Postprint: Ecological Potential Analysis of Energy-Conversion Straw from Major Crops in China Based on Soil Function

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Abstract

Ecological return of straw to fields is of great significance to the development of ecological agriculture in China and the sustainable development of straw energy utilization. Accordingly, from the perspectives of preventing soil and water erosion, maintaining soil organic matter, and preserving long-term crop yields, the concept of soil ecological retention capacity is proposed, and three ecological retention scenarios (low scenario, medium scenario, and high scenario) for different crop straws are designed; comprehensively employing grey neural network, linear regression, and other methods to predict the aforementioned factors, a bottom-up dynamic evaluation model is constructed to evaluate and analyze the ecological potential of energy-utilizable straw resources across various regions of China, and relevant development recommendations are proposed. The study reveals: Under low, medium, and high crop straw ecological retention scenarios, the total ecological amounts of energy-utilizable straw in 2030 are 227.96 million t, 137.18 million t, and 77.56 million t respectively, with straw resource densities of approximately 172 t·km 2, 103 t·km 2, and 58 t·km 2 respectively; regarding straw resource composition, low and medium scenarios are dominated by rice, tuber crops, and wheat straw, while the high scenario is dominated by tuber crops and sugarcane straw; in all three scenarios, energy-utilizable straw resources are mainly distributed in Henan, Shandong, Heilongjiang, Sichuan, and other regions. In the low scenario, only Beijing, Tianjin, Shanghai, and Tibet cannot develop direct combustion power generation and fuel ethanol projects; in the medium scenario, 50,000 t/year fuel ethanol projects are only suitable for planning in Fujian, Guangdong, Guangxi, Hainan, and Chongqing; in the high scenario, only Fujian, Guangdong, Guangxi, Hainan, and Chongqing can plan 25 MW direct combustion power generation projects or 50,000 t/year fuel ethanol projects.

Full Text

Abstract

The return of crop residue to soils can prevent soil and water erosion, maintain soil organic matter and plant nutrient balance, etc. Meanwhile, the utilization of crop residue energy can relieve energy stress and improve energy structure in China. Therefore, it is important for the development of ecological agriculture and the sustainable use of agricultural biomass to evaluate ecological potential of crop residues in terms of energy utilization and protection of soil functions. To this end, this study first advanced a concept of Ecological Straw Returning Amount with the consideration of soil and water conservation, soil organic matter maintaining and crop yield increase. Then a scenario analysis method was used to design optimal ecological straw return of different crops. Three scenarios (low, medium and high return) were designed for each crop residue return. The ecological potential of straw energy use was not only affected by ecological straw return, but influenced by crop planting area, per-unit crop yield, crop planting structure and other crop residue uses such as industrial and agricultural uses. Therefore a bottom-up dynamic analysis model that was coupled with Gray Neural Network and linear regression analysis was built to calculate ecological potential of straw energy utilization in different regions of China. Ecological potential of energy-oriented utilization of crop residues of different regions was evaluated from three aspects –spatial distribution, resource density and residual resource components. Then based on the direct straw-fired power generation and cellulosic ethanol project, some recommendations were put forward for the development of crop residue energy utilization. The study revealed that: 1) In low, medium and high scenario conditions, ecological potentials of straw in terms of energy utilization were respectively 2.28×10^8 tons, 1.37×10^8 tons and 7.76×10^7 tons, with crop residual densities of 172 $\mathrm{t \cdot km^{-2}}$, 103 $\mathrm{t \cdot km^{-2}}$ and 58 $\mathrm{t \cdot km^{-2}}$. Available ecological straw resource for the production of bio-energy comprised mainly of paddy straw, potato straw and wheat straw under low and medium scenario conditions, and mainly of potato straw and sugar straw under high scenario condition. The resource was mainly distributed in Henan, Shandong, Heilongjiang and Sichuan Provinces under the three scenario conditions. 2) Under low scenario condition, residue resource density and total amount of straw in the provinces in mainland China (with the exception of Beijing, Tianjin, Shanghai and Tibet) met the requirement for 6 MW direct straw-fired power generation that was the equivalent of an annual output of 10,000 tons of cellulosic ethanol. Under the medium scenario, only the crop straw resources of Fujian, Guangdong, Guangxi, Hainan and Chongqing were suitable for an annual output of 50,000 tons of cellulosic ethanol. A 25 MW direct straw-fired power generation or an annual output of 50,000 tons of cellulosic ethanol was possible for Fujian, Guangdong, Guangxi, Hainan and Chongqing under the high scenario condition.

Keywords: Ecological Straw Return Amount; Straw energy utilization; Biomass energy; Crop residual resource; Ecological potential

Introduction

As a major agricultural country, China produces enormous quantities of crop straw, representing abundant agricultural biomass energy resources. Scientific and effective assessment of agricultural biomass energy resources constitutes an important prerequisite and foundation for their development and utilization. Currently, the most fundamental estimation method employs GIS to calculate planting areas of different crops, then comprehensively evaluates biomass energy resources by considering crop yield, straw-to-grain ratio, and collectability. For instance, Liu et al. [?] calculated Canada' s agricultural biomass energy potential at approximately 37.3 million tons by accounting for crop yield, land use change, and greenhouse gas emissions. Lourinho et al. [?] used GIS software to determine the effective collection range of agricultural and forestry biomass residues, concluding that the Alto Alentejo region had an available total of 40,000 $t \cdot a^{-1}$. Zheng et al. [?] estimated Nanning' s energy-oriented potential of straw from seven crops including rice (*Oryza sativa*), maize (*Zea mays*), and peanut (*Arachis hypogaea*) at approximately 3.3 million tons by considering straw-to-grain ratio and conversion coefficients. Xing et al. [?] estimated total agricultural biomass energy from straw and agricultural processing by-products in Nantong City at about 1.05 million tons annually using straw-to-grain ratio, collection coefficient, conversion coefficient, and by-product coefficient.

Some scholars have also evaluated the collectible and utilizable potential of biomass by considering various uses of crop residues such as returning to field, feed, industrial materials, and fuel. Regarding the calculation of return-to-field amounts, most studies employ a simple return ratio without considering how different crop straws affect soil ecological requirements. For example, Roberts et al. [?] estimated agricultural biomass potential in General Pueyrredón at approximately 205,000 tons by considering crop types, planting area, and yield. Chandra et al. [?] calculated Fiji' s agricultural biomass energy potential at about 72.67 PJ for 2003–2012 by considering crop yield, collection rate, and usage. Tian et al. [?] estimated China' s total energy-oriented crop straw at approximately 344 million tons by considering different straw-to-grain ratios and uses including fuel, fertilizer, feed, and industry. Mi et al. [?] calculated theoretical crop straw quantity in Tongliao at 6.0173 million tons and collectible amount at 5.6752 million tons by considering crop yield, straw-to-grain ratio, and collection coefficient.

However, different crop straws have distinct compositions and return methods, leading to varying effects on soil erosion prevention and organic matter maintenance. Therefore, calculating straw return amounts using a single return ratio is inappropriate. Based on this understanding, our study proposes the concept of soil ecological retention amount from the perspective of preventing soil erosion, maintaining soil organic matter, and ensuring long-term crop yields. Additionally, as crop planting area, yield, and planting structure change over time, they affect the potential and spatial distribution of energy-oriented straw resources. Existing studies rarely evaluate future energy-oriented straw resource potential from the perspective of changes in crop planting area, yield, and structure. Therefore, building upon previous research, this study constructs a bottom-up dynamic evaluation model for the ecological potential of energy-oriented straw resources by considering soil ecological retention amounts for different crops and incorporating changes in planting area, yield, and structure. This model is then used to evaluate and analyze the ecological potential of energy-oriented straw resources from major crops in different regions of China. The findings provide decision-making support for regional renewable energy target allocation, straw energy industry layout and planning, and hold important practical significance for developing ecological agriculture in China.

1.1 Calculation Methods

Assuming the total national crop sowing area in year t is S , the sowing area of province i can be expressed as S , $= a$, $\times$ S , where a , represents the proportion of province i' s crop sowing area to the national total in year t. If there are m major crops, the straw yield of crop j in province i in year t (P , ,) can be expressed as:

$$P_{t,i,j} = S_{t,i} \times b_{t,i,j} \times g_{t,i,j} \times d_j \quad (1)$$

where b , , represents the planting proportion of crop j in province i in year t, g , , represents the unit yield of crop j in province i in year t, and d represents the straw-to-grain ratio of crop j. The total crop straw amount in province i in year t (P ,) can be expressed as:

$$P_{t,i} = \sum_{j=1}^{m} P_{t,i,j}$$

Besides returning to field, current straw uses can be divided into three major categories: agricultural use, industrial use, and rural household energy [?]. Therefore, the total energy-oriented straw amount in province i in year t (P , *) can be expressed as:

$$P^*_{t,i} = \sum_{j=1}^{m} P_{t,i,j} \times (1 - r_{t,i,j} - m_{t,i,j} - n_{t,i,j})$$

where r , , , m , , , and n , , represent the soil ecological retention amount, agricultural use amount, industrial use amount, and rural household use amount of crop j in province i in year t, respectively. The total national energy-oriented straw ecological amount in year t (P) can be expressed as:

$$P_t = \sum_{i=1}^{31} P^*_{t,i}$$

where 31 represents the number of mainland provinces, excluding Hong Kong, Macao, and Taiwan.

1.2.1 Data Sources

Sample data for national and provincial crop sowing areas, provincial crop yields, and provincial planting areas of major crops were all obtained from the National Data Agricultural Database [?], with consistent statistical 口径 (caliber) for similar indicators.

1.2.2 Provincial Crop Sowing Area Prediction

Crop sowing area is influenced by economic development, policy, agricultural infrastructure level, and other uncertain factors, exhibiting nonlinear changes. Meanwhile, sample sizes for medium- and short-term predictions are relatively small. Therefore, a gray neural network was adopted to predict the total national crop sowing area. First, GM(1,1) models with sequence lengths of 6, 8, and 10 were constructed based on sample values of total crop sowing area from 1995–2004, and the equal-dimension rolling method was used to predict the total sowing area for 2005–2014. Second, the prediction results from the three GM(1,1) models were used as input values for a BP neural network, with sample values of total sowing area for 2005-2014 as output values. All layer transfer functions used Sigmoid functions. The fitting results between final predicted and actual values are shown in [Figure 1: see original paper]. The total sowing areas for 2016, 2020, 2025, and 2030 are 1.672×10^{8} hm^{2}, 1.709×10^{8} hm^{2}, 1.711×10^{8} hm^{2}, and 1.711×10^{8} hm^{2}, respectively.

Provincial crop sowing area proportion predictions employed linear regression. Based on regression coefficients of provincial sowing area proportions from 2000–2012, 14 provinces including Tianjin, Hebei, and Inner Mongolia showed strong linear correlation with time ($R^2>0.8$). Eleven provinces including Beijing, Shanxi, and Jilin showed relatively strong correlation ($0.5<R^2<0.8$), while six provinces (Liaoning, Jiangxi, Hubei, Hunan, Hainan, Guizhou) showed weak linear correlation ($R^2<0.5$). Therefore, the mean values of agricultural sowing area proportions for these six provinces from 2000–2012 were used as predictions. After normalization and combining with future national crop sowing areas, provincial agricultural sowing areas are shown in [Figure 2: see original paper].

1.2.3 Selection of Major Crops and Planting Proportion Design

China has numerous crop varieties. Grain crops mainly include rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), potatoes (mainly *Solanum tuberosum*), and soybean (*Glycine max*). Among economic crops, rapeseed (*Brassica campestris*), peanut (*Arachis hypogaea*), cotton (*Gossypium arboreum*), and sugarcane (*Saccharum officinarum*) have relatively concentrated planting areas and can be utilized at scale. Therefore, these nine crops were selected as research objects. From 2000-2012 planting proportions [?], rice, wheat, cotton, peanut, rapeseed, and sugarcane showed discrepancies between predicted and actual values. As relevant studies are limited, a combined model prediction and expert prediction approach was adopted. First, linear regression was applied based on provincial yields of major crops from 2000-2012. Then, experts in relevant fields independently assessed yields for 2020 and 2030. If the linear regression prediction was lower than the expert prediction, the linear regression value was adopted; otherwise, the expert prediction was used, with weighted averaging for other years. Final yields for 2020 and 2030 are shown in (potato yields are grain-equivalent after conversion at a 5:1 ratio).

1.2.4 Soil Ecological Retention Amount Design

First, literature on relationships between straw return amounts and soil erosion, soil organic matter/carbon, and crop yields was retrieved from CNKI and compiled to determine corresponding straw retention ranges. Second, studies were classified by crop type, and the mean values of upper and lower retention limits were calculated to obtain new retention ranges for different crops, which were treated as the value range for soil ecological retention amount. The lower limit was set as the low scenario value, the upper limit as the high scenario value, and the average as the medium scenario value. Due to limited research on rapeseed, potato, peanut, and sugarcane, rapeseed scenarios adopted wheat settings due to similar composition and proportions [?]. Minimum retention amounts for potato, peanut, and sugarcane used the mean of other crops' minimum retention values, as detailed in .

1.2.5 Straw-to-Grain Ratio and Straw Use Design

China' s cotton production statistics use lint cotton yield, so reference [?] was consulted, while other crops followed references [?], as shown in . For straw use design, straw used as industrial raw materials (e.g., papermaking, artificial boards, tableware) was classified as industrial use ratio, excluding energy-oriented straw. Straw used for feed, fertilizer, and mushroom cultivation was classified as agricultural use ratio. Straw used for rural household energy and heating was classified as rural household use ratio. This study synthesized literature [?] to design industrial, agricultural, and rural household use ratios for different crops, as shown in .

2.1 Ecological Potential of Energy-Oriented Straw Resources by Province

Under low, medium, and high scenarios, energy-oriented straw amounts in 2030 are 227.96 million tons, 137.18 million tons, and 77.56 million tons, respectively. In the low scenario, energy-oriented straw is mainly distributed in Henan, Shandong, Heilongjiang, Sichuan, and Guangxi, accounting for approximately 10.64%, 7.70%, 6.36%, 5.65%, and 5.57% of the total in 2030, respectively. Beijing, Tianjin, Shanxi, Shanghai, Zhejiang, Fujian, Hainan, Tibet, Qinghai, and Ningxia each account for less than 1%. Hebei, Jilin, Anhui, Jiangxi, Guangdong, and Yunnan each account for 3%-5%, with remaining provinces between 1%-3%. In the medium scenario, distribution concentrates in Henan, Shandong, Sichuan, Heilongjiang, and Yunnan, accounting for 11.16%, 8.02%, 7.63%, 6.13%, and 5.69%, respectively. Beijing, Tianjin, Shanxi, Shanghai, Zhejiang, Hainan, Tibet, Shaanxi, Qinghai, and Ningxia each account for less than 1%. Hebei, Anhui, Hunan, Guangdong, and Chongqing each account for 3%-5%, with others between 1%-3%. In the high scenario, distribution concentrates in Guangxi, Henan, Shandong, Sichuan, and Heilongjiang, accounting for 10.54%, 10.01%, 8.93%, 8.67%, 7.15%, and 5.41% of the total energy-oriented straw. Beijing, Tianjin, Shanxi, Shanghai, Zhejiang, Tibet, Shaanxi, Qinghai, and Ningxia each account for less than 1%. Hebei, Inner Mongolia, Jiangsu, Hubei, Hunan, Guangdong, Chongqing, Gansu, and Xinjiang each account for 3%-5%, with remaining provinces between 1%-3%. Energy-oriented straw amounts and totals under different scenarios are shown in .

2.2 Composition Analysis of Energy-Oriented Straw Resources by Province

The composition and changing trends of energy-oriented straw resources under different soil ecological retention scenarios are shown in . In the low retention scenario, energy-oriented straw consists mainly of rice, potato, and wheat straw, accounting for approximately 30.61%, 30.18%, and 18.63% in 2016, and 29.57%, 29.88%, and 18.84% in 2030, respectively. In the medium retention scenario, it also consists mainly of rice, wheat, and potato straw, accounting for 22.20%, 15.24%, and 43.07% in 2016, and 22.21%, 15.73%, and 42.64% in 2030, respectively. In contrast, the high retention scenario consists mainly of potato and sugarcane straw, accounting for 63.53% and 20.26% in 2016, and 63.22% and 18.57% in 2030, respectively.

2.3 Density Analysis of Energy-Oriented Straw Resources by Province

For enterprises, crop planting areas vary across time and regions, while cultivated land area remains relatively constant. Therefore, crop sowing area was used to calculate straw resource density. Energy-oriented straw resource densities under different scenarios are shown in . In the low scenario, the density of major crop energy-oriented straw resources in 2030 is approximately 172 $\mathrm{t \cdot km^{-2}}$. Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, and Xinjiang have relatively high densities exceeding 200 $\mathrm{t \cdot km^{-2}}$. Beijing, Hebei, Liaoning, Jilin, Anhui, Jiangxi, Henan, Hubei, Hunan, Guizhou, Yunnan, Tibet, Gansu, Qinghai, and Ningxia have densities between 100-200 $\mathrm{t \cdot km^{-2}}$. Remaining provinces have densities below 100 $\mathrm{t \cdot km^{-2}}$. In the medium scenario, the density is approximately 103 $\mathrm{t \cdot km^{-2}}$ in 2030, with only Guangdong, Guangxi, Hainan, and Chongqing exceeding 200 $\mathrm{t \cdot}$

km^{-2}. Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Henan, Hubei, Hunan, Sichuan, Yunnan, Tibet, Gansu, Qinghai, and Xinjiang have densities between 100-200 $t \cdot km^{-2}$, with all others below 100 $t \cdot km^{-2}$. In the high scenario, the density is approximately 58 $t \cdot km^{-2}$ in 2030, with only Guangxi exceeding 200 $t \cdot km^{-2}$. Only Fujian, Guangdong, Hainan, Chongqing, and Qinghai have densities between 100-200 $t \cdot km^{-2}$, with all others below 100 $t \cdot km^{-2}$.

3 Discussion and Conclusions

The calculation of total ecological energy-oriented straw resources is primarily based on soil ecological retention amount, provincial crop sowing area predictions, and crop yield predictions. The soil ecological retention amount was designed based on literature [?], ensuring objectivity. For total sowing area prediction, the total area will peak at 1.7106\$×10^{8}\$ hm^2 in 2024 before stabilizing, which is lower than the maximum sowing area proposed in literature [?]. Provincially, crop sowing areas in Anhui, Henan, and other provinces are basically consistent with literature [?]. For crop yield prediction, literature [?] predicted that by 2030, China’ s rice, wheat, maize, soybean, potato, and rapeseed yields would be approximately 6,700 $kg \cdot hm^{-2}$, 6,500 $kg \cdot hm^{-2}$, 7,500 $kg \cdot hm^{-2}$, 2,300 $kg \cdot hm^{-2}$, 6,000 $kg \cdot hm^{-2}$, and 2,200 $kg \cdot hm^{-2}$, respectively. This study’ s 2030 average yields are approximately 6,847 $kg \cdot hm^{-2}$ for rice, 4,788 $kg \cdot hm^{-2}$ for wheat, 6,871 $kg \cdot hm^{-2}$ for maize, 2,166 $kg \cdot hm^{-2}$ for soybean, 4,716 $kg \cdot hm^{-2}$ for potato, and 1,917 $kg \cdot hm^{-2}$ for rapeseed, which are largely consistent except for wheat and potato yields. Cotton and sugarcane yields are also basically consistent with literature [?].

Prioritizing soil ecological retention, the total ecological energy-oriented straw resources in low and medium scenarios are comparable to studies using return-to-field ratios [?, ?], while the high scenario is significantly lower than existing research. Regarding regional distribution, low scenario results are basically consistent with existing studies [?, ?], mainly distributed in Henan, Shandong, and Heilongjiang. However, with time and increasing soil ecological retention amounts, differences emerge in total amount, composition, and spatial distribution compared to existing research. Over time, energy-oriented straw resources show spatial agglomeration. In low and medium retention scenarios, economically developed regions like Beijing, Tianjin, Shanghai, and Jiangsu show declining trends, while northeast China, Inner Mongolia, and Xinjiang show increasing trends, and Henan, Shandong, Anhui, Hunan, Hubei, and Sichuan remain relatively stable. With increased soil ecological retention amounts, spatial distribution and composition shift. Spatially, resources transfer mainly to Guangxi, Yunnan, and Sichuan. Compositionally, resources shift mainly to potato and sugarcane straw.

These phenomena occur primarily because existing studies use return-to-field ratios, making total straw return a weighted average of different crops. In contrast, soil ecological retention amount is designed for specific crops, potentially resulting in return amounts exceeding theoretical straw quantities in some regions. Additionally, differences in regional crop sowing areas, planting structures, and yields cause spatial distribution, density, and composition of ecological energy-oriented straw resources to change over time and with minimum retention adjustments. Straw energy utilization is related not only to regional total resources but also to resource density and composition, which have important practical significance for industrial layout, strategic planning, process design, and agricultural ecological protection.

Using direct-fired power generation and cellulosic ethanol projects as examples, research indicates that 6 MW and 25 MW straw-fired power plants require regional straw densities of 24 $t \cdot hm^{-2}$ and 92 $t \cdot hm^{-2}$, respectively, while 10,000 $t \cdot a^{-1}$ and 50,000 $t \cdot a^{-1}$ cellulosic ethanol plants require densities of 31 $t \cdot km^{-2}$ and 153 $t \cdot km^{-2}$, respectively [?]. Disregarding other factors, all provinces except Beijing, Tianjin, Shanghai, and Tibet can develop 6 MW direct-fired power plants or 10,000 $t \cdot a^{-1}$ cellulosic ethanol plants in the low scenario. In the medium scenario, only Jiangsu, Zhejiang, Fujian, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Gansu, and Xinjiang are suitable for 25 MW direct-fired power generation, while 50,000 $t \cdot a^{-1}$ cellulosic ethanol plants are only suitable for Fujian, Guangdong, Guangxi, Hainan, and Chongqing. In the high scenario, Beijing, Tianjin, Shanxi, Shanghai, Anhui, Tibet, Shaanxi, Qinghai, and Ningxia are unsuitable for either project type, while only Fujian, Guangdong, Guangxi, Hainan, and Chongqing can establish 25 MW direct-fired power plants or 50,000 $t \cdot a^{-1}$ cellulosic ethanol plants.

Different crop straws have varying physicochemical properties that affect energy conversion processes, such as boiler fouling and fermentation temperature/pH requirements. Therefore, regional composition of energy-oriented straw resources influences process design. Overall, low and medium scenarios should prioritize the impact of rice, potato, and wheat straw on processes, while the high scenario should prioritize potato and sugarcane straw.

Based on the above analysis, conclusions are as follows: In the low scenario, all provinces except Beijing, Tianjin, Shanghai, and Tibet can develop direct-fired power generation and cellulosic ethanol projects due to insufficient resources, with priority consideration for rice, potato, and wheat straw process impacts. In the medium scenario, all provinces except Beijing, Tianjin, Shanxi, Shanghai, Tibet, Qinghai, and Ningxia can develop such projects, with 50,000 $t \cdot a^{-1}$ cellulosic ethanol plants only suitable for Fujian, Guangdong, Guangxi, Hainan, and Chongqing. In the high scenario, Beijing, Tianjin, Shanxi, Shanghai, Anhui, Tibet, Shaanxi, Qinghai, and Ningxia are unsuitable for these projects, with only Fujian, Guangdong, Guangxi, Hainan, and Chongqing capable of supporting 25 MW direct-fired power plants or 50,000 $t \cdot a^{-1}$ cellulosic ethanol plants, while prioritizing potato and sugarcane straw process impacts.

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