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RESEARCH ARTICLE

Spatiotemporal variation and evaluation of agriculture green development: a case study of Hainan Province, China

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KEYWORDS

Agriculture, environmental impact, green and sustainable development, Hainan Province, index evaluation system

HIGHLIGHTS

- Knowledge of the quantitative evaluation of changes in agriculture green development (AGD) is currently insufficient at the regional scale.
- Progress and potential pathways towards AGD in Hainan Province were assessed.
- The AGD index for Hainan Province improved from 38.8 in 1988 to 40.9 in 2019.
- Optimized nutrient management and diet structure improved the AGD index significantly.
- This approach can be used to assess the effects of future policies.

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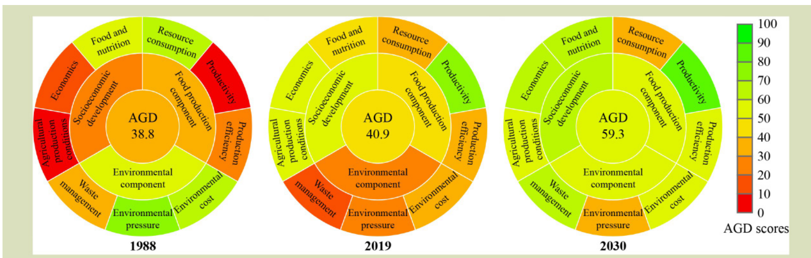
GRAPHICAL ABSTRACT



ABSTRACT

The realization of green and sustainable development of agriculture is the common pursuit all over the world. Agriculture green development (AGD) program has been proposed as a sustainable development strategy in China, but insufficient is known about the quantitative evaluation of spatiotemporal variation in AGD at the regional scale. This study aimed to assess spatiotemporal patterns in AGD at the county/city-based regional level. For this purpose, a systematic index evaluation system was developed to assess the performance of socioeconomic, food production and environmental components in a key economic region (Hainan Province) of China. Hainan improved its AGD index (representing the overall performance toward achieving AGD) from 38.8 in 1988 to 40.9 in 2019. The socioeconomic development and agricultural productivity have improved with time;

environmental quality declined due to overuse of chemicals from 1988 to 2013, but steadily improved after 2013, indicating positive effects of reducing chemical input. There was a higher AGD index in the coastal vs. central regions and the southern vs. northern regions. Scenarios featuring improved nutrient management or optimized diet structure and reduced waste improved economic benefits and social productivity while concurrently reducing environmental degradation. These results provide new insights for the future development of green and sustainable agriculture and formulation of agricultural policies in Hainan Province of China and even other developing countries that are facing or will soon face similar challenges.

1 Introduction

One of the major challenges for humanity is to ensure improved food security for a growing world population while concurrently improving environmental health[1–3]. Over recent decades, China has made remarkable progress in producing sufficient food for a rapidly increasing national population[4]. However, increasing numbers of studies report that large increases in agricultural productivity in China, and in other parts of the world, have resulted in serious environmental problems and reduced resource use efficiency in the food-production systems[3,5,6]. Also, farmers have received only limited benefits from agricultural production[7]. An urgent need for China is to transform its agricultural production from high resource input to a resource-saving and more environmentally-friendly model[8–10].

With the increasing environmental and resource problems associated with agriculture[11], the promotion of sustainable agricultural development has been recommended in many areas of China and also beyond its borders[12–14]. In 2015, United Nations, comprising 193 member states, formally adopted 17 Sustainable Development Goals (SDGs) aimed to address development of social, economic and environmental activities in an integrated manner and to move society toward a more sustainable developmental path[15]. As a contribution to achieving these development goals, the Chinese government first proposed green development in 2015 and implemented the agriculture green development (AGD) program in 2017 to address a range of issues related to the future development of agriculture in China and the well-being of people living in rural areas. In contrast to the concept of traditional agricultural development, AGD is a benign development strategy that integrates environmental sustainability into sustainable economic and social development[13]. It is to pursue socioeconomic development while also ensuring the resilience of the ecological environment, rather than stopping development to protect the ecological environment and vice versa. The main aim of AGD is high agricultural productivity, with increased resource utilization efficiencies and low environmental costs (Fig. 1(a)), which requires coordination of *green* (environmental sustainability) and *development* to achieve the green transformation away from the current agricultural and land-use practices with high resource consumption and potentially high environmental penalties[13]. Potential sustainable development plans in future agriculture are also being discussed and introduced in many other countries[16].

Extensive research has shown that quantifying and tracking progress toward sustainable development is essential to guiding the policy development and implementation in different regions[6,14,17]. Several scholars have assessed the effectiveness of policies aimed at the delivery of more sustainable development using index evaluation systems. Xu et al.[17] have developed and tested a systematic approach to quantify progress in China toward improvements regarding 17 different SDGs at both national and sub-national levels. A sustainable agriculture matrix has been developed by Zhang et al.[14] to quantify the national performance indices in agricultural development. Wang et al.[6] have evaluated the interactions between the SDGs for water pollution in China, and Zhang et al.[18] analyzed the impact of changes in the scores of individual SDGs at the provincial level in China between 2015 to 2018.

In individual countries or geographical regions there is often a significant regional variation in economic benefits, environmental status and production conditions brought about by changes in the development strategies. Therefore, to quantify AGD at a national scale, the high-resolution assessment methods are needed to monitor past and present progress and trends toward AGD. However, there is no broad agreement on how spatiotemporal variation of AGD should be quantified to produce numerical values to represent appropriately the overall performance of AGD. Spatiotemporal analysis of AGD can help track the progress toward achieving AGD, identify regional hotspots and develop targeted policies[13,17].

Hainan Province was established as a new administrative province due to its relatively independent location on an island in 1988, which is regarded as an important strategic pivot of the 21st Century Maritime Silk Road[19]. As a relatively large tropical island, Hainan location and focused developmental policies over three decades provide unique opportunities for the comprehensive analysis of progress toward sustainable development of the region, as a microcosm reflecting Chinese economic development. In 1988, Hainan was designated a Special Economic Zone, and this has brought significant social and economic prosperity. Since 2018, China has operated a pilot free-trade zone and a national pilot zone for *ecological civilization* in Hainan[19]. As the second national AGD pilot zone approved by Chinese government, Hainan Province is of great significance to the realization of AGD for the country. In this context, how to improve the socioeconomic development and food production in the province without damaging the environment has important theoretical and practical implications for planning the future green and sustainable development of the region, even for other developing countries with similar challenges.

The analysis reported here takes Hainan Province as a case study in evaluating agricultural development and its impacts. It is based upon the operation of a modified NUFER (nutrient flows in food chain, environment and resource use) model[20,21], used to assess the effects of strategy development and the pathway of AGD over space and time from 1988 to 2019. Scenario analysis was used to predict the future progress of AGD in Hainan Province, providing a reference for the formulation of relevant development policies for the region. Four questions are addressed: (1) how has AGD in Hainan Province progressed at the provincial level; (2) how have different components of AGD changed; (3) what is the spatiotemporal variation of AGD in Hainan; and (4) what are the most effective pathways to achieve AGD at scale.

2 Methods

2.1 Study area

Hainan Province is located in the south of China, and has nine cities and 10 counties, covering a land area of 35,400 km^2. Its agriculture is mainly concentrated on Hainan Island, so this study focuses on agriculture in 18 regions (the city of Sansha is not included in the study due to limited agriculture). The island has a tropical monsoon climate, resulting in a rainy season from May to October and a dry season from November to April. The topography of Hainan is characterized by hilly regions in the middle of the island, surrounded by lowlands in the coastal regions.

In 2019, the cultivated land area in Hainan Province was 438,000 ha, and the multiple cropping index (the ratio of the total sown area of crops on cultivated land to the area of cultivated land during the year) was 1.6[22]. The remaining 88% of the land includes ornamental gardens, forests, grasslands, wetlands, urban villages, industrial and mining land, transportation corridors, and water and water conservancy facilities. By 2019, the total population was 9.4 million, and the regional gross domestic product (GDP) was 77 billion USD, with the output values of agriculture (also including forestry, animal husbandry and fishery) and tourism accounting for 31.8% and 19.9% of the regional GDP, respectively. These numbers illustrate the importance of food production to the province and its economy and the potential importance of moving toward increased AGD. Tourism, with its high value to the economy of Hainan, should not be threatened by the agricultural land-use practices that may potentially damage the environment.

The agricultural production model of Hainan Province transitioned over time from low-input/low-output to high-input/high-output[22]. From 1988 to 2019, the total sown area in Hainan Province decreased by 6.1%, and the area sown to grain crops decreased by 45.1%. The areas of orchards and vegetables increased by 2.9 and 4.9 times, respectively. By 2019, the total output of fruit and vegetables in Hainan Province increased 12.4 times to 10.2 Mt annually. The amount of fertilizer use increased 2.7 times to 1.2 Mt in 2019. Livestock and poultry production per unit area increased 1.2 times, reaching 7.0 LU (standard livestock units) per hectare (LU·ha^{-1}) in 2019. These parameters indicate that between 1998 and 2019 agricultural production of Hainan gradually developed into a high-input/high-output model dominated by cash crops.

2.2 Calculation of the parameters used in the evaluation of AGD index

2.2.1 NUFER-AGD model

To assess the progress of AGD at regional level and quantify the impact of potential management strategies on AGD, we conceptualized an evaluation framework with three components (socioeconomic development, food production and the environment) (Fig. 1). The levels of food production, environmental quality and socioeconomic development of the food system in question were evaluated using AGD indices calculated for three components (Fig. 1(b)). The food production component provides the supply of consumption goods promoting socioeconomic development, and socioeconomic component reflects the demand of consumption goods and feeds back to regulate food production (Fig. 1(a)). Food production, including crop production and livestock production, brings environmental pressure in the production process, and the resource recycling can improve the efficiency of food production. The socioeconomic development has brought pressure to the environment, and protecting the environment is conducive to sustainable socioeconomic development. The three components are interconnected and constitute the agricultural system together. It is important to select representative indicators from each component to reflect development status and then assess the progress of AGD.

Taking SDG index as a reference[17], 35 second-level indicators closely linked to agricultural development are divided into nine first-level indicators (Fig. 1(b); Table S1). The socioeconomic component of the model includes three first-level indicators: agricultural production conditions (e.g., proportion of effective irrigated area), economics (e.g., disposable income of rural residents per capita), and food and nutrition (e.g., protein intake per capita per year). The component of food production in the model includes three first-level indicators: resource consumption (e.g., nitrogen input per unit sown area), productivity (e.g., calorie yield per unit cultivated area) and production efficiency (e.g., nitrogen-use efficiency in the cropping system). The environmental component of the model includes three first-level indicators: waste management (e.g., recycling rate of livestock manure), environmental pressure (e.g., nitrogen surplus per unit cultivated area) and environmental cost (e.g., greenhouse gases emissions per unit cultivated area) (Table S1).

We developed the NUFER-AGD model by combining three components related to AGD (socioeconomic development, food production and the environment) based on the NUFER model[20,21] and evaluated the changes in AGD indices for Hainan from 1988 to 2019. NUFER-AGD is a deterministic and static model that calculates indicators for the development of the agriculturally-related environment, society and economy. Inputs and outputs for crop and animal production, food processing, retail activity and consumption were determined at the regional scale in China on an annual basis according to the material flow analysis (MFA) methodology. MFA is used widely in resource efficiency assessment, material recycling, and environmental risk assessment[23].

2.2.2 Calculation of AGD index

AGD is a crucial part of achieving SDG. By increasing the sustainability of agricultural system, it provides a practical way for coordinate environmental and socioeconomic development. We have adopted a three-step approach to calculate AGD index using SDG index as a reference[17]. AGD index represents the overall performance toward achieving AGD, with higher AGD index showing better performance.

2.2.2.1 AGD calculation step 1: boundary selection

We determined upper and lower boundary for each indicator to ensure comparability across different indicators and offset the effects of extreme values. Our method of setting an upper limit was similar to that used by Xu et al.[17] in order to facilitate the comparison of Hainan with other provinces. The upper boundary for each indicator was determined using a three-step approach. If the conditions of the previous steps were met, all subsequent steps were skipped. Firstly, for indicators where targets existed, we set science-based targets for 2030. Secondly, we set the upper boundary of some indicators to the national or advanced-world level. Thirdly, the upper boundary of the other indicators was determined by the highest level of the province over the years (e.g., fruit yield per unit sown area). Similarly, we used a two-step method to determine the lower boundary as (1) a value denoting deterioration at the national or world level, or (2) the worst indicator value for the whole province over the years. We specified the best and worst AGD indicator values rather than simply dividing the data into high or low value groups because low values of some AGD indicators (e.g., greenhouse gas emissions per unit cultivated area and nitrogen input per unit sown area) may represent good performance.

2.2.2.2 AGD calculation step 2: normalization of index values

After determining the upper and lower limits for each indicator, we normalized AGD index values from 0 to 100 using the formula:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{1}$$

where, x is the original data value of each indicator, max/min is the upper/lower boundary of the best or worst performance, and x' is the standardized individual score of the given indicator.

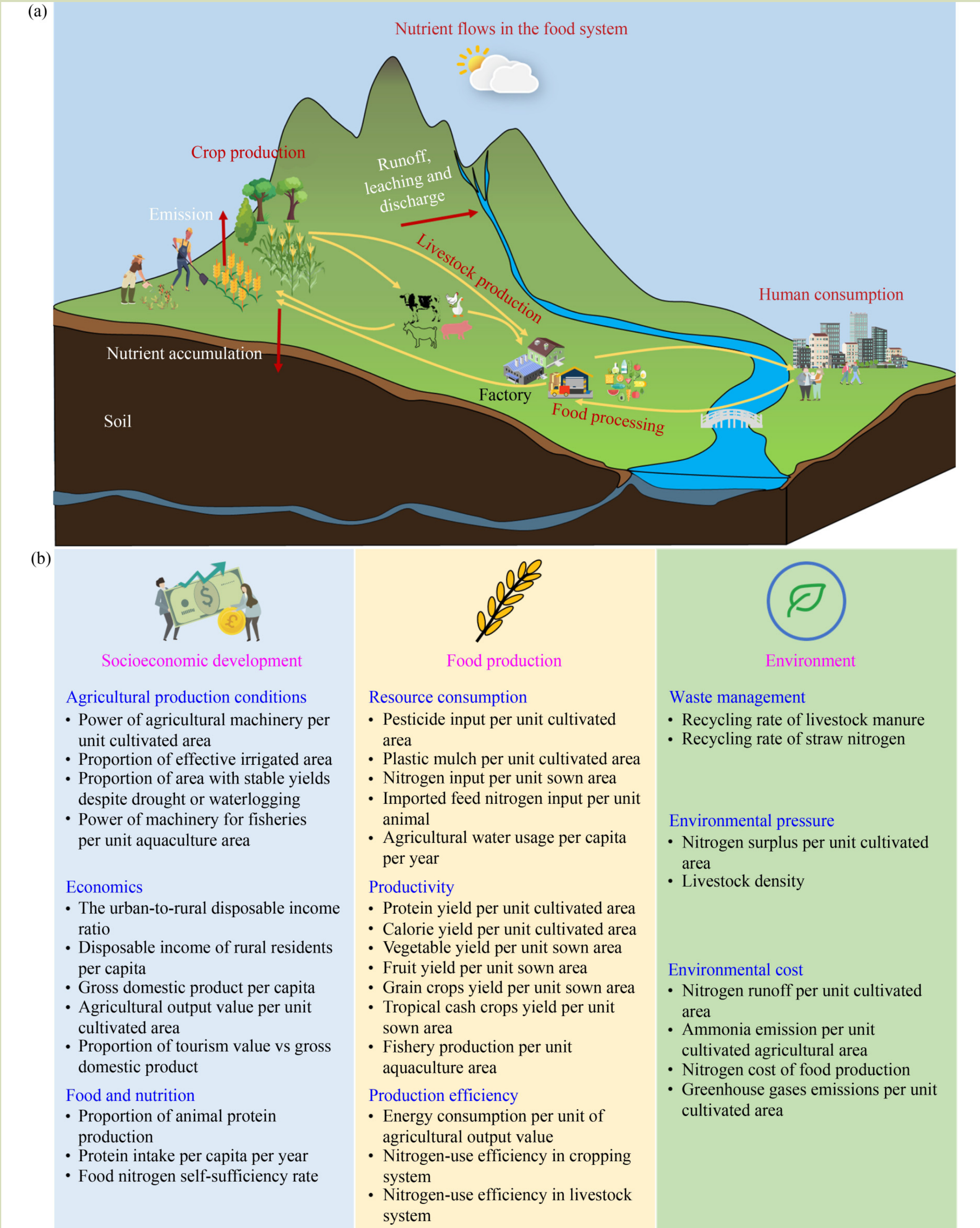


Fig. 1 Nutrient flows in the food production system (a) and AGD index evaluation system (b). Yellow arrows represent nutrient flows and red arrows indicate nutrient loss pathways. The AGD index evaluation system consists of three components closely related to agricultural development, including socioeconomic development, food production and environment components (light purple text). Thirty-five second-level indicators (black text) closely linked to agricultural development are grouped into nine first-level indicators (blue text).

All normalized values greater than the upper boundary were assigned score of 100, and all normalized values less than the lower boundary were assigned 0. The values between the upper and lower boundaries are distributed along a spectrum from worst (score 0) to best performance (score 100).

2.2.2.3 AGD calculation step 3: calculation of AGD indices

We calculated AGD index using arithmetic means. Each component of AGD (for AGD index calculations), the first-level indicators within each AGD component and the second-level indicators within each first-level indicator were weighted equally.

2.2.3 Sensitivity analysis for AGD index

We conducted a sensitivity analysis to assess the sensitivity of the AGD index to changes in one of the 35 second-level indicator values used to calculate the AGD index. A widely used measure of sensitivity (*Sx*) was calculated based on Wang et al.[24]:

$$Sx = \frac{\Delta X/X}{\Delta P/P} \tag{2}$$

where, X is the AGD index calculated using the original parameters, ΔX is the difference between the AGD index with the original parameters and that calculated with one indicator changed (increased or decreased by 10%), P is the indicator value in the original conditions, and ΔP is the difference between the indicator value in the original and the modified conditions.

2.2.4 Data sources

The data sources for the various data used to assess AGD indices in the food chain are listed in Table S1. Hainan Province statistical yearbooks and bulletins were used to derive data on changes in human population, gross regional domestic product, fertilizer and pesticide use, use of plastic mulch, input of mechanical power, crop yields, cultivated areas, number of animals, and average food consumption per capita for the period 1988–2019[22]. Data on nitrogen in harvested crops and animal products, irrigation water nitrogen content, nitrogen excretion values for each animal category, and the separation of animal products into food products and other parts were obtained from the literature[20]. Parameters for nitrogen inputs and outputs in crop and animal production, including biological nitrogen fixation, nitrogen deposition, runoff coefficient, ammonia volatilization, nitrous oxide emission and denitrification coefficient of animal manure were derived from the published data[20,21]. The values indicating recycling of straw and livestock manure were derived from the bulletin of Hainan Agriculture and Rural Affairs Department.

2.3 Scenarios illustrating changes in the AGD index

Using the year 2019 as a reference and 2030 as the target year, four main scenarios were developed (Table 1): S0 (business as usual, BAU) means that indicators related to socioeconomic development, food production and environmental quality are expected to change following the current trend; S1 (improved nutrient management, INM) means that agricultural and livestock production efficiencies are expected to increase significantly; S2 (reduced consumption and wastage, RCW) means that people are expected to consume less meat and waste less food; and S3 representing integration of S1 and S2.

2.3.1 S0, business as usual (BAU)

This scenario reflects the current food production situation in Hainan Province. We assume that the diet of the urban population will not change by 2030 compared with 2019. However, due to rapid economic development, we assume that the diets of rural and urban populations will become similar by 2030 (Table S2). In addition, according to the 14th Five-Year Plan of Hainan Province for National Economic and Social Development and the Outline of the Long-Term Goal of

Table 1 Key changing parameters for each scenario

Scenario	Comparator	Description
S0	2019	Diets of rural and urban populations will become similar by 2030. GDP, tourist population and tourism revenue will increase by more than 11%, 11% and 15%, respectively
S1	BAU	Nitrogen inputs by mineral fertilizer and manure match the crop demand. The proportion of manure and straw returned to croplands will increase from 35.3% and 54.6% in 2019 to 85.0% and 90.0% in 2030, respectively
S2	BAU	Scenario is designed to follow the EAT-Lancet dietary guidelines. The consumption of plant-based foods (e.g., fruit, legumes, nuts, vegetables and whole grains) will increase by 39.5%, milk consumption will increase 24.4 times, and meat consumption will decrease by 61.3%, and a 50% decrease in food waste by 2030
S3	BAU	Impacts of S1 and S2 are assessed together

Note: S0, business as usual (BAU); S1, improved nutrient management (INM); S2, reduced consumption and wastage (RCW); S3, integration of S1 and S2.

2035[25], we expect GDP, tourist population and tourism revenue will increase by more than 11%, 11% and 15%, respectively. This will result in more intensive livestock production. We expect that livestock numbers (e.g., cattle, pigs and sheep) will increase by 5% and broiler numbers by 50% between 2019 and 2030. Fertilizer and pesticide inputs are expected to be reduced by 15% in this scenario[25]. The population growth rate (0.86%) is calculated from the published trends in the population of Hainan over the past 20 years.

2.3.2 S1, improved nutrient management (INM)

This scenario builds on the BAU scenario but considers a reduced use of nitrogen fertilizer in crop production by optimizing the application rate (i.e., the nitrogen inputs by mineral fertilizer and manure match the crop demand)[26]. We further consider that the proportion of manure and straw returned to croplands will increase from 35.3% and 54.6% in 2019 to 85.0% and 90.0% in 2030, respectively[25].

2.3.3 S2, reduced consumption and wastage (RCW)

This scenario is designed to simulate a healthier food consumption following the EAT-Lancet dietary guidelines[27]. On the basis of dietary guidelines, the consumption of plant-based foods (e.g., fruit, legumes, nuts, vegetables and whole grains) will increase by 39.5%, milk consumption will increase 24.4 times, and meat consumption will decrease by 61.3% compared with BAU (Table S2). We factor in a 50% decrease in food waste by 2030[2,27].

2.3.4 S3, integration of S1 and S2

In this scenario, the impacts of S1 and S2 are assessed together.

3 Results

3.1 Temporal (1988–2019) variation of AGD index

Our analysis indicated that the AGD index for Hainan Province increased from 38.8 in 1988 to 45.9 in 1999 (up by 18.3%). There was a gradual decrease in the AGD index from 45.9 in 1999 to 32.5 in 2005 followed by an increase to 40.9 in 2019.

Of the three components of the AGD (socioeconomic development, food production and the environment), the greatest increase in the score occurred in the socioeconomic development (from 24.6 in 1988 to 52.9 in 2019) (Fig. 2). There

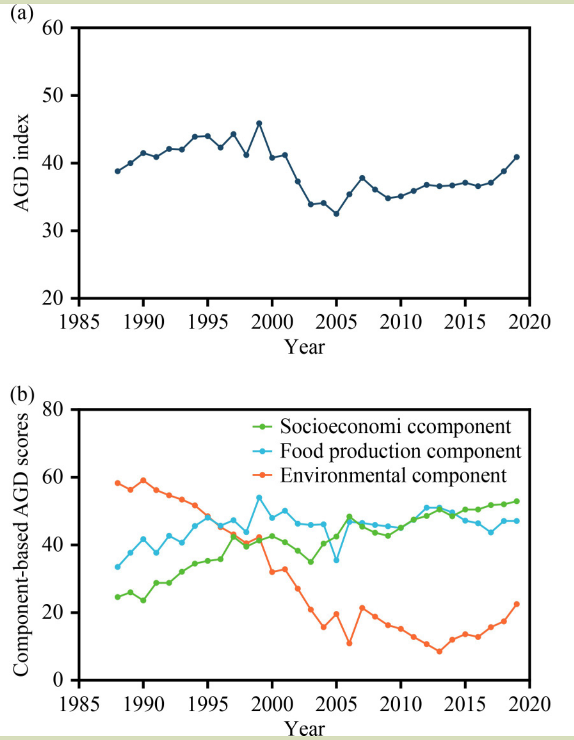


Fig. 2 Changes over time of AGD index (a) and its three major components (b) in Hainan Province.

was a big increase in two of the three first-level indicators of socioeconomic component. The scores for agricultural production conditions (AGD1) and economics (AGD2) increased from 4.0 and 13.1 in 1988 to 58.1 and 51.6 in 2019, respectively (Fig. 3(a)), but the food and nutrition score (AGD3) decreased from 56.7 to 49.1 in the same period (the differences in scores between 1988 and 2019 are given in Fig. 4).

Three of the 12 second-level indicators of socioeconomic development decreased between 1988 and 2019, and the remaining nine indicators increased (Table S1). The scores for urban-to-rural disposable income ratio, proportion of animal protein production and food nitrogen self-sufficiency rate decreased from 57.6, 34.4 and 51.9 in 1988 to 34.3, 14.8 and 34.3 in 2019, respectively. The three second-level indicators of socioeconomic component with the strongest increasing trends were effective irrigated area, GDP per capita, and agricultural output value per unit cultivated area (increasing from 0.2, 1.1 and 3.5 to 44.1, 50.0 and 100, respectively).

The second AGD component (food production) had a fluctuating upward trend from 33.5 in 1988 to 51.0 in 2013 and then decreased slightly to 47.1 in 2019 (Fig. 2). There was a sharp decrease in resource consumption (AGD4) score from

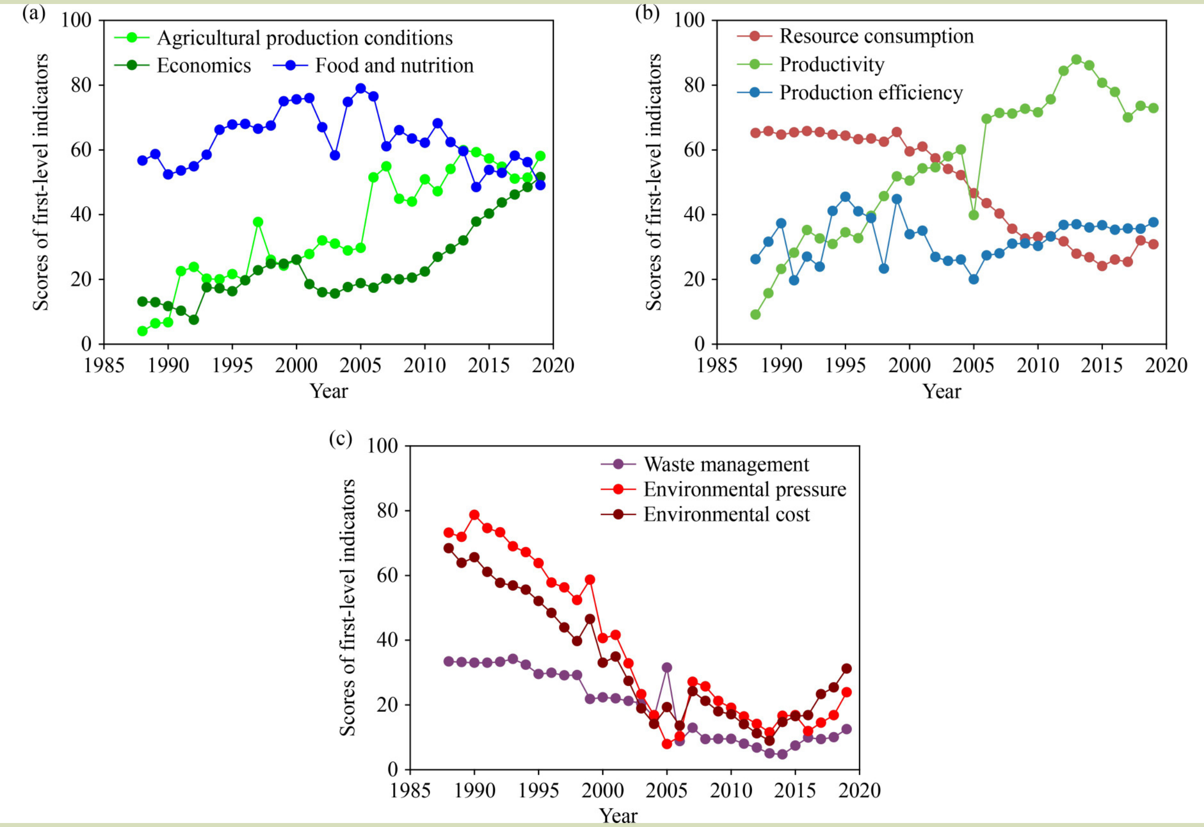


Fig. 3 Changes in the first-level indicator scores (within each of the three main components of AGD, see Table S1) for Hainan Province (provincial level) from 1988 to 2019: (a) socioeconomic; (b) food production; (c) environmental components.

65.2 in 1988 to 24.1 in 2015, followed by an increase to 30.8 in 2019 (Fig. 3(b)). Application of fertilizers and pesticides led to an increase in productivity (AGD5) score from 9.1 in 1988 to 72.9 in 2019 (an increase of 63.8, Fig. 4(a)). Production efficiency (AGD6) score fluctuated between 19.7 and 45.5 for the 17-year period leading to 2005 and then increased steadily from 20.0 in 2005 to 37.6 in 2019.

A total of 15 second-level indicators of food production were considered, with nine increasing, five decreasing, and one (agricultural water usage per capita per year) remaining constant from 1988 to 2019 (Table S1). The strongest increasing trends were for calorie yield per unit cultivated area, fishery production per unit aquaculture area, and protein yield per unit cultivated area, increasing from almost 0 to 44.3, 66.3 and 55.4, respectively. The strongest decrease occurred in the plastic mulch per unit of cultivated area and nitrogen inputs per unit sown area, decreasing from almost 100 to 0.1 (plastic mulch) and 9.3 (nitrogen input).

The score for the environmental component of AGD decreased from 58.3 in 1988 to 8.5 in 2013, and then increased to 22.5 in 2019 (Fig. 2). The trends in the three first-level indicator scores were similar to the trends for the whole environmental component. The scores for waste management (AGD7), environmental pressure (AGD8), and environmental cost (AGD9) decreased from 33.4, 73.2 and 68.4 in 1988 to 5.0, 11.5 and 8.9 in 2013, respectively, followed by an increase to 12.5, 23.9 and 31.2 in 2019, respectively (Fig. 3(c)).

Seven of the eight second-level indicators for the environmental component decreased and only one increased from 1988 to 2019 (Table S1). The three second-level indicators of environment with the strongest decreasing trends were recycling rate of livestock manure, nitrogen cost of food production and nitrogen surplus per unit cultivated area, which decreased from 43.2, 33.9 and 73.1 to 2.0, 4.3 and 14.1, respectively. However, the score for greenhouse gases emission per unit cultivated area increased from 44.8 to 60.5 between 1988 and 2019.

3.2 Spatial variation of AGD index

At the county/city-based regional level, the spatial distribution

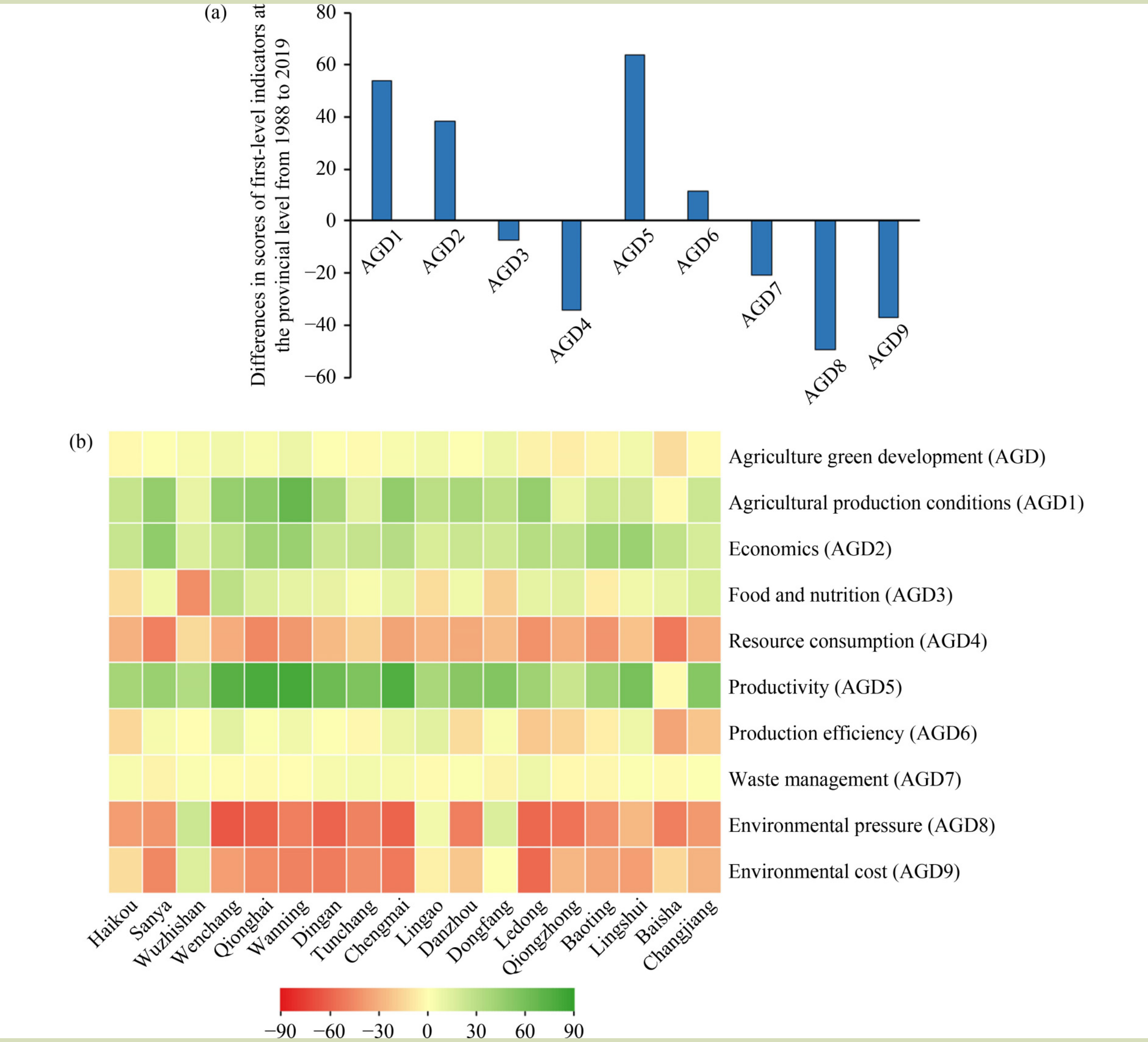


Fig. 4 Differences in (a) the first-level indicators within each of the three main components of AGD (see Table S1 for acronym explanation) between 1988 and 2019 at the provincial level (Hainan Province) and (b) at the county/city-based regional level. The color scale indicates the changes in the values of first-level indicator scores.

of AGD indices varied in between years, indicating significant changes over time in the status of AGD in different regions of Hainan (Fig. 4(b); Table 2). The AGD index at the county/city level ranged from 35.9 to 44.6 (mean of 40.6) in 1988, from 38.8 to 49.6 (mean of 43.4) in 1999, from 33.1 to 49.1 (mean of 39.1) in 2009, and from 29.8 to 50.1 (mean of 41.3) in 2019. The cities in the south of the island had a higher AGD index than the cities in the north, and the coastal cities had a higher AGD index than central cities, especially after 2009 (Table 2; Table S3).

The AGD index increased for 11 out of 18 cities on Hainan Island and decreased for seven cities between 1988 and 2019 (Fig. 4(b); Table 2). A relative increase in the AGD index was largest for the city of Dongfang (from 38.3 in 1988 to 46.6 in 2019, an increase of 21.7%). The AGD index for the city of Baisha decreased from 43.2 to 29.8 (by 31.0%) during the same period.

With the exception of Wuzhishan, the score for socioeconomic component of the AGD increased over time for all cities (Table S4). The strongest increasing trend occurred in Wanning (from 28.2 in 1988 to 68.7 in 2019), followed by Wenchang (from 26.1 in 1988 to 60.3 in 2019). In 2019, the score for the socioeconomic component of the AGD was highest in Wanning (68.7) and lowest in Haikou (35.1).

Table 2 Spatial pattern of AGD index for 18 regions of Hainan Island in 1988, 1999, 2009 and 2019

Regions	AGD index			
	1988	1999	2009	2019
Haikou	40.4	42.3	37.7	38.4
Sanya	43.9	44.6	42.9	44.8
Wuzhishan	39.7	41.1	33.7	43.9
Wenchang	39.8	45.5	49.1	45.5
Qionghai	40.2	45.3	41.6	43.9
Wanning	35.9	42.3	38.1	43.6
Dingan	39.0	42.8	38.1	39.0
Tunchang	36.9	40.6	36.1	35.8
Chengmai	38.5	41.3	39.4	42.1
Lingao	41.5	43.4	36.9	47.1
Danzhou	41.2	46.0	43.7	41.4
Dongfang	38.3	38.8	39.7	46.6
Ledong	44.6	49.1	43.2	39.7
Qiongzhong	41.0	41.1	38.8	34.4
Baoting	40.3	43.3	35.4	36.8
Lingshui	44.6	49.6	38.8	50.1
Baisha	43.2	39.9	37.5	29.8
Changjiang	41.4	45.0	33.1	40.0

Across the 18 regions considered, the score for the food production component of AGD was between 28.0 and 57.8 in 2019 (Table S4). Eleven regions had increased scores between 1988 and 2019, and the remaining seven regions had decreased scores. The strongest increasing trend in the food production component score occurred in Wenchang (from 31.9 in 1988 to 49.5 in 2019) whereas the biggest decrease was found in Baisha (from 57.5 to 28.0). In 2019, the score for the food production component of the AGD was highest in Lingshui (57.8) and lowest in Baisha (28.0).

From 1988 to 2019, the score for the environmental component of the AGD decreased in 16 of the 18 regions, with the strongest decrease in Chengmai (from 48.2 to 12.0) (Table S4). In contrast, the largest increase in the environmental component score occurred in Wuzhishan (from 20.0 in 1988 to 33.3 in 2019). In 2019, the score for environmental component was highest in Dongfang (52.0) and lowest in Chengmai (12.0).

3.3 Scenario analysis

If Hainan follows the current development trends (BAU), the AGD index would increase from 40.9 in 2019 to 47.9 in 2030 (by 17.1%) (Fig. 5). Over the same period, the scores for the socioeconomic, food production and environmental components would increase from 52.9, 47.1 and 22.5 to 61.3, 51.5 and 31.0, respectively (Fig. S1).

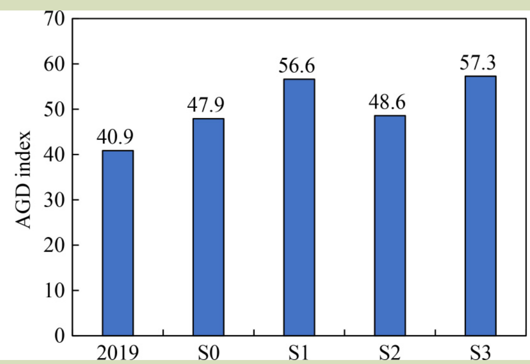


Fig. 5 Forecasts of AGD index in 2030 according to the four scenarios (S0, S1, S2 and S3) as compared to the year 2019. S0, business as usual (BAU); S1, improved nutrient management (INM); S2, reduced consumption and wastage (RCW); and S3, integration of S1 and S2.

Under scenario S1, based on balanced fertilizer input and manure management, the AGD index for Hainan Province in 2030 was calculated to increase from 47.9 (under BAU) to 56.6, with an increase of 18.2% (Fig. 5). Increased nutrient-use efficiency in both cropping systems and livestock production would contribute to the increased scores for food production (Fig. S1(b)) and environmental components (Fig. S1(c)). The largest score increase would occur in the environmental component (from 31.0 under BAU to 51.0 under S1) (Fig. S1(c)). Compared with the BAU scenario, the score for the food production component under scenario S1 (Fig. S1(b)) would be expected to increase from 51.5 to 57.5, whereas the score for socioeconomic component would remain constant.

Diet planning and food waste reduction are the two major pillars of scenario S2. Compared to the S0 scenario, the AGD index for Hainan Province in 2030 was calculated to increase slightly (from 47.9 to 48.6) under scenario S2 (Fig. 5). The score for the socioeconomic component was predicted to increase from 61.3 to 62.9 due to a more reasonable dietary pattern and less food waste (Fig. S1(a)). The estimated scores for the food production (Fig. S1(b)) and environmental components (Fig. S1(c)) would increase only slightly.

The scenario S3 would have a positive impact on the socioeconomic and food production components and would alleviate environmental impact (increased nutrient cycling, reduced environmental costs), which would increase the AGD index from 47.9 under the BAU scenario to 57.3 (Fig. 5; Fig. 6). Under scenario S3, the largest increase was calculated to occur for the environmental component (from 31.0 under BAU to 51.2) (Fig. S1(c)), followed by the food production component (from 51.5 under BAU to 57.8) (Fig. S1(b)), and the socioeconomic component (from 61.3 under BAU to 62.9) (Fig. S1(a)). It should be noted that although the score for the environmental component was predicted increased the most under scenario S3, it was still lower than the scores for the socioeconomic and the food production components.

3.4 Sensitivity analysis of AGD index

We took the AGD index for Hainan Province as well as one city in each of the north (Haikou), south (Sanya) and the central part of the island (Wuzhishan) as examples. To assess the level of sensitivity, we recalculated the AGD indices for 1988, 1999, 2009 and 2019, considering various scenario conditions where a single second-level indicators was increased or decreased by 10%. We found that the sensitivity of AGD index to changes in the individual indicator data values was small (less than 0.2, i.e., equivalent to less than 20%) (Fig. S2).

4 Discussion

4.1 Spatiotemporal variation of AGD at the county/city-based regional level

As the newly-developed province, development in Hainan has paralleled China as a whole (Fig. 6). In 1988, agriculture-related industries were the primary source of income for the population of Hainan Province. This accounted for about 50% of GDP[22]. Food crops (e.g., rice and sweet potato) were farmed across the whole island and less than 15% were cash crops (e.g., fruit and vegetables) in 1988. Most farmers raised livestock in backyards of domestic housing, and mixed crop-livestock systems led to almost all animal manure being recycled back to cropland[28]. In 1988, the fertilizer and chemical industry in China was in its infancy, and farmers applied little or no inorganic fertilizer and pesticides[1,29]. Low soil fertility and lack of high-quality crop varieties were the

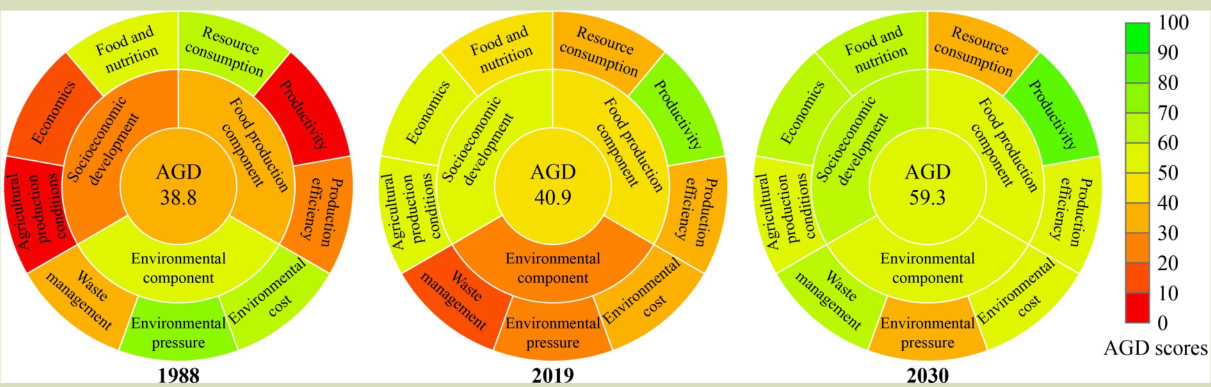


Fig. 6 The AGD report cards for Hainan Province in 1988 and 2019 and the estimates (based on scenario S3) for 2030.

foremost reasons for low grain yields at that time. There was no formal management system for fisheries in Hainan Province, resulting in the dominance of artisanal fisheries in that time. Tourism was still relatively underrepresented due to the unique geographical location (Hainan Island is separated from mainland China by the Qiongzhou Strait) and undeveloped transport networks. Although regional economic development and food production were restricted by poor agricultural production conditions and inadequate infrastructure, this combination of factors instead had a beneficial effect on the natural environment.

The AGD index for Hainan increased continuously from 1988 to 1999. During this time, Hainan underwent a gradual increase in agricultural productivity and economic development. With the rise in fertilizer industry, mineral fertilizers were used more widely in this period, resulting in rapid accumulation of soil nutrients[1,30]. Agricultural management generally became more sophisticated and thus both grain yield and nutrient-use efficiency increased. To obtain higher economic benefits, farmers began to shift their focus from traditional food crops (rice and sweet potato) to cash crops (fruit and vegetables). The improvement in mechanization at this stage was beneficial for productivity of fisheries, resulting in the gradual development of large-scale fishery industries in both fresh and salt water. The continuous expansion of the railway and highway network in Hainan Province in the 1990s laid the foundation for the rapid development of tourism[31].

A significant decrease in the area of grain and sugarcane cropping occurred in Hainan Province from 1999 to 2013, with growing fruit and vegetables gradually becoming the dominant focus of food production. To pursue higher yields and increased incomes, agriculture in Hainan over the decade of the 1990s became more intensive with increased inputs of fertilizers and pesticides[1]. However, excessive fertilizer inputs as well as increased use of agricultural machinery resulted in exacerbated environmental pollution and considerable energy consumption[32]. Also, to meet the increasing food requirements of the population and especially a desire for increased meat consumption by an ever-growing population[33], traditional backyard livestock farming systems were slowly replaced by modern, high-intensity livestock systems[28]. However, such systems disconnect crop and livestock production, resulting in a significant reduction in recycling of animal manure[34]. The untreated manure has a high environmental risk and can lead to pollution of water bodies and air[28] as well as to enhanced greenhouse gas emissions[35]. In contrast to improved agricultural productivity in the 1999–2013 period, the environmental quality declined rapidly and substantially. This shows that Hainan still follows the traditional way of development, with increasing socioeconomic development and agricultural productivity at the expense of the environmental quality[36].

Since 2013, to break the apparent link between an upward trend of economic development and a decline in environmental quality, the Chinese government has paid more attention to environmental protection[37]. In 2013, the Hainan government issued Regulations on the Prevention and Control of Livestock and Poultry Breeding Pollution[38]. This policy was intended to reduce manure discharge and increase recycling of manure. The government-led project, “Zero increased use of chemical fertilizer”, was initiated in 2015, and this led to a reduction in synthetic fertilizer use and potential pollution[39]. In 2016, the government issued the Regulations on Hainan Ecological Protection Red Line Management to restrict crop and livestock production in environmentally vulnerable areas[40]. In 2017, these regulations were revised to restrict further wastewater discharge and pollutant emissions[41]. Since the implementation of the International Tourism Island strategy in 2009, Hainan had made a substantial progress in tourism, increasing tourist population and tourism income[22]. By 2019, the output value of tourism in Hainan accounted for about 19.9% of its GDP, well above the average level of tourism in China (11.1%)[42]. Also, farmer income rapidly increased, with considerable development of tropical fruit and vegetable industries. Overall, the scores for socioeconomic development and environmental quality increased steadily for Hainan from 2013 to 2019.

There was a large spatial variation in the AGD index for various cities on Hainan Island. The AGD indices were higher for the coastal than the central region and for the southern compared with the northern region. The relatively flat terrain around the coast made this area suitable for both human habitation and agricultural production, leading to a higher AGD index. Most of the cultivated land is in the flat coastal area (84.6%) rather than in the central area (15.4%). Conversely, the central mountainous area is dominated by woodland, restricting economic development due to traffic problems. Higher scores for socioeconomic development in coastal cities reflected well-developed tourism as well as fisheries.

The AGD indices were higher in the southern than the northern region because the northern region is planted largely with grain crops. In contrast, the southern region is planted largely with cash crops. Secondly, the southern region had better infrastructure and agricultural production conditions (e.g., water availability, fertilizer and irrigation facilities) compared with the northern region[22]. Thirdly, the rapidly developing tourism in the southern region contributed to its social and economic prosperity[42,43].

4.2 Pathways for achieving AGD

In the 1988–2013 period, our AGD index showed that the higher the score for economy and social development was, the lower the environmental score was for Hainan Province, indicating it was unsustainable to develop the economy and food productivity. Therefore, the realization of AGD in Hainan depends not only on improved crop yields and economic benefit to the communities, but also on introducing the means/policies to restrict environmental pollution and degradation. Potential adaptations include optimized spatial planning of agricultural communities, rational fertilizer application in agriculture, a healthier diet, and a reduction in food waste. In addition, many countries now place emphasis on land management policies that make room for nature using techniques such as land sparing or land sharing[44].

It is essential to coordinate region-specific food production, economy and environmental requirements for improving AGD. In the spatial planning of agriculture, a balance should be achieved between improving both crop productivity and protection of the natural environment[45]. This requires designating specific zones for ecological functions, environmental quality and resource utilization according to the *ecological redline* policy proposed by the Chinese central government[46,47]. For example, vulnerable zones regarding nitrogen and phosphorus losses need stricter policies on nutrient and land management, and farmers in these regions should get subsidies from the government[48,49]. To implement a well-designed spatial planning in agricultural and integrate economic development and environmental protection, the farmers and policymakers should be provided with information, guidance and financial support to promote sustainable agricultural production (e.g., integration of crop and livestock production systems) and reduce unintended risks (e.g., pollution swapping)[50].

Nutrient management in both cropping and livestock systems is critical to achieving AGD[51]. In the present study, scenario S1 showed that improved nutrient management (i.e., balanced fertilization and increased nutrient cycling) could effectively improve the AGD index, especially regarding the environmental and food production components. However, the application of these measures by farmers in practical agricultural production is limited. Hence, the major challenge is to transfer this nutrient management knowledge from research to practice through education, training, demonstration, extension services and appropriate economic incentives[52]. The Science and Technology Backyards have promoted communication between government, industry, university and farmers and propagated the knowledge about appropriate agricultural management[53]. This knowledge exchange and the farmer-training approach has been replicated across China with great effect[54].

The problems of overconsumption and overnutrition (e.g., obesity and chronic diseases) are important constraints of AGD. Emphasizing dietary changes aimed at improving human health and reducing food waste is one of the most important and promising paths toward AGD[9,52]. Diets link human health and environmental sustainability[27,55]. In the present study, the results for scenario S2 (reduced consumption and wastage of food) showed that the dietary adjustment and waste reduction supported the improvement in all three components of AGD (socioeconomic, food production and environment). Previous studies indicated that diet changes contributed to a rapid increase in livestock numbers more than the population growth[28,56]. The EAT-Lancet Commission developed the universal health diet guidelines[27]. The guidelines recommended that people in particular parts of the world should increase intake of vegetable and dairy protein in place of animal protein. Global adoption of this win-win diet (i.e., human and environmental health) would enhance the sustainability of food systems[27,57]. However, the major challenge is that, with urbanization, the food preferences have changed toward a meat-based diet, with the plant-based component of the diet gradually decreasing.

Reducing food loss and waste is another way of reducing the environmental impact of food production[58]. Globally, it is estimated that more than one-third of total food produced is lost or wasted before it reaches the market[59]. In China, 27% of food produced annually for human consumption is lost or wasted[60]. To achieve the global SDGs, food losses and waste should be halved at least[2,27]. Food losses should be reduced along the supply chain and consumer awareness of the importance of not wasting food needs to increase, especially in developed countries. The food-processing factories need to improve the efficiency of transforming raw materials and foodstuffs into food by using improved production technologies[61]. The governments should support public campaigns and advertising through media to minimize food waste and improve human diets. In addition, consumers can contribute to reducing food waste by learning to buy and prepare food appropriately.

Based on the result of scenario analysis, we found that the optimization measures can increase the AGD index significantly. However, due to inherent differences in natural environment and socioeconomic development, the responses to the given policies vary between cities, even in the same province. As a result, each city needs to formulate specific policies according to their exact problems (e.g., pollution, socioeconomic development, diet structure and productivity) that hinder their pathway to AGD. For example, the environment pollution issues should be considered as a priority in the regions with high agricultural productivity but also with a high pollution level. In these areas, the government should advocate for reducing the intensity of crop and livestock production (e.g., small mixed farms and regenerative agriculture), even if this may affect the agricultural production of the region.

4.3 Limitations and perspectives

An index-based approach is imperative for monitoring and assessing AGD because it provides a basis to measure progress toward AGD goals, while providing a reference for policy making[62]. Sustainable agriculture indicators in previous studies focused on nation-level assessments. However, such approaches do have limitations in reflecting the heterogeneity of agricultural sustainability performance within a country or province[14,17]. The AGD index evaluation system developed in this study consists of three components, nine first-level indicators and 35 second-level indicators. The realization of AGD requires the coordination of green and development (Fig. 1). The progress of AGD was determined by the combined performance of socioeconomic, food production and environmental components, in which the indicators of the socioeconomic component all represent development, the indicators of the environmental component all represent green, and the indicators of food production involve both green and development. The results suggested a sensitive index evaluation system (Fig. S2). The proposed index system was suitable for the specific situation of different regions, which can accurately reveal the trend of agricultural transformation.

Our study quantified the spatiotemporal progress toward AGD in Hainan Province, highlighting important implications for future policies. This method can help evaluate the impact on food production, economics and environment of implementing the fertilizer-reduction policies in regions. However, such evaluation is sensitive to the choice of indicators to be used[18,63]. Although the selected indicators in this study were determined taking SDG index as a reference, there is still uncertainty in what constitutes a suitable indicator system for AGD. The proposed indicators are easily accessible and can provide a comprehensive picture of regional AGD progress, hence, our analysis can be replicated (or modified as appropriate) by other regions. However, we did not consider all the sectors in the food chain (e.g., food processing) and some ecological indicators (e.g., soil erosion, heavy metal pollution and pesticide residues) were not considered due to the difficulty in obtaining the relevant data. Therefore, the future research can focus on the following three aspects. First, for the AGD index framework to be refined at different scales, more effort will be needed to monitor the interactive (and offsetting) effects of the AGD components. Secondly, more accurate municipal data will be needed to analyze more accurately the regional differences in AGD. Thirdly, given that the formulation and implementation of policies is the focus of AGD, careful assessment of the impacts of policies on the AGD indices will also be needed.

5 Conclusions

We developed an index evaluation system to assess and visualize AGD in Hainan Province and to track the spatiotemporal variation in achieving AGD. The AGD index for Hainan increased from 38.8 in 1988 to 40.9 in 2019, with an increase in the 1988–1999 period, followed by a rapid decline (1999–2013), and then a further increase (2013–2019). The socioeconomic development and agricultural productivity have been improved with time; environmental quality declined from 1988 to 2013, but it steadily improved after 2013. There was a large spatial variation in the AGD index across the Hainan, with higher scores in the coastal areas than in the central region, and in the south than in the north. Improved nutrient management, optimized diet structure and less waste would increase the AGD index for Hainan Province in 2030, with the greatest contribution from improvements in the environmental quality score. The approach can effectively simulate and assess the integrated effects of potential policies in regional development over time. Context-specific solutions suggested by this AGD analysis can be applied to optimize both environmental and human health.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2024538 contains supplementary materials

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Compliance with ethics guidelines

Tianxiang Yu, Jichen Zhou, Lin Ma, Fusuo Zhang, Zed Rengel, William J. Davies, and Jianbo Shen declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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