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Article

Spatiotemporal Changes in Crop Residues with Potential for Bioenergy Use in China from 1990 to 2010

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Abstract: China has abundant crop residues (CR_E) that could be used for bioenergy. The spatiotemporal characteristics of bioenergy production are crucial for high-efficiency use and appropriate management of bioenergy enterprises. In this study, statistical and remote-sensing data on crop yield in China were used to estimate CR_E and to analyze its spatiotemporal changes between 1990 and 2010. In 2010, China's CR_E was estimated to be approximately 133.24 Mt, and it was abundant in North and Northeast China, the middle and lower reaches of the Yangtze River, and South China; CR_E was scarce on the Loess and Qinghai–Tibet Plateaus. The quantity of CR_E increased clearly over the 20-year analysis period, mainly from an increase in residues produced on dry land. Changes in cultivated land use clearly influenced the changes in CR_E. The expansion of cultivated land, which mainly occurred in Northeast and Northwest China, increased CR_E by 5.18 Mt. The loss of cultivated land, which occurred primarily in North China and the middle and lower reaches of the Yangtze River, reduced CR_E by 3.55 Mt. Additionally, the interconversion of paddy fields and dry land, which occurred mostly in Northeast China, increased CR_E by 0.78 Mt. The findings of this article provide important information for policy makers in formulating plans and policies for crop-residue-based bioenergy development in China, and also for commercial ventures in deciding on locations and production schedules for generation of bioenergy.

Keywords: China; spatiotemporal changes; bioenergy; crop residues

1. Introduction

Limited national fossil resources and sustained increases in energy prices have resulted in international efforts to study and deploy alternative energy sources [1–4]. From the early 1990s, the biofuel and biodiesel industry has begun to play an important role in alleviating global energy shortages [5]. A report from the World Bioenergy Association (WBA) in 2010 stated that reasonable and sustainable use of global biomass energy could meet global energy demand [6]. Total bioenergy potential in China is approximately 25.2 EJ per year, which represents approximately 30.2% of China's energy consumption in 2008 (83.4 EJ) [7]. Residues of crops such as cereal and corn straw can be converted into liquid or gaseous biofuels by thermochemical or biological techniques and represent potential bioenergy resources [8]. Biofuels can be substituted for fossil energy and reduce pressure on global food security. Importantly, they are environmentally friendly [9]. To address the dual issues of energy and food security, China's renewable energy development strategy has emphasized the use of crop residues (CR_E) for bioenergy production.

Accurate estimation of crop residues available for use as bioenergy sources is very important, and information on the spatiotemporal distribution of and variation in available residues is crucial for assessing the potential for a regionally based commercial biofuel industry. Several studies have estimated the utility of crop residues by examining yield, residue collection, and potential for bioenergy use. Estimates of residue availability vary substantially among these reports. Yearly variability in crop residues ranges between +23% and −28% of the average value among the 27 member states of the European Union (EU27) [10]. In Brazil, the minimum and maximum energy potential from biofuels are reported to be 4947 and 9272 MW, respectively [11]. Estimates of crop residues differ widely for China. Liao *et al.* [12] estimated that 939 Mt of agricultural residues were produced in 1998, whereas Zhou *et al.* [7] indicated that 684 Mt were produced in the same year. The yield of crop residues in China in 2005 was reported by Zhang *et al.* to be 729 Mt [13], whereas yield in that year was 842 Mt according to Bi [14]. The Chinese Academy of Agricultural Engineering reported collectable crop residues of 372 Mt in 2006 [15]; Wang *et al.* [16] suggested that 686 Mt were produced in 2005. The primary reasons for the large variation in estimates include differences in statistical resources, crop types, and key parameters employed in estimates.

Existing studies have calculated the yield [17–21] and collectable quantity of crop residues [10,14,16], but few have evaluated their potential for bioenergy use [15,22–24] beyond traditional uses in industrial raw materials, livestock feed, organic fertilizer, and rural energy [3,4]. Furthermore, research on crop residues has tended to focus on a single year rather than longer time periods. Information on the spatial distribution of crop residues in China is also lacking. Thus, it is important to estimate the potential of CR_E using appropriate methods and to analyze the long-term spatiotemporal distribution and variability of these resources.

The objectives of this study were to: (1) assess the potential of CR_E in China using current statistical and remote-sensing data; (2) examine the spatiotemporal characteristics of CR_E using Geographic

Information System (GIS) methods; and (3) determine the relationship between the quantity of CR_E and cultivated land change.

2. Data, Methods, and Assumptions

2.1. Data Sources

Our sources for estimating CR_E included data on agricultural statistics, farmland distribution, and net primary productivity (NPP).

2.1.1. Agricultural Statistical Data

Agricultural statistical data covered the yield of each crop type at the county level, which were used to calculate the potential amount of CR_E from 1990 to 2010. These data were obtained from the *China Statistical Yearbook* (1990, 1995, 2000, 2005 and 2010 editions) [25–29].

2.1.2. Farmland Distribution Data

Data on the distribution of farmland were derived from a land-use dataset (scale 1:100,000) from the Data Center for Resources and Environmental Sciences (RESDC) of the Chinese Academy of Sciences. These data were produced by visual interpretation of Landsat TM/ETM remote sensing images. Detailed information about this database can be found in previous papers [30–34]. The land-use data were classified into six first-class objects (farmland, woodland, grassland, water body, residential area, and unused land). Farmlands include paddy and dry land. To evaluate the accuracy of this classification, a field survey and a random sample check were conducted. For example, a cumulative 75,271 km, 74,482 km and 77,350 km survey were taken across China to assess the accuracy of the land-use interpretation in 2000, 2005 and 2010, respectively. This evaluation suggested that the overall accuracy of the land-use classification was approximately 93%, 95% and 96% in 2000, 2005, and 2010, respectively. In this study, farmland data were extracted for five time periods (1990, 1995, 2000, 2005 and 2010) and used to calculate the spatial distribution of CR_E.

2.1.3. Net Primary Productivity Data

Net primary productivity (NPP) data were estimated based on the Global Production Efficiency Model (GLO-PEM). GLO-PEM consists of linked components that describe the absorption and use of canopy radiation and autotrophic respiration and the regulation of these processes by environmental factors including temperature, water vapor-pressure deficit, and soil moisture [35–38]. We used GLO-PEM and NOAA/NASA Pathfinder Advanced Very High Resolution Radiometer (AVHRR) Land (PAL) data at resolutions of 8 km and 10 days to estimate NPP for 1990, 1995, 2000, 2005 and 2010. Correlation analyses were used to check the accuracy of the NPP results. The correlation coefficient for modeled and statistically derived NPP was 0.68, indicating that GLO-PEM could estimate NPP at an acceptable level. Detailed descriptions of GLO-PEM and the correlation analyses are provided in Yan *et al.* [35].

2.2. Methods

2.2.1. Potential CR_E

We considered residues generated from the following agricultural crops: wheat, rice, corn, potato, soybean, fiber, cotton, sugarcane, sugar beet, oil plant, and beet. The assessment of CR_E takes into account: (a) types of crops and area planted; (b) crop yield; (c) residue-to-crop production ratios; (d) crop residue removal rate; and (e) competitive use of crop residues [39].

In China, there are large differences in crop yield between provinces, as yield depends on climate conditions and planting patterns. Data on crop yield are readily available, but data on crop residue yields are scarce and variable. Wide variation in the residue-to-seed ratio is reported in the literature, as this ratio is influenced by plant varieties, farming practices, and climate [40,41]. To account for this variability, we used the median values of residue-to-seed ratios reported in the documents listed in Table 1.

Table 1. Residue-to-production ratio for various crops.

Crops	Matsumura *et al.* [42]	Liu *et al.* [43]	Kim & Dale [44]	Zeng *et al.* [45]	Lal [21]	Shen *et al.* [46]	Cui *et al.* [15]	Jia [47]	Bi [14]	Ding *et al.* [19]	Renewable energy project [48]	Median
Wheat	2.53	1.336	1.3	1.336	1.5	1.1	0.73	0.73	1.3	1.28	0.62	1.30
Rice	1.43	0.623	1.4	0.623	1.5	1	0.68	0.78	0.95	0.952	1.37	0.95
Corn	1.1	2	1	2	1	2	1.25	0.75	1.1	1.247	2	1.25
Potato	1.14	0.5	-	0.5	0.25	1	-	-	0.96	0.5	0.5	0.50
Soybean	2.14	1.5	-	1.5	1	1.7	-	0.75	1.6	1.5	1.5	1.50
Fiber	-	2.5	-	2.5	-	2	-	-	1.9	-	-	2.25
Cotton	-	3	-	3	1.5	3	5.51	3.53	5	3.136	3	3.00
Sugarcane	0.52	0.1	0.6	0.1	0.25	0.1	-	-	0.24	0.1	0.25	0.24
Oil plant	-	2	-	2	-	3	1.01	1.15	2.8	2.212	2	2.00
Beet	-	1	-	1	0.25	0.1	-	-	0.1	-	-	0.25

Sustainable rates of residue removal depend on crop species, soil conditions, climate, and harvesting equipment [49,50]. Therefore, estimated quantities of collectable residues may vary widely and have a high degree of uncertainty. In Europe, researchers considered sustainable removal rates of 40% for wheat, barley, and oats and 50% for maize, rice, and sunflower [10,51]. We chose two influential studies in China as references for collection coefficients [15,16]. According to the most recent official statistics, the proportions of rice, wheat, corn, and oil plants that are harvested mechanically are 46.3%, 92.4%, 9.7% and 6.0% respectively. Using the proportions of mechanical and manual harvest for each crop and the corresponding collection coefficients, we calibrated collection coefficients for rice, wheat, corn, and oil plant at the national level (Table 2).

Table 2. Collection coefficients of main crop residues.

Sources	Coefficients	Wheat	Rice	Corn	Potato	Soybean	Fiber	Cotton	Sugarcane	Oil plant	Beet
Cui *et al.* [15]	Coefficient of mechanized harvesting	0.77	0.66	1	-	-	-	-	-	0.85	-
	Coefficient of manual harvesting	0.9	0.9	1	-	-	-	0.94	-	0.95	-
	Collection coefficient	0.76	0.78	0.95	-	-	-	0.89	-	0.9	-
Wang *et al.* [16]	Collection coefficient	0.83	0.83	0.9	0.8	0.88	0.87	0.9	0.88	0.85	0.88
This study	Collection coefficient	0.74	0.75	0.95	0.8	0.88	0.87	0.9	0.88	0.88	0.88

Estimates of CR_E should consider competitive uses for these crops such as rural fuel energy, animal breeding, mushroom production, and soil fertilizer. In agriculture, straw is mainly used for crop protection [52]. Based on field surveys and literature analysis, we considered fertilization rates of 20% in the Loess Plateau, Mongolia–Xinjiang region, Qinghai–Tibet Plateau, and North China; 15% in Northeast and Southwest China; and 12% in other regions [13,14]. To estimate the use of crop residues for animals in a given region, the quantity of livestock and sources of feed must be determined. Straw is also used as a substrate for mushroom production, as an industrial resource for producing pulp and paper, and as fuel in rural areas [13,14,48,53]. In this study, we performed statistical analyses and calculated CR_E from the collectable amount of crop residues at the provincial level (Table 3).

Table 3. Ratio of collected residue to bioenergy (e_i) in various Chinese provinces (%).

Province	e_i	Province	e_i
Beijing	14.2	Shanghai	62.9
Tianjin	15	Jiangsu	34.9
Hebei	13.6	Zhejiang	39.3
Shandong	17.1	Anhui	34.2
Henan	29.5	Hubei	30.8
Liaoning	11.8	Hunan	14.9
Jilin	40.3	Jiangxi	31.9
Heilongjiang	40	Chongqing	18.9
Shanxi	3.9	Sichuan	3.8
Shaanxi	7.4	Guizhou	14.1
Gansu	10.9	Yunnan	12.7
Inner Mongolia	18	Fujian	14.6
Ningxia	13.5	Guangdong	29.9
Xinjiang	26.5	Guangxi	34.9
Xizang	4.1	Hainan	46.9
Qinghai	5.3	-	-

This study assumed that the key coefficients were constants because of their high degree of uncertainty and the lack of available data. Thus, the quantity of CR_E is a theoretical sum that indicates the largest potential amount of biomass energy. Based on this assumption, we can assess the consequences of land-use changes on CR_E in China. CR_E was calculated as follows:

$$CR_E = \sum_{i=1}^{n} Qc_i \cdot r_i \cdot f_i \cdot e_i \quad (1)$$

where Qc_i is the total yield of crop i, r_i is the residue-to-crop production ratio of crop i, f_i is the collection coefficient of crop i, and e_i is the ratio of the collected residue to bioenergy.

2.2.2. Spatial Distribution of CR_E

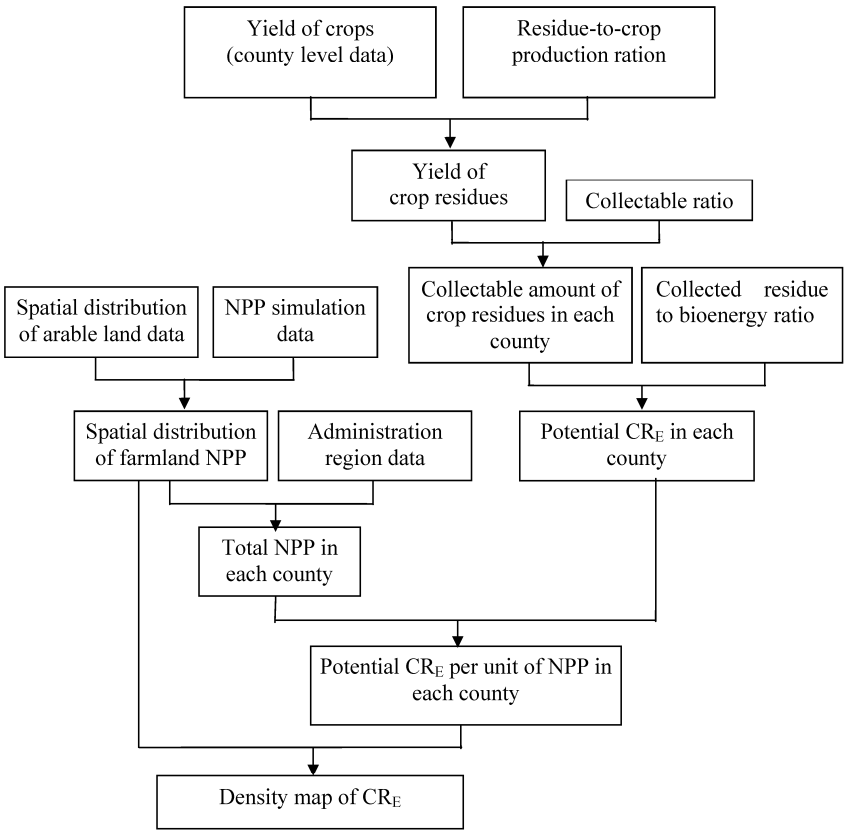
Total crop yield was measured at the provincial level, suggesting that the potential CR_E was distributed evenly over a given administrative region. In reality, crop-residue resources are usually spread out unevenly on farmland. A sufficient density of data on the spatial distribution of CR_E is crucial for designing bioenergy facilities in China. Jiang *et al.* [17] assigned values of straw yield to

individual geographic units (100 m × 100 m) according to proportion of farmland area in each unit. This method considered only the existence of crop residues in each parcel and contained no information on site-specific growth variables such as precipitation, solar radiation, temperature, and soil properties. Monforti *et al.* [22] predicted available crop residues by geographic region based on spatial features, including land cover, and expected biomass productivity derived from soil parameters, climatic zones, and topographical context. We chose land-cover and NPP data to assess the spatial distribution of residues. NPP is defined as gross primary productivity minus autotrophic respiration. Elmore *et al.* [8] calculated the spatial distribution of rice straw in China using NPP and land-cover maps and found that this method could reasonably predict census results at the provincial scale. Gehrung and Scholz [54] also found that weighting the distribution of crop residues with NPP was more accurate than disaggregating potential CR_E using land-cover data.

We assumed that crop residues were harvested from all areas of arable land and that rice was produced in paddy fields and the other crops on dry land. We used NPP to weight the distribution of crop residues. This method is based on the assumption that the distribution of CR_E is influenced directly by biomass increment, which could account for the impacts of climate and location factors [54].

A flow chart illustrating the calculation of CR_E distribution is presented in Figure 1. We first calculated potential CR_E at the county level using methods presented in Section 2.2.1. Then, the density of CR_E was estimated with NPP data. To summarize the NPP of farmland in each county, we first extracted the NPP of farmland for use as a weighting factor.

Figure 1. Flow chart for estimating the distribution of CR_E.



The potential quantity of CR_E in a given county and grid cell ($D_{c_i g_j}$) was calculated using Equation (2):

$$D_{c_i g_j} = (CR_{Ec_i} / \sum_{i=1}^{n} NPP_{g_j}) \times NPP_{g_j} \quad (2)$$

where c_i represents county i; g_j represents grid cell i; CR_{Ec_i} is the total CR_E given by Equation (1) in county c_i; and NPP_{g_j} is the value of NPP in grid cell g_j based on the GLO-PEM Model.

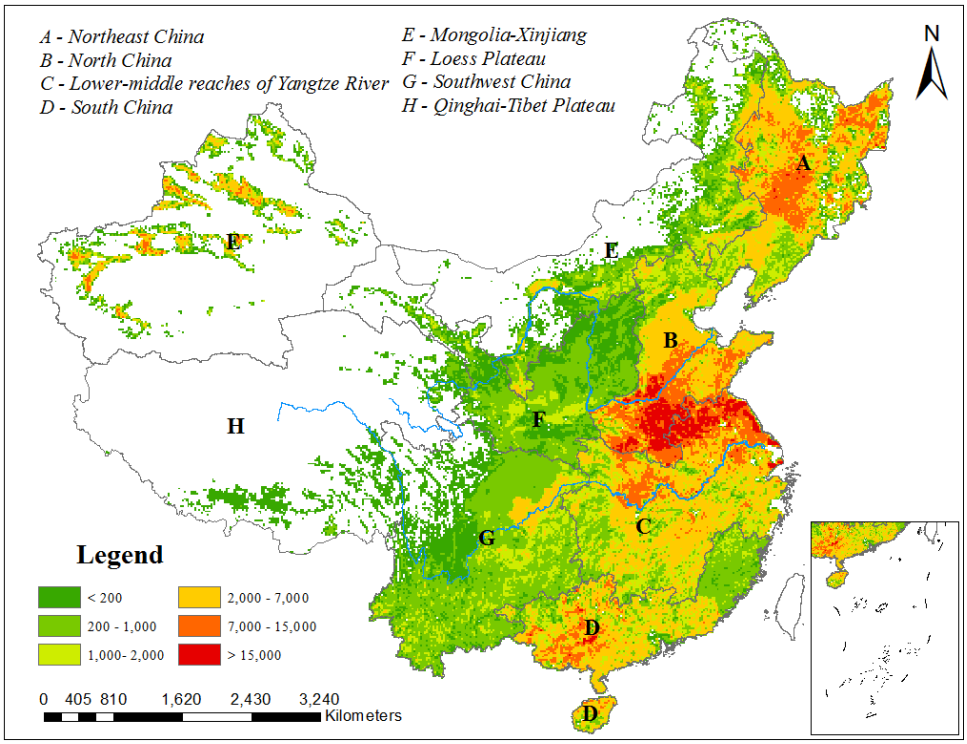
When the potential value of CR_E was determined at the grid-cell level, we further analyzed the spatiotemporal characteristics of CR_E and impacts of changes in cultivated land on CR_E using GIS methods.

3. Results and Analysis

3.1. Current Spatial Distribution Pattern of CR_E

The value of CR_E in China in 2010, as derived from its estimated spatial distribution, was 133.24 Mt (Figure 2). Of this total, 98.13 Mt corresponded to crop residues from wheat, corn, potato, soybean, fiber, cotton, sugarcane, beet, and oil plants in dryland areas. The generation of rice residues in paddy fields accounted for 35.11 Mt. The average density of CR_E on farmland, dryland, and in paddy fields was 74.34, 73.81, and 74.34 t/km^2, respectively.

Figure 2. The distribution of CR_E in 2010 (t/10 km^2).



A significant regional imbalance in CR_E was observed (Figure 2). The most abundant yields occurred in the lower-middle reaches of the Yangtze River, accounting for 29.5% of the national yield. North China, Northeast China, and South China produced 24.6%, 20.6%, and 11.6% of CR_E, respectively. The lowest yield (0.09%) was obtained from the Qinghai–Tibet Plateau. In general, CR_E was concentrated in the eastern part of China and declined gradually from east to west.

The spatial distribution of CR_E showed that crop residues from paddy fields were predominantly derived from fields in the lower-middle reaches of the Yangtze River (19.79 Mt in 2010), which accounted for 56.4% of the CR_E from paddy fields. The second most important regions for CR_E production in paddy fields were South and Northeast China, which generated 5.97 and 5.90 Mt, respectively. In dryland areas, CR_E was mainly generated in North and Northeast China, which produced 32.7% (31.59 Mt) and 22.30% (21.51 Mt) of the total dryland CR_E, respectively (Table 4).

Table 4. Amount (1×10^4 t) and density (t/km^2) of CR_E produced in different land-use areas in each region.

Region	Cultivated land		Paddy field		Dry land	
	Amount	**Density**	**Amount**	**Density**	**Amount**	**Density**
Lower-middle reaches of Yangtze River	3932.94	111.58	1979.47	86.91	1953.47	156.46
North China	3270.61	102.83	111.85	76.10	3158.76	104.12
Northeast China	2741.43	90.27	590.14	125.48	2151.29	83.81
South China	1549.62	124.52	597.19	87.60	952.43	169.11
Mongolia–Xinjiang	925.6	45.64	25.35	38.31	900.25	45.88
Southwest China	662.07	23.53	203.19	23.11	458.88	23.73
Loess Plateau	230.17	11.27	4.13	4.28	226.04	11.59
Qinghai–Tibet Plateau	11.56	8.52	0.02	0.48	11.55	8.65
Total	13,324.00	74.34	3511.34	75.84	9812.67	73.81

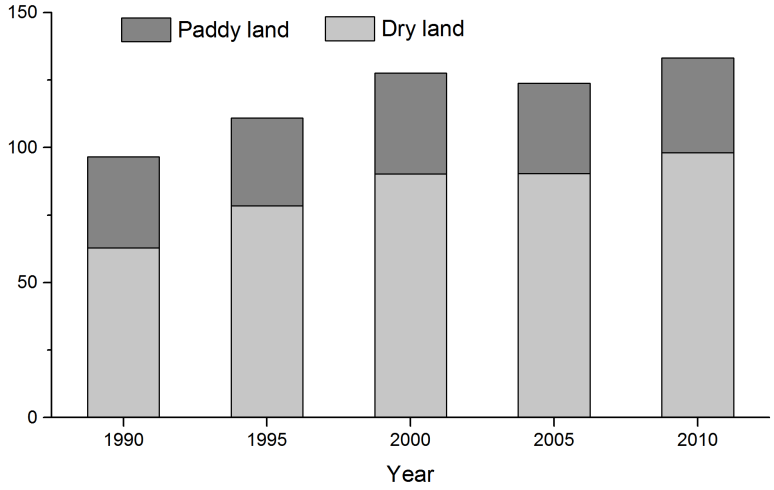
3.2. Temporal Changes in Characteristics of CR_E

From 1990 to 2010 (the period of study), total CR_E produced on cultivated land in China showed an increasing trend (Table 5). Potential CR_E increased from 96.60 Mt in 1990 to 133.24 Mt in 2010. The average annual growth rate in potential CR_E was 2.1% during 1990–2010, but this trend slowed after 2000. Temporal variation in CR_E from 1990 to 2010 is illustrated in Figure 3. CR_E exhibited two phases: a phase of rapid growth from 1990 to 2000 and a phase of fluctuating increase from 2000 to 2010. Gross CR_E increased to 30.99 Mt at an average annual rate of 3.2% during the first phase, and it rose to 56.52 Mt at an average annual rate of 0.6% during the second phase. CR_E in paddy fields remained nearly constant over the 20-year period, whereas gross CR_E on dry land increased (Figure 3). From 1990 to 2010, CR_E increased by 35.37 Mt on dry land, representing an annual average growth rate of 3.1%. The increasing trend of CR_E on dry land was consistent with the trend on cultivated land; thus, we concluded that the increase resulted primarily from the increase on dry land. During the first phase, CR_E on dry land increased by 27.53 Mt (an average increase of 4.4% per year), which exceeded the rate on cultivated land. CR_E from paddy fields increased by only 3.46 Mt during the same period (an average increase of 1.0% per year). During the second phase, the rate of increase fell to 1.1% on dry land and to −5.87% (a decrease) in paddy fields.

Table 5. Temporal changes in the amount (Mt) and density (t/km^2) of CR_E in China from 1990 to 2010.

Year	Dry land		Paddy land		Cultivated land	
	Amount	Density	Amount	Density	Amount	Density
1990	62.76	47.97	33.85	72.63	96.60	54.43
1995	78.40	59.23	32.62	69.75	109.98	61.4
2000	90.28	67.82	37.30	78.91	127.59	70.73
2005	90.43	67.79	33.33	71.71	123.76	68.8
2010	98.13	73.81	35.11	75.84	133.24	74.34

Figure 3. Changes in CR_E during past 20 years (Mt).



According to the density statistics (Table 5), CR_E increased from 54.43 t/km^2 in 1990 to 74.34 t/ km^2 in 2010 (an increase of 36.6%). The variability on dry land differed from that on paddy land; the density of CR_E on dry land showed a net increase of 53.87% since 1990, whereas that in paddy fields was largely unchanged (4.4%). Thus, the increase in crop residues on dry land was the main factor in the increased density of CR_E in cultivated areas countrywide.

3.3. Regional Changes in CR_E

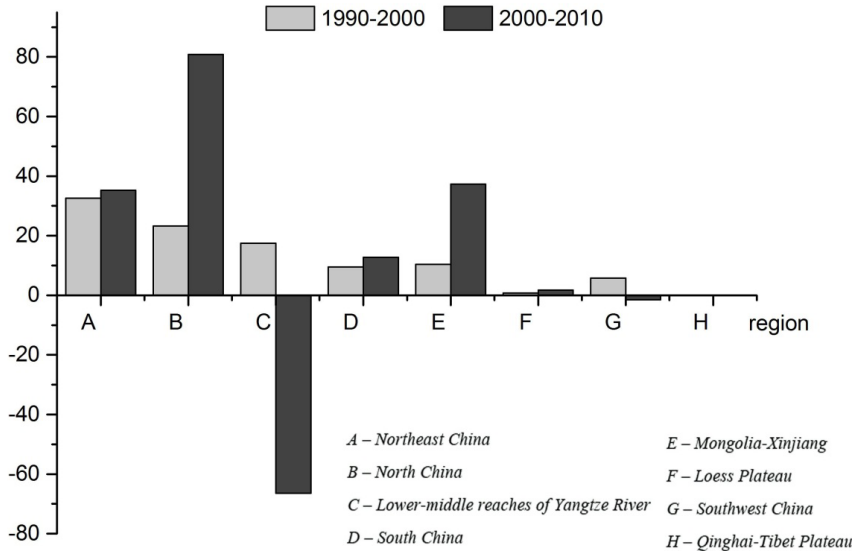
China's CR_E increased by 37.22 Mt from 1990 to 2010. Of this amount, 35.46 Mt was produced in dryland areas and 1.75 Mt in paddies (Table 6). More than 70% of the increase occurred in North and Northeast China and Inner Mongolia–Xinjiang (33%, 32%, and 14.51%, respectively). Changes in CR_E at the regional scale were primarily concentrated in dryland areas. Of the 11.92-Mt increase in North China, 96.7% was produced on dry land; the net increase in the Northeast was 12.28 Mt, 63.6% of which was generated in dryland areas. In contrast, available CR_E in paddy fields in the lower-middle reaches of the Yangtze River, South China, and the Loess Plateau decreased by 1.78, 1.54 and 0.02 Mt, respectively.

Table 6. Changes in CR_E in various regions of China from 1990 to 2000 (units, 1×10^4 t).

Region	1990–2000			2000–2010			1990–2010		
	Dry land	Paddy field	Sum	Dry land	Paddy field	Sum	Dry land	Paddy field	Sum
Lower-middle reaches of Yangtze River	536.91	16.04	552.95	−182.02	−193.82	−375.84	354.89	−177.78	177.11
North China	707.36	27.94	735.3	445.93	11.28	457.21	1153.29	39.22	1192.51
Northeast China	751.75	277.01	1028.76	29.82	169.51	199.33	781.57	446.52	1228.09
South China	258.86	42.66	301.52	268.98	−196.9	72.08	527.84	−154.24	373.6
Mongolia–Xinjiang	320.99	8.2	329.19	208.73	2.09	210.82	529.72	10.29	540.01
Southwest China	158.58	23.05	181.63	1.83	−9.99	−8.16	160.41	13.06	173.47
Loess Plateau	24.37	−0.58	23.79	10.75	−0.92	9.83	35.12	−1.5	33.62
Qinghai–Tibet Plateau	3.15	0	3.15	0.21	0	0.21	3.36	0	3.36
Total	2761.97	394.32	3156.29	784.23	−218.75	565.48	3546.2	175.57	3721.77

The temporal variance in CR_E in each region is illustrated in Figure 4. North China is a traditional agricultural region in which the main type of land use is dryland farming. Between 1990 and 2000, CR_E on dry land increased by 7.07 Mt (96.2% of the total increase in CR_E on cultivated land during this period). In the lower-middle reaches of the Yangtze River, 97.1% in the increase in CR_E was generated from crop growth in dryland areas.

Figure 4. Percentage changes in CR_E in various regions of China.



From 2000 to 2010, CR_E increased dramatically in North China, Mongolia–Xinjiang, and Northeast China, and it declined in the lower-middle reaches of the Yangtze River and Southwest China. The increase in CR_E in North China was the most impressive, accounting for 80.85% of the total increase in China during this period. This gain in crop residues in North China occurred mostly on dry land (97.5% of the total increase). Most of the increase in CR_E in Mongolia–Xinjiang from 2000 to 2010 occurred on dry land (99%), whereas in Northeast China, paddy fields were responsible for 85.0% of the gain during this period. The main region in which CR_E declined from 2000 to 2010 was the lower-middle reaches of Yangtze River.

3.4. Effects of Changes in Cultivated Land on CR_E

Changes in cultivated land, such as expansion, shrinking, and interconversion of paddy fields and dry land, were the main reasons for changes in crop-residue resources (Table 7). During 1990–2010, changes in cultivated land showed substantial spatiotemporal variation across China, increasing in the north and decreasing in the south, for a net increase of 3×10^6 ha. Expansion of dry land made the largest contribution [33,55]. From 2000 to 2010, cultivated land area decreased by 1.24×10^6 ha; 0.69×10^6 of this decrease occurred during 2000–2005, and 0.55×10^6 during 2005–2010 [56,57].

Table 7. Changes in CR_E as affected by land-use changes (units, 1×10^4 t).

Change type	1990–2000	2000–2010	1990–2010
Expansion of cultivated land	383.93	134.29	518.22
Loss of cultivated land	−194.63	−160.61	−355.24
Interconversion of paddy field and dry land	47.34	30.39	77.73
Total	236.64	4.07	240.71

Expansion of cultivated land occurred mainly in Northeast and Northwest China due to reclamation of forest and grassland (Figure 5). In contrast, loss of cultivated land occurred primarily in North China and the lower-middle reaches of the Yangtze River (Figure 6). Expansion of urban areas into large areas of high-quality cultivated land in Huanghuaihai Plain and the Yangtze and Pearl River deltas caused the most significant reductions in CR_E . Interconversion of paddy fields and dry land, another main factor in the change of CR_E (Figure 7), mainly occurred in Northeast China. This change caused the density of CR_E in Northeast China to increase.

Figure 5. Increase in CR_E as affected by expansion of cultivated land from 1990 to 2010 (t/10 km^2).

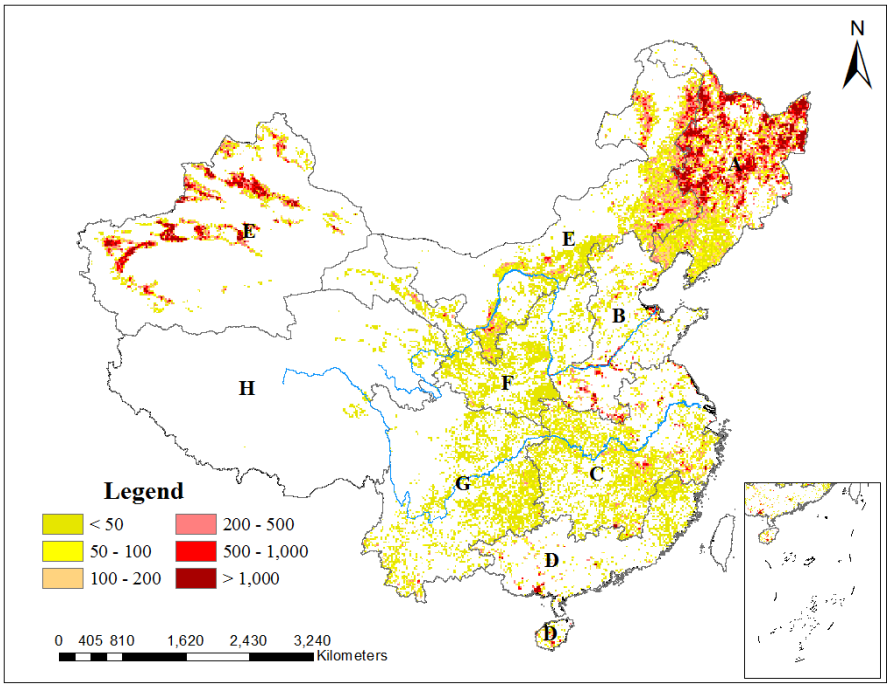


Figure 6. Decrease in CR_E as affected by loss of cultivated land from 1990 to 2010 (t/10 km^2).

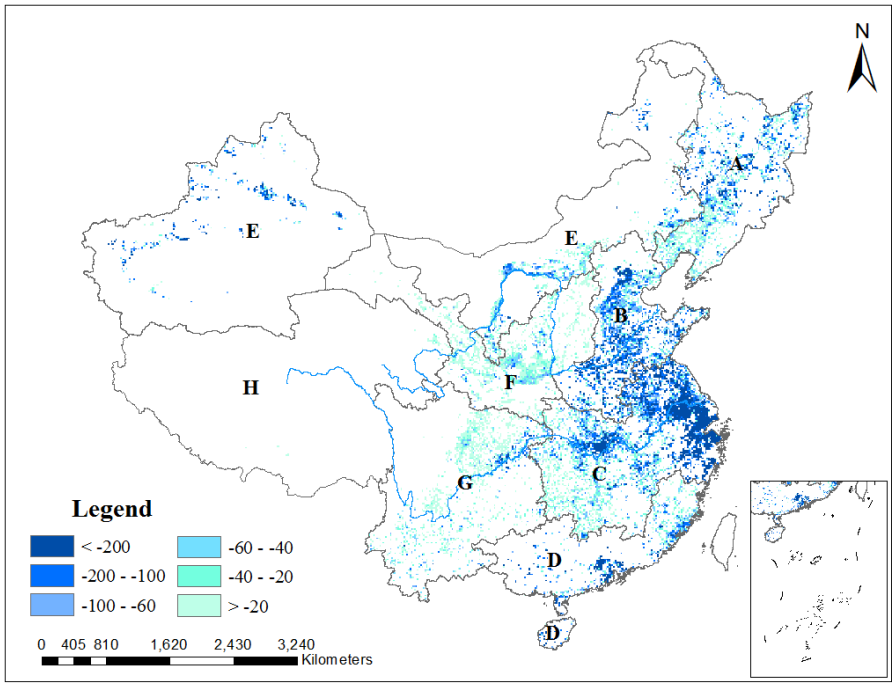
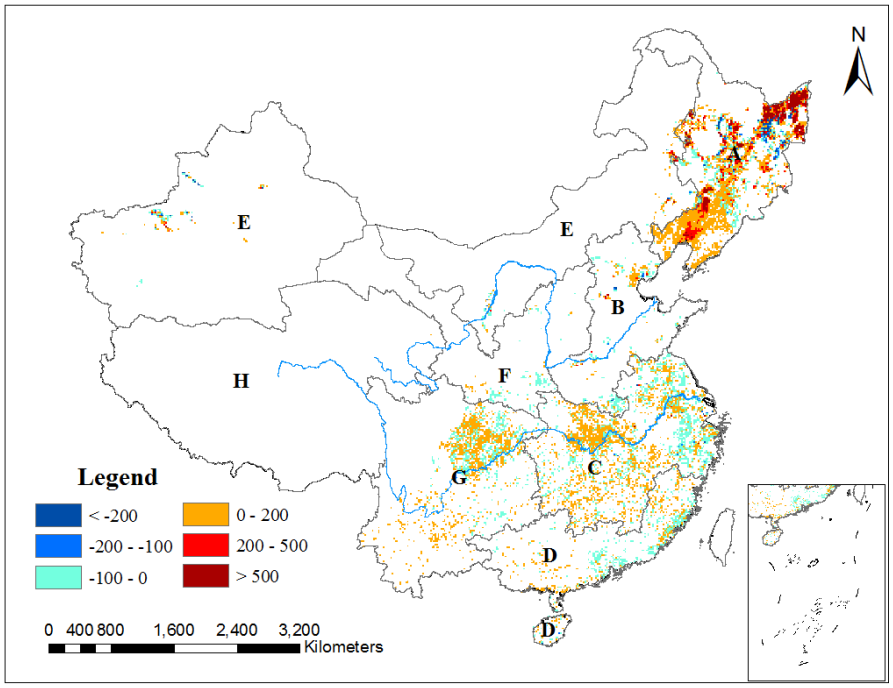


Figure 7. Changes in CR_E affected by interconversion of paddy fields and dry land from 1990 to 2010 (t/10 km^2).



4. Discussion and Conclusions

China, as a big traditional agricultural country, has abundant crop residues resources for bioenergy utilization. But the crop residue resource is uncertainty in spatial distribution and temporal change process. The accurate estimate of the availability of crop residues for bioenergy purpose is very

important for the development of bioenergy. Based on statistical data on crop yield and remote-sensing data on land use, we estimated potential CR_E in China during 1990–2010. We used density maps to analyze the spatiotemporal characteristics of changes in CR_E during this time period. Below, we present a summary of our findings.

(1) China's CR_E in 2010 was 133.24 Mt, and the average residue density was 74.34 t/km^2. The potential production of CR_E was higher on dry land than in paddy fields. China's CR_E showed significant differences in spatial distribution. Crop residues were abundant in East China and declined gradually from east to west. CR_E was most abundant in Northeast China, North China, and the lower-middle reaches of the Yangtze River, and it was scarce on the Loess and Qinghai–Tibet Plateaus.

(2) From 1990 to 2010, the quantity of CR_E in China generally increased, at an average rate of 2.11% per year. CR_E in paddy fields remained essentially the same, but it increased dramatically on dry land.

(3) Regional variability in the changes in CR_E was remarkable during the period of analysis. CR_E increased mainly in Northeast and North China and Mongolia–Xinjiang due to increased growth on dry land. Changes in CR_E varied among regions during the period of analysis. In 1990–2000, potential CR_E increased in North and Northeast China and the lower-middle reaches of the Yangtze River. During 2000–2010, CR_E increased in North and Northeast China and Inner Mongolia and declined in the lower-middle reaches of the Yangtze River and Southwest China.

(4) Changes in cultivated land, such as expansion, shrinking, and interconversion of paddy fields and dry land, were the primary reasons for changes in crop-residue resources. The expansion of cultivated land area occurred mostly in Northeast and Northwest China, leading to a net increase in CR_E of 5.18 Mt. The loss of cultivated land, concentrated in North China and the lower-middle reaches of the Yangtze River, reduced net CR_E by 3.55 Mt. Interconversion of paddy fields and dry land in Northeast China led to a net increase in CR_E of 0.78 Mt.

With the depletion of fossil fuels, an upsurge of popular support for conserving energy and reducing emissions of greenhouse gases is attracting attention worldwide. Renewable bioenergy resources are already demonstrating their value in mitigating the energy crisis and climate change, and there is a growing global trend toward developing biofuels. Crop residues represent a renewable resource that has received widespread attention because of its potential to address climate change and the energy crisis. Efforts to develop and use crop residues are important to resolving the current and future disparity between energy supply and demand. Thus, determination of spatiotemporal changes in available crop residues is the first step in their development and use. China, where traditional agricultural practices have been conducted on a large scale, has abundant crop residues that are potential resources for bioenergy. However, the spatial distribution of and temporal changes in this resource are uncertain. Accurate estimation of the availability of crop residues for bioenergy purposes is critical to the development of bioenergy in China.

In this study, an operational GIS-based approach was employed for comprehensive assessment of the current quantity of available crop residues. The patterns of spatial distribution and interannual changes in crop residues presented here could provide the basis for planning, site selection, and

prediction of raw material supply and demand in the intensive use of biomass energy. Nevertheless, the estimates of CR_E may have systematic deviation compared with the actual potential in some areas, as we assumed the key coefficients were constants from 1990 to 2010. Considering with the density of CR_E and change characteristics in each region, this paper suggested that (1) Northeast and North China are the key areas of CR_E development and utilization. The CR_E resources in these areas are very abundant and increasing conspicuously. In North China, growth of crop residues mainly came from improvement of crop yield per unit. In Northeast, part of the crop residues increase came from the expansion of cultivated land. These areas are suitable for bioenergy enterprise; (2) South China, Lower-middle reaches of Yangtze River and Mongolia-Xinjiang are the suitable areas for the development and utilization of CR_E. The CR_E are relatively concentrated in South China and Lower-middle reaches of Yangtze River, but interannual fluctuation changed significantly as the land is mainly covered with paddy field. The CR_E in Mongolia-Xinjiang increase slowly. Therefore, these areas should be cautious of developing bioenergy enterprise; (3) Southwest, loess plateau and Qinghai-Tibet are the limited areas for the development and utilization of CR_E. Resources of CR_E is scarce and distribution is scattered. These areas are under developed, so the energy enterprises are not applicable. Our findings provide important information for policy makers in formulating plans and policies for crop-residue-based bioenergy development in China, and also for commercial ventures in deciding on locations and production schedules for generation of bioenergy.

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Conflicts of Interest

The authors declare no conflict of interest.

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