

Assessment of agricultural carbon emissions reduction potential and optimisation pathways based on a framework of equity and efficiency principles: Evidence from Fujian Province in China

JIE YE^{1,2}, RENSHAN XIE³, XINGWEI DENG⁴, MINLING LIN⁴, YANG CHEN⁴,
KETAO LIN^{5*}, JIANZHOU YANG^{6*}

¹College of Business, Quanzhou Normal University, Quanzhou, P. R. China

²Private Economic Development Research Institute of Characteristic New Think Tank for Universities in Fujian Province, Quanzhou, P. R. China

³Quanzhou Rural Revitalization Group, Quanzhou, P. R. China

⁴Anxi College of Tea Science, Fujian Agriculture and Forestry University, Quanzhou, P. R. China

⁵College of Resource and Environment Sciences, Quanzhou Normal University, Quanzhou, P. R. China

⁶School of Economics and Management, Fujian Agriculture and Forestry University, Fuzhou, P. R. China

*Corresponding author: taolink@foxmail.com; yjzfafu@163.com

Citation: Ye J., Xie R., Deng X., Lin M., Chen Y., Lin K., Yang J. (2024): Assessment of agricultural carbon emissions reduction potential and optimisation pathways based on a framework of equity and efficiency principles: Evidence from Fujian Province in China. *Agric. Econ. – Czech*, 70: 125–136.

Abstract: Fujian Province, China was chosen as the study area for estimating the marginal agricultural abatement costs within the province based on data for 2010–2020. The study employed these estimations as a pivotal factor affecting the efficiency of carbon emissions reduction, constructed an index model to gauge the potential of agricultural carbon emissions reduction, and delved into the urban agricultural carbon emissions reduction potential from the perspectives of economic development rights (equity) and carbon emissions reduction difficulty (efficiency). Our findings indicated a marked regional disparity in the marginal abatement costs of agriculture across Fujian Province, with the highest recorded at EUR 1.3771×10^8 per 10^4 tonnes and the lowest at EUR 0.6526×10^8 per 10^4 tonnes, albeit demonstrating general upward inter-annual trends. Furthermore, the assessment of agricultural carbon emissions reduction potential, grounded in the principles of equity and efficiency, revealed four distinct developmental tiers. Resource allocation pathways for carbon emissions reduction were subsequently delineated, informed by the stratification of high- and low-carbon emissions reduction potential indices alongside typological characteristics. The outcomes of this study offer strategic guidance to the government of Fujian Province in crafting suitable carbon emissions reduction strategies and in devising targeted action plans aimed at achieving the twin goals of 'carbon peaking' and 'carbon neutrality'.

Keywords: agricultural marginal abatement costs; reduction potential index modelling; equity and efficiency indices

Supported by the National Natural Science Foundation of China under Grant No. 71773016, the Natural Science Foundation of Fujian Province under Grant No. 2021J05184, the Major Project of Social Science Research Base of Fujian Province under Grant No. FJ2022MJDZ044, and the Ministry of Education of Humanities and Social Science Project under Grant No. 21YJCZH006.

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Agriculture is one of the major sources of greenhouse gas (GHG) emissions, and, as a major agricultural country in the world, China's reduction in agricultural carbon emissions is an important means and an effective way for it to achieve the twin goals of 'carbon peaking' and 'carbon neutrality' (van Veelen 2021), which fully reflects China's more active participation in addressing climate change as well as the formulation of global climate governance. As China's first ecological civilisation pilot area, Fujian Province shoulders an important responsibility with respect to low-carbon economic reform and development. During the period of the 13th Five-Year Plan, Fujian Province strengthened its carbon emissions intensity target constraints (which are 1.5 percentage points higher than the national standard for carbon emissions intensity reduction) and began to explore the green development road at a higher standard and higher level. Since 2013, the Fujian provincial government has implemented the 'Controlling Greenhouse Gas Emissions in Fujian Province' policy, which focuses on controlling the use of agricultural inputs (fertilisers, agricultural films, straw, etc.) to achieve zero carbon emissions growth and reduce agricultural carbon emissions at source. The figures for Fujian Province's agricultural carbon emissions for 2010–2020 measured in this study (Figure 1) show that emissions peaked as early as 2012 and that reduction efforts achieved clear and verifiable results. However, it is a matter of concern that, from 2019 to 2020, agricultural carbon emissions decreased by only 12 400 tonnes, or approximately 0.53 percentage points, meaning that the potential for future reductions in Fujian Province's agricultural carbon emissions has become very limited.

However, China's carbon peaking and carbon neutrality targets have not yet been achieved, and Fujian Province still needs to make efforts in that direction. Therefore, for government policymakers, how to formulate carbon emissions reduction tasks, that meet the characteristics of regional carbon emissions reduction potentials in light of the differences in the development levels of different regions, is of great theoretical and practical importance for accelerating the low-carbon transformation of agriculture, promoting its sustainable development, and then promoting the work of green and low-carbon development to move to a higher level, which was the central aim of this study.

Agricultural carbon emissions reduction is an ecological topic that has attracted considerable attention and discussion both at home and abroad in recent years. The discussion has centred mainly on the quantitative prediction of agricultural carbon emissions reductions that agricultural carbon emitters can achieve through appropriate technologies, that is, the issue of the spatial decline in agricultural carbon emissions in the future. For example, Nimkar et al. (2015) studied the contribution of the clean development mechanism (CDM) to the GHG emissions reduction potential of the agricultural sector in 19 countries, and Yang et al. (2023) projected the potential for agricultural carbon emissions reduction in Beijing, China during the period of the 14th Five-Year Plan. They concluded that agricultural carbon emissions could be reduced effectively by optimising cultivation patterns, animal husbandry, and land use. Most of the policy insights from the study results focused on the formulation of carbon emissions reduction policies from the perspective of the principle

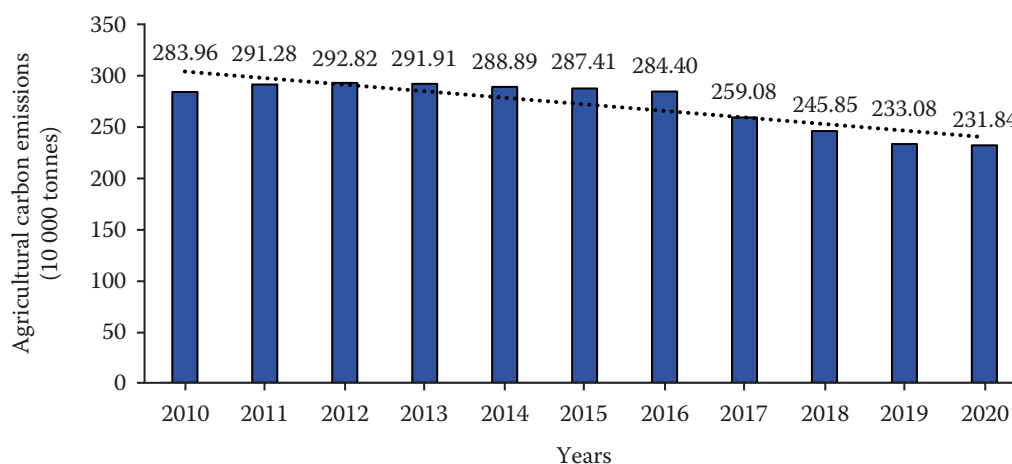


Figure 1. Trends in total agricultural carbon emissions in Fujian Province from 2010 to 2020

Source: Authors' own elaboration

<https://doi.org/10.17221/329/2023-AGRICECON>

of equity, that is, the allocation of carbon emissions reduction tasks according to the size of the carbon emissions reduction capacity based on the differences in the levels of economic development and carbon emissions in different regions (von Wright et al. 2022). However, most studies tended to ignore agricultural carbon emissions as a necessary input constraint to economic output, which is not consistent with actual carbon abatement policymaking (Ma et al. 2019; Tang and Ma 2022). This is because agricultural economic growth has always depended on the necessity of carbon emissions (Xia et al. 2022). Although the application of energy-efficient and clean technologies in agricultural practice reduces carbon emissions, the link between agricultural economic development and carbon emissions cannot be broken (Elahi et al. 2022). According to the theory of marginal productivity, if carbon emissions are treated as an input element of economic output, they can reflect the opportunistic cost that needs to be foregone in order to reduce carbon emissions, that is, the marginal abatement cost. Marginal abatement costs increase with advances in technological innovation (Bauman et al. 2008). Liu and Feng (2018) measured the marginal abatement costs for 165 countries globally for the period 2000–2014 to be approximately USD 673.74–697.73/tonne, which means that, for every tonne of carbon emissions reduced, USD 673.74–697.73 were sacrificed in economic output, and the cost therefore increased. Li et al. (2023) found that China's marginal abatement cost was positively correlated with carbon efficiency, and, from the perspective of minimising economic costs, further abatement tasks should be undertaken by less developed regions in the central and western parts of the country. Technological progress promotes economic growth and reduces carbon emissions intensity by excluding carbon emissions as a factor of production (Yang et al. 2021). However, as technology continues to evolve, the marginal cost of reducing carbon emissions becomes higher. Therefore, based on the principle of efficiency, the allocation of carbon emissions reduction tasks in agricultural practice should also focus on the economic increment sacrificed by different regions in order to reduce carbon emissions.

It has been shown that, despite the obvious characteristics of regional differentiation, different regions have tended to imitate each other's carbon emissions reduction strategies, and most of these reduction strategies have similar problems (He et al. 2020). Therefore, a more balanced and reasonable carbon emissions reduction potential indicator is needed to guide the de-

velopment of reduction strategies, and various carbon emissions reduction allocation tasks need to be analysed in a more comprehensive manner. These include the following research questions:

- i) How do the principles of fairness and efficiency affect the allocation of carbon emissions reduction tasks in agricultural practice?
- ii) How should an agricultural carbon emissions reduction potential index that is consistent with regional carbon emissions reduction capacity be constructed?
- iii) How do government policymakers allocate carbon emissions reduction resources, especially from the perspective of the variability of agricultural carbon emissions reduction potential?

The contribution that this study makes to the discussion has three aspects:

- i) We have taken small-scale regions as the object of research, and we have constituted the agricultural carbon emissions reduction potential index by combining the right to agricultural economic development and the difficulty of carbon emissions reduction, which enriches the relevant research content in the field of agricultural carbon emissions reduction.
- ii) We have explored the impact of differences in policymakers' preferences on the potential of agricultural carbon emissions reduction.
- iii) Based on the results of the agricultural carbon emissions reduction potential index, the allocation of resources and optimisation paths for agricultural carbon emissions reduction were investigated, which is, to the best of our knowledge, one of the first attempts to do this.

MATERIAL AND METHODS

Mechanisms of influence

Impact of the equity principle on carbon emissions reduction. The current mainstream principle applied in setting carbon dioxide (CO₂) emissions reduction quotas is the principle of fairness, which focuses on highlighting the concept of people-centred development and emphasises equal resource utilisation for all (Grubb 1990). To a certain extent, carbon emissions rights represent the right to regional economic development, and any region that accepts a CO₂ emissions reduction quota allocation needs to reduce its pace of economic development in order to reduce its CO₂ emissions. From the point of view of fairness, the allocation of emissions reduction quotas to regions should be differentiated according to their different stages or levels of economic development. This dif-

ferentiated formulation is aimed at achieving carbon emissions reduction equity from the perspective of the regional population, combined with the concepts of 'equal carbon rights for all' and 'historical carbon emissions and future carbon emissions uniformity' to guide the reasonable distribution of CO₂ emissions quotas. Currently, academics generally believe that CO₂ emissions per capita and gross domestic product (GDP) per capita should be used as the two criteria for allocating CO₂ emissions allowances to individual regions, which can reduce the differences between regions due to their different stages of economic development and thus make the distribution of CO₂ emissions reduction quotas more equitable (Zhou et al. 2014).

Impact of the efficiency principle on carbon emissions reduction. Based on the principle of efficiency, the carbon emissions reduction capacity of carbon-emitting entities is taken into consideration in the formulation of CO₂ emissions reduction quotas. Due to their different levels of economic, scientific and technological development, the main carbon-emitting entities also have differences in terms of their ability to reduce carbon emissions. This difference in reduction ability is generally reflected in carbon emissions intensity. The latter represents the amount of carbon emitted per unit of GDP. Higher rates of carbon emissions intensity mean a greater carbon emissions reduction space, and it is relatively easy for carbon-emitting entities to reduce their carbon emissions intensity through technical means and industrial structure adjustment, meaning that, according to the principle of efficiency, they can undertake more CO₂ emissions quota reduction tasks. In contrast, at lower rates of carbon emissions intensity, the industrial structure of carbon-emitting entities is more reasonable and the space for carbon emissions adjustment is smaller, meaning that, based on the principle of efficiency, they are not suited to undertaking additional CO₂ emissions quota reduction tasks. The carbon emissions reduction ability of carbon-emitting entities can also be understood from the perspective of marginal carbon emissions reduction costs. When the latter cost of the carbon-emitting entity is higher, the GDP sacrificed by reducing the unit carbon emissions is higher and the carbon emissions reduction efficiency is also reduced. Therefore, based on the principle of efficiency, carbon-emitting entities should not undertake additional CO₂ emissions quota reduction tasks.

Study methodology

Agricultural carbon emissions reduction equity index. Based on the principle of equity, the total amount

of carbon emitted by agricultural practices should not be used as the basis for formulating mitigation policies. Instead, such policies should also take into account the size of a region's population. Therefore, per capita carbon emissions from agriculture were selected in our study as one of the criteria for drawing up the equity index. Based on the principle of ability to pay, and considering the differences in the level of agricultural economic development of each prefecture-level city in Fujian Province, the per capita output value was used to measure the development of the regional economy, which could then also indicate the per capita level of ability to pay for emissions reduction. Therefore, per capita agricultural carbon emissions (*PC*) and per capita gross agricultural output (*PP*) were selected to construct the equity index (Shi et al. 2023), see Equation (1):

$$equity_{i,t} = a \times PC + (1 - a) \times PP \quad (1)$$

where: i – i^{th} prefecture-level city; t – year; a – weight value, in the range [0,1]; in this study, *PC* and *PP* were considered to be equal in the equity index, so the value of a was taken as 0.5.

Agricultural carbon emissions reduction efficiency index. In this study, based on marginal productivity theory, the shadow price of agricultural carbon emissions (*RC*) was used to express the marginal abatement cost of carbon emissions reduction in agriculture, i.e. the reduction in gross agricultural product per unit of reduction in carbon emissions from agriculture, with the other factor of production inputs remaining unchanged. Following previous studies, agricultural capital input (*K*), labour input (*L*), and CO₂ emissions (*C*) were selected as explanatory variables, with agricultural gross product (*Y*) as the explained variable, urbanisation rate (*U*), and rural per capita income (*R*) as the control variables, and v as the residual (Li and Zhu 2014; Cui and Wang 2016; Chen 2019; Du et al. 2022). The trans-log production function was constructed as follows:

$$\begin{aligned} \ln y_{it} = & \beta_0 + \beta_1 \ln C_{it} + \beta_2 \ln K_{it} + \beta_3 \ln L_{it} + \\ & + \beta_4 \ln L_{it} \times \ln K_{it} + \beta_5 \ln C_{it} \times \ln L_{it} + \\ & + \beta_6 \ln K_{it} \times \ln L_{it} + \beta_7 \ln C_{it}^2 + \beta_8 \ln K_{it}^2 + \\ & + \beta_9 \ln L_{it}^2 + \beta_{10} \ln R_{it} + \beta_{11} U_{it} + u_{it} + v_{it} \end{aligned} \quad (2)$$

where: v_{it} – random error; u_{it} – output loss due to technological inefficiency, it is assumed that $u_{it} \geq 0$ and follows a truncated normal distribution.

<https://doi.org/10.17221/329/2023-AGRICECON>

Thus, these definitions follow:

$$u_{it} \sim N^+(\mu, \sigma_\mu^2) \text{ and } cov(v_{it}, u_{it}) = 0, v_{it} \sim N(0, \sigma_v^2) \quad (3)$$

where: N – normal distribution; μ – mean value; σ – variance.

The elasticity of agricultural GDP concerning carbon emissions can be obtained by taking the partial derivative of $\ln y$ with respect to $\ln c$:

$$\frac{dy/y}{dc/c} = \frac{\partial \ln y}{\partial \ln c} = \beta_1 + \beta_4 \ln k + \beta_5 \ln l + 2\beta_7 \ln c \quad (4)$$

where: y – agricultural gross product; c – CO₂ emissions; k – agricultural capital input; l – labour input.

This yields the marginal output of y for c as:

$$\frac{dy}{dc} = \frac{y}{c} (\beta_1 + \beta_4 \ln k + \beta_5 \ln l + 2\beta_7 \ln c) \quad (5)$$

According to the theory of factor price determination and the theory of marginal productivity, it can be shown that, for Fujian Province, RC is equal to the marginal productivity of agricultural carbon emissions, so $RC = dy/dc$. Since agricultural carbon intensity (CI) indicates the amount of agricultural carbon emissions produced by one unit of agricultural GDP, the higher the CI , the easier it is to reduce carbon emissions through industrial restructuring and technological advancement, and the more efficient therefore its carbon emissions reductions are. RC refers to the abatement cost that needs to be paid to reduce a unit of agricultural carbon emissions; therefore, CI and RC were selected as the necessary components of the efficiency index:

$$efficiency_{i,t} = b \times CI + (1 - b) \times RC \quad (6)$$

where: b – weight value, in the range $[0,1]$; in this study, the importance of CI and RC in the efficiency index were considered to be equal, so the value of b was taken as 0.5.

Equity and efficiency carbon index (EECI) construction. This study drew on the work of Wei et al. (2012), based on the principles of equity and efficiency, to calculate the $EECI$ of agricultural carbon emissions reduction potential from the perspective of coordinating carbon emissions reduction in terms of equity and effi-

ciency. The $EECI$ consists of an equity index and an efficiency index [Equation (7)].

$$EECI_{i,t} = w \times equity_{i,t} + (1 - w) \times efficiency_{i,t} \quad (7)$$

$$equity_{i,t} = a \times PC + (1 - a) \times PP$$

$$efficiency_{i,t} = b \times CI + (1 - b) \times RC$$

where: w – decision-making preferences of policymakers with regard to the balance between the principles of equity and efficiency in formulating agricultural carbon emissions reduction policies.

In this study, three scenarios were set according to different weight selections for w .

- Scenario 1: For $w = 0.5$, policymakers have no special preference for equity or efficiency in formulating agricultural carbon emissions reduction policies, regarding them as equally important in following the principle of balancing equity with efficiency.
- Scenario 2: For $w = 1/3$, policymakers focus more on the efficiency of agricultural carbon emissions reduction and believe that the formulation of reduction policies should give more consideration to the efficiency of emissions reduction in each prefecture-level city and focus on the effectiveness of those reductions, following the principle of prioritising efficiency.
- Scenario 3: For $w = 2/3$, policymakers focus more on the fairness of agricultural carbon emissions reduction and believe that the formulation of reduction policies should give more consideration to the fairness of agricultural carbon emissions reduction among prefecture-level cities and focus on the economic implications of agricultural carbon emissions reduction in each prefectural city, following the principle of prioritising fairness.

Data processing and sources. Because of the different unit attributes of each component indicator in the formula, the data used in the calculation of the equity and efficiency indices need to be dimensionless. The PC and PP , which constitute the equity index, represent the obligation to share the responsibility for carbon emissions reduction and the ability to pay, respectively; the larger the value, the greater the potential for agricultural carbon emissions reduction, which is positively efficacious and is therefore treated positively. The component indicator of the efficiency index, CI , represents the amount of agricultural carbon emissions per unit of total agricultural output

value, reflecting, to a certain extent, the degree of dependence of agricultural economic growth on agricultural carbon emissions. The *RC* reflects the total value of agricultural economic output that needs to be sacrificed for each unit of reduction in agricultural carbon emissions. The higher the value of *RC*, the lower the efficiency and the smaller the potential for agricultural carbon emissions reduction, which is negative in nature and is therefore treated negatively.

Equity and *CI* having positive effects:

$$u_{ij} = \frac{x_{ij} - b_{ij}}{a_{ij} - b_{ij}} \quad (8)$$

RC having negative effects:

$$u_{ij} = \frac{a_{ij} - x_{ij}}{a_{ij} - b_{ij}} \quad (9)$$

where: x_{ij} – sample value of indicator j in area i ; a_{ij} and b_{ij} – maximum and minimum values of indicator j in area i , respectively; u_{ij} – size of the contribution of agricultural carbon emissions reduction potential to the index, in the range $[0,1]$; for $u_{ij} = 0$, the indicator has the worst effect on the agricultural carbon emissions reduction potential index, and the size of the contribution is almost 0; for $u_{ij} = 1$, the system has the best effect on the agricultural carbon emissions reduction potential index.

The data for the indicators in this study came from the 2011–2021 Statistical Yearbooks published on the website of the Bureau of Statistics (<https://tjj.fujian.gov.cn/>) of each prefecture-level city in Fujian Province, and some of the missing data were supplemented by interpolation.

RESULTS

Marginal abatement costs in agriculture. From the perspective of regional differences, the average values of *RC* in Fuzhou, Ningde, and Nanping prefectures ranked in the top three columns in Fujian Province from 2010 to 2020, at $\text{EUR } 1.3771 \times 10^8$ per 10^4 tonnes, $\text{EUR } 1.1383 \times 10^8$ per 10^4 tonnes, and $\text{EUR } 0.9136 \times 10^8$ per 10^4 tonnes, respectively, and the cost of agricultural carbon emissions reduction was relatively large. These three cities are concentrated in the northern and coastal regions of Fujian Province, and the sources of agricultural carbon emissions were mainly agricultural material inputs (fertilisers, pesticides, ag-

ricultural film, etc.) and livestock and poultry farming (pigs, cows, and sheep). These cities also have a higher level of agricultural economic development, a more advanced level of agricultural production technology relative to other prefecture-level cities and a certain advantage in the comprehensive utilisation rate of agricultural material inputs. Therefore, they can maintain a certain level of agricultural GDP while generating relatively fewer agricultural carbon emissions, and under the established agricultural production factor inputs, the marginal output benefits are higher, so more units of agricultural GDP need to be given up in order to reduce the cost of a unit of agricultural carbon emissions (Wu et al. 2018). The *RC* values in Xiamen, Putian, Longyan, Sanming, Quanzhou, and Zhangzhou prefectures were relatively low, with Zhangzhou, Xiamen, and Quanzhou ranking in the bottom three of the nine cities, at $\text{EUR } 0.6526 \times 10^8$ per 10^4 tonnes, $\text{EUR } 0.7113 \times 10^8$ per 10^4 tonnes, and $\text{EUR } 0.7138 \times 10^8$ per 10^4 tonnes, respectively. It is worth noting that Zhangzhou's agricultural carbon emissions were almost twice as high as those of the other prefectures and that its agricultural production was relatively crude, with backward production technology and low marginal output efficiency. As a result, the reduction in agricultural carbon emissions per unit of GDP meant that less economic output needed to be sacrificed, and its *RC* value was the lowest among the nine cities.

EECI for agricultural carbon emissions reduction.

As can be seen from the data in Table 1, the agricultural carbon emissions fairness index of the nine prefecture-level cities in Fujian Province is characterised by obvious differentiation and more serious polarisation, with the highest value for Zhangzhou (0.5792) and the lowest value for Sanming (0.0947). The top three agricultural carbon emissions reduction fairness indices in Fujian Province were in Zhangzhou (0.5792), Nanping (0.5706), and Longyan (0.4466), followed by Fuzhou in fourth place. For specific analysis, the per capita gross agricultural output values of Zhangzhou, Nanping, and Longyan were $\text{EUR } 8\,667$, $\text{EUR } 11\,441$, and $\text{EUR } 8\,637$ /person, respectively, which were foremost among the nine prefecture-level cities, indicating that their ability to pay for carbon emissions reduction in agriculture was relatively strong. Although the per capita gross agricultural output values of Zhangzhou and Longyan were lower than that of Fuzhou, in terms of the comprehensive *PC* value, the *PC* values of Zhangzhou (0.6983 tonnes/person), Nanping (0.6054 tonnes/person), and Longyan (0.5538 tonnes/person) were all higher than that of Fuzhou. They resided in the top three columns of the nine prefecture-level cities, increasing the overall agricultur-

<https://doi.org/10.17221/329/2023-AGRICECON>

Table 1. Estimated results for agricultural carbon emissions reduction efficiency index and carbon equity index in Fujian Province from 2010 to 2020

City	Carbon emissions from agriculture per capita (tonnes/person)	Agricultural GDP (EUR 10 000/person)	Carbon equity index	Rank	Carbon emissions intensity (tonnes/EUR)	Shadow price (EUR 10 000/tonne)	Carbon emissions efficiency index	Rank
Fuzhou	0.4223	1.1366	0.4017	4	68.9722	1.3771	0.2799	9
Xiamen	0.4609	0.7319	0.3259	6	111.4951	0.7113	0.5916	3
Putian	0.4621	0.8572	0.3613	5	111.0699	0.7958	0.5654	5
Nanping	0.6054	1.1441	0.5706	2	104.1079	0.9136	0.5118	7
Ningde	0.3116	0.7249	0.1879	8	80.4116	1.1383	0.3814	8
Longyan	0.5538	0.8637	0.4466	3	116.8889	0.8301	0.5709	4
Sanming	0.2832	0.4797	0.0947	9	109.4328	0.8739	0.5379	6
Quanzhou	0.3853	0.5404	0.2044	7	131.1668	0.7138	0.6438	2
Zhangzhou	0.6983	0.8667	0.5792	1	151.8313	0.6526	0.7175	1
Average value	–	–	0.3525	–	–	–	0.5334	–

Source: Authors' own elaboration

al carbon emissions equity index. Therefore, these three prefectures should have been responsible for greater agricultural carbon emissions reductions, in terms of both ability to pay and the principle of equity. Quanzhou, Ningde, and Sanming were lower than the other six prefectures, both in terms of *PC* and *PP*, so their agricultural carbon emissions reduction fairness index rankings were the lowest, namely, Quanzhou (0.2044), Ningde (0.1879), and Sanming (0.0947).

The agricultural carbon emissions efficiency index for Fujian Province, in descending order, was Zhangzhou (0.7175) > Quanzhou (0.6438) > Xiamen (0.5916) > Longyan (0.5709) > Putian (0.5654) > Sanming (0.5379) > Nanping (0.5118) > Ningde (0.3814) > Fuzhou (0.2799). The differentiation in the characteristics of the agricultural carbon emissions efficiency index of the nine prefecture-level cities is obvious. It is worth noting that the *RC* value in Zhangzhou was only EUR 0.6526×10^8 per 10^4 tonnes, which was the lowest cost of agricultural carbon emissions reduction among the nine prefectures, and its agricultural carbon emissions intensity topped the list, which increased the value of the agricultural carbon emissions reduction efficiency. In contrast, Fuzhou had an agricultural carbon emissions intensity of 68.9722 tonnes/EUR, which was the lowest in the province, and its *RC* value was as high as EUR 1.3771×10^8 per 10^4 tonnes, and its cost of agricultural carbon emissions reduction was the highest, which reduced the value of agricultural carbon emissions reduction efficiency in Fuzhou.

Agricultural carbon emissions reduction potential index for Fujian Province. In this study, three policy scenarios were set up according to the different preferences of policymakers for equity and efficiency with respect to agricultural carbon emissions reduction, namely, equity and efficiency combined ($w = 1/2$), equity prioritised ($w = 2/3$), and efficiency prioritised ($w = 1/3$), and the potential indices of agricultural carbon emissions reduction measured under the different scenarios are presented in Table 2.

Of the nine cities, Zhangzhou, Nanping, and Longyan still ranked in the top three in Fujian Province in terms of the agricultural carbon emissions reduction potential index under the three policymakers' preferences scenarios. According to the official data compiled by the Fujian Provincial Bureau of Statistics (<https://tjj.fujian.gov.cn/>), Zhangzhou City had a high level of agricultural carbon emissions, with an average reaching 716 100 tonnes, and accounting for 26% of the total agricultural carbon emissions in the province; the intensity of agricultural carbon emissions reached 151.8313 tonnes/EUR, and *PC* reached 0.6983 tonnes/person, ranking first among the nine prefecture-level cities, which is a clear feature of rough agriculture. The responsibility of Zhangzhou City for agricultural carbon emissions reduction is large. At the same time, the cost of agricultural carbon emissions reduction (shadow price) in Zhangzhou City was also the lowest, at only EUR 0.6526×10^8 per 10^4 tonnes, and the difficulty of agricultural carbon emissions reduction was low. Nanping and Longyan

Table 2. Carbon emissions reduction potential index values from agriculture in Fujian Province under different scenarios for policymakers' preferences

City	Scenario 1		Scenario 2		Scenario 3	
	equity principles and efficiency principles ($w = 1/2$)		equity prioritisation principle ($w = 2/3$)		efficiency prioritisation principle ($w = 1/3$)	
	<i>EECI</i>	rank	<i>EECI</i>	rank	<i>EECI</i>	rank
Fuzhou	0.3408	7	0.3611	6	0.3205	8
Xiamen	0.4588	5	0.4145	5	0.5031	4
Putian	0.4634	4	0.4293	4	0.4974	5
Nanping	0.5412	2	0.5510	2	0.5314	2
Ningde	0.2847	9	0.2524	8	0.3169	9
Longyan	0.5088	3	0.4881	3	0.5295	3
Sanming	0.3163	8	0.2424	9	0.3902	7
Quanzhou	0.4241	6	0.3509	7	0.4973	6
Zhangzhou	0.6484	1	0.6253	1	0.6714	1

EECI – equity and efficiency carbon index

Source: Authors' own elaboration

had high per capita gross agricultural output values, at EUR 11 441 and EUR 8 637/person, respectively, almost twice that of Sanming (EUR 4 797/person) and Quanzhou (EUR 5 404/person), and their ability to pay for agricultural carbon emissions reduction was greater. Therefore, these three prefecture-level cities had certain emissions reduction advantages and were able to take on more responsibility for agricultural carbon emissions reduction in Fujian Province regardless of policymakers' preferences. Ningde's per capita gross agricultural output value (EUR 7 249/person) and *PC* (0.3116 tonnes/person) seriously lowered the city's agricultural carbon emissions reduction fairness index; even if the priority given to the principle of efficiency in the agricultural carbon emissions reduction index was increased, Ningde still scored below the other eight prefectures. Its ability to pay for agricultural carbon emissions reduction was poor, and the task of reduction should be reduced appropriately so that it can adjust its agricultural industrial structure and rationally formulate low-carbon agricultural development goals under a policy environment of agricultural carbon emissions reduction constraints.

DISCUSSION

Analysis of marginal abatement costs in agriculture. From Table 3, it can be seen that the shadow prices of agricultural carbon emissions in all nine prefecture-level cities of Fujian Province showed an in-

creasing trend between 2010 and 2020, which implies that the economic costs paid by the nine prefectures to reduce agricultural carbon emissions had been increasing. This result is generally consistent with the trend in marginal carbon abatement costs across China (Li et al. 2023). The definition of the cost of agricultural carbon emissions reduction in this study reflects the marginal productivity of carbon emissions as a factor of production. Over time, the low-carbon technology level of the main body of agricultural carbon emissions continued to improve, and the reduction in agricultural carbon emissions also ensured a certain level of agricultural economic growth. Simply put, the intensity of agricultural carbon emissions will always be weakened, and the higher the marginal productivity of carbon emissions as a factor of production, the higher the economic cost of a reduction in a unit of carbon emissions. In general, the marginal abatement cost of agriculture in advanced regions tends to be higher than that in regions lagging behind, and a greater economic cost is required to undertake carbon abatement tasks (Ao et al. 2023). Therefore, it is necessary for Fujian Province to coordinate the allocation of carbon emissions reduction tasks, taking into account the minimisation of the cost of carbon emissions reduction.

Optimising the path to agricultural carbon emissions reduction. Based on the above results and analysis, this study examined the degree of differentiation between the ability to pay and the right to economic development (equity), the difficulty of agricultural

<https://doi.org/10.17221/329/2023-AGRICECON>

Table 3. Shadow price unit of agricultural carbon emissions in Fujian Province from 2010 to 2020 (EUR 10⁸ per 10⁴ tonnes)

Year	Fuzhou	Xiamen	Putian	Nanping	Ningde	Longyan	Sanming	Quanzhou	Zhangzhou
2010	0.8238	0.4006	0.4518	0.4754	0.6282	0.4242	0.4982	0.4421	0.3919
2011	0.9384	0.4338	0.5049	0.6208	0.7577	0.5102	0.5770	0.5180	0.4519
2012	1.0516	0.4434	0.5521	0.6648	0.8806	0.5480	0.6278	0.5492	0.4841
2013	1.1500	0.4631	0.6046	0.7117	0.9665	0.6065	0.6966	0.5820	0.5237
2014	1.2245	0.6542	0.6685	0.7619	1.0261	0.6590	0.7688	0.5971	0.5513
2015	1.1953	0.6671	0.6967	0.8189	1.0767	0.7351	0.7991	0.6465	0.5862
2016	1.3882	0.7518	0.7746	0.8884	1.2145	0.8735	0.8779	0.7191	0.6681
2017	1.5792	0.7539	0.9115	1.1609	1.3092	0.9324	0.9371	0.7529	0.7167
2018	1.7448	0.9003	1.0337	1.2148	1.4592	1.0503	1.0988	0.9063	0.8270
2019	1.9748	1.1695	1.2643	1.3398	1.5970	1.3692	1.2833	1.0435	0.9471
2020	2.0780	1.1868	1.2914	1.3916	1.6056	1.4222	1.4477	1.0954	1.0311
Average value	1.3771	0.7113	0.7958	0.9136	1.1383	0.8300	0.8739	0.7138	0.6526

Source: Authors' own elaboration

carbon emissions reduction and the cost of agricultural carbon emissions reduction (efficiency) in nine prefecture-level cities in Fujian Province from the perspectives of fairness and efficiency, and constructed two-dimensional 'fairness-efficiency' matrix of agricultural carbon emissions reduction (Figure 2) in the hope that it could take into account not only the strengths and weaknesses of the equity and efficiency of agricultural carbon emissions reduction in each prefecture-level city but also the coordination of the two and thus help to formulate a reasonable, scientific

and effective sharing of tasks for reductions in agricultural carbon emissions.

Based on the perspectives of equity and efficiency, the nine prefecture-level cities in Fujian Province should start by improving the efficiency of agricultural carbon emissions reduction and reducing the right to agricultural carbon emissions before attempting to complete the twin goals of carbon peaking and carbon neutrality (He et al. 2022). If agricultural carbon emissions reduction efficiency and rights are regarded as resources in the region, government policymakers

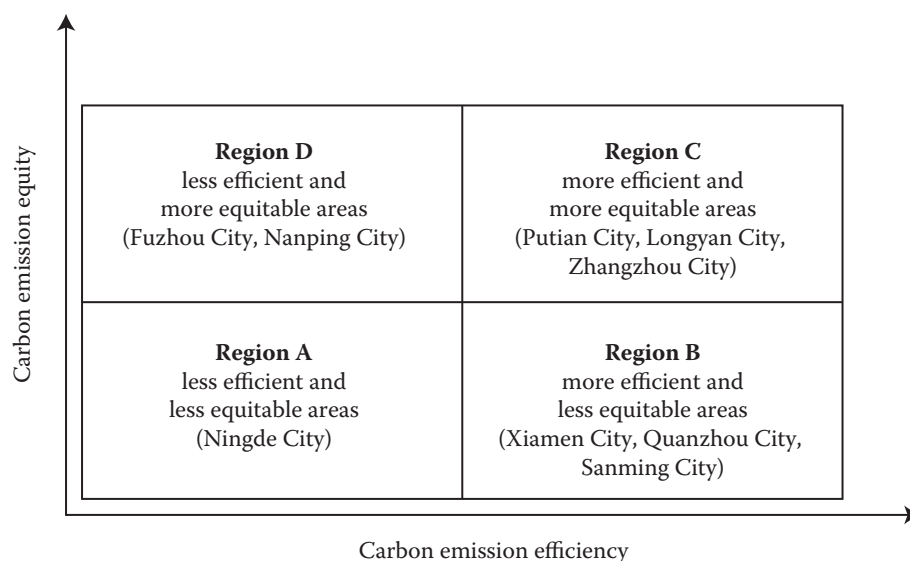


Figure 2. 'Equity-efficiency' two-dimensional matrix graph

Source: Authors' own elaboration

should give corresponding allocation support to these resources to help each region complete their agricultural carbon emissions reduction tasks and completely realise the transformation of low-carbon agricultural development. Therefore, each prefecture-level city was divided into four categories based on the average of the fairness and efficiency indices: *i*) for a fairness index > 0.3525 and an efficiency index > 0.5334 , the prefecture-level city was of the 'high-efficiency and fairer' type; *ii*) for a fairness index > 0.3525 and an efficiency index < 0.5334 , the prefecture-level city was of the 'low efficiency and fairer' type; *iii*) for a fairness index < 0.3525 and an efficiency index > 0.5334 , the prefecture-level city was of the 'high-efficiency and unfair' type; and *iv*) for a fairness index < 0.3525 and an efficiency index < 0.5334 , the prefecture-level city was of the 'inefficient and unfair' type. Based on this classification, a two-dimensional matrix was constructed (Figure 2).

This study found that the optimisation path for agricultural carbon emissions reduction in each region should take Region A (Ningde) as a benchmark, focus on supporting Region B (Quanzhou), and focus on reducing the efficiency of agricultural carbon emissions reduction in Region B (Quanzhou), for example, by increasing support for Region B in agricultural low-carbon technology inputs, transforming methods of agricultural energy consumption etc., to reduce the intensity of agricultural carbon emissions in Region B and improve the marginal productivity of agriculture. To realise the transition from Region B to Region A so that Region B can complete the task of agricultural carbon emissions reduction, the following four factors need to be taken into consideration to pursue this optimisation path:

- i*) Region A is an inefficient and inequitable region, and Ningde, which is included in the region, is characterised by a low level of agricultural carbon emissions, a high shadow price of agricultural carbon emissions, and has the advantage of agricultural carbon emissions reduction capacity for realising the transition to green and low-carbon agricultural practices. Using this region as a demonstration area for agricultural carbon emissions reduction requires minimal external government support, and can also serve as an exemplary driving force for other regions.
- ii*) Region B has long been in a state of high efficiency and low equity, and the problem of inconsistency between equity and efficiency in agricultural carbon emissions reduction is more serious in this region than in the others. The cost of introducing

agricultural low-carbon technologies and realising agricultural industrial restructuring is higher here. Central government needs to support Region B in terms of agricultural carbon emissions reduction resources, which can reflect the government's determination to complete the green and low-carbon transformation of agriculture, and can also fully reflect its duty of care.

- iii*) The government's financial and material resources are limited, and it is difficult to ensure that the resources available to support regional agricultural carbon emissions reduction efforts can be fully utilised (Klemun et al. 2020). Combined with the cost of agricultural carbon emissions reduction (shadow price), the difficulty in improving the efficiency of agricultural carbon emissions reduction in Region B is relatively small compared to that in Regions C and D, and the emissions reduction effect achieved by focusing on supporting Region B will be more efficient and significant.
- iv*) Key support for Region B can form an incentive mechanism for agricultural carbon emissions reduction in Region C. By focusing on supporting Region B, Region C will be induced to take the initiative to adjust the structure of its agricultural industry, reduce the use of high-carbon materials, and reduce the production of agricultural carbon emissions so that it can transition to Region B. When Region C transitions to Region B, it will receive government support for agricultural low-carbon technologies and clean energy, and will reduce its agricultural carbon emissions, thereby reducing the efficiency of agricultural carbon emissions reduction and realising the agricultural carbon emissions reduction path from C to A.

In addition, there are significant differences in agricultural carbon emissions among the prefecture-level cities in Region C, which engenders greater complexity in agricultural carbon emissions reduction paths. Longyan and Putian in Region C are located in the middle and upper reaches of Fujian Province with their small agricultural populations, which leads to their being considered 'medium-carbon and high-equity' prefecture-level cities, and therefore their intensity of agricultural carbon emissions and shadow prices are in the middle and upper values for Fujian Province. Priority should be given to further developing the level of agricultural technology of these two prefectures, improving the comprehensive utilisation of traditional agricultural materials (pesticides, fertilisers, and agricultural films) and reducing the intensity of agri-

<https://doi.org/10.17221/329/2023-AGRICECON>

cultural carbon emissions so that they can transition to Region D. Moreover, relying on continuing advances in the level of agricultural technology, they should further promote the use of alternative agricultural clean energy to that of high-carbon energy, reduce *PC*, and realise the path of agricultural carbon emissions reduction from $C \rightarrow D \rightarrow A$. Zhangzhou is a 'high-carbon and high-efficiency' city due to its low level of agricultural production technology and rough use of agricultural resources and is better suited to measures that prioritise the promotion of agricultural intensification (Chen et al. 2019). Zhangzhou can consider focusing its agricultural economy on low energy-consuming industries to ensure that *PC* is lowered while agricultural economic efficiency grows steadily, completing the transition from $C \rightarrow B$, and then improving the efficiency of agricultural energy use through governmental support for low-carbon technologies to realise the $C \rightarrow B \rightarrow A$ agricultural carbon emissions reduction pathway.

CONCLUSION

This study quantified the cost of agricultural carbon emissions reduction in nine prefecture-level cities in Fujian Province between 2010 and 2020, and, on this basis, constructed an equity and efficiency index (*EECI*) model in order to evaluate the capacities and responsibilities of these nine prefectures in terms of agricultural carbon emissions reduction from the perspectives of equity and efficiency. We examined the central government's pathway for allocating resources for carbon emissions reduction. The main findings of our study are as follows:

- i) The differentiation of marginal emissions reductions in agriculture in Fujian Province is clearly obvious, and the overall fluctuations show an increasing trend from year to year. Areas of intensive agricultural practice face greater economic losses in taking on carbon emissions reduction tasks than less intensively farmed areas. Therefore, it is suggested that, in order to achieve the twin goals of 'carbon peaking' and 'carbon neutrality', Fujian Province should adopt incentives and subsidies to motivate areas of intensive agriculture to use clean energy, control the carbon footprint generated by agricultural economic activities, and achieve sustainable carbon emissions reduction (Bekun 2024).
- ii) The results for the agricultural carbon emissions reduction potential index show that, regardless of the differences in the preferences of policymakers for

equity (economic development rights) and efficiency (economic costs) of carbon emissions reduction, Zhangzhou, Fujian Province, had the highest potential for carbon emissions reduction in agriculture and thus had the responsibility and ability to take on more carbon emissions reduction tasks. Therefore, Fujian Province should promote the development of low-carbon agricultural practices with differentiated emissions reduction strategies. According to the differences in the agricultural carbon emissions reduction potential indices of different regions, carbon emissions reduction targets should be set reasonably. In addition, considering that Ningde has the weakest potential for agricultural carbon emissions reduction, we suggest that the agricultural carbon emissions reduction task in Ningde should focus on tapping the function of agricultural carbon sequestration and sink enhancement to play a leading role in agricultural low-carbon development for other prefecture-level cities.

- iii) This study constructed a two-dimensional matrix of 'equity-efficiency' and innovatively mapped out the implementation path for agricultural carbon emissions reduction in Fujian Province. The results of this study provide policy implications for how to allocate limited carbon emissions reduction resources in Fujian Province in order to promote the transformation and development of low-carbon agriculture in the region.

Although this study was different from previous studies of the potential for agricultural carbon emissions reduction, in that it focuses on the quantity of agricultural carbon emissions that can be reduced through the efforts of carbon-emitting entities in the future, it focused on the ability of carbon-emitting entities to undertake carbon emissions reduction tasks, which is important for effective practical guidance.

However, this study also had some limitations based on objective realism. Due to limited data availability, this study focused only on the analysis of agricultural carbon emissions reduction potential in Fujian Province between 2010 and 2020. At the same time, there was a lack of further empirical research to explore the boundary criteria for high- and low-carbon emissions reduction potential. In addition, the complexity of agricultural carbon emissions within the region prevented this study from fully reflecting its agricultural carbon emissions reduction capacity. Future more detailed studies will further improve the evaluation system for agricultural carbon emissions reduction potential.

<https://doi.org/10.17221/329/2023-AGRICECON>

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Received: September 30, 2023

Accepted: March 7, 2024

Published online: March 25, 2024