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Integrated assessment of straw utilization for energy production from views of regional energy, environmental and socioeconomic benefits

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ABSTRACT

This study develops an integrated model for dynamically predicting the energy potential of straw resources and assessing regional energy, environmental, and socioeconomic benefits of straw utilization for energy production. Jilin Province, China is taken as an empirical study area. The quantity of straw resources is estimated by principal component analysis and autoregressive integrated moving average model considering panel data of six influential factors and grain yield. The regional energy, environmental, and socioeconomic benefits of straw utilization through three bioenergy conversion technologies (direct-combustion power generation, briquette fuel and cellulosic fuel ethanol) are quantitatively evaluated referring to Global Bioenergy Partnership's sustainability indicators. The results indicate that the quantity of straw available for energy production has continuous rising trend spanning 15 years (2016–2030) and could amount to 47.10 million t (Mt) by 2030. According to local government planning within 15 years, three straw-energy industries could contribute to a net profit of 2.2 billion USD. The accumulative mitigation amount of greenhouse gases, SO_2, NO_x and $PM_{2.5}$ is 700.25 Mt, 3.99 Mt, 2.05 Mt and 3.94 Mt, respectively in contrast to fossil fuels burning and open-burning of straw. In total 166.05 thousand employments could be created. The methods and results presented are expected to provide decision makers with guidance for regional development of bioenergy industries.

1. Introduction

The problems of energy shortage, climate change and environmental pollution caused by continuous economic growth are increasingly severe worldwide. In this context, bioenergy as the fourth largest energy source following coal, oil and natural gas is playing a considerable role on emerging renewable energy in the world (Konur, 2012). Especially, crop straw resources as typical bioresources are relatively abundant and low sulfur-containing (Gawronska and Gawronski, 2016). In addition, the combustion of straw is considered as carbon neutral since the amount of carbon dioxide released is comparable to that absorbed from the atmosphere during crop growth (Weldemichael and Assefa, 2016). $PM_{2.5}$ emissions and the haze phenomenon aggravated by the open burning of discarded straw could be dramatically alleviated once it is utilized for energy use instead (Ding et al., 2013; Hong et al., 2016). Straw can be converted through various energy conversion technologies (ECTs) into energy products, including electricity, heat, and solid, gaseous and liquid biofuels, which are diversified and appeal to the market demand. Not only the environmental burdens could be ameliorated, but also certain benefits for farmers could be created (employments, income from straw sales), if straw resources could be fully exploited for energy production to realize industrial development.

Currently, the theoretical researches on straw utilization for energy production are mainly focused on the following directions: (1) estimation of the available potential of straw resources; (2) optimization of the whole supply system of straw utilization; and (3) environmental and economic assessments of ECTs. Quantification of the energy potential of straw is based on three levels: theoretical reserve, collectable quantity and quantity available for energy production (Said et al., 2013). The theoretical reserve is calculated based on the grain yield and straw-grain ratio, which is referred to The Food and Agriculture Organization's (FAO's) calculation method. The collectable quantity is calculated based on the theoretical reserve excluding the loss during collection and

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Subscripts and superscripts

t	year (from 2016 to 2030)
i	bioenergy conversion technologies (ECTs)
k	resource-island (the total number is n)

Variables and coefficients

Y_t	grain yield (t)
X_u	the u-th influential factor of grain yield
Z_m	the m-th principal component (T_m is the total principal components, $m = 1, 2$)
a_m	corresponding eigenvector of principal component Z_m
Q_t	quantity of straw available for energy production (t)
Q_t^c	collectable quantity of straw (t)
Q_t^l	theoretical reserve of straw (t)
μ	energy utilization coefficient
λ	collection coefficient
η	straw-grain ratio
D_t	energy density of straw (t/km^2)
S_t	sown area of grain (hm^2)
R_k	radius of resource-island k (km)
$L_{k,i}$	transportation distance outside island k (km)
M_i	straw demand of ECTi (t/a)
C_i	total cost of ECTi (USD/a)
p	unit price of purchasing (processing, loading and storing) straw (USD/t)
NP_i	net profit of ECTi (USD/a)
N_i	production amount of energy product of ECTi (kWh, t)
I_i	total income of ECTi (USD)
ρ_i	price of energy product of ECTi (USD/kWh, USD/t)
E_i	total emissions of ECTi (kg)
f	tortuosity factor of road
φ	price rate of transportation (USD/t·km)
ξ	diesel consumption rate of transportation (kg/t·km)
ς	diesel consumption rate of processing (kg/kg)
τ_i	consumption of coal-fired power of unit energy product of ECTi (kWh/t)
e_d	emission coefficient of diesel (kg/kg)
e_c	emission coefficient of coal-fired power (kg/kWh)

transportation. The quantity available for energy production is calculated based on the collectable quantity through deducting that used in other utilization ways (returning to cropland, fertilizer, feed, papermaking, etc). Jiang et al. (2012) and Liu et al. (2012) statically analyzed the temporal energy potential of different crop straw in different regions of China using the above method. Monfortiet et al. (2015) and Weiser et al. (2014) also estimated the energy potential of straw in the European Union, Germany and other regions in a similar way. On this basis, studies regarding dynamic prediction of the energy potential of straw were carried out. Ji (2015) predicted the yield of crop residues in China with an artificial neural network (ANN) mode. Che (2014) adopted the Geographical Information System (GIS) technology to simulate the spatial distribution of straw resources in China and estimated the future resource potential by the grey prediction method.

Based on regional energy potential and the energy density of straw resources, an optimal location for establishment of a straw-energy project needs to be identified considering spatial factors and a supply system (consisting of collection, pretreatment, storage and transportation) needs to be optimized to pursue a logistics process with lower cost and emissions (Shafie et al., 2014; Sun et al., 2017; Delivand et al., 2015; Venier and Yabar, 2017). Hohn et al. (2013) used a GIS based method to analyze the spatial distribution and amount of potential biomass feedstock for biogas production and optimal locations, sizes and number of biogas plants in southern Finland. Aldana et al. (2014) considered energy production maximization and total cost minimization by constructing a comprehensive Mixed Integer Linear Programming (MILP) model to analyze the supply chain of biofuel production with agricultural residues in Mexico. Zhao and Li (2016) developed a bi-objective 0–1 integer programming model for designing optimal locations and corresponding feedstock supply chain based on relevant data of biomass power generation in China, to achieve a win-win situation between cost and greenhouse gas (GHG) emissions.

Because of the divergence in the performances of energy production, cost, profit, GHG emissions, sustainability performance, ECTs of straw attracted more scholars to carry out assessments of these performances with life cycle assessment (LCA), emergy analysis, SWOT (strengths, weakness, opportunities and threats) analysis, multi-criteria decision making analysis (MCDMA) and some others (Portugal-Pereira et al., 2015; Martire et al., 2015; Vaidya and Mayer, 2016; Hiloidhari et al., 2017). Hu et al. (2014) conducted a preliminary LCA on a straw briquette fuel plant in China and covered only emissions of GHGs and air pollutants. Wang et al. (2015) evaluated the energy consumption and GHG emissions of a direct-combustion power generation project with forestry residues as feedstock using the layered hybrid evaluation model. Zhao et al. (2016) applied a five-force competitive model to assess the current situation and future development of China's biomass power generation industry. Khishtandar et al. (2017) used the MCDMA method based on the hesitant fuzzy linguistic data to deal with the prioritization of different bioenergy technologies in Iran. In addition, some researchers have conducted studies regarding industrial development of straw utilization from the perspectives of government, farmers and markets to put forward macro policy measures (Thompson and Tyner, 2014; Golecha and Gan, 2016).

It could be found in the reviewed studies that the prediction of future quantity of straw resources is generally based on the historical data of straw's quantity, without considering complex impacts on the yield of grain, the basis for the calculation of straw's quantity. This would affect the accuracy of the prediction results of straw's quantity, as well as the energy potential of straw. The reviewed studies have attached emphasis to the environmental and economic performances of specific ECTs, however disregarding how a certain region could benefit from straw utilization through multiple ECTs quantitatively. At present, regional energy demand is diverse, stimulating development of various straw-energy industries (SEIs). This also necessitates evaluating the overall benefits contributed by industrialization of straw utilization with regards to energy security, environmental impacts, social contribution and economic benefits for a region.

This study attempts to construct an integrated model for dynamically assessing the energy, environmental, and socioeconomic benefits of straw utilization for energy production for a certain region. Taking Jilin Province, China as a typical study area, six factors that affect the grain yield are taken into consideration for estimating the quantity of straw resources spanning 15 years (2016–2030) by principal component analysis (PCA) and autoregressive integrated moving average (ARIMA) model. The straw available for energy production is considered to be allocated to