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Impacts of Energy Price on Agricultural Production, Energy Consumption, and Carbon Emission in China: A Price Endogenous Partial Equilibrium Model Analysis

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Abstract: Energy market volatility will have systemic effects on agricultural production, energy consumption and carbon emissions. This paper aims to evaluate the impacts of energy price on agricultural production, energy consumption, and carbon emission in China. To achieve the objective, this paper, firstly, constructed a price endogenous partial equilibrium model, and then designed four scenarios of energy price fluctuations, finally evaluating the impacts of energy price fluctuations on agricultural production and its energy consumption and carbon emission. The results revealed that: (1) The impacts on agricultural production are very limited, but higher energy price will result in producers' welfare loss by 0.6% to 1.4%, under different scenarios. (2) Energy price drives negative impacts on agricultural energy consumption and carbon emission, 1.6%/3.2% and 1.3%/2.6%, respectively, in low/high amplitude scenarios. (3) Heterogeneous impacts are confirmed in the regional analysis; South China is simulated to be the most sensitive area. To mitigate the impacts from energy price and reduce carbon emission in agriculture, several policy implications have recently been proposed, including strengthening supervision of the energy market, constructing an energy saving price-setting mechanism, launching policy instruments to improve energy efficiencies and facilitate cleaner farming techniques, and formulating specific measurements of energy saving and emission reduction for different regions.

Keywords: energy price; agricultural production; energy consumption; carbon emission; price endogenous partial equilibrium model

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1. Introduction

Along with the development of agricultural modernization and mechanization, energy consumption in the Chinese agriculture sector, including diesel, electricity and fertilizer, has been growing rapidly, since the rural reform began in the 1980s [1]. Though agricultural machinery and the growth in energy consumption contributed a lot to the agricultural output and productivity during the past decades in China, several environmental and economic problems have accompanied. Firstly, non-renewable energy consumption created the largest amount of carbon emissions (27.2%, higher than that of other sources) in the Chinese agriculture sector; 237 million tons of carbon emissions were generated from agricultural energy consumption in 2018, which was almost eight times higher than that of the early 1980s. Secondly, inputting energy resources, especially under the fluctuation of energy prices, will not only affect the farming cost of agriculture, but will influence farmers' planting decisions as well. The proportions of diesel expenditure in the total material and service cost of China's rice, wheat and corn production in 2018 were 15.7%, 12.5%, and 12.4%, respectively, while those of fertilizers are 6.8%, 7.4%, and 8.4% [2]. Due to the foreseeable trend and strategy of promoting modernization and mechanization, the Chinese agriculture sector is supposed to be equipped with more machines and a generate higher demand for energy resources. In this regard, the fluctuation of energy prices can be a major risk that farmers face in modern and machinery agriculture.

Many studies in the literature have discussed the issues related to agriculture energy over the past decades. Some have addressed the linkage between energy price and agricultural commodity price. Non-linear causality, medium-run co-movements, transmission channel and other significant relations and impacts are verified by economists [3–9]. Due to this linkage, rising energy prices will bring higher costs and lower income to rural households, weakening farmers' ability to adjust their input decisions in a timely manner [10–14].

Considering the mitigation of climate change impacts, another set of studies concentrate on the determinants of agricultural energy consumption and carbon emission, as well as the energy intensity and efficiency. Employing a co-integration analysis and error correction model, Fei and Lin investigated the influencing factors of agricultural energy consumption in China since 1980, and their results revealed that agricultural output and mechanical power would push up energy consumption, while industrial structures, fiscal expenditure and energy price have negative impacts [15]. Decomposed by the method of the logarithmic mean Divisia index (LMDI), agricultural output, energy input structure, rural residents' income and land use are regarded as main driving factors of agricultural energy consumption and carbon emission, while reducing energy intensity can significantly cut down the emission quantity [16–19]. Employing two-stage least-square regression, Long et al. pointed out that it is important to enhance indigenous innovation for green agriculture [20]. Wei et al. applied an energy–economic-environment CGE model to simulate Chinese agricultural output and energy consumption in 2030, and their results revealed that the growth rate of agricultural energy consumption is higher than that of agricultural output; 120% more carbon emissions will be released from the Chinese agriculture sector, but technical progress in both total factor productivity (TFP) and energy-augmented productivity are potential solutions to eliminate overly intense energy input and carbon emission [21]. Li et al. identified a significant direct impact of the focal province's price change on CO_2 emissions and an indirect effect exerted by energy price changes in adjacent provinces [22].

Improving energy efficiency has been proven to be the dominant aspect in reducing energy intensity by earlier studies [23–27], and a significant amount of data envelopment analysis (DEA) research revealed that China has a great potential for improving its energy efficiency in the agriculture sector [28–30]. Jiang et al. created a framework to empirically evaluate the energy–environment performance in the Chinese agriculture sector through the DEA method and Tobit model, and their findings indicated that the development of mechanization brought down performance significantly, and similar effects can be found in control variables, such as energy price and agricultural industrial structure [31]. However, if the energy rebound effect is considered, the contribution of improving energy efficiency only accounted for 27.8% of the expected agricultural energy saving target in the short term, and 47.2% in the long term. Apart from efficiency, several studies incorporated structure element into analysis [32]. Wu and Ding decomposed agricultural energy intensity by the components of efficiency and structure, and their penal data estimates with fixed effects illustrated that the efficiency component dominated the impact, while the structure component contributed in a very limited way [33]. From the perspective of input–output, Yu et al. constructed a structural decomposition analysis to energy-related carbon emissions and reduction in the Chinese agriculture sector, with their results indicating that the growth of carbon emissions was inhibited by the input structure effect and energy intensity effect, while the energy structure effect failed to reduce emissions because of vague optimization of the consumption structure on the supply side [34].

Existing studies have made great efforts in energy-related problems in agriculture and economists have revealed the linkage between prices of energy and agricultural commodities, determinants of agricultural energy consumption and carbon emission, and factors influencing energy intensity. Most of the studies applied econometric approaches to assess or evaluate historical data sets, although very few of them paid enough attention to future scenarios. Moreover, econometric approaches perform well in investigating casualties between variables, but when it comes to coupling effects and changes among multi-variables, systematic modelling frameworks, such as equilibrium analyses, are regarded as being more appropriate and effective.

This paper might contribute to the existing literature in at least two aspects. For one thing, the present study constructs a systematic model based on the theory of partial equilibrium analysis, namely, a price endogenous partial equilibrium model (PEM), incorporating variables of energy price, energy consumption, carbon emissions and agricultural production into an integrated model. For another, within the systematic model, this study designs several scenarios of energy price changes and then evaluates the impacts of energy price on agricultural production, energy consumption and carbon emission, among main crops and regions in China. The rest of this paper is organized as follows: Section 2 introduces the systematic framework and exact model used in this research, as well as the data source, model calibration and simulating scenarios; Section 3 provides the model simulation results, and discussion of this study will be included in Section 4; Section 5 is the conclusion, presenting several remarks from this study and finally, proposes policy implications.

2. Materials and Methods

2.1. Model Construction

In systematic modelling research of agricultural economics, linear programming method can be used in resource allocation decision analysis when input and output prices are hypothesized to be constant. However, this hypothesis may not be valid at the department level because of the existence of price response effects from the comprehensive demand–supply system. Thus, agricultural economists developed the price endogenous partial equilibrium model (PEM) through a non-linear programming method. In PEM, market equilibrium prices and quantities are determined by maximizing market surplus under a unified framework of simultaneous equations. PEM has been regarded as a well-performed method in policy evaluation and wildly used in agricultural and environmental economic research [35–37].

This paper aims at evaluating the systematic impacts of energy price fluctuation on agricultural production, energy consumption and related carbon emissions under different scenarios. Compared with general equilibrium models such as CGE, PEM can assess external shock impacts on agricultural production and the environment with lower data requirements and fewer equations to be solved, which is more flexible and feasible when constructing specific empirical models [38]. Therefore, PEM is employed in this research. According to the essential features of China's agricultural production and market, four assumptions are proposed in advance:

- Integration of domestic market. Agricultural commodities can be traded and transported freely among provinces.
- Stabilization of international trade. Domestic supplies are sufficient, import or export quantities do not exceed base year numbers.
- Rationality of agricultural producers (or farmers). They autonomously adjust their producing behaviors with the purpose of maximizing welfare.
- Other production inputs and their quantities remain constant.

The PEM used in this study is constructed as follows:

1. Objective function. Refers to the maximization of total welfare of agriculture, or the aggregated surplus from both agricultural producers and consumers.

$$MaxW = \sum_j \int_0^{x_j^d} P_j^d dX_j^d + \sum_j (X_j^{ex} P_j^{ex} - X_j^{im} P_j^{im}) - \sum_{ijk} P_i^{eg} Q_{ij}^{eg} A_{jk} - \sum_{lj} C_{lj}^{ot} A_{jk} \quad (1)$$

where W is the target welfare of agricultural sector, $P_j^d(X_j^d)$ is the inverse demand function, X_j^d is demand of crop j, i represents kinds of energies, including direct energies (diesel, electricity) and indirect energies (fertilizer, pesticide and agro-film), j represents kinds of crops, including rice, wheat, corn, soybean, peanut, rape seed and potato, k refers to regions (31 provinces in China), l is regarded as other producing inputs except energy, P_i^{eg} and Q_{ij}^{eg} are the price of energy and its intensity in growing crop I, A_j is the acreage of crop j, C_{lj}^{ot} is the non-energy cost, including all the costs except direct and indirect energy cost in production, such as the costs of labor, irrigation, seeds, land and machine renting etc., P_j^{im}/P_j^{ex} and X_j^{im}/X_j^{ex} are import/export prices/quantities.

2. Constraints. This includes supply–demand balance constraint, land use constraint and water use constraint.

$$X_j^d \geq \overline{X_j^d} \tag{2}$$

$$X_j^s + X_j^{im} \geq X_j^d + X_j^{ex} \tag{3}$$

$$A_k = \sum_m \tau_m * h_{im} + \sum_n \gamma_n * S_{in} \tag{4}$$

$$\sum_m \tau_m + \sum_n \gamma_n \leq 1 \tag{5}$$

$$\sum_s A_i W_{it} \leq W_{tt} \tag{6}$$

Equation (2) states that the exogenous demand constraints (the domestic demand) shall be equal to or greater than the exogenously given target demand $\overline{X_j^d}$. Equation (3) expresses the market supply–demand balance constraint, total supply (sum of domestic supply and import quantity) shall be equal or greater than total demand (sum of domestic demand and export quantity). Land use constraint is defined by Equations (4) and (5). h_{km} is the observation of history land area, S_{kn} is the maximum acreage in feasible practice. This constraint contains an assumption that farmers' decisions would be affected by past experiences and present conditions [39]. τ_m and γ_n are the weights of h_{km} and S_{kn} in decision, and sum or the weights shall be less than or equal to 1. Equation (6) is the water use constraint. Irrigation water capacity of all crops shall not be over the agricultural water supply. W_{it} represents the capacity of crop i in time t, W_{tt} is the total supply of irrigation water.

3. Estimation of energy consumption and carbon emission.

Energy consumption in agriculture can be divided into direct and indirect components. Direct energy consumption includes the use of diesel and electricity, while indirect energy consumption refers to the inputs of fertilizer, pesticide and agricultural film. Considering the multiple sources of energy consumption and various units of measurement, this study applies a convert method to unify measurements of energy consumption [40,41]. This method aims at converting one specific source of energy consumption into standard coal consumption with the mediator of conversion coefficients:

$$TE = \sum_{ijk} E_{ijk} L_{jk} \alpha_i \tag{7}$$

$$EI = TE/P_j X_j^s \tag{8}$$

In Equation (7), TE is the total energy consumption of agriculture, i represents energy sources, j refers to specific kinds of crops, k is the regional or provincial code. E_{ijk} and L_{jk} are energy input amount of energy i and sowing acreage of crop j in province k. Conversion coefficients are described as α_i. EI in Equation (8), represents energy intensity, X_j^s refers to supply quantity or the output of crop j.

Based on energy consumption estimation, carbon emission estimation can be processed by Equation (9):

$$TC = \sum_{ijk} EU_{ijk}\beta_i \tag{9}$$

TC is the total amount of carbon emission from energy consumption in agriculture. EU_{ijk} refers to the consumption of energy i in growing crop j from province k. Conversion coefficients between carbon emission and energy consumption are described as β_i.

2.2. Data Source

Data required in this study can be broken down into four parts:

1. Agricultural production, including acreages and outputs of seven main crops (rice, wheat, corn, soybean, rapeseed, potato and peanut) in China. These data sets are derived from "China Statistical Yearbook 2019" and "National Database" of National Bureau of Statistics (NBS) [42].

2. Demands and prices of agricultural products. Total demand is divided into food ration demand, seed demand, industrial demand and depletion [43]. These parts of demand are calculated individually and then summed together. Necessary data are captured from "China Statistical Yearbook 2019" and "BRIC Agricultural Database". Demand elasticities are referenced from existing studies [44–46], prices of agricultural products are given by "Compilation of cost-benefit data of national agricultural products 2019" [47].

3. Quantities and prices of energy inputs, including diesel, electricity, fertilizer, pesticide and agricultural film. These data sets are derived from "Compilation of cost-benefit data of national agricultural products 2019".

4. Conversion coefficients of energy consumption and carbon emission (shown in Table 1). Standard coal coefficients of fuel and electricity are derived from "China Energy Yearbook 2019"; those of fertilizer, pesticide and agricultural film are given by "Handbook of Agrotechnical Economics" [48]. Carbon emission coefficients of fuel and electricity are calculated by the Intergovernmental Panel on Climate Change (IPCC) [49], while those of fertilizer, pesticide and agro-film are referenced from former research [50–52].

Table 1. Reference coefficient of energy conversion.

Energy Types	Standard Coal Conversion Coefficients	Carbon Emission Coefficients
Diesel	1.457 kgce·kg^{-1}	3.160 kgc·kg^{-1}
Electricity	0.123 kgce·kwh^{-1}	0.703 kgc·kwh^{-1}
Fertilizer	0.821 kgce·kg^{-1}	0.896 kgc·kg^{-1}
Pesticide	3.429 kgce·kg^{-1}	4.934 kgc·kg^{-1}
Agro-film	1.600 kgce·kg^{-1}	5.181 kgc·kg^{-1}

2.3. Model Calibration

Using quantity and price data sets of energy and other inputs obtained above, this study simulates the calibrated acreages, outputs and prices of seven main crops in China. After calibration, CASM results on China's agricultural production closely match the 2018 observed data (shown in Table 2). According to simulation results, the deviations of model calibrated values and practical observed values are all lower than 5%. Therefore, the constructed PEM in this paper can be regarded as a reliable and valid model suitable for further analysis.

Table 2. Observed and calibrated data of China's agricultural production in 2018.

	Acreage (Million hm^2)			Output (Million Tons)			Price (CHY/kg)		
	Obs.	**Cal.**	**Dev.**	**Obs.**	**Cal.**	**Dev.**	**Obs.**	**Cal.**	**Dev.**
Rice	30.19	30.11	−0.26%	212.13	212.13	0.00%	2.59	2.59	0.00%
Wheat	24.27	24.11	−0.65%	131.44	131.44	0.00%	2.22	2.22	0.00%
Corn	42.13	42.13	0.01%	257.18	257.18	0.00%	1.75	1.75	0.00%
Soybean	8.41	8.15	−3.12%	15.97	15.97	0.00%	3.84	3.84	0.00%
Peanut	4.65	4.68	1.10%	17.33	17.99	3.78%	5.70	5.92	3.79%
Rapeseed	6.55	6.35	−3.05%	13.28	13.45	1.30%	5.23	5.28	0.96%
Potato	4.94	4.71	−4.64%	18.71	18.71	0.00%	1.56	1.56	0.00%

2.4. Scenario Design

The fluctuations in energy prices are commonly identified as external shocks to many sectors of national economy. Existing studies have revealed the price correlations between crude oil and its refinery products or other kinds of energies, for instance, 10% fluctuation in crude oil price would bring 3.1% fluctuation in gasoline, diesel and kerosene prices, 0.3% in prices of thermal power electricity [53]. In agriculture sector, 10% rise in crude oil price would induce 0.95%, 0.81% and 1.03% of price rises in industries of fertilizers, pesticides and plastic products, respectively [54]. Based on these correlation coefficients, this paper assumes that 1% fluctuation in crude oil price will generate 0.31%, 0.03%, 0.095%, 0.081% and 0.103% price changes of diesel, electricity, fertilizer, pesticide and agro-film. The annual average price of Brent crude oil fluctuates between USD 41.84 and USD 71.31 per barrel from 2018 to 2020. Considering the unstable trend of the world energy price, simulating scenarios in this study are designed for both upward and downward price fluctuations in crude oils. Additionally, high (50%) and low (25%) amplitudes of energy price fluctuation are considered. Therefore, downward-low amplitude (scenario I), downward-high amplitude (scenario II), upward-low amplitude (scenario III) and upward-high amplitude (scenario IV) will be simulated in this research.

3. Results

3.1. Agricultural Cultivated Area and Welfare

Table 3 presents the simulation results of the main crops' cultivated area under baseline and four designed scenarios. All the simulations are executed by GAMS 33.2.

Table 3. Main crops' cultivated area under different scenarios.

	Baseline	Scenario I	Scenario II	Scenario III	Scenario IV
Wheat	24.11	24	23.89	24.22	24.36
		−0.46%	−0.91%	−0.46%	−1.06%
Rice	30.11	29.97	29.83	30.25	30.39
		−0.46%	−0.92%	−0.46%	−0.93%
Corn	42.13	41.9	41.67	42.37	42.65
		−0.55%	−1.09%	−0.57%	−1.24%
Soybean	8.15	8.11	8.07	8.19	8.2
		−0.49%	−0.99%	−0.5%	−0.62%
Peanut	4.68	4.66	4.63	4.7	4.72
		−0.44%	−0.87%	−0.45%	−0.92%
Rapeseed	6.35	6.35	6.35	6.35	6.35
		0%	0%	0%	0%
Potato	4.71	4.69	4.68	4.73	4.75
		−0.37%	−0.73%	−0.37%	−0.74%
Total	120.24	119.68	119.11	120.81	121.42
		−0.46%	−0.92%	−0.47%	−0.99%

Notes: units of cultivated area are million hm^2; "%", representing deviation compared with baseline.

As for the results of the cultivated area, most crops (except rapeseed) are thought to be adjusted. Crops' acreages are reduced when the energy price reduces (0.37–0.55% in the low scenario and 0.73–1.09% in the high scenario) and expanded on the contrary (0.37–0.57% in the low scenario and 0.62–1.24% in the high scenario). Among these seven main crops, corn shows the greatest sensitivity to the changes in energy price, in all four scenarios, while potato is the least sensitive crop. A potential explanation of the similar fluctuation between energy price and crop acreage could be that a lower (or higher) price of energy might motivate (or restrain) producers to input more energy resources, and then the productivity and yield levels of these crops could be improved (or reduced). Therefore, the demands of agricultural products can be satisfied by a smaller amount of crop growing acreages.

As shown in Table 4, it should be noted that though higher fluctuation in energy prices will bring greater changes in the main crops' output and acreage, the impacts are regarded as very limited. According to the overall simulation results in the last two rows, there are barely any changes in the output columns, and the influence rates of acreage are below 0.5%/1% in low/high scenarios.

Table 4. Total cost of agricultural production and welfare under different scenarios.

	Baseline	**Scenario I**	**Scenario II**	**Scenario III**	**Scenario IV**
Total cost (billion CHY)	1 967.2	1 948.8	1 929.7	1 985.1	2 002.7
		−0.93%	−1.91%	0.91%	1.80%
Welfare (billion CHY)	2 593.7	2 611.4	2 629.9	2 576.4	2 559.5
		0.69%	1.40%	−0.66%	−1.32%

Notes: "%" representing deviation compared with baseline.

Table 4 indicates the PEM simulation results of welfare and total cost of agricultural production under different scenarios. According to the results, the fluctuation in energy price has an evident driving impact on total cost. Over 0.9% changes in total cost are induced in low scenarios, and the numbers in high scenarios rise up to 1.91% and 1.80%. Meanwhile, there appears to be an apparent inverse relationship between welfare and energy price, meaning producers could benefit from downward energy prices. Compared with the changes in the total cost of agricultural production, the impacts of energy price on welfare are approximately one-fourth slighter. These results are consistent with the research expectation and existing studies, that a higher energy price pushes up production costs, and this cost effect will result in welfare loss for producers or the agriculture sector.

3.2. Agricultural Energy Consumption and Carbon Emission of Main Crops

Table 5 gives the PEM simulation results of the main crops' energy consumptions and carbon emissions, under baseline and four designed scenarios. Compared with the results in Table 3, the impacts of energy price fluctuation on energy consumption and carbon emissions are much higher and cannot be ignored (Table 5). According to the overall simulation results in the last two rows, there are considerable changes in both the energy consumption and carbon emission columns; the average impacts on energy consumption are around 1.6%/3.2% changes in low/high scenarios, and the numbers are 1.3%/2.6% in the carbon emission columns.

Table 5. Main crops' energy consumptions and carbon emissions under different scenarios.

	Baseline		**Scenario I**		**Scenario II**		**Scenario III**		**Scenario IV**	
	En. Con	**Car.Emi**	**En. Con**	**Car.Emi**	**En. Con**	**Car.Emi**	**En. Con**	**Car.Emi**	**En. Con**	**Car.Emi**
Wheat	1336.25	3572.34	1353.34	3599.18	1370.19	3625.50	1318.96	3545.09	1300.16	3507.93
			1.28%	0.75%	2.54%	1.49%	−1.29%	−0.76%	−2.70%	−1.80%
Rice	1698.74	3818.43	1730.10	3877.49	1761.06	3935.65	1667.00	3758.56	1634.89	3697.88
			1.85%	1.55%	3.67%	3.07%	−1.87%	−1.57%	−3.76%	−3.16%
Corn	1879.09	4690.94	1907.55	4755.14	1935.71	4818.80	1850.24	4625.85	1820.41	4558.28
			1.51%	1.37%	3.01%	2.73%	−1.54%	−1.39%	−3.12%	−2.83%
Soybean	156.44	374.88	159.39	380.97	162.29	386.96	153.44	368.69	148.26	357.10
			1.89%	1.63%	3.74%	3.22%	−1.92%	−1.65%	−5.23%	−4.74%
Peanut	164.59	384.88	167.16	390.27	169.74	395.69	162.00	379.46	159.39	374.00
			1.56%	1.40%	3.13%	2.81%	−1.57%	−1.41%	−3.16%	−2.83%
Rapeseed	167.15	314.77	170.97	322.45	174.49	329.56	163.32	307.09	159.49	299.41
			2.29%	2.44%	4.39%	4.70%	−2.29%	−2.44%	−4.58%	−4.88%
Potato	233.03	555.04	236.46	562.18	239.87	569.26	229.57	547.85	226.08	540.59
			1.47%	1.29%	2.93%	2.56%	−1.49%	−1.30%	−2.98%	−2.60%
Total	5635.28	13,711.28	5724.97	13,887.69	5813.35	14,061.41	5544.52	13,532.58	5448.68	13,335.18
			1.59%	1.29%	3.16%	2.55%	−1.61%	−1.30%	−3.31%	−2.74%

Notes: units of energy consumptions and carbon emissions are million tce and million tc; "%" representing deviation compared with baseline.

Energy price has a negative influence on energy consumption. Higher (or lower) energy prices result in reduced (or increased) energy consumption by agricultural producers, which is consistent with the fundamental economic theory. Among the seven crops, rapeseed seems to be more sensitive to the energy price fluctuation than others, and the impacts are around 2.3%/4.5% changes in low/high scenarios, over 40% greater than the average impacts. On the contrary, wheat shows the least sensitivity to energy prices, as its fluctuation rates are below 1.3%/2.7% in low/high scenarios. If on was to simply classify crops into sensitive and non-sensitive to the energy price fluctuation, with the standard of above or below the average impacts, rapeseed, as well as soybean and rice, can be regarded as sensitive crops to energy prices, while the other four crops, including wheat, corn, peanut, and potato, are classified as non-sensitive crops. Because of the tight interrelationship between energy consumption and carbon emission, the impacts of energy price fluctuations on carbon emissions share similar features with those on energy consumption. Energy price still has a negative influence; rapeseed and wheat are the most and least sensitive crops to the price changes, while the impacts are slighter than those on energy consumption.

When comparing the results between downward and upward energy price scenarios, it should be noted that the fluctuation rates of energy consumption and carbon emission are greater in upward scenarios than in downward scenarios, especially in high amplitude scenarios. The negative influences from energy prices on energy consumption and carbon emission are simulated to be more obvious when energy prices are increasing.

3.3. Agricultural Energy Consumption and Carbon Emission of Different Regions

Table 5 provides the simulation results from the crop level, while Table 6 presents additional results from the regional perspective. Based on Physical Geographic Regionalization of China, from "China Physical Geographics (2015)", 31 provinces are categorized into seven regions: East (Anhui, Fujian, Jiangsu, Jiangxi, Shandong, Shanghai and Zhejiang), North (Beijing, Hebei, Inner Mongolia, Shanxi and Tianjin), South-West (Chongqing, Guizhou, Sichuan, Xizang and Yunnan), North-West (Gansu, Ningxia, Qinghai, Shaanxi and Xinjiang), South (Guangdong, Guangxi and Hainan), Central (Henan, Hubei and Hunan) and North-East (Heilongjiang, Jilin and Liaoning). Agricultural energy consumption and carbon emissions from these seven regions, under different scenarios, are listed in

Table 6. Note that Hong Kong, Macao and Taiwan are not included because of limited data sources and qualities.

Table 6. Main regions' agricultural energy consumptions and carbon emissions under different scenarios.

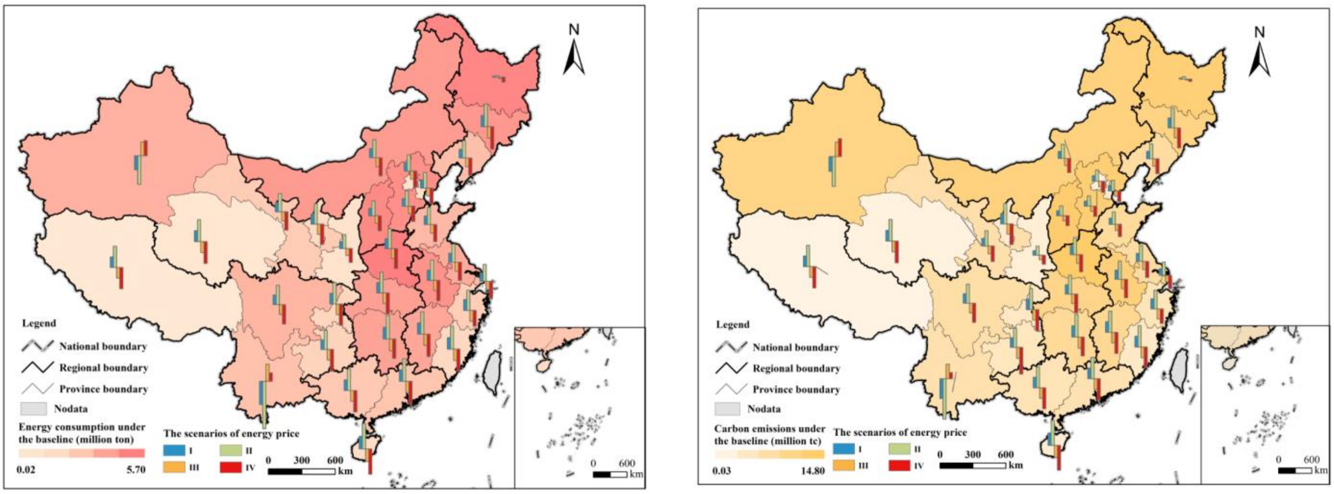
	Baseline		**Scenario I**		**Scenario II**		**Scenario III**		**Scenario IV**	
	En. Con	**Car.Emi**	**En. Con**	**Car.Emi**	**En. Con**	**Car.Emi**	**En. Con**	**Car.Emi**	**En. Con**	**Car.Emi**
East China	1527.21	3579.64	1559.86	3648.41	1592.21	3716.61	1494.56	3510.87	1463.13	3444.61
			2.14%	1.92%	4.26%	3.83%	−2.14%	−1.92%	−4.20%	−3.77%
North	874.76	2594.70	890.54	2630.12	906.32	2665.55	858.98	2559.27	843.20	2523.84
			1.80%	1.37%	3.61%	2.73%	−1.80%	−1.37%	−3.61%	−2.73%
South-West	462.65	861.94	462.91	864.42	462.88	866.35	461.98	858.57	460.35	852.72
			0.06%	0.29%	0.05%	0.51%	−0.14%	−0.39%	−0.50%	−1.07%
North-West	524.56	1559.23	524.65	1549.86	524.48	1539.93	524.28	1568.18	518.89	1560.23
			0.02%	−0.60%	−0.01%	−1.24%	−0.05%	0.57%	−1.08%	0.06%
South	258.93	511.84	265.36	525.08	271.79	538.32	252.49	498.59	246.06	485.35
			2.48%	2.59%	4.97%	5.17%	−2.48%	−2.59%	−4.97%	−5.17%
Central	1039.02	2261.27	1063.40	2312.34	1087.78	2363.41	1014.63	2210.20	992.68	2163.77
			2.35%	2.26%	4.69%	4.52%	−2.35%	−2.26%	−4.46%	−4.31%
North- East	948.16	2342.66	958.26	2357.46	967.89	2371.24	937.60	2326.88	924.36	2304.67
			1.07%	0.63%	2.08%	1.22%	−1.11%	−0.67%	−2.51%	−1.62%
China Nationwide	5635.28	13,711.28	5724.97	13,887.69	5813.35	14,061.41	5544.52	13,532.58	5448.68	13,335.18
			1.59%	1.29%	3.16%	2.55%	−1.61%	−1.30%	−3.31%	−2.74%

Notes: units of energy consumptions and carbon emissions are million tce and million tc; "%" representing deviation compared with baseline. Concerning the proper length of Table, provincial simulation data can be found in Table S1.

Apart from several similar conclusions derived from Table 5, such as greater impacts shown in upward price scenarios, the simulation results from the regional perspective in Table 6 have additionally revealed geographical heterogeneities in agricultural energy consumptions and carbon emissions among different regions. East, North, South and Central China are regarded as sensitive regions to energy price fluctuation, since simulated changes are higher than the average changes around the whole nation. South China, particularly, is the most sensitive region, where the impacts reach 2.5%/5% changes in energy consumption and 2.6%/5.2% changes in carbon emission in low/high scenarios. North-East China is classified as a non-sensitive region; however, the rates of changes in the simulations are over 1%/2% on energy consumption and 0.6%/1.2% on carbon emission in low/high scenarios. While the other two non-sensitive regions, South-West and North-West China, have shown exceptional results. From the perspective of energy consumption, the impacts from energy prices are very limited and close to zero, especially under downward price scenarios. As for carbon emissions, the simulation results from South-West China are consistent with economic theories, while the results from North-West China are on the contrary. Downward energy prices are simulated to bring lower carbon emissions, and reductions of 0.6%/1.24% are shown in low/high scenarios.

In order to further investigate the results, simulations of energy consumption and carbon emissions at province-level are pictured in Figure 1a,b.

As shown in Figure 1, provinces are categorized into five tiers, in terms of quantities of agricultural energy consumption and carbon emissions. Two main agricultural provinces in China, Heilongjiang from the North-East and Henan from the Central region, consume the largest amount of energy in agriculture, and consequently, generate more carbon emissions than other provinces. Hebei, Shanxi and Inner Mongolia from the North, Anhui from the East, and Jilin from the North-East region, are located at the 2nd tier of agricultural energy usage, followed by the 3rd tier group, including Hubei and Hunan from the Central region, Jiangxi and Jiangsu from the East, Sichuan from the South-West, and Xinjiang from North-West China. The rest of the provinces are regarded as 4th and 5th tiers.



(**a**) (**b**)

Figure 1. Simulation results of agricultural energy consumption and carbon emission in China. (**a**) energy consumption; (**b**) carbon emission.

The changing rates of simulations compared with baseline under four scenarios are presented in four columns in each province. The shapes of the columns in 29 provinces are consistent with economic theories that energy price has a negative impact on energy consumption and carbon emissions. In scenario I and III, or low-price fluctuation scenarios, most of the changing rates in energy consumption and carbon emissions are located between 1.5% to 2.5%, while in scenario II and IV, or high-price fluctuation scenarios, the interval rises to 3% and 5%. However, the columns in the other two provinces, Xinjiang from the North-West and Yunnan from the South-West, have shown symmetrical shapes. Energy price has a positive impact on energy consumption and carbon emissions, which can be considerable explanations for the exceptional results of the North-West and South-West, indicated in Table 6. As a matter of fact, Xinjiang is the main exploitation area of crude oil in China. The fluctuation of energy prices would bring greater impacts and higher risks on the economy of Xinjiang than on other provinces in China. Due to the close linkages among departments with economics, these effects are very likely passing through the energy and agriculture sectors. For instance, price competition motivates cleaner technologies in production and reducing energy intensity in practical usage. Carbon emissions, consequently, go down when energy efficiencies are improved. Yunnan is a province lacking plain land and rich in mountainous areas, and the development of agricultural machinery, especially applying large equipment, is restricted in practical farming. In this sense, the impact of energy price on the usage of agricultural machines is regarded as limited. Unfortunately, the systematic model in this paper is not able to investigate the exact mechanism inside the relations; further econometric empirical studies and causal inference analyses should be applied to explain these exceptional results.

4. Discussion

Concerning the uncertainty of the energy market, the scenarios simulated in this paper are designed across two dimensions: the direction and the amplitude of energy price fluctuation. From the direction perspective, greater impacts are shown in price upward scenarios, meaning that agricultural production, energy consumption and carbon emission are more sensitive when energy prices are increasing. The findings of this paper suggest that an increase in energy prices will drive an increase in the total cost of crop production, a finding that has been confirmed in a wide range of studies in the literature [11–13]. If the amplitude dimension is considered, these greater impacts are intensified under high amplitude scenarios. Additionally, these simulation results are consistent with the finding from the existing literature that the intercorrelation coefficients between prices of energy and agricultural products are higher in the escalating period of energy pricing [11–14]. Our study also pays particular attention to the negative influence of energy price fluctuation on the social welfare of the agricultural sector, which has often been neglected in previous studies in the literature.

The results suggest that energy consumption and carbon emissions can be effectively suppressed by raising the energy price. Energy price has a negative influence on energy consumption, predicted by the neoclassical economic theory [55]. Li et al. revealed that increasing energy price significantly reduces provincial CO_2 emissions in China, with the coefficients ranging from −0.127 to −0.168, which is slightly higher than the coefficients of −0.052 (upward price scenarios) and −0.064 (downward price scenarios) in agriculture in this paper [22]. This result is reasonable, considering the relatively low proportion of energy input in agriculture.

The results indicate that changes in energy price/cost have modest impacts on planted area, which is consistent with the findings of Marshall et al. [56], Rajcaniova et al. [57], Diermeier and Schmidt [58], Piroli et al. [59] and Wesseler and Drabik [60]. The modest changes in agricultural production costs, relative to energy price fluctuation, reflect the fact that energy-related input costs represent only a portion of overall agricultural operating costs. The increase in total costs, due to higher energy prices, will drive down energy use. In the static comparative analysis of this study, lower energy input leads to lower yields, and in the long run, more land is needed for crop production to meet the crop demand. Most of the literature asserted that rising energy (oil) prices and bioenergy production significantly contribute to an increase in the area to produce maize, soybean oil, sugar, and wheat, through the direct and indirect land use change impact [57–60].

Most of the previous studies did not examine the heterogeneous impact of energy prices on energy consumption carbon emissions in agricultural systems, by region and by crop. General econometric models tend to study the linear relationships between variables, making it difficult to explore the heterogeneity of different variables. Under the framework of a price endogenous partial equilibrium model (PEM), this paper evaluates the systematic and heterogeneous impacts of energy price fluctuation on agricultural production, energy consumption and carbon emission. The PEM model can solve the problem of the inability of standard econometrics to deal with limited and incomplete information [61]. PEM is more flexible and feasible when constructing specific empirical models because it requires lower-level data sets and fewer module equations [38]. The heterogeneous empirical results will provide more scientifically refined guidance to policy makers. The primary disadvantage is that such PEM models generate point estimates of production, consumption, and price, and do not possess statistical properties. Furthermore, the model is constructed based on assumptions of market completeness, product competition, and integration of domestic market, etc. Therefore, the findings presented in this paper should be considered within the limits and assumptions of the model we have adopted.

5. Conclusions and Policy Implications

This paper aimed at evaluating the impacts of energy price fluctuation on agricultural production, energy consumption, and carbon emission in China. By constructing a framework of a price endogenous partial equilibrium model (PEM), this paper firstly calibrated the model with data sets derived from 2018, and then designed four scenarios, according to the direction and amplitude of energy price fluctuation. Thereafter, simulations were executed at both crop and regional levels. Modelling results revealed that: (1) The impacts on agricultural production are relatively limited. However, a higher energy price pushes up agricultural production costs, resulting in the loss of social welfare in the agricultural sector, by around 0.6% to 1.4%, under different simulating conditions. (2) Energy price has negative impacts on agricultural energy consumption and carbon emission; the average impacts are approximately 1.6%/3.2% changes in energy consumption, and 1.3%/2.6% changes in carbon emission columns, in low/high amplitude scenarios. Rapeseed and wheat are the most and least sensitive crops to energy price fluctuations. (3) Heterogeneous impacts are confirmed in regional simulations. South China is the most sensitive region, where the impacts under low/high amplitude scenarios reach 2.5%/5% changes in energy consumption and carbon emission, while, according to the baseline, Henan and Heilongjiang are the largest energy consumption and carbon emission areas, at present, in China.

Based on the results above, derived from the PEM simulations, several policy implications might be proposed, as follows: (1) The fluctuation in energy price will finally affect social welfare in the agricultural sector because of the intercorrelations between prices of energy and agricultural products. To alleviate the farmers' livelihood risk and the losses in agricultural social welfare, caused by energy-induced costs, such as strengthening supervision on the energy market, sharing energy-related information, promoting technological progress in agricultural energy use, and improving agricultural energy use efficiency in time would be effective. (2) In terms of its negative influence on energy consumption, energy price can play a critical role in reducing agricultural emissions. Thus, constructing an energy saving price-setting mechanism for agriculture-used energy might be an accessory way of achieving cleaner agricultural production. Considering the ongoing trend of agriculture machinery and foreseeable rise in energy consumption, the Chinese government should launch more policy instruments to facilitate cleaner farming techniques. For instance, subsidizing farmers to purchase energy saving machines and equipment, and applying greener energy sources to support facilities. (3) The existence of heterogeneous effects requires differentiated policy designs across regions in China, and policy effects might vary between energy price sensitive and non-sensitive regions. Policy makers should deeply investigate agricultural structures, farmers' preferences, including risk aversions, and economic geographical conditions beforehand, and then formulate specific measurements of energy saving and emission reduction.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14053002/s1, Table S1: Agricultural energy consumptions and carbon emissions under different scenarios.

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