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Research paper

Study on the ecological potential of Chinese straw resources available for bioenergy producing based on soil protection functions

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ABSTRACT

Straw return has positive effect on improving soil ecological environment, and now there are serious ecological problems of arable land in China. Therefore, the concept of basic straw returning amount (BSRA) was put forward based on soil protection functions, and literature review and scenario analysis method were adapted to design BSRA. Based on this, a bottom up dynamic accounting model was built, which considering the changes of sown area, unit crop yield, planting structure and crop straw utilization. Then, the model was applied to assess the potentials of straw resources for bioenergy production. Usable straw resources in low, middle and high BSRA scenario (Table 1) are 265.70, 180.25 and 117.51 Tg respectively in 2030, mainly composed of paddy rice (*Oryza sativa L.*) stalk, maize (*Zea mays L.*) stalk and potato (*Solanum tuberosum L.*) stalk in low and middle scenario, and maize stalk, potato stalk and sugarcane (*Saccharum officinarum*) stalk in high scenario. Available crop residues mainly distribute in Sichuan, Henan, Heilongjiang and Shandong Province under the three scenarios. There will be interzone spatial transfer of usable straw resources, over time, mainly transferring to Northeast China, North China and Northwest China. The usable straw amount will have shape decrease in August and September as the increase of BSRA.

1. Introduction

To solve problems caused by energy shortages and environmental pollution, the exploitation and utilization of bioenergy has increased in this century. According to predictions from the International Energy Agency (IEA), bioenergy will account for about 20% of global total energy consumption in 2050 [1]. Many countries and organizations have set ambitious goals for biomass energy, including the United States [2], the European Union [3] and Brazil [4]. With advances in research and application, agricultural by-products have been identified as a significant potential for bioenergy production. In addition, incorporation of straw into the soil plays a positive role in protecting the soil's ecological environment and combating soil erosion [5,6]. Some studies also found that continuing straw return will improve crop yield in the long term [7]. However, if too little straw is returned, improvements in the ecological environment of the soil and reductions in erosion are not effective [8,9]. On the other hand, due to the slow decomposition of straw under natural conditions, returning too much straw not only affects the rooting and survival of crops, but also encourages pests, causes short-term soil acidification and is an inconvenience for field management [10–12]. Therefore, understanding the optimal balance between the amount of straw available for bioenergy utilization and the amount of straw to return is very important for the environment and the effective utilization of straw for energy production.

Crop straw resource was calculated by multiplying crop yield by the straw-grain ratio [13,14]. Based on this fundamental method, researchers investigated the collection ratio of crop straw [15–18]. Some studies used Geographic Information System (GIS) to analyse the hectares of crops sown in different areas. Then crop yields, straw-grain ratio and collection ratio were considered to calculate the potential amount of straw resource [19–22]. In General, these studies [13–22] only calculated the straw yield for a given year; the effects of changes in land use, unit crop yield change and planting structure were not considered. The results obtained from these methods are theoretical crop straw resource estimates.

Based on the theoretical straw resource estimate, some researchers considered the factor of crop incorporation when assessing the amount of straw to be used for bioenergy production. However, most studies adopted a straw return ratio to assess the amount of crop straw

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available for bioenergy production, but to calculate straw return amount, they used a scenario analysis method to assess the amount available for return under based on different ratio [23,24]. However, for different crop residue, the effects on protection of soil function and reduction of soil erosion are also different after returning. Therefore, determining an ideal amount to be returned is more effective than using a return ratio. However, there are few studies that use straw return amount to evaluate the potential amount of crop straw that is available for bioenergy production [13–22].

To calculate the optimal straw return amount, some studies conducted field experiments to examine the amount of returned straw needed to prevent soil erosion or keep the correct level of organic carbon (SOC) in the soil [25,26]. Some studies researched the relationship between straw removal and soil erosion, soil organic matter or crop yields with Erosion-Productivity Impact Calculator model (EPIC), Agricultural Policy Environmental eXtender model (APEX) and Cornell Soil Health Test model (CSHT) [27–29]. However, these models all have the same limitation, considering only one of the factors mentioned above.

In addition to the factor of straw return, some researchers considered other utilizations of crop straw. Fodder usage, industrial usage and rural household usage were frequently considered [30,31]. When calculating the amount of straw for other purposes, some studies set a direct proportion of the theoretical crop straw resource amount [32–34]. However, the amounts of crop straw needed for different usages are different for the different crops.

This paper summarizes the contributions of the above-mentioned studies as follows:

1. Calculation of BSRA. This paper reviewed and analysed studies that examined the relationship between removal amount and soil erosion, organic soil composition and long-term crop yield. A scenario analysis method was used to design the BSRA, using three scenarios, low scenario, middle scenario and high scenario.
2. Forecasting area of crop sown, per unit crop yield and planting structure. Over time, total regional sown area, unit crop yield and cropping structure change. Therefore, Grey Neural Network model (GNN), linear regression forecasting, and specialist forecasting were applied to forecast these factors. GNN is a combined model of grey model and Artificial Neural Network (ANN) [56]. Sample data are all taken from the National Database (http://www.stats.gov.cn/).
3. Statistics of other straw usage. The literature review method was applied to comb through the usages of different crops for different applications. In addition to bioenergy utilization, there are many other uses for crop straw [35,36]. In order to simplify the analysis, this paper divides the utilization of crop straw into agricultural uses and rural household uses.

2. Model framework

The accounting model is divided into four parts: data forecast, BSRA calculation, straw usage statistics and outcome evaluation part (see Fig. 1). In China, primary food crops are paddy rice, wheat (*Triticum aestivum L.*), maize, potato and soybean (*Glycine max (Linn.) Merr.*). In addition, the growing areas of rapeseed (*Brassica napus L.*), cotton (*Gossypium spp*), peanut (*Arachis hypogaea Linn.*) and sugarcane are relatively concentrated in cash crops, convenient for large scale use of residue. Compared with above crops, the planting area of sesame (*Sesamum indicum*), sunflower (*Helianthus annuus*) and sugar beet (*Beta vulgaris L.*) are too small and dispersed. Other crops, like jute (*Crotalaria juncea*) and tobacco (*Nicotiana L.*), which have specific uses are not considered, nor are vegetables. Therefore, paddy rice, wheat, corn, soybean, potato, cotton, peanut, rapeseed and sugarcane were chosen as the research subjects.

Based on the fundamental crop straw calculation model [13,14], if the total sown area in China in year t is S_t, the sown area of province i can be expressed as $S_{t,i} = S_t{\cdot}\alpha_{t,i}$, where $S_{t,i}$ is the sown area of province i in year t, $\alpha_{t,i}$ is the proportion of total sown area of province i in year t. If there are m kinds of crops, the theoretical straw yield of crop j in province i in year t ($P_{t,i,j}$(dry straw)) can be expressed as

$$P_{t,i,j} = S_{t,i}{\cdot}\beta_{t,i,j}{\cdot}\gamma_{t,i,j}{\cdot}\delta_j. \tag{1}$$

Where $\beta_{t,i,j}$ is the planting proportion of crop j in province i in year t, $\gamma_{t,i,j}$ is the unit yield of crop j in province i in year t, δ_j is the residue-to-product ratio of crop j. The total theoretical straw amount of province i in year t ($P_{t,i}$(dry straw)) can be expressed as:

$$P_{t,i} = \sum_{j=1}^{m} P_{t,i,j} = \sum_{j=1}^{m} S_{t,i}{\cdot}\beta_{t,i,j}{\cdot}\gamma_{t,i,j}{\cdot}\delta_j \tag{2}$$

If giving straw return priority over other usages, the bioenergy utilization straw amount of province i in year t ($P^*_{t,i}$(dry straw)) can be expressed as:

$$P^*_{t,i} = \sum_{j=1}^{m} (S_{t,i}{\cdot}\beta_{t,i,j}{\cdot}\gamma_{t,i,j}{\cdot}\delta_j - \varepsilon_{t,i,j} - \theta_{t,i,j} - \sigma_{t,i,j} - \mu_{t,i,j}) \tag{3}$$

Where $\varepsilon_{t,i,j}$, $\theta_{t,i,j}$, $\sigma_{t,i,j}$, $\mu_{t,i,j}$ respectively are amounts for straw return, industrial use, agricultural use, and rural household use of crop j in province i in year t. Here, we do not consider the effect of straw collecting ratio because most uncollected crop straw remains in the field and can be included amount returned. Therefore, the total usable bioenergy utilization straw amount P_t (dry straw) can be expressed as formula 4.

$$P_t = \sum_{i=1}^{31}\left[\sum_{j=1}^{m} (S_{t,i}{\cdot}\beta_{t,i,j}{\cdot}\gamma_{t,i,j}{\cdot}\delta_j - \varepsilon_{t,i,j} - \theta_{t,i,j} - \sigma_{t,i,j} - \mu_{t,i,j})\right] \tag{4}$$

Where 31 refer to the number of provinces in mainland China; provinces in Taiwan, Hong Kong and Macao are not included. The spatial distribution of straw resources used for bioenergy production can be calculated using formula 4. However, as crops are harvested at different times in each province, another formula is required to express the distribution over time.

Suppose there are X ($0 \le X \le m$) kinds of crops can be harvested in the same time period, and one year is divided into Y periods. Thus, the available straw for bioenergy in y time period in province i in year t ($T^*_{t,i,y}$(dry straw)) can be expressed as formula 5.

$$T^*_{t,i,y} = \sum_{x=1}^{X} (S_{t,i}{\cdot}\beta_{t,i,x}{\cdot}\gamma_{t,i,x}{\cdot}\delta_x - \varepsilon_{t,i,x} - \theta_{t,i,x} - \sigma_{t,i,x} - \mu_{t,i,x}) \tag{5}$$

Based on formula 5, the total available straw for bioenergy in y period in year t ($T_{t,y}$(dry straw)) can be expressed as formula 6.

$$T_{t,y} = \sum_{i=1}^{31}\left(\sum_{x=1}^{X} (S_{t,i}{\cdot}\beta_{t,i,x}{\cdot}\gamma_{t,i,x}{\cdot}\delta_x - \varepsilon_{t,i,x} - \theta_{t,i,x} - \sigma_{t,i,x} - \mu_{t,i,x})\right) \tag{6}$$

Where $\beta_{t,i,x}$ is the planting proportion of crop x in y period in province i in year t, $\gamma_{t,i,x}$ is the per unit yield of crop x in province i in year t, δ_x is the straw-grain ratio of crop x. $\varepsilon_{t,i,x}$, $\theta_{t,i,x}$, $\sigma_{t,i,x}$, $\mu_{t,i,x}$ respectively are amounts for straw return, industrial use, agricultural use, and rural household use of crop x in y period in province i in year t.

3. Materials and data

3.1. BSRA

3.1.1. The concept of BSRA

Early studies mainly researched the relationship between straw return amount and soil erosion using the Revised Universal Soil Loss Equation (RUSLE) or Wind Erosion eQuation (WEQ) [8,9]. Later research showed that continued straw return improves the SOC levels and long-term crop yields [37,38]. Other research examined the effects of