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Dynamic Energy Use Efficiency, Carbon Input, and Agricultural Benefits of Multiple Cropping in Southern China—A Case Study from Guangdong Province

Tantan Zhang [1,†], Siying Deng [1,†], Yanhong Li [2], Bowen Qing [1], Wu Li [1,3,4] and Zhaowen Mo [1,5,6,*]

1 State Key Laboratory for Conservation and Utilization of Subtropical Agro-Bioresources, College of Agriculture, South China Agricultural University, Guangzhou 510642, China; tantanzhang@stu.scau.edu.cn (T.Z.)
2 Institute of Facility Agriculture, Guangdong Academy of Agricultural Sciences, Guangzhou 510640, China; liyanhong@gdaas.cn
3 Guangdong Province Key Laboratory of Crop Genetic Improvement, Crops Research Institute, Guangdong Academy of Agricultural Sciences, Guangzhou 510640, China
4 Zhanjiang Research Institute of Agricultural Sciences, Zhanjiang 524094, China
5 Scientific Observing and Experimental Station of Crop Cultivation in South China, Ministry of Agriculture and Rural Affairs, Guangzhou 510642, China
6 Guangzhou Key Laboratory for Science and Technology of Fragrant Rice, Guangzhou 510642, China
* Correspondence: zwmo@scau.edu.cn
† These authors contributed equally to this work.

Abstract: Background: With the purpose of exploring the development of new quality productive forces in Guangdong, the present study hypothesized that reducing energy and carbon inputs was beneficial for increasing Guangdong's multi-cropping agricultural energy output and economic returns. Methods: The energy use efficiency of crop production and the corresponding carbon input and agricultural benefit trends from 2011 to 2021 were examined by linear regression analysis for Guangdong Province, China. The corresponding development trends were also predicted using a grey model. Results: The results indicated that the total energy output increased by 12.50%, wherein the energy productivity levels of peanuts, vegetables, mulberry, and fruits increased greatly (51.27–106.17%), while the total energy input and the total carbon input decreased by 12.17% and 6.37%, respectively. Moreover, the energy input per carbon input decreased by 6.19%, while the energy output per carbon input increased by 20.15%. Both energy-related indicators and economic-related indicators all had substantially increased (28.08–44.97% and 83.86–120.91%, respectively). Grey model predictions show that the agricultural output value increased steadily under the current agricultural policy of reducing fossil energy input. Conclusions: The current low-carbon and high-output agricultural model is beneficial for increasing Guangdong's multi-cropping agricultural economic returns and mitigating greenhouse effects.

Keywords: multiple cropping; energy input; energy output; carbon input; economic return

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1. Introduction

Analyzing the current state of the global food system—with a specific focus on crop planting development and stable yield assurance for staple crops—has emerged as a central and enduring field of scholarly interest in the context of global food provision. The priority task for the Chinese government is the formulation of measures to improve nutrition and achieve sustainable food production [1,2]. With the expansion of China's population from 1.35 billion in 2011 to 1.41 billion in 2021, the demand for agricultural products has increased, while the required resources and environmental carrying capacity have followed the opposite trend [3,4]. In 2023, the Ministry of Agriculture and Rural Affairs initiated a nationwide effort with the goal to substantially enhance the per unit area yield of major crops, such as grain and oil, in accordance with China's resource endowment and production conditions [5]. Moreover, China has the most extensive smallholder production economy with great potential for sustainable agricultural intensification [6–8]. It is imperative for China's agricultural development to shift from a high-input agriculture type to a modern ecological high-value agriculture type.

Multiple cropping (i.e., the practice of growing two or more crops on the same piece of land during one year) has remained the mainstream of Chinese agriculture from ancient times to the present, and plays a key role in China's food security [9]. In particular, South China provides sufficient water and heat resources as well as development opportunities for multiple cropping cultivation, and Guangdong Province is a typical demonstration province in this regard [10]. In addition to direct economic benefits obtained by increasing the number of harvests and the biomass extracted, multiple cropping can also improve the function of agricultural systems and reduce detrimental environmental consequences associated with crop production [11]. The intensification of global warming has triggered a northward shift of China's entire agro-climatic belt, resulting in an expansion of multiple cropping areas and an increase in the multiple cropping indices [12]. However, over the past 30 years, the expansion of multiple cropping systems triggered by climate change has increased greenhouse gas emissions in the North China Plain and its surrounding areas [13]. Moreover, climate change is also a key factor driving the change of the multiple cropping indices in Southwest China [14]. The resulting excessive use of chemical fertilizers and pesticides at the family scale also hinders the restoration of the ecological environment in hilly and mountainous (and similar) areas [15]. To ensure the high yield of multiple cropping products, multiple cropping inevitably requires a high input of agricultural factors (such as chemical fertilizers, pesticides, and diesel), which poses a threat to sustainable agricultural development. Analyzing the energy use efficiency (EUE) of agricultural inputs to study sustainable agriculture is a common and practical method [16,17]. Estimating the dynamic trends of productivity and carbon emissions in the production system can provide constructive insights for multi-cropping-sustainable agricultural policy adjustments. Therefore, the multiple cropping agriculture development strategy of Guangdong Province provides an instructive lesson for other multiple cropping planting areas.

In agricultural production, the consumption of energy is closely related to the carbon emissions intensity [18]. The reasonable and effective reduction in the total energy consumption of agricultural production without sacrificing the development of the agricultural economy while realizing a decoupling of agricultural energy consumption and carbon emissions from agricultural economic development remains a major problem associated with efforts to promote sustainable agricultural development [19]. By studying the decoupling stability coefficient, Zhen et al. [20] found that the threat of high-carbon crop production in Guangdong Province has not been eliminated. Moreover, the economic development and carbon emissions of Guangdong Province are in a state of weak decoupling [21]. The development of the agricultural economy is the main driving factor for reductions of carbon emissions in Guangdong Province [22]. However, the high-quality development value of land use in certain areas of western and northern Guangdong Province is low, and the economic value of ecological land in this area needs to be further examined to improve the versatility of the land [23]. The decline of rural areas and uncertain rural resilience under intergenerational changes are not conducive to the government's stimulation efforts of rural economic vitality [24].

The Guangdong–Hong Kong–Macao Greater Bay Area (GBA) holds an important strategic position in China's new development pattern and has been projected to grow into one of the most promising growth poles of the world in the future [25]. Agricultural development and food safety guarantees form the basis of the efforts to enhance the international competitiveness of the GBA and for creating a high-quality bay area lifestyle [26]. Because of the lack of natural resources in Hong Kong and Macao, the history of mainland agricultural product supply to Hong Kong and Macao can be traced back to the 1960s [27]. Guangdong Province remains the main production and supply base of fresh agricultural products and food in both Hong Kong and Macao [28]. High-quality agricultural development is related to major strategic issues of the transformation and upgrading of China's macroeconomic structure and the food structure and nutritional structure of its residents [29]. It is of great significance to study the future development trend of agriculture in Guangdong Province for the future construction of production-living-ecological spaces in the GBA. Owing to its special institutional environment of 'One country, two systems, and three tariff zones', the regional coordinated development of GBA encompasses multiple geographical scales and complex relationships among various entities [30]. The future trend of multiple cropping agricultural production driven by the rapid economic development of the GBA remains to be further explored.

Hence, this article hypothesized that scientifically reducing and converting energy-carbon inputs in multiple cropping agriculture areas into energy output can result in higher agricultural returns in Guangdong. Through a series of related indicators and grey prediction models, the interactions between energy input, energy output, carbon input, and economic return in the multiple cropping production system of Guangdong Province from 2011 to 2021 were investigated. The relationships between these factors are disclosed with the goal to analyze the matching degree of resources and environmental carrying capacity as well as the sustainability of agricultural economic development. In doing so, this paper provides a scientific reference for the new quality productive forces used in the development of Guangdong, the future construction of the GBA, and the comprehensive launch of the '14th Five-Year Plan'.

2. Materials and Methods

2.1. Data

The analysis focused on calculating the energy inputs for agricultural crop production, the energy output of crop yields, and the corresponding carbon inputs in Guangdong Province from 2011 to 2021. The data originate from the Guangdong Statistical Yearbook and Guangdong Rural Statistical Yearbook [31].

2.2. Data Calculation Methods

The data calculation methods were mainly based on [32–34]. Energy input was calculated from statistics on agricultural production factors, which included machinery, chemical fertilizers, plastic agricultural film, diesel, and pesticides. Energy output was calculated from statistics on the total production of rice, tubers, soybeans, sugarcane, peanuts, tobacco, vegetables, tea, mulberry, and fruits (which includes all major crops grown in Guangdong Province). To calculate the energy-related indicators and carbon input, the data were converted into energy input, output, and carbon input levels using equivalent energy values and emission coefficients for each commodity. Supplemental Table S1 provides the energy equivalents for inputs and outputs [33,35–39], Supplemental Table S2 provides the emission coefficients for carbon inputs [40–44], and Supplemental Table S3 provides the abbreviations of the indicators related to energy, carbon input, and economic return [45–48].

2.3. Grey Model GM (1,1) Prediction

The Grey Model GM (1,1) model [49–52] was applied and divided into five steps, and is represented by the values of nominal economic return in crop production (NEcR), nominal economic return on energy input (NEcRI), nominal economic return on energy output (NEcRO), nominal economic return per unit sowing area (NEcRA), and nominal economic return on carbon footprint in crop production (NEcRC) in the year 2011, denoting $x^{(0)}(1)$:

(1) The modeling original sequence is initialized and denoted as follows:

$$X^{(0)} = \left\{ x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n) \right\}$$

(2) The 1-AGO of the original sequence is generated and denoted as follows:

$$X^{(1)} = \left\{x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)\right\}$$

(3) The adjacent mean of the 1-AGO generated sequence is generated and denoted as follows:

$$x^{(1)}(k) = \sum_{i=0}^{k} x^{(0)}(i) = x^{(1)}(k-1) + x^{(0)}(k), k = 1, 2, \ldots, n$$

(4) The development coefficient *a* and the grey action *b* of the grey model are calculated as follows:

Expressing the GM (1,1) equation as $x^0(k) + az^{(1)}(k) = b, \hat{a} = (a, b)^T$, the parameters satisfy the condition for the least squares solution as $\hat{a} = \left(B^T B\right)^{-1} B^T Y_n$, where

$$B = \begin{bmatrix} -z^{(1)} & (2) & 1 \\ -z^{(1)} & (3) & 1 \\ \ldots & \ldots & \ldots \\ -z^{(1)} & (n) & 1 \end{bmatrix} Y_n = \begin{bmatrix} x^{(0)} & (2) \\ x^{(0)} & (3) \\ & \ldots \\ x^{(0)} & (n) \end{bmatrix}$$

(5) The differential equation is solved to obtain the prediction simulation equation. The expression of the original sequence model is as follows:

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k), k = 1, 2, \ldots, n$$

Based on this, simulated values can be calculated, followed by the calculation of the simulated error values, where $k > n$, $\hat{x}^{(0)}(k)$ represents the predicted value of the original sequence. Then, the magnitude of residuals between the original values and simulated values was calculated to assess model performance. A large residual indicates lower model accuracy, while a smaller residual indicates higher accuracy. The specific criteria for assessment are as follows: at a relative error of residuals of $a \leq 0.01$, the accuracy of the model was considered high; for $0.01 < a \leq 0.05$, the accuracy of the model was relatively high; for $0.05 < a \leq 0.10$, the accuracy of the model was relatively low; and for $0.10 < a \leq 0.20$, the accuracy of the model was low. Overall, this predictive model demonstrates high or relatively high accuracy, with $a \leq 0.05$, except for NEcRC in 2018 which had a value of 0.07 (Supplemental Table S4).

2.4. Statistical Analysis

The OriginPro 2021 (OriginLab Corporation, Northampton, MA, USA) was used to perform linear fitting, analyze linear regression equations, and make figures. The grey model was analyzed and established by Microsoft Excel 2021 (Microsoft Corporation, Redmond, NM, USA).

3. Results

3.1. Analysis of Energy Input and Energy Output

The energy input change in crop production in Guangdong Province from 2011 to 2021 is shown in Figure 1a. The total energy input decreased by 12.17% from 170.97 PJ in 2011 to 150.12 PJ in 2021, with an average reduction value of 2.08 PJ over the sampled period. Energy input per unit sowing area (EIPA) decreased by 15.95%, from 31.56 GJ·ha^{-1} in 2011 to 26.53 GJ·ha^{-1} in 2021, with an average reduction value of 0.50 GJ·ha^{-1}. As shown in Supplemental Figure S1, the examined categories of energy input include machinery power, chemical fertilizer, plastic agricultural film, diesel, and pesticides. The chemical fertilizers, pesticides, and diesel had significant linear trends with higher R^2 values (0.813, 0.847, and 0.453, respectively) from 2011 to 2021. Additionally, chemical fertilizers, diesel, and pesticides accounted for a large proportion of energy input. During the study period, the proportion of chemical fertilizers and pesticides in energy inputs decreased by 3.16%

and 4.61%, respectively, while the proportion of diesel increased by 7.73%. The chemical fertilizers studied include nitrogen, potassium, phosphorus, and compound fertilizers, which decreased according to a significant linear trend by 24.53%, 17.66%, and 10.59%, respectively (Supplemental Figure S2).

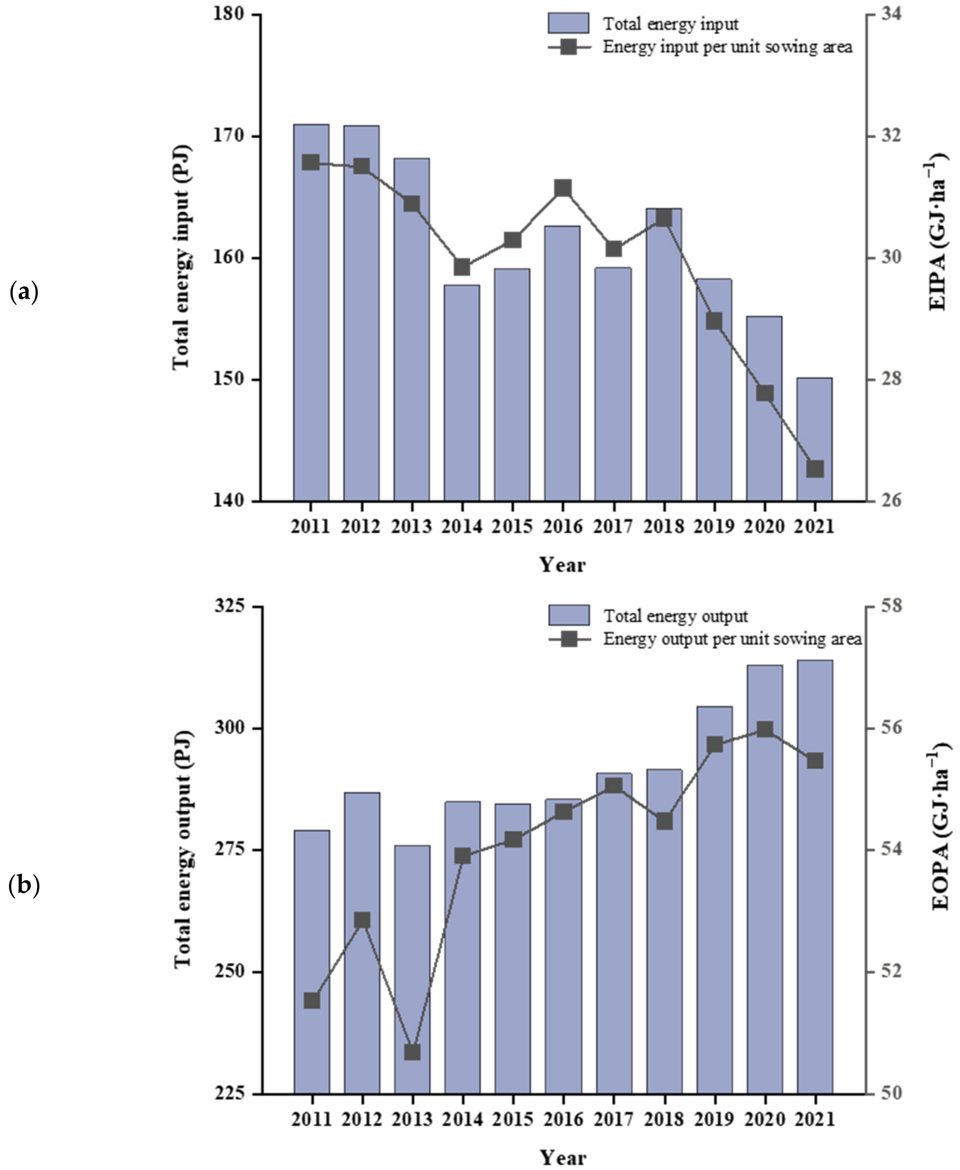

Figure 1. Trends in (**a**) energy input (PJ) and energy input per unit sowing area, and (**b**) energy output (PJ) and energy output per unit sowing area (GJ·ha^{-1}) in crop production in Guangdong Province, China from 2011 to 2021.

The energy output change in crop production in Guangdong Province from 2011 to 2021 is shown in Figure 1b. The total energy output increased by 12.50%, from 279.00 PJ in 2011 to 313.88 PJ in 2021, representing an average growth of 3.49 PJ over the studied period. Energy output per unit sowing area (EOPA) increased by 7.65%, from 51.52 GJ·ha^{-1} in 2011 to 55.46 GJ·ha^{-1} in 2021, with an average increase value of 0.39 GJ·ha^{-1} over this period. As shown in Figure 2, the categories of energy output studied include rice, tubers, soybean, sugarcane, peanuts, tobacco, vegetables, tea, mulberry, and fruits. In the study period, except for tubers, the energy output of other crops increased to varying degrees, and the energy outputs of rice, soybean, peanuts, tobacco, vegetables, mulberry, and fruits increased linearly by 6.94%, 17.21%, 32.37%, 18.69%, 27.14%, 42.79%, and 73.28%, respectively. On average, rice had the largest share (61.91%) of the total energy output, followed by fruits (9.15%), vegetables (8.62%), peanuts (8.40%), mulberry (5.36%), and sugarcane (4.77%), while the other four crops only had a share of 1.79%. The planting areas of vegetables and tobacco increased slightly, but those of other crops decreased to varying degrees.

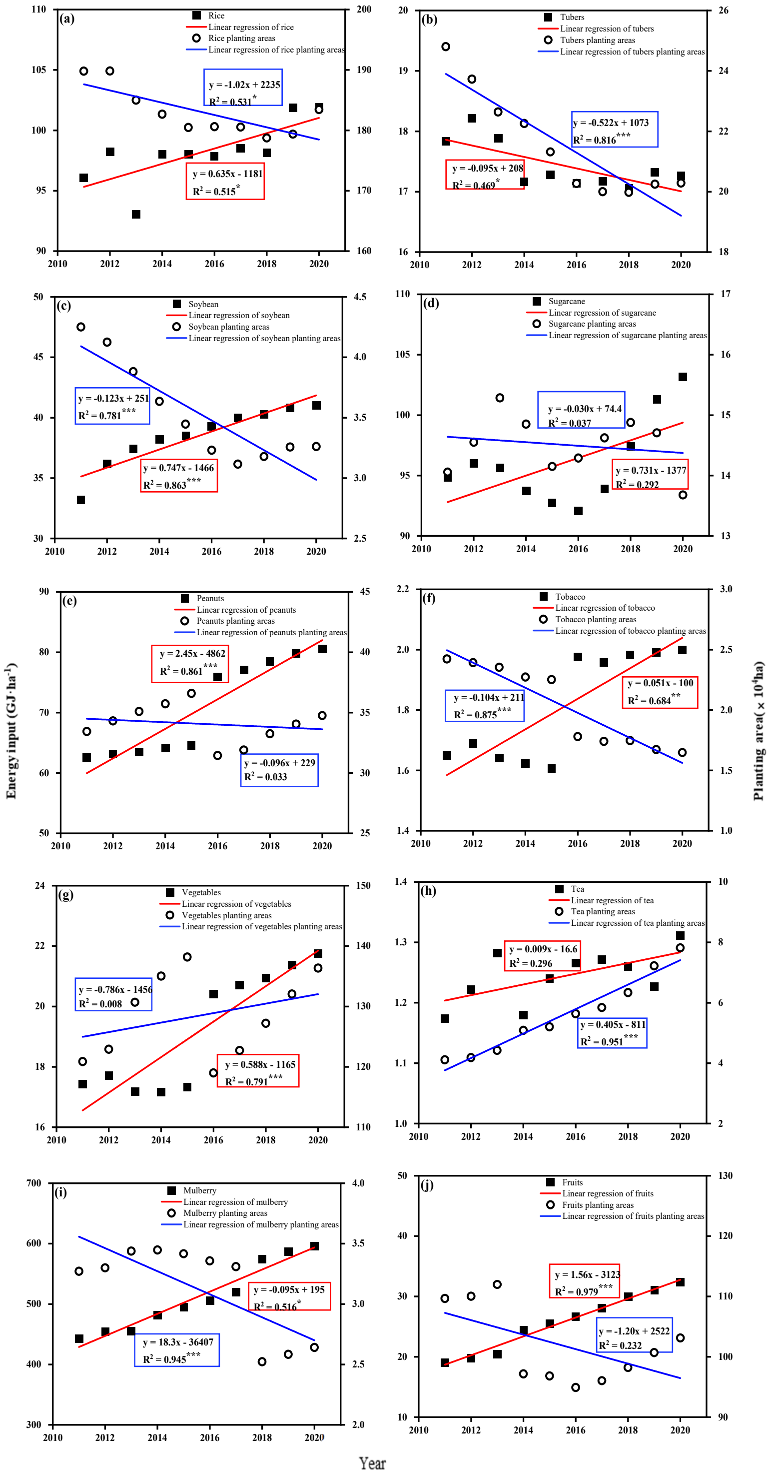

Figure 2. Changes in the energy output (GJ·ha^{-1}) and planting area ($\times 10^4$ ha) in the production of different crop categories, i.e., rice (**a**), tubers (**b**), soybean (**c**), sugarcane (**d**), peanuts (**e**), tobacco (**f**), vegetables (**g**), tea (**h**), mulberry (**i**), and fruits (**j**) in Guangdong Province, China from 2011 to 2021. "*", "**" and "***" means $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively, the same below.

3.2. Energy-Related Indexes

The changing trend of EUE, NE, and EPF in Guangdong Province from 2011 to 2021 is shown in Figure 3. With significant linear trends over this period, EUE, NE, and EPF increased by 28.08%, 44.97%, and 72.49%, respectively. SE and EP in the production of different crop categories from 2011 to 2021 are tabulated in Supplemental Tables S5 and S6, respectively. Peanuts, vegetables, mulberry, and fruits had greater change ratios in SE and EP: The reduction ratios of SE were 36.51%, 33.90%, 41.14%, and 51.50%, respectively, and the growth ratios of EP were 57.50%, 51.27%, 69.89%, and 106.17%, respectively.

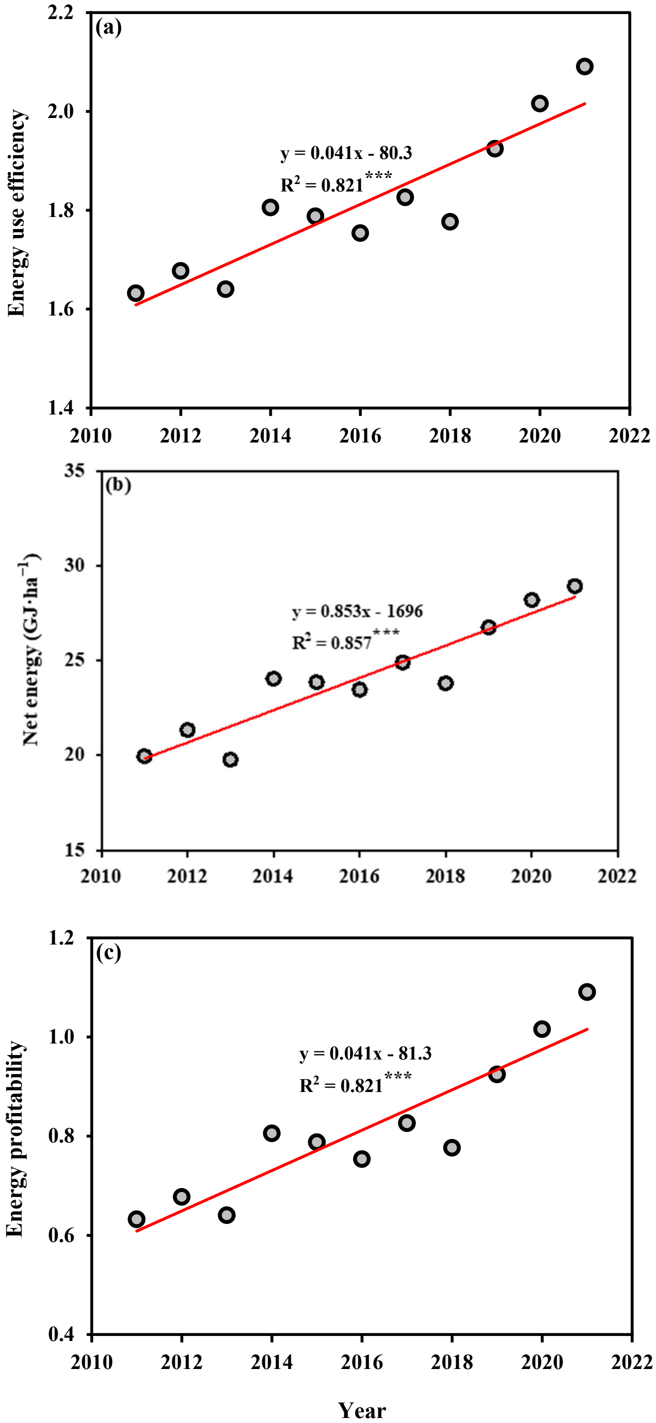

Figure 3. Dynamic changes in energy use efficiency (**a**), net energy (GJ·ha^{-1}) (**b**), and energy profitability (**c**) in crop production in Guangdong Province, China from 2011 to 2021.

3.3. Analysis of Carbon Input

The carbon input change in crop production in Guangdong Province from 2011 to 2021 is shown in Figure 4a. The total carbon input decreased by 6.37%, from 7993.81 CO_2e·kg in 2011 to 7484.78 CO_2e·kg in 2021, with an average reduction of 50.90 CO_2e·kg over this period. Carbon input per unit sowing area (CIPA) decreased by 7.01%, from 1187.88 (CO_2e·kg)·ha^{-1} in 2011 to 1104.63 (CO_2e·kg)·ha^{-1} in 2021, with an average reduction of 0.50 (CO_2e·kg)·ha^{-1} over this period. As tabulated in Supplemental Table S7, the categories of carbon input studied include machinery power, nitrogen, potassium, phosphorus, plastic agricultural film, diesel, and pesticides. The main carbon input resources were chemical fertilizers, diesel, and pesticides. Among different kinds of chemical fertilizers, nitrogen was the most important. Although the proportion of diesel in carbon input increased from 39.71% to 46.79% during the study period, the proportion of chemical fertilizers and pesticides decreased.

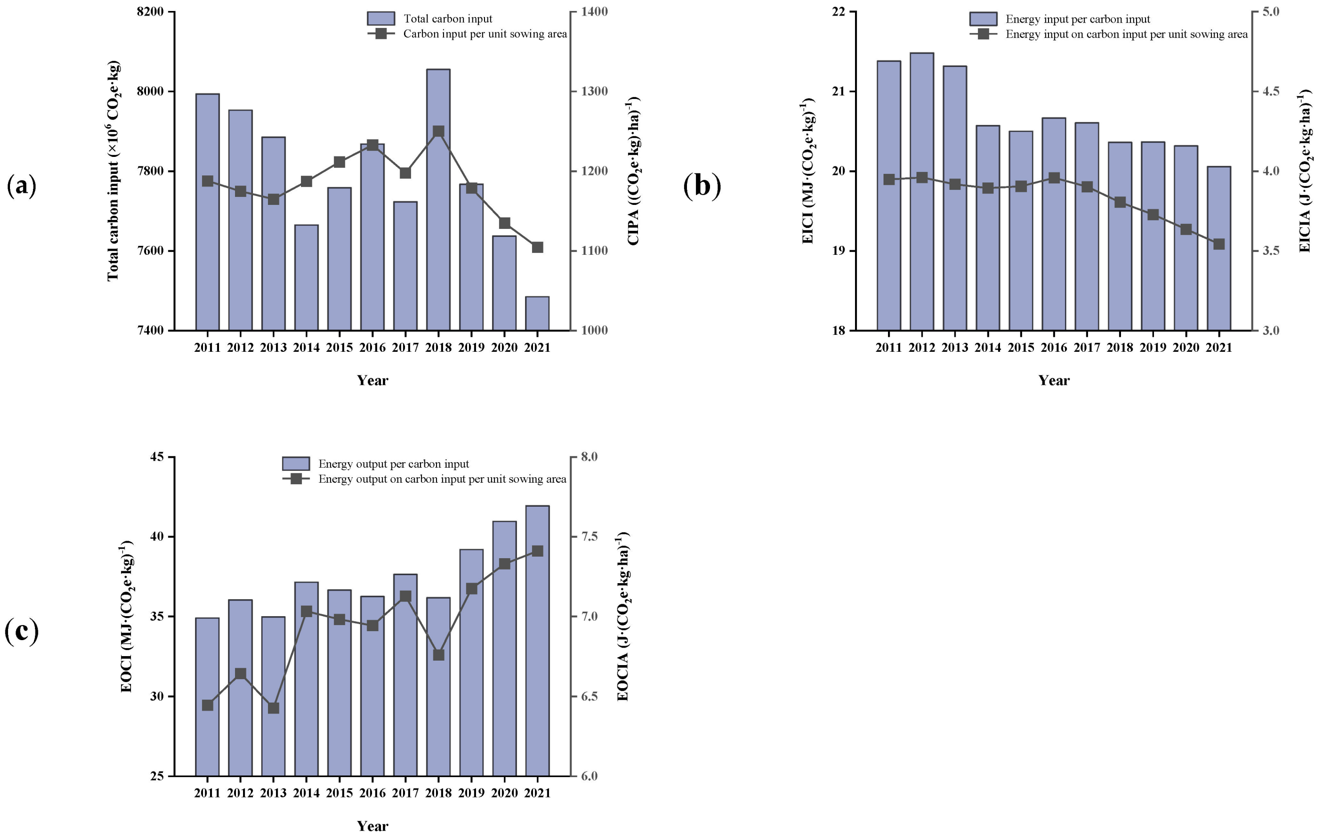

Figure 4. Trends in (**a**) carbon input (×10^6 CO_2e·kg) and carbon input per unit sowing area ((CO_2e·kg)·ha^{-1}); (**b**) energy input per carbon input (MJ·(CO_2e·kg)$^{-1}$) and energy input on carbon input per unit sowing area (J·(CO_2e·kg·ha)$^{-1}$); and (**c**) energy output per carbon input (MJ·(CO_2e·kg)$^{-1}$) and energy output on carbon input per unit sowing area (J·(CO_2e·kg·ha)$^{-1}$) in crop production in Guangdong Province, China from 2011 to 2021.

An analysis of the combined energy with carbon input is shown in Figure 4b,c. The energy input per carbon input (EICI) decreased by 6.19%, from 21.38 MJ·(CO_2e·kg)$^{-1}$ in 2011 to 20.06 MJ·(CO_2e·kg)$^{-1}$ in 2021, which reflects an average reduction of 0.13 MJ·(CO_2e·kg)$^{-1}$ over this period. Energy input on carbon input per unit sowing area (EICIA) decreased by 10.24%, from 3.95 J·(CO_2e·kg·ha)$^{-1}$ in 2011 to 3.54 J·(CO_2e·kg·ha)$^{-1}$ in 2021, which is an average reduction of 0.04 J·(CO_2e·kg·ha)$^{-1}$. Simultaneously, the energy output per carbon input (EOCI) increased by 20.15%, from 34.90 MJ·(CO_2e·kg)$^{-1}$ in 2011 to 41.94 MJ·(CO_2e·kg)$^{-1}$ in 2021, which reflects an average growth of 0.70 MJ·(CO_2e·kg)$^{-1}$. Energy output on carbon input per unit sowing area (EOCIA) increased by 14.97%, from

6.45 J·(CO_2e·kg·ha)$^{-1}$ in 2011 to 7.41 J·(CO_2e·kg·ha)$^{-1}$ in 2021, reflecting an average growth of 0.10 J·(CO_2e·kg·ha)$^{-1}$.

3.4. Analysis of Agricultural Economic Return and Grey Model Prediction

The dynamic changes and grey model prediction in NEcR, NEcRI, NEcRO, NEcRA, and NEcRC in Guangdong Province from 2011 to 2021 are presented in Table 1. Over the study period, NEcR increased by 106.84%, from 1910.21 × 10^9 CNY in 2011 to 3951.14 × 10^9 CNY in 2021, which reflects an average growth of 204.09 × 10^9 CNY. NEcRA increased by 97.93%, from 352,750.75 CNY·ha^{-1} in 2011 to 698,198.10 CNY·ha^{-1} in 2021, which reflects an average growth of 34,544.79 CNY·ha^{-1}. From 2011 to 2021, NecRI, NecRO, and NecRC increased by 135.49%, 83.86%, and 120.91%, respectively, reflecting average growth values of 1514.37 CNY·GJ^{-1}, 574.16 CNY·GJ^{-1}, and 28.89 CNY·(CO_2e·kg)$^{-1}$, respectively. Table 1 also shows that the average relative error between the actual value and the predicted value does not exceed 2%, indicating that the accuracy of the grey model was relatively high. Therefore, if the current agricultural development model is followed in the future and fossil fuel investment is reduced, NEcR, NEcRI, NEcRO, NecRA, and NecRC will retain their growth trends.

Table 1. Dynamic changes and grey model predictions in nominal economic return in crop production (NEcR; ×10^9 CNY), nominal economic return on energy input (NEcRI; CNY·GJ^{-1}), nominal economic return on energy output (NEcRO; CNY·GJ^{-1}), nominal economic return per unit sowing area (NEcRA; CNY·ha^{-1}), and nominal economic return on carbon footprint in crop production (NEcRC; CNY·(CO_2e·kg)$^{-1}$) in Guangdong Province, China from 2011 to 2021.

Year	NEcR		NEcRI		NEcRO		NEcRA		NEcRC	
	Actual Value (×10^3)	Predicted Value (×10^3)	Actual Value (×10^4)	Predicted Value (×10^4)	Actual Value (×10^3)	Predicted Value (×10^3)	Actual Value (×10^5)	Predicted Value (×10^5)	Actual Value (×10^2)	Predicted Value (×10^2)
2011	1.91	1.91	1.12	1.12	6.85	6.85	3.53	3.53	2.39	2.39
2012	2.06	2.03	1.21	1.20	7.19	7.41	3.80	3.89	2.59	2.55
2013	2.23	2.19	1.33	1.31	8.09	7.87	4.10	4.17	2.83	2.76
2014	2.36	2.36	1.49	1.43	8.28	8.36	4.46	4.46	3.08	2.99
2015	2.49	2.54	1.57	1.56	8.76	8.88	4.74	4.77	3.21	3.24
2016	2.76	2.74	1.70	1.70	9.69	9.44	5.29	5.11	3.51	3.51
2017	2.89	2.95	1.82	1.85	9.94	10.03	5.47	5.47	3.74	3.80
2018	3.09	3.18	1.88	2.01	10.60	10.65	5.77	5.85	3.84	4.12
2019	3.53	3.43	2.23	2.19	11.60	11.32	6.46	6.26	4.54	4.46
2020	3.77	3.70	2.43	2.39	12.05	12.03	6.75	6.70	4.94	4.83
2021	3.95	3.99	2.63	2.60	12.59	12.78	6.98	7.17	5.28	5.23
2025		5.38		3.67		1.63		9.40		7.20
2030		7.84		5.63		2.20		13.19		10.74
Mean value										
2011–2015	2.21	2.20	1.34	1.32	7.83	7.87	4.13	4.16	2.82	2.79
2016–2020	3.21	3.20	2.01	2.03	10.78	10.69	5.95	5.88	4.11	4.14
2021–2025		4.66		3.11		14.47		8.25		6.18
2026–2030		6.78		4.78		19.59		11.57		9.21

4. Discussion

Based on the statistical data from the Guangdong Statistical Yearbook and Rural Statistical Yearbook from 2011 to 2021, this study examined the temporal variation characteristics of non-renewable energy inputs, main crop energy outputs, carbon inputs, and agricultural outputs of Guangdong Province, China. In addition, a series of related indicators were used to analyze the relationship between energy, carbon input, and agricultural economic returns during the studied period. This analysis provides references for the adjustment of multiple cropping structures, thus enabling the optimization of agricultural support policies in the GBA.

Although the period and scope of this study differed from those of [53], similar results were obtained. The data analyses showed the dynamic variation of the energy balance of the agricultural system in Guangdong Province from 2011 to 2021, indicating that the EUE followed an increasing trend (Figures 1 and 3a). Chemical fertilizers contributed the most to the total energy input, followed in decreasing order by diesel, pesticides, and plastic agricultural film, while machinery power contributed the least (Supplemental Figure S1). Even if the energy input of diesel increased, the gross energy input of nitrogen fertilizer, potassium fertilizer, compound fertilizer, and pesticides decreased more. This development may have benefitted from agricultural technicians in Guangdong Province who integrated agronomic fertilization measures and agricultural machinery precision fertilization technology. They relied on new agricultural production and management entities, as well as specialized agrochemical service organizations to vigorously promote, and ultimately achieve, precision fertilization while reducing fertilization in crop cultivation to a large extent [54]. During the 13th Five-Year Plan period, the comprehensive mechanization rate of rice in Guangdong reached 75.3% [55]. The introduction of new multiple cropping types of economic crops has played an important role in improving crop production efficiency and land use efficiency, thus contributing to the development of a low-carbon agricultural economy in Guangdong Province [56]. Furthermore, several new environmentally friendly eco-farming techniques have also emerged in Guangdong Province, for example, combined rice/water mimosa intercropping and nitrogen fertilizer reduction, which achieved a reduction of approximately 40 kg·ha^{-1} of nitrogen fertilizer use [57]. This combination not only offers advantages in controlling the pests and diseases of rice but also reduces the use of pesticides and improves rice yields and food quality, thus increasing the income of workers in agricultural management. Therefore, the most important step towards improving the development of green agriculture is the effective transformation of the achievements of agricultural science and technological innovation into a real driving force that promotes crop production.

Currently, the pace of urbanization and agricultural modernization in China is accelerating, and the planting scales, planting methods, business entities, and organizational models of agricultural production are quietly undergoing profound changes [58]. Similar changes have taken place in agricultural production in Guangdong Province. According to the changes in energy output and cultivated land areas of different crops between 2011 and 2021, the planting scale and planting structure of crops in Guangdong Province have changed to varying degrees (Figure 2). During the study period, the total energy output and EOPA increased overall, showing fluctuations. In terms of the proportion of energy output, vegetables, fruits, tea, and peanuts increased by 2.28%, 3.57%, 0.02%, and 1.73%, respectively, while other crops decreased (among which rice decreased the most at 5.54%). Over the past 30 years, the crop planting structure in the GBA has gradually changed from grain to vegetables and fruits [59]. There is a positive spatial correlation in vegetable production in the GBA [60]. Fruit production in Guangdong Province is mainly based on subtropical orchards in hilly and mountainous areas. The gradual maturity of 5G technology and the rapid development of artificial intelligence technology provide new technical support and transformation space for the development of intelligent agricultural machinery and intelligent orchards [61]. Simultaneously, high-quality standardized ecological tea gardens have become a characteristic and profitable industry in Guangdong Province, helping to develop prosperous villages. The planting area of peanuts in Guangdong Province is stable while the yield per unit area increases year by year, resulting in a steadily increasing total yield; however, the small planting scale and low mechanization degree limit the peanut production space in Guangdong Province [62]. Furthermore, Guangdong Province established an echelon development pattern of modern agricultural parks, where most of the high-quality modern agricultural industrial parks are government-led and enterprise-operated since 2018 [63]. Although the allocation of resources for crop production still needs to be optimized further, the agricultural park model is meaningful for the accelerated transformation from traditional agriculture to modern agriculture and plays an important role in the increase in energy output in crop production. Therefore, regarding the further improvement of EUE in crop production, it is not only necessary to adjust agricultural production factors to obtain the maximum output, but also to update the agricultural development model to identify optimal solutions.

Regarding the assessment of EUE, other energy attributes such as NE, EPF, EP, and SE are meaningful indicators [64]. In multi-biological systems that contain heterotrophic organisms, the proportion of NE is a key determinant of the viability and complexity of the resulting community structure [65,66]. EPF is a further indicator of the EUE of this system [67]. SE shows the potential impact of agricultural production factors, and EP can be used to evaluate the effect of a reduced energy input [68]. In the studied period, NE, EPF, and EP all increased, while SE decreased (Figure 3, Supplemental Tables S5 and S6). As suggested by these results, crop production in Guangdong Province required lower energy inputs of agricultural production factors. This was achieved through policy adjustments and agricultural achievement transformation over the past decade, which in turn achieved higher crop energy outputs, thereby achieving higher EUE. Furthermore, lower energy inputs were accompanied by lower carbon inputs. During the study period, the greenhouse gas emissions of nitrogen fertilizer, potash fertilizer, plastic agricultural film, and pesticides showed a clear reduction (Supplemental Table S7), indicating the fluctuating decline of total carbon input (Figure 4). Moreover, Figure 4 also shows the relationship between energy balance and carbon input, wherein the EICI sustained a decrease and the EOCI increased (with fluctuations). Their change trends were not affected by the increase in planting area. Guangdong Province accelerated the transformation of industrial structures, developed low-carbon agriculture, and contributed to China's emission reduction targets. Examples are the cultivation of high-quality crop varieties with high disease resistance and high carbon sink capacity, the promotion of new models of green agriculture, and the development of environmentally friendly fertilizers and pesticides [69–71]. With the rapid development of urban agglomerations in the GBA, the pressure and necessity of stringent nitrogen pollution control has received increasing attention. The synergistic control of cross-media nitrogen pollution was achieved via the promotion of fertilizer reduction and sludge land reuse [72]. These measures not only improved the quality and safety of agricultural products, but also (directly or indirectly) contributed to energy savings and emission reductions in crop production.

Additionally, in this study, for the time series of agricultural economic returns and energy changes or indicators related to carbon input from 2011 to 2021, only the changes in the related indicators and time were known, while information on other influencing factors still remains unknown. The grey prediction GM (1,1) model was applicable, and the accuracy of the model was relatively high, indicating that it is credible and effective in practice. The conducted data analysis and model predictions showed that changes in energy use and carbon inputs in the current agricultural system are conducive to improving economic returns from agricultural production (Table 1). This implies that in the case of increased production, reducing the energy investment ratio positively affects multiple cropping ecological environment security and improves multiple cropping agricultural economic returns. On the one hand, this is the result of the important role of crop selection for measuring and developing the potential of multiple cropping [72], while on the other hand, the per capita income of farmers is also an important factor affecting the intensity of multiple cropping in Southern China [73]. In recent years, the overall costs of the agricultural means of production in China have increased, which not only increases the cost of agricultural production and thus erodes the profit margin of agricultural products, but also affects the quality of agricultural production [74]. However, because of the continuous promotion of large-scale operations, agricultural socialization services, and agricultural new technology promotion, the application intensity of pesticides and fertilizers has decreased year by year, as the main focus was to improve quality and efficiency [75,76], which lead to cost reductions and increased economic benefits. For instance, Western Guangdong has become the largest sericulture production base in Guangdong Province under the implementation of the national 'east mulberry move to westward' strategic decision [77]. The sericulture industry has played an important role in the overall adjustment of the local agricultural industrial structure and the increase in farmers' income. Li et al. [78] found that the three-cropping rotation mode of 'economic crops–middle and late rice–winter potato' used for sweet corn and other economic crops instead of early rice can achieve a smoother crop stubble connection. This has the advantages of improving soil physical and chemical properties, reducing pests and diseases, and enhancing system productivity, thus increasing the overall economic benefits of three-season crops. Overall, the changes in energy use and carbon inputs in the agricultural system of Guangdong Province greatly aid in the development of an ecologically high-value agriculture system, which is complementary to the high-quality development of the GBA.

5. Conclusions

Through an analysis of energy change, carbon inputs, agricultural output values, and their corresponding indicators from 2011 to 2021 in Guangdong Province, a comprehensive conclusion has been drawn. Energy inputs and carbon inputs for agricultural production continued to decrease (with fluctuations), while the crop energy outputs increased slowly and the agricultural economic return also followed an increasing trend. These findings and the grey prediction model analysis results align with our hypothesis. However, from a long-term perspective, there is still a need for the Guangdong government, enterprises, and farmers to form closer linkages so that they can effectively transform new agricultural technologies into productive agricultural practices, thus promoting the development of high-quality multiple cropping agriculture and strong food security in the GBA.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14040641/s1, Table S1: Energy equivalent of inputs and outputs in various agricultural production systems; Table S2: Emission factors used to estimate greenhouse gas emissions from agricultural inputs; Table S3: Abbreviation for indicators related to energy, carbon input, and economic return; Table S4: Magnitude of residuals between original values and simulated values to assess model performance; Table S5: Changes in the specific energy in the production of different crop categories in Guangdong Province, China from 2011 to 2021 ($kg{\cdot}GJ^{-1}$); Table S6: Changes in the energy productivity in the production of different crop categories in Guangdong Province, China from 2011 to 2021 ($GJ{\cdot}kg^{-1}$); Table S7: Changes in greenhouse gas emissions from agricultural inputs in Guangdong Province, China from 2011 to 2021 ($(CO2e{\cdot}kg){\cdot}ha^{-1}$); Figure S1: Changes in the energy input categories, i.e., machinery (a), chemical fertilizers (b), plastic agricultural films (c), diesel (d), and pesticides (e) in crop production in Guangdong Province, China from 2011 to 2021 ($GJ{\cdot}ha^{-1}$); Figure S2: Changes in the energy input of fertilizers, i.e., nitrogen fertilizers (a), phosphorus fertilizers (b), potassium fertilizers (c), and compound fertilizers (d) in crop production in Guangdong Province, China from 2011 to 2021 ($GJ{\cdot}ha^{-1}$). References [33,35–48] are cited in supplementary materials.

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