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广州市南沙区农业区域海平面上升应对策略

RESILIENCE STRATEGIES TO IMPACTS OF SEA LEVEL RISE ON THE AGRICULTURAL AREAS IN NANSHA DISTRICT OF GUANGZHOU

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摘要

海平面上升将造成低地淹没、风暴潮加剧、海岸侵蚀等一系列生态环境影响。珠江三角洲地区农业系统发达，洪涝灾害频繁；鉴于粤港澳大湾区建设的重要性及其所面临的海岸灾害的高风险性，针对该地区农业用地受海平面上升和风暴潮灾害影响的研究十分必要。

本研究以广州市南沙区农业区域为对象，采用“源－途径－受体－影响”框架构建农业区域脆弱性评估模型，以暴露度、敏感性和适应性为基础构建评估指标体系，并基于ArcGIS平台定量化评估未来海平面上升和风暴潮对研究区域潜在的淹没风险、经济损失及其脆弱性空间分布特征。结果表明，在最低灾害风险预景和最高灾害风险预景下，南沙区农业区域淹没面积占比分别为73.38%和87.96%，经济损失分别为389 738.55万元和714 049.79万元；南沙中部地区的农业区域淹没风险较大，但北部和南部的农业区域脆弱性较高。研究进一步提出，未来可以通过防御、适应及迁移等一系列应对策略降低南沙农业区域的受灾风险和损失。

关键词

海平面上升；沿海农业区域；脆弱性评估；应对策略；防御；适应；迁移

ABSTRACT

It envinces that sea level rise aggravates low-lying terrain inundation, storm surges, beach erosion, and other ecological damages. The developed agricultural system in the Pearl River Delta is at a high risk to floods; and, in light of the tactical significance of the Guangdong-Hong Kong-Macao Greater Bay Area and its high vulnerability to sea level rise and storm surges, it urgently requires to study their impacts on the agricultural areas in this region.

Taking Nansha District, Guangzhou City, Guangdong Province, China as the study area, this study builds a vulnerability evaluation model of agricultural areas with the Source-Pathway-Receptor-Consequence framework using an indicator system upon exposure, sensibility, and adaptation, and quantitatively predicts the inundation risk level, financial loss, and vulnerability patterns of varied scenarios of sea level rise superimposed with storm surges with the ArcGIS. The main findings include 1) the stimulated proportion of inundated areas in minimum-risk and maximum-risk scenarios is 73.38% and 87.96% respectively, and the estimated financial loss in both scenarios is RMB 3,897.3855 million and 7,140.4979 million, respectively; 2) the central Nansha will suffer from a higher inundation risk, and the northern and southern agriculatural parts within the study area have a higher vulnerability to flood disasters. Resilience strategies—through defense, adaptation, or relocation—for each vulnerable zone are then proposed accordingly.

KEYWORDS

Sea Level Rise; Coastal Agricultural Area; Vulnerability Evaluation; Resilience Strategy; Defense; Adaptation; Relocation

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1 研究背景

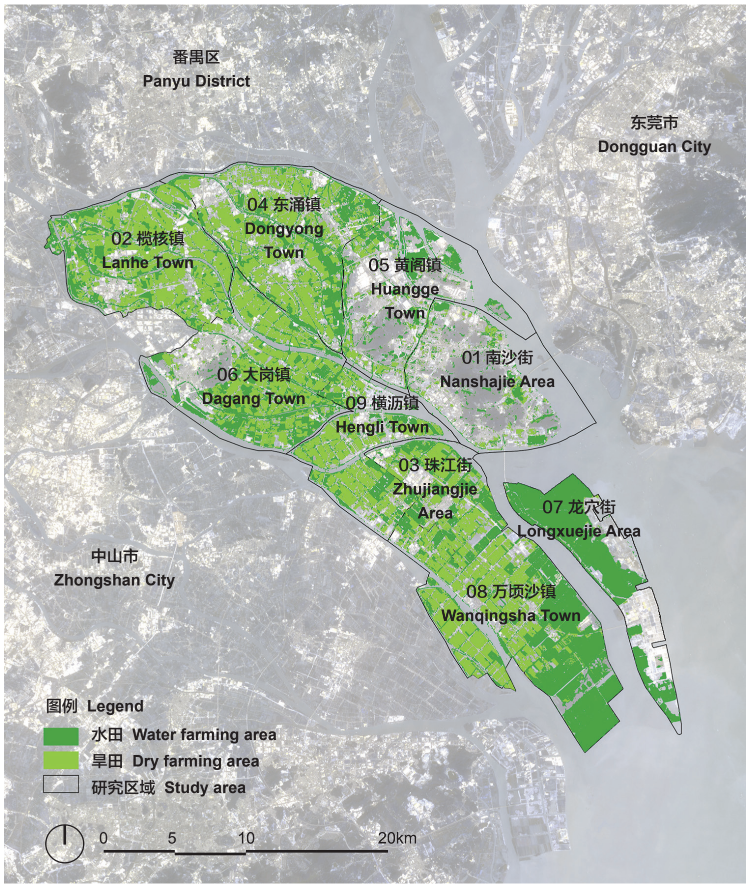
全球气候变化、海平面上升风险等议题已引发全球广泛关注。政府间气候变化专门委员会第五次评估报告表明，受温室气体排放浓度上升和人类活动影响，1901~2010年全球平均海平面上升了0.19m[1]。海平面上升将加剧风暴潮、海岸侵蚀、海水入侵等灾害，给沿海地区的自然环境和社会经济发展造成巨大破坏[2][3]。有研究显示，在未来海平面上升1m的预景下，全球将有近500万平方公里的土地面临被淹没风险，约三分之一的耕地和10亿人口将遭受影响[4]。

农业景观是人们在农业生产活动过程中形成的重要物质资源，对地方的生态环境保护、环境教育、旅游观光，以及社会文化和经济发展等发挥着重要作用[5]。然而，全球气候变暖、极端气候事件及海平面上升等导致农业灾害频发，严重影响了农业生产系统和生产能力[6]~[8]。目前，国内外学者对此展开的相关研究主要包括以下几个方面：1）评估海平面上升对农业生产和经济的影响，包括预测因风暴潮和海平面上升导致的土地淹没范围，并对不同农业作物生产可能受到的影响及其经济损失进行评估[9]~[11]；2）评估海平面上升对农业水土环境的影响[12]~[14]，并结合工程试验提出优化农业结构、提升农业基础设施及转变生产方式等对策[15]；3）评估研究农业脆弱性，通过构建社会、经济及人口等评价指标体系，采用综合指标系统对研究区域进行脆弱性等级评价[16]~[19]。总体而言，已有研究主要采用淹没深度和损失率进行风险评估，对适应性因素考虑不足[20][21]，而且鲜有研究综合考虑海平面上升和风暴潮对沿海地区农业景观的叠加影响。同时，已有研究发现，在海平面上升叠加风暴潮的影响下，中国沿海地区被淹没的各类土地中农业用地占比最大[22]。珠江三角洲地区农业系统发达，洪涝灾害频繁；鉴于未来粤港澳大湾区建设的重要性及其所面临的海岸灾害的高风险性，针对该地区农业用地受海平面上升和风暴潮灾害影响的研究十分必要。

1 Research Background

Topics such as the risks of global climate change and sea level rise have attracted extensive attention worldwide. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reveals that global mean sea level, impacted by increased greenhouse gas emissions and human activities, rose by 0.19 meter from 1901 to 2010[1]. Sea level rise aggravates storm surges, beach erosion, and seawater intrusion, wrecking the natural ecosystems and socioeconomic development of coastal areas[2][3]. Studies predict that the 1-meter sea level rise would lead globally to nearly 5 million square kilometers of submerged land, inflicting about one third of the existing arable land and 1 billion population[4].

In human's production history, agricultural landscapes are essential material resources shaped by centuries' agricultural activities and an indispensable component to local ecosystem protection, environmental education, and tourism, as well as social, cultural, and economic development[5]. However, global warming, extreme climate events, and sea level rise have resulted in frequent agricultural disasters, causing severe damages to the agricultural system and its productivity[6]~[8]. Existing studies focus mostly on risk and loss assessment, specifically: 1) evaluating the impacts of sea level rise on agricultural production and economy, including simulating inundated area caused by storm surges and sea level rise, as well as predicting possible impacts on and estimating economic losses of different crops[9]~[11]; 2) evaluating the impacts of sea level rise on agricultural soil and water environment[12]~[14], combining with engineering-tested measures for improving agricultural structures, infrastructures, and production modes[15]; and 3) evaluating agricultural vulnerability by designing associated social, economic, and demographic indicator systems and rating the vulnerability of studied territories under comprehensive indicator systems[16]~[19]. Overall, however, existing studies give less attention to studying adaptive factors[20][21], and little research has explored the superimposed impacts of sea level rise and storm surges on the agricultural landscapes in coastal areas. Nonetheless, research findings alarm that under the superimposed impact by sea level rise and storm surges, the agricultural land accounts for the largest proportion among all types of submerged land in China's coastal regions[22]. The developed agricultural system in the Pearl River Delta is at a high risk to floods. In light of the tactical significance of the Guangdong-Hong Kong-Macao Greater Bay Area and its high vulnerability to sea level rise and storm surges, it urgently requires to study such impacts on the agricultural areas in this region.



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1. 南沙区现有农业区域分布

1. Distribution of the existing agricultural areas of Nansha District

在此背景下，本研究选取广州市南沙区为研究区域，采用“源—途径—受体—影响”（SPRC）框架构建农业区域脆弱性评估模型[23]，以暴露度、敏感性和适应性为基础构建评估指标体系，从而结合量化研究方法预测在未来海平面上升叠加风暴潮预景下的风险程度、受灾农业空间特征和经济损失，并进一步提出应对未来沿海地区环境变化风险的农业景观适应性策略。

2 研究区域与研究方法

2.1 研究区域概况

南沙区地处广东省广州市最南端，位于珠江三角洲中心位置（22° 26′ ~23° 06′ N，113° 13′ ~113° 43′ E），是珠江口岸城市群水陆交通的枢纽，也是广州市唯一的出海通道。南沙区包括9个镇（街道）行政单位，总面积803km^2（图1），城镇化建设水平较高的区域主要位于黄阁镇和南沙街一带。南沙区总体地势较低，常年遭受台

Taking Nansha District, Guangzhou City, Guangdong Province, China as the study area, this study builds a vulnerability evaluation model of agricultural areas with the Source-Pathway-Receptor-Consequence (SPRC) framework[23] using an indicator system upon exposure, sensibility, and adaptation, and quantitatively predicts the risk level, vulnerability patterns, and financial loss of varied scenarios of sea level rise and storm surges. Adaptive strategies for each vulnerable zone are then proposed accordingly.

2 Study Area and Research Methods

2.1 Study Area

Nansha District sits in the southernmost part of Guangzhou and at the center of the Pearl River Delta (22°26′ ~ 23°06′ N, 113°13′ ~ 113°43′ E). It acts as the land- and water-transportation hub of the cities along the Pearl River and the only channel connecting the city with the sea. Covering an area of 803 km^2, the district is composed of 9 towns and

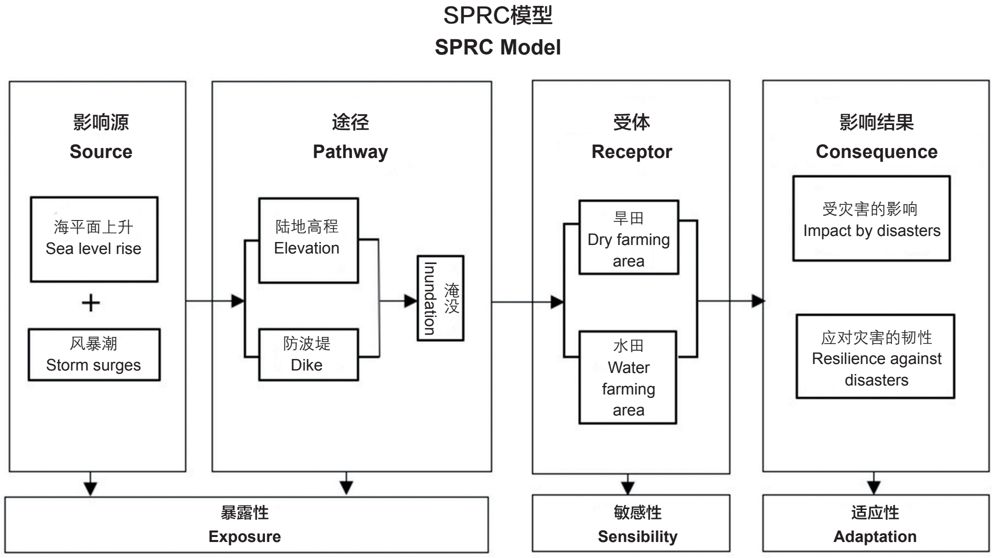
风、暴雨等自然灾害影响；研究表明，半个多世纪以来该地区海平面上升速度为4.08mm/yr[24]。

南沙区水网密布，湖塘众多，农业资源丰富，农业类型以种植业（旱田）和水产养殖业（水田）为主，前者面积为119.14km^2，后者面积为80.03km^2。2017年农业总产值为86.32亿元，其中种植业产值为46.13亿元，水产养殖业为32.78亿元[25]。然而，随着近年来全球气候变化的加剧和地区社会经济的快速发展，农业土地日渐损失，景观生态格局遭到破坏，不断削弱该地区在应对农业灾害方面的韧性[26]。同时，南沙区沿岸湿地资源丰富，位于入海口的龙穴街和万顷沙等地区的滨海湿地对内陆农业系统起重要防护作用，但沿岸频繁的人为活动和开发建设也进一步加大了农业区域的受灾风险。

2.2 脆弱性评估模型

“脆弱性”（vulnerability）一词最早出现在灾害研究领域，目前也广泛应用于土地利用变化、气候变化及生态环境评估等相关研究中[3]。气候变化研究领域目前广泛采用IPCC对于脆弱性的定义，即“一个系统容易遭受或无法应对气候变化——包括气候变率和极端天气——所带来不利影响的程度，是系统内的气候变化特征、幅度、变化速率及其敏感性和适应能力的函数”①[27]。

在气候变化影响下的海岸带脆弱性评估研究中，目前应用较为广泛的是SPRC模型，它以因果关系为基础，可以体现系统之间的相互影响及其过程特征。该模型最初由欧盟THESEUS项目提出，并用于评估气候变化威胁下海平面上升和风暴潮对海岸地区社会经济的影响[23][29]。在本研究的SPRC模型（图2）中，源（S）表示气候变化所导致的绝对海平面上升及风暴潮灾害；途径（P）表示影响源对受体产生影响的过程，在本研究中主要表现为上升的海平面和风暴潮破坏圩堤、对处于较低高程的农业区域造成的淹没影响；受体（R）表示受到海平面上升



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2. 海平面上升叠加风暴潮影响下南沙区农业区域脆弱性评估的SPRC模型

2. The SPRC model for the assessment on agriculture vulnerability to sea level rise superimposed with storm surge in Nansha District

sub-districts (Fig. 1), among which the Huangge Town and Nanshajie Area are more urbanized. On the whole, Nansha is topographically low-lying and prone to natural disasters such as typhoons and rainstorms. Research evidences that the sea level in this area rose at an annual rate of 4.08 mm over the past half century[24].

Nansha boasts considerable agricultural resources and a rich network of rivers, lakes, and ponds. Its agriculture is pillared by crop farming and aquaculture—119.14 km^2 for dry farming and 80.03 km^2 for water farming. In 2017, the total agricultural output stood at RMB 8.632 billion, to which the crop farming and the aquaculture contributed RMB 4.613 billion and 3.278 billion respectively[25]. However, the increasing global climate change and rapid urbanization lead to a huge loss of agricultural land and are destroying the ecological pattern of local landscapes, undermining the resilience against agricultural disasters[26]. At the same time, Nansha enjoys a large number of coastal wetlands; the ones in offshore areas such as Longxuejie Area and Wanqingsha Area are well protecting the inland agricultural systems. Still, intensive human activities along the coastal areas aggravate the risks of agricultural disasters.

2.2 Vulnerability Evaluation Model

Vulnerability was first used in disaster study and now has been adopted in research on land use changes, climate change, and ecological environment evaluation[3]. In the field of climate change, as defined by IPCC, “vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity”①[27].

The SPRC model is most-used to evaluate the vulnerability of coastal areas under the impact of climate change. This causality-based model can reveal the interactions between systems and the process characteristics. It was first proposed in the THESEUS project to evaluate the social and economic impact of sea level rise and storm surges on coastal areas under climate change[23][29]. For the SPRC model (Fig. 2) employed in this study, Source (S) stands for the absolute sea level rise and storm surges resulted from climate change; Pathway (P) stands for the impacting process of the source on the receptor, i.e. the dikes’ damage and the inundation of the agricultural areas in low-lying terrains caused by sea level rise and storm surges; Receptor (R) stands for the agricultural areas affected by sea level rise and storm surges, i.e. the dry and water farming

① 依据IPCC的定义，许多研究将脆弱性评估指标概括为：某个系统的暴露度、敏感性及适应性，它们之间的关系可以简单表示为：V=E+S-A；式中，V为系统的脆弱性，E为系统的暴露度，S为系统的敏感性，A为系统的适应性（参见参考文献[28]）。

① Based on the definition by IPCC, a number of studies adopt indicators to evaluate a certain system's vulnerability (V) upon exposure (E), sensitivity (S), and adaptation (A), i.e. V = E + S - A (Source: Ref. [28]).

表1：海平面上升影响下的南沙区农业区域脆弱性评估指标体系
Table 1: The indicator system for vulnerability evaluation of the sea level rise impact on farming areas in Nansha District

评估方面 Aspect	评估指标 Indicator	单位 Unit	数据来源 Data source(s)	极性 Polarity
暴露度 **Exposure**	淹没深度 Inundation depth	m	IPCC第五次评估报告海平面上升预测结果（参考文献[1]） 李国胜等人对风暴潮增水的预测值（参考文献[30]） The estimated sea level rise by the 5th IPCC Report (Ref. [1]) The findings by Li Guosheng et al. on the estimated increasing water level by storm surge (Ref. [30])	-
敏感性 **Sensibility**	旱田经济价值损失 Financial loss of dry farming area	RMB/hm^2	2017年广州南沙国民经济和社会发展统计年鉴（参考文献[31]） 2017 Statistical Yearbook on Economic and Social Development of Nansha District, Guangzhou (Ref. [31])	-
	水田经济价值损失 Financial loss of water farming area	RMB/hm^2	2017年广州南沙国民经济和社会发展统计年鉴（参考文献[31]） 2017 Statistical Yearbook on Economic and Social Development of Nansha District, Guangzhou (Ref. [31])	-
适应性 **Adaptation**	地方财政收入 Local fiscal revenue	RMB	2017年广州南沙区政府信息公开目录（参考文献[32]） Public Information Inventory of Nansha District Government, Guangzhou (Ref. [32])	+
	农业人口比重 Proportion of agricultural population	–	南沙区第三次全国农业普查主要数据公报5号报告（参考文献[33]） No. 5 Report of the Communique on Major Figures of the Third National Agricultural Census of Nansha District (Ref. [33])	-
	文盲人口比重 Proportion of illiterate population	–	广州市第六次全国人口普查主要数据公报（参考文献[34]） Communique on Major Statistics of the 6th National Population Census of Guangzhou City (Ref. [34])	-
	单位面积通车里程 Mileage per unit area	km/hm^2	OpenStreetMap地图数据库 Database of OpenStreetMap	+
	森林覆盖率 Forest coverage	–	南沙区森林资源二类调查报告（参考文献[35]） Planning and Design Report of Forest Resource Inventory of Nansha District (Ref. [35])	+

注
“-”表示负向影响因素，“+”表示正向影响因素。

NOTE
"-" means negative factor and "+" means positive factor.

及风暴潮影响的农业区域，在本研究中分为旱田和水田两类；影响结果（C）表示海水淹没对农业区域所造成的影响，影响结果损失评估主要基于淹没范围及经济价值两大方面展开。

2.3 脆弱性评估指标体系

基于SPRC评估模型，本研究从暴露度、敏感性和适应性三个方面构建了海平面上升叠加风暴潮影响下南沙区农业区域脆弱性评估指标体系，用以评估农田被洪水淹没的深度及相应的经济损失。该指标体系可量化地反映海平面上升对南沙区农业所造成的影响，同时，指标还能反映时空的异质性（表1）。

2.3.1 淹没深度

本研究预测了在50年一遇、100年一遇及200年一遇的海平面上升叠加风暴潮预景下的淹没深度，计算方式为：

$$H=H_T+(T-T_0)\times(V_l-V_g) \quad (1)$$

式（1）中，H为当地海平面相对上升高度，H_T为预测年份全球

areas; and Consequence (C) stands for the impact of sea level rise on agricultural areas in inundated area and financial loss.

2.3 Indicators for Vulnerability Evaluation

With the SPRC evaluation model, this study develops an indicator system on exposure, sensibility, and adaptation to evaluate the vulnerability of the agricultural areas in Nansha District to sea level rise and storm surges. In addition to quantifying the predicted inundation depth and financial loss in varied scenarios, this indicator system is used to map the regional temporal-spatial heterogeneity as well (Table 1).

2.3.1 Inundation Depth

This study predicts the inundation depth by sea level rise superimposed with 50-year, 100-year, and 200-year storm surges respectively. The employed calculation equations are:

$$H=H_T+(T-T_0)\times(V_l-V_g) \quad (1)$$

where H stands for the relative rise of local sea level, H_T for the rise of global sea level in the predicted year, T for the

海平面上升高度，T为预测年份，T_0为基准年，V_l为当地海平面上升速率，V_g为全球海平面上升速率。

淹没深度计算公式为：

$$D=H+S-E \tag{2}$$

式（2）中，D为淹没深度，H为当地海平面相对上升高度，S为风暴潮增水高度，E为淹没区实际高程。

式（1）中，预测年份全球海平面上升高度主要采用美国海洋研究委员会预测的2030、2050和2100年全球海平面上升高度值[36]；当地海平面上升速率依据何蕾等人的研究成果，取值为0.004m/yr[24]；全球海平面上升速率依据IPCC第五次评估报告预测结果，取值为0.0017m/yr[1]。式（2）中，风暴潮增水预测值采用的是李国胜等人根据广东省中部沿海地区17个潮位站30年的数据，分别就50年一遇、100年一遇及200年一遇预景进行的增水值预测[30]；研究高程数据采用珠江高程基准的12m × 12m精度数字高程模型（DEM）。研究由此得出2030年、2050年和2100年海平面上升叠加风暴潮的总上升高度（表2），进一步在ArcGIS 10.0平台中通过计算与淹没区域实际高程值之差获得淹没深度。

2.3.2 旱田及水田经济损失

农田洪涝淹没损失程度受淹没的深度影响，参照史瑞琴等人的洪涝损失评估研究[37]，获得不同淹没深度及与旱田/水田经济损失之间的折算关系（表3）。基于此，本研究采用的经济损失计算公式为：

$$DW_e=DW_f \times DW_u \times DW_l \tag{3}$$

式（3）中，DW_e为旱田/水田淹没经济损失，DW_f为旱田/水田淹没面积，DW_u为旱田/水田单位面积产值，DW_l为旱田/水田损失率。其中，旱田/水田淹没面积及其深度通过在ArcGIS 10.0平台中三种海平面上升叠加风暴潮增水预景下的计算结果获得，旱田/水田单位面积经济产值采用2017年广州南沙国民经济和社会发展统计年鉴[31]中的相应数据。

predicted year, T_0 for the benchmark year, V_l for the speed of local sea level rise, and V_g for the speed of global sea level rise.

Inundation depth is obtained with

$$D=H+S-E \tag{2}$$

where D stands for the inundation depth, H for the relative rise of local sea level, S for the increased water height by storm surge, and E for the existing elevation of the predicted inundated terrain.

In Equation (1), the forecasted values of global sea level rise in 2030, 2050, and 2100 are sourced from the Ocean Studies Board of the National Research Council, the United States[36]; the simulated rate of local sea level rise is set with 0.004 m/yr, according to the findings by He Lei et al.[24]; and the simulated rate of global sea level rise is set with 0.0017 m/yr, sourced from the 5th evaluation report of IPCC[1]. In Equation (2), the predicted increasing water height by storm surge in 50-year, 100-year, and 200-year predictions each is sourced from the findings by Li Guosheng et al.[30] based on their 30-year data collection at 17 tide monitoring stations in the coastal regions of central Guangdong; and the elevation data comes from the 12 m × 12 m digital elevation model (DEM) based on the Pearl River Datum. The total predicted height of sea level rise by storm surges in 2030, 2050, and 2100 is obtained (Table 2), then subtracts the existing elevation of the inundated terrain to get the relative inundation depth on the ArcGIS 10.0 platform.

2.3.2 Financial Loss of Dry and Water Farming Areas

The financial loss of agricultural areas is highly related with the inundation depth, and a rough financial loss can be estimated according to the coefficients (Table 3) between inundation depth and financial loss, sourced from the study made by Shi Ruiqin et al.[37] The financial loss in this study is calculated with the equation below:

$$DW_e=DW_f \times DW_u \times DW_l \tag{3}$$

where DW_e stands for the financial loss of farming area, DW_f for the inundated area, DW_u for the agricultural yield per unit, and DW_l for the coefficient between inundation depth and financial loss of agricultural yield. The inundated area and the inundation depth are obtained through the calculation in each scenario with the ArcGIS 10.0 platform. The agricultural yield per unit is sourced from the 2017 Statistical Yearbook on Economic and Social Development of Nansha District, Guangzhou[31].

表2：不同阶段海平面上升叠加风暴潮的淹没情景
Table 2: Three different scenarios of sea level rise coupled with storm surge

年份 Year	海平面上升高度（m） Sea level rise (m)	风暴潮增水（m） Storm surge (m)	总上升高度（m） Total rising height (m)
2030	0.180	50年一遇 50-year storm (2.606)	2.79
		100年一遇 100-year storm (2.843)	3.02
		200年一遇 200-year storm (3.078)	3.26
2050	0.398	50年一遇 50-year storm (2.606)	3.00
		100年一遇 100-year storm (2.843)	3.24
		200年一遇 200-year storm (3.078)	3.48
2100	1.137	50年一遇 50-year storm (2.606)	3.74
		100年一遇 100-year storm (2.843)	3.98
		200年一遇 200-year storm (3.078)	4.22

The study area's adaptation to disasters can be measured with indicators such as local fiscal revenue, proportion of agricultural / illiterate population, mileage per unit area, and forest coverage. The local fiscal revenue is positively correlated with the resilience against floods[38]; People's production and living activities would be more vulnerable to disasters if there is a larger proportion of agricultural population[39]; According to previous hypothesis, a lower proportion of illiterate population in the study area reflects that the locals have a stronger disaster relief awareness and capacity[40]. The mileage per unit area defines the transfer efficiency of population and properties when floods occur—a better accessibility leads to less losses and a higher adaptation[41]; Since forests help regulate climate and conserve water and soil resources, a higher forest coverage leads to a lower agricultural vulnerability to floods[42]. Table 1 lists all the data sources above.

2.4 Calculation of Vulnerability Index

Based on the vulnerability evaluation model and the indicator system, this study calculates the vulnerability index to assess the relative vulnerability levels of each town or sub-district in Nansha. Referring to the study by Huang Yunfeng et al.[43], this study adopts the equation below for the calculation of vulnerability index:

$$VI = \frac{SI}{AI} \tag{4}$$

where VI stands for the vulnerability index, SI for the sensitivity index, and AI for the adaptation index. To eliminate

地方财政收入、农业／文盲人口比重、单位面积通车里程及森林覆盖率等指标体现了应对灾害的适应性。地方财政收入与洪涝灾害地区抗灾能力水平密切相关，财政收入水平越高，应对灾害的能力越强[38]；农业人口比重越大，生产及生活受到灾害威胁的家庭越多，适应性也越低[39]；区域受教育的程度间接影响了灾害应对的意识与能力，文盲人口比重越小，应灾意识与能力越强[40]；单位面积通车里程可反映洪灾来临时人员和财产的转移速度（即救灾水平），若交通通达性好，则淹没损失小、适应性强[41]；森林具有调节气候、涵养水源、保持水土等功能，森林覆盖率与区域农业洪水灾害脆弱性成负相关，森林覆盖率越高，适应性越强[42]。研究所采用的以上相关数据来源详见表1。

2.4 脆弱性指数计算

基于脆弱性评估模型和指标体系，本研究计算了脆弱性指数，以

表3：淹没深度与损失率折算关系
Table 3: Coefficients between inundation depth and financial loss of agricultural yield

农田类型 Agriculture type	淹没深度（m） Inundation depth (m)				
	0 ~ 0.5	0.5 ~ 1.0	1.0 ~ 2.0	2.0 ~ 3.0	> 3.0
旱田 Dry farming area	0.25	0.5	0.8	1	1
水田 Water farming area	0.1	0.2	0.3	0.6	1

注
该损失率折算关系参考史瑞琴等人的洪涝损失评估研究（参见参考文献[32]），未考虑农作物种类的差别。

NOTE
The coefficients are sourced from the study by Shi Ruiqin et al. (Source: Ref. [32]), which does not take the differences of crop types into account.

评估南沙区各区域的相对脆弱性程度。参照黄云峰等人的研究[43]，脆弱性指数的计算方式为：

$$VI = \frac{SI}{AI} \tag{4}$$

式（4）中，VI为脆弱性指数，SI为敏感性指数，AI为适应性指数。为消除不同指标的量纲影响，需要对敏感性与适应性指标进行归一化处理。本研究采用现已被运用于灾害韧性评价分析研究的多维度评估指标标准化中的最大—最小归一化方法[44]，计算方式为：

$$z_j = \frac{x_{ji} - \min x_j}{\max x_j - \min x_j} \tag{5}$$

式（5）中，j为指标类型，i为一类指标中某一具体的值，z_j为第j类指标的标准化指数，x_{ji}为第j类的指标i，min x_j为第j类指标的最小值，max x_j为第j类指标的最大值。基于式（5），敏感性指数SI计算方式为旱田和水田经济损失标准化指数之和；适应性指数AI计算方式为地方财政收入、农业／文盲人口比重、单位面积通车里程及森林覆盖率等指标的标准化指数之和。

3 结果

3.1 不同风险预景下农业区域的淹没深度及经济损失

由50年一遇、100年一遇及200年一遇的风暴潮叠加海平面上升预景下的淹没面积和经济损失见表4。总体而言，淹没面积和经济损失随着海平面上升程度的加剧而增长。在不同预景下，旱田的淹没面积和经济损失始终高于水田，可能是由于南沙地区旱田面积占比较大或单位面积旱田淹没损失率较高。在最低灾害风险预景，即2030年海平面上升0.180m叠加50年一遇风暴潮预景下，淹没农田面积占比为

the dimensional impact of different indicators, sensitivity and adaptation indicators are normalized with the maximization-minimization algorithm in this study on the resilience assessment against disasters[44]. Below is the calculation equation:

$$z_j = \frac{x_{ji} - \min x_j}{\max x_j - \min x_j} \tag{5}$$

where j stands for the type of indicator; i for the indicator value; z_j for the normalized value of the j type indicator; x_{ji} for the value of the j type indicator; min x_j for the minimum value of the j type indicator; and max x_j for the maximum value of the j type indicator. Based on Equation (5), SI (sensitivity index) is the normalized index total of the financial loss of dry and water farming areas; and AI (adaptation index) is the normalized index total of indicators such as local fiscal revenue, proportion of agricultural / illiterate population, mileage per unit area, and forest coverage.

3 Results

3.1 Inundation Depth and Financial Loss of Agricultural Areas in Varied Scenarios

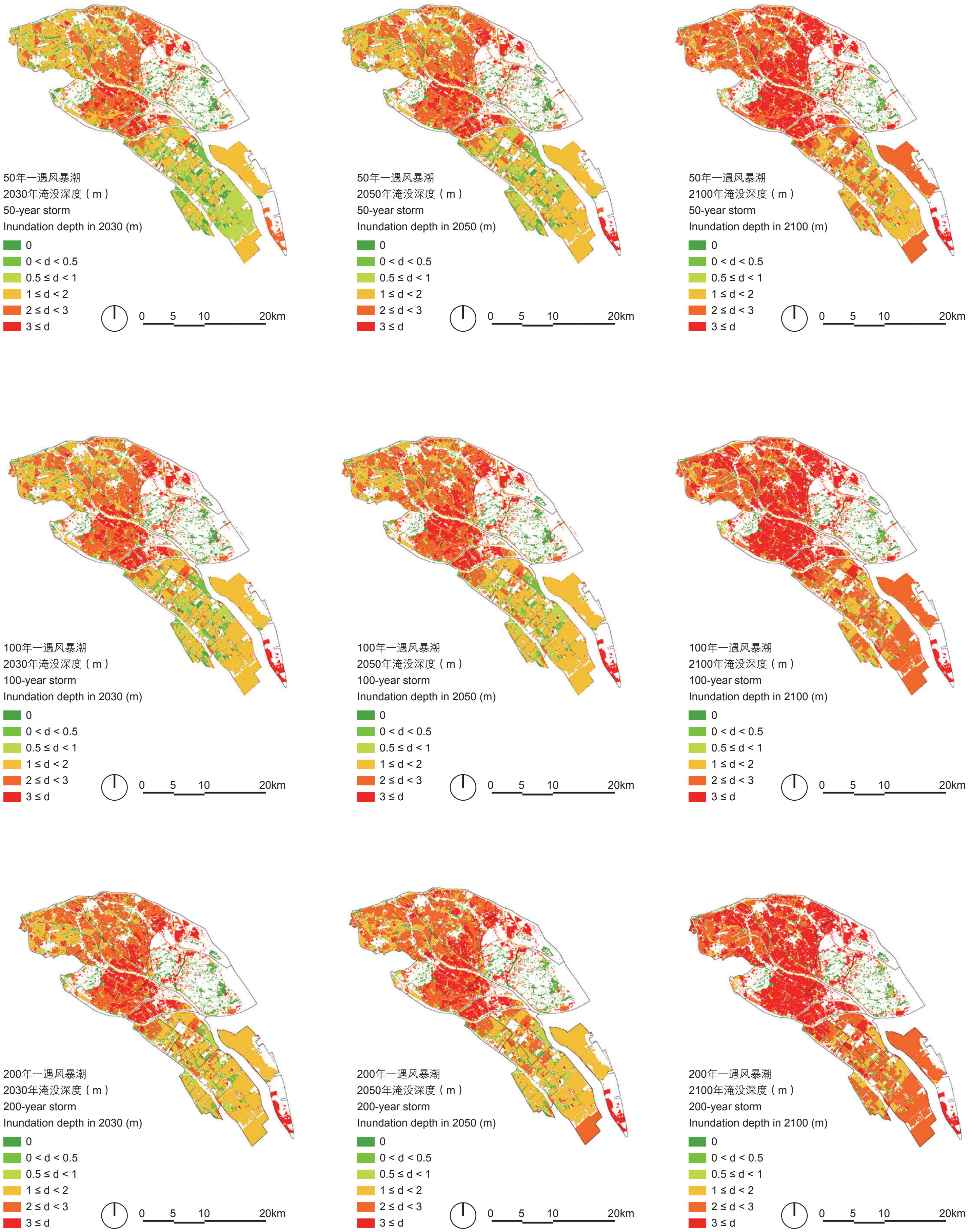
Table 4 lists the simulated inundated area and the associated financial loss by sea level rise superimposed with 50-year, 100-year, and 200-year storm surges. Generally, the inundated area and financial loss increase as sea level further rises, and those of dry farming areas keep larger than those of water farming areas across the scenarios—probably because the dry farming area takes a larger proportion in the study area and has a higher financial loss coefficient. In the minimum-risk scenario, i.e. sea level rises by 0.180 meter in 2030 superimposed with a 50-year

表4：不同风险情景下农业区域的淹没面积率及经济损失
Table 4: Flooding area ratio and financial loss of agricultural area under different risk scenarios

海平面上升高度（m） （年份） Sea level rise (m) (year)	旱田淹没面积率 （经济损失／万元） Crop farming flooding area ratio (financial loss / ten thousand RMB)			水田淹没面积率 （经济损失／万元） Aquaculture flooding area ratio (financial loss / ten thousand RMB)			总计 Total		
	50年一遇风暴潮 50-year storm	100年一遇风暴潮 100-year storm	200年一遇风暴潮 200-year storm	50年一遇风暴潮 50-year storm	100年一遇风暴潮 100-year storm	200年一遇风暴潮 200-year storm	50年一遇风暴潮 50-year storm	100年一遇风暴潮 100-year storm	200年一遇风暴潮 200-year storm
0.180 (2030)	40.74% (304,218.33)	43.87% (339,333.41)	43.94% (447,070.61)	32.64% (85,520.22)	35.48% (105,814.32)	35.57% (112,055.35)	73.38% (389,738.55)	79.35% (445,147.73)	79.51% (559,125.96)
0.398 (2050)	43.87% (337,309.98)	43.89% (352,207.45)	46.24% (462,651.58)	35.48% (105,309.00)	35.49% (111,200.53)	37.74% (121,008.07)	79.35% (442,618.98)	79.38% (463,407.98)	83.98% (583,659.65)
1.137 (2100)	46.13% (391,065.59)	46.14% (396,633.77)	48.00% (530,592.36)	37.83% (151,649.82)	37.87% (169,399.89)	39.96% (183,457.43)	83.96% (542,715.41)	84.01% (566,033.66)	87.96% (714,049.79)

3. 不同风险预景下的农业区域淹没深度

3. Inundation depths of agricultural areas in different risk scenarios



50年一遇风暴潮
2030年淹没深度（m）
50-year storm
Inundation depth in 2030 (m)

50年一遇风暴潮
2050年淹没深度（m）
50-year storm
Inundation depth in 2050 (m)

50年一遇风暴潮
2100年淹没深度（m）
50-year storm
Inundation depth in 2100 (m)

100年一遇风暴潮
2030年淹没深度（m）
100-year storm
Inundation depth in 2030 (m)

100年一遇风暴潮
2050年淹没深度（m）
100-year storm
Inundation depth in 2050 (m)

100年一遇风暴潮
2100年淹没深度（m）
100-year storm
Inundation depth in 2100 (m)

200年一遇风暴潮
2030年淹没深度（m）
200-year storm
Inundation depth in 2030 (m)

200年一遇风暴潮
2050年淹没深度（m）
200-year storm
Inundation depth in 2050 (m)

200年一遇风暴潮
2100年淹没深度（m）
200-year storm
Inundation depth in 2100 (m)

3 © 陈崇贤，夏宇，杨潇豪

73.38%，经济损失为389 738.55万元；在最高灾害风险预景，即2100年海平面上升1.137m叠加200年一遇风暴潮预景下，淹没农业景观面积占比为87.96%，经济损失为714 049.79万元。

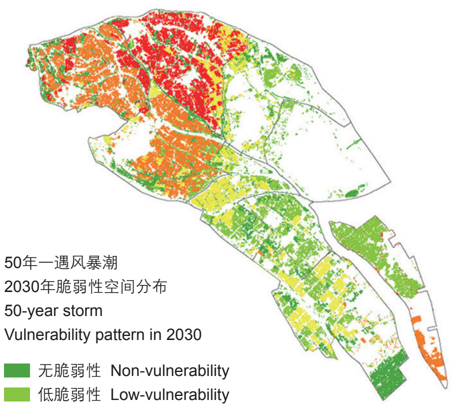
不同预景下的淹没空间分布结果表明，随着海平面逐渐上升，整体淹没深度不断加大（图3）。其中，在最低风险预景，即2030年海平面上升0.180m叠加50年一遇风暴潮预景下，大部分农田淹没深度在0.5~2m之间；在最高风险预景，即2100年海平面上升1.137m叠加200年一遇风暴潮预景下，大部分农田淹没深度处于2m以上。通过对比不同

storm surge, 73.38% of agricultural areas would be inundated and the estimated financial loss is RMB 3 897.3855 million. In the maximum-risk scenario, i.e. sea level rises by 1.137 meter in 2100 superimposed with a 200-year storm surge, the estimated figures are 87.96% and RMB 7 140.4979 million.

The simulated inundation depth increases as sea level rises across the scenarios (Fig. 3). In the minimum-risk scenario, i.e. sea level rises by 0.180 meter in 2030 superimposed with a 50-year storm surge, the inundation depth of most agricultural areas ranges from 0.5 meter to 2 meters. In the maximum-risk scenario, i.e. sea level rises by 1.137 meters in 2100 superimposed with a 200-year storm surge, the inundation depth of most agricultural areas exceeds 2 meters. It is concluded that

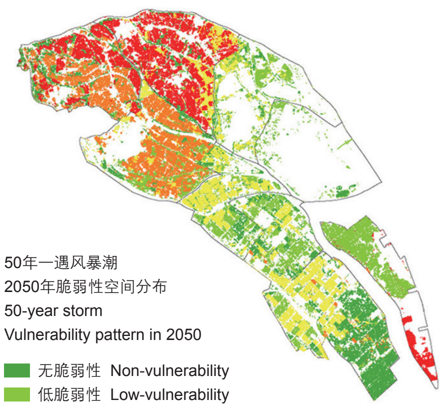
表5：不同风险情景下不同地区的农业区域脆弱性指数
Table 5: The vulnerability index of agricultural areas in different administrative units under different risk scenarios

南沙区 各区域名称 Area	**年份 Year**								
	2030			**2050**			**2100**		
	50年一遇风暴潮 50-year storm	100年一遇风暴潮 100-year storm	200年一遇风暴潮 200-year storm	50年一遇风暴潮 50-year strom	100年一遇风暴潮 100-year storm	200年一遇风暴潮 200-year storm	50年一遇风暴潮 50-year storm	100年一遇风暴潮 100-year storm	200年一遇风暴潮 200-year storm
01 南沙街 Nanshajie Area	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.02	0.02
02 榄核镇 Lanhe Town	0.62	0.82	1.02	0.72	1.03	1.08	0.87	1.26	1.27
03 珠江街 Zhujiangjie Area	0.08	0.11	0.13	0.09	0.13	0.15	0.14	0.21	0.22
04 东涌镇 Dongyong Town	0.91	1.26	1.49	1.00	1.51	1.54	1.20	1.91	1.92
05 黄阁镇 Huangge Town	0.09	0.21	0.23	0.10	0.22	0.24	0.12	0.26	0.27
06 大岗镇 Dagang Town	0.44	0.63	0.74	0.48	0.74	0.75	0.53	0.89	0.89
07 龙穴街 Longxuejie Area	0.20	0.87	0.88	0.28	0.88	0.88	0.50	1.54	1.55
08 万顷沙镇 Wanqingsha Town	0.29	0.57	0.67	0.38	0.68	0.79	0.55	1.15	1.20
09 横沥镇 Hengli Town	0.19	0.25	0.30	0.21	0.30	0.31	0.24	0.35	0.36



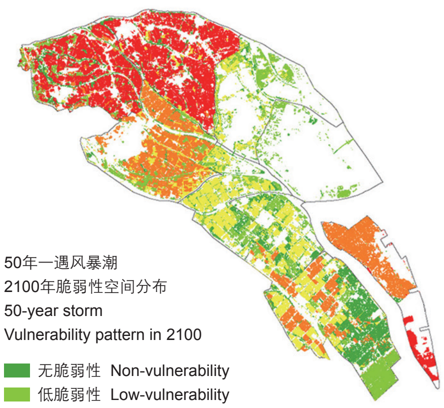
50年一遇风暴潮
2030年脆弱性空间分布
50-year storm
Vulnerability pattern in 2030

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



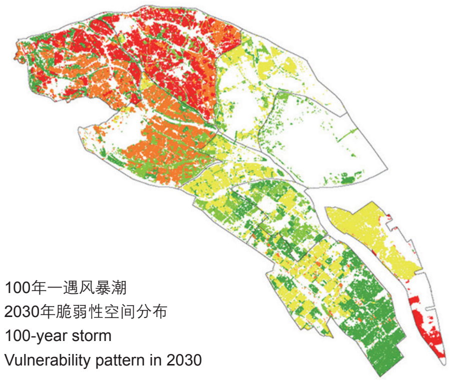
50年一遇风暴潮
2050年脆弱性空间分布
50-year storm
Vulnerability pattern in 2050

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



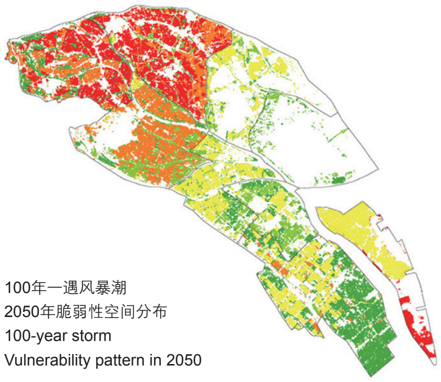
50年一遇风暴潮
2100年脆弱性空间分布
50-year storm
Vulnerability pattern in 2100

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



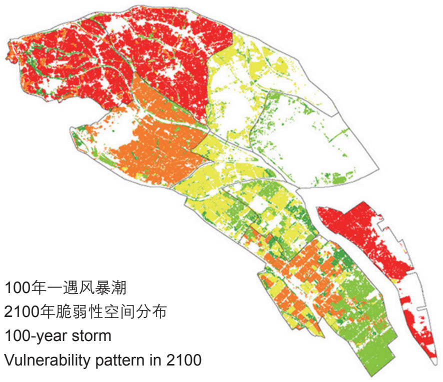
100年一遇风暴潮
2030年脆弱性空间分布
100-year storm
Vulnerability pattern in 2030

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



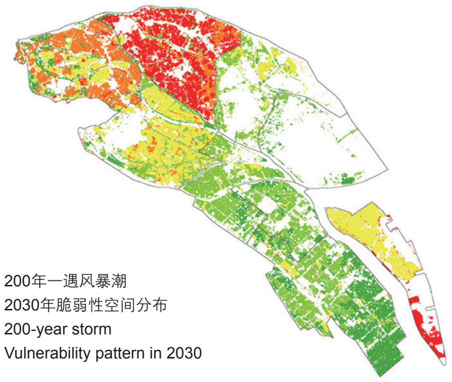
100年一遇风暴潮
2050年脆弱性空间分布
100-year storm
Vulnerability pattern in 2050

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



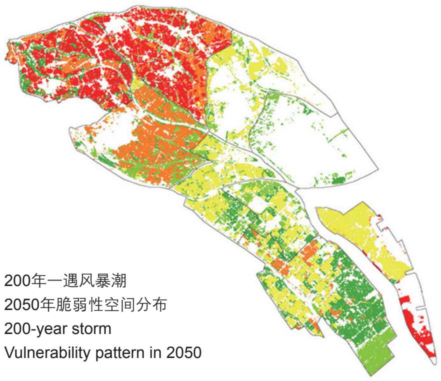
100年一遇风暴潮
2100年脆弱性空间分布
100-year storm
Vulnerability pattern in 2100

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



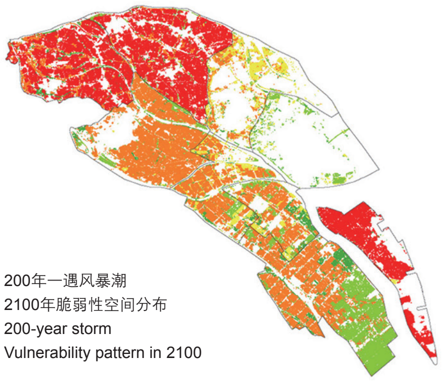
200年一遇风暴潮
2030年脆弱性空间分布
200-year storm
Vulnerability pattern in 2030

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



200年一遇风暴潮
2050年脆弱性空间分布
200-year storm
Vulnerability pattern in 2050

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability



200年一遇风暴潮
2100年脆弱性空间分布
200-year storm
Vulnerability pattern in 2100

🟩 无脆弱性 Non-vulnerability
🟩 低脆弱性 Low-vulnerability
🟨 中脆弱性 Mid-vulnerability
🟧 高脆弱性 High-vulnerability
🟥 极高脆弱性 Extremely-high-vulnerability

4. 不同风险预景下的农业区域的脆弱性空间分布

4. Vulnerability patterns of agricultural areas in different risk scenarios

4 © 陈崇贤，夏宇，杨潇豪

预景后发现，位于南沙中部的片区四、片区六与片区九的农田受淹没的风险最大，一直处于3m以上的淹没深度范围。

3.2 不同风险预景下农业区域的脆弱性评价

根据上述脆弱性指数计算方法，并在ArcGIS平台上进行空间叠加计算，得到各区域的脆弱性指数及空间分布特征。从2030到2100年，随着海平面上升幅度加大，南沙各区域的脆弱性指数也呈现出增长趋势（表5）；其中，片区四的脆弱性指数最高，片区一最低。其可能原因是片区四的淹没深度和面积较大，而适应能力又弱，片区一的淹没深度和面积较小，而适应能力较强。从2050到2100年，片区七和片区八的脆弱性指数出现较大增长，这主要与海平面上升和风暴潮造成淹没面积或深度的显著增加有关。

通过在ArcGIS平台中将脆弱性指数分布利用自然断点法分成5个等级，得到不同海平面上升叠加风暴潮预景的脆弱性空间分布结果（图4）。脆弱性较高的区域主要分布于南北两端，包括片区二、片区四和片区七，这些地区一直处于高脆弱性以上水平。脆弱性相对较低的区域主要位于片区一和片区八的南部，主要原因可能是该区域的适应性能力较强，同时，片区八现有的防护堤建设也在一定程度上降低了未来该区域的脆弱性水平。在最高风险预景，即2100年海平面上升叠加200年一遇风暴潮预景下，南沙的农业区域整体处于中脆弱性以上水平，北部的片区二和片区四，以及南部的片区七则基本处于极高脆弱性水平。

4 应对策略

在气候变化加剧和海平面上升风险不断升高的背景下，为南沙区的农业区域制定有效的应对策略是该地区未来发展的必要性工作。当前，沿海地区针对海平面上升普遍采用的应对策略主要包括：防御、适应和迁移[45]。本研究结合研究区域的现状条件，着重分析了其在三种适应性策略下的差异、利弊及相应的景观形式和空间布局特点（图5）。

4.1 防御性策略

防御是指在不改变现有农业结构和生产模式的前提下，为了确保现有农业资源遭受未来海平面上升叠加风暴潮破坏的程度最小，而

the agricultural areas in the central Nansha (mainly including Areas 4, 6, and 9) are most vulnerable, which will be inundated with floods of over 3 meters as simulated.

3.2 Vulnerability Evaluation of Agricultural Areas in Varied Scenarios

After calculating the vulnerability index of each town or sub-district with the equations above, a vulnerability pattern of the study area is obtained with the ArcGIS platform. From 2030 to 2100, the vulnerability index in Nansha grows as sea level rises (Table 5), among which the index of Area 4 is the highest and that of Area 1 the lowest. It is probably because Area 4 suffers from a larger inundation depth and a larger inundated area while being weak in adaptation; and things in Area 1 are on the contrary. The indexes of Areas 7 and 8 grow by a large margin from 2050 to 2100, which is resulted from the considerable increase of the inundated area or inundation depth caused by sea level rise and storm surges.

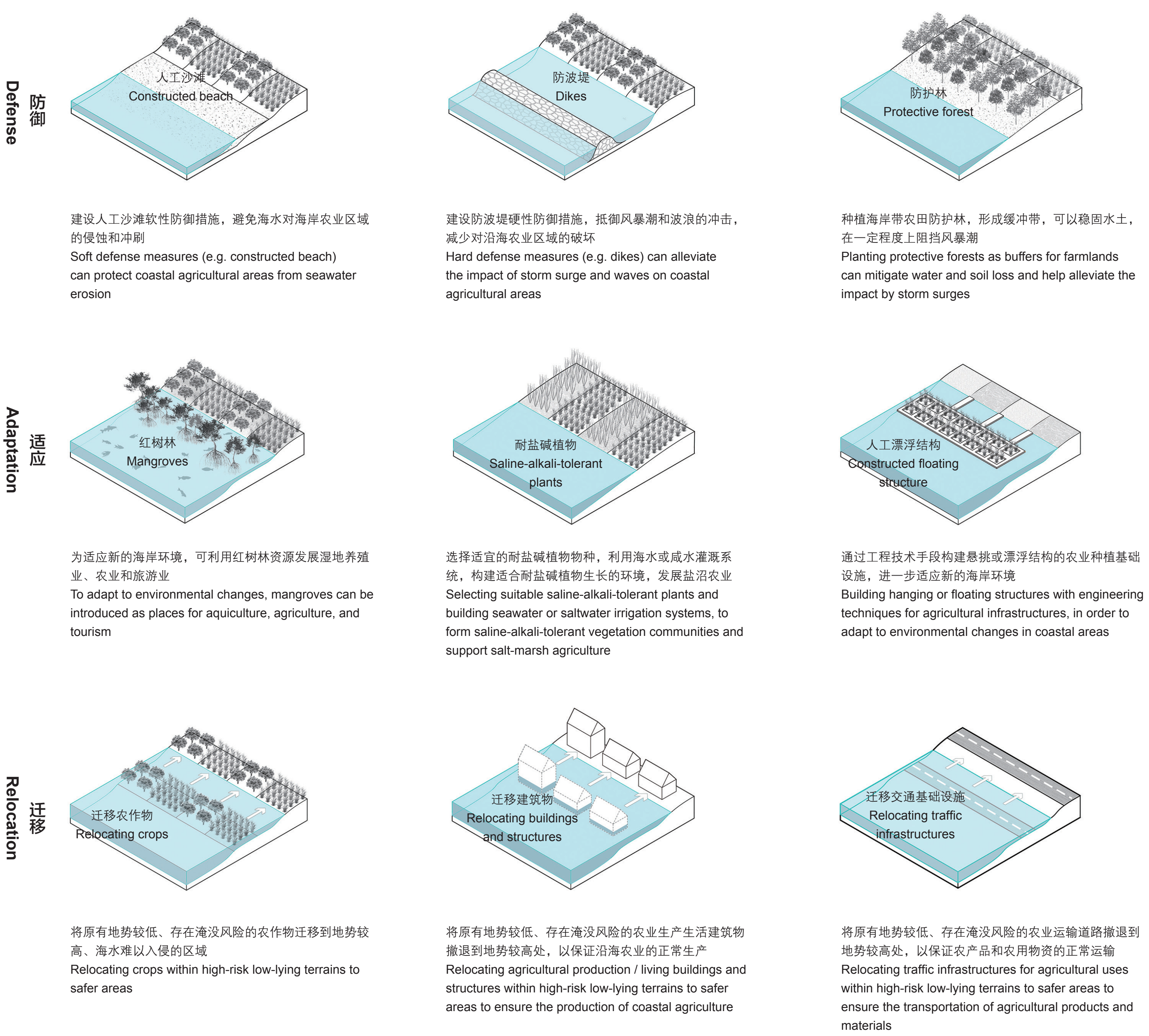
By identifying the vulnerability indexes into 5 levels with the Natural Breaks in the ArcGIS platform, the distribution pattern of each scenario of sea level rise superimposed storm surges is obtained (Fig. 4). It reveals that the southernmost and northernmost parts in the study area are the most vulnerable (covering Areas 2, 4, and 7, all in a high-level vulnerability), while Area 1 and the southern part of Area 8 are less vulnerable—Both two parts have a better adaptation, and particularly, the embankment in Area 8 enhances its resilience against disasters in future. In the maximum-risk scenario, the overall vulnerability of the agricultural areas in Nansha is above the medium level, and Areas 2 and 4 in the north and Area 7 in the south will suffer from an extremely high vulnerability.

4 Resilience Strategies

As climate change intensifies and sea level continues to rise, it is pressing to come up with effective adaptive strategies for the agricultural areas in Nansha which matters concerning regional future development. At present, strategies to sea level rise that are widely adopted for coastal regions include defense, adaptation, and relocation[45]. Based on the existing conditions of the study area, this research examines the differences, pros and cons, and the spatial patterns of each kind of strategy (Fig. 5).

4.1 Defense

Defensive strategies are often developed to minimize the impact of sea level rise and storm surges on a territory's agricultural resources by strengthening coastal protection



建设人工沙滩软性防御措施，避免海水对海岸农业区域的侵蚀和冲刷
Soft defense measures (e.g. constructed beach) can protect coastal agricultural areas from seawater erosion

建设防波堤硬性防御措施，抵御风暴潮和波浪的冲击，减少对沿海农业区域的破坏
Hard defense measures (e.g. dikes) can alleviate the impact of storm surge and waves on coastal agricultural areas

种植海岸带农田防护林，形成缓冲带，可以稳固水土，在一定程度上阻挡风暴潮
Planting protective forests as buffers for farmlands can mitigate water and soil loss and help alleviate the impact by storm surges

为适应新的海岸环境，可利用红树林资源发展湿地养殖业、农业和旅游业
To adapt to environmental changes, mangroves can be introduced as places for aquiculture, agriculture, and tourism

选择适宜的耐盐碱植物物种，利用海水或咸水灌溉系统，构建适合耐盐碱植物生长的环境，发展盐沼农业
Selecting suitable saline-alkali-tolerant plants and building seawater or saltwater irrigation systems, to form saline-alkali-tolerant vegetation communities and support salt-marsh agriculture

通过工程技术手段构建悬挑或漂浮结构的农业种植基础设施，进一步适应新的海岸环境
Building hanging or floating structures with engineering techniques for agricultural infrastructures, in order to adapt to environmental changes in coastal areas

将原有地势较低、存在淹没风险的农作物迁移到地势较高、海水难以入侵的区域
Relocating crops within high-risk low-lying terrains to safer areas

将原有地势较低、存在淹没风险的农业生产生活建筑物撤退到地势较高处，以保证沿海农业的正常生产
Relocating agricultural production / living buildings and structures within high-risk low-lying terrains to safer areas to ensure the production of coastal agriculture

将原有地势较低、存在淹没风险的农业运输道路撤退到地势较高处，以保证农产品和农用物资的正常运输
Relocating traffic infrastructures for agricultural uses within high-risk low-lying terrains to safer areas to ensure the transportation of agricultural products and materials

5 © 陈崇贤，夏宇，杨潇豪

5. 南沙区农业区域三种应对策略

5. Three kinds of resilience strategies for agricultural areas in Nansha District

通过加强海岸线防护能力来降低应对灾害脆弱性的方式。在本研究范围中，片区一、片区七和片区八沿岸受海水冲刷和侵蚀的破坏风险较大，需要加强防御设施来提高海岸的防护标准。同时，片区七和片区八南部地区分布有较为丰富的水田农业和湿地资源，单一的硬性防御措施（即通过工程技术手段或建设海岸工程项目进行保护的方式）将

measures against disasters without altering its existing spatial structure and production mode. In this case, Areas 1, 7, and 8 are prone to seawater erosion, where high-standard defensive measures should be put in place. At the same time, the southern parts of Areas 7 and 8 have considerable aquaculture and wetland resources. As single-purpose hard-engineering defensive measures (e.g. constructed embankments) would damage the coastal wetlands and disturb related ecosystems, soft resisting

对海岸湿地资源及相关生态系统造成负面影响。因此，可以采取软性防御性措施与现有工程防护堤相结合的方式：通过在现有工程设施基础上引入湿地植物和人工沙丘，形成自然缓冲区，从而避免现有岸线及生态系统遭受海水的侵蚀和冲刷。片区一沿岸以人工建成环境占主导，可以通过加强该区域现有硬性工程防御措施的方式，有效降低海岸建成环境受破坏而造成的经济损失。

4.2 适应性策略

适应是指对未来海平面上升和风暴潮风险所做出的趋利避害的反应，包括过程、措施或结构上的改变，以减轻或抵消未来潜在的风险[27][46]。从以上淹没分析结果可知，研究区域中部的片区四、片区六和片区九受淹没的风险较大。针对这些地区，一方面可以借助现代工程和技术手段（如提高现有农业建筑和道路等基础设施的防洪标准水平）支持现有农业区域的发展；另一方面，由于该地区当前主要为旱田农业，未来不断加大的海平面上升和风暴潮淹没风险将淹没低地，改变所淹地区的生境条件，因此可通过调整农业类型和结构及生产方式来适应未来的环境变化：例如，可增加种植适合该地区的耐盐碱植被，丰富鱼、虾、蟹及其他水产养殖类型，拓展水上农作物种植类型；同时引入农业旅游休闲、科普教育和科学研究等内容，培育新的生产和经济模式。

4.3 迁移性策略

迁移是指将所进行的农业生产生活活动从高风险区域内转移到无/低风险区域，或者将其划定为非建设活动区，实施避害性发展策略。从以上风险评估结果可知，片区二、片区四和片区七的农业区域脆弱性较高；实施迁移策略可最大程度地降低这些区域农田未来的受灾受损风险。同时，由于该策略不依赖海岸工程防御措施和技术，而允许未来海平面上升淹没一些区域，因而能够减少基础设施建设方面的资金投入。例如，通过将片区七北部的大部分水田移至无/低风险区域，禁止或限制人类活动的干扰，可促进自然生态系统的修复与演替，进一步发挥其作为其他区域缓冲带的防御作用。

5 结论与讨论

本研究针对广州市南沙区农田系统，以SPRC模型为基础，构建了脆弱性评价指标体系；进而通过量化评估未来海平面上升叠加风暴潮

methods need to be more employed, for example, introducing wetland plants and man-made sand dunes to form natural buffers so as to protect shores and ecosystems from seawater erosion. The coasts of Area 1 is mostly occupied by built-up urban development, where hard-engineering defensive measures can be adopted to cushion the damage to urban properties.

4.2 Adaptation

Adaptive strategies are conceived to relieve or mitigate the potential impact by sea level rise and storm surges by making adjustments in process, measure, or structure[27][46]. As analyzed above, the central Nansha, covering Areas 4, 6, and 9, are at a higher risk of being inundated. For these areas, modern engineering and technical approaches (such as raising flood control standards of agricultural structures, traffic facilities, and other infrastructures) should be adopted to support the development of the existing agricultural areas; meanwhile, as these areas are dominated by low-lying dry farming land, the agricultural structure and production mode need to be adjusted to cope with environmental changes by aggravating sea level rise and storm surges. Measures, such as introducing more saline-alkali-tolerant plants into the possible inundated habitats, diversifying aquaculture products, and enriching water-farming crops, would help. Also, programs in agricultural tourism, public education, and academic research are encouraged to foster new production modes and spur economic growth.

4.3 Relocation

Relocation strategies are made to avoid or alleviate disaster damages by moving the agricultural population and farming activities in high-risk areas to no- or low-risk areas, or by limiting physical construction in high-risk areas. In this case, the agriculture lands in Areas 2, 4, and 7 are predicted with a high-level vulnerability, where relocation approaches are suitable. In addition, relocation relies less on engineering measures or technologies and can turn some land into floodable areas, meaning fewer required investments for infrastructural construction. For example, most water farming areas in the northern part of Area 7 can be relocated to safer areas and human activities need to be minimized to facilitate the restoration and evolution of natural ecosystems, acting as a buffer in the region.

5 Conclusion and Discussion

By using the SPRC model, this study establishes a vulnerability evaluation indicator system for the agricultural

不同预景下农田区域的潜在淹没风险、经济损失及脆弱性空间分布特征，提出适应未来海岸环境的应对策略。研究显示：

从淹没风险及经济损失来看，在最低和最高风险预景下，淹没农田面积占比分别为73.38%和87.96%，经济损失分别为389 738.55万元和714 049.79万元。总体上，不同预景下的大部分研究区域的淹没深度都达0.5m以上；从空间分布来看，位于南沙区中部的片区四、片区六和片区九的淹没风险最大。

从脆弱性空间评估结果来看，高脆弱性区域主要分布在南沙区的南北两端，而脆弱性相对最低的区域主要位于片区八南部。

在未来海平面上升风险背景下，片区一、片区七和片区八可在海岸带加强防御措施，保护已有农田；片区四、片区六和片区九可通过加强适应性基础设施建设或调整农业结构等方式，适应未来海岸环境变化；迁移位于高风险区的片区七北部农业生产生活活动，控制该区域人为活动，以有效恢复自然生态系统的防御功能。

海平面上升及其对海岸环境的影响是一个复杂的动态过程。本研究在评估其对沿海农业区域的影响方法层面做了一定的尝试，但仍需进一步探索在海平面上升影响下，沿海植物生境的动态迁移过程，以及海平面上升和风暴潮风险的多预景模拟。同时，未来应对策略的实施需要结合当地具体实际情况，进一步探讨相关政策的制定，以健全韧性措施体系。**LAF**

致谢

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areas in Nansha District, Guangzhou, and stimulates the inundation risks, financial losses, and vulnerability patterns in varied scenarios of sea level rise superimposed with storm surges. It finally comes up with resilience strategies for the study area. The findings of this study are concluded as below.

1) In terms of inundation risk and financial loss, the proportion of inundated areas in minimum-risk and maximum-risk scenarios is 73.38% and 87.96% respectively, and the estimated financial loss in both scenarios is RMB 3,897.3855 million and 7,140.4979 million. Across all the scenarios, most areas of Nansha will be inundated with floods of 0.5 meter at least, and the central Nansha (covering Areas 4, 6, and 9) will be the most vulnerable, as predicted.

2) The most vulnerable areas are the southernmost and northernmost parts of the study area, while the southern part of Area 8 sees the lowest vulnerability.

3) In face with the growing risk of sea level rise, the agricultural lands in Areas 1, 7, and 8 can be protected with defensive measures; For Areas 4, 6, and 9, adaptive infrastructures or adjustments on agricultural structures can be introduced to respond to the environmental changes in the coasts; and, by relocating the agricultural production and living activities to safer areas, the high-risk northern part of Area 7 can be ecologically restored by limiting human activities.

Sea level rise and its impact on coasts is a complicated, dynamic process. This study explores its impact on coastal agricultural areas; for future research, it expects more efforts in studying the dynamic movement of coastal vegetation habitats under the impact of sea level rise, and improving the scenario simulation of the risks by sea level rise and storm surges. At the same time, strategies should be more specific to the authentic conditions and resilience systems need to be improved with policy guarantees. **LAF**

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