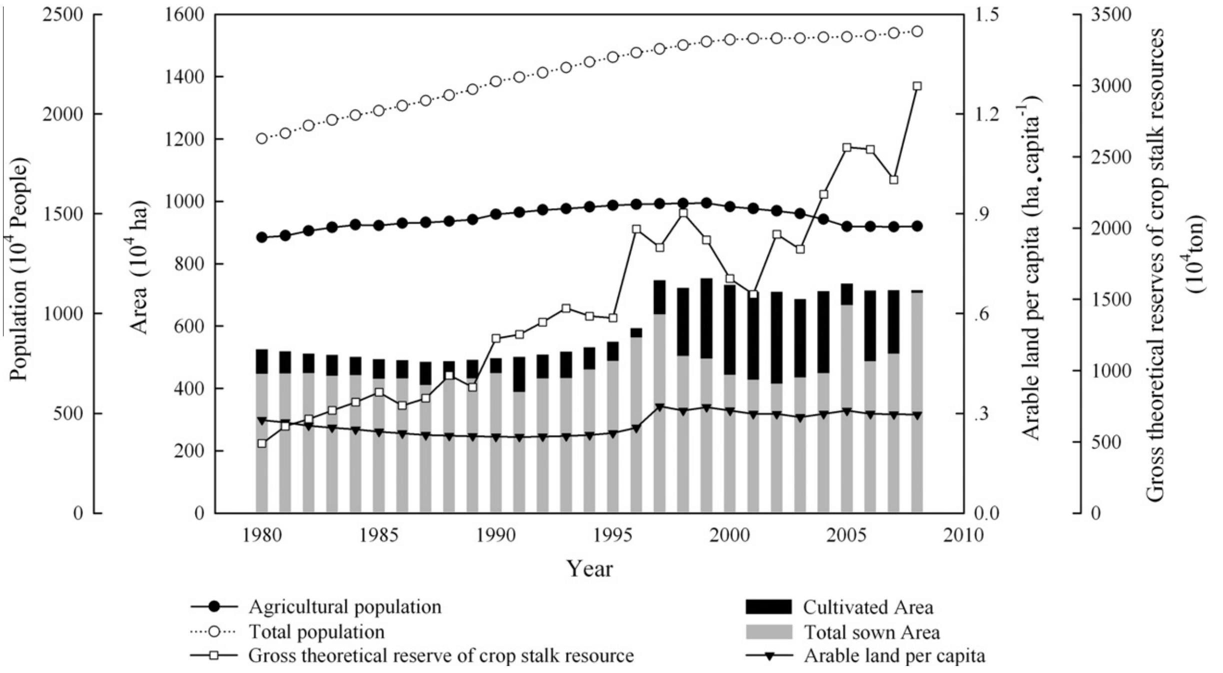

Fig. 3. Changes in the gross theoretical reserves of crop stalk resources, cultivated area, total sown area, total population, agricultural population, and arable land per capita in Inner Mongolia between 1980 and 2008.

and Shen [38], 484 million tons in 2005 by Liu et al. [19], and 433 million tons in 2006 by Cui et al. [18]. By comparing the gross stalk yield of IMAR with that of the whole country, we derived the proportions of stalk yield of IMAR as 2.6%, 2.0%, 3.0%, 3.1%, 3.8%, 3.1%, 5.3%, and 5.9% in the past 8 years respectively. The proportion of IMAR's stalk yield has kept a stable increase in recent years.

The distribution of theoretical stalk yield was quite uneven at both the league (prefecture) and banner (county) levels (Table 5). The top three prefectural-level units for theoretical stalk yield were Tongliao City, Chifeng City, and Bayannaoer City. The average annual stalk yield (over a 29-year period) was 3.335 million tons for Tongliao City, 2.421 million tons for Chifeng City, and 2.033 million tons for Bayannaoer City. The total stalk output of these three prefectural cities accounted for 53% of the gross theoretical stalk resources in IMAR. At the banner level, the annual stalk yield of 26 counties exceeded the regional average level (0.167 million tons), together accounting for 72% of the total theoretical annual stalk yield of the entire region.

3.2. Total regional biofuelable stalk resources in IMAR

During past 29 years, the trend of total regional biofuelable crop stalk resources was in accordance with that of the theoretical reserve of crop stalk resources, but its increase was slightly gentler (Fig. 3 and 4). In IMAR, grain crop stalk yield accounted for the majority of the total biofuelable stalk and the amount of them showed a similar trend. The yield of oil-bearing and other economic crops (e.g., fiber crops, cotton, and sugar beet) accounted for a small proportion and their growth was negligible compared

Table 5
Average theoretical and biofuelable stalk yields (1998–2008) of each banner (county/municipal district/local city) in Inner Mongolia (data are presented as means ± SD, $n = 29$).

City (league)	Banner (county/municipal districts)	Theoretical stalk yield (10^4 ton)	Biofuelable stalk yield (10^4 ton)
Hohhot City	Municipal districts	12.2 ± 5.8	3.9 ± 2.3
	Tumotezuo Banner	29.7 ± 15.1	9 ± 5.3
	Tuoketuo County	14.6 ± 8.0	4.5 ± 2.9
	Helingeer County	13.2 ± 7.1	4.2 ± 2.7
	Qingshuihe County	6.9 ± 3.6	2 ± 1.2
	Wuchuan County	11.4 ± 7.4	3.4 ± 2.6
Baotou City	Municipal districts	9.5 ± 5.3	3 ± 2.0
	Tumoteyou Banner	38.5 ± 24.2	11.8 ± 8.7
	Guyang County	9.6 ± 5.7	2.9 ± 2.0
	Daerhanmaomingan Union Banner	5.3 ± 4.0	1.6 ± 1.3
Hulunbeier City	Hailaer district	3.2 ± 2.3	0.9 ± 0.7
	Manzhouli City	47.6 ± 35.1	17.2 ± 12.7
	Molidawadawoer National Autonomous Banner	50.6 ± 39.9	20.2 ± 16.0
	Elunchun National Autonomous Banner	16.4 ± 12.5	6.7 ± 5.3
	Ewenke National Autonomous Banner	2.9 ± 2.5	0.8 ± 0.7
	Chenbaerhu Banner	5 ± 4.1	1.5 ± 1.1
	Xinbaerhuzuo Banner	1.6 ± 1.7	0.5 ± 0.5
	Xinbaerhuyou Banner	0.2 ± 0.4	0.1 ± 0.2
	Manzhouli City	0.1 ± 0.0	0.0 ± 0.0
	Yakeshi City	11.9 ± 8.4	3.5 ± 2.5
	Zhalantun City	35.3 ± 21.8	11.8 ± 7.0
	Eerguna City	13.1 ± 9.0	3.7 ± 2.3
	Genhe City	0.2 ± 0.2	0.1 ± 0.1
Xingan League	Wulanhaote City	5.7 ± 3.0	1.8 ± 1.1
	Aershan City	2.2 ± 1.0	0.6 ± 0.2
	Keerqinyouyiqian Banner	40.7 ± 17.9	13.3 ± 6.1
	Keerqinyouyizhong Banner	18.5 ± 11.7	6.2 ± 4.2
	Zhalaite Banner	45.7 ± 23.3	15.4 ± 8.1
	Tuquan County	35.3 ± 15.9	11.4 ± 5.5
Tongliao City	Keerqin district	81.4 ± 27.8	28.6 ± 10.7
	Keerqinzuoyizhong Banner	72.3 ± 32.8	23.7 ± 11.4
	Keerqinzuoyihou Banner	46.5 ± 24.5	16.1 ± 8.9
	Kailu County	54.8 ± 26.3	19.2 ± 10.0
	Kulun Banner	17 ± 10.7	5.3 ± 3.5
	Naiman Banner	35.4 ± 19.4	11.6 ± 6.8
	Zhalute Banner	25.4 ± 13.5	8.4 ± 4.8
	Huolinguole City	1.3 ± 0.9	0.4 ± 0.2
Chifeng City	Municipal districts	54.7 ± 25.9	17.3 ± 8.8
	Alukeerqin Banner	14 ± 8.4	4.4 ± 3.0
	Balinzuo Banner	19.1 ± 8.8	6 ± 3.3
	Balinyou Banner	7.0 ± 4.6	2.2 ± 1.6
	Linxi County	13.6 ± 7.0	4.0 ± 2.3
	Keshiketeng Banner	10.1 ± 3.9	3.0 ± 1.4
	Wengniute Banner	34 ± 19.5	10.3 ± 6.3
	Kalaqin Banner	15.7 ± 4.8	4.6 ± 1.7
	Ningcheng County	37.0 ± 17.7	11.2 ± 6.0
	Aohan Banner	38.3 ± 20.0	11.4 ± 6.6
Xilinguole League	Erlianhaote City	0.0 ± 0.2	0.0 ± 0.0
	Xilinhaote City	0.7 ± 0.5	0.2 ± 0.1
	Abaga Banner	0.0 ± 0.0	0.0 ± 0.0
	Sunitezuo Banner	0.0 ± 0.0	0.0 ± 0.0
	Suniteyou Banner	0.2 ± 0.1	0.1 ± 0.0
	Dongwuzhumuqin Banner	1.4 ± 1.2	0.4 ± 0.3
	Xiwuzhumuqin Banner	0.1 ± 0.1	0.0 ± 0.0
	Taipusi Banner	7.2 ± 3.6	2.0 ± 1.0
	Xianghuang Banner	0.0 ± 0.0	0.0 ± 0.0
	Zhengxiangbai Banner	1.0 ± 0.6	0.3 ± 0.2
	Zhenglan Banner	1.5 ± 0.9	0.5 ± 0.3
	Duolun County	4.8 ± 2.7	1.4 ± 1.0
Wulanchabu City	Jining district	0.3 ± 0.5	0.1 ± 0.1
	Fengzhen City	13.2 ± 4.4	3.8 ± 1.7
	Zhuozi County	9.9 ± 3.9	2.9 ± 1.5
	Huade County	6.2 ± 3.5	1.9 ± 1.2
	Shangdu County	11.7 ± 5.6	3.5 ± 2.0
	Xinghe County	11.7 ± 4.6	3.3 ± 1.6
	Liangcheng County	15.3 ± 7.4	4.6 ± 2.8
	Chahaeryouyiqian Banner	12.0 ± 4.8	3.4 ± 1.7
	Chahaeryouyizhong Banner	9.9 ± 5.4	3.0 ± 1.8
	Chahaeryouyihou Banner	7.2 ± 4.3	2.3 ± 1.5
	Siziwang Banner	9.6 ± 6.3	3.0 ± 2.1

Table 5 (*continued*)

City (league)	Banner (county/municipal districts)	Theoretical stalk yield (10^4 ton)	Biofuelable stalk yield (10^4 ton)
Ordos City	Dongsheng district	2.9 ± 2.2	0.8 ± 0.8
	Dalate Banner	37.5 ± 20.7	11.8 ± 7.2
	Zhungeer Banner	9.4 ± 4.3	2.8 ± 1.6
	Etuokeqian Banner	4.6 ± 4.2	1.6 ± 1.5
	Etuoke Banner	3.6 ± 2.8	1.2 ± 1.0
	Hangjin Banner	15.1 ± 12.0	4.5 ± 3.7
	Wushen Banner	7.3 ± 5.2	2.5 ± 1.9
	Yijinhuoluo Banner	7.7 ± 4.5	2.4 ± 1.6
Bayannaoer City	Linhe district	50.0 ± 15.1	14.2 ± 4.7
	Wuyuan County	45.9 ± 19.5	12.2 ± 5.4
	Dengkou County	9.6 ± 4.5	2.8 ± 1.4
	Wulateqian Banner	41 ± 21.3	11.2 ± 6.3
	Wulatezhong Banner	13.6 ± 9.2	3.9 ± 2.7
	Wulatehou Banner	1.5 ± 1.0	0.5 ± 0.3
	Hangjinhou Banner	41.2 ± 11.4	12.1 ± 3.8
Wuhai City	Municipal districts	1.7 ± 1.4	0.5 ± 0.5
Alashan League	Alashanzuo Banner	5.8 ± 5.8	1.8 ± 1.8
	Alashanyou Banner	0.5 ± 0.6	0.2 ± 0.2
	Ejina Banner	0.4 ± 0.5	0.2 ± 0.2

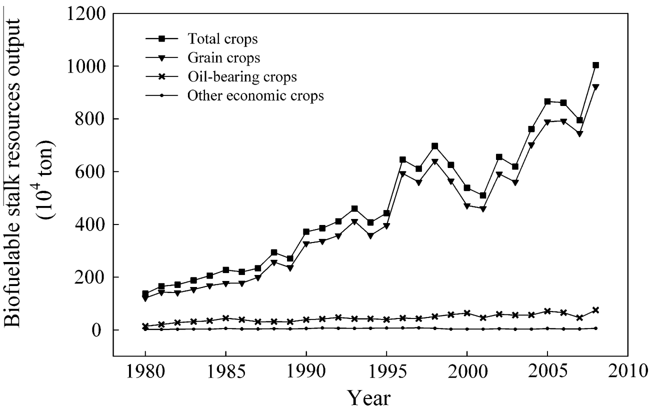

Fig. 4. Changes in crop stalk resources available for energy utilization in Inner Mongolia between 1980 and 2008.

with that of grain crop stalk; though from 1980 to 2008 their yields increased by four times and twice, respectively (Fig. 4).

Specifically, the composition alterations of total biofuelable stalk resources were as follows: (1) the proportions of corn stalk and legumes stalk continued to increase; (2) the proportions of wheat stalk, other cereal crop stalk, sunflower stalk, other oil-bearing crops stalk, and other economic crops stalk continued to decrease; (3) the proportions of rice stalk and tubers stalk dropped in the 1990s and then increased in the past 10 years (Fig. 5). The proportion of corn stalk increased most by up 21%, and became the crucial factor that determined the amount of biofuelable stalk resource (Fig. 5).

The distribution of biofuelable stalk yield was not uniform among the leagues as well as among the banners (see Table 5 for detail). The three prefectural units with the highest biofuelable stalk yields were Tongliao City, Chifeng City, and Hulunbeier City, the first two of which also were among the top three prefectures

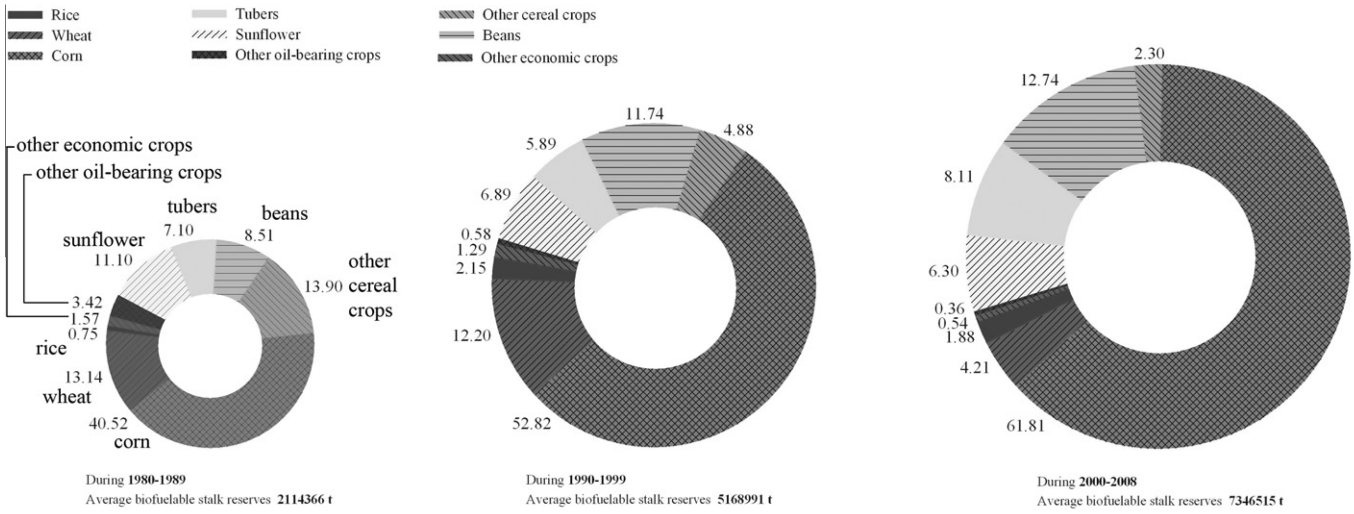

Fig. 5. Temporal changes in the composition of crop stalk resources available for energy utilization in Inner Mongolia for three periods between 1980 and 2008.

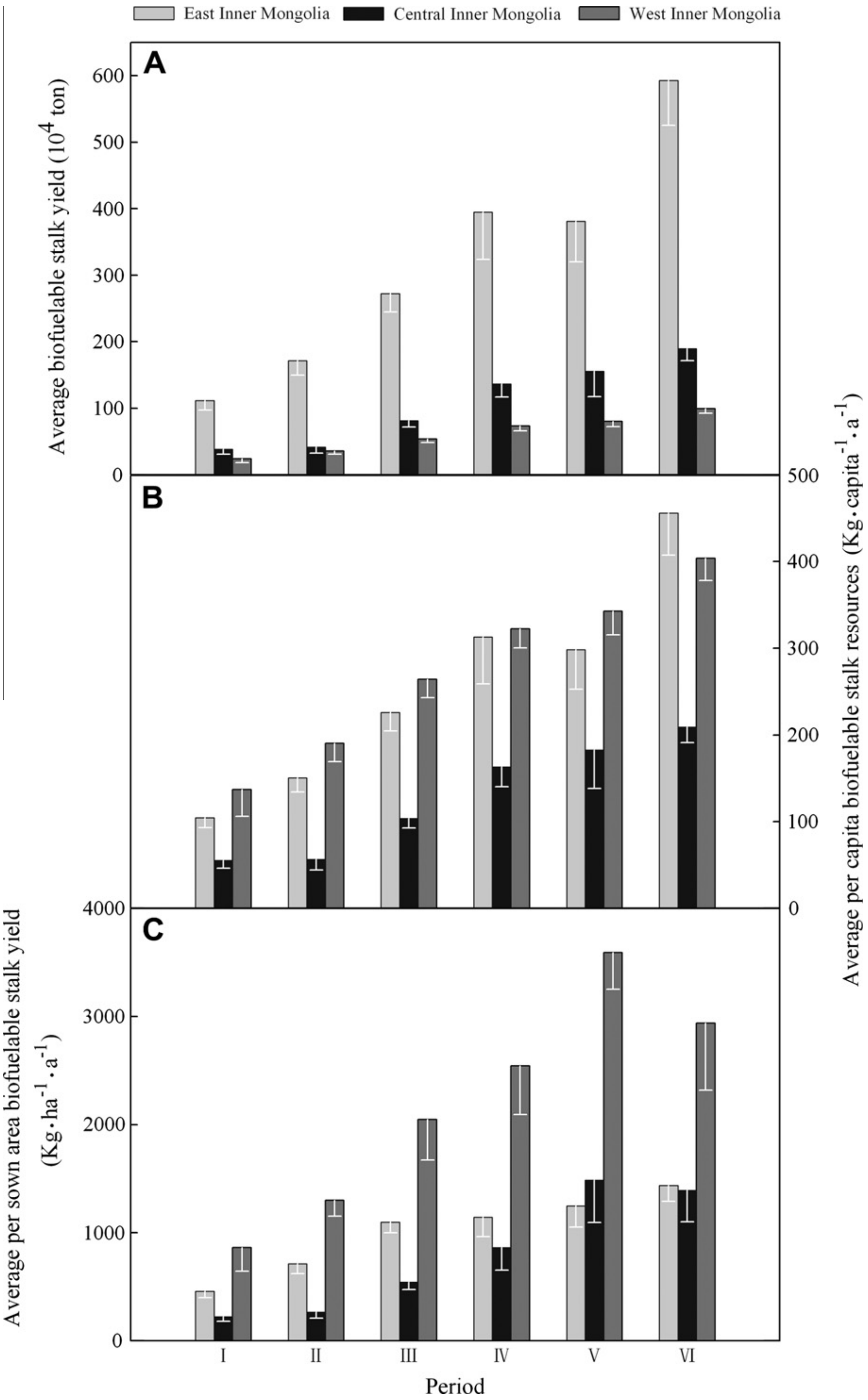

Fig. 6. Spatiotemporal patterns of (A) the gross amount of crop stalk resources available for energy utilization, (B) per capita stalk resources available for energy utilization, (C) per sown area stalk yield available for energy utilization in Inner Mongolia during different periods between 1980 and 2008.

with the highest theoretical stalk yields. The annual biofuelable stalk yield was 1.132 million tons for Tongliao City, 0.745 million tons for Chifeng City, and 0.688 million tons for Hulunbeier City, together accounting for 54% of the total biofuelable stalk resources in IMAR. Again, for 26 banners the annual biofuelable stalk yield exceeded the regional average level (0.053 million tons), together amounting to 74% of the total regional annual biofuelable crop stalk yield. The ranking of the 26 banners was not exactly the same as that for the theoretical stalk yield discussed earlier. These differences were due mainly to different cropping systems and variable yields in each banner.

3.3. The temporal and spatial distribution characteristics of biofuelable stalk resources

3.3.1. The temporal and spatial pattern of the gross biofuelable stalk yield

By comparing the average values of every 5 years from 1980 to 2008, we found that the spatial distribution of biofuelable stalk resources in IMAR showed a clear trend of ‘‘being higher in the East and being lower in the West’’, with pronounced variations among the three sub-regions; the increase of biofuelable stalk resources was ‘‘more robust in the East and more gentle in the West’’, with

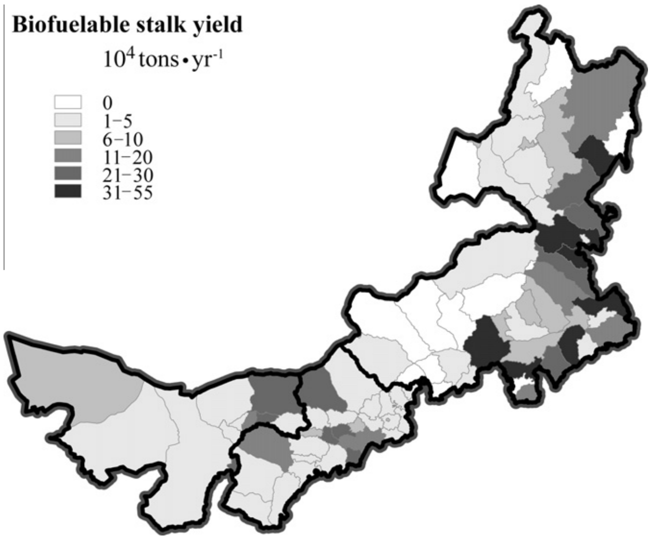

Fig. 7. The spatial distribution of biofuelable crop stalk production in Inner Mongolia (based on the average values between 2005 and 2008).

the inter-annual variation decreasing from the East to the Middle to the West (Fig. 6A).

The biofuelable stalk resources were mainly in agricultural areas of East Inner Mongolia, accounting for more than 60% of the total resources. Central Inner Mongolia accounted for about 20% of total regional stalk production. West Inner Mongolia had the least stalk resources available for energy utilization, most of which were mainly produced in Bayannaoer City (Fig. 7).

3.3.2. The temporal and spatial pattern of per capita biofuelable stalk resources

At the sub-region scale, per capita biofuelable stalk resources in the six periods was all "high in the East and West and low in the middle" (Fig. 6B). The indicator of West Inner Mongolia was higher than that of East Inner Mongolia before 2005. In recent years, however, East Inner Mongolia has exceeded West Inner Mongolia in terms of per capita biofuelable stalk resources. Central Inner Mongolia kept in step with West Inner Mongolia in the trend of per capita biofuelable stalk resources with a positive growth, whereas West Inner Mongolia had a more steady increase. Before the mid-1990s, East and West Inner Mongolia had similar trend in per capita biofuelable stalk growth. Since then, however, East Inner Mongolia had a much faster growth than West Inner Mongolia did, but with fluctuations (Fig. 6B). Now the center of national agricultural production is shifting to Northeast of China. Central Inner Mongolia prioritizes the development of coal and rare earths industries and related industry chains, and farming technologies are undergoing continuous progress. In such context, the growth potential of per capita biofuelable stalk resources in East Inner Mongolia is expected to be the highest among the three sub-regions. Consequently, the gap between sub-regions would be widened further. The pattern of relative abundance of the biofuelable stalk resources may change to be "high in the East, low in the Middle, and intermediate in the West".

At banner scale, the difference between average per capita value and average regional value from 2005 to 2008 was used as criterion to determine the relative abundance degree of stalk resources of each banner in IMAR. Fig. 8A depicted spatial distribution of the relative abundance of different areas in IMAR. Currently the regional per capita biofuelable stalk resources was 360 kg/a, higher than the national level of 246 kg/a [18]. Per capita biofuelable stalk yield of 34 banners was above average regional level, among which, Molidawadawoer National Autonomous Banner had the highest per capita value of 1563 kg/a.

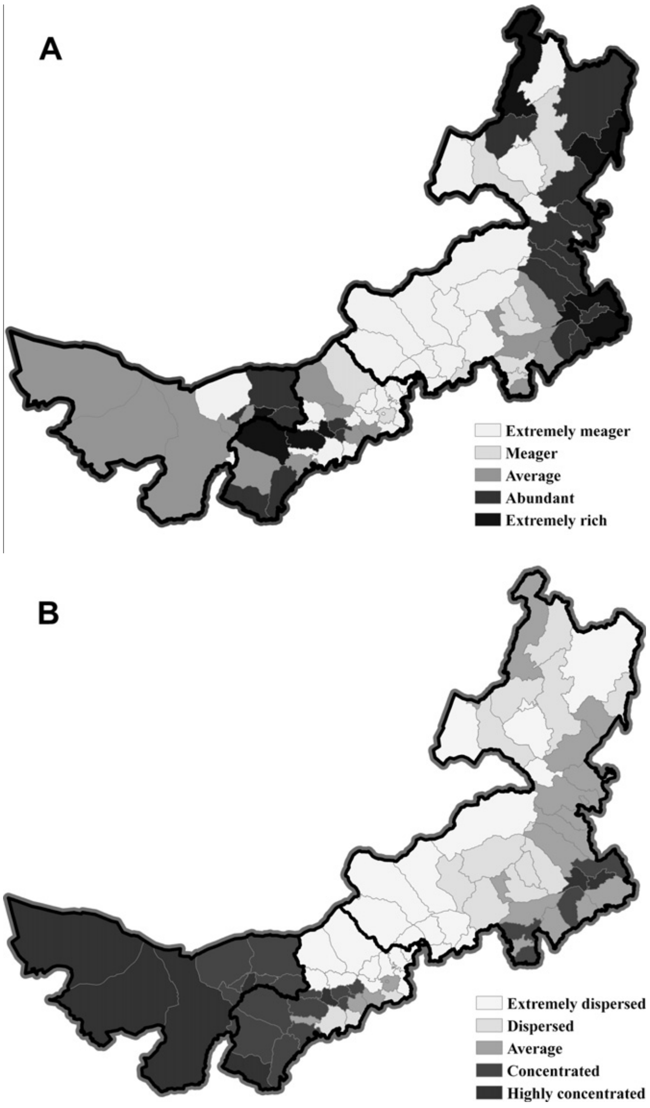

Fig. 8. The spatial pattern of the relative abundance (tons/person) and concentration (tons/ha) of stalks for energy production in Inner Mongolia. (A) Extremely rich = greater than 200% of the regional average value; Abundant = between 125% and 200% of the regional average; Average = between 75% and 125% of the regional average; Meager = between 50% and 75% of the regional average; Extremely meager = less than 50% of the regional average. (B) Highly concentrated = greater than 200% of the regional average; Concentrated = between 125% and 200% of the regional average; Average = between 75% and 125% of the regional average; Dispersed = between 50% and 75% of the regional average; Extremely dispersed = less than 50% of the regional average.

3.3.3. The temporal and spatial pattern of per unit sown area biofuelable stalk yield

At the sub-region scale, biofuelable stalk yield per sown area displayed different distribution patterns during the six periods. Generally, the resource concentration was high at East and West Inner Mongolia and low in the middle (Fig. 6C). From 2000 to 2004, however, the resource concentration became significantly high in the West, low in the East, and medium in the Middle (Fig. 6C). Overall, West Inner Mongolia had higher stalk resource concentration than East and Central Inner Mongolia. Central Inner Mongolia kept in step with West Inner Mongolia in the trend of biofuelable stalk yield per sown area with a significant positive growth before 2004 and a slight decrease afterwards. Though East Inner Mongolia maintained a positive growth in stalk resource concentration in all the periods, the growth rate was lower than the other two sub-regions and the biofuelable stalk resource concentration remained unchanged in 1990s (Fig. 6C). The dynamics of biofuelable stalk concentration distribution might be largely attributable to the fact that East Inner Mongolia increased its stalk resources by expanding sown area, while West and Central Inner Mongolia by improving yield per hectare.

At banner scale, the difference between average biofuelable stalk yield per sown area and average regional value from 2005 to 2008 was used as criterion to determine the concentration degree of biofuelable stalk resources of different areas in IMAR. Fig. 8B depicted spatial distribution of the concentration of different areas in IMAR. Currently, regional biofuelable stalk resource yield per sown area was 1.512 tons/ha, a little lower than national level of 1.92 tons/ha [18]. Biofuelable stalk yield per sown area of 34 banners was above the average regional level as well, among which Ejina Banner had the highest concentration of biofuelable stalk resources of 11.957 tons/ha.

3.4. Overall evaluation of biofuelable stalk resources

Based on the results of relative abundance and concentration of biofuelable stalk resources in IMAR, we evaluated the stalk resources as a bioenergy stock in 89 banners in regard to exploitation and utilization. We gave priority to the relative abundance rather than the concentration. Using Cui et al.'s classification method [18], we classified the areas into three classes, which were areas for intensive exploitation, areas for moderate exploitation and areas restricted from exploitation (Fig. 9).

Geographically, in IMAR, the areas for intensive exploitation were mainly located in west bank of Nengjiang river, Western Liao river basin, Tumote plain, south area of Ordos basin, and Hetao plain. The areas for moderate exploitation were mainly distributed in Alashan League and Chifeng City, whereas most parts of Xilinguole League, Wulanchabu League, Hohhot City and Baotou City were not suitable for stalk bioenergy exploitation because these districts were located either in steppe zone or mountainous and hilly areas or even urban industrial zone.

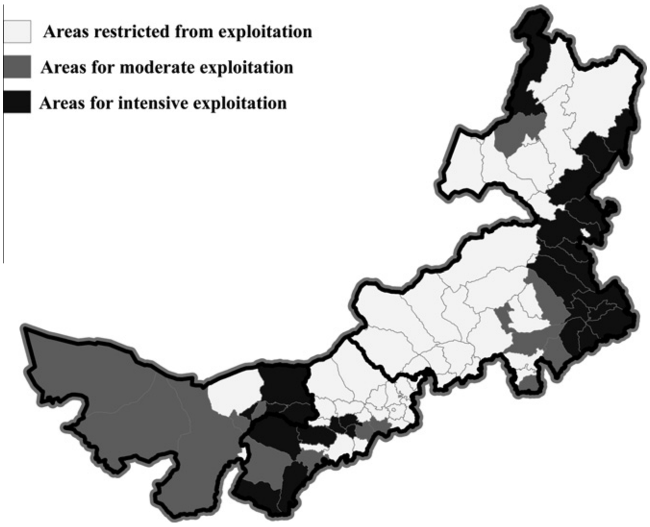

Fig. 9. The spatial distribution of potential development zones for stalk-based bioenergy in Inner Mongolia. Areas for intensive exploitation are places where stalk resources were at least abundant in the abundance ranking and average in the concentration ranking (see Fig. 8); areas for moderation exploitation are places with stalk resources that were average in abundance and dispersed in concentration; and areas restricted from exploitation are places where the level of stalk resources is meager or extremely meager in abundance and extremely dispersed in concentration.

The results revealed that 26 banners in IMAR, which together accounted for 67% of total regional biofuelable stalk resource yield up to about 5.87 million tons, were suitable for intensive stalk resource exploitation. Fifteen banners were suitable for moderate stalk resource exploitation and they together accounted for 15% of total regional biofuelable stalk resource yield equivalent to about 1.35 billion tons. Thus all the stalk resources suitable for bioenergy exploitation in IMAR could reach 7.22 million tons, equivalent to 3.72 million tons of standard coal, and could meet at least 3% of primary energy demand in IMAR if they were fully exploited.

4. Discussion

4.1. Assessment of stalk resources in IMAR

4.1.1. Crop stalk production and affecting factors

Four major factors contributed to the overall growth and intra-annual fluctuation of the theoretical reserve of crop stalk resources in IMAR: climate conditions, pressures from population growth, institutional changes, and agricultural modernization. Located in arid and semi-arid areas, more than half of IMAR consists of cultivated areas that are dependant on precipitation, although irrigated farmland increased from 23% in 1980 to 42% in 2008 of the total cultivated area in the region. Precipitation is a main limiting factor for crop yields and thus stalk resources. Precipitation decreases gradually from east to west across IMAR, and varies greatly form year to year, with frequent spring draughts especially in the western part of the region. In the past several decades, the population of IMAR increased steadily and reached about 25 million in 2010 (Fig. 3). The growing population led to increases in both cropland area and crop stalk resources. This observation is corroborated by the strong correlation between the population size of the region and the theoretical reserve of crop stalk resources ($R^2 = 0.912$, $p = 0.000$, $n = 29$).

National and provincial policies have also had important impacts on land use practices in general and agricultural production in particular. The total cultivated area in IMAR decreased from the early 1960s to mid-1980s due to industrialization, mining, urbanization, desertification, and conversion from cropland to pastures and forests. After that, however, the total cultivated area began to increase and reached a peak around the mid-1990s because of incentives from agricultural products. Since 1997, the total cultivated area shrank again, but only moderately, as a consequence of China's West Development and "Grain for green" policies. Differences in cropping systems with different residue/crop product ratios also contributed to the variations in the estimated theoretical stalk yield. In addition, as the level of agricultural modernization improved, irrigated areas increased from 1.10 million ha in 1980 to 2.87 million ha in 2008; the annual application of chemical fertilizer increased nearly 20 times during the 29 years; and the total power of machinery for faming and animal husbandry increased from 6.14 M kW in 1980 to 27.79 M kW in 2008. Our statistical analysis indicates that irrigation, fertilizer, and machinery were strongly correlated with the theoretical stalk output ($R^2_{\text{irregation}} = 0.918, p_{\text{irregation}} = 0.000; R^2_{\text{fertilizer}} = 0.962, \quad p_{\text{fertilizer}} = 0.000; R^2_{\text{machinery}} = 0.901, p_{\text{machinery}} = 0.000$).

There is still room for increasing the theoretical reserve of crop stalk resources in IMAR. Despite the decline in agricultural population between 2000 and 2009, the crop stalk yield continued to increase, suggesting that crop production in IMAR was not limited by labor forces or that the technological improvements in agricultural practices played a much more important role. In addition, the arable land per capita remained at 0.3 ha since 1997, higher than the average for the previous 17 years. While this number is not likely to increase in the future, the multi-crop index (the ratio of the sown area to the cultivated area) in IMAR was low (Fig. 3), indicating that more arable land could be planted. Also, the limitation by precipitation to crop yield could be alleviated by irrigation and application of fertilizers [39]. With scientific progress and technological innovations, the crop stalk production can be further increased through intercropping to harvest crops twice a year in relatively warmer (southern) parts of several prefectures, including Hulunbeier City, Chifeng City, Tongliao City, Wulanchabu City, Ordos, and Bayannaoer City.

4.1.2. Comparing stalk productions between IMAR and other provinces in China

How important is the stalk production of IMAR at the national level? To address this question, we compared our results with those for China's provinces reported in a recent study by Bi [40]. Limited by data availability, our comparison was only possible for the year of 2008. The gross crop stalk output in 2008 was estimated to be 842.19 million tons for mainland China (not including Hong Kong, Macao, and Taiwan) and 29.77 million tons for IMAR [40] – which was quite close to our estimate of 29.97 million tons. IMAR was ranked thirteenth in the nation.

According to Bi [40], provinces that produced more crop stalks than IMAR were Henan Province (87.65 million tons), Shandong Province (71.91 million tons), Heilongjiang Province (54.59 million tons), Jiangsu Province (48.56 million tons), Hebei Province (48.32 million tons), Sichuan Province (47.22 million tons), Anhui Province (47.19 million tons), Guangxi Zhuang Autonomous Region (45.77 million tons), Hubei Province (39.94 million tons), Hunan Province (39.87 million tons), Jilin Province (34.98 million tons), and Xinjiang Uygur Autonomous Region (29.93 million tons). The stalk production of four types of crop species in IMAR was dominant at the national level: sunflower, grains except wheat, rice and corn, sugar beets, and oil flaxes, respectively, accounting for 42%, 19%, 17%, and 10% of its national total. The theoretical stalk yield per unit of sown area in 2008 for IMAR was 4.34 tons/ha, which was below the national average of 5.39 tons/ha [40]. The per capita theoretical stalk yield in 2008 for IMAR, however, was 1.23 tons/person which was much higher than the national average of 0.64 tons/person. This put IMAR in the fourth place among the 31 provinces that were considered.

4.1.3. Uncertainties in estimating crop stalk production

Residue/crop product ratios are key determinants in estimating the theoretical crop stalk yields. There are different systems of residue/crop product coefficients developed in China [40] and the residue/crop product ratios vary substantially in their values among these systems (Table 6). The first was developed by China Agricultural Regionalization Committee in the early 1980s and then adopted by China Association of Rural Energy Industry for estimating the stalk quantities available for fuel. But this system did not indicate information on the water content of stalks. The second was introduced in Agricultural Technology & Economy Handbook [41]. The third, which included belowground biomass in calculating residue yield, was developed by Zhang and Zhu [42]. The fourth was described by Liang et al. [43]. In addition, other sources of uncertainty include the effects of soil, climate, and cropping systems on the residue/crop product ratios of different crops or even the same crops in different areas [18]. Also, the advances in crop breeding and agricultural production efficiency tend to reduce the residue/crop product ratios in general [44]. Thus, it is important to consider the time sensitivity of residue/crop product coefficients in estimating stalk yields for different historical periods.

Being aware of the above sources of uncertainty, we took great care of selecting residue/crop product ratios that are widely accepted, and geographically and temporally compatible. To minimize methodological inconsistencies in the reported residue/crop product ratios, we applied five criteria in the selection process: (1) data from field measurements, (2) methods adequately described, (3) containing information on stalk water content, (4) covering the entire Inner Mongolia region, and (5) published after 2006. As a result, we compiled the residue/crop product ratios mainly from Cui et al. [18], Jia [34], and Song et al. [23]. These re-

Table 6
Comparison of the residue/crop product ratios from different literatures.

Crops	China Association of Rural Energy Industry [40]	Niu and Liu [41]	Zhang and Zhu [42]	Liang et al. [43]	Zhong et al. [13]	Jia [34]	Liu and Shen [38]	Cui et al. [18]
Food crops	–	–		–	–	–	–	–
Grain crops	–	–	–	–	–	–	–	–
Rice	0.623	0.9	–	0.966	1.1	0.78	1	0.68
Wheat	1.366	1.1	1.323	1.03	1.1	0.73	1.1	1.25
Corn	2.0	1.2	1.718	1.37	2.0	0.90	2	1.25
Millet	–	–	1.269	1.51	2.0	–	1.5	–
Sorghum	–	–	1.616	1.44	2.0	–	2	–
Others	1	1.6	1.592	1.60	1.5	–	1.6	–
Beans	1.5	–	–	–	2.0	–	1.7	–
Soybean	–	1.60	–	1.71	–	0.75	–	–
Tubers	0.5	0.5	1.295	0.61	1.2	–	1	–
Potato	–	–	–	–	–	–	–	–
Sweet potato	–	–	–	–	–	–	–	–
Oil-bearing crops	2.0	–	–	–	–	–	–	–
Peanuts	–	0.8	–	1.52	2.0	–	1.5	–
Rape	–	1.5	1.348	3	3.0	1.29	3	1.01
Sesame	–	2.2	2.985	0.64	3.0	–	2	–
Oil flax	–	–	5.882	–	2.0	–	2	–
Sunflower	–	–	1.808	0.6	3.0	–	2	–
Cotton	3.0	3.4	2.217	–	3.0	3.53	3	5.51
Fiber crops	1.70	–	1.613	–	–	–	1.7	–
Ramie	–	–	–	–	1.7	–	–	–
Hemp	–	3.0	–	–	1.7	–	–	–
Flax	–	–	–	–	1.7	–	–	–
Sugar crops	–	–	–	–	–	–	–	–
Sugar beet	0.1	–	–	–	0.1	–	0.1	–

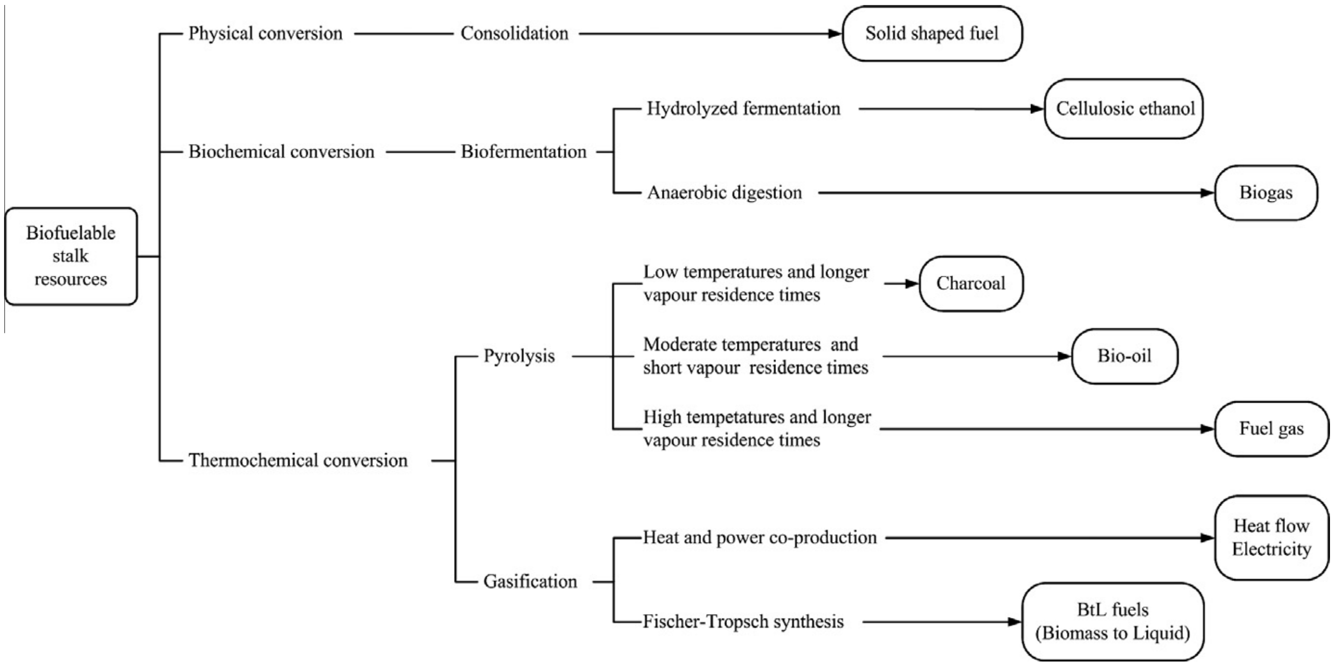

Fig. 10. Illustration of modern bioenergy conversion technologies and their relevant products (based on [11,40]).

cent studies combined both previous data from the literature and additional field observations. Because of the lack of metadata we were not able to conduct a detailed uncertainty analysis. Nevertheless, we believe that the level of uncertainty in our results is acceptable in that they came out of a systematic and comprehensive analysis based on the most reliable data sources up to date.

In addition, crop stalk resources in our study refer mainly to crop stalks and leaves, excluding residue byproducts such as peanut shells and corn cobs. This may have underestimated the theoretical crop stalk yields and thus biofuelable stalk production. Peanuts were not an important oil-bearing crop in IMAR, and the peanut shell production accounted only for 0.01% of our calculated gross stalk yield (the peanut shell/peanut ratio was 0.28 [40]). The production of corn cobs (the corn cob/corn ratio was 0.21 [40]) accounted for 8.14% of the gross stalk yield. We did not consider such crops as tobaccos, vegetables, and melons, which together could produce 179.5×10^4 tons of additional stalks. Without these crops included in the analysis, our study has somewhat underestimated the gross crop stalk production in IMAR, but we believe that our main conclusions remain robust.

4.2. Developing crop stalk-based bioenergy for Inner Mongolia

4.2.1. Selection of energy utilization pathways of stalk resources

A number of conversion technologies are available to obtain bioenergy from stalks [11,40] (Fig. 10). In general, stalks can be converted into biofuels by physical, biochemical, and thermochemical conversion technologies, and stalk-produced biofuels can be of solid, liquid, and gaseous forms. At present, there is only one stalk-based bioenergy generation plant (a demonstration project) in operation in IMAR, which is located at Wuyuan County of Bayannaoer City [23]. The plant was designed to use sorghum stems to produce bioethanol through solid-state fermentation in rotate-drum bioreactors and the pilot experiment succeeded in 2006, with the xylitol conversion ratio reaching 94.4% while bioethanol formation was higher than 87% of the theoretical value [23]. Assuming that 4 tons of crop residues can produce 1 ton of bioethanol [45], the stalk-based bioethanol production potential in IMAR is 7.49 million tons, which is equivalent to 2.0×10^9 MJ (caloric value at 20 °C is 26.8 MJ/kg [46]) or 4.70 million tons of petrol (fuel equivalence ratio is 0.63:1 [46]). This is nearly 1.6 times the total petrol consumption of IMAR in 2008.

Conversion technologies for crop stalks in China, such as cellulosic ethanol and BtL (Biomass to Liquid) fuels, are still in the experimental or demonstration stage. The most commonly used technique in pretreatment of cellulosic materials is acid hydrolysis since it is usually the least expensive [47]. In the current debate on biofuels, the proponents have argued that biofuels can produce positive net energy balance (NEB) and reduce GHG emissions [5,48–51], but the opponents have shown exactly the opposite [3,52,53]. Two general reasons underline this controversy: one involving the great variations in selecting the system boundary, parameters, and input data sources for LCA, and the other associated with the complex dynamics of agricultural production systems in terms of land use pattern and economic and policy changes [54].

As a key strategic energy base of China for the 21st century, IMAR's most important energy source is coal. Ordos City is rich in coal resources which are concentrated in Dalate Banner, Yijinhuoluo Banner, Wushen Banner, and Zhungeer Banner, together accounting for 80% of the regional coal reserve area [55]. In the past few decades, Ordos City has witnessed a flood of coal-based industries and a break-neck economic growth. The region lies in the centre of areas suitable for intensive stalk exploitation in West Inner Mongolia (Fig. 9), where annual biofuelable stalk resources are around 2.0 million tons. If moderate chemical industries are set up here to produce methanol, gasoline, diesel oil and so on by co-firing approach, using coal and stalk as raw materials, the energy conversion efficiency can be improved substantially [56]. Meanwhile, GHG and atmospheric pollutant emissions can be reduced [57] and the income of local farmers increased. Similarly, the stalk resources in East Inner Mongolia can be transported to Zhalainuoer, Baorixile, Yimin, and Dayan coal mines in Hulunbeier City, Huolinhe coal field in Tongliao City, Baiyinhua and Shengli coal fields in Xilinguole League to generate power or produce liquid fuels by co-firing approach. However, no matter what kind of energy utilization pathway of stalk resources is selected for developing bioenergy industries in IMAR, evaluation of effects on water resources is an important issue that needs to be further studied [58].

Collecting crop stalks over large areas may not be practical at present because the stalk resource abundance is low in most areas across IMAR. Producing molded solid biofuels or fuel gas through pyrolysis may be more feasible. This can improve the energy situation in rural areas in that locally produced high-quality and clean energy helps improve both the environment and the quality of life of the local people. In areas where stalk resource abundance is too low (e.g., a number of places in Xilinguole League and Wulanchabu City), crop stalks should not be collected for biofuel production. But rather, they should be used locally for different purpose, such as animal feed and composting. For instance, Xilinguole League has been an important livestock production base in China, and crop stalks can be used as fodder to alleviate the grazing pressure on the grasslands.

4.2.2. Utilization of stalk resources as an alternative energy source in IMAR

Our analysis indicates that one third of total theoretical reserves of crop stalk resources in IMAR can be used as bioenergy stock every year. After converting them into standard coal by crop types (see conversion coefficients in Ref. [38]), we compared the energy value of stalk resources with total primary energy consumption of each year in IMAR. We found that stalk resources could provide 3–10% of the total primary energy consumption in the region. If these resources are used properly, they can help change the current energy consumption structure in IMAR which is dominated overwhelmingly by coal (accounting for more than 90% of the total energy consumption). Developing bioenergy from stalk resources with modern technologies may also help reduce carbon emissions.

Large-scale energy utilization of stalk resources has not yet been developed in IMAR. Instead, in most rural regions stalks used for energy are consumed through the traditional combustion, which leads to not only the waste of fuels due to low energy use efficiency but also adverse impacts on the environmental and human health [59]. The emission factors for CO_2, SO_2, and NO_x from combustion of stalks were 1.247 ton ton^{-1} [59], 37.5 ton PJ^{-1} [60], 91.1 ton PJ^{-1} [60], respectively. Based on these numbers, we estimated that 100 million tons of CO_2, 500 million tons of SO_2, 1.2 billion tons of NO_x could have been released into the atmosphere by traditional combustion of stalks in IMAR from 1980 to 2008. This estimate does not include emissions of field burning. However, if the stalk resources in IMAR had been utilized by modern bioenergy technologies, combined with capture and sequestration technologies of CO_2 and other air pollutants, IMAR might have reduced the emissions of CO_2, SO_2, and NO_x by 200 million tons, 800 million tons, and 1.8 billion tons, respectively, during the past 29 years.

As a supplementary energy source, stalk resource-based bioenergy may play an important role in achieving sustainable development in IMAR. Firstly, stalk-based bioenergy industries can help improve stalk utilization for energy production, increase energy use efficiency, improve indoor air quality, and take advantage of surplus labor forces in rural areas. Secondly, they can help promote agricultural economics and improve the wellbeing of rural people by providing value-added products.

4.3. Implications for China's sustainable energy future

The Eleventh Five-Year Plan of the People's Republic of China for National Economic and Social Development states that the optimization of the energy industries must "give priority to conservation, rely on domestic supply, take coal as the basic resource, diversify energy resources, and optimize the energy production and consumption structure so as to develop a stable, economical, clean and safe energy supply system". Based on our analysis, IMAR has the potential to develop stalk-based bioenergy to promote its sustainable development goals. However, more detailed and comprehensive studies are needed to help design and implement plans that ensure social, economic, and ecological benefits. At least three factors are important to achieving this goal. First, technologies for large-scale bioenergy production from lignocelluloses stocks must become commercially operational; Second, governmental policies and mechanisms, as well as economic measures such as subsidies, fiscal incentives, and tax exemptions must be in place to ensure the supply of raw materials and prevent competition between energy and forage utilization of stalk resources; Third, sustainable criteria of biofuels and new ensuring environmental benefits regulations on bioenergy products should be intensively developed to make the market standardized [61].

China's new Five-Year Planning has set several green targets to be achieved by 2015, four of which have immediate relevance to the subject matter of our study here: (1) reducing energy and carbon intensity by 16% and 17%, respectively, (2) capping energy use at 4 billion tonnes of coal equivalent, (3) increasing the proportion of non-fossil fuels to 11.4% from the current 8.3%, and (4) reducing emissions of chemical oxygen demand and sulfur dioxide by 8% [62]. As Inner Mongolia is a primary energy base for China, it must fundamentally change its current energy consumption pattern and develop new alternative energy sources (including bioenergy as well as wind, solar, and hydrologic energy), if a sustainable energy future is to be achieved for the region and for the entire country.

5. Conclusion

Inner Mongolia produced about 26 million tons a year in the recent decade, 34% of which were biofuelable. It ranked number 13 among the 32 provinces and district municipalities of China. These numbers will likely continue to increase in the future. Grain crops contributed most to the total production of crop stalks. Thus, our study suggests that Inner Mongolia has the potential for developing stalk-based bioenergy to change its current coal-dominated energy structure. The abundance of biofuelable crop stalk resources in Inner Mongolia was spatially heterogeneous – "high on East and West and low in the middle". However, considering the extremely low amount and high variability of precipitation in the western part of the region, the greatest potential for stalk-based bioenergy development is in the eastern part of Inner Mongolia. Furthermore, any large-scale bioenergy development should simultaneously consider social, economic, and ecological benefits that promote the regional sustainability.

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References

[1] Holdren JP. Energy and sustainability. Science 2007;315:737.

[2] Szuromi P, Jasny B, Clery D, Austin J, Hanson B. Energy for the long haul. Science 2007;315:781.

[3] Pimentel D. Ethanol fuels: energy balance, economics, and environmental impacts are negative. Natural Resour Res 2003;12:127–34.

[4] De Oliveira MED, Rykiel EJ, Vaughan BE. Ethanol as fuels: energy, carbon dilxide balance, and ecological footprint. Bioscience 2005;55:593–602.

[5] Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci 2006;103:11206–10.

[6] Wallace L, Palmer MW. LIHD biofuels toward a sustainable future. Front Ecol Environ 2007;5:115.

[7] Ou X, Zhang X, Chang S, Guo Q. Energy consumption and GHG emissions of six biofuel pathways by LCA in (the) PRC. Appl Energy 2009;86(Suppl. 1):S197–208.

[8] Haberal H. The global socioeconomic energetic metabolism as a sustainability problem. Energy 2006;31:87–99.

[9] Jordan N, Boody G, Broussard W, Glover JD, Keeney D, McCown BH, et al. Sustainable development of the agricultural bio-economy. Science 2007;316:1570–1.

[10] Anselmo Filho P, Badr O. Biomass resources for energy in north-eastern Brazil. Appl Energy 2004;77:51–67.

[11] Liu J, Wu JG. Perspectives and prospects of biofuels. Acta Ecol Sin 2008;28:1339–53.

[12] Han LJ, Yan QJ, Liu XY, Hu JY. Straw resources and their utilization in China. Trans CSAE 2002;18:87–91.

[13] Zhong HP, Yue YZ, Fan JW. Characteristics of crop straw resourecs in China and its utilization. Resour Sci 2003;25:62–7.

[14] Liao CP, Yan YJ, Wang CZ, Huang HT. Study on the distribution and quantity of biomass residues resource in China. Biomass Bioenergy 2004;27:111–7.

[15] Liu JS. Analyses on the distribution pattern of the crop-straw resource and the status quo of its application in China. Beijing: China Agricultural University; 2005.

[16] Li JF, Hu RQ, Song YQ, Shi JL. Assessment of sustainable energy potential of non-plantation biomass resources in China. Biomass Bioenergy 2005;29:167–77.

[17] Cai JM, Liu RH, Deng CJ. An assessment of biomass resources availability in Shanghai: 2005 analysis. Renew Sust Energy Rev 2008;12:1997–2004.

[18] Cui M, Zhao LX, Tian YS, Meng HB, Sun LY, Zhang YL, et al. Analysis and evaluation on energy utilization of main crop straw resources in China. Trans CSAE 2008;24:291–6.

[19] Liu H, Jiang GM, Zhuang HY, Wang KJ. Distribution, utilization structure and potential of biomass resources in rural China: with special references of crop residues. Renew Sust Energy Rev 2008;12:1402–18.

[20] Lian J. Practice and prospects of sustainable development in Inner Mongolia. In: Wu JG, editor. Proceedings of the first SUCCESS symposium on sustainability science. Huhhot: Inner Mongolia University Press; 2007. p. 34–52.

[21] Duan G, Chen W. Discussion on the comprehensive utilization of wind resource in Inner Mongolia. Inner Mongolia Science Technology & Economy 2010:207.

[22] Zhou SL, Wang HS, Gao J, Zhang WB, Xu Y, Chang DS. Research on the characteristics of solar energy resources spatial distribution and utilization of PV grid-integrated in Inner Mongolia. Electric Power Technol 2010;19:5–8.

[23] Song AD, Zhang BL, Wang FQ, Xie H, Wang GH, Li SZ. Potential analysis on bioethanol production using cellulose material in China 2008.

[24] Miao Z. Statistics on Inner Mongolian grassland resources. Huhhot: Inner Mongolian Grassland Survey and Design Institute; 1988. p. 452.

[25] Inner Mongolia Autonomous Region Bureau of Statistics. Inner Mongolia statistical yearbook 1989–2009. Beijing: China Statistics Press; 1989–2009.

[26] Inner Mongolia Autonomous Region Bureau of Statistics. Statistical yearbook on agricultural and livestock production in Inner Mongolia 1980–1986. Beijing: China Statistics Press; 1980–1986.

[27] Rural and Pastoral Areas' Social Economy Investigation Team. Statistical yearbook on rural social economy in Inner Mongolia 1987–1991. Beijing: China Statistics Press; 1987–1991.

[28] Rural and Pastoral Areas' Social Economy Investigation Team. Statistical yearbook on rural and pastoral areas' social economy in Inner Mongolia 1992–1993. Beijing: China Statistics Press; 1992–1993.

[29] Rural and Pastoral Areas' Social Economy Investigation Team. Statistical yearbook on rural and pastoral areas' social economy in Inner Mongolia 1999–2005. Beijing: China Statistics Press; 1999–2005.

[30] Inner Mongolia Agricultural Department. Basic data on agriculture and animal husbandry economy in Inner Mongolia 1995–1997. Beijing: China Statistics Press; 1995–1997.

[31] National Bureau of Statistics Survey Office in Inner Mongolia. Inner Mongolia economy and society investigation yearbook. Beijing: China Statistics Press; 2006–2009.

[32] Inner Mongolia Autonomous Region Bureau of Statistics. Inner Mongolia statistical yearbook 1995. Beijing: China Statistics Press; 1995.

[33] Yi ZY. The yearbook of agricultural mechanization in China. Beijing: Chinese Agricultural Science and Technology Publishing House; 1991–2007.

[34] Jia XL. Survey and research on resource availability and its correlated questions for supplying heat and generating electricity program of combusting crop stalk (3). Solar Energy 2006:10–5.

[35] Chinese Academy of Agricultural Engineering. Technical code of crop straw surveying and evaluating. NY/T 1701-2009. Beijing: Ministry of Agriculture of the People's Republic of China; 2009. p. 1–13.

[36] Gao XZ, Ma WQ, Ma CB, Zhang FS, Wang YH. Analysis on the current status of utilization of crop straw in China. J Huazhong Agric Univ 2002;21:242–7.

[37] Zeng XY, Ma YT, Ma LR. Utilization of straw in biomass energy in China. Renew Sust Energy Rev 2007;11:976–87.

[38] Liu G, Shen L. Quantitive appraisal of biomass energy and its geographical distribution in China. J Natural Res 2007;22:9–19.

[39] Agricultural geography in Inner Mongolia Editorial Committee. Agricultural geography in Inner Mongolia. 1 ed. Huhhot: Inner Mongolia People's Publishing House; 1982. p. 331.

[40] Bi YY. Study on straw resources evaluation and utilization in China. Beijing: Chinese Academy of Agricultural Sciences; 2010.

[41] Niu RF, Liu TF. Agricultural technology and economy handbook (revised edition). Beijing: China Agricultural Press; 1984.

[42] Zhang FC, Zhu ZH. Harvest index for various crops in China. Sci Agric Sin 1990;23:83–7.

[43] Liang YS, Liu YL, Zhou XY, Guo TS. Non-conventional feed resources development and utilization. Beijing: China Agricultural Press; 1996.

[44] Fu J. The formulation and genetic improvement of rice harvest index. Crop Res 1997:1–3.

[45] Li SZ, Chan-Halbrendt C. Ethanol production in (the) PRC: potential and technologies. Appl Energy 2009;86:162–9.

[46] Rutz D, Janssen R. Biofuel technology handbook. Munich, Germany: WIP Renewable Energies; 2007.

[47] Badger PC. Ethanol from cellulose: a general review. In: Janick J, Whipkey A, editors. Trends in new crops and new uses. Alexandria (VA): ASHS Press; 2002. p. 17–21.

[48] Shapouri H, Duffield JA, Graboski MS. Estimating the net energy balance of corn ethanol. Agricultural economics, report no. AER721; 1995. p. 24.

[49] Shapouri H, Duffield JA, Wang M. The energy balance of corn ethanol: an update; 2002.

[50] Macedo IdC, Leal MRLV, Silva JEARd. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. Report to the Government of the State of São Paulo; 2004. p. 32.

[51] Nguyen TLT, Gheewala SH. Fossil energy, environmental and cost performance of ethanol in Thailand. J Cleaner Prod 2008;16:1814–21.

[52] Pimentel D, Patzek TW. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural Resour Res 2005;14:65–76.

[53] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319:1235–8.

[54] Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM. Ethanol can contribute to energy and environmental goals. Science 2006;311:506–8.

[55] Chen W. The study on sustainable development of the coal industry in Inner Mongolia. Beijing: China University of Geosciences; 2007.

[56] Larson ED, Fiorese G, Liu G, Williams RH, Kreutz TG, Consonni S. Co-production of synfuels and electricity from coal + biomass with zero net carbon emissions: an Illinois case study. Energy Environ Sci 2010;3:28–42.

[57] Lawrence B, Annamalai K, Sweeten JM, Heflin K. Cofiring coal and dairy biomass in a 29 kwt furnace. Appl Energy 2009;86:2359–72.

[58] Tian YS, Zhao LX, Meng HB, Sun LY, Yan YJ. Estimation of un-used land potential for biofuels development in (the) People's Republic of China. Appl Energy 2009;86(Suppl. 1):S77–85.

[59] Wang XH, Feng ZM. Biofuel use and its emission of noxious gases in rural China. Renew Sustain Energy Rev 2004;8:183–92.

[60] David GS, Stephanie TW. Biofuel use in Asia and acidifying emissions. Energy 1998;23:1029–42.

[61] Yan J, Lin T. Biofuels in Asia. Appl Energy 2009;86(Suppl. 1):S1–S10.

[62] Qiu J. China unveils green targets. Nature 2011;471:149.