The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1756-137X.htm

Dual carbon goals and the impact on future agricultural development in China: a general equilibrium analysis

Received 5 February 2022
Revised 21 June 2022
11 July 2022
Accepted 13 July 2022

Wei Wei
Management Academy of China Cooperatives, Beijing, China
Qi Cui
School of Economics and Resource Management, Beijing Normal University, Beijing, China, and
Yu Sheng
China Center for Agricultural Policy, School of Advanced Agricultural Sciences, Peking University, Beijing, China

Abstract

Purpose – This paper aims to explore the future path of agricultural development in China toward 2060 under the dual carbon goals, so as to inform better policy choices for facilitating agricultural and rural transformation toward the goal of maintaining food security, sustainable income growth and low carbon emission.

Design/methodology/approach – This study employs a single-country, multi-sectoral computable general equilibrium model, CHINAGEM model and develops eight illustrative scenarios to simulate the impacts of attaining dual carbon goals on agricultural development in China. Additional two scenarios have also been designed to inform better policy making with the aim to offset the negative impact of the decarbonization schemes through facilitating agricultural technology progress.

Findings – Dual carbon goals are projected to impose substantial negative impact on agricultural productions and consumptions in China in the coming four decades. Under the assumption of business as usual, agricultural production will reduce by 0.49–8.94% along with the attainment of carbon neutrality goal by 2060, with the production of cereals and high-value being more severely damaged. To mitigate the adverse impact of the decarbonization schemes, it is believed that fastening technology progress in agriculture is one of the most efficient ways for maintaining domestic food security without harming the dual carbon goals. In particular, if agricultural productivity (particularly, for cereals and high-value products) can be increased by another 1% per year, the production losses caused by carbon emission mitigation will be fully offset. This implies that promoting technology progress is still the best way to facilitate agricultural development and rural transformation in future China.

Originality/value – The paper contributes to the literature in better informing the impact of dual carbon goals on China's agriculture and the effectiveness of technology progress in agriculture on buffering the adverse impact of the decarbonization schemes and promoting agricultural development.

Keywords CGE model, Agricultural development, Dual decarbonization scheme, Technology progress

Paper type Research paper

1. Introduction

Achieving the national dual carbon goals is not only essential for China's future sustainable development by 2060 but also contributes substantially to global carbon emission reduction. However, the implementation of decarbonization schemes is expected to pose great

China Agricultural Economic Review
Vol. 14 No. 4, 2022
pp. 664-685

1756-137X
DOI 10.1108/CAER-02-2022-0020

The authors received their respective financial supports from the National Natural Sciences Foundation of China (71903014; 72173006), National Social Science Foundation of China (21&ZD092) and Beijing Natural Science Foundation (9222016) and highly appreciated the constructive comments of anonymous reviewers.

challenges to China’s future agriculture development. In 2019, China’s CO_2 emission has reached 99.19 million tons, accounting for 29.5% of the world’s total CO_2 emissions (IEA, 2022). As the largest carbon emitter, China announced her dual carbon goals in 2020 that “the country will peak carbon emissions before 2030 and achieve the carbon neutrality by 2060”. The attainment of these decarbonization goals, though promising, may require a pronounced decrease in fossil fuel consumption and the transformation to low-carbon energy sources, which will inevitably impose an adverse impact on China’s economic growth (Duan *et al.*, 2021; Zhang *et al.*, 2022). While all other sectors are uneasy about the decarbonization schemes, agriculture should be paid special attention to. This is because that agriculture plays an irreplaceable role in ensuring food security and improving rural livelihood of the poorest in the country, and on the other hand, faces the challenges of climate change and other market and non-market uncertainties.

While it is important for assessing the impact of dual carbon goals on the future agricultural development in China, few studies have been conducted in this field with no agreement having been reached on how decarbonization schemes may affect agricultural development (Henderson *et al.*, 2018; Olale *et al.*, 2019; Dumortier and Elobeid, 2021). For example, some international studies have found that carbon abatement policies (e.g. carbon tax) led to the decreases in agricultural productions and consumptions as well as an increase in the price level of agricultural products and worsened farmers’ income and welfare (Bourne *et al.*, 2012; Moberg *et al.*, 2021; Gren *et al.*, 2021). Whereas, other studies have found that carbon abatement policies may do harm to agricultural production by raising energy costs along with the increased prices of essential intermediate inputs such as fertilizer, seeds and chemicals (Meng, 2015; Murray and Rivers, 2015; Hasegawa *et al.*, 2016; Mardones and Lipski, 2020). In case of China, most existing studies focus only on estimating/forecasting agricultural carbon emissions and their determinants (Xu and Lin, 2017; Lin and Xu, 2018; Jin *et al.*, 2021; Dai *et al.*, 2021; Wu and Ding, 2021), while neglecting potential impacts of carbon abatement policies on future agricultural development in China. Let alone the analyses on the possible policy choices to cope with these challenges imposed by the decarbonization schemes.

This paper aims to assess economic impacts of dual carbon goals on China agricultural development toward 2030 and 2060 and to explore the role of agricultural technology progress in facilitating agricultural development while mitigating the adverse impact of attaining dual carbon goals. Rather than using the reduced formed regression models, we employ a single-country, multi-sectoral computable general equilibrium model of China (namely, CHINAGEM) to conduct the exercise. Compare with the conventional partial equilibrium analysis, the general equilibrium approach connects the concerned sectors with the rest of the economy, through input-output relations and price adjustment mechanisms, and thus allow for the feedback effects from other sectors (Meng, 2015). Thus, the computable general equilibrium (CGE) model could provide a relatively more comprehensive assessment for the aggregated impacts of dual carbon goals. Based on the model, we designed eight illustrative scenarios to simulate the potential impact of dual carbon schemes when they are implemented in different stages. Meanwhile, we also provide two policy scenarios to explore the role of improving agricultural technology progress in mitigating the adverse impact of dual carbon goals on future agricultural development in China.

Our study contributes to the existing literature in the three ways. First, we are among the first group of studies that have attempted to assess the potential impact of dual carbon goals on agricultural productions and consumptions in China by using a general equilibrium framework. This helps to provide a systematic assessment on the potential economic costs related to implementing dual carbon schemes from a quantitative perspective, through endogenizing the conflictive nature between the decarbonization policy and future agricultural development. Second, our study points out the importance of improving agricultural technology progress in mitigating the adverse impact of the decarbonization schemes while promoting agricultural development. The attainment of dual carbon goals should harmonize with the goal of agriculture development, which includes maintaining food security, improving production efficiency and diversifying outputs, and making the agriculture to be sustainable and inclusive. This goal cannot be achieved without substantial technology progress, facing to constrained land and water supply (Garnett, 2011; Chen *et al.*, 2014; Bryngelsson *et al.*, 2016; He *et al.*, 2021). Our study here provides supportive evidence for this argument, which has important policy implications.

The rest of this paper is organized as follows. Section 2 describes the opportunities and challenges faced by China's agriculture under dual carbon goals. Section 3 introduces the CGE model to be used in this exercise and scenarios. Section 4 analyses the impacts of dual carbon schemes on China's agriculture. Section 5 discusses the offsetting effects of improving agricultural technology progress. Section 6 provides a discussion on the results. Section 7 concludes this study with some policy implications.

2. China's agricultural development under decarbonization schemes toward 2060

The past four decades have witnessed a rapid growth in agricultural production in China. Between 1978 and 2020, agricultural gross output value (in real term) increased rapidly with the annually averaged growth rate of 5.4% (NBSC, 2021). Compared with the population growth rate (1.0%), the increasing agricultural production ensured China's food security largely. The productions of high-value agricultural products (such as livestock, fishing, diary and fruits) grew more rapidly than low-value products (such as grains and cotton). Underlying the rapid expansion of agricultural production, there are four main drivers including technology progress, institutional innovations, marketization reforms and increased public investment, having contributed to rapid agricultural productivity growth (Huang and Shi, 2021). For the period of 1978–2020, agricultural TFP has grown at the rate of 2.3% per year, which has accounted for around half of agricultural output growth. Benefited from the rapid agricultural growth, China's maintained a relatively high food self-sufficiency level and rapid income growth of rural residents. Per capita income of rural residents has increased from 134 yuan in 1978 to 17,131 yuan in 2020, with the annual-average growth rate of 12.3% (NBSC, 2021).

While having made great achievement, there are quite a lot of challenges to be faced by future agricultural development, including the attainment of China's dual carbon goals. Although agriculture in China is not a big emitter (compared to other industries such as electricity generation and steel making, etc.), it is still important for the industry to limit carbon emission for its sustainable development in future. The carbon dioxide emission from agriculture as a whole increased from 83.87 million tons in 1990 to 125.99 million tons in 2017 with the annually averaged growth rate of 2.4% (FAO, 2021). It only accounted for around 1.31% of China's total carbon dioxide emission in 2017 (9,336 million tons). Within agriculture, the production of horticulture products (including fruit and vegetable) is the largest emitter, which accounted for 26.4% of total agriculture carbon emissions. Apart from horticulture, agricultural services, fishery, and pork and poultry production are also important source of carbon emission, which have accounted for 19.1%, 12.8% and 10.1% of total agricultural carbon emissions, respectively. The rest of the industry, including rice, wheat and maize, adds up together to emit the remaining 15.2% of agricultural carbon emission. For the achievement of the decarbonizations scheme, agriculture also needs to curb its carbon emission so as to maintain its long-term sustainable development. China's government also required to develop the low-carbon and sustainable agriculture and reduce agricultural carbon emissions in recent official documents (MOA, 2021; NDRC, 2022), though it has specified no exact indicators.

Although the long-term goal of agricultural development in China is clear, it is not known what would be costs related to attaining the dual carbon goals in China's agriculture. In literature, imposing the decarbonization policies may generate negative impacts on agricultural production and consumption. On the supply side, the decarbonation policies will raise the costs of using fossil fuels and other fossil fuel–related intermediate inputs (i.e. fertilizers and chemicals) in agricultural sectors. Since agriculture is a low margin sector, the increased production costs will reduce agricultural output. On the demand side, the decarbonization policy will reduce consumers' disposable income by raising the consumption prices, which in turn reduce the demand for high-valued agricultural products. Meanwhile, when taking into account of inter-industry linkages, the downstream industries of agriculture may also contract, when facing the increased prices of agricultural products. In sum, the imposition of dual carbon schemes would cause damages to agricultural production and consumption through multiple impact mechanisms. Yet, how the impact would be will depend not only on the direct impact of the decarbonization policy but also on the indirect impact from the feedbacks of other sectors.

In this study, we propose to employ a CGE model with high-disaggregated agricultural sectors to quantify the impact of dual carbon goals on agricultural development. The purpose is to better understand whether dual carbon schemes will significantly affect the achievement of future agricultural development goals, which include maintaining food security, improving production efficiency and diversifying agricultural outputs, and making the agriculture to be sustainable and inclusive. These agricultural development goals appear to be harmed by dual carbon schemes, which may need more rapid technology progress to increase the efficiency of agricultural production and abate carbon emissions (Ismael *et al.*, 2018).

3. Methodology

To assess the impacts of dual carbon schemes on China's agricultural development in future, we employ a multi-sectoral CGE model, namely CHINAGEM, to quantify the general equilibrium effects in this study.

3.1 CHINAGEM model

The CHINAGEM model is developed based on the ORANI model, designed by Centre of Policy Studies, Victoria University of Australia (Horridge, 2003), and has now widely used to studying agricultural development related issues in China (Cui *et al.*, 2020, 2021). Compared with other CGE models, such as CEEPA model (Liang and Wei, 2012), SICGE model (Li *et al.*, 2014), NDRC-CGE model (Vennemo *et al.*, 2014) and CHEER model (Cao *et al.*, 2021), the CHINAGEM model has highly-disaggregated agriculture and energy sectors for China. Thus, it could simulate the heterogeneous impacts of dual carbon goals on different agriculture sectors and reveal the complicated impact mechanisms. Methodologically, the static version of the model contains six economic agents (production, investment, consumption, government, foreign and inventory) and three primary factors (labor, capital and land), which can be solved by using the multi-linear optimization software (e.g. GEMPACK software). The modules of production, investment, consumption, exports and equilibrium are briefly introduced in Appendix.

To construct a database for the CHINAGEM model, we make use of China's input–output table of the year 2017 with 149 original production sectors. It only includes five aggregated agricultural sectors, i.e. crop planting, animal husbandry, forest, fishing and agricultural services. To examine the heterogeneous impacts of dual carbon goals on agriculture sectors, we split the original sector of crop planting to eight disaggregated sectors, including rice, wheat, maize, horticulture, soybean, sugar, cotton and other crops, based on the input–output coefficients from GTAP Version 10 database (Aguiar *et al.*, 2019). Similarly, the original sector of animal husbandry is split to three disaggregated sectors, i.e. pork and poultry, beef and mutton, and diary. Finally, we obtain 14 agriculture sectors.

Then to simulate the dual carbon schemes, we also disaggregate energy commodities and add modules of the carbon emissions and carbon tax to producing sectors and households. The input–output table of China contains five aggregated energy products, that are coal, crude oil and gas, coke, electricity, and gas supply. The original sector of crude oil and gas is spit to crude oil and crude gas. The sector of electricity is split to coal-fired power, gas-fired power, nuclear power, hydropower, wind power, solar power, biomass power, and power transmission and distribution. Finally, we obtain 14 disaggregated energy sectors. Total carbon emission in China is calibrated according to IEA (2022), and the carbon emissions of agriculture are calibrated according to FAO (2021). The nesting structure of energy products for producing sectors is introduced in the Appendix.

Since the dual carbon goals are attainted in the next four decades, following Horridge (2000), we employ a standard long-run closure for the macro-economic variables. As shown in Figure 1, the real labor wage is flexible with the full employment assumption, taking the employment as an exogenous variable. The supply of capital is flexible to meet the capital demand, and the capital is allowed to flow across producing sectors. Taking the rate of return on capital as an exogenous variable, the capital stock is determined by the capital demand of producing sectors. The trade balance term is fixed proportional to national GDP, which indicates that China would maintain the balance between total export and import in long term. The household and governmental consumptions move together in opposite direction of the investment.

3.2 Scenarios for model simulation

Several studies preliminarily have assessed the evolving path of China's carbon emission under dual carbon goals (Duan *et al.*, 2021; Yu *et al.*, 2021; Zhang *et al.*, 2021, 2022; Ding, 2021). They suggested that under the path of dual carbon goals, China will peak its carbon emission at 105 to 115 million tones CO_2 during period of 2025–2028. National carbon emission should fall to below 100 million tones CO_2 in 2030, around 10% lower than the value of carbon peak. After a platform period lasting 5–10 years, the carbon emission will drop rapidly owing to the ambitious abatement policies in coming decades. China's carbon emission should be reduced to 15 to 25 million tones CO_2 by 2060, depending on the projection of carbon sequestration from CCUS (Carbon Capture, Utilization and Storage) and ecological system. Hence, to attain carbon neutrality goal, China's carbon emission should be reduced by 75–85% in 2060 relative to the value of carbon peak.

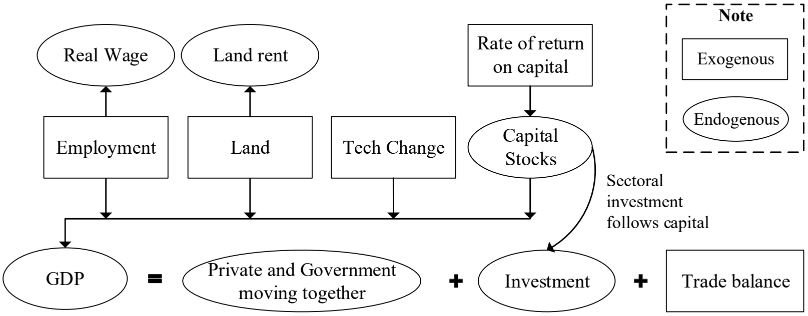


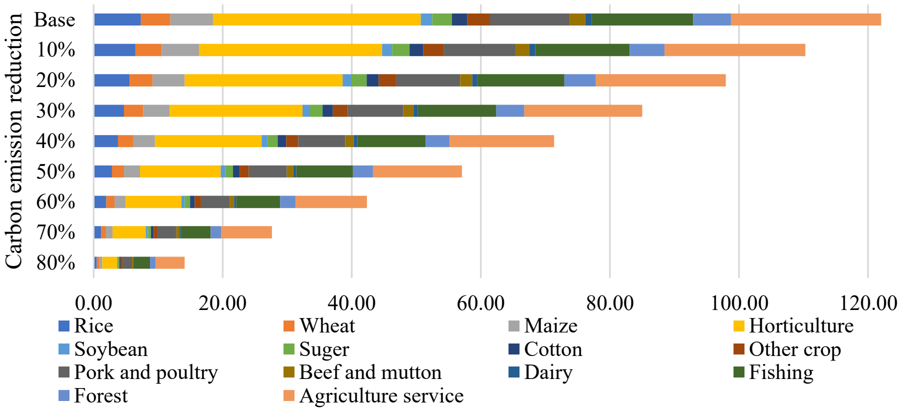
Figure 1.
The theoretical framework of CHINAGEM model

Based on these studies, we establish eight pre-assumed scenarios for dual carbon schemes. The impact on China's agriculture of attaining dual carbon goals by 2030 is simulated by the scenario of reducing national total carbon emission in the CHINAGEM model by 10% (Scenario E1). The impact of carbon neutrality goal, which will be attained by 2060, is simulated by the scenario of reducing national total carbon emission in the CHINAGEM model by 80% (Scenario E8). To illustrate the intermediate stages from the time period of peaking carbon emission to carbon neutrality, we also simulate the carbon emission reduction by 20%, 30%, 40%, 50%, 60% and 70% respectively, marked as Scenario E2–E7. In above scenarios, China's carbon emission is reduced by endogenously-determined carbon price, which raises the burning cost of fossil fuels for producing sectors and residents. The rising carbon price will force them to reduce the consumptions of energy products, turn to renewable energy sources and cut down the productions and consumptions of high carbon-intensive products, which consequently mitigate China's carbon emission. In addition, the revenue of carbon pricing is recycled to the private consumers, considering the fact that China's government will expand residential consumption persistently to stimulate economic growth and mitigate the economic damages caused by dual carbon goals.

Several previous studies have employed the static CGE models to simulate the long-term impact of climate change and carbon emission abatement (Xie *et al.*, 2018; Liu *et al.*, 2022). They simulated the future changes in exogenous variables with the static CGE models, revealing what will happen if these changes are imposed to the base data. The simulation results could be compared to the results calculated by recursive dynamic CGE models, except not considering the changes in the baseline scenario.

4. The challenges of dual carbon schemes to China's future agricultural development

In this section, we analyze the impact of dual carbon schemes on carbon emission of the industry, agricultural production, consumption, and rural income and among others in China under different scenarios of abating carbon dioxide emissions. For the illustration purpose, we split dual carbon schemes into different stages in time horizon: the carbon peak stage by 2030 (Scenario E1), carbon neutrality stage (Scenario E8) and intermediate process stages (Scenario E2-E7), and the corresponding simulation results are presented in Figures 1–5.



Source(s): CHINAGEM model

Figure 2.
Impact of dual carbon schemes on CO_2 emission in China's agriculture (million tons)

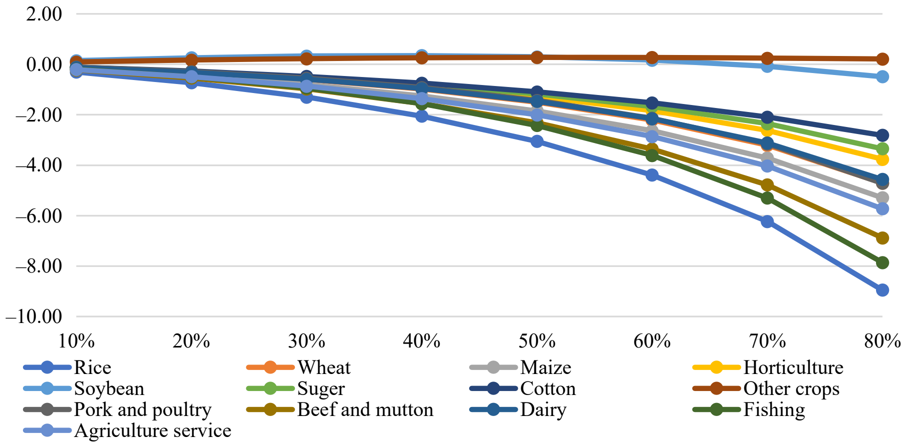


Figure 3. The impact of dual carbon schemes on China's agricultural productions (%)

Source(s): CHINAGEM model

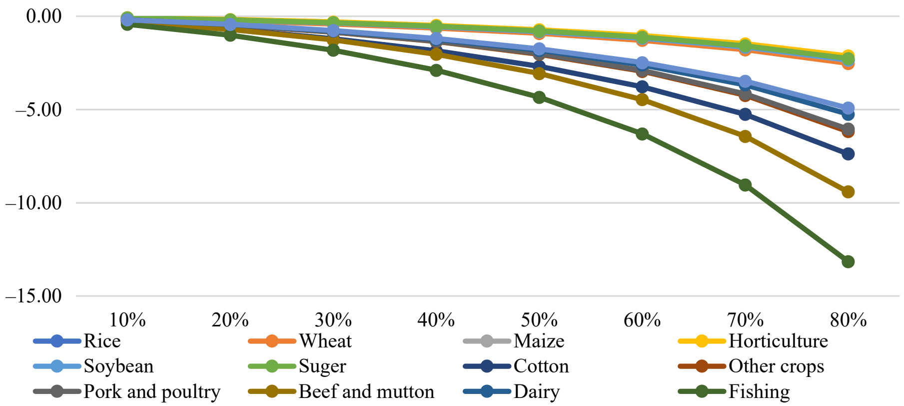
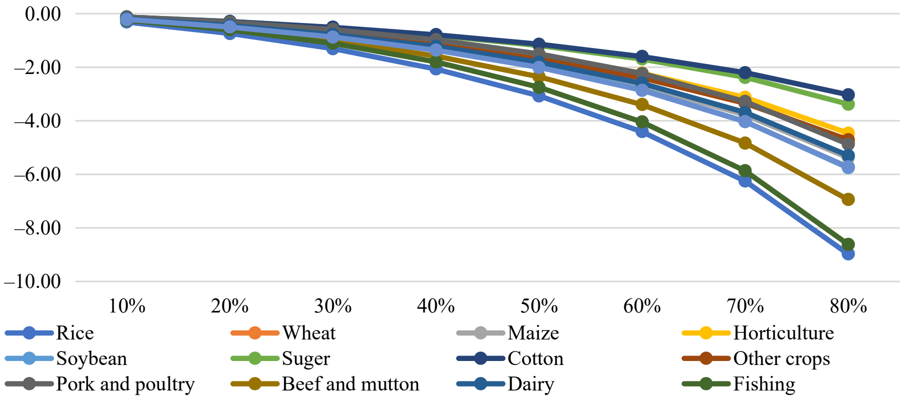


Figure 4. The impact of dual carbon schemes on China's agricultural consumption (%)

Source(s): CHINAGEM model

4.1 Carbon emission reductions in agriculture

Although carbon emissions of agriculture in China are relatively small compared to other industries such as electricity generation and steel making, etc. reducing carbon emission of agriculture is still essential for its sustainable development in future. As it is discussed in Section 2, the purpose of imposing dual carbon schemes is to reduce carbon emission in China. Thus, our first task is to assess the impact of dual carbon schemes on agricultural carbon emission. Using the pre-determined eight scenarios, we simulate carbon emission reduction for 14 agricultural sectors under different decarbonization stages. In the CHINAGEM model, dual carbon schemes reduce carbon emissions of agriculture sectors through two channels. On one hand, the rising endogenized carbon prices would raise the burning costs of fossil fuels in agriculture sectors, forcing them to substitute fossil fuels with renewable energy. On the other hand, the reduction of agricultural productions would also cut down the demand of agriculture sectors for energy products. As a result, carbon dioxide emission of agriculture



Source(s): CHINAGEM model

Figure 5. The impact of dual carbon schemes on total supply consumption of agricultural products in China (%)

sectors would be reduced by the decarbonization schemes. The simulation results are presented in Figure 1.

Using 2017 as the base year when total carbon dioxide emission from agriculture as a whole is 122.03 million tons, our simulation shows that for the achievement of dual carbon goals, the carbon emission of agriculture in China would reduce by around 20 million tons toward 2030 and by around 100 million toward 2060 respectively. This reduction is allocated across sectors. The horticulture, agricultural services and fishery industry will become the most important sources for reducing carbon emission, followed by pork and poultry and grains. Meanwhile, as more carbon emission is reduced to meet the carbon neutrality goal over time, the more difficultly the decarbonization schemes will be implemented.

4.2 Impact on agricultural productions and consumptions

As a trade-off of dual carbon schemes, agricultural productions and consumptions will definitely be influenced. Yet, how this impact would be is still not known. To answer this question, we simulate the impact of imposing dual carbon schemes on agricultural productions at the aggregate level and by-products. As shown in Figure 3, the projected output for most agricultural products tend to decrease throughout the whole dual carbon period, and the fitting curves that reflects the percentage changes of agricultural production bend backward more quickly when the abatement of carbon emissions increases [1]. This implies that imposing dual carbon schemes will generate more increasing adverse impact on agricultural production as more strict carbon emission reduction policies are imposed over time. In particular, comparing between Scenario E1 (corresponding to total carbon emission is reduced by 10% for attaining dual carbon goals by 2030) and Scenario 8 (corresponding to total carbon emission is reduced by 80% for the carbon neutrality goal by 2060), total loss in agricultural output increased from 0.14% to 4.90%, which increased by more than ten folds. This result suggests that the losses in agricultural productions are more likely to appear in the second stage of dual carbon schemes, attaining carbon neutrality goal.

Apart from its aggregate negative impact, dual carbon schemes may also generate asymmetric impacts for different products. Specifically, under Scenario 8, rice production will fall by 8.94%, ranking as the top loser, followed by some high-value products, such as fishery (7.86%) and beef and mutton (6.88%). The production of other grains such as wheat and maize (falling by around 5%), and some high-value products such as pork and poultry (4.71%), and dairy (4.56%) will also suffer substantially from dual carbon schemes. Yet, in comparison, the adverse impact on other agricultural products, such as horticulture, sugar, soybean and other crops, are relatively smaller. This implies that the attainment of dual carbon goals will do more harm to the production of grains and some high-value products. A possible explanation on the above phenomenon is that the productions of grains and these high-value products depend more on carbon-intensive inputs than other agricultural products (Zhou *et al.*, 2022; Zhu *et al.*, 2022).

Next, we simulate the impact of imposing dual carbon schemes on agricultural consumptions. Comparing different scenarios (Figure 3), we show that the attainment of dual carbon goals will also do harm to the aggregated agricultural consumption. As is shown in Figure 4, the aggregate consumption of agricultural products will fall by 0.19 and 5.84% under Scenario E1 and Scenario E8 respectively. Moreover, the adverse impact on the consumption of high-value agricultural products is also more serious than that of other products. For example, under Scenario E8, the consumption of fishery products will fall by 13.15%, followed by beef and mutton (9.41%), pork and poultry (6.04%), and dairy (5.25%). In comparison, the consumption of horticulture, soybean and sugar will fall by less than 3%. It is worth noted, as an exception, the adverse impact on grain consumptions is much smaller than that on their productions. This is partly because that these agricultural products have relatively lower income elasticities (Cui and Huang, 2017). Thus the decline in households' income caused by dual carbon schemes will be likely to generate less impact on grain consumptions than on high-value products.

Combining the impact of imposing dual carbon schemes on agricultural productions and consumptions, we show that the decarbonization will deteriorate the capacity of ensuring domestic supply of agricultural products or the food self-sufficient ratio. Imposing dual carbon schemes will lower the market prices of agricultural products by discouraging agricultural consumption. While such a negative impact on food price will raise the relative competitiveness of China agricultural products in international market (Figures A3 and A4), it will further reduce the supply of agricultural products if there is no other policy intervention. According to our simulation, total supply of agricultural products will fall by 0.18 and 5.56% for the "carbon peak" period (Scenario E1) and for the "carbon neutrality" period (Scenario E8), respectively. Again, the supply of grains and high-value agricultural products will suffer more losses than other agricultural products. The above results suggest that imposing dual carbon schemes will not only reduce agricultural productions and consumptions in total amount but also worsening the food self-sufficiency level, in particular in the second stage of dual carbon schemes.

Finally, it is to be mentioned, the above adverse impact of imposing dual carbon schemes on agricultural productions, consumptions and food self-sufficiency contains many different channels. Under our model simulation (which could capture both the direct and indirect impact of dual carbon schemes on agricultural productions), there are at least three channels needed to be highlighted, which include: (1) imposing dual carbon schemes raise the utilization costs of fossil fuels and energy-intensive inputs (like chemical fertilizer, pesticide and plastic mulch), and thus reduce agricultural production; (2) the rising utilization costs of fossil fuel deteriorate the production of down-stream industries through the foreword linkage, reducing households' disposable income and thus their demand for agricultural products; (3) the rising prices of other commodities also erode the budget for food consumption, which in turn indirectly lower agricultural production, in particular for high-value products.

4.3 Macro-economic impacts of dual carbon schemes

Imposing dual carbon schemes will not only affect agricultural productions and consumptions but also reshape the economic development pattern in China through affecting labor income, investment and trade. Table 1 shows the economic impact of dual carbon schemes based on the eight pre-assumed scenarios. Several findings are discussed as below.

First, imposing dual carbon schemes will generate the negative impact on economic development (in terms of real GDP), but the negative impact will be incremental gradually over time and its magnitude is not large. As shown in Table 1, the loss of GDP is projected to be 0.049% under Scenario E1, representing the economic cost of attaining dual carbon goals by 2030). The loss of GDP is projected to be 2.122% under Scenario E8, representing the economic cost of attaining carbon neutrality goal by 2060. Dual carbon schemes will accelerate the development of renewable energy and related industries and bring certain economic benefits, partially offsetting the economic losses of fossil fuel and high carbon-intensity industries. We also compared the impacts of the carbon neutrality goal on China's GDP growth between this study and previous studies that utilized the recursive dynamic CGE models (such as Duan *et al.*, 2021; Yu *et al.*, 2021; Zhang *et al.*, 2021; Ding, 2021; Zhang *et al.*, 2022). These studies found that the economic cost of dual carbon goals is not significant, and the attainment of the carbon neutrality goal will reduce China's GDP in 2020–2060 by a range of 1–5%. The simulation result of this study is fundamentally consistent with these studies. In-between the two stages, total economic losses are gradually accumulated. This implies that the impact of dual carbon schemes on China's future economic growth is negative but the magnitude of the adverse impact is not substantial.

Second, along with the implementation of dual carbon schemes, total consumption and total export will decrease, but total investment will increase. On one hand, the decarbonization will not only raise the prices of consumption goods but also reduce the disposable income of households. Thus, it will reduce household consumption. According to our simulation, even if the carbon tax revenue is transferred back to residents, total consumption is still projected to drop by 0.489 and 13.004% under all scenarios. On the other hand, the decarbonization will increase the demand for clean energy, which will drive up investment in renewable energy sectors and the related sectors. According our simulation, total investment will increase ranging from 0.544% to 11.219% under different scenarios, although investment in fossil fuel sectors will decline. Meanwhile, total export will decline moderately in response to the rising costs of producing sectors.

Third, imposing dual carbon schemes will impose the negative impact on the labor wage but raise the capital rent. On one hand, the carbonization will raise the costs of sectors by increasing the price of intermediate inputs, and thus reduce the marginal return to (and thus the demand for) labor. Under different scenarios, average wage will fall by 0.711%–10.507%. Considering that rural labor largely relies on labor income, imposing dual carbon schemes could negatively affect rural income growth (and thus threaten the further poverty reduction in rural areas). On the other hand, an increasing demand for investment in renewable energy

	10%	20%	30%	40%	50%	60%	70%	80%
GDP	−0.049	−0.131	−0.252	−0.423	−0.659	−0.985	−1.446	−2.122
Consumption	−0.489	−1.140	−1.996	−3.115	−4.577	−6.512	−9.152	−13.004
Investment	0.544	1.218	2.056	3.104	4.417	6.078	8.233	11.219
Export	−0.135	−0.301	−0.503	−0.748	−1.047	−1.417	−1.882	−2.461
Import	−0.013	−0.028	−0.043	−0.053	−0.054	−0.037	0.027	0.224
Labor quantity	−0.847	−1.868	−3.107	−4.633	−6.558	−9.079	−12.575	−17.895
Labor wage	–	–	–	–	–	–	–	–
Capital quantity	−0.711	−1.512	−2.421	−3.466	−4.689	−6.163	−8.017	−10.507
Capital rent	0.055	0.122	0.206	0.313	0.454	0.640	0.900	1.303

Source(s): CHINAGEM model

Table 1. The impacts of dual carbon schemes on China's macro-economy (%)

sectors (which are capital-intensive industries) will drive up the demand for capital. This in turn will raise the capital rent. In our simulation, capital rent will increase by 0.020%–0.434% under different scenarios.

5. Agricultural technology progress and its offsetting effects: path toward sustainable development

How to mitigate the negative impact of dual carbon schemes? As is well documented in the literature, the answer to this question may lie in promoting agricultural technology progress. Yet, to what extent we may need agricultural technology progress in future to meet the demand remains to be a question. In this section, we develop two scenarios to simulate the impact of agricultural technology progress and its role in offsetting the negative impact of dual carbon schemes. Based on the scenario E8 for the carbon neutrality goal, the scenario A1 assumes that the TFP for all sub-sectors in agriculture will grow at 0.5% point per year during 2017–2060. For the static CGE model, this shock is equivalent to the TFP progress of all sub-sectors by 22.08% relative to the base year. The other scenario (Scenario A2) is designed to consider the asymmetric impact of the decarbonization scheme on different sub-sectors in agriculture. Specifically, we assume that the TFP will grow at the rate of 1% per year for grains and high-value products and 0.5% per year for other sub-sectors during 2017–2060. For static CGE model, these shocks are equivalent to the TFP progress by 53.40% for grains and high-value products and 23.92% for other sub-sectors, relative to the base year. During the period of 1978–2020, agricultural TFP has grown at the rate of 2.3% a year, which has accounted for around half of agricultural output growth. Considering this historical trend, agricultural TFP by 1% per year could be easily realized, if China's government maintains supportive policies to agriculture. The simulation results are reported in Table 2.

Under the scenario A1, grains and high-value products still suffer production losses, but the adverse impact will be substantially mitigated. As is shown in Table 2, the productions of rice, wheat and maize will decline by 5.41%, 0.65% and 2.02%, respectively, much lower than those under the Scenario E8. At the same time, the losses in production of high-value products are reduced by over 2 percentage points. As for the production of other agricultural products, most of them will also gain benefits from the TFP progress. Therefore, the TFP progress will substantially compensate for the negative impact caused by imposing dual carbon schemes.

Table 2. The effect of TFP progress in agriculture on China's agricultural productions and consumptions (%)

	Production		Residential consumption	
	A1	A2	A1	A2
Rice	−5.41	−1.67	−1.52	−0.09
Wheat	−0.65	3.05	−1.94	−0.96
Maize	−2.02	0.31	−1.55	−0.21
Horticulture	1.78	2.74	−0.99	−1.07
Soybean	24.58	26.75	−1.88	−1.97
Sugar	−1.32	−1.06	−1.32	−1.40
Cotton	7.10	8.28	−6.97	−7.27
Other crops	23.26	25.55	−3.09	−3.29
Pork and poultry	−2.42	0.29	−3.22	0.68
Beef and mutton	−4.56	−2.64	−4.21	4.19
Dairy	−2.17	0.29	−4.84	−4.19
Fishing	1.44	2.11	−7.06	−7.30
Agriculture service	−1.74	−0.89	−3.77	−3.82

Source(s): CHINAGEM model

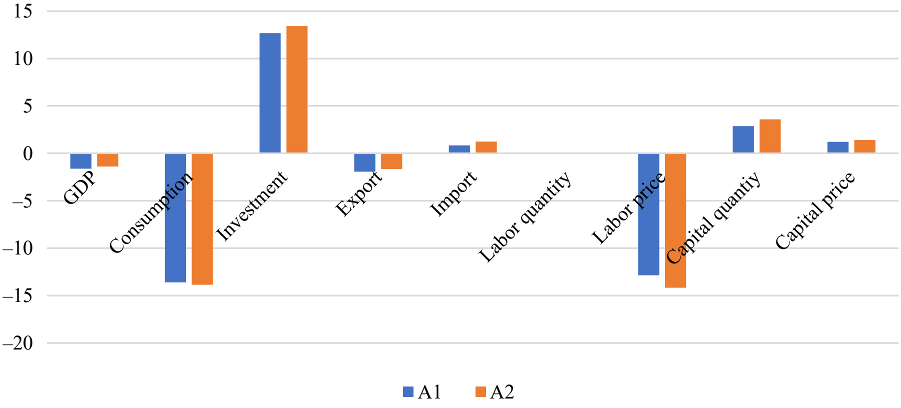
Under the scenario A2, additional technology progress for high-value products can further reduce the production losses of high-value products. Compared between the simulation results obtained from the two scenarios, the production losses of rice and beef and mutton are further reduced down to 1.67 and 2.64% respectively, much lower than those under the first scenario. At the same time, the productions of wheat, maize, pork and poultry and diary will increase by 3.05%, 0.31%, 0.29% and 0.29%, respectively. In other words, the asymmetric growth in agricultural productivity for high-value products will fully cover the production losses of grains and high-value products incurred by imposing dual carbon schemes. Meanwhile, the output of other agricultural products would also increase, compared with the first scenario, partly due to the benefit obtained from the increased household income.

Technology progress in agriculture can also mitigate the adverse impact of dual carbon schemes on agricultural consumptions. Under both scenarios, agricultural consumption continues to decline but the magnitude of the adverse impact is substantially reduced. However, it is to be noted: since agriculture consumption is mainly determined by the changes in residents' disposable income and the commodity prices, agricultural technology progress may generate fewer offsetting effects on agricultural consumption than production.

Finally, agricultural technology progress will also reduce loss in economic growth at the national level caused by dual carbon schemes. The national GDP will fall by 1.63% under the scenario A1 and 1.38% under the scenario A2. Both the impacts are substantially lower than the benchmark scenario, namely, scenario E8 (by −2.12%). In addition, agricultural technology progress will also raise demand for investment in agriculture. As a consequence, total investment will increase by 12.69 and 13.41% under the two scenarios. Simultaneously, it will also lift the prices of capital and labor and raise the commodity prices, deteriorating total consumption. Compared with the benchmark scenario (13.00%), the consumption will decline by a larger amount by −13.58% and −13.85% respectively (see Figure 6).

6. Discussion

Future agricultural development in China faces to a lot of challenges. First, the rapid growth of agricultural output has been achieved at expense of excessive resource depletion, environmental pollution and land degradation (Zhang *et al.*, 2013; Lu *et al.*, 2015). Second, rapidly rising prices of primary factors (including labor and land) due to ongoing urbanization and industrialization has incurred additional production costs for agriculture



Source(s): CHINAGEM model

Figure 6.
The effect of TFP progress in agriculture on China's macroeconomy (%)

and deteriorated the competitiveness in the global market (Wang *et al.*, 2017; Huang *et al.*, 2017). Third, food self-sufficiency rate continuously declined, partly caused by increasing food demand due to rapid income growth. As an example, grain self-sufficiency rate has fallen from 97% in 2001 to 83% in 2020. Fourth, the small-scale farming practice continues to dominate agricultural production, which increasingly hindered further improvement of labor productivity and agricultural modernization. All the above four challenges will hold back the goal of achieving sustainable agriculture development by 2060, which includes: (1) maintaining food security, (2) improving production efficiency and output diversification (3) making the agriculture to be sustainable and inclusive.

To cope with the above challenges, Chinese government have made a large number of efforts to facilitate agricultural development for the past decade. These efforts include (1) facilitating institutional reforms to improve land tenure and the rental market so that land can be consolidated; (2) substantially enhancing scientific and technological innovation capacity (the *cang-liang-yu-ji*) to boost agricultural productivity in the long run; (3) increasing investment in land and water infrastructure (the *cang-liang-yu-di*) to improve agricultural production capacity in the long run. With these efforts in place, it is believed that China will gradually achieve the transformation of agriculture toward a sustainable development path.

As is projected by a recent study of China Center for Agricultural Policy, Peking University (Huang *et al.*, 2022), China's agricultural development by 2050 will preserve three features. First, as the demand for food grains (i.e. rice and wheat) will decline persistently, China could achieve the almost self-sufficiency of rice and wheat in 2050. Second, the demand for feed grains (e.g. maize and soybean) will largely exceed the domestic production, leading to the increasing imports. Third, if the import restrictions of feed grains are released, pork, poultry, egg and fishing products could maintain high self-sufficiency rates over 95% in 2050. However, as residential demands for beef, mutton and diary will increase more rapidly than the productions, the self-sufficiency rates of these products are projected to fall to below 80%.

Considering the goal of sustainable agriculture development, the strategic priorities for China's future agricultural development under dual carbon schemes should include: (1) improving agricultural productivity, through increasing investment in technology and infrastructure; (2) maximizing the comparative advantages of agricultural products and enhancing the development of advantageous agriculture and agriculture with large demand potentials based on ensuring food security; (3) promoting green, high-efficiency and high-value agriculture, by improving the market environment by rectifying market failures to support the development of high-value agriculture; (4) guaranteeing sustainable utilization of agricultural water and soil resources and maintaining sustainable agricultural production; and (5) guiding modern agricultural development through institutional, policy and investment reforms.

This study is not immune from several limitations and outlines some directions for future studies. First, this study employs a static CGE model to simulate the impact of attaining China's dual carbon goals on its future agricultural development. Although we have utilized a long-term closure to consider the fact that the dual carbon goals will be realized in coming four decades, the static CGE model could not capture the future changes in the structures of residential consumptions and agricultural productions without the decarbonization policies. However, this study still could provide important insights on the heterogeneous impacts of China's dual carbon goals on its future agricultural development and find the more significant decreases in outputs and consumptions of high-value agricultural products. The vital role of agriculture technology progress is also illustrated in prompting agricultural development and abating carbon emissions. Furthermore, the simulation results for macro-economic variables are fundamentally consistent with the previous studies that employed the recursive dynamic CGE models. For the future studies, we should establish a dynamic CGE model with highly-disaggregated agricultural sectors and calibrate a baseline scenario toward 2060 to explore the impacts of dual carbon goals further.

Second, this study only accounted carbon dioxide emissions of producing sectors and residents. China's agriculture has a great amount of non-CO_2 emissions, including methane and nitrogen oxide, and most of them are emitted from ruminants. There is the great uncertainty whether China's government will incorporate non-CO_2 emissions into the coverage of its dual carbon goals. The mitigation of non-CO_2 emissions would raise the reductions of agricultural production and consumption further, which should be analyzed further in future studies. Third, this study examined the effectiveness of agricultural technology progress in promoting agricultural development and abating carbon emissions. Several studies have discussed the benefits of the transition of food consumption pattern in promoting agricultural development and abating carbon emissions, which may lower down the costs of carbon emission mitigation. Future studies concerning on the agricultural development should consider the policies from the supply and demand side simultaneously.

7. Conclusions and policy implications

China maintained a rapid growth in agricultural production for the past four decades, benefited from ongoing technology progress, institutional innovations, marketization reforms and increased public investment. However, moving toward future, agricultural production needs to undertake a substantial reduction in carbon emission to meet China's dual carbon goals, while maintaining domestic food security. Yet, little is known on how this goal could be achieved and what will be the economic cost. This paper employs a multi-sectoral CGE model for China, CHINAGEM model, to examine the impact of imposing dual carbon schemes on agricultural development in China. To replicate different stages for dual carbon goals, we developed eight illustrative scenarios for carbon emission reduction and designed two illustrative scenarios to assess the role of agricultural technology progress in mitigate the adverse impact of dual carbon schemes.

We show that imposing dual carbon schemes will generate a large adverse impact on agricultural production and consumption, as well as deteriorate the domestic food security. On average, agricultural productions will fall by 0.49–8.94% when moving from the carbon peak stage by 2030 to the carbon neutrality stage by 2060. Moreover, agricultural production structure will also be reversed, since dual carbon schemes will generate more negative impact on the productions of grains and high-value products than other agricultural products. To mitigate the adverse impact of dual carbon schemes, the most efficient way is to promoting agricultural technology progress. According to our simulation, the losses in agricultural production will be significantly lower if agricultural productivity could grow proportionally across sub-sectors in agriculture at the 0.5% per year in addition. All adverse impact will be offset if agricultural productivity could grow faster for grains and high-value products (say, by annual 1%).

Based on our findings, several policy implications can be generated. First, to mitigate the adverse impact of dual carbon schemes, agricultural productivity should be enhanced substantially, as our study suggests that agricultural technology progress could effectively offset the adverse impact of dual carbon schemes on agricultural productions and consumptions. This could be made either through the continuous institution reforms, supporting policies, and increasing public investment, or through the technology progress and diffusion. Second, the adoption of green agricultural production technologies should be encouraged by the government to reduce the green-house gas emissions of agriculture. These technologies include conservation tillage practice, soil testing and fertilizer recommendations technology, deep ploughing, and water-saving irrigation technology as well as advanced feeding practices and manure management. The adaptation of these technologies will achieve double-dividend effects, by reducing the resource consumption and green-house gas emissions and increasing agricultural production. Third, the strategic investment in technology progress with focus on grains and high-value products will bring more benefits, as dual carbon schemes will impose more serious impacts on grains and high-value products than other agricultural products. We also show that if agricultural productivity could grow faster for grains and high-value products, the adverse impact will be almost offset. Fourth, as agricultural technology progress is unable to fully offset the adverse impact on food consumption, government should issue some subsidy to stabilize agricultural consumption, particularly for the low-income households.

Note

1. We conduct a sensitivity analysis through increasing/decreasing the substitution elasticity between labor, land and capital-energy composite input (σ_{FAC}) and the substitution elasticity between capital and energy input (σ_{KE}) by 50%. As shown by Figure A6, the value of key substitution elasticities in the CHINAGEM model would not significantly change the results, confirming the robustness of our simulation results.

References

Aguiar, A., Chepeliev, M., Corong, E., McDougall, R. and van der Mensbrugghe, D. (2019), "The GTAP data base: version 10", *Journal of Global Economic Analysis*, Vol. 4 No. 1, pp. 1-27.

Bourne, M., Childs, J., Philippidis, G. and Feijoo, M. (2012), "Controlling greenhouse gas emissions in Spain: what are the costs for agricultural sectors?", *Spanish Journal of Agricultural Research*, Vol. 10, pp. 567-582.

Bryngelsson, D., Wirsenius, S., Hedenus, F. and Sonesson, U. (2016), "How can the EU climate targets be met? A combined analysis of technological and demand-side changes in food and agriculture", *Food Policy*, Vol. 59, pp. 152-164.

Cao, J., Dai, H., Li, S., Guo, C., Ho, M., Cai, W., He, J., Huang, H., Li, J., Liu, Y. and Qian, H. (2021), "The general equilibrium impacts of carbon tax policy in China: a multi-model comparison", *Energy Economics*, Vol. 99, 105284.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W. and Zhang, F. (2014), "Producing more grain with lower environmental costs", *Nature*, Vol. 514, pp. 486-489.

Cui, Q. and Huang, J. (2017), "Food expenditure responses to income/expenditure shocks in rural China", *China Agricultural Economic Review*, Vol. 9 No. 1, pp. 2-13.

Cui, Q., Liu, Y., Ali, T., Gao, J. and Chen, H. (2020), "Economic and climate impacts of reducing China's renewable electricity curtailment: a comparison between CGE models with alternative nesting structures of electricity", *Energy Economics*, Vol. 91, p. 104892.

Cui, Q., He, L., Liu, Y., Zheng, Y., Wei, W., Yang, B. and Zhou, M. (2021), "The impacts of COVID-19 pandemic on China's transport sectors based on the CGE model coupled with a decomposition analysis approach", *Transport Policy*, Vol. 2021, pp. 103-115.

Dai, X., Sun, Z. and Muller, D. (2021), "Driving factors of direct greenhouse gas emissions from China's pig industry from 1976 to 2016", *Journal of Integrative Agriculture*, Vol. 20 No. 1, pp. 319-329.

Ding, Z. (2021), "Research on China's carbon neutralization framework roadmap", *China Industry and Information Technology*, Vol. 8, pp. 54-61, [In Chinese].

Duan, H., Zhou, S., Jiang, K., Bertram, C., Harmsen, M., Kriegler, E., Vuuren, D., Wang, S., Fujimori, S., Tavoni, M., Ming, X., Keramidas, K., Lyer, G. and Edmonds, J. (2021), "Assessing China's efforts to pursue the 1.5°C warming limit", *Science*, Vol. 372, pp. 378-385.

Dumortier, J. and Elobeid, A. (2021), "Effects of a carbon tax in the United States on agricultural markets and carbon emissions from land-use change", *Land Use Policy*, Vol. 103 No. 8, 105320.

FAO (Food and Agriculture Organization of the United Nations) (2021), *FAO Statistics*, Rome, available at: http://faostat.fao.org/.

Garnett, T. (2011), "Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)?", *Food Policy*, Vol. 36 supp-S1, pp. 23-32.

Gren, I.M., Hglind, L. and Jansson, T. (2021), "Refunding of a climate tax on food consumption in Sweden", *Food Policy*, 102021.

Hasegawa, T., Fujimori, S. and Matsuoka, Y. (2016), "Introducing detailed land-based mitigation measures into a computable general equilibrium model", *Journal of Cleaner Production*, Vol. 114, pp. 233-242.

He, P., Zhang, J. and Li, W. (2021), "The role of agricultural green production technologies in improving low-carbon efficiency in China: necessary but not effective", *Journal of Environmental Management*, Vol. 293, 112837.

Henderson, B., Golub, A., Pambudi, D., Hertel, T., Godde, C., Herrero, M., Cacho, O. and Gerber, P. (2018), "The power and pain of market-based carbon policies: a global application to greenhouse gases from ruminant livestock production", *Mitigation and Adaptation Strategies for Global Change*, Vol. 23 No. 3, pp. 349-369.

Horridge (2000), "ORANI-G: a general equilibrium model of the Australian economy", Monash University, CoPS/IMPACT Working Paper Number OP-93, Centre of Policy Studies, Australia.

Horridge, M. (2003), *ORANI-G: A Generic Single-Country Computable General Equilibrium Model*, Monash University, Centre of Policy Studies and Impact Project.

Huang, J. and Shi, P. (2021), "Regional rural and structural transformations and farmer's income in the past four decades in China", *China Agricultural Economic Review*, Vol. 13 No. 2, pp. 278-301.

Huang, J., Wei, W., Cui, Q. and Xie, W. (2017), "The prospects for China's food security and imports: will China starve the world via imports?", *Journal of Integrative Agriculture*, Vol. 16 No. 12, pp. 2933-2944.

Huang, J.K., Xie, W., Sheng, Y., Wang, X.B., Wang, J.X., Liu, C.F. and Hou, L.L. (2022). "Trends of global agriculture and prospects of China's agriculture toward 2050", *Strategic Study of CAE*, Vol. 24 No. 1, pp. 29-37 (In Chinese).

IEA (International Energy Agency) (2022), available at: https://www.iea.org/data-and-statistics.

Ismael, M., Srouji, F. and Boutabba, M.A. (2018), "Agricultural technologies and carbon emissions: evidence from Jordanian economy", *Environmental Science and Pollution Research*, Vol. 25, pp. 10867-10877.

Jin, S., Lin, Y. and Niu, K. (2021), "Driving green transformation of agriculture with low carbon: characteristics of agricultural carbon emissions and its emission reduction path in China", *Reform*, Vol. 327 No. 5, pp. 29-37, [In Chinese].

Li, J.F., Wang, X., Zhang, Y.X. and Kou, Q. (2014), "The economic impact of carbon pricing with regulated electricity prices in China-An application of a computable general equilibrium approach", *Energy Policy*, Vol. 75, pp. 46-56.

Liang, Q.M. and Wei, Y.M. (2012), "Distributional impacts of taxing carbon in China: results from the CEEPA model", *Applied Energy*, Vol. 92, pp. 545-551.

Lin, B. and Xu, B. (2018), "Factors affecting CO2 emissions in China's agriculture sector: a quantile regression", *Renewable and Sustainable Energy Reviews*, Vol. 94 No. 10, pp. 15-27.

Liu, Yu, Du, M., Qi, C., Lin, J., Liu, Y., Liu, Q., Tong, D., Feng, K. and Hubacek, K. (2022), "Contrasting suitability and ambition in regional carbon mitigation", *Nature Communications*, Vol. 13, 4077.

Lu, Y.L., Jenkins, A., Ferrier, R.C., Bailey, M., Gordon, I.J., Song, S., Huang, J.K., Jia, S.F., Zhang, F.S., Liu, X.J., Feng, Z.Z. and Zhang, B. (2015), "Addressing China's grand challenge of achieving food security while ensuring environmental sustainability", *Science Advances*, Vol. 1, e1400039.

Mardones, C. and Lipski, M. (2020), “A carbon tax on agriculture? A CGE analysis for Chile”, *Economic Systems Research*, Vol. 32 No. 2, pp. 262-277.

Meng, S. (2015), “Is the agricultural industry spared from the influence of the Australian carbon tax?”, *Agricultural Economics*, Vol. 46, pp. 1-13.

MOA (Ministry of Agriculture and Rural Affairs) (2021), “National agricultural green development plan in the 14th five year plan”, available at: http://www.gov.cn/zhengce/zhengceku/2021-09/07/content_5635867.htm.

Moberg, E., Säll, S., Hansson, P. and Röös, E. (2021), “Taxing food consumption to reduce environmental impacts – identification of synergies and goal conflicts”, *Food Policy*, Vol. 101 No. 2021, p. 102090.

Murray, B. and Rivers, N. (2015), “British Columbia’s revenue-neutral carbon tax: a review of the latest ‘grand experiment’ in environmental policy”, *Energy Policy*, Vol. 86, pp. 674-683.

NBSC (National Bureau of Statistics of China) (2021), *China Statistical Yearbook*, China Statistics Press, Beijing, [In Chinese].

NDRC (National Development and Reform Commission) (2022), Comprehensive work plan for energy conservation and emission reduction in the 14th five year plan.

Olale, E., Yiridoe, E.K., Ochuodho, T.O. and Lantz, V. (2019), “The effect of carbon tax on farm income: evidence from a Canadian province”, *Environmental and Resource Economics*, Vol. 74 No. 2, pp. 605-623.

Vennemo, H., He, J. and Li, S. (2014), “Macroeconomic impacts of carbon capture and storage in China”, *Environmental and Resource Economics*, Vol. 59 No. 3, pp. 455-477.

Wang, J., Li, Y., Huang, J., Yan, T. and Sun, T. (2017), “Growing water scarcity, food security and government responses in China”, *Global Food Security*, Vol. 14, pp. 9-17.

Wu, S. and Ding, S. (2021), “Efficiency improvement, structural change, and energy intensity reduction: evidence from Chinese agricultural sector”, *Energy Economics*, Vol. 99, 105313.

Xie, W., Xiong, W., Pan, J., Ali, T., Qi, C., Guan, D., Meng, J., Mueller, N.D., Lin, E. and Davis, S.J. (2018), “Decreases in global beer supply due to extreme drought and heat”, *Nature Plants*, Vol. 4 No. 11, pp. 964-973.

Xu, B. and Lin, B. (2017), “Factors affecting CO2 emissions in China’s agriculture sector: evidence from geographically weighted regression model”, *Energy Policy*, Vol. 104, pp. 404-414.

Yu, B., Zhao, G., An, R., Chen, J., Tan, J. and Li, X. (2021), “Research on China’s CO2 emission pathway under carbon neutral target”, *Journal of Beijing Institute of Technology (Social Sciences Edition)*, Vol. 23 No. 2, pp. 17-24, [In Chinese].

Zhang, F.S., Chen, X.P. and Vitousek (2013), “Chinese agriculture: an experiment for the world”, *Nature*, Vol. 497, pp. 33-35.

Zhang, S., An, K., Li, J., Weng, Y., Zhang, S., Wang, S., Cai, W., Wang, C. and Gong, P. (2021), “Incorporating health co-benefits into technology pathways to achieve China’s 2060 carbon neutrality goal: a modelling study”, *Lancet Planet Health*, Vol. 5 No. 11, pp. 808-817.

Zhang, X., Huang, X., Zhang, D., Geng, Y., Tian, L., Fan, Y. and Chen, W. (2022), “Research on the pathway and policies for China’s energy and economy transformation toward carbon neutrality”, *Management World*, Vol. 38 No. 1, pp. 35-66, [In Chinese].

Zhou, Y., Yan, X.Y., Gong, S.L., Li, C.W., Zhu, R., Zhu, B., Liu, Z.Y., Wang, X.L. and Cao, P. (2022), “Changes in paddy cropping system enhanced economic profit and ecological sustainability in central China”, *Journal of Integrative Agriculture*, Vol. 21 No. 2, pp. 566-577.

Zhu, Z.P., Zhang, X.M., Dong, H.M., Wang, S.T., Reis, S., Li, Y. and Gu, B.J. (2022), “Integrated livestock sector nitrogen pollution abatement measures could generate net benefits for human and ecosystem health in China”, *Nature Food*, Vol. 3, pp. 161-168.

Appendix

A. The introduction of the CHINAGEM model

(a) Production

The producing sectors determine their utilization of intermediate inputs and primary factors according to the cost minimization, and the allocation of outputs in the domestic and international market according to the profit maximization. A nesting structure of constant elasticity of substitution (CES) functions describes the input structure used by each producing sector (Figures A1–A3). On the top level of Figure A1, all the intermediate inputs (excluding energy products), primary factors (including energy composited input) and other input are composited with a Leontief function as shown in Eq. A1.

$$X1TOT(i) = \frac{1}{G1(i)} * MIN\left[All, c, COM : \frac{X1\_S(c,i)}{A1\_S(c,i)}, \frac{FAC(i)}{A1\_F(i)}, \frac{OCT(i)}{A1\_O(i)}\right], \quad c = \{1, \ldots, N\} \tag{A1}$$

COM is the set for intermediate inputs. The i, c, and s are index industry, commodity, and source, respectively. $X1TOT(i)$ represents the i-th sector's output. $X1\_S(c,i)$ is the intermediate input c used by sector i, which comprises the domestic and import sources with the CES function, as shown in Eq. A2. SRC is the set for the sources of intermediate inputs, including domestically-produced (*dom*) and imported (*imp*). $FAC(i)$ represents the primary factor used by the sector c, which comprises labor, land and capital-energy composited input with the substitution elasticity of 0.5, as shown in Eq. A3. $OCT(i)$ represents other costs. $G1(i)$ is the parameter for neutral technological progress. $A1\_S(c,i)$ is the technology parameter augmented to intermediate inputs and primary factors.

$$X1\_S(c,i) = CES\left[All, s, SRC : \frac{X1(c,s,i)}{A1(c,s,i)}\right], \quad s = \{dom,\ imp\} \tag{A2}$$

$$FAC(i) = CES\left[\frac{X1LAB(i)}{A1LAB(i)}, \frac{X1CAP(i)}{A1CAP(i)}, \frac{X1LND(i)}{A1LND(i)}\right] \tag{A3}$$

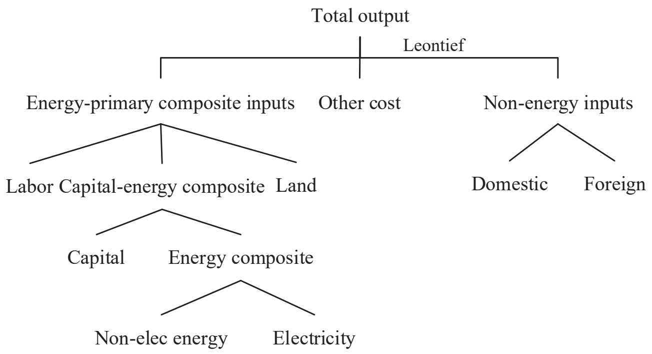


Figure A1.
The nesting structure of the producing input used by sectors

On the lower level, capital is regarded as a partial substitution of energy product, as the firms could utilize high-efficient machineries to save energy input when facing the increasing energy price. The substitution elasticity between capital and energy product is set to 0.5. On the next level, energy product is bundled by electricity and non-electricity product, with a substitution elasticity of 0.5. The non-electricity energy is composed by gas composite, coal composite and oil composite. Then the non-electricity product is composited by coal, oil and gas, described by a CES function with the substitution elasticity of 0.16 (Figure A2). On the bottom level of non-electricity product, coal is composited by crude coal and coke, oil is composited by crude oil and petroleum product and gas is composted by crude gas and gas supply. The substitution elasticities at this level are set to 0.5.

Compared with non-electricity product, the structure of electricity with different power sources is much complicated (Figure A3). The CHINAGEM model incorporates seven electricity generation sectors with different power sources, including coal-fired, gas-fired, nuclear, hydro, wind, solar, and biomass power, and one sector for electricity transmission and distribution. At the top of the nesting structure of electricity, Leontief function is employed to assume the utilization of electricity as a fixed proportion of transmission and distribution. Then electricity utilization is composited by the base-load and variant-load power, described by a CES function with the substitution elasticity of 3. Then the base-load power is

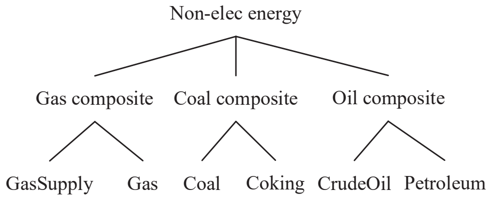


Figure A2.
The nesting structure of non-electricity energy used by producing sectors

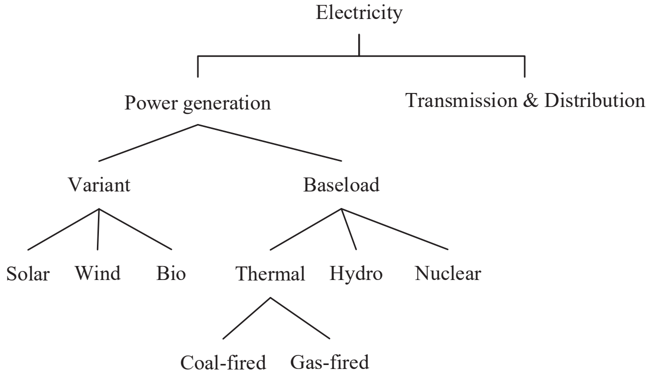


Figure A3.
The nesting structure of electric powers used by producing sectors

Table A1.
The substitution elasticities of CHINAGEM models

Symbols	The meaning	The value
σ_{FAC}	The substitution elasticity between labor, land and capital-energy composite input	0.5
σ_{KE}	The substitution elasticity between capital and energy input	1
σ_{E}	The substitution elasticity between electricity and non-electricity energy	0.5
σ_{NELE}	The substitution elasticity between coal, oil, and gas	0.16
σ_{COAL}	The substitution elasticity between crude coal and coke	0.5
σ_{OIL}	The substitution elasticity between crude oil and petroleum product	0.5
σ_{GAS}	The substitution elasticity between crude gas and gas supply	0.5
σ_{ETD}	The substitution elasticity between electricity generation and electricity transmission and distribution	0
σ_{ELE}	The substitution elasticity between base-load and variant-load power	3
σ_{BASE}	The substitution elasticity between thermal power, hydropower and nuclear power	5
σ_{VAR}	The substitution elasticity between solar power, wind power and biomass power	5
σ_{THERM}	The substitution elasticity between coal-fired and gas-fired power	10

composited by the thermal power, hydropower and nuclear power, with the substitution elasticity of 5. The variant-load power is composited by solar power, wind power and biomass power, with the substitution elasticity of 5. On the bottom level, the thermal power is composited by coal-fired and gas-fired power, with substitution elasticity of 10.

(b) Investment

Similar to the intermediate inputs, the sectors determine the purchases of investment commodities according to the cost minimization. On top of the nested structure, the investment of sector i is composited by different investment commodities with a Leontief function (Eq. A4).

$$X2TOT(i) = \frac{1}{G2(i)} * MIN\left[All, c, COM : \frac{X2\_S(c,i)}{A2\_S(c,i)}\right], COM = \{1, \ldots, N\} \tag{A4}$$

where, $X2TOT(i)$ is the total investment of sector i. $X2\_S(c,i)$ is the purchase of investment commodity c by sector i. Similarly, $G2(i)$ is the parameter for neutral technological progress. $A2\_S(c,i)$ is the technology parameter augmented to investment commodities. $X2\_S(c,i)$ is the composite of domestic and import sources with CES function as shown in Eq. A5.

$$X2\_S(c,i) = CES\left[All, s, SRC : \frac{X2(c,s,i)}{A2(c,s,i)}\right], \quad SRC = \{dom, imp\} \tag{A5}$$

(c) Consumption

The household consumption is determined by the utility maximization subjected to residential income. We employ the Klein-Rubin function to describe the household consumption of different commodities (Eq. A6).

$$MAX\ U = \prod_{c=1}^{N}\left[\frac{X3\_S(c)}{Q} - A3SUB(c)\right]^{\beta(c)}.\ s.t.\ \sum_{c}\frac{X3\_S(c)}{Q} * P3\_S(c) = \frac{Y}{Q} \tag{A6}$$

where U represents the household utility, and Y is the disposal income of a representative household. Q represents the population. $X3\_S(c)$ is the consumption of commodity c by the household. $X3SUB(c)$ is the subsistence consumption of commodity c, and $A3SUB(c)$ is the parameter on the subsistence consumption. $P3\_S(c)$ is the price of commodity c. $\beta(c)$ represents the marginal consumption propensity of commodity c. With Lagrange optimization, the linear expenditure system is obtained in Eq. A7. The consumption of $X3\_S(c)$ is the composite of domestic and import sources with CES function.

$$X3\_S(c) = X3SUB(c) + \frac{\beta(c)}{P3\_S(c)} * \left[Y - \sum_{c=1}^{n} X3SUB(c) * P3\_S(c)\right] \tag{A7}$$

(d) Export

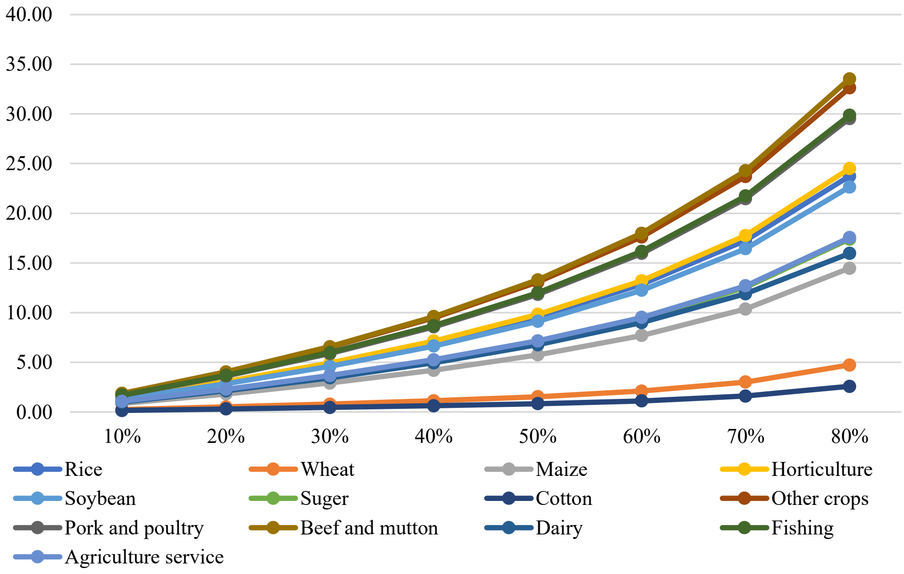
$$X4(c) = F4Q(c)\left[\frac{P4(c)}{PHI * F4P(c)}\right]^{EXP\_E(c)} \tag{A8}$$

As shown in Eq. A8, the export demand for tradable commodities is negatively correlated with the export price. $X4(c)$ is the export of commodity c. $P4(c)$ is the export price in foreign currency and PHI represents the exchange rate. $F4Q(c)$ and $F4P(c)$ are the shift variables to the export curve. The price elasticity of commodity c's export, $EXP\_E(c)$, is negative.

(e) Equilibrium

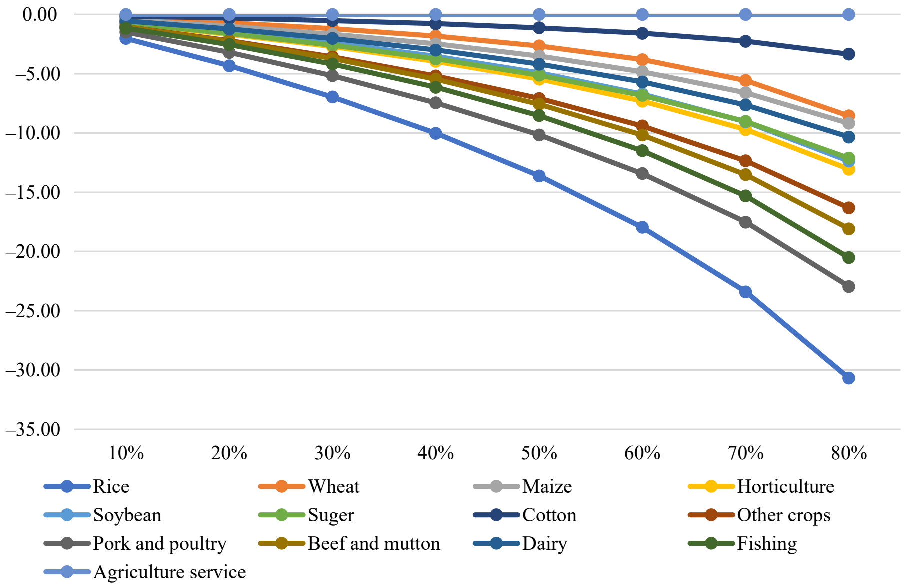
Following most CGE models, the general equilibrium of CHINAGEM requires the clearance of all the commodity and factor markets, zero profit of producing sectors and the balance between saving and investment.

B. The impact of dual carbon schemes on agricultural exports and imports



Source(s): CHINAGEM model

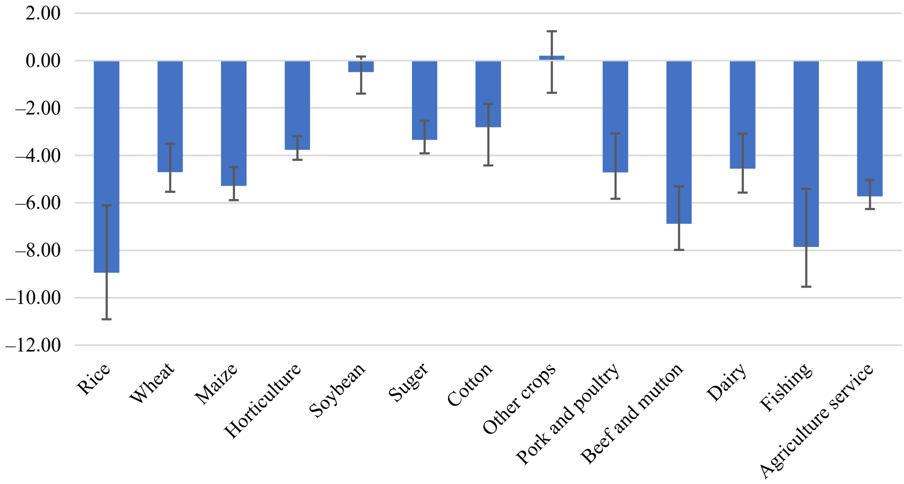
Figure A4.
The percentage changes in agricultural exports under different carbon abatement scenarios (%)



Source(s): CHINAGEM model

Figure A5.
The percentage changes in agricultural imports under different carbon abatement scenarios (%)

C. The sensitivity analysis on key substitution elasticities of the CHINEGEM model



Source(s): CHINAGEM model

Figure A6.
The impact of attaining carbon neutrality goal on agricultural productions with different substitution elasticities (%)

Corresponding author
Yu Sheng can be contacted at: ysheng.ccap@pku.edu.cn