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Green recovery of cropland carrying capacity in developed regions: empirical evidence from Guangdong, China

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Abstract

This paper evaluates the carrying capacity of cultivated land in Guangdong Province, China, using the entropy weight method. Ecological and environmental pressure significantly impacts capacity, while economic and social factors are stable. Production pressure fluctuates and rises. To improve capacity, we must reduce ecological and environmental pressure, protect cultivated land resources, develop and promote green technology, and maintain water conservation facilities. The results indicate that reducing ecological and environmental pressure is essential to improve the carrying capacity of cultivated land in Guangdong Province. In conclusion, this study highlights the importance of balancing economic growth with environmental sustainability in developing regions like Guangdong Province. It suggests that a holistic approach that considers ecological, economic, and social factors is necessary to ensure long-term food security and sustainable land use practices.

Keywords Staple grain · Cropland land carrying capacity · Grading evaluation

JEL Classification Q57

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1 Introduction

The sustainable use of land is an important global concern as it affects food security, environmental health, and climate change. In developed regions, increasing population and industrialization have put pressure on cropland, which in turn has affected the cropland carrying capacity. Therefore, there is a need for green recovery approaches to increase cropland carrying capacity while promoting sustainability. Land degradation has become a significant concern globally, with estimates suggesting that approximately 33% of the world's land is degraded, and a further 20% is under threat of degradation (Li and Umair 2023). The consequences of land degradation include a decline in soil fertility, reduced agricultural productivity, and an increase in greenhouse gas emissions, leading to climate change. Cropland degradation is a significant contributor to land degradation, and the loss of cropland has led to food insecurity in some regions (Liu et al. 2023).

Developed regions face additional challenges to cropland degradation, including urbanization, industrialization, and pollution. Urbanization and industrialization lead to the conversion of cropland to urban and industrial areas, while pollution affects soil fertility, limiting the cropland carrying capacity. Therefore, green recovery approaches are essential to increase the cropland carrying capacity while promoting sustainability (Fang et al. 2022). The concept of green recovery aims to restore degraded land while promoting sustainable land use practices. Green recovery approaches include soil improvement techniques, precision agriculture, and the use of organic fertilizers. Soil improvement techniques, such as terracing and conservation tillage, help to improve soil fertility and reduce erosion. Precision agriculture involves the use of technology, such as sensors and drones, to optimize crop yields while minimizing inputs. The use of organic fertilizers, such as compost and manure, enhances soil fertility while reducing environmental impacts (Pan et al. 2023).

Guangdong is a representative region of China's rapid industrialization, urbanization, and agricultural development. According to data from the U.S. Department of Agriculture, by the summer of 2022, China's grain reserves rose to 69% of the world's maize, 60% of its rice, and 51% of its wheat.[1] However, even though China has alleviated the problem of food quantity, the Chinese government still attaches great importance to grain production and actively implements various subsidy policies to ensure the production of food while promoting the recultivation and replanting of abandoned farmland (Wu et al. 2022). In recent decades, Guangdong has experienced significant land use changes, including the conversion of cropland to industrial and urban areas. The loss of cropland has led to food insecurity, particularly for low-income households. Even Guangdong—an economically developed province—cannot be exempted from the responsibility to pursue grain production, and it is a normal task for Guangdong to maintain the recovery growth of grain sown areas. Guangdong is the largest economic province in China, with a permanent

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[1] "China Stockpiling Food at Historically High Levels." The Watchers, 14 Jan. 2022, https://watchers.news/2022/01/14/china-stockpiling-food-historically-high-levels/.

population of more than 100 million, with the country's largest GDP since 1989, and represents one-eighth of the state's total economic output. It is also the largest grain sales area in China, with a grain self-sufficiency rate of less than 35% while food security is mainly met from outside the province. In 2021, Guangdong's total grain output was 12.799 million tons and the sown area of grain was 2.2131 million hectares, representing increases in area, yield, and total output.[2] Moreover, total grain output reached its highest level in the past nine years and the early rice yield the same for the past 22 years (Umair and Dilanchiev 2022; Xiuzhen et al. 2022).

However, while the food security problem has been alleviated, the contradiction between cultivated land's ecological security and socioeconomic development has gradually become an issue in Guangdong Province, which is in the vanguard of national economic development. One of the central problems is the industrial pollution caused by economic development. According to the first national pollution source census, Guangdong Province's industrial pollution account for 17.1% of the country's total environmental damage, especially in the Pearl River Delta region, where the soil on the outskirts of the city is polluted by industrial waste water, gas, and residue, respectively (Ullah et al. 2020). Once released into the natural environment, these heavy metals or acid wastewater accumulate easily in soil layers and have proved difficult to biodegrade or decompose, which has had a negative effect on food safety and human health. Recently, most of the low-level manufacturing industry in cities has moved to areas outside the Pearl River Delta, and therefore some rural and underdeveloped areas have also been polluted by industrial production. Another pollution problem is caused by the agricultural production system. The increasingly frequent use of chemical fertilizers, pesticides and agricultural film has a negative impact on the ecological security of cultivated land. According to the first national survey of pollution sources, chemical oxygen demand and ammonia nitrogen emissions—the main emission indicators of water pollutants—accounted for 31.7% and 24.9% of agricultural pollution sources in Guangdong Province, respectively. Regarding livestock industry emissions, the COD emissions of the pig industry accounted for 61.77% and the emissions of ammonia nitrogen accounted for 90.55%, becoming the main source of COD and ammonia nitrogen emissions of water pollutants. The last problem is disasters caused by the natural ecosystem. The rainy season in Guangdong Province is concentrated in the period from March to September, which is marked by heavy rainfall and typhoons, and the uneven distribution of rainfall in some areas results in drought, so the climate also affects the ecological security of cultivated land to a certain extent (Mohsin et al. 2020a).

Over the past ten years, the concept of economic development at the expense of the ecological environment seems to have changed. In 2013, President Xi Jinping first suggested that "lucid waters and lush mountains are invaluable assets."[3] In

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[2] Guangdong Provincial Bureau of Statistics. "2021 Guangdong Agricultural Production Operation Brief." Guangdong Provincial Bureau of Statistics, 18 Jan. 2022, http://stats.gd.gov.cn/tjkx185/content/post_3768144.html.

[3] On September 7, 2013, President Xi Jinping delivered a speech at Nazarbayev University in Kazakhstan on environmental protection issues. He pointed out: "We want both green mountains and blue waters as well as gold and silver mountains. We prefer green mountains and blue waters to gold and silver

2016, a series of documents in the 13th five-year plan were issued to integrate this concept of green development into all aspects of the national economy and people's livelihoods. Several years later, Guangdong Province, in the vanguard of economic development, has taken a new step toward the green development of agriculture. To make up for ecological shortcomings in agricultural development, the Department of Natural Resources of Guangdong Province issued the *Regulations on the Quality Management of Cultivated Land in Guangdong Province*, which aims to further protect and improve the ecological safety quality of cultivated land, ensuring food security, improving the quality of agricultural products, and promoting the sustainable development of agriculture. All municipal-level governments actively carry out rotation, strive to use less fertilizer and pesticides and more effectively, and pursue the remediation and treatment of contaminated cultivated land. Over the past decade Guangdong Province has implemented the largest agricultural non-point source pollution control project in Asia, with a total investment of 213 million US dollars, becoming the first province in China to use World Bank funds. In 2022, the Guangdong Provincial Government issued its *Opinions on Comprehensively Promoting the High-level Protection and Efficient Utilization of Natural Resources*, emphasizing the need to achieve both the "high-level protection" of cultivated land resources alongside the "efficient utilization" of cultivated land resources. From the above analysis, we can draw two conclusions: Firstly, the arable land carrying capacity of Guangdong Province has declined in the past few decades. Secondly, the ecological security of cultivated land may be an important direction in terms of guaranteeing the carrying capacity of arable land in Guangdong Province in the future. At present, it is difficult to achieve further improvement in the quantity and quality of food security; therefore, ecological security plays a key role in the rise and fall of the province's arable land carrying capacity.

Thus, this paper analyzes the situation of Guangdong Province from 2009 to 2020, scientifically measuring the overall arable land carrying capacity and the impact of changes in the composition of the bearing capacity system. This study highlights the importance of implementing sustainable practices in developed regions to enhance the carrying capacity of cropland. We present empirical evidence from Guangdong, China, demonstrating that a green recovery strategy can improve the productivity of cropland and increase its capacity to support agricultural production. The study shows that practices such as precision agriculture, water-saving irrigation, and soil improvement can significantly increase the yield of crops, while reducing the environmental impact of farming. This study have attempted to establish a specific mathematical model to analyze land carrying capacity in various places from the perspective of arable land resources water resources and the atmospheric environment but these studies are still lacking in empirical evidence in relation to ecological resource improvements affecting the carrying capacity of arable land to form green restoration. The results of the study will make marginal

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Footnote 3 (continued)

mountains, and green mountains and blue waters are gold and silver mountains." This vividly expresses the Chinese government's firm determination to promote ecological construction.

contributions to related fields and are expected to be instructive for the formulation of green development policies in developing countries.

2 Literature review

Decreases in both the quantity and quality of cultivated land in China have drawn close attention recently due to threats to food security (Iqbal et al. 2019). Earlier studies of arable land carrying capacity focused on the measurement of water and soil availability in livestock systems. From the perspective of cultivated land resources (Shah et al. 2019) mention that China's crop production will become more difficult given climate change, resource scarcity and environmental degradation. Ikram et al. (2019) examine changes to the area of cultivated land and its potential agricultural productivity in China, finding that the country recorded a net increase in cultivated land which almost offset the decrease in average potential productivity between 1986 and 2000. Mohsin et al. (2020b) used a soil quality coefficient to measure the potential productivity of cultivated land. The analysis based on Sichuan Province showed a grain gap and population overload in the whole province after 2000. From the perspective of water resources, Zhang et al. (2021) made a comprehensive assessment of the carrying capacity of agricultural water resources in Songhua River District. From the perspective of climate carrying capacity, Iqbal et al. (2022) used a stepwise correction method to study the regional climatic productive potential and its variation characteristics. The empirical study of Anhui Province showed that the climate potential production of the whole province has been in decline since the 1960s.

From the ecological perspective, (Xia et al. 2020) put forward the concept of the "maximum limit of the number of individual organisms existing under specific environmental conditions." In the study of human ecology, it mainly refers to the combination of living space, nutrients, sunlight and other ecological factors. The term was subsequently defined as "environmental carrying capacity" by the Chinese Academy of Environmental Sciences, reflecting the interaction between the intensity of human activities and the environment (Agyekum et al. 2021). A study by Luo et al. (2019) showed that there were significant inter-provincial differences in the ecological footprint of cultivated land in China, while the cultivated land ecological index of food security in major grain-producing areas showed an inverted U trend of deficit expansion from 2007 to 2016. Another part of the study was based on monitoring and early warning regarding the food security situation. Mohsin et al. (2020a) believed that the establishment of a food security early warning and monitoring index system was essential to food security. Network technology should be fully utilized to establish an automatic early warning and monitoring system. Mohsin et al. (2022) proposed a multi-factor food security assessment method based on information fusion. Chang et al. (2023) constructed the change rate of grain yield and food security index model from the perspective of food supply and consumption to judge the regional food security situation. On the other hand, Chang et al. (2022b) used the entropy weight extension decision model in their research. Chang et al. (2022a) developed the yield forecasting method of wheat in the key growth period of the county between years and over production seasons. Wang et al. (2021) used the arable land pressure model to verify the spatiotemporal latitude of food security in China's major grain-producing areas. This study is enlightening in terms of the diverse perspectives and methods of existing studies, focusing on the carrying capacity of production factors. Zameer et al. (2022) constructed an evaluation index system based on atmospheric environmental carrying capacity, with the research showing that the level of atmospheric environmental carrying capacity in Jing-Jin-Ji region showed an upward trend from 2013 to 2016. Atmospheric conditions have shown great progress in improving air quality in recent years and is expected to improve further.

2.1 Green economic recovery

Green recovery is a concept that refers to the idea of building back the economy after a crisis in a way that is sustainable, resilient and equitable. The concept has gained significant attention in recent years, particularly in the context of the COVID-19 pandemic, which has had a profound impact on economies around the world. Governments and organizations are increasingly recognizing the need to adopt green recovery strategies to not only address the immediate economic challenges but also to tackle long-term issues related to climate change, environmental degradation, and social inequality (Zhang and Dilanchiev 2022).

Numerous studies (Wahid et al. 2020) have been conducted on the concept of green recovery and its potential benefits. According to a report by the United Nations Environment Programme (UNEP), investing in green sectors such as renewable energy, sustainable transport, and energy efficiency could lead to significant job creation and economic growth. The report suggests that green recovery measures have the potential to create up to 24 million new jobs globally by 2030, while reducing greenhouse gas emissions and increasing energy efficiency. The report also highlights the need to prioritize investments in vulnerable communities and sectors to ensure that the benefits of green recovery are distributed equitably.

Similarly, a study by the International Renewable Energy Agency (IRENA) suggests that investing in renewable energy could lead to significant economic benefits, including increased GDP, job creation, and improved energy security. The report argues that renewable energy technologies are becoming increasingly cost-competitive, making them a viable option for governments looking to invest in green recovery.

In addition to economic benefits, green recovery strategies also have the potential to address environmental challenges. According to a report by the Global Commission on Adaptation, investing in climate adaptation measures such as infrastructure improvements and ecosystem restoration could generate significant environmental benefits, including improved air and water quality, reduced flood risk, and enhanced biodiversity. The report suggests that green recovery measures could help to build more resilient and sustainable communities, which are better equipped to cope with future environmental challenges (Batool et al. 2022).

Despite the potential benefits of green recovery, there are also challenges associated with implementing these strategies. One challenge is the need to overcome resistance from industries and stakeholders that may be opposed to changes in the status quo. For example, some fossil fuel companies may resist a shift toward renewable energy, which could impact their bottom line. Similarly, there may be challenges associated with financing green recovery measures, particularly in countries with limited resources (Huang et al. 2022).

To overcome these challenges, governments and organizations must take a proactive approach to green recovery. This could include implementing policies that encourage investment in green sectors, providing incentives for companies to adopt sustainable practices, and investing in research and development of new technologies. Additionally, there is a need for greater collaboration between governments, businesses, and civil society to ensure that green recovery strategies are implemented effectively and equitably (Dilanchiev and Taktakishvili 2022).

In conclusion, green recovery is an important concept that has the potential to address both immediate economic challenges and long-term environmental and social issues. While there are challenges associated with implementing these strategies, there is growing recognition of the need to adopt sustainable and equitable approaches to building back the economy after a crisis. With the right policies and investments, green recovery measures could create significant economic, environmental, and social benefits for communities around the world.

To sum up, the relevant researches on cultivated land resource productivity focus on the livestock system, water resources, and climate-carrying and ecological carrying capacities, respectively. Scholars have carried out many measurements of cultivated land productivity system in developing countries such as China, and these studies confirm the importance of ecological resources in terms of the carrying capacity of arable land, but there is little evidence that ecosystem improvements can provide the impetus for green recovery in terms of the overall quality of cultivated land. By conducting long-term measurement of the carrying capacity of arable land in Guangdong Province—the fastest growing province in China—this paper aims to observe the impact of ecosystem improvement on the restoration of cultivated land productivity to support green recovery.

3 Theoretical framework

The theoretical framework is the basis of the evaluation of the carrying capacity of grain production resources which is directly related to the accuracy and scientific validity of the evaluation results. In this paper, referring to the evaluation research of (Castellani and Giovannetti 2010) on the setting of food security, the evaluation system is set as three systems. The following is an explanation of the composition of these index systems.

3.1 Economic pressure system

Economy and population are the essence of pressure on the cultivated land resources. The economic development of a place helps population agglomeration and produces large amounts of human society and management activities, which demand natural resources several times more than the agglomeration generated by natural human reproduction. Therefore, the pressure on food production generated by economic, demographic and social factors is summarized as a system of economic pressures, they include:

(1) *Economic development* Guangdong Province is the leading economy in the country. Economic development has had a great impact on the development of agriculture and rural areas. Recent studies have found that economic development is also an objective factor affecting food production (Borio 2020). The development of the national economy is driven by the increase in rural residents' income on the one hand and a boosting of rural residents' consumption expenditure on the other. Therefore, the two factors are also a factor that makes up the carrying capacity of local food security.

(2) *Social factors* Agricultural production benefit is an important part of ensuring the improvement of farmers' income and also an important factor affecting the carrying capacity of cultivated land. On the other hand, the agricultural output benefit per unit area of cultivated land has also continued to grow, and the increase in agricultural production efficiency is largely attributed to the adjustment of the industrial structure (Scharf et al. 2020).

3.2 Production pressure system

The amount of soil and water resources in use are the main factors that ensure grain carrying capacity, which can be reflected not only in terms of the quality of cultivated land and resource endowment, but also by the quantity of the production factors of modern agriculture. Specifically, these include:

(1) *Resource endowment* In order to further consolidate the foundation of the grain reserve guarantee and to improve the ability to guarantee food security, natural conditions and grain resource endowment are necessary. Undoubtedly, the cultivated land area is a basic indicator reflecting the endowment of food resources (Lu et al. 2021). In addition, the per capita cultivated land area reflects the per capita situation of land resource endowment.

(2) *Background quality* The background quality of land is the basis of grain quality and security, and the function of soil and water conservation is the primary factor of background quality. Therefore, agricultural water use is directly related to grain production safety. In addition, the change of the multiple cropping index of rice production has an important impact on national food security (Çelebi et al. 2015). The multiple cropping index refers to the proportion of the sown area of

the planting industry in the cultivated land area. A high multiple cropping index plays an important role in developing agricultural production and increasing output.

(3) *Production conditions* The level of agricultural mechanization is an indicator of the quality of grain production conditions in a region and an important factor ensuring the scale and modernization of the grain industry.

3.3 Ecological and environmental pressure system

Ecological security is the guarantee of food and cultivated land security, respectively, and represents a barrier to maintaining, in turn, the quality of crops, the stability of the functional structure of the cultivated land ecosystem, and the sustainable use of cultivated land within a certain time and space. Specifically, ecological security encompasses:

(1) *Natural factors* Natural disasters have a great impact on food security and stability of grain yield, and the affected area refers to the sown area of crops reduced by more than 10% due to disaster. Guangdong Province is located in the "typical climate vulnerable zone" and is one of the provinces prone to various natural disasters, including heavy rainfall and flooding, tropical cyclones, droughts, cold spells, earthquakes, geological disasters, red tides, biological disasters, and forest fires. There are many kinds of disasters with the characteristics of long durations, high frequencies, and serious conditions. In the context of global climate warming, extreme weather events have posed a real challenge to food security. Sustainable forestry is an important barrier to food security (Gao and Hou 2016), and "forest coverage rate" refers to the ratio of forest area to the total land area, which is an important indicator of the actual level of forest resources and forestland occupation in a given country or region. Over the past two decades, Guangdong Province has invested a lot of human and material resources to strengthen the construction of its forest and wetland ecosystems and to protect biodiversity, which has not only realized the coordinated development of forest resources and the forestry industry, but also indirectly strengthened those environmental conditions conducive to agricultural production https://baike.baidu.com/item/%E6%B9%BF%E5%9C%B0%E7%94%9F%E6%80%81%E7%B3%BB%E7%BB%9F/2031298.

(2) *Environmental factors* with the increase in industrial inputs into agricultural production environment, the situation of food production is serious and urgent, bringing some challenges to food security. The implementation of environmental behaviors regarding reduction, reuse, and low pollution in food production by farmers is the key to curbing agricultural pollution at source and achieving sustainable development. In Guangdong Province, the three agricultural pollution indicators of chemical fertilizer, pesticide, and agricultural film use showed a trend of increasing and then decreasing over the past 21 years, especially in the last decade, which has been well controlled. Since the period of the 11th five-year plan, Guangdong has carried out a comprehensive promotion of soil testing

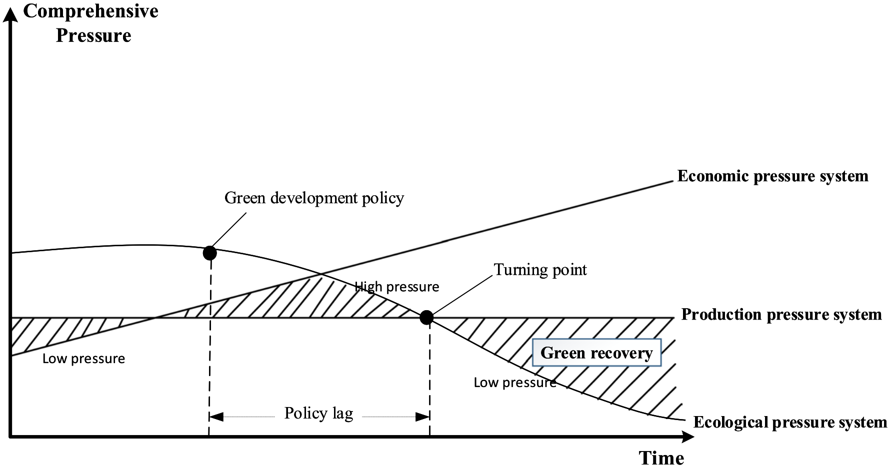

Fig. 1 Internal relationship between the arable land pressure system and green recovery

formula fertilization, applied pesticide reduction technology, and initiated the implementation of the "action of zero growth of fertilizer and pesticide use."[4] By 2020, the amount of fertilizer and pesticides applied in the province had achieved negative growth for five consecutive years. The comprehensive utilization rate of livestock and poultry manure was more than 75%, the comprehensive utilization rate of straw reached 91%, and the recovery rate of agricultural film reached more than 90%.

3.4 Improvement of the ecological pressure system mitigates the whole system

From the perspective of the economic development trend, the pressure of land production is mounting as the relationship between population and land is under strain. This trend particularly exists in developing countries (Alavi et al. 2016), which leads to constant high pressure between the economic and production pressure systems. With the rise in environmental awareness in emerging developing countries in the twenty-first century and the need for green economic recovery in the new era (Firpo et al. 2017), a new development philosophy that highlights innovation, coordination, greenness, openness, and sharing has appeared in China's development plan. Some top-down reforms have occurred, such as the need to improve human settlement environments, control non-point source pollution, and construct high-standard farmland, which have largely solved the problems of regional ecosystem degradation and low quality economic development. By 2020, green governance had become an important practice in China's rural development. We believe that China's green

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[4] In February 2015, the Chinese government issued the "Action Plan for Zero Growth of Fertilizer Use by 2020" and the "Action Plan for Zero Growth of Pesticide Use by 2020". The "Zero Growth Action for Fertilizer and Pesticide" was officially launched in various provinces and regions across the country.

development measures have also brought green recovery to the carrying capacity of arable land, thereby easing the pressure on the economy and production.

We draw a simple theoretical framework (Fig. 1) to illustrate this green recovery. Owing to the growth of the national economy, the economic pressure system is represented as a straight line with a positive slope, which makes a positive contribution to the total pressure. The production pressure system is represented as a horizontal straight line, and due to the decline in population growth, the improvement of farmland facilities, and the continuous increase in food production, we hold the view that production pressure should fluctuate from year to year, which can be shown in a gentle straight line under the leveling effect of time. The environmental pressure system is presented as a curve with an overall downward trend due to a series of policies under the concept of green development promoted by the state. Otherwise, at the front end of the line segment, the trend is supposed to be upward. The shaded area is the pressure interval generated by the three systems, which reflects the overall pressure of the cultivated land system. It can be seen that, after the excessive policy lag, the general system will return to the turning point and is expected to enter the low-pressure range again, thereby achieving a green recovery.

4 Data, variable selection and model setting

4.1 Data

The years 1999–2020 are selected as the research period. The main data sources are as follows: *Guangdong Statistical Yearbook (2001–2020)*, *Guangdong Rural Statistical Yearbook (2001–2020)*, EPS global statistical data platform China Macroeconomic Database, China Land and Resources Database, China Water Conservancy Database, China Environment Database, China Agriculture and Forestry Database and other related databases. Of these, cultivated land data have statistical caliber changes before and after 2005. In this study, the new statistical caliber is used as the standard, and the cultivated land data from 2000 to 2005 are converted into equal ratio during data processing. In addition, the data of cultivated land area in 2009 and 2010 are not publicized because the data of the second land survey have not been confirmed by the state. The data are based on the average change rate of cultivated land area in the five years before and after the missing year.

4.2 Variable selection

In this paper, the evaluation system of grain production capacity is divided into three subsystems: economic, production and ecological environment pressures, respectively (Müller et al. 2021). Of these, the subsystem of economic pressure includes four indicators of economic development and three indicators of social factors. Production pressure also includes two indexes of resource endowment, three indexes of background quality, and three indicators of modern production factors. Ecological and

Table 1 Evaluation index system of food production resources and environment

First criterion layer	Second criterion layer	Indicator layer	Description of variables	Data source
The economic pressure	The economic development	GDP per capita	GDP/population	Guangdong Statistical Yearbook
		Consumption level of rural residents	Consumption level of rural residents	Guangdong Rural Statistical Yearbook
		Per capita net income of farmers	Per capita net income of farmers	Guangdong Rural Statistical Yearbook
		Level of urbanization	The urban population/total population	Guangdong Statistical Yearbook
	Agricultural output value and structure	Output value per unit of land	Total agricultural output value/arable land area	Guangdong Rural Statistical Yearbook
		Output per capita Per capita output value	Total agricultural output value/total population	Guangdong Rural Statistical Yearbook
		Adjustment of agricultural structure	Agricultural output value/Total output value of agriculture, forestry, animal husbandry and fishery	Guangdong Rural Statistical Yearbook
Production pressure	Resources endowment	Area of cultivated land	Area of cultivated land	Guangdong Rural Statistical Yearbook
		Per capita cultivated land area	Cultivated area/population	Guangdong Rural Statistical Yearbook
	Soil quality	Water resources per capita	Total water resources/total population	Economy Prediction System
		Irrigation guarantee rate	Effective irrigated area/cultivated area	Economy Prediction System
		Multiple cropping index of grain	Total sown area/cultivated area	Guangdong Rural Statistical Yearbook
	Modern factors of production	Agricultural mechanization level	Total mechanical power/cultivated area	Economy Prediction System
		Rural electricity consumption per unit area	Rural electricity consumption/arable land area	Economy Prediction System

Table 1 (continued)

First criterion layer	Second criterion layer	Indicator layer	Description of variables	Data source
Ecological environment pressure	Natural factors	Area affected by natural disasters	Area affected by natural disasters	Guangdong Water Conservancy Statistical Yearbook
		Forest coverage rate	Forest coverage rate	Economy Prediction System
		Proportion of investment in environmental governance	Investment in environmental governance/GDP	Economy Prediction System
	Environmental factors	Fertilizer load per unit area of cultivated land	Fertilizer application rate/cultivated area	Guangdong Rural Statistical Yearbook
		Pesticide load per unit area of cultivated land	Pesticide application rate/cultivated area	Guangdong Rural Statistical Yearbook
		Plastic film load per unit area of cultivated land	Plastic film application rate/cultivated area	Guangdong Rural Statistical Yearbook

environmental pressure also includes three indicators of natural factors and three of environmental factors (Table 1).

4.3 Model setting

4.3.1 Data standardization

Due to the different dimension unit and properties of each indicator, in order to avoid the difference in the order of magnitude and dimension of the original data, the original data are first processed using the following formula:

Positive indicators:

$$x'_{ij} = \frac{x_{ij} - x_{j\min}}{x_{j\max} - x_{j\min}}$$

Contrarian indicators:

$$x'_{ij} = \frac{x_{j\max} - x_{ij}}{x_{j\max} - x_{j\min}}$$

where x'_{ij} is the standardized indicator and x_{ij} is the jth index of the ith year.

4.3.2 Weight computing

The evaluation of the carrying capacity of grain production resources is a multi-attribute decision-making problem. In order to avoid the interference of human factors and compare different years in order to objectively analyze weights of indicators, the specific steps used are as follows:

Step 1 Determine the weight of the jth index in the ith year.

$$s_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}}$$

Step 2 Measure entropy value of the jth index.

$$h_j = -\frac{1}{\ln(rn)} \times \sum_{i=1}^{n} s_{ij} \ln\left(s_{ij}\right)$$

Step 3 Calculate the redundancy of information entropy.

$$a_j = 1 - h_j$$

Step 4 Calculate index weights.

$$w_j = \frac{a_j}{\sum_{j=1}^{m} a_j}$$

Table 2 Basic statistical values and weights of each index

Indicator layer	Annual mean of original data	Annual mean of standardized data	Entropy weight entropy weight	Annual mean of weighted data	Indicators of plus or minus
Per capita GDP	44,282.9	0.605	0.076	0.029	Positive
Rural residents' consumption level	7593.5	0.637	0.060	0.025	Negative
Rural per capita net income	8626.8	0.604	0.035	0.019	Negative
Urbanization level	0.635	0.430	0.031	0.019	Positive
Unit land output value	0.674	0.379	0.017	0.011	Positive
Unit per capita output value	0.367	0.410	0.022	0.013	Positive
Agricultural structure adjustment	0.479	0.456	0.050	0.029	Negative
Cultivated land area	2819.9	0.317	0.094	0.031	Negative
Farmland areas per person	0.290	0.302	0.070	0.021	Negative
Per capita water resources	1899.2	0.434	0.035	0.020	Negative
Probability of irrigation	0.659	0.557	0.028	0.014	Negative
Grain multiple cropping index	1.663	0.509	0.039	0.013	Positive
Agricultural mechanization level of cultivated land per unit area	0.777	0.484	0.060	0.028	Positive
Rural electricity consumption per unit area	0.360	0.565	0.029	0.018	Positive
Natural disaster area	893.9	0.580	0.027	0.016	Positive
Forest coverage percentage of forest cover	48.991	0.332	0.044	0.021	Negative
Proportion of investment in environmental governance	0.00089	0.399	0.020	0.011	Negative
Fertilizer load per unit area of cultivated land	0.080	0.429	0.055	0.024	Positive
Pesticide load per unit area of cultivated land	0.00355	0.456	0.065	0.031	Positive
Film load per unit area of cultivated land	0.00075	0.435	0.053	0.023	Positive

According to the formula, the index weights of the grain production resources carrying capacity evaluation system in Guangdong Province are calculated as illustrated in Table 2.

Table 2 provides basic statistical values and weights of each index used in the study. The table includes 19 indicators and their annual mean of original data, annual mean of standardized data, entropy weight, annual mean of weighted data, and indicators of plus or minus. The entropy weight column shows the weight assigned to each indicator based on the entropy method, which is a multi-criteria decision-making technique used to determine the weight of each criterion. The higher the entropy weight, the more important the indicator is in the study.

The annual mean of standardized data column shows the normalized value of each indicator, with a range of 0–1. The annual mean of weighted data column shows the weighted value of each indicator based on the entropy weight. The indicators of plus or minus column indicate whether the indicator has a positive or negative impact on sustainable agriculture. For example, per capita GDP and urbanization level have a positive impact, while rural residents' consumption level and rural per capita net income have a negative impact. From the table, we can see that per capita GDP has the highest entropy weight (0.076), indicating that it is the most important indicator in the study. This is followed by the entropy weights of rural residents' consumption level (0.060) and agricultural structure adjustment (0.050). Some of the indicators that have a negative impact on sustainable agriculture include rural residents' consumption level, rural per capita net income, cultivated land area, farmland areas per person, and proportion of investment in environmental governance. On the other hand, indicators such as per capita GDP, urbanization level, unit land output value, unit per capita output value, and grain multiple cropping index have a positive impact on sustainable agriculture.

4.3.3 Calculation and classification method of the carrying capacity index of grain production resources

The evaluation system of the carrying capacity of cultivated land resources includes three subsystems: economic pressure, production pressure and ecological environment pressure indexes, respectively. This paper adopts the comprehensive evaluation method to calculate the carrying capacity using the following formula:

$$E = \sum_{j=1}^{m} x'_{ij} \times w_j$$

where E is food security and farmland carrying capacity index; x'_{ij} is the standardized index value; and w_j is the index weight.

Table 3 Index of grain security and cultivated land carrying capacity in each year

Years	Economic pressure index	Production pressure index	Ecological pressure index	Comprehensive carrying capacity index
2000	0.20	0.23	0.33	4.04
2001	0.22	0.29	0.15	4.54
2002	0.23	0.24	0.23	4.27
2003	0.25	0.28	0.43	3.23
2004	0.30	0.36	0.32	3.08
2005	0.33	0.42	0.35	2.76
2006	0.36	0.39	0.32	2.80
2007	0.38	0.40	0.46	2.44
2008	0.40	0.42	0.44	2.40
2009	0.46	0.42	0.58	2.07
2010	0.46	0.54	0.60	1.91
2011	0.50	0.59	0.63	1.79
2012	0.55	0.72	0.79	1.50
2013	0.56	0.70	0.76	1.52
2014	0.58	0.77	0.78	1.45
2015	0.59	0.84	0.78	1.40
2016	0.61	0.85	0.82	1.35
2017	0.64	0.65	0.83	1.44
2018	0.66	0.73	0.79	1.40
2019	0.69	0.74	0.64	1.45
2020	0.75	0.75	0.53	1.45

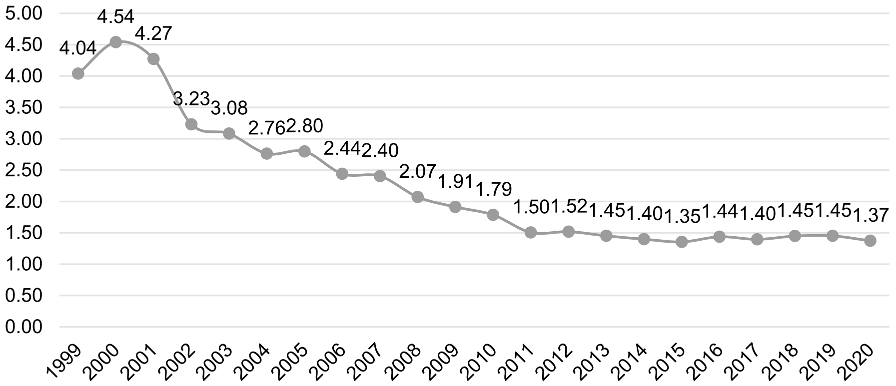

Fig. 2 Comprehensive carrying capacity of cultivated land resources in Guangdong Province from 1999 to 2020

5 Analysis of comprehensive evaluation results

5.1 Overall evaluation results

Based on the above index system and formula, the carrying capacity index of cultivated land in Guangdong Province from 2000 to 2020 is calculated. The carrying capacity indexes of three subsystems are further distinguished in this study. The specific results are shown in Table 3.

In general, the carrying capacity of cultivated land resources in Guangdong Province has showed a downward trend since the twenty-first century (Fig. 2). The economic, production and ecological environmental pressures of cultivated land all show an upward trend, among which the economic pressure index rises most smoothly, the production pressure index shows a fluctuating upward trend, and the ecological pressure index obviously shows a trend of rising first and then falling. Overall, the evolution of the carrying capacity of cultivated land resources in Guangdong Province can be divided into four stages:

5.1.1 The period of gentle development (before 2005)

During this period, the characteristics of the cultivated land carrying capacity system in Guangdong Province were as follows: low enthusiasm for grain planting and the rapid pace of economic development meant that the pressure on cultivated land tended to be balanced and moderate. On the eve of the reform of agricultural taxes and fees, grain producers bore the double burden of “field rent” and “miscellaneous fees” while farmers’ enthusiasm for grain cultivation experienced a gradual decline. As a major location launching the reform and opening up process, Guangdong faced the situation that its arable land carrying capacity was simultaneously tested by both economic development and grain yield protection, while cultivated land was under pressure from the slow climb of economic development and production capacity. At the same time, Guangdong was in the early stages of industrial transformation. Even though township enterprises actually caused greater damage to the rural ecological environment, quality and safety-related problems were not prominent while environmental problems had not yet become the focus of public attention as the degree of grain commercialization was low at that time, and most agricultural land was subsistence crop field. As a result, environmental pressure could be maintained at a relatively low level.

5.1.2 The period of over-development (2006–2010)

The characteristics of the carrying capacity system of cultivated land in this stage were as follows: ecological pressure gradually emerged, while production and economic pressures kept pace. After canceling agricultural tax, the rural society of Guangdong Province entered into a new stage of development. The national position for farmers gradually transitioned from “taking” to “giving,” and reforms to agricultural taxes and fees undoubtedly encouraged farmers to grow food. In addition, the country intensified the subsidy of food production, leading to a significant increase in pressure on arable land production during that period (Falchetta and Mistry 2021). At the same time, agricultural production was facing serious challenges, including the continued reduction of available arable land, weak infrastructure, overall deterioration of the environment, and water shortages. Coupled with China’s then emerging food quality and safety issues and frequent meteorological disasters, the ecological and environmental pressure on arable land rose steeply, while the ecological and environmental pressure index increased at a faster rate and is now running at an unprecedentedly high level (Vishwanathan and Murty 2000).

5.1.3 The period of transformation and protection (2011–2015)

The characteristics of cultivated land carrying capacity system in this stage are as follows: economic and production pressures increased steadily, while ecological pressure increased slowly. Guangdong Province entered the stage of agricultural modernization, and the idea of agricultural development changed to “stable supply” and “quality assurance.” During this period, agricultural production in Guangdong Province had initially reflected the prototype of standardization, modernization and scale. Under the progress of science and technology and given the development of business entities, the production pressure index had steadily and slowly improved. On the other hand, with the emergence of “cadmium rice,” “gutter oil” and other food security incidents, Guangdong Province began to attach importance to the construction of agricultural quality and safety systems and standardized production and set up a testing system of agricultural products. As the World Bank began the implementation of a non-point source pollution control project in Guangdong, the government increased investment in the environmental protection of arable land (World Bank 2013). Under the dual attention of society and government, the rise in the ecological pressure index slowed down. Under the dual objectives of quantity and quality, the tension of cultivated land and the contradiction between human and land had not been effectively alleviated. The excessive and inefficient use of chemical fertilizers and pesticides still put pressure on the ecological safety of cultivated land in Guangdong Province.

5.1.4 The period of green recovery (after 2016)

The characteristics of cultivated land carrying capacity system at this stage were as follows: While economic and production pressures increased steadily, ecological pressure decreased substantially. The report of the 19th National Congress pointed out that “we must establish and practice the concept that clear water and green mountains are gold and silver mountains” (Xi 2017). Guangdong Province achieved results in the construction of modern agriculture and made new strides in the green development of agriculture. During the period, the agricultural development of

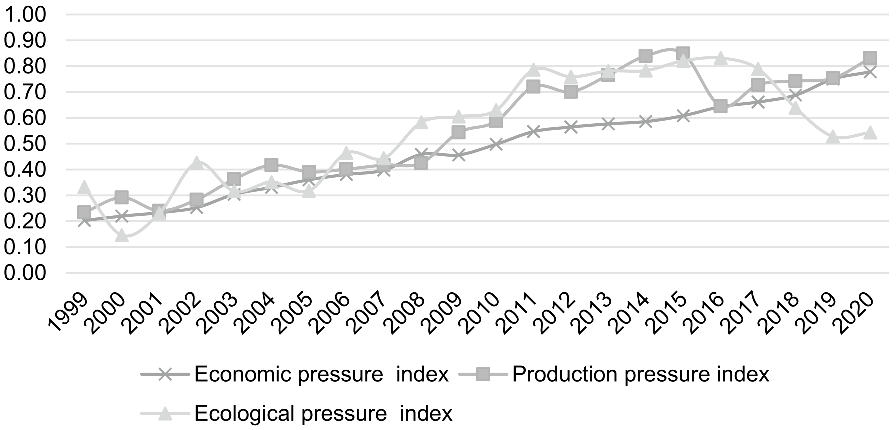

Fig. 3 Sub-index of cultivated land carrying capacity in Guangdong Province, 1999–2020

Guangdong Province started making up for ecological shortcomings. The province's fertilizer and pesticide application achieved negative growth for four consecutive years, the comprehensive utilization rate of livestock and poultry manure was above 75%, the comprehensive utilization rate of straw 91%, and the recycling rate of agricultural film more than 90%.[5] In this context, the ecological pressure coefficient of arable land declined rapidly. However, while implementing the hard indicators of ecological environment protection, the production pressure on cultivated land has maintained the original rate of increase. The economic pressure has also continued to rise.

With the change of orientation of agricultural production in Guangdong Province, the carrying capacity of cultivated land has also experienced different development stages. Two basic situational judgments can be drawn from the above analysis: First, the carrying capacity of grain production in Guangdong Province has decreased over the past 21 years. Out of the four periods, the comprehensive carrying capacity of the first three periods tends to decrease continuously, and the latter half of the period after 2016 shows signs of a rebound. Secondly, the contribution of the three subsystems (economic, production and ecological environment pressures, respectively) to the carrying capacity of cultivated land always increases and decreases. From the point of view of each period, the comprehensive carrying capacity index is either dragged down by production or ecological pressures, while the influence of economic pressure on the carrying capacity of cultivated land has been very stable, which also indicates that there is little possibility of adjusting the system. Thirdly, the ecological security of cultivated land may be an important direction in terms of ensuring the future carrying capacity of cultivated land in Guangdong Province.

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[5] Guangdong Provincial People's Government. "Guangdong Province's Plan for Advancing the Modernization of Agriculture and Rural Areas in the 14th Five-Year Period". Guangdong Provincial People's Government Website. 20 Aug. 2021. Web. 21 Mar. 2023 https://www.gd.gov.cn/xxts/content/post_3508047.html.

Over the past 21 years, the greatest fluctuations in the ecological pressure subsystem indicate that the system is relatively unstable and reveals that ecological security plays a key role in the rise and fall of the comprehensive carrying capacity of cultivated land, reflecting that it is difficult to make further progress in terms of the quantity and quality security of food. The contribution of each subsystem will be further analyzed in the following sections.

5.2 Analysis of grain security and farmland carrying capacity subsystem in Guangdong Province

This study analyzes the contribution of the three subsystems to food security and cultivated land carrying capacity and further tests them by comparative analysis.

5.2.1 Response analysis of economic pressure subsystem

In the past 21 years, the economic pressure index of grain production in Guangdong Province has gradually risen (Fig. 3). Overall, the growth rate has not fluctuated much in the past 21 years. Food quantity security is an important foundation for economic development, social stability and national security. In particular, since 2015, the People's Government of Guangdong Province has assumed primary responsibility for ensuring food security in the region. How to ensure basic self-sufficiency in grain, absolute grain security, and secure the rice bowl locally is a major challenge that Guangdong Province has to deal with.

By comparing several indicators of cultivated land economic pressure, we found that in the year of relatively large increase in economic pressure coefficient (2008), the indicators that reflected the increase the most were output value per unit land and output value per capita, respectively. In other words, the increase in the economic pressure index on cultivated land in Guangdong Province is attributable mainly to the increase in yield per unit area of crops. Over the past two decades, Guangdong has promoted the upgrading of the grain industry. The reform of state-owned grain enterprises has been deepened while mergers and reorganizations of state-owned grain enterprises have been promoted. The provincial government has supported grain enterprises to promote the application of advanced technology and equipment and carried out technological transformation and upgrading. Guangdong Province has also encouraged large- and medium-sized staple food processing enterprises to both develop cold chain facilities for warehousing and logistics and extend production and marketing networks to towns and rural areas. These measures have not only promoted industrial upgrading, but also further promoted the regional concentration of grain production in major grain-producing counties, while intensive production improves the benefits available to individual farmers.

5.2.2 Response analysis of the production pressure subsystem

Over the past 21 years, the grain production pressure index in Guangdong Province reflects a fluctuating upward trend. In 2009, a year with a large increase in production pressure, the indicators that contributed the most to this include per capita cultivated land area and cultivated land area. This is enough to show that the total amount of cultivated land in Guangdong Province has made a key contribution to the carrying capacity of cultivated land resources. The province was once the main production area of double-season rice in China and also one of the traditional southern rice areas. With the rapid growth of Guangdong's economy, the proportion of its secondary and tertiary industries participating in the national economy has gradually risen, and the position of agriculture in national economy—especially in relation to the plantation industry—has become more marginalized. The food industry, a weak industry that needs to be subsidized, does not generate local tax revenues while occupying a large amount of land. Therefore, its output, output value and future development are bound to be crowded out in the process of urbanization and industrialization while Guangdong's grain production position has changed from "main crop-producing area" to "main grain-consuming area."

In addition, the pressure on arable land production is strongly related to the commercialization rate of grain. During the period of high rates of grain self-sufficiency, the proportion of farmland devoted to the grain ration is large and the problems of production factors such as field facilities and levels of mechanization are not prominent. With the reform of agricultural tax, a significant increase has been witnessed in the enthusiasm of farmers for food production and food commercialization. The supply of food is gradually reflected in the security of production factors. Problems such as insufficient mechanization and old water conservancy facilities have also emerged (Amores et al. 2021).

On the contrary, in 2006, when the production pressure index showed a big decline, the indicators that reflected this to the largest extent were the irrigation guarantee rate and water resources per capita. This indicates that the decline evident in the index coincides with the year of abundant water resources. Guangdong Province belongs to a hilly region in the south. Although precipitation resources are relatively rich, old agricultural irrigation facilities result in flooding, water pollution and other problems. Therefore, agricultural water use is also a key factor regarding the carrying capacity of cultivated land in Guangdong.

5.2.3 Response analysis of the cultivated land ecological security subsystem

Over the past 21 years, the cultivated land ecological security index in Guangdong Province has first increased and then decreased. In 2002, when the ecological pressure index of cultivated land increased significantly, the indicators reflected the largest contribution were the proportion of investment in environmental governance and the areas affected by natural disasters. This indicates that the insufficient proportion of investment in environmental governance in Guangdong Province is the main reason for the decline of cultivated land ecological security, while serious natural disasters in different years are another reason for the decline of ecological security of cultivated land. A joint study by World Bank (2007) suggests that China's investment in air and water pollution control should be increased to 2 percent of GDP by 2020. Furthermore, the proportion of investment in basic capacity building should be increased. Therefore, the investment in environmental protection in Guangdong

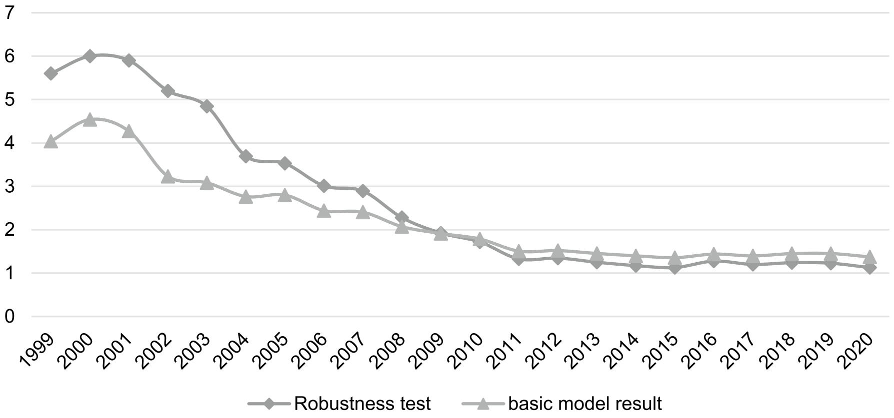

Fig. 4 Robustness test and benchmark model fitting diagram

Province (at most 0.18 percent of GDP over the past 21 years) is indeed seriously insufficient.

On the contrary, the years when the ecological pressure system of cultivated land showed a big decline (2018 and 2019) were mainly due to the reduction of pesticide use and fertilizer application. This shows that the improvement of the ecological safety of arable land in Guangdong Province depends on a reduction in the use of agricultural inputs. With the rapid development of agriculture and the rural economy China, agricultural chemicals such as chemical fertilizers, pesticides, and plastic films have increased year by year while the number of farms and the scale of farming have also grown (Pasiouras and Kosmidou 2007). At the same time, the low utilization rate of agricultural inputs and the lagging treatment of breeding waste have led to the increasingly prominent problem of pollution from non-point agricultural sources. Since 2012, Guangdong has implemented the largest agricultural non-point source pollution control project in Asia and the first World Bank-funded agricultural pollution control project in China (World Bank 2013). Comprehensive prevention and control technologies such as soil testing and formula fertilization technology, solar insecticidal lamps, natural enemies, biopesticides, and unified control services have been promoted in 28 counties (cities and districts) of Guangdong Province. In addition, a subsidy has been granted to the application of formula fertilizer, slow (controlled) release fertilizer, and water-fertilizer integration technology in the project area. Over the past three years, a total of 234 million Yuan of World Bank loans and provincial matching funds have been invested to provide 32,000 tons of formula fertilizers and 33 tons of biopesticides and high-efficiency and low-toxicity pesticides. In addition, Guangdong also attaches importance to, and supports the development of the fertilizer and pesticide industry, focusing on strengthening process supervision while placing equal emphasis on production and management.

In conclusion, over the past 21 years, the carrying capacity of cultivated land resources in Guangdong Province has shown a continuous decline; however, this rate of decrease has eased in the past decade. Most of the reduction has been achieved through the amelioration of ecological pressures and there are also

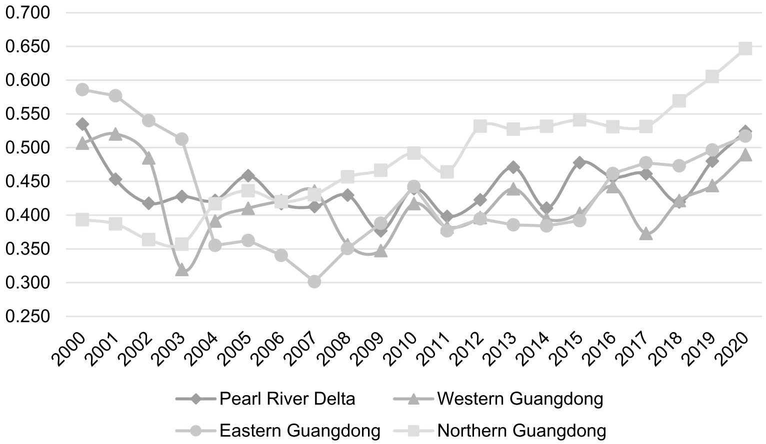

Fig. 5 Cultivated land carrying capacity index of Guangdong Province, 2000–2020 (summary)

consequences given fluctuating production pressures. Furthermore, the decrease in eco-environmental pressure in Guangdong Province has been achieved mainly by the reduction of the amount of inputs such as fertilizers and pesticides, while at an earlier stage the government's insufficient investment in environmental protection and natural disasters led to increased ecological pressures.

5.3 Robustness test

The entropy weight method used above is an effective way to achieve a multi-index comprehensive evaluation and it has been applied in much of the literature because of its efficiency and convenience (Ehsanullah et al. 2021). Compared with the subjective assignment method, the advantage of entropy weight is that it avoids the bias caused by human factors. Meanwhile, it can be prone to ignoring the intentions of the researcher. Therefore, based on the discussion outlined in the theoretical framework, the study divides 20 variables into three subsystems and then weights the indicators separately, which to some extent makes up for the defects of the entropy weight method. To ensure the broad applicability of the research results, we will conduct a robustness test. To be specific, we will use the entropy weight method to weight the 20 variables above without grouping while observing whether the comprehensive evaluation results are similar to the above. The results of the comprehensive evaluation of empowerment are shown in Fig. 4. The curve with triangle is the comprehensive land bearing capacity score of the benchmark model in Fig. 2, and the curve with a diamond shape is the comprehensive land bearing capacity score after re-empowerment. It is easy to conclude that, in addition to the steeper curve in the robustness test, the two curves have trend consistency and the data fit is comparatively better, which may reflect the robustness of the above method.

6 Analysis of spatial–temporal characteristics of the evaluation results

In this part, the above methods are used to select one city from each of the four regions of Guangdong Province, namely the Pearl River Delta, Eastern Guangdong, Western Guangdong, and the mountainous areas in Northern Guangdong. The data of the prefectures are obtained from the *Guangdong Rural Statistical Yearbook (2001–2021)*, local statistical yearbooks, and the *Statistical Bulletin of National Economic and Social Development*. One variable regarding the proportion of environmental investment to GDP is excluded from the indicator system of Jiangmen, Maoming and Shantou due to missing data for a number of years in some cities. In the index system of Shaoguan City, two variables, namely per capita consumption of rural residents and the proportion of environmental investment in GDP, are eliminated. The comprehensive evaluation results of the four regions are shown in Fig. 5.

6.1 Pearl River Delta region: alleviate the contradiction between economic development and insufficient cultivated land by controlling pollution and protecting the environment

In the Pearl River Delta, the land carrying capacity of Jiangmen City shows a downward trend in the early stage and a recovery in the later period (Fig. 5). The Pearl River Delta is one of only two plains in Guangdong Province, whose geographical location was originally very suitable for field crop cultivation. However, due to economic development, the contradiction between economic development and agricultural land use is very obvious. In addition, urban construction and arable land retention have developed a trade-off relationship. Therefore, as shown in Table 4, both per capita GDP (2.78) and unit land output value (1.87) have a positive influence on the cultivated land pressure system, which has become a disadvantageous factor for the carrying capacity of cultivated land in this region, while for the cultivated land area (2.11), the per capita cultivated land area (2.02) has become the dominant factor of arable land carrying capacity and the potential to ease production pressure. In the ecological environment pressure system, the proportion of environmental treatment investment (2.06) has also become an important factor in countering the negative impact of economic development on the cultivated land carrying capacity; after 2012 in particular, Jiangmen City concentrated on fighting agricultural environmental pollution, concentrating on green ecological technology-based prevention and control, as well as on soil testing formula promotion and application, and all of this work paid off. Therefore, in recent years the comprehensive carrying capacity of arable land has shown a stable upward trend, based on the decompression of ecological environment pressure.

6.2 Eastern Guangdong: the planting methods of high input and multiple cropping have caused great pressure on the carrying capacity of arable land

The carrying capacity of grain production in Shantou has shown a downward trend from 2000 through to early 2020, and fluctuated in the later period (see Fig. 5). As a

Table 4 Ranking of advantages and disadvantages of cultivated land carrying capacity pressure system in different regions of Guangdong Province (Top 2)

Region	Advantages & disadvantages of economic pressure system	Total contribution value	Advantages & disadvantages of production pressure system	Total contribution value	Advantages & disadvantages of ecological environment pressure system	Total contribution value
Pearl River Delta Jiangmen City	GDP per capita	(+)2.78	Area of cultivated land	(−)2.11	Proportion of investment in environmental governance	(−)2.06
	Output value per unit of land	(+)1.87	Per capita cultivated land area	(−)2.02	Natural disaster area	(+)1.92
Eastern Guangdong Shantou City	GDP per capita	(+)2.18	Grain multiple cropping index	(+)2.93	Pesticide load of cultivated land	(+)2.01
	Consumption level of rural residents	(−)1.91	Per capita cultivated land area	(−)1.63	Fertilizer load of cultivated land	(+)1.96
Western Guangdong Maoming City	Level of urbanization	(+)2.18	Irrigation guarantee rate	(−)3.33	Area affected by natural disasters	(+)2.47
	Adjustment of agricultural structure	(−)2.15	Water resources per capita	(−)1.48	Fertilizer load of cultivated land	(+)2.33
Northern Guangdong Shaoguan City	Per capita net income of farmers	(−)2.44	Rural electricity consumption	(+)3.08	Fertilizer load of cultivated land	(+)2.96
	Adjustment of agricultural structure	(−)2.42	Agricultural mechanization level	(+)1.93	Forest coverage rate	(−)2.47

special economic zone in eastern Guangdong, the comprehensive grain carrying capacity of Shantou is still constrained by economic pressure, as shown in Table 4. In addition, a per capita GDP (2.18) is the main disadvantageous factor affecting arable land carrying capacity, while the consumption level of rural residents in Shantou City (1.91) is higher, which is related to the local emergence of a processing industry based on intensive farming agricultural products. The high added value attached to agricultural products can alleviate the shortage of local land and improve the carrying capacity of arable land. The rain multiple cropping index (2.93) reflects the disadvantaged index of cultivated land pressure in Shantou City, indicating that high-intensity crop cultivation puts pressure on the local production system, similar to the Pearl River Delta, while the per capita arable land area (1.63) still reflects the local arable land pressure advantage index. Pesticide load and the fertilizer load of cultivated land are disadvantageous factors in the local ecological environment pressure system, which in turn have a negative impact on the local cultivated land carrying capacity.

6.3 Western Guangdong: farmland water conservancy facilities and natural disaster response are the keys to improving the arable land carrying capacity

The carrying capacity of grain production in Maoming City has shown fluctuations over the past 20 years (Fig. 5). Western Guangdong has assumed an important role in agricultural production in Guangdong Province, whose urbanization level has lagged behind the Pearl River Delta and developed areas in eastern Guangdong. However, in recent years, with the implementation of the green agricultural development strategy, the situation has improved. As shown in Table 4, the urbanization level (2.18) has also become a pressure indicator of arable land carrying capacity, so attention should be paid to reconciling the contradiction between urban development and agricultural production. At the same time, a constantly adjusted agricultural industrial structure has led to a “burden reduction” effect on the carrying capacity of arable land. In Maoming’s production pressure system, the irrigation guarantee rate (3.33) and per capita water resources (1.48) have become important advantageous factors because water shortage is an important factor restricting the arable land carrying capacity in western Guangdong; many areas still have to sow seeds based on climate conditions; therefore, an urgent problem has been to maintain water conservation facilities to alleviate the pressure on cultivated land production. Areas affected by natural disasters (2.47) and the chemical fertilizer load of cultivated land (2.33) are the disadvantageous factors that have caused the unstable carrying capacity of arable land in western Guangdong, while the high-quality development of agriculture in the region depends on the scientific use of chemical fertilizers, therefore attention should be paid to the green reduction of chemical fertilizers and pesticides and other inputs to promote the healthy growth of crops.

6.4 Northern Guangdong: promoting the transformation of agricultural production to low-carbon agriculture is the key to enhancing the arable land carrying capacity

Over the past 20 years, Shaoguan City's arable land carrying capacity has shown a steady upward trend (Fig. 5). North Guangdong is the area with the most favorable ecological environment in Guangdong Province, and meanwhile, it was also the area with the weakest arable land carrying capacity in the past. As shown in Table 4, the dominant factors in Shaoguan's economic pressure system are concentrated in the per capita net income of farmers (2.44) and agricultural restructuring (2.43), which may be due to the fact that Shaoguan's key projects focus mainly on infrastructure construction, improvement and the contribution of industry to economic growth. In terms of production pressure system, the region's rural electricity consumption (3.08) and agricultural mechanization level (1.93), respectively, caused pressure on the local arable land carrying capacity, while cultivated land fertilizer load (2.96) was the disadvantageous factor in the local ecological environment pressure system; forest coverage rate (2.47) was the dominant factor affecting the local ecological environment pressure system. In recent years, the ecological security of arable land in northern Guangdong has improved, benefiting from the control of the quality of arable land, water resources, machinery and equipment, and the use of chemicals. However, there is still the threat of extreme weather posed by global warming. Therefore, in the future, food security should not only pay attention to quantity and quality, but also promote the transformation of agricultural production to low-carbon agriculture while promoting the development of higher level food production, namely higher quality, more efficient, and pursued in a more sustainable manner.

7 Conclusion and policy recommendations

This paper uses an entropy-based comprehensive analysis model to study the carrying capacity of cultivated land resources in Guangdong Province, one of the most economically developed provinces in China. It is found that the carrying capacity of cultivated land in Guangdong Province has experienced a process of "gentle development, over-development, transformation and protection and green recoveration," in which economic, production, and environmental ecological pressures, respectively, play an important role in the fluctuation of the carrying capacity of cultivated land. The comprehensive analysis of the whole of Guangdong Province shows that economic pressure and carrying capacity tend to follow each other, while production pressure shows fluctuations that are difficult to figure out and environmental ecological pressure is often the easiest to alleviate. The relief of environmental ecological pressure can even be used to offset economic and production pressures, thereby realizing the green recover of arable land carrying capacity.

At present, the level of food security in China is very high, the total supply of grain is sufficient, and the inventory is well-stocked. However, contradictions in grain production still exist in many countries we advocate that developing states implement the following practices to achieve green recovery of land productivity.

First, the government should pay attention to the restoration of abandoned land. It is imperative to stabilize overall grain production and the effective supply of important agricultural products while further revitalizing and making good use of arable land resources. Second, it is important to promote the R&D of green technology. Measures such as R&D devoted to biological control, accurate fertilization and other technologies should be pursued to reduce the amount of chemical fertilizers and pesticides applied in food production. In view of the pressure on resources and the environment caused by grain production in major producing areas, a further increase in subsidies is needed for the application of green production technologies such as water-saving irrigation and returning straw to the field.

7.1 Policy recommendations

Overall, the promotion of sustainable land use practices, adoption of green technologies, investment in agricultural infrastructure, diversification of agricultural production, strengthening of environmental regulations, and support for research and development are crucial policy recommendations for promoting green recovery of cropland carrying capacity in developed regions. These policies can help to increase agricultural productivity, reduce the environmental impact of agricultural production, and promote sustainable agriculture in the long term. The following policy recommendations can be made for promoting green recovery of cropland carrying capacity in developed regions:

Promote sustainable land use practices The government should implement policies and incentives to promote sustainable land use practices, such as crop rotation, intercropping, and conservation tillage. This will help to improve soil health, reduce the use of chemical fertilizers and pesticides, and increase crop yields.

Encourage the adoption of green technologies The government should provide incentives for farmers to adopt green technologies such as precision agriculture, drip irrigation, and biodegradable mulch films. This will help to reduce water and chemical inputs, reduce soil erosion, and increase crop yields.

Invest in agricultural infrastructure The government should invest in agricultural infrastructure, such as irrigation systems, drainage networks, and rural roads. This will help to improve the efficiency of agricultural production, reduce post-harvest losses, and increase access to markets.

Promote the diversification of agricultural production The government should promote the diversification of agricultural production by supporting the cultivation of high-value crops, such as fruits and vegetables. This will help to increase the income of farmers, reduce dependence on traditional crops, and promote sustainable agriculture.

Strengthen environmental regulations The government should strengthen environmental regulations and enforcement mechanisms to reduce the negative impacts of agricultural production on the environment. This includes monitoring and reducing the use of chemical fertilizers and pesticides, promoting the recycling of agricultural waste, and preventing the conversion of agricultural land to non-agricultural uses.

Support research and development The government should support research and development in the field of sustainable agriculture, including the development of new technologies, crop varieties, and farming practices. This will help to increase the resilience of the agricultural sector to environmental challenges and promote sustainable agriculture in the long term.

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Declarations

Ethical approval We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all the authors.

Conflict of interest The authors declare that they have no known conflict financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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