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A spatial equilibrium analysis of using agricultural resources to produce biofuel

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Abstract: In order to alleviate the potential damage from climate change and fulfil the requirements contracted in the Paris Agreement (COP 24), China has promulgated the mandatory regulation on ethanol-blend gasoline to reduce current levels of CO_2 emissions. Since large-scale bioenergy development involves various aspects such as feedstock selection (energy crops, crop wastes), technology alternatives (conventional and cellulosic ethanol, pyrolysis), government subsidy (land use, energy crop subsidy) and carbon trade mechanism, an analysis that integrates economic, environmental, and social effects is necessary to explore the optimal biofuel strategy and social effects. This study proposes a price endogenous, partial equilibrium mathematical programming model to investigate how the selection of bioenergy crops and bioenergy technologies influences the amount of net bioenergy production, carbon sequestration, government subsidies, and cultivation patterns. We show that the conjunctive use of agricultural wastes can be an effective addition to current biofuel production. The results also indicate that at high gasoline and emissions prices, more land used for the energy crop program results in a significant change in government expenditure. In addition, net emissions reduction and emissions offset efficiency can vary substantially when different bioenergy techniques are adopted.

Keywords: carbon offset; ethanol; mathematical programming; resource utilisation; sustainability

Sustainable development ensures that the welfare of future generations will not worsen as measured by the availability of visible and invisible resources. From this viewpoint, fossil fuels are not a reliable energy source to achieve sustainable social development for at least two reasons. First, the over-exploitation of nonrenewable fossil fuels reduces their availability for unborn generations. Second, a huge amount of greenhouse gas (GHG) emissions emitted from the use of fossil fuels will speed up the global climate shift and increase the occurrence of extreme climate events (Grashuis 2019). Searching for renewable and low-carbon energy sources thus becomes an important issue in modern society.

Various renewable energy sources are qualified candidates and have been utilised in many countries and regions (Li et al. 2019). Among these alternatives, bioenergy is attractive in China as there is a substantial amount of labour and cropland that can be transferred to the bioenergy industry. However, before China launches a large-scale bioenergy program, information on the selection of energy crops and bioenergy techniques, potential changes in cultivation patterns, government subsidies, and environmental consequences should be obtained. To investigate subsequent environmental and economic impacts, this study selects Jiangxi province, an agriculture-intensive province, as a study area.

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Ethanol is a common form of bioenergy (Grashuis 2019) that has been considered as an effective approach to combat climate change, but whether it can be considered low-carbon energy and results in net emissions reduction depends on production processes (Bridgwater and Peacocke 2000; Karmee 2018). Previous studies focus on important issues, such as: (i) energy conversion rates of crops (Tso and Su 2009); (ii) production of ethanol under various conditions (Chen et al. 2011); (iii) the relationship between government subsidies and land-use change (Cao et al. 2017); (iv) bioenergy induced GHG consequences (McCarl and Schneider 2000); and (v) biofuel production from crop residuals (Doshi et al. 2014; Braden and Bai 2018), but they are rarely analysed simultaneously. To fill those gaps, we propose a price-endogenous partial-equilibrium model to evaluate renewable energy production and emissions offsets under crop and technique competition, as well as their influences on cropland utilisation and government subsidies in response to changes of energy and emissions prices.

Specifically, we examine the following issues: (i) ethanol production from selected energy crops; (ii) ethanol production from associated crop wastes; (iii) impacts of carbon sequestration under market operation; (iv) influences of market factors on biofuel industry promotion; (v) changes in the use of production inputs.

This work makes following contributions. First, the study indicates the competition of energy crops among bioenergy techniques. With such information the decision-makers would be able to determine the most efficient support policy on energy crop plantation. Second, the emission consequences under various bioenergy production patterns are analysed. The results point out the influences of market power so that the government could determine whether to involve or not when the market is highly distorted. Third, the capital requirement of bioenergy development is examined and the changes in possible agricultural practice, market operations, and emission offsets are also compared. The government would be able to design or reform agricultural, environmental, and renewable energy policies to optimize the overall economic, social, and environmental effects.

LITERATURE REVIEW

Utilisation of renewable energy can enhance a nation's energy security, protect the environment, and stimulate future development (Arvizu 2008; Cao et al. 2017). Bioenergy has the capacity to meet such needs and has been studied intensively in the United States, Brazil, and Europe for decades (Couto et al. 2015; Qambrani et al. 2017). Daniel et al. (2007) predicted that the cumulative displacement of oil from 2007 to 2030 could be up to 10.48 billion barrels, and the USD 629 billion could be saved, and many studies also indicate such benefits can be captured by other countries (Grashuis 2019).

The unintended environmental consequences of biofuels, such as increased COR$_2$R emissions due to deforestation and sudden major shifts in land use must be justified. To evaluate such problems, lifecycle analysis is considered to be an effective approach. McCarl and Schneider (2000) show that the ability of conventional bioenergy on carbon sequestration is uncertain, and thus studies do highlight the need for a comprehensive analysis of the aggregate effects (Chen et al. 2011; Cao et al. 2017).

Additionally, conventional biofuel is produced from agricultural commodities such as corn, soybean, and sweet potatoes (Hall and Dale 2011). Under the consideration of food-to-energy competition, biofuel technology is also evolving. Arvizu (2008) mentioned that second-generation biofuels have higher potential to reduce carbon emissions than first-generation biofuel technologies. Although this study points out that because the challenge to the US in reducing dependence on foreign oil is too great to abandon first-generation technology and the second-generation biofuel technologies may not be highly competitive in recent years, it is very likely to be profitable when various wastes can be utilised (Liu et al. 2017; Karmee 2018).

MATERIAL AND METHODS

Theoretical foundation of sectoral analysis. The sectoral analysis model is originally proposed by Samuelson (1950) who shows that the equilibrium in the perfect competition market can be derived from the optimisation model. Since bioenergy production is highly dependent on agricultural activities, it is necessary to explore the market equilibrium of agricultural markets. However, finding the equilibrium of the agricultural sector can be complex because agricultural activities generally involve multiple producers, various cultivars, different land qualities, and even international trades.

It is also unsurprising that the government have price support policy, import quota limit and tariffs in agricultural markets. Therefore, to find the equilibrium of the agricultural market, effects form international trades must be incorporated. Figure 1 illustrates

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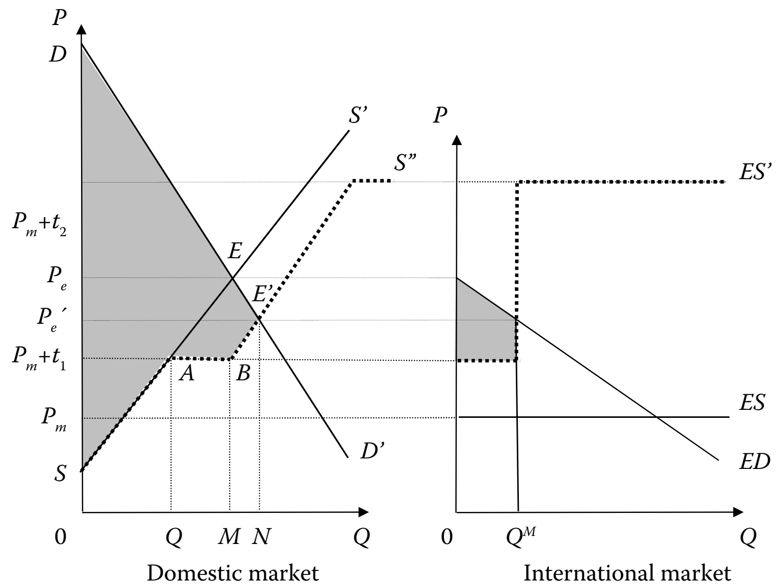

Figure 1. Welfare effects for open economies

Figure 1 illustrates how social welfare may change when international trades do occur. Suppose there is a small and closed economy, the domestic equilibrium price (P_e) can be determined by the supply curve *SS'* and the demand curve *DD'*. In an open economy where the imports and exports exist, the international commodity price (P_m) is then determined by the domestic excess demand and the excess supply from other countries. Suppose the government have two tariffs t_1 and t_2, where $t_1 < t_2$, the new equilibrium will shift downward to *E'*, thereby increasing the total welfare by the area of *ABE'E*

Source: Cao et al. (2017)

how social welfare may change when international trades do occur.

Specification of spatial equilibrium model. Following Samuelson (1950), Takayama and Judge (1971) established a mathematical programming model on a spatial model. McCarl and Spreen (1980) pointed out that this model is useful in policy analysis, especially in its property of price endogeneity.

To maximize total welfare these components should be accommodated into the nonlinear programming formulation. The inverse demand curves of commodity i is expressed as $\psi(Q_i)$ while the inverse supply curves of production inputs such as land and resource available in k region are expressed as $\alpha_k(L_k)$ and $\beta_k(R_k)$, respectively. Other inputs engaged in production processes are available at per-unit cost C_{ik}, and the resulted expenses can be described as the sum of unit price C_{ik} times total activity X_{ik} for every commodity i planted in region k, or mathematically $\sum_i \sum_k C_{ik} X_{ik}$. Since government intervention is observed, we then formulate the support policy $\sum_i P_i^G \times Q_i^G$ and land subsidy $\sum_k P^L \times AL_k$ to reflect policies. Finally, if the CO_2 emission reduction can be officially traded in some markets, biofuel production results in addition benefits from carbon trading, which can be expressed as $P_{GHG} \times \sum_g GWP_g \times GHG_g$ for every greenhouse gas g. By accommodating all influences together, the objective function is then formulated as in Equation (1).

Subject to:

$$Q_i + Q_i^X + Q_i^G - \sum_k Y_{ik} X_{ik} - \left(Q_i^M + TRQ_i\right) \le 0 \quad \text{for all } i \quad (2)$$

$$\sum_i X_{ik} + AL_k + \sum_j EC_{jk} - L_k \le 0 \quad \text{for all } k \quad (3)$$

$$\sum_i f_{ik} X_{ik} + \sum_j f_{jk} X_{jk} \le ResourceAvail_k \quad \text{for all } k \quad (4)$$

$$\sum_i h_{ik} X_{ik} + \sum_j h_{jk} X_{jk} \le InputPurchase_k \quad \text{for all } k \quad (5)$$

$$\sum_{i,k} E_{gik} X_{ik} - Baseline_g = GHG_g \quad \text{for all } g \quad (6)$$

where:

Q_i – domestic demand of i^{th} product;
Q_i^G – government purchases quantity for price supported i^{th} 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;

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

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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 participated land;
AL_k – participated acreage in k^{th} region;
$ED\left(Q_i^M\right)$ – inverse excess import demand curve for i^{th} product;
$ES\left(Q_i^X\right)$ – 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 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 emissions from i^{th} product in k^{th} region;
$Baseline_g$ – greenhouse gas emissions under the baseline of the g^{th} gas;
EC_{jk} – land used in energy crop plantation;
$ResourceAvail_k$ – resource available in region k;
$InputPurchase_k$ – input purchased in region k;
GHG_g – amount of g^{th} total emission.

The coefficients f_{ik}, f_{jk}, h_{ik}, and h_{jk} represent the resources and inputs usage associated with general crops and energy crops, respectively.

Model validation. This formulation should be verified before it is considered as an effective approach to efficiently depict the regional agricultural practice and associated resource allocations. Following Chen et al.'s (2011) approaches with an updated dataset, small deviations (less than 5%) of major agricultural and livestock product between simulation results and actual data are resulted, implying the proposed model should be reliable.

Study setup. This study is designed to answer the following questions. First, how may ethanol benefit society in terms of bioenergy production and emissions offset? Second, how will biofuel producers and farmers respond to the market operation? Third, how economic and environmental benefits from various production processes can be aggregated?

The base gasoline price is set on the ongoing market price of USD 0.94 per litre. To examine the potential effects in ethanol productions in the face of changes in gasoline prices, we set 4 additional price scenarios which reflecting the 10% and 20% increase and decrease in gasoline price. We then do similar settings for emission prices. The simulated prices are based on current fuel and emission prices. Scenarios A to E correspond to 5 different gasoline prices (from low to high), and each scenario is simulated under 10 emission prices.

Data. The data used in this study come from various sources and literature. The production data of agricultural activities are collected from: (i) Annual Statistics of Jiangxi Agriculture (ASJA 2016); (ii) Commodity Prices Statistics Monthly (CPSM 2016); and (iii) Statistics of Agricultural Prices and Costs Monthly of Jiangxi Province (SAPCM 2015). The emission coefficients are collected from previous studies such as Chen et al. (2011) and Kung et al. (2013). Most of the commodity data is updated as of 2016.

RESULTS AND DISCUSSION

Bioenergy production and discussion. Based on the mathematical programming model, we find that under current gasoline price and emission price, the net ethanol production is approximately 600 000 t (Table 1). At low emission price scenarios, the results indicate the variance of biofuel production is relatively small, but when emission prices double to USD 10 per ton, the net production could increase by about 32 000 t or 5%. However, the expansion on ethanol production will increase by 5% when gasoline price increases by 20%, given the same emission price. Our results provide an important implication to the biofuel industry: the market responds more to the gasoline price than to the emission price, and thus the policies designed to promote biofuel industry must be focused more on the energy prices. The comprehensive simulation results are presented in Table S1 [Table S1 in electronic supplementary material (ESM); for the supplementary material see the electronic version].

The results show that to fulfil the regulation of ethanol blend, Jiangxi province can produce up to 1.22 billion L of ethanol annually, of which 53% comes from the use of energy crops and 47% of total ethanol production relies on the use of crop residuals. The net ethanol production under various gasoline and emission price is displayed in Figure 2. As indicated, when the gasoline price increases, more ethanol will be produced because energy crops will be planted in more area and the amount of crop residuals also increases. Since emission offset is the by-product from ethanol production that has value, ethanol production also inclines at higher emission prices.

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Table 1. Impacts of emission prices on ethanol production

Terms	Unit	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Gasoline price	USD/L			0.94		
Emission price	USD/t	1	2	3	4	5
Ethanol (energy crop)	t	591 438	602 096	608 266	606 553	612 188
Ethanol (energy crop residual)	t	376 860	388 738	393 057	391 858	395 802
Ethanol (general crop residual)	t	125 178	125 277	124 834	116 950	125 276
Total production	t	1 093 477	1 116 112	1 126 156	1 115 360	1 133 266
Emission price	USD/t	6	7	8	9	10
Ethanol (energy crop)	t	630 850	631 160	644 242	644 136	644 141
Ethanol (energy crop residual)	t	424 884	425 101	450 970	450 895	450 899
Ethanol (general crop residual)	t	124 778	124 778	124 778	124 778	124 778
Total production	t	1 180 512	1 181 039	1 219 990	1 219 809	1 219 818

Source: Author calculation

The production patterns and emission consequences are relatively straightforward, but how about the social costs associated with biofuel production? The cultivated area for energy crops and associated government expenses under various market conditions are presented in Table 2. More than 0.226 million ha are used in sweet potato production. The total cultivated area increases from 0.211 million ha to more than 0.226 million ha as gasoline prices increase from the lowest to highest levels, reflecting that at higher gasoline prices, more land with higher marginal production is converted to energy crop plantation. The same situation occurs

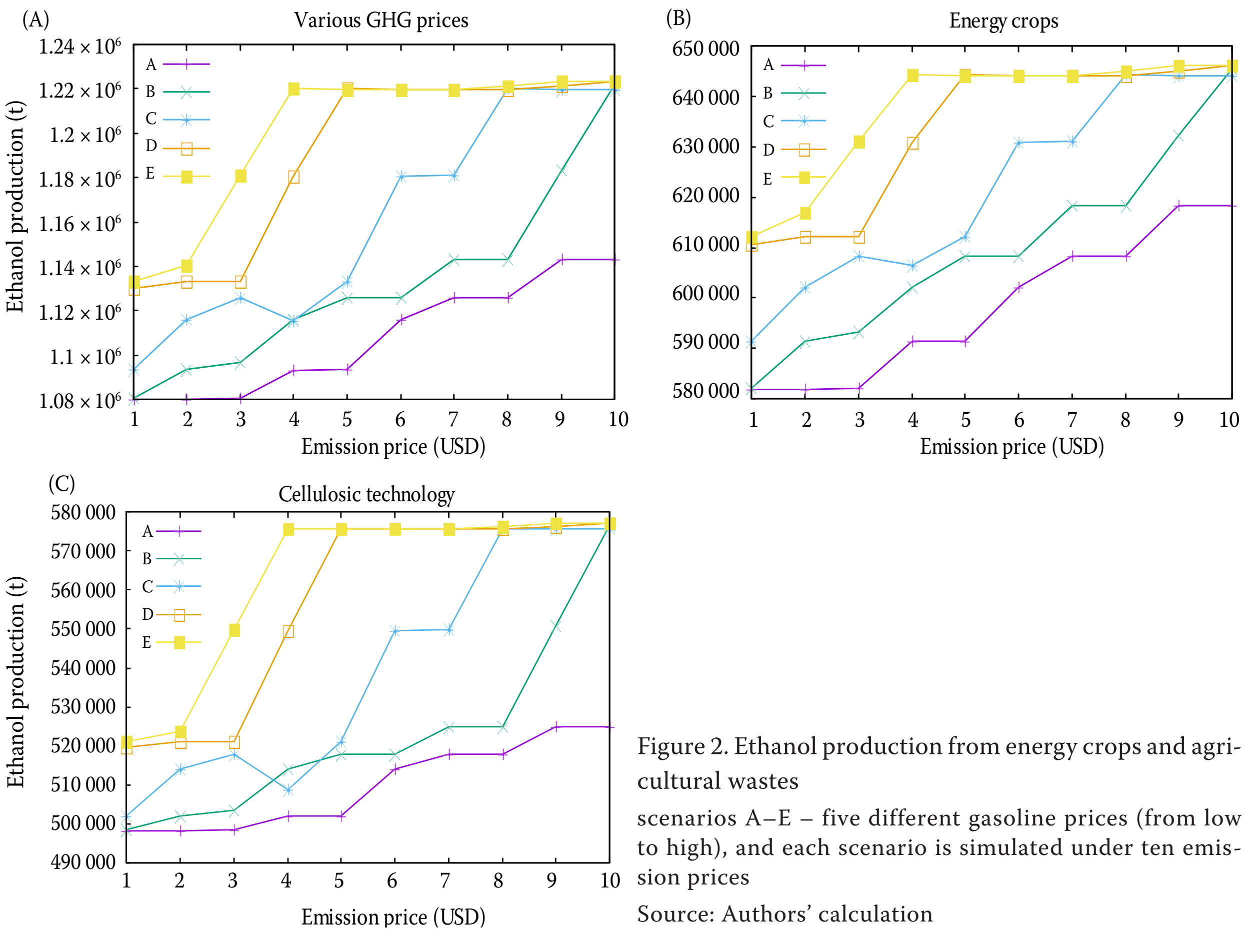

Figure 2. Ethanol production from energy crops and agricultural wastes

scenarios A–E – five different gasoline prices (from low to high), and each scenario is simulated under ten emission prices

Source: Authors' calculation

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Table 2. Government expenditure and planted area of energy crops

Terms		Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Gasoline price		USD/L	0.75	0.85	0.94	1.04	1.13
Emission price		USD/t			1.00		
Energy crop promotion	sweet potato	million USD	58.0	58.0	58.5	62.6	62.9
	poplar		13.3	13.3	14.5	12.8	12.8
	land subsidy		195.8	195.8	187.3	197.7	178.6
Land engaged	sweet potato	million ha	0.168	0.168	0.170	0.182	0.183
	poplar		0.043	0.043	0.047	0.041	0.041
Emission price		USD/t			3.00		
Energy crop promotion	sweet potato	million USD	58.0	58.8	62.2	62.9	70.2
	poplar		13.3	14.5	12.8	12.8	6.5
	land subsidy		195.8	187.3	202.6	178.6	206.9
Land engaged	sweet potato	million ha	0.168	0.171	0.181	0.183	0.204
	poplar		0.043	0.047	0.041	0.041	0.021
Emission price		USD/t			5.00		
Energy crop promotion	sweet potato	million USD	58.5	62.2	62.9	77.4	77.3
	poplar		14.5	12.8	12.8	–	–
	land subsidy		187.3	202.6	178.6	206.9	206.9
Land engaged	sweet potato	million ha	0.170	0.181	0.183	0.225	0.225
	poplar		0.047	0.041	0.041	–	–
Emission price		USD/t			7.00		
Energy crop promotion	sweet potato	million USD	62.2	63.5	70.2	77.3	77.3
	poplar		12.8	12.8	6.5	–	–
	land subsidy		202.6	206.5	206.9	206.9	206.9
Land engaged	sweet potato	million ha	0.181	0.184	0.204	0.225	0.225
	poplar		0.041	0.041	0.021	–	–
Emission price		USD/t			9.00		
Energy crop promotion	sweet potato	million USD	63.5	70.4	77.3	77.6	77.7
	poplar		12.8	6.5	–	–	–
	land subsidy		206.5	206.5	206.9	217.0	215.9
Land engaged	sweet potato	million ha	0.184	0.205	0.225	0.225	0.226
	poplar		0.041	0.021	–	–	–

Source: Authors' calculation

when GHG prices increase. Therefore, if both ethanol and emissions prices increase simultaneously, the reduction of poplar production accelerates. The land-use change among energy crops is displayed in Figure 3.

To ensure stable feedstock supply in bioenergy production, government subsidies may be an important economic incentive for farmers to be willing to participate in energy crop plantations. The study simulates potential government expenditure on crop subsidies for various market conditions, providing useful information on subsidy design and budget considerations. The results show that the total government expenditure on energy crops range from USD 195.8 million to USD 215.9 million. Moreover, gasoline prices, instead of emissions prices, have a larger influence on total subsidies. When gasoline prices increase, net subsidies can increase up to 10% but this increase is limited to 1% when emissions price increases.

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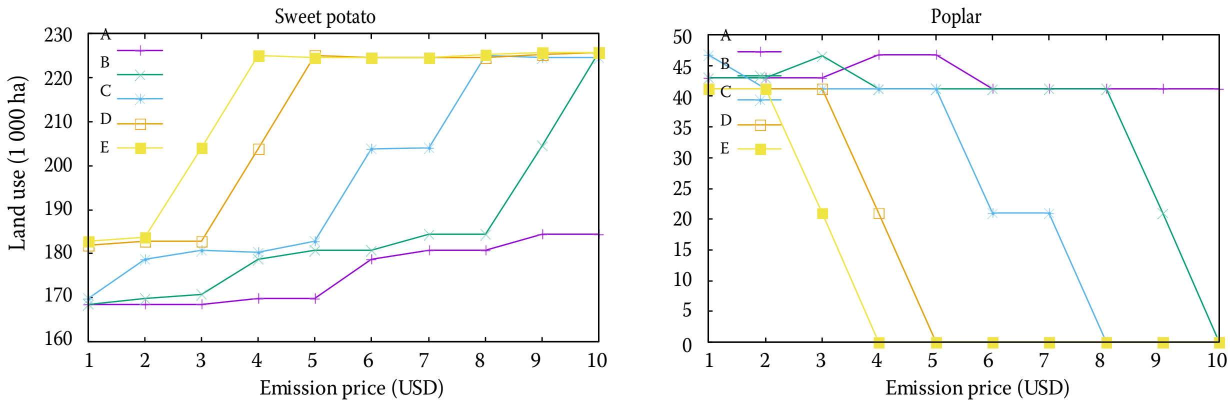

Figure 3. Land-use change of energy crops under different emission prices

scenarios A–E – five different gasoline prices (from low to high), and each scenario is simulated under ten emission prices

Source: Authors' calculation

Table 3 presents the emissions offsets for different scenarios. It is obvious that when ethanol is the only bioenergy produced, the net emissions offset ranges from 120 000 t to 137 000 t. Generally, the emission

Table 3. Emission reduction from ethanol production (by source)

Terms		Unit	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Gasoline price		USD/L	0.75	0.85	0.94	1.04	1.13
Emission price		USD/t			1.00		
Emission offset	energy crop	t	64 917	64 940	65 977	68 147	68 332
	energy crop residual		41 785	41 801	42 208	44 200	44 330
	general crop residual		14 018	14 018	14 020	13 995	14 031
Total offset		t	120 720	120 759	122 205	126 342	126 693
Emission price		USD/t			3.00		
Emission offset	energy crop	t	64 940	66 191	67 893	68 332	70 571
	energy crop residual		41 801	42 362	44 022	44 330	47 611
	general crop residual		14 018	14 020	13 981	14 031	13 975
Total offset		t	120 759	122 574	125 897	126 693	132 158
Emission price		USD/t			5.00		
Emission offset	energy crop	t	65 977	67 893	68 332	72 155	72 143
	energy crop residual		42 208	44 022	44 330	50 509	50 500
	general crop residual		14 020	13 981	14 031	13 975	13 975
Total offset		t	122 205	125 897	126 693	136 639	136 619
Emission price		USD/t			7.00		
Emission offset	energy crop	t	67 893	69 021	70 571	72 143	72 144
	energy crop residual		44 022	44 812	47 611	50 500	50 501
	general crop residual		13 981	13 972	13 975	13 975	13 975
Total offset		t	125 897	127 806	132 158	136 619	136 620
Emission price		USD/t			9.00		
Emission offset	energy crop	t	69 021	70 703	72 143	72 240	72 370
	energy crop residual		44 812	47 704	50 500	50 568	50 659
	general crop residual		13 972	13 972	13 975	13 976	13 981
Total offset		t	127 806	132 380	136 619	136 783	137 010

Source: Authors' calculation

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reduction from energy crops and their residuals provide more than 88.3% of total reduction at low gasoline and emission prices, and when these prices increase, their contribution in terms of emission offset slightly increases to 89.7%. These scenarios suggest an important policy implication by showing the relationship between bioenergy development, residual utilisation, and climate change mitigation are usually positively related, and if the government should promote the use of cellulosic ethanol so that the net ethanol production can increase ranging from 85.64% to 89.32%. Table S2 present the emission consequences of bioenergy production under various gasoline and emission prices [Table S2 in electronic supplementary material (ESM); for the supplementary material see the electronic version].

Since resource available is usually fixed in the short run, the potential change in resource used among sectors should be examined. Figure 4 shows the results of 6 major production inputs associated with agricultural ac-

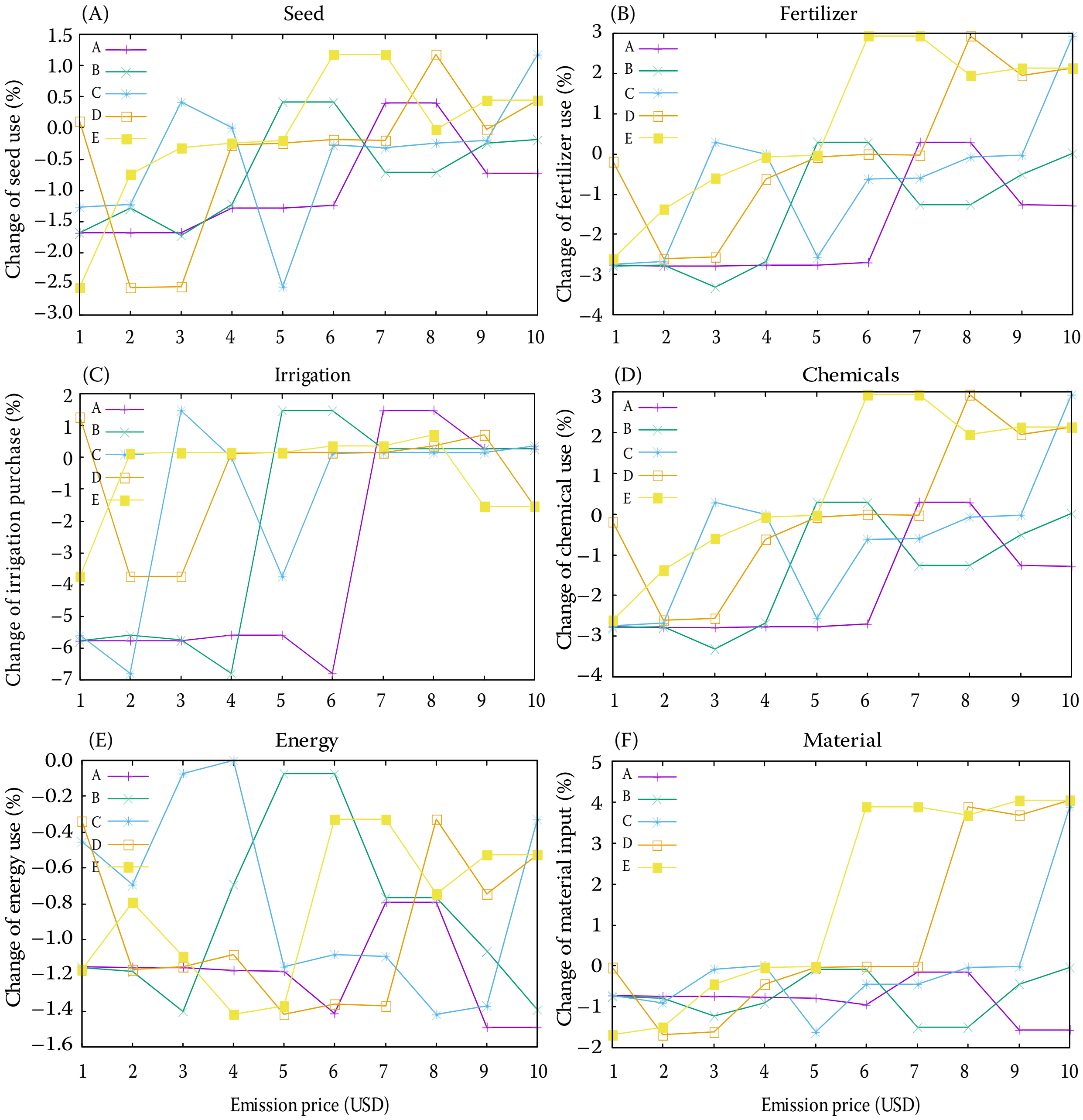

Figure 4. Change in resource use under various market operations

scenarios A–E – five different gasoline prices (from low to high), and each scenario is simulated under ten emission prices

Source: Authors' calculation

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tivities. It is obvious that the total resource use generally decreases by 1.5% to 6% at low emission and gasoline prices. This result implies that resource-intensive but less profitable crops will be firstly displaced by energy crops. When gasoline prices and emission prices incline, more barren land would be converted into energy crop plantation, driving up the resource use.

The constraint of total ethanol production is perceived due to the short-run availability of resources. From the simulation results, we show that the total land use is generally bounded at 0.226 million ha, implying that beyond this point the farmers facing higher production costs cannot make profits from selling commodities and residuals, thereby constraining the total ethanol production.

The result is useful to regional biofuel analysis. For example, Cao et al. (2017) indicate that pyrolysis can be an attractive technology to enhance regional electricity supply; however, their study does not point out how such a development could benefit transportation sector in the face of mandatory biofuel regulation. This study explicitly explores the policy effects on biofuel production with conjunctive utilisation of crop residues so that the competition between bioenergy production and food consumption can be examined. The results illustrate the biofuel potential from crop residues and provide insights of alternative bioenergy technologies to policy-makers.

POLICY IMPLICATION

Since the effectiveness of the biofuel application may be limited under certain real-world considerations, there is merit to discuss possible policy implications to provide more insights to policymakers.

Potential climate consequences. The results indicate that market power can greatly influence bioenergy production, assuming constant input supply. However, in the cases where this situation does not hold, the results may be biased. For example, climate change is considered to have substantial impacts on the environment such as temperature and precipitation, all of which may alter the stability of input supply *via* the changes in crop yields. Therefore, the government must take the potential climate impacts into account to achieve effective and efficient bioenergy development.

Market conditions. Energy and emission prices are key factors enhancing the participation of energy crop plantation and subsequent bioenergy production. Therefore, a floor price of these prices may be determined to guarantee the feedstock supply and bioenergy production; otherwise, the development goal may not be achieved.

Resource shifts. By comparing the results of different price scenarios, the resource allocated to the agricultural sector could fluctuate considerably. This could be either due to the changes in agricultural practice or the switch among land types. Since farmers are usually more sensitive to expected income, they are very likely to invest their resources in the most profitable cultivars, which are not necessarily the energy crops.

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CONCLUSION

In recent decades, China's energy consumption has doubled, placing significant pressure on global reserves of fossil fuels. In addition, the use of fossil fuels is intensifying the global climate shift through emissions of unprecedented amounts of GHGs. Moreover, fossil fuels will be depleted. Renewable energy is considered to offer crucial and feasible technologies for social development through sustainable economic growth and environmental protection.

The results indicate that under current mandatory regulations of ethanol use, Jiangxi province can produce more than 1.2 billion L annually. However, we show that the changes in gasoline and emission prices can vary the results. We also show that the crop residuals can provide approximately 47% of total ethanol production, implying the proper utilisation of agricultural wastes can be beneficial.

Changes in agricultural activities must be included in bioenergy analysis. Since the bioenergy production is highly dependent on agricultural activities, agricultural, environmental, and renewable energy policies that influence agricultural activities via changing prices should also be considered.

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