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An environmental and economic evaluation of carbon sequestration from pyrolysis and biochar application in China

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Abstract: In the past decade, China has more than doubled its consumption of fossil fuels resulting in the emission of substantial amounts of carbon dioxide (CO_2), which are considered to be the main cause of climate change. To mitigate climate change and ensure the continued survival of life on earth, the current level of CO_{2R} emissions must be cut. This study establishes a price endogenous mathematical programming (Jiangxi Agricultural Sector Model) and incorporates bioenergy technologies such as ethanol, conventional co-firing and pyrolysis to examine how an agricultural province may contribute to bioenergy development and carbon sequestration. The results indicate that under moderate energy and greenhouse gas (GHG) prices, net electricity generation reaches 6.5 billion kWh annually. Net emission reduction is affected by market operations. At high GHG prices, pyrolysis and biochar application can sequester up to 4.74 million tons of CO_{2R} emissions annually. However, this measure fluctuates significantly when GHG prices vary. Our study shows that pyrolysis and biochar application provide significant environmental effects in terms of carbon sequestration.

Keywords: climate change, GHG mitigation, renewable energy, soil amendment

Sustainable development is an important issue currently facing the world and is concerned with the continuous and stable availability of visible and invisible resources across generations. Fossil fuels are typical non-renewable resources and modern civilizations have been largely dependent on their utilisation. Over-exploitation of fossil fuels not only reduces their availability for subsequent generations but also intensifies the greenhouse gas (GHG) effect, which increases the occurrence of extreme climatic events and results in negative effects for both current and future generations (McCarl et al. 2000; Chang 2002).

Many countries, including China, have been engaged in research aimed at the development of renewable and low-carbon energy sources to replace fossil fuels. Solar energy, hydro power and bioenergy are qualified candidates, but bioenergy may be the most attractive option for China because it is an agricultural country and more than half a billion of the population are still engaged in agricultural-related sectors, implying that the vast resources of land and substantial labour force could be harnessed for the bioenergy industry. However, emphasis is not being put on bioenergy in most agricultural regions as local governments do not have enough information to allow them to make informed decisions regarding different energy crops and bioenergy technologies. Other factors that influence the production of bioenergy include the price volatility of energy, GHG emissions, farmers' willingness to participate in energy crop plantation, land-use changes and emission reductions. To provide more information about how energy crops and bioenergy technologies compete with each other under market operations, this study selects a conventional agricultural province, the Jiangxi province, to explore the potential influences of different bioenergy technologies on the economy and the environment.

Bioenergy can be produced in liquid or electric forms (Boschiero et al. 2015; Sastre et al. 2015) and several bioenergy technologies such as those based on ethanol, direct fire, co-fire and pyrolysis have been developed. However, it is necessary to take the net GHG effects into account because the potential of bioenergy to be a low-carbon energy source depends on production processes (Wang 2007; Glaser et al. 2009). In addition, although ethanol and co-fire can be considered as low-carbon technologies, they still result in a net increase in emissions being released into the air. Unlike ethanol and conventional co-fire technology, pyrolysis involves heating biomass in the absence of oxygen, which decomposes feedstocks into bio-oil, bio-gas and biochar (Bridgwater and Peacocke 2000). Bio-oil and bio-gas can be used to generate electricity while biochar can be either used to generate electricity in the pyrolysis plant or applied to croplands as a soil amendment (Glaser et al. 2002). If biochar is used as a soil amendment, it can store carbon in a stable form for thousands of years (Glaser et al. 2002; Lehmann et al. 2006). For this reason, pyrolysis is considered as a "carbon-negative" technology that reduces the net CO_{R2R} concentration in the atmosphere (Glaser et al. 2002, 2009; Bridgwater 2005; Lehmann et al. 2006; Lehmann 2007a, b; Fargione et al. 2008). However, pyrolysis and biochar technology is essentially a form of bioenergy, which requires substantial amounts of land. As the agricultural sector, also the least profitable sector in China, engages more than 50% of residents in the Jiangxi Province, farmers have suffered from low income and consequently, low living standards, for several decades. In order to sustainably increase farmer incomes and to improve the sustainability of future development, it is necessary to change existing agricultural production patterns. With pyrolysis and biochar applications, farmers may enjoy potential economic benefits from energy production and yield enhancement, while the society has access to better water and ecosystems. This study analyses the potential reductions in GHG emission and renewable energy production for multiple bioenergy technologies including ethanol, conventional co-fire and pyrolysis and biochar technology in Jiangxi using multiple agricultural feedstocks such as sweet potato, poplar and switchgrass under various energy and GHG trade prices. Specifically, the study examines the following issues:

(a) Bioenergy production under market operations;
(b) Effects of pyrolysis-based electricity on GHG;
(c) Potential carbon sequestration resulting from biochar utilization;
(d) Changes in land-use patterns.

The importance of our study lies in several aspects. Firstly, the study attempts to determine the best energy crop for Jiangxi, i.e., the one that allows the highest level of bioenergy production and farmer revenue. Secondly, the results illustrate potential fluctuations in net bioenergy production when market prices of energy and emissions change significantly. Thirdly, carbon sequestration resulting from the use of renewable energy and biochar application is calculated and analysed for multiple bioenergy technologies. Finally, production savings and increases in crop yield that result from biochar utilisation are also incorporated into this analysis, both of which are useful for future environmental and agricultural policy decisions. The study also provides guidelines for potential carbon trade mechanism design.

LITERATURE REVIEW

The non-sustainable nature of fossil fuel-induced global climate change is an important concern and, thus, developing renewable and low-carbon fuels has assumed increasing importance. Moreover, renewable energy sources may ultimately enhance a nation's energy security and protect the environment. As bioenergy is one of the substitutes that meets such needs, it has been studied widely and has actually already been produced in the USA and Europe for decades (McCarl et al. 2000; Wang, 2007; Boschiero et al. 2015; Sastre et al. 2015). Although bioenergy seems a feasible choice, studies claim that caution must be exercised in order to avoid the unintended consequences of biofuels and that increased use of biofuels will actually increase COR$_2$R emissions because of deforestation and a sudden major shift in land use (Field and Campbell 2008; Searchinger et al. 2008; Djomo et al. 2015; Gustavsson et al. 2015). Wang (2007) showed that ethanol production may eventually result in higher GHG emissions in a well-to-wheels analysis. Fargione et al. (2008) mentioned that the production process is crucial for biofuel to

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be a potential low-carbon energy source. Field and Campbell (2008) pointed out that the net effect of biomass energy on the climate could be either cooling or warming, depending on the crop and the technology, the difference in carbon stocks and the reflectance of solar radiation between the biomass crop and the pre-existing vegetation. Therefore, although conventional bioenergy reduces reliance on fossil fuels and provides sustainable energy, carbon sequestration is not a guaranteed consequence. Instead, pyrolysis and biochar technology may be an interesting alternative because of their carbon-negative properties (Glaser et al. 2002; Lehmann et al. 2006).

Pyrolysis describes the chemical decomposition of organic materials by heating in the absence of oxygen (Bridgwater and Peacocke 2000). During pyrolysis, biomass is converted into bio-oil, bio-gas and biochar (Bridgwater and Peacocke 2000; Czernik and Bridgwater 2004; Lehmann and Joseph 2009). Fast and slow pyrolysis are predominantly used in biochar production. They are distinguished by their heating rate and heating duration and hence, different output ratio. Slow pyrolysis yields more biochar and less bio-oil while fast pyrolysis produces more bio-oil and less biochar (Wright et al. 2008; Sohi et al. 2010). Wright et al. (2008) showed that fast pyrolysis yields about 15% biochar, 70% bio-oil and 13% bio-gas. Ringer et al. (2006) indicated that under slow pyrolysis, about 35% of the feedstock ends up as biochar, 30% as bio-oil and 35% as bio-gas. Because many organic materials such as crop and forestry residuals, urban-yard wastes, industrial biomass by-products, animal manures and municipal sewage sludge can be utilised in pyrolysis, output yield can vary substantially and toxic heavy metals may be contained in outputs necessitating additional removal processes. Bio-oil can be cleaned and upgraded to higher-quality fuels (Lehmann and Joseph 2009), used to produce electricity or it can be refined to produce chemical feedstocks. Biochar has been used to provide energy in plant operation, but Lehmann et al. (2006) calculated that the CO_2 emission offset can be 12 to 84% greater if biochar is put back into the soil instead of being burned to reduce fuel costs. McCarl et al. (2009) showed that pyrolysis can have offset efficiencies of greater than 100% when compared with the emissions of the fossil fuel inputs that are replaced. Kung et al. (2013) concluded that biochar application is economically feasible in Taiwan and that a stable supply of feedstocks can reduce pyrolysis costs and improve environmental quality significantly.

In addition to the net renewable electricity from pyrolysis, appropriate use of biochar can result in environmental and economic benefits. Firstly, biochar improves nutrient and water retention. Deluca et al. (2009) illustrated a potential mechanism to describe how biochar modifies nutrient transformations. They showed that bioavailable C may be adsorbed to biochar surfaces. In addition, biochar was found to remain in the soil for more than thousands of years (Glaser et al. 2002; Lehmann et al. 2006), but is potentially eroded by precipitation and runoffs (Major et al. 2009). Traditional slash-and-burn exerts a short-term influence on N availability, but biochar is able to maintain this effect for decades. Secondly, biochar can increase crop yields because more nutrients are retained. Chan et al. (2007) showed that if N fertiliser was not added, biochar application did not increase the yield of radishes even at a high biochar application rate. However, they showed that if biochar and N fertiliser are applied together, the biochar-nitrogen fertiliser interaction is significant and biochar can improve the fertiliser efficiency of the plant. In their experiments they found that the dry material of radishes increases from 95% to 266% under different biochar application rates. Nehls (2002) showed that rice production increases up to 300%, depending on the soil condition. The effects of the application of biochar and similar materials on crop yields have been studied since 1980 (Iswaran et al. 1980; Kishimoto and Sugiura 1985; Chidumayo 1994; Oguntunde et al. 2004; Steiner et al. 2007). Since biochar also helps improve the quality nearby water bodies, its use is now recognised as a tool to raise awareness of water resources and to support policy makers in improvement of water resource management (Chapagain and Hoekstra 2008) and cultivation practices (Scown et al. 2011; Marta et al. 2012; Guieysse et al. 2013; Van Meerbeek et al. 2015).

STUDY SETUP AND MODEL SPCIFICATION

Jiangxi, one of the poorest provinces in China with approximately 70% of forest land on its 185 000 km^2 territory, has 44 million residents. More than half of its residents are engaged in agriculture because the hundreds of lakes distributed from the north to the south of the province make irrigation easy. Poyang Lake is the largest and the most important wetland in China, playing an important role in water supply, bio-diversity, watershed protection, tourism, as well as for migrant birds and forest conservation. In 2009, the Chinese government acknowledged the importance of the lake and established the Poyang Lake Eco-Economic Zone, the first national program in Jiangxi focusing on sustainable environment, social influence and economic development for both current and future generations.

Model specification

In this study, we examined the potential of pyrolysis and biochar application as a sustainable strategy to utilise the agricultural sector effectively and efficiently in terms of renewable energy production, cropland patterns and GHG emission effects. We have constructed the Jiangxi Agricultural Sector Model (JASM), which is derived from the Agricultural Sector Model-ASM (McCarl and Spreen 1980) and the Taiwan Agricultural Sector Model-TASM (Chen and Chang 2005). The JASM is modified by incorporating the potential GHG implications and local market effects to evaluate bioenergy crop production together with competition with other land use changes. The JASM is a multi-product partial equilibrium model based on previous works (Burton and Martin 1987; Chang et al. 1992; Coble et al. 1992; Kung et al. 2014a, b). This empirical structure has been adapted in many policy-related studies such as those of Chang (2002), Chen and Chang (2005) and Kung et al. (2015). The current version of JASM accommodates more than 80 commodities in 11 sub-regions and simulates market operations under assumptions of perfect competition where individual producers and consumers are price-takers. It also incorporates price-dependent product demand, input supply curves and demand elasticities. However, if more provinces are included in the JASM, this assumption is not valid since quantity demand and quantity supply may change endogenously rather than exogenously. In this study, we evaluated biochar application on a 5-ton per ha basis in Jiangxi's 100 counties, which are aggregated into 11 sub-regions. Sub-regional production activities are specified in the model for each commodity. Crop and livestock mix activities and constraints are also specified at the sub-regional level, but the input markets for cropland, pasture land, forest land and farm labour are specified at the regional level.

The methodology used in the JASM is based on price endogenous mathematical programming, which was originally illustrated by Samuelson (1952), who showed that the equilibrium in the perfect competition market can be derived from the optimisation model that maximises the consumer surplus and producer surplus. Takayama and Judge (1971) established a mathematical programming model on a spatial model based on Samuelson's idea. McCarl and Spreen (1980) pointed out that this model is useful in policy analysis, especially because of its property of price endogeneity and they compared the linear programming models used by other planned economic systems to the price endogenous model, finding that the price endogenous model can represent the economic system in a perfectly competitive market. The JASM is similar in its specifications to the ASM (McCarl and Spreen 1980) and TASM (Chen and Chang 2005), allowing the model to specify the study region with a mapping function. Other components such as input usage, production patterns and regional policy can be employed in the same way. Tariffs must be specified to reflect the influences on international trade, and are also different.

Details of the Jiangxi Agricultural Sector Model

The JASM is constructed under the framework of the ASM and TASM. Regional characteristics, agricultural policies, energy crops and GHG effects are added in the JASM.

The objective function and constraints of the JASM are expressed as follows:

$$\begin{aligned} Max \ & \sum_i \int \psi(Q_i)\, dQ_i - \sum_i \sum_k C_{ik}X_{ik} - \sum_k \int \alpha_k(L_k) dL_k - \sum_k \int \beta_k(R_k) dR_k + \sum_i P_i^G * Q_i^G + \sum_k P^L \times AL_k \\ & + \sum_i \int ED(Q_i^M) dQ_i^M - \sum_i \int ES(Q_i^X) dQ_i^X + \sum_i \int EXED(TRQ_i) dTRQ_i \\ & + \sum_i [tax_i \times Q_i^M + outtax_i \times TRQ_i] - P_{GHG} \times \sum_g GWP_g \times GHG_g \end{aligned} \tag{1}$$

Subject to:

$$Q_i + Q_i^X + Q_i^G - \sum_k Y_{ik} X_{ik} - \sum_j EC_{jk} X_{jk} - (Q_i^M + TRQ_i) \leq 0 \qquad \text{for all } i \tag{2}$$

$$\sum_{i} X_{ik} + AL_k + \sum_{j} EC_{jk} - L_k \leq 0 \qquad \text{for all } k \qquad (3)$$

$$\sum_{i} f_{ik} X_{ik} - \sum_{j} f_{jk} X_{jk} - R_k \leq 0 \qquad \text{for all } i \qquad (4)$$

$$\sum_{i,k} E_{gik}\, X_{ik} - Baseline_g = GHG_g \qquad \text{for all } g \qquad (5)$$

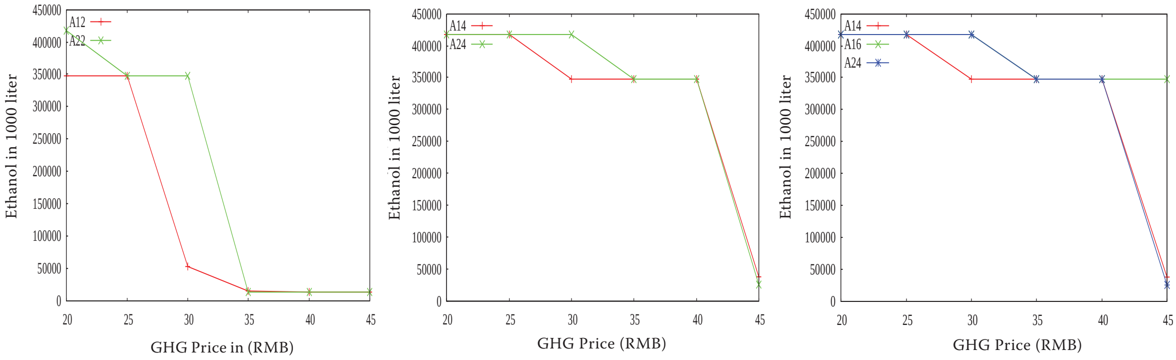
where

Q_i = Domestic demand of product
Q_i^G = Government-purchased quantity of price-supported product
Q_i^M = Import quantity of i^{th} product
Q_i^X = Export quantity of i^{th} product
$\psi(Q_i)$ = Inverse demand function of i^{th} product
P_i^G = Government purchase price of i^{th} product
C_{ik} = Purchased input cost in k^{th} region for producing i^{th} product
X_{ik} = Land used for i^{th} commodities in k^{th} region
L_k = Land supply in k^{th} region
$\alpha_k(L_k)$ = Land inverse supply in k^{th} region
R_k = Labour supply in k^{th} region
$\beta_k(R_k)$ = Labour inverse supply in k^{th} region
P^L = Subsidy of participating land
AL_k = Participating acreage in region
$ED(Q_i^M)$ = Inverse excess import demand curve for i^{th} product
$ES(Q_i^X)$ = Inverse excess export supply curve for i^{th} product
TRQ_i = Import quantity exceeding the quota for i^{th} product
$EXED(TRQ_i)$= Inverse excess demand curve of i^{th} product that the import quantity is exceeding the quota
tax_i = Import tariff for i^{th} product
$outtax_i$ = Out-of-quota tariff for i^{th} product
Y_{ik} = Per hectare yield of i^{th} commodity produced in k^{th} region
E_{gik} = g^{th} greenhouse gas emission from i^{th} product in k^{th} region
P_{GHG} = Price of GHG gas
GWP_g = Global warming potential of g^{th} greenhouse gas
GHG_g = Net greenhouse gas emissions of g^{th} gas
$Baseline_g$ = Greenhouse gas emissions under the baseline of the g^{th} gas
fR_{ik} = Labour required per hectare of commodity i in region k

The objective function of the JASM model is to maximise the social welfare in the agricultural sector. To achieve this goal, the study incorporates the production activities in all study regions, along with domestic and trade policies. Because the use of bioenergy sequesters emissions and increases social welfare, this component is incorporated. In the objective function, emission that is not offset is included, reflecting the fact that GHG emissions reduce social welfare. Equation (2) is the balance constraint for commodities where Equations (3) and (4) are the resource endowment constraints, ensuring that the use of commodities and resources cannot exceed their supply. Equation (2) ensures that commodities consumed plus import should be equal to or less than commodities supplied plus export. Equation (3) controls cropland and Equation (4) is the other resource constraint. Equation (5) is further modified to reflect the greenhouse gas balance which shows that the emissions of the CO_{R2R} equivalent that are emitted cannot be greater than total emissions.

Study setup and data

We established a mathematical programming model to simulate the effects of pyrolysis and biochar application on the environment in Jiangxi. The agricultural and forest sectors, bioenergy technologies, biochar uses and market operations are included. Ethanol, co-fire electricity and pyrolysis-based electricity are the main bioenergy technologies, while biochar can only be produced from pyrolysis. In this study, pyrolysis-based electricity and ethanol production are competing with each other since available cropland and feedstocks are limited. Biochar is assumed to be applied to cropland as a soil amendment, instead of as a fuel for plant operation. Therefore, the effects of biochar on crop yield change and CO_{R2} sequestration are incorporated into the pyrolysis scenarios. Moreover, because market prices of gasoline, coal and GHG emissions are important factors affecting the net GHG emission reduction and renewable energy production, the study simulates six gasoline prices (4 Chinese yuan/litre, 5/litre, 6/litre, 7/litre, 8/litre and 9/litre,), two coal prices (0.4 Chinese yuan/kg and 0.7/kg) and 6 GHG prices (20 Chinese yuan/ton, 25/ton, 30/ton, 35/ton, 40/ton and 45/ton). The energy prices simulated in this study are based on China's historical energy price. However, because China does not have his own emission trade market, the GHG prices used in simulations are based on the Chicago Climate Exchange. With the combinations of energy and GHG prices, we attempted to explore the potential environmental benefits of biochar application and bioenergy production in Jiangxi.



(a) (b) (c)

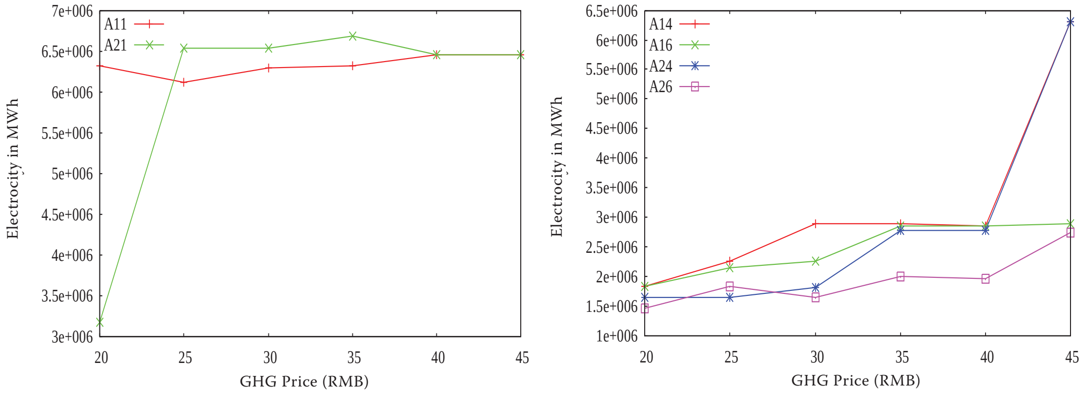
Figure 1. Ethanol production under different gasoline and GHG prices

The data sources of agricultural commodities come from published government statistics, research reports and household surveys. Demand elasticities of agricultural products come from various sources and were gathered and analysed by Chang and Chen.

RESULTS AND DISCUSSION

Although ethanol can replace the use of fossil fuels, the low emission offset rate of ethanol makes it less competitive compared to electricity. In fact, the simulation results (see Appendix in electronic supplementary material (EMS)) indicate that when environmental concern is important, higher GHG prices lead to a huge decrease in ethanol production. Under these circumstances, feedstocks are transferred to pyrolysis systems to obtain higher benefits from emission trades. Figure 1 presents this idea clearly. At low gasoline and GHG prices, ethanol production is low because producers do not gain much from the bioenergy production (Figure 1a), but ethanol production expands when gasoline increases (Figure 1b). If the gasoline price increases moderately, ethanol is very likely to be driven out from the market. At high gasoline price, ethanol production is not seriously affected by the GHG price (Figure 1c).

Pyrolysis-based electricity is potentially carbon-negative when combined with biochar application. Since pyrolysis offsets more GHG emissions, higher GHG prices lead to the expansion of electricity generation, as shown in Figure 2a and 2b. Electricity generation is sensitive to the GHG prices at low coal prices. Under low GHG prices, fast pyrolysis, which generates higher electricity on a per ton feedstock basis, is the dominant technology. However, when GHG price increases to higher levels, slow pyrolysis combined with biochar application is preferred and, thus, feedstocks are switched from fast pyrolysis into slow pyrolysis. Competition exists between ethanol and pyrolysis. As shown in Figure 2b, net electricity generation reaches approximately 6.5 billion kWh at low gasoline price and falls to 3 billion kWh at high gasoline prices. The results show that pyrolysis technology is highly influenced by GHG prices. When emission offset is valuable, producers are likely to



(a) (b)

Figure 2. Electricity production under different gasoline, coal and GHG prices

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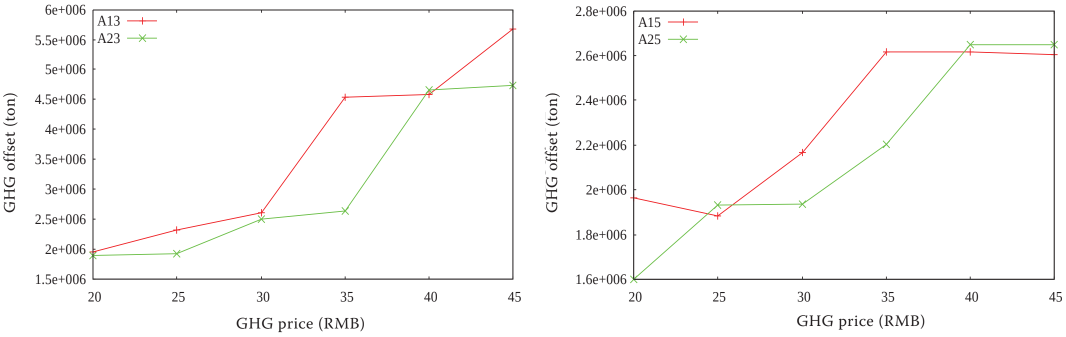

(a) (b)

Figure 3. Net GHG emission offset under different gasoline, coal and GHG prices

adopt slow pyrolysis and gain more benefits from biochar application, instead of focusing on sale of electricity. In this study, we have assumed that producers can adjust their production pattern immediately with no additional costs. However, this may not be true in reality and the issue requires further investigation.

GHG emission reduction is low at high gasoline price, due to the high production level of ethanol. At low gasoline price, pyrolysis is more profitable and ethanol production shrinks resulting in a higher GHG emission offset (Figure 3a and 3b). More than 4.736 million tons of GHG emissions could be offset at low gasoline price, but this amount will drop sharply in response to high gasoline prices. Figure 3 shows important implications for Jiangxi's emission reduction and renewable energy production.

Firstly, if the gasoline price is high, net GHG emissions will not be reduced significantly since more ethanol will be produced, leaving less space for electricity generation, whose GHG offset ratio will be higher. Secondly, market recognition of GHG emissions plays an important role. If markets do not place a high value on GHG emissions, firms may not pay high abatement costs to reduce their emissions. Consequently, net emissions may eventually increase. Therefore, a low GHG emission price may be a signal that the market ignores the positive environmental effect from emission reduction. Instead, producers will focus on ethanol production, which is more profitable. In general, the carbon-negative property of biochar makes a significant contribution to carbon sequestration, but the extent of this property could be small when the emission price is very low. As the results have indicated, the government is required to determine whether more energy or more emission reduction is needed prior to bioenergy development.

Approximately one-third of net GHG emission offset come from biochar-induced environmental effects. This implies that if the producers do not value biochar properly and use biochar as an energy source, more electricity will be generated and lower amounts GHG emissions can be offset. Therefore, when considering future environmental-related policies, the various uses of biochar could lead to huge variations in terms of carbon sequestration and bioenergy production. The results imply that when the long-term environmental consequences outweigh the supply of bioenergy, the government may need to design certain mechanisms or policies to encourage the use of pyrolysis and to increase the supply of biochar.

CONCLUSION

Renewable energy is important for the sustainable development of the economy and for the environment in terms of stable energy supply and CO_{R2R} emission sequestration. As Chinese energy consumption has doubled compared to the last decade, more pressure is being placed on the world reservoir of fossil fuels. Fossil fuel-induced climate change is an important concern, which results in a deterioration of the atmosphere due to increased concentrations of GHG.

In this study, we examined the development of bioenergy together with biochar application in Jiangxi to explore to what extent these problems can be alleviated. Our results indicate that pyrolysis, especially fast pyrolysis, provides a substantial amount of renewable energy. Ethanol is an excellent source of renewable supply, but it does not contribute to environmental upgradation. Under moderate energy and GHG prices, net electricity generation can reach up to 6.5 billion kWh annually. However, it is vulnerable when market conditions vary. If gasoline price increases by 50%, ethanol production will increase seven-fold, leaving fewer feedstocks for pyrolysis.

Under these circumstances, net electricity generation will shrink to 3 billion kWh. The net GHG emission reduction is affected by these market figures because pyrolysis-based electricity offers higher potential for emission mitigation. At higher coal and GHG prices, ethanol is less competitive than pyrolysis and electricity generation will be the main bioenergy source. Conventional co-fire is outcompeted by pyrolysis because its per unit electricity generation and carbon sequestration is lower.

The results show that biochar exerts significant environmental effects in terms of carbon sequestration. However, the amount of biochar that can be applied is heavily constrained by the technology selection and market valuation of emissions. The choice of plant site is also important because it affects the hauling costs and simulation results may change significantly. In addition, multiple plants are possible as long as production scale is large. Therefore, it is possible to analyse the net economic and environmental impacts on a multiple plant scenario. Approximately one-third of net GHG emission offset derives from biochar application, implying the proper use of biochar could be a potential alternative for future environmental policy regarding climate change mitigation. Government subsidies may be required as an incentive under certain circumstances because when facing low gasoline and GHG prices, producers are less willing to generate renewable energy.

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