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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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Supplemental materials

1 Principles for constructing the agriculture green development (AGD) index evaluation system

1.1 Comprehensiveness

AGD is a comprehensive concept, reflecting the basic characteristics of green development from the perspective of the three major components (socio-economic development, food production and environmental quality).

1.2 Science-based

AGD must be based on the scientific and objective principles. In the process of indicator selection, we should give priority to important indicators that (1) have a sufficient scientific basis tested by practice and (2) accurately reflect the current situation of AGD to ensure the reliability of calculation results.

1.3 Testability

Firstly, each indicator should be statistically testable, quantifiable and comparable, and the selected indicators should be clearly defined and easily accessible. Secondly, this model should easily be replicated in other countries and regions. The indicators we selected were based mainly on the Hainan statistical yearbooks, or governmental bulletins, and a few were based on the publicly available literature data.

2 The importance of each indicator

AGD emphasizes both “development” and “green”, and we cannot sacrifice “green” for “development” nor limit “development” by “green”. We partitioned AGD into three equally important components: socio-economic, food production and environment. In each of these we selected as many representative and easily accessible indicators (35 second-level indicators) as possible. For example, socio-economic component contains three first-level indicators of equal importance (Table S1). In the calculation, we summarize the 35 AGD indicators into nine first-level indicators, and then summarize them into three components, and finally summarize them into the AGD index. 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.

Table S1 Summary of the three components and selected first- and second-level indicators for calculating the AGD index, data sources and scores of second-level indicators in 1988 and 2019 for Hainan Province

Components	First-level indicators	Second-level indicators	AGD targets (upper/lower boundary)	Data sources	Sources for determining AGD targets	Scores of second-level indicators	
						1988	2019
Socio-economic component	AGD1 Agricultural production conditions	Power of agricultural machinery per unit cultivated area	11.5 kW·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	10.2	100.0
		Proportion of effective irrigated area	57.0%	Hainan Statistical Yearbook	Ministry of Agriculture and Rural Affairs, 2021 ^[1]	0.2	44.1
		Proportion of area with stable yields despite drought or waterlogging	53.6%	Hainan Statistical Yearbook	Central People's Government of the People's Republic of China, 2016 ^[2]	2.6	19.1
		Power of machinery for fisheries per capita aquaculture area	25.0 kW·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	3.0	69.1
	AGD2 Economics	The urban-to-rural disposable income ratio	1.2	Hainan Statistical Yearbook	Zeng and Hu, 2008 ^[3] ; Pan and Wei, 2011 ^[4]	57.6	34.3
		Disposable income of rural residents per capita	12,400 USD	Hainan Statistical Yearbook	National Bureau of Statistics of China, 2023 ^[5]	0.7	17.5
		Gross domestic product per capita	16,037 USD	Hainan Statistical Yearbook	The People's Government of Hainan Province, 2021 ^[6]	1.1	50.0
		Agricultural output value per unit cultivated area	36,600 USD·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	3.5	100
		Proportion of tourism value vs gross domestic product	33.0%	Hainan Statistical Yearbook	The People's Government of Hainan Province, 2021 ^[6]	2.4	56.4
		AGD3 Food and nutrition	Proportion of animal protein production	55.0%	Hainan Statistical Yearbook, NUFER model	Luo et al., 2017 ^[7]	34.4
Protein intake per capita per year	21.4 kg		Hainan Statistical Yearbook, NUFER model	Willett et al., 2019 ^[8]	83.7	98.1	

Food production	AGD4 Resource consumption	Food nitrogen self-sufficiency rate	156%	Hainan Statistical Yearbook, NUFER model	Extreme values in Hainan Province from 1988 to 2019	51.9	34.3
		Pesticide input per unit cultivated area	2.5 kg·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	90.7	49.5
		Plastic mulch per unit cultivated area	0 kg·ha ⁻¹	Hainan Statistical Yearbook, Chinese Agricultural Yearbook	Extreme values in Hainan Province from 1988 to 2019	100	0.1
		Nitrogen input per unit sown area	181 kg·ha ⁻¹	Hainan Statistical Yearbook, Chinese Agricultural Yearbook	Extreme values in Hainan Province from 1988 to 2019	99.7	9.3
		Imported feed nitrogen input per unit animal	0 kg·LU ⁻¹ N	Hainan Statistical Yearbook, NUFER model	Extreme values in Hainan Province from 1988 to 2019	0.8	26.0
		Agricultural water usage per capita per year	480 t	Hainan Statistical Yearbook, NUFER model	Hoekstra, 2018 ^[9]	100	100
	AGD5 Productivity	Protein yield per unit cultivated area	705 kg·ha ⁻¹	Hainan Statistical Yearbook, NUFER model	Extreme values in Hainan Province from 1988 to 2019	0.2	55.4
		Calorie yield per unit cultivated area	29.9 million kcal·ha ⁻¹	Hainan Statistical Yearbook, NUFER model	Extreme values in Hainan Province from 1988 to 2019	0	44.3
		Vegetable yield per unit sown area	23.0 t·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	2.2	93.3
		Fruit yield per unit sown area	23.0 t·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	4.6	95.1
		Grain crops yield per unit sown area	6.0 t·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	24.8	87.7
		Tropical cash crops yield per unit sown area	28.0 t·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	31.9	68.4
	AGD6 Production efficiency	Fishery production per unit aquaculture area	18.0 t·ha ⁻¹	Hainan Statistical Yearbook	Extreme values in Hainan Province from 1988 to 2019	0.1	66.3
Energy consumption per thousand dollars of agricultural output value	941 MJ	Hainan Statistical Yearbook, NUFER model	Extreme values in Hainan Province from 1988 to 2019	35.9	100		

		Nitrogen-use efficiency in cropping system	65.0%	Hainan Statistical Yearbook, NUFER model	Ministry of Agriculture of the People's Republic of China, 2015 ^[10]	28.7	10.9
		Nitrogen-use efficiency in livestock system	30.0%	Hainan Statistical Yearbook, NUFER model	Ma et al., 2012 ^[11]	13.9	2.0
Environmental component	AGD7 Waste management	Recycling rate of livestock manure	100%	Hainan Statistical Yearbook, NUFER model	Central People's Government of the People's Republic of China, 2016 ^[2]	43.2	2.0
		Recycling rate of straw nitrogen	100%	Hainan Statistical Yearbook, NUFER model	Central People's Government of the People's Republic of China, 2016 ^[2]	23.6	23.1
	AGD8 Environmental pressure	Nitrogen surplus per unit cultivated area	90.0 kg·ha ⁻¹	Hainan Statistical Yearbook, NUFER model	Ministry of Agriculture and Rural Affairs, 2015 ^[12]	73.1	14.1
		Livestock density	1.1 LU·ha ⁻¹	Hainan Statistical Yearbook, NUFER model	Zhang et al., 2020 ^[13]	73.3	33.7
	AGD9 Environmental cost	Nitrogen runoff per unit cultivated area	9.0 kg·ha ⁻¹	Hainan Statistical Yearbook, NUFER model	Extreme values in Hainan Province from 1988 to 2019	97.2	24.1
		Ammonia emission per unit cultivated agricultural area	101 kg·ha ⁻¹	Hainan Statistical Yearbook, NUFER model	Extreme values in Hainan Province from 1988 to 2019	97.5	35.8
		Nitrogen cost of food production	3.0 kg·kg ⁻¹	Hainan Statistical Yearbook, NUFER model	Leach et al., 2012 ^[14] ; Guo et al., 2017 ^[15]	33.9	4.3
		Greenhouse gases emissions per unit cultivated area	3500 kg·ha ⁻¹ CO ₂ -eq	Hainan Statistical Yearbook, NUFER model	FAO, 2021 ^[16]	44.8	60.5

Table S2 Food consumption per person in Hainan Province in the period 1988 to 2019 and predicted for 2030 (kg·yr⁻¹)

Regions	Food types	1988	1999	2009	2019	BAU	S1	S2	S3
Rural	Cereals	262.0	247.9	198.2	132.1	86.8	86.8	121.2	121.2
	Beans	5.8	6.8	6.8	8.1	7.9	7.9	18.3	18.3
	Vegetables	65.0	62.3	82.2	91.5	96.5	96.5	109.5	109.5
	Fruit	1.7	4.3	10.8	20.2	39.6	39.6	73.0	73.0
	Pork	9.3	10.4	14.8	19.5	20.9	20.9	2.6	2.6
	Beef	0.4	0.2	0.7	0.5	0.9	0.9	0.5	0.5
	Milk	0.1	0.1	2.8	3.2	3.6	3.6	91.3	91.3
	Sheep and goat meat	0.5	0.7	2.2	1.7	3.4	3.4	2.0	2.0
	Poultry	2.8	5.9	12.6	25.6	24.0	24.0	10.6	10.6
	Eggs	0.5	1.1	1.9	4.2	5.1	5.1	4.7	4.7
Fish	8.9	10.8	15.7	30.3	24.7	24.7	10.2	10.2	
Urban	Cereals	133.9	76.2	59.5	86.8	86.8	86.8	121.2	121.2
	Beans	6.1	7.1	7.1	7.9	7.9	7.9	18.3	18.3
	Vegetables	101.5	96.0	105.7	96.5	96.5	96.5	109.5	109.5
	Fruit	12.1	24.1	40.2	39.6	39.6	39.6	73.0	73.0
	Pork	21.3	19.1	25.6	20.9	20.9	20.9	2.6	2.6
	Beef	1.4	0.5	0.7	0.9	0.9	0.9	0.5	0.5
	Milk	0.2	0.6	3.2	3.6	3.6	3.6	91.3	91.3
	Sheep and goat meat	2.0	1.5	2.3	3.4	3.4	3.4	2.0	2.0
	Poultry	10.6	12.5	1.5	24.0	24.0	24.0	10.6	10.6
	Eggs	1.6	3.0	7.5	5.1	5.1	5.1	4.7	4.7
Fish	20.7	21.6	27.1	24.7	24.7	24.7	10.2	10.2	

Note: BAU, business as usual means that all indicators followed the current trend; S1, improved nutrient management; S2, reduced consumption and wastage; S3, integration of S1 and S2.

Table S3 Counties/cities included in each region of Hainan Island

Regions	Eastern region	Western region	Southern region	Northern region	Central region	Coastal region
Counties/cities	Lingao Danzhou Dongfang Changjiang	Qionghai Wanning	Sanya Ledong Baoting Lingshui	Haikou Wenchang Dingan Chengmai	Wuzhishan Dingan Tunchang Qiongzong Baoting Baisha	Haikou Sanya Wenchang Qionghai Wanning Chengmai Lingao Danzhou Dongfang Ledong Lingshui Changjiang

Table S4 The scores of socio-economic, food production and environmental components of AGD in 1988, 1999, 2009 and 2019 for 18 counties/cities of Hainan Island

Counties/cities	Socio-economic component				Food production component				Environmental component			
	1988	1999	2009	2019	1988	1999	2009	2019	1988	1999	2009	2019
Haikou	23.0	36.3	29.7	35.1	39.9	53.5	46.9	38.0	58.2	37.0	36.4	42.0
Sanya	34.8	52.0	65.2	68.5	43.2	52.2	47.0	42.9	53.8	29.7	16.5	23.0
Wuzhishan	55.9	53.6	44.2	49.4	43.1	48.9	38.2	49.1	20.0	20.9	18.9	33.3
Wenchang	26.1	30.5	53.8	60.3	31.9	49.4	59.6	49.5	61.4	56.4	33.8	26.8
Qionghai	32.1	48.9	53.8	67.6	37.5	61.7	55.7	48.8	50.9	25.2	15.2	15.2
Wanning	28.2	43.2	48.9	68.7	32.8	51.6	47.8	48.3	46.8	32.1	17.6	13.6
Dingan	29.4	35.1	41.0	53.2	38.9	51.4	53.6	51.1	48.8	42.0	19.7	12.8
Tunchang	27.6	30.5	28.7	41.7	39.8	55.4	52.8	51.5	43.5	35.8	26.8	14.0
Chengmai	27.9	31.8	46.7	58.2	39.5	63.1	52.8	56.0	48.2	29.1	18.9	12.0
Lingao	38.4	39.0	55.6	49.2	35.5	51.4	43.9	42.4	50.6	39.7	11.3	49.8
Danzhou	27.2	38.4	41.4	49.4	45.6	64.2	58.0	47.4	50.7	35.5	31.9	27.5
Dongfang	32.4	41.9	43.1	42.8	34.4	42.6	47.4	45.0	48.2	32.0	28.7	52.0
Ledong	28.1	42.2	41.1	57.7	51.1	63.4	38.1	43.7	54.4	41.8	50.3	17.8
Qiongzong	28.6	42.1	25.6	45.1	41.7	41.1	39.3	33.4	52.8	40.2	51.5	24.6
Baoting	41.3	39.8	38.8	59.8	40.1	53.0	43.7	37.8	39.5	37.0	23.6	12.7
Lingshui	35.6	39.5	51.4	58.9	43.3	57.2	53.2	57.8	54.9	52.2	11.8	33.6
Baisha	31.0	40.7	26.4	42.5	57.5	51.8	54.3	28.0	41.2	27.2	31.7	19.0
Changjiang	24.8	36.5	31.1	43.6	46.1	59.7	44.6	46.0	53.2	38.9	23.6	30.3

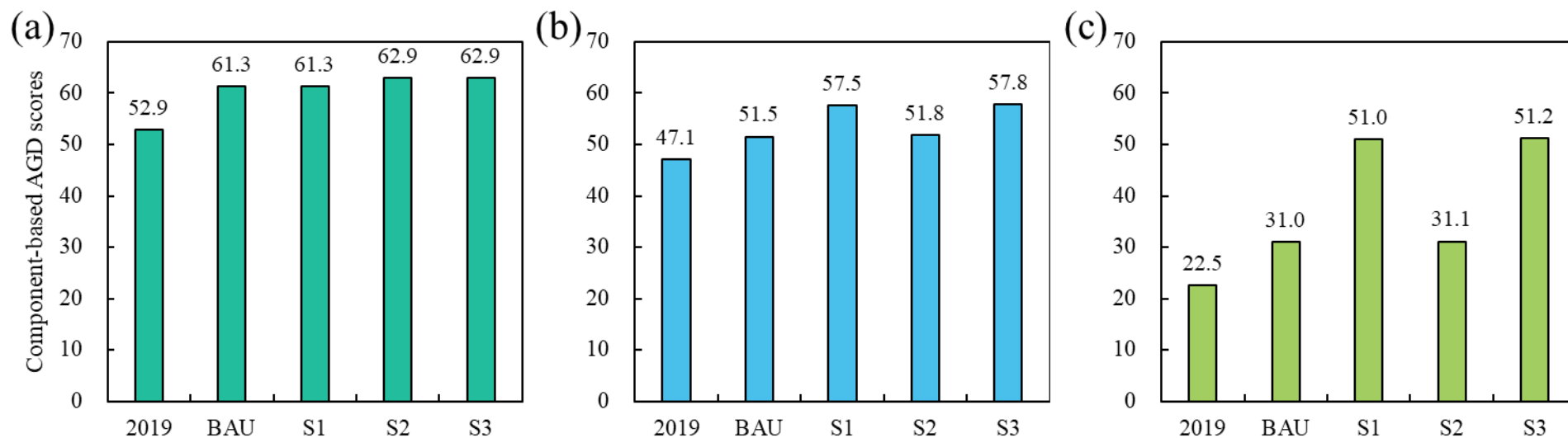


Fig. S1 Forecasts of the scores for three components of AGD (for 2030) according to the four scenarios as compared to 2019. (a), Socio-economic component. (b), Food production component. (c), Environmental component. BAU, business as usual means that all indicators followed the current trend; S1, improved nutrient management; S2, reduced consumption and wastage; S3, integration of S1 and S2.

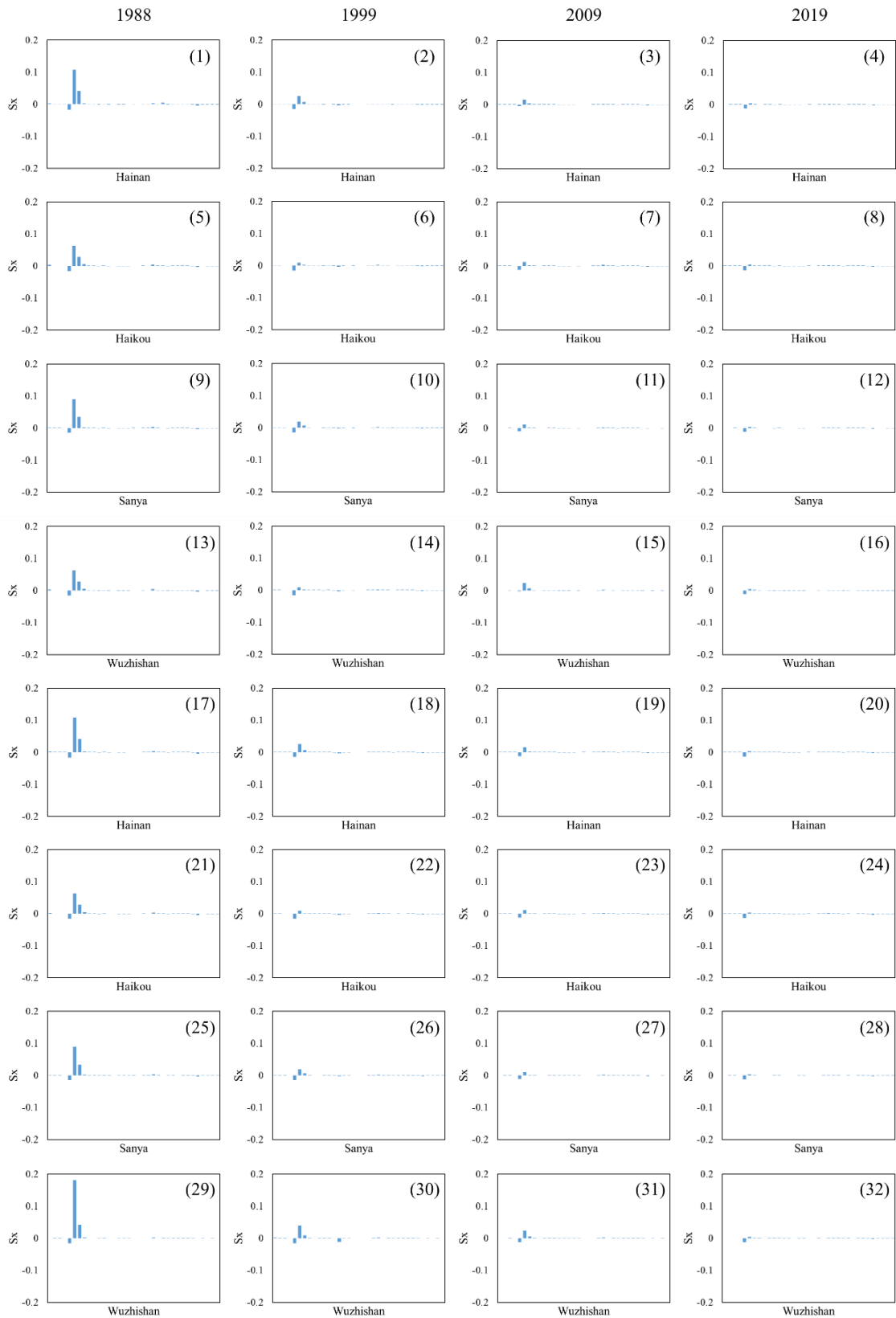


Fig. S2 Sensitivity (S_x) of AGD index to changes in one of the 35 second-level indicators used in calculating the AGD index. The original values of 35 indicators for Hainan Province as well as Haikou, Sanya and Wuzhishan cities in 1988, 1999, 2009 and 2019 were increased by 10% (graphs 1–16) or decreased by 10% (graphs 17–32). The second-level indicators of AGD arranged from 1 to 35 are on the X-axis. The Y-axis is the sensitivity (S_x) of AGD indices varying due to changes in one of the 35 constituting indicators (for the list of indicators and their corresponding order see Table S1).

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