Supplementary Information for

Local over Global: Anthropogenic Stressors Outpace Climate Impacts on Coral Reef Collapse in the South China Sea

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Supporting Information Text

Integrated Coast-Reef Management (ICRM). We propose an Integrated Coast-Reef Management (ICRM) framework for coral reef conservation. Considering the unique characteristics of coral ecosystems, we introduce several assessment indicators and/or realization paths for the five steps applicable to coral reefs (Fig. 4). The first step is to evaluate coral reef status based on our and global data scale of LCC and macroalgae coverage (MC)[1,2], dividing it into three levels of low resilience (LCC < 10%), moderate resilience (10% < LCC < 30%, MC/LCC < 1/3), and high resilience (LCC > 30%). The second step is to identify ecological stressors, such as overfishing, CoTS, nutrient pollution, coastal engineering, ocean warming and other stressors. Particularly, the stressors identification in individual subregions should not only address fragmented and proximal drivers but also encompass multi-scale and systematic levels.

The third step is to develop tailored strategies in local communities, focusing on integration of land-sea infrastructure development and existing ecological restoration techniques to reduce environmental stressors on local coral reefs. In the capacity-building component, the pathways involve a variety of biological and physical interventions in the sea and on land. For example, biological interventions include removal of harmful organisms (CoTS or *Drupa morum*), species-focused stocking, coral nursery garden or transplantation[3,4] (Fig. S9) and preservation of coral species resources. In light of global warming, we also propose to build a 'Noah's Ark' for coral species protection - a large-scale land-based ecological aquaculture system with good water quality and temperature control system, which has been proven viable in Hainan, China[5]. Physical interventions include the establishment of Reef Natural Reserves, and the repair of coral habitat (e.g., artificial reefs) through engineering (Fig. S9). Moreover, active restoration of coral reefs is increasingly recognized as a major trend now, therefore, quantifying stressors and developing tailored mitigation measures from land to sea is necessary. Interventions aimed at mitigating land-to-sea pollution encompass the implementation of coastal engineering restrictions to minimize sediment discharge into the sea, reduction of nutrient emissions from agriculture and aquaculture into water bodies, and restoration of upstream coastal ecosystems adjacent to coral reefs such as seagrass beds and mangroves[6].

The fourth step is the implementation and enforcement of strategies, which require long-term support from government, corporations, scientists, and other social stakeholders, to provide technical and financial guarantees. Certainly, any intervention should be monitored to assess whether the targets have been achieved and to evaluate its ecological and economic cost-effectiveness. The final step is the regulation and maintenance of the environment, which requires regular monitoring and predicting of relevant ecological systems, such as water quality of estuarine and coral reef, and intensity of human activity. Long-term monitoring of interventions can help accumulate data and knowledge, allowing managers to update and improve strategies and interventions over time (i.e. adaptive management)[7]. Long-term nature-based ecosystem restoration should be the primary goal of adaptive conservation strategies to avoid the high financial costs of temporary solutions. Furthermore, monitoring and evaluation should pay attention to the relationship between species adaptation and climate change.

Supplementary Methods

Coral community data. Each survey site consisting to 2~6 transects was deployed at a depth of 2 ~ 9 m. The video transects were analyzed in the laboratory by freezing the video at every 10 cm interval (scale points) to quantify the substrate and organism composition up to the 50 m scale point. Each 50 m transect was partitioned into two 20 m sub-transects spaced 5 m apart, resulting in a total of 400 scale points per transect. For each point, the distribution of benthic component (including rock, sand, rubble, Scleractinia corals (≥5 cm diameter), coral recruit (< 5 cm diameter), dead coral, bleached coral, crown-of-thorns starfish (CoTS), macroalgae, calcified algae and sponge etc.) under the transect line was counted from the images. For example, the live coral coverage is calculated by dividing the number of all live Scleractinia corals by 200, namely the total scale points of each transect, expressing it as a percentage. CoTS abundance is calculated by dividing the number of CoTS by transect area. Similar methods were used for analyzing other substrate types, and all species identification supported by clear pictures of corals, macroalgae etc.

The banded transect video was used for the coral reef fish investigation. And each monitoring station is 300 $_m$×300 $_m$ range. Each video was taken for at least 5 min from the starting point to the end after laying the tape for 10 min. The lens was located 0.5 m from the bottom, with a front vision of approximately 5 m. The drivers aimed to contain each captured fish in the frame of video within the scope of 2.5 m on both sides of the tape. Coral reef fish density is calculated by dividing the number of fish by transect area. Photographs and specimens of fish were also taken to aid in identification.

Data on biotic and abiotic drivers of coral coverage change. Some environmental factors are influential variables in explaining coral growth and habitat state, including temperature (℃), chlorophyll a (Chl a (μg L^{-1})), photosynthetically active radiation (PAR (E m^{-2} s^{-1})), and turbidity (K_d490)[8,9]. These data were obtained from NASA's Earth Observing System Data and Information System (EOSDIS) Modis-Aqua satellite database, which has an ~4 km resolution beginning in mid-2002 through to December 2020 (https://oceandata.sci.gsfc.nasa.gov). Light availability (PAR) is a crucial physical factor driving coral distribution along depth gradients[10]. To represent turbidity, defined as the attenuation of light at depth, we used the diffuse attenuation coefficient of light at the 490 nm wavelength (K_d490) from NASA[8]. The Chl a, PAR and K_d490 factors were extracted for month of the year at each site. And we calculated the annual mean Chl a, PAR and K_d490 value for each site.

Temperature variables directly impact coral health and consequently have long-term implications for reef ecosystem health. Therefore, we also assessed sea surface temperature (SST) variations using the monthly composite temperature data extracted from the NOAA Coral

Reef Watch who conduct global monitoring of heat stress based on satellite SST data (https://www.star.nesdis.noaa.gov/pub/sod/mecb/crw/data/5km/v3.1/nc/v1.0/monthly/; accessed December 2020). Temperature variables also included means and maxima of monthly composite Degree Heating Weeks (DHW)[11]. Degree Heating Weeks are the global standard for determining the likelihood of thermal stress inducing coral bleaching on coral reefs. One DHW represents a 1 °C increase in the local mean climatic temperature for 1 week over the previous 12 weeks[12]. These data are highly robust for predicting bleaching[13], and are specified at the highest resolution available (~4.6 km at the equator). For each site, we calculated the maximum DHW that occurred in the year.

Typhoon exposure. Typhoon impact data were obtained from the China Meteorological Administration tropical cyclone database, which contains the track and scale of every tropical cyclone that landed in China in the period 2000–2020[14,15] (http://typhoon.zjwater.gov.cn/). The spatial cumulative impact of all tropical cyclones was estimated based on the level and azimuth radius of the surface winds[16]. For each transect, maximum values and various percentiles of sustained surface-wind speed, the direction of cyclone-generated winds during the hour of maximum wind speed, duration of exposure to gale-force winds (≥17 m s^{-1}), distance to the path, hours of gale-force winds, and total energy (sum of wind speed times duration) were calculated from the modeled wind estimates. Maximum hourly wind speeds were converted to categories of Australian cyclonic intensity, based on maximum 10-min sustained wind speeds (in m s^{-1}; = 3.6 km h^{-1}) and central pressure: category 1: ≥17–24.5 m s^{-1}, 985–1,000 hPa; category 2: 24.6–32.5 m s^{-1}, 970–985 hPa; category 3: 32.6–44.2 m s^{-1}, 945–970 hPa; category 4: 44.2–55.3 m s^{-1}, 920–945 hPa; category 5: ＞55.3 m s^{-1},＜920 hPa. At cyclone intensity category distributions, the loss of coral coverage (i.e., typhoon damage coefficients,TDC) are 0.05, 0.25, 0.65, 0.85 and 0.95 for inshore reefs, and 0.02, 0.15, 0.38, 0.62, and 0.95 for offshore reefs. The 56 cyclones have passed near the study subregion since 2000 (category ≥3 with 16，category ≥ 4 with 3).

Rainfall. The monthly precipitation data for each city of Hainan were obtained from the Hainan Meteorological Center, and the annual rainfall from 2000 to 2020 was calculated based on the monthly rainfall data.

Water quality *in situ*. The Hainan Academy of Ocean and Fishery Sciences water quality database includes data from 13 locations within Hainan waters that have been collected since 2004 (Fig. S2), and the annual water quality from 2004 to 2020 was calculated based on all voyages data in the year, with voyages ranging from 1-3 times per year. At each station, water quality parameters are monitored at three different depths: bottom, mid-depth, and surface. Surface parameters measured at 1 m below the surface were used in this study because symbiont bearing Scleractinia are typically found at shallow depths. Ten physiochemical and nutrient-related water quality parameters were selected as potential drivers of coral diversity based on previous studies[9,17]. Physicochemical parameters chosen were salinity, SST, dissolved oxygen concentration (DO), chemical oxygen demand (COD), and nutrient parameters were Chl a, nitrate, nitrite, ammonium salt, dissolved inorganic phosphorus (as phosphate; DIP), and suspended solids concentration (SS).

Data on socio-economic drivers of coral coverage change. Some socioeconomic indicators were selected to calculate exposure stress (Fig. S3 & Fig. S4). The three anthropogenic factors were selected, including local human population, number of overnight visitors and total agriculture N per year to the water in native city (Fig. S5 - S7). The statistical data came from Hainan Statistical Yearbook during 2000 to 2020 (Hainan Statistical Yearbook). Total nutrient (nitrogen and phosphorus) emissions per year to the water require additional calculations. The following data were selected to calculate nutrient (nitrogen and phosphorus) emissions, such as local human population, urban and rural population, the crop planting area and production, livestock amount, chemical fertilizer application, the area and output of freshwater aquaculture and mariculture etc. These investigation data included crop fertilization, crop product, straw destination, planting and management methods, information on livestock housing, manure storage, and treatment by farmers. Then, N and P emissions to water bodies from food system come from crop, livestock, freshwater aquaculture, and mariculture systems, and human consumption system from human waste and excrete (Fig. S6). A parameters-localized NUFER model was used to estimate N and P emissions. The NUFER model follows the principle of mass conservation and can be used to estimate the nutrient input, migration, transformation, and output from crop, livestock, aquaculture, and human consumption systems[18-20]. The detail of parameters in Hainan used can be seen in our previous studies[18,21].

$$I_F = Ic_{Fertilizer} + Ic_{Irrigation} + Ic_{Deposition} + Ic_{BNF} + I_{LExogenous\ feed} + I_{AExogenous\ feed} + I_{Fertilizer} + I_{ABNF} + I_{ADeposition} + I_{AFry} + I_{AWater} + F_{Import} + I_{Fishing} \quad (1)$$

Where I_F is the N input of food system; $Ic_{Fertilizer}$, $Ic_{Irrigation}$, $Ic_{Deposition}$ and Ic_{BNF} represent the N input from fertilizer, irrigation water, deposition and biological N fixation to the crop subsystem, respectively. $I_{LExogenous}$ feed and $I_{AExogenous}$ feed are the N of exogenous feed in the livestock subsystem and aquaculture subsystem. $I_{Fertilizer}$, I_{ABNF}, $I_{ADeposition}$, I_{AFry} and I_{AWater} represent the aquaculture N input from fertilizer, biological N fixation, deposition, fry and water (freshwater and seawater), respectively. F_{Import} is food N import from other areas outside Hainan Island, $I_{Fishing}$ is the fishing from rivers and ocean.

$$O_F = Oh_{Retained\ in\ body} + O_{Air} + Oc_{Water} + O_{Soil\ accumulation} + O_{Process\ loss} + F_{Export} \quad (2)$$

Where O_F is the N output of food system; $Oh_{Retained\ in\ body}$ is the food N stored in the human body through digestion–absorption functions; O_{Air}, Oc_{Water} and $O_{Soil\ accumulation}$ represent the total air, water N emissions and N accumulation in soil, respectively. $O_{Process\ loss}$ is total N loss from food processing stages, including handling, storage, processing, and distribution; F_{Export} represent export N of food products from Hainan Island to other areas.

It is noteworthy that agriculture N and P from crop production accounted for about 50% of total agriculture N and P emissions into water (Fig. S6b & 6c). HNE are characterized by tropical agriculture (over 900,000 inhabitants in 1988), dominated by rice, coconut palm and fruit cultures in over 60,000 hm^2 cultivated land area (Fig. S7d). Besides, the agriculture nutrient from mariculture in HNE increased at the fastest since 2000 (Fig. S6), and the wastewater was discharged directly from aquaculture ponds into the sea[18]. In 2008-2010, the mariculture areas in Wenchang city of HNE was greatly increased (about 1,644 hm^2, Fig. S7c), accompanied by a reduction in mangrove forest area and seagrass coverage (Fig. S7a & S7b). Hence, it is aquaculture and crop systems that are key module of agriculture nutrient emission into water.

Tropical coastal ecosystem changes closely related to coral reefs. Data about mangrove forest area and seagrass coverage extracted from published reports and literature.

Fishing status. The data of motorized marine fishing vessels number and marine fishing production of 2006 - 2020 were obtained from the Hainan Statistical Yearbook and China Fishery Statistical Yearbook. And the fishing hours data for northern SCS since 2012 were obtained from the Global Fishing Watch (GFW) (https://globalfishingwatch.org).

Supplementary Figures and Tables

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Table S6. Parameter estimates from the scenario analysis of local reef management based on ICRM framework.

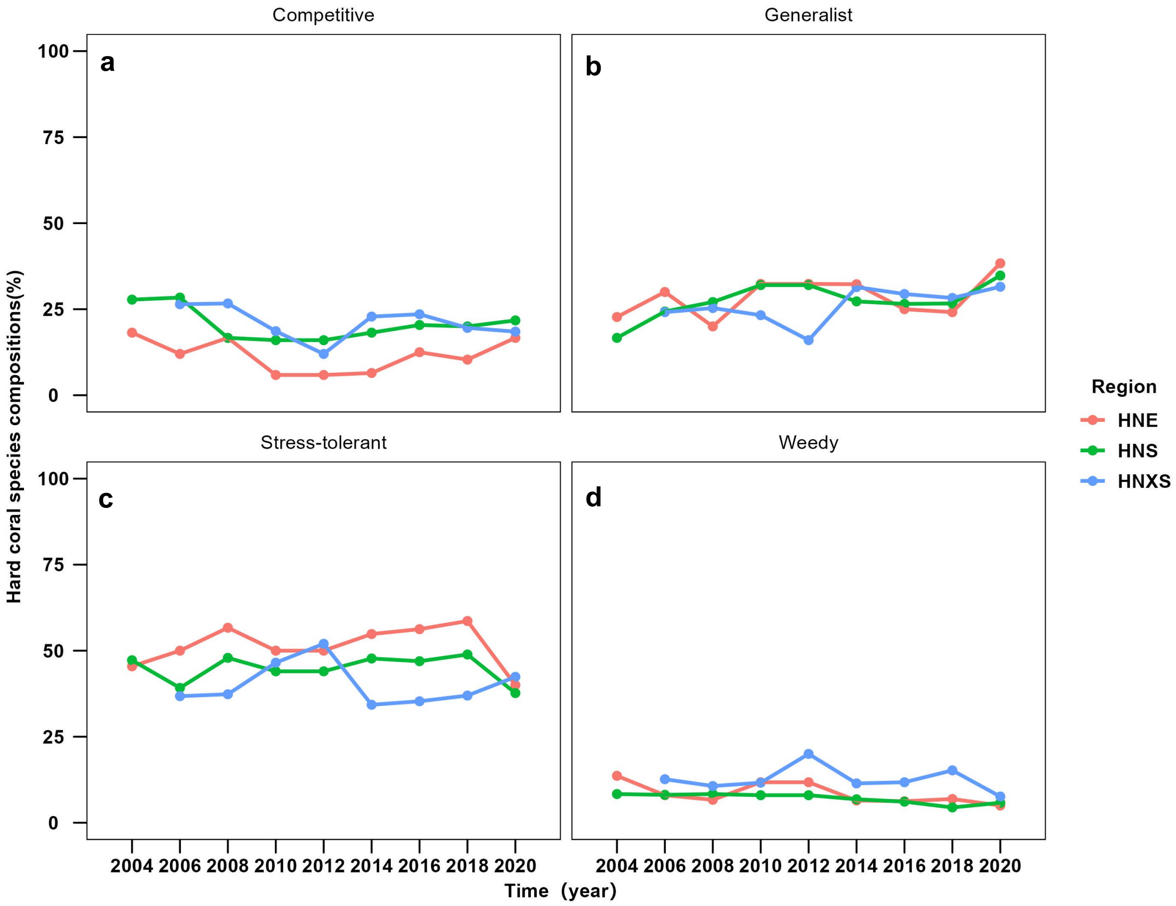

Fig. S1. Changes of hard coral species composition in four life history types. The four life history types: fast-growing competitive (*Acropora*); slow-growing and long-lived massive stress-tolerant (*Platygyra*); subdominant generalist (*Echinopora*); and fast-growing brooding weedy taxa (*Pavona*). Classifications were based on published species traits including colony growth form, growth rate, maximum size and reproduction to derive species-level classifications and updated by genera-level classifications informed by expert opinion (Darling, et al., 2019). Percentage of hard coral species composition with four different life histories from 13 reef surveys in 3 subregions.

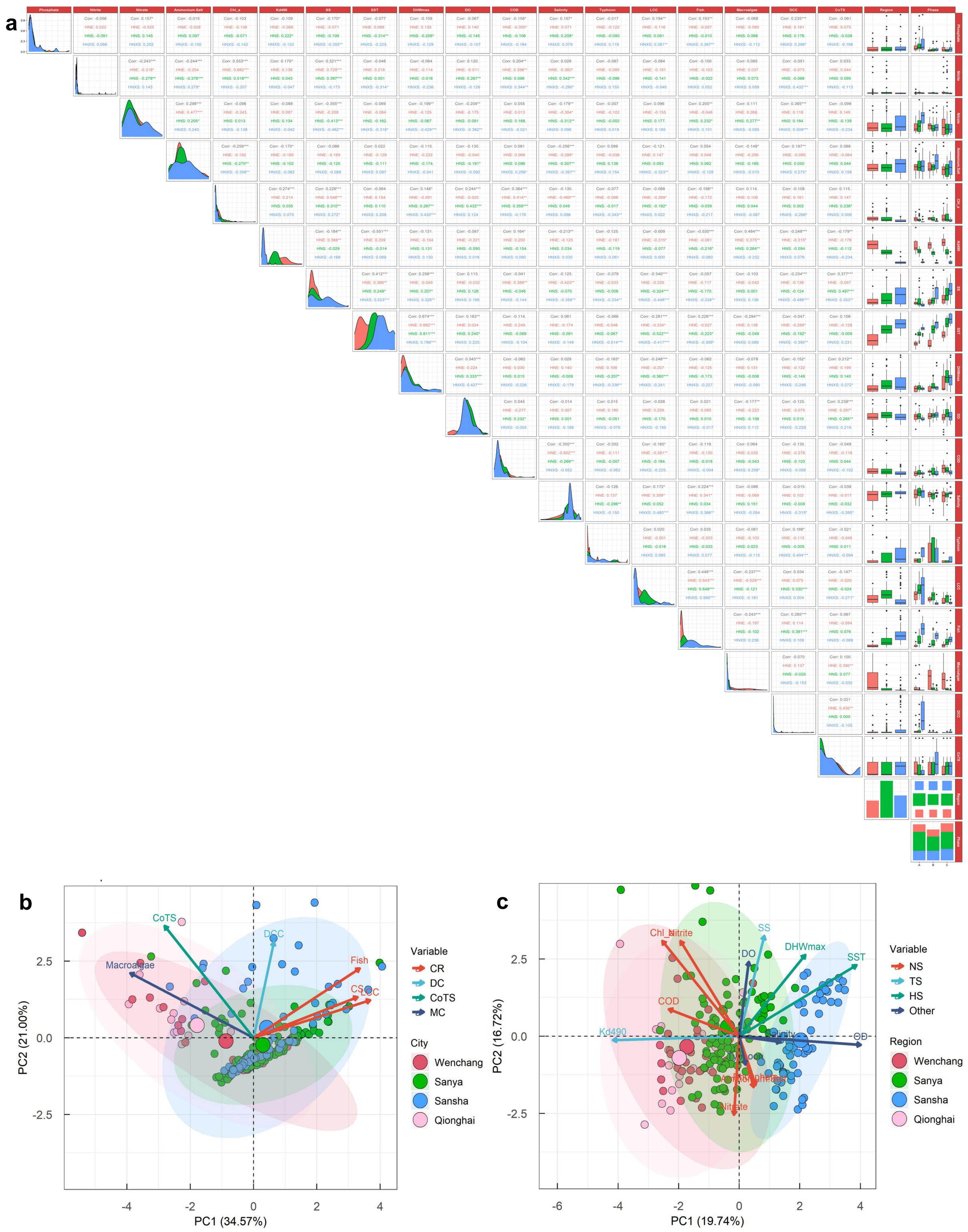

Fig. S2. The correlation coefficients for all variables and ordination plot of coral reef change based on principal component analysis (PCA). a) The correlation coefficients for all variables. A final set of 13 covariates and 2 dependent variables was included in the statistical models, whereby all covariates pairwise correlation coefficients were < 0.65, indicating that multicollinearity was not a serious concern. b) PCA of biotic communities in coral reefs. The research sites (13 monitoring stations of four cities from 2004 to 2020) can be clearly divided into two groups, Group1 (Wenchang and Qionghai, represented higher macroalgae) and Group2 (Sanya and Sansha, represented lower macroalgae); c) PCA of environmental factors in coral reefs. The research sites can be clearly divided into three groups, Group 1 (Wenchang and Qionghai city located at 19° North Latitude (NL), named as HNE in this study), Group 2 (Sanya city located at 18°NL, named as HNS), Group 3 (Sansha city located at 17°NL, named as HNXS). The proportions of variance explained by the principal components are presented in the axis labels. Circles indicate the annual mean for each station, different colors indicate different city. Each arrow represents a factor indicator. Abbreviation: CR, Coral reef biome; DC, Dead coral coverage (DCC); CS, Coral species; LCC, Live coral coverage; MC, Macroalgae coverage; NS, Nutrient stress; TS, Turbidity stress; HS, Heat (thermal) stress; COD, Chemical oxygen demand; SS, Suspended solids; SST, Seawater surface temperature; OD, Offshore distance; CoTS, Crown of thorns starfish; DO, Dissolved oxygen; Chl a, Chlorophyll a.

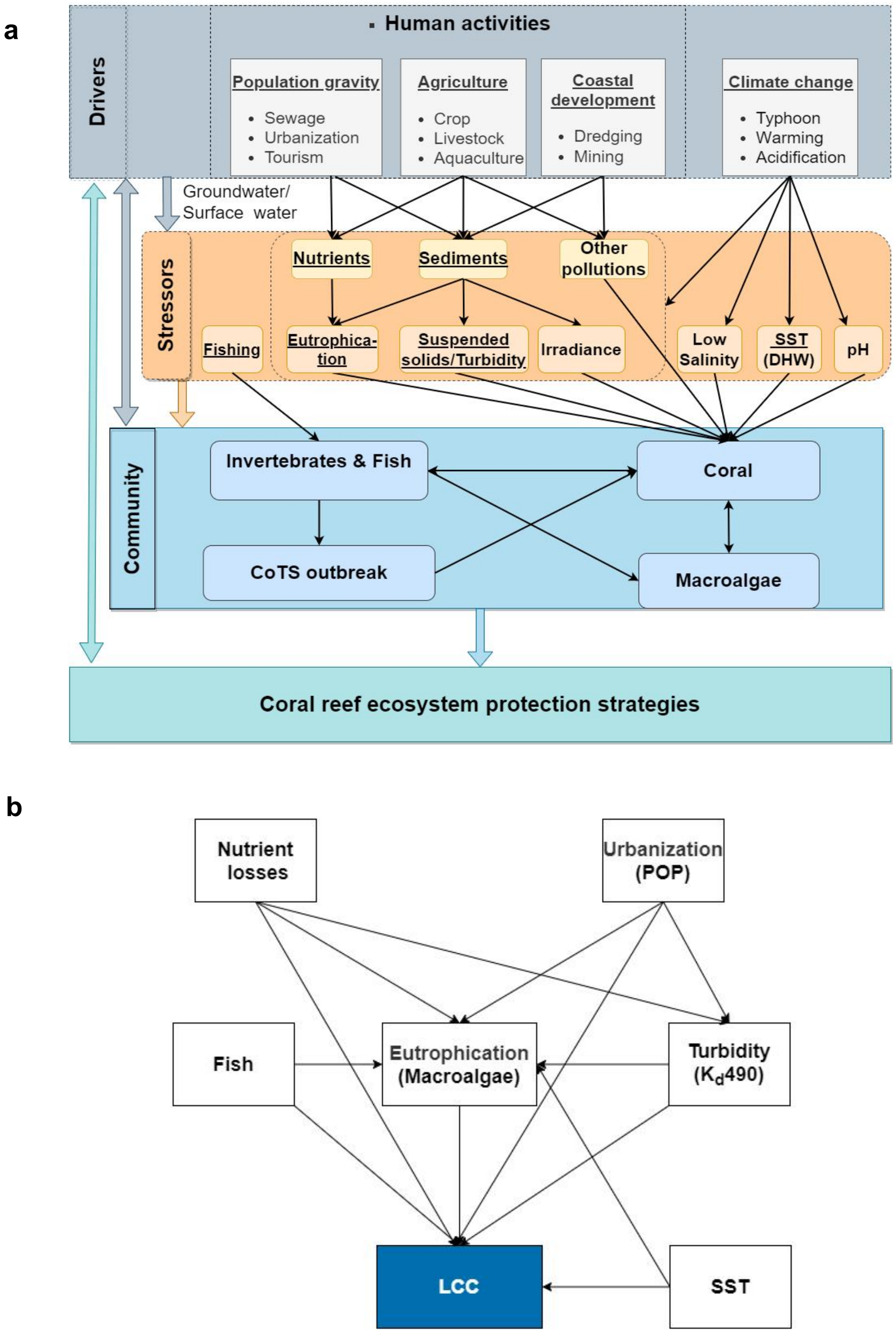

Fig. S3. Conceptual models showing linkages and feedbacks between anthropogenic activities and coral communities and the initial model for structural equation model (SEM) exploring the effects of environment variables on live coral coverage. a) Conceptual models showing linkages and feedbacks between anthropogenic activities and coral communities in coastal subregions. Drivers are traits in social-economical systems that indirectly influence how people interact with coral reefs. Stressors directly affect coral reef ecosystems. Single-headed arrows indicate how the pathway flows from drivers to stressors and coral reef. Double-headed arrows show the complex linkages and feedback that also occur between the various components. Modified from Hughes et al. (2017). b) The initial model for SEM exploring the effects of environment variables on LCC. The ecological environment factors involve coral reef fishery resources, water quality and human activity factors.

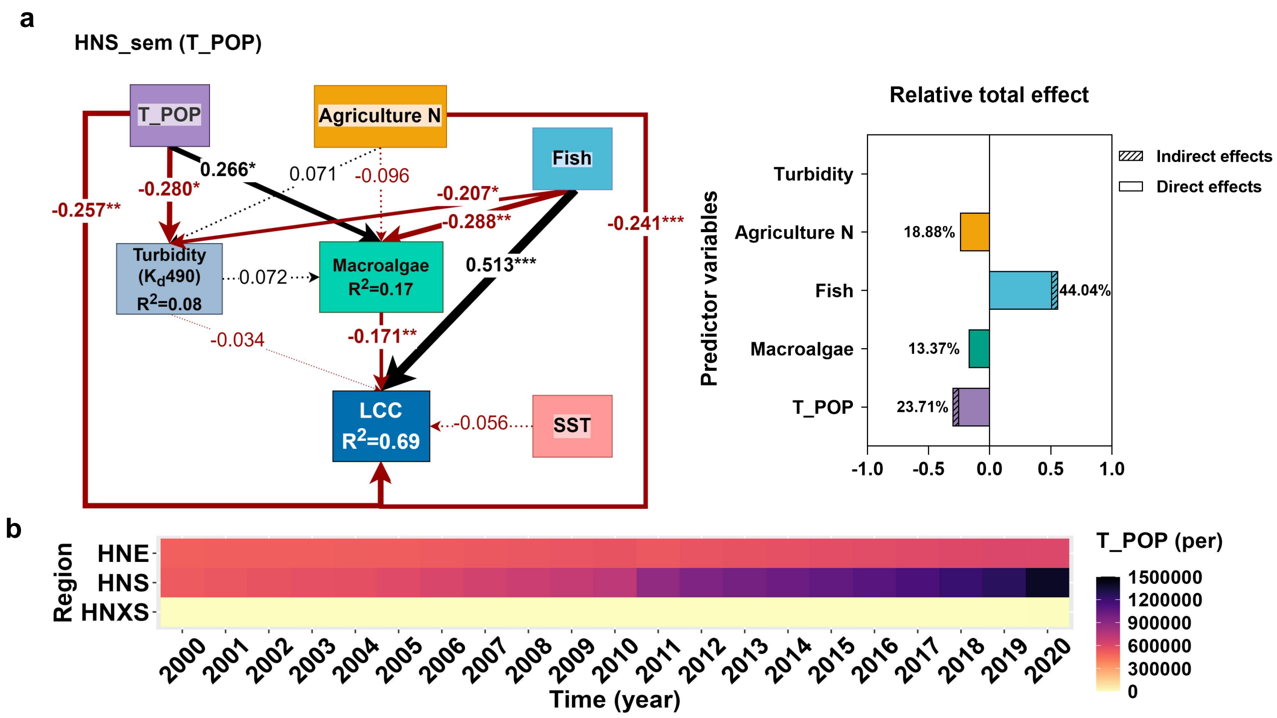

Fig. S4. Structural equation model of HNS performed to explore the direct and indirect effects of environmental variables on live coral coverage. a) SEM for HNS. b) Resident Population (T_POP) from 2000 to 2020 in HNE, HNS and HNXS. Fish denotes the level of reef fish density. Macroalgae denotes the degree of eutrophication of the water, while the diffuse attenuation coefficient of light at the 490 nm wavelength (K_d490) denotes the turbidity of the water. Resident Population (T_POP), including overnight tourists travel were converted to resident population per year**,** denotes local urban development gravity - an indicator of nearby human settlements potential influences on coral reefs (e.g., water quality and land use), while the agriculture N denotes total agriculture nitrogen (N) emissions per year to the water in native city. This SEM is determined through model comparison and fits the data well (Fisher's C = 2.56, d.f. = 4, p = 0.64; K = 13; n = 106). Boxes represent measured variables, while arrows represent relationships among variables. Black and red arrows denote positive and negative effects, respectively. Dashed and solid lines denote 95% credible intervals overlapping with zero or not, respectively. Standardized path coefficients are given for each significant path, the width of which is scaled by the magnitude of the standardized path coefficient. The conditional Rc^2 for each endogenous variable is reported in the corresponding boxes. The direct, indirect, and relative total effects are calculated and shown in the right part of this figure.

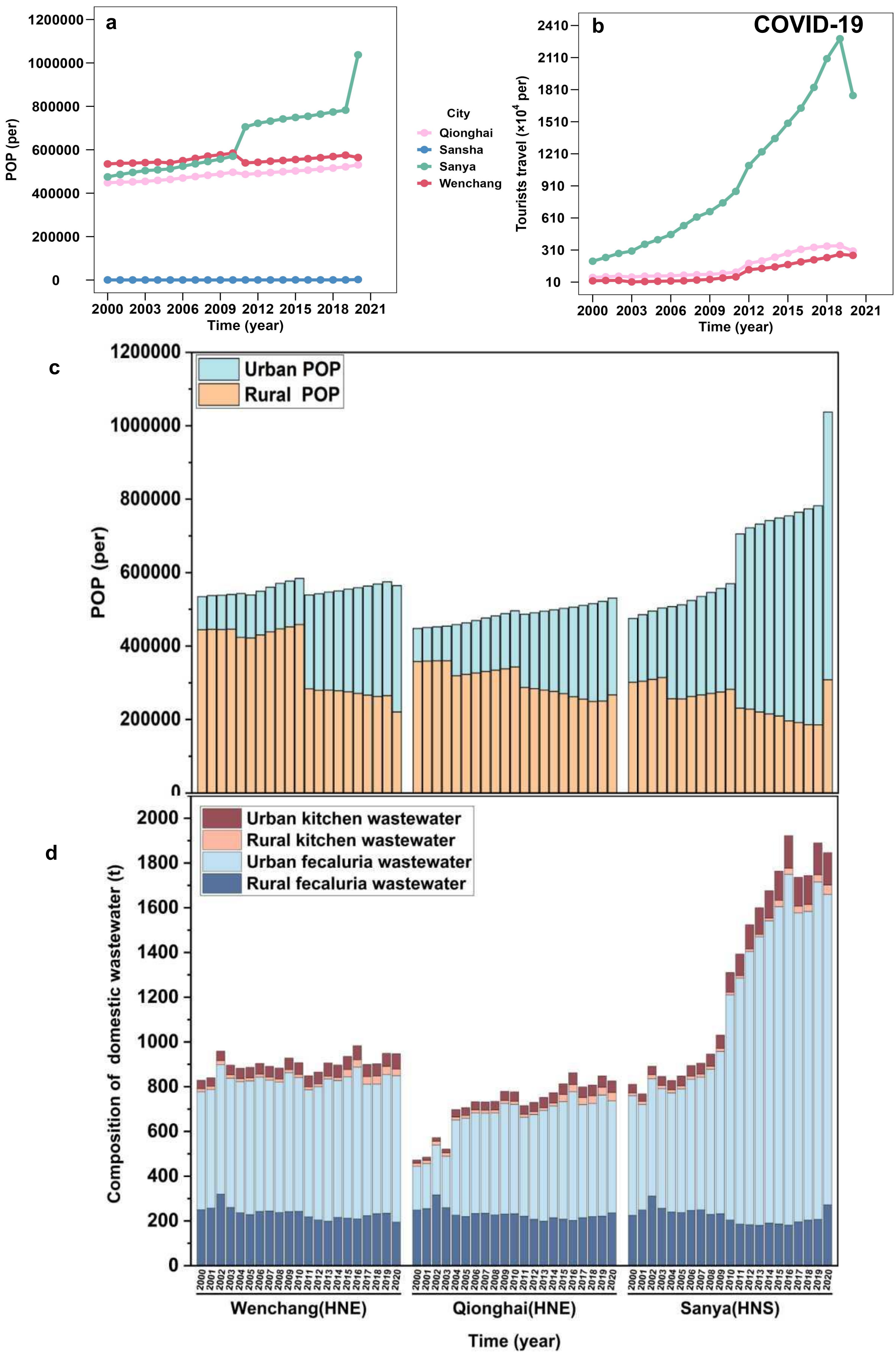

Fig. S5. **The human population flow and domestic wastewater from 2000 to 2020**. a) Resident Population (POP) in HNE (Wenchang and Qionghai), HNS (Sanya) and HNXS (Sansha). b) Overnight tourists travel per year in HNE and HNS. c) The urban and rural structure change of POP in HNE and HNS. And there is no rural POP in HNXS. d) The domestic sewage to water per year in HNE and HNS. COVID-19, denotes Corona Virus Disease 2019.

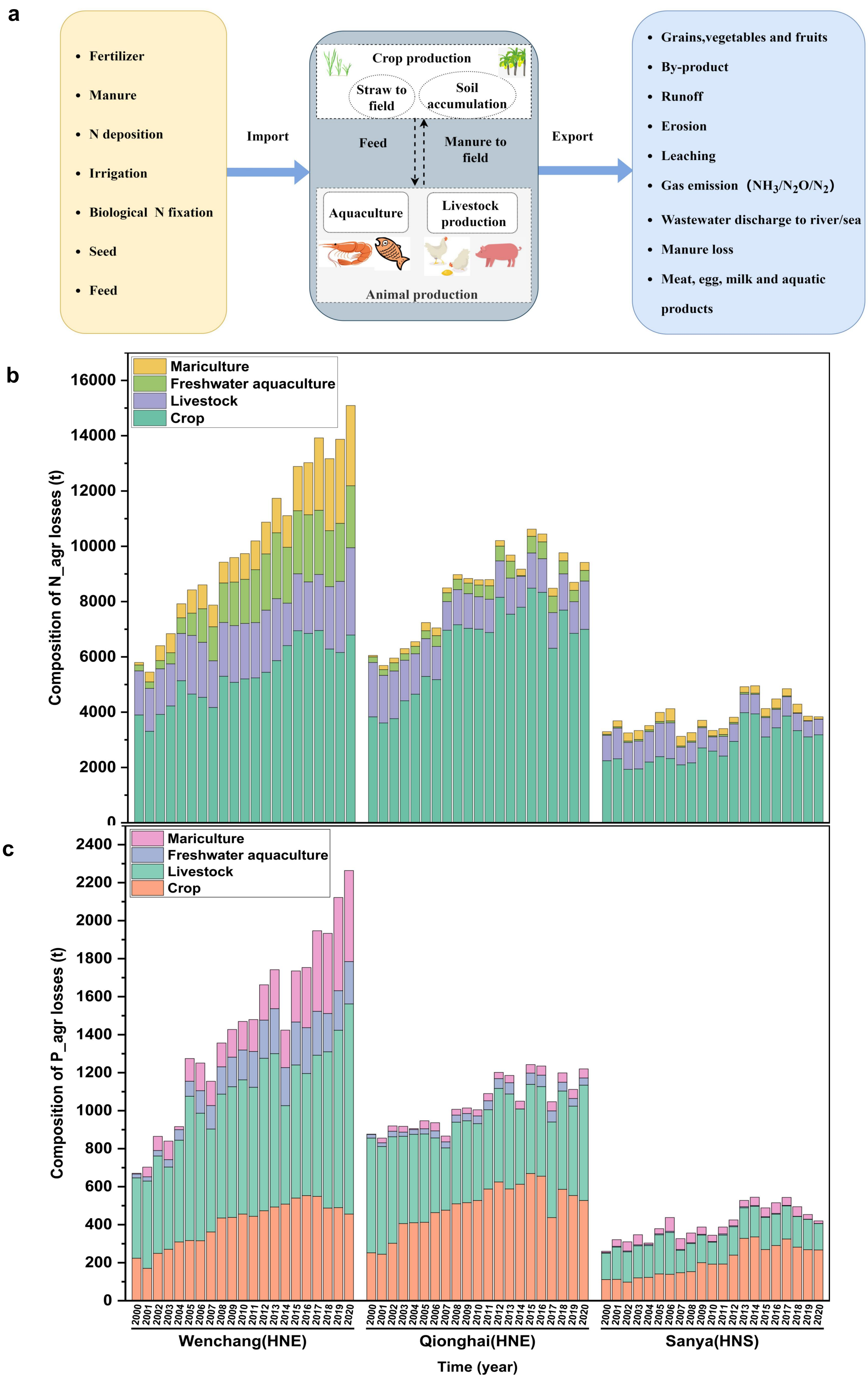

Fig. S6. Schematic diagram of nitrogen and phosphorus flows model in the agriculture production system, and total agriculture nitrogen (N) and phosphorus (P) emissions in subsystems of food chain to the water from 2000 to 2020. a) Schematic diagram of nitrogen and phosphorus flows model in the farming and animal production system. b) Total agriculture nitrogen (N) emissions per year to the water and its composition in HNE and HNS. c) Total agriculture phosphorus (P) emissions per year to the water and its composition in HNE and HNS.

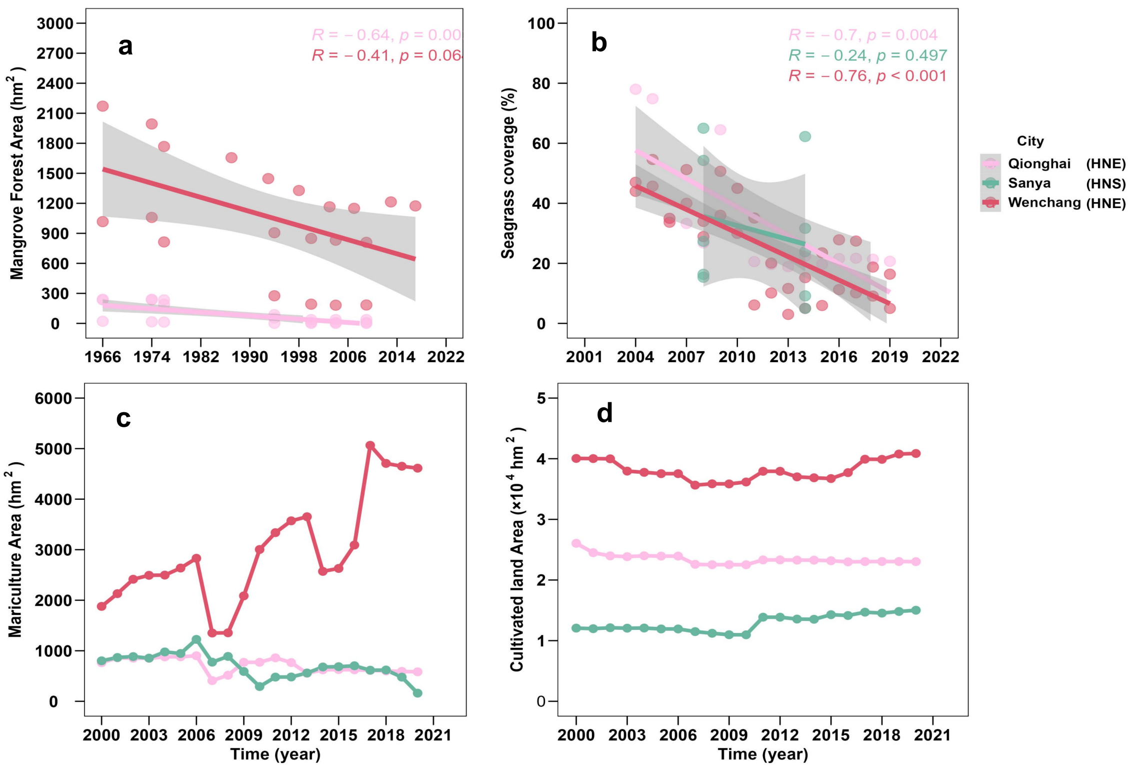

Fig. S7. **Tropical coastal ecosystem changes closely related to coral reefs.** a) Mangrove forest area; b) Seagrass coverage; c) Mariculture area; d) Cultivated land area.

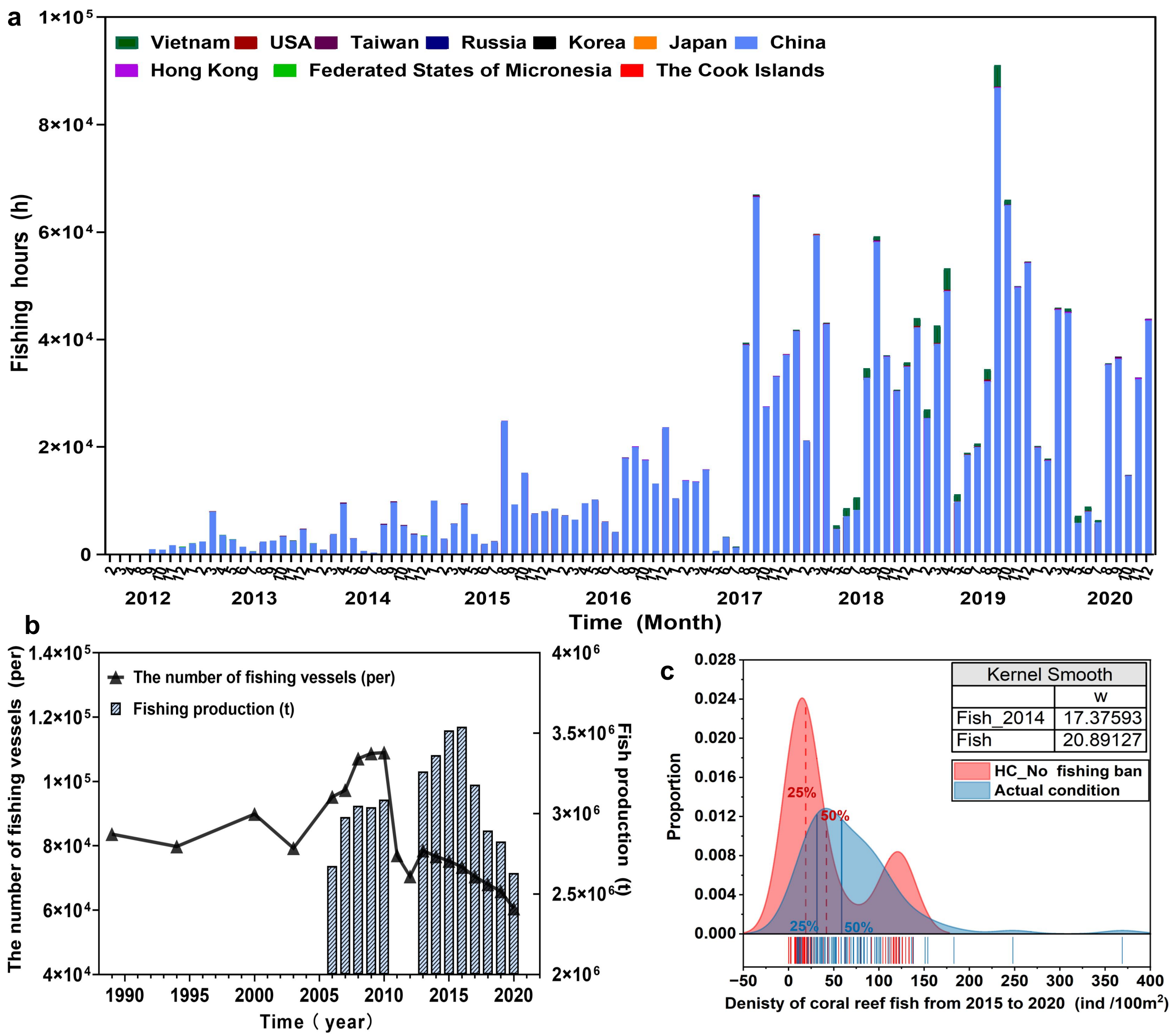

Fig. S8. **Changes in fisheries before and after the implementation of of the South China Sea fishing ban.** a) The fishing hours for northern South China Sea area during from 2012 to 2020 based on the analysis of Global Fishing Watch (GFW) data. b) The number of motorized marine fishing vessels of South China Sea area of 1989 - 2020 and marine fishing production of 2006 - 2020. c) Predictions of the density of coral reefs fish in Hainan in the hypothetical cases (HC)_No fishing ban during the period of 2015 - 2020.

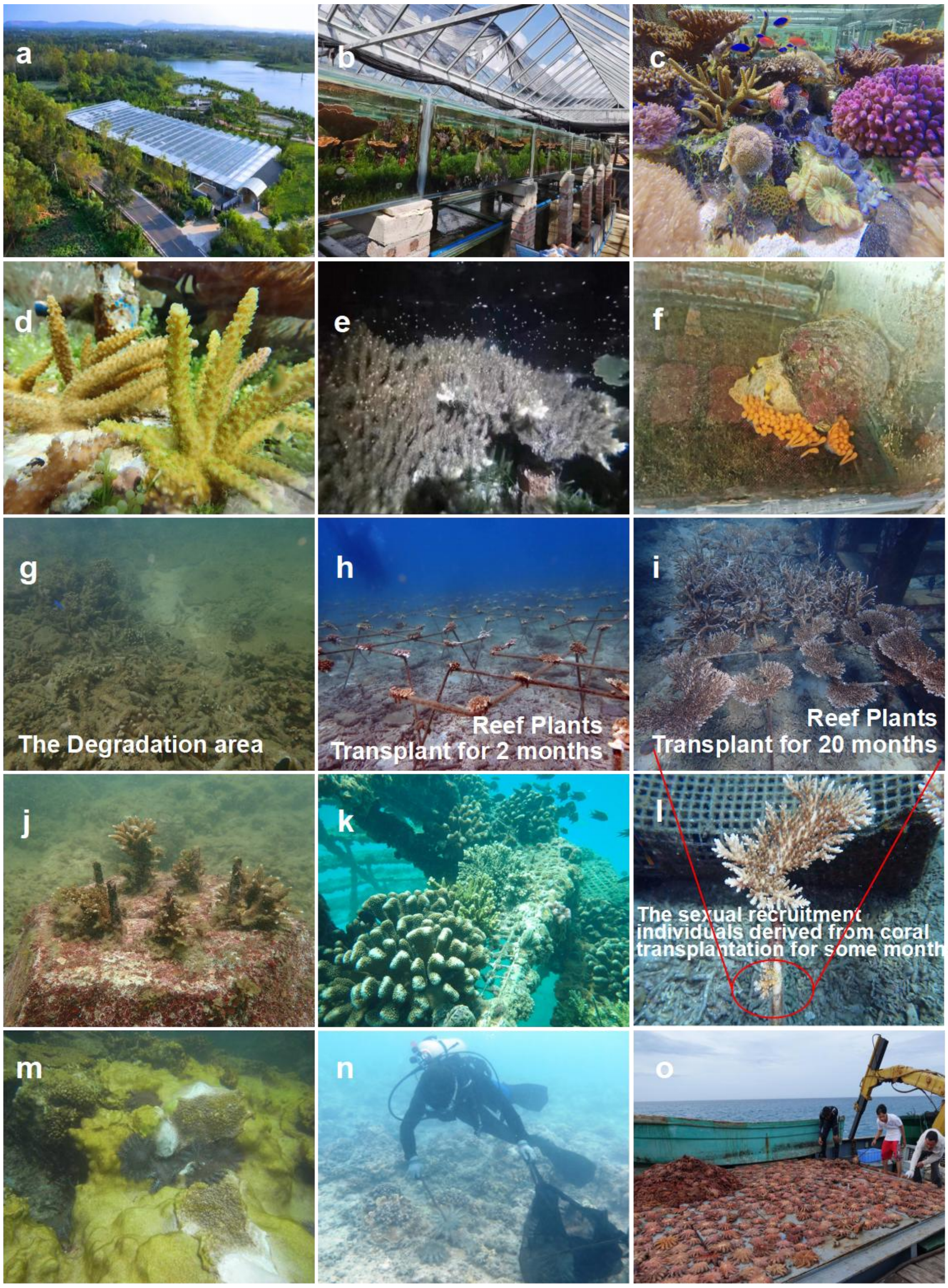

Fig. S9. **The cases of coral conservation and restoration. a) - f) Noah's Ark on land -- A coral breeding base established in Hainan Island since 2017.** a) The coral breeding base on land; b-d) Live reef-building corals and their fragments; e) Coral spawning of *Acropora hyacinthus*; f) *Charonia tritonis* spawning. **g) - l) The case of building juvenile coral nursery garden in situ.** g) - i) In situ coral nursery restoration (Reef Plants) in the same site of Wuzhizhou island (HNS), Hainan, China. j) - k) In situ coral nursery restoration in the light of local conditions (such as grids, artificial reefs) in the other reef of Hainan, China. m) Coral reef community status and an outbreak of the crown-of-thorns starfish (CoTS, *Acanthaster planci*) near Yongxing Island, Xisha Islands, South China Sea in 2006. n) - o) Divers caught the CoTS and dried them on board.

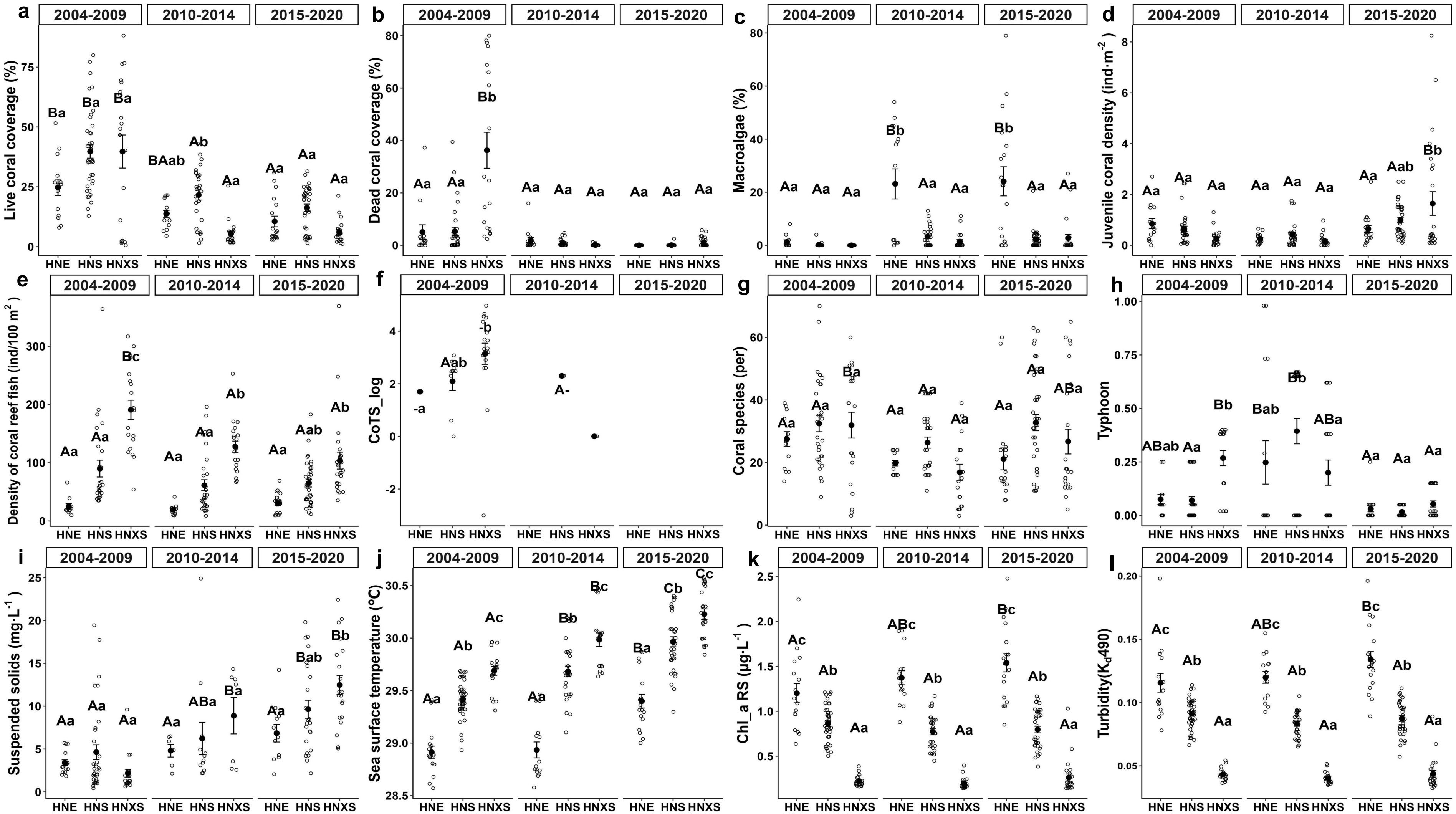

Fig. S10. Factor variance analysis (Phase and subregion two-factor analysis of variance) of coral reef biome. a) Live coral coverage in coral reefs; b) Dead coral coverage; c) Macroalgae coverage; d) Juvenile coral density; e) Coral reef fish density (fishery resources); f) The crown-of-thorns starfish (CoTS, *Acanthaster planci*) density; g) Coral species; h) Typhoon; i) Suspended solids; j) Sea surface temperature (SST); k) Chlorophyll a from remote sense (Chl_a RS); l) Turbidity (K_d490). Note: HNE:Wenchang and Qionghai city located at 19°North Latitude (NL), HNS: Sanya city located at 18°NL, named as HNS), HNXS: Sansha city located at 17°NL. Time is divided into three phases, i.e. 2004 - 2009 year, 2010 - 2014 year and 2015 - 2020 year. A ,B and C indicate that there are significant differences in phases ($p < 0.05$)，a ,b and c indicate that there are significant differences in regions ($p < 0.05$).

Table S1. Relevant protection measures for local coral reefs.

Time(yyyy-m)	Legal name	Legislative department	Note
1992/7	Notice on the Protection of Sanya Coral Reef National Nature Reserve	The People's Government of Sanya City, China	
1995/8	Notice on Prohibition of Exploitation, Capture and Sale of Corals, Hawksbill Turtles and Their Products	The People's Government of Sanya City, China	
1995	Fishery Law of the People's Republic of China - Implement the Seasonal fishery closures policy in the marine	Ministry of Agriculture,China	
1998/10	Coral Reef Protection Regulations of Hainan Province	The Standing Committee of the People's Congress of Hainan Provincial, China	
1999	Fishery Law of the People's Republic of China- Implementation of the Seasonal fishery closures policy in the South China Sea	Ministry of Agriculture,China The Standing Committee of the National People's Congress of the People's Republic of China	
2009/5	**Coral Reef Protection Regulations of Hainan Province (Revised Draft)**	The Standing Committee of the People's Congress of Hainan Provincial, China	
2014/9	Regulations of Hainan Province on Nature Reserves	The Standing Committee of the People's Congress of Hainan Provincial, China	
2015	**Fishery Law of the People's Republic of China-The South China Sea fishing ban**	Ministry of Agriculture,China	
2016/7	Regulations of Hainan Province on the Management of Ecological Protection Red Line	The Standing Committee of the People's Congress of Hainan Provincial, China	
2016/11	Regulations of Hainan Province on the Protection of Coral Reefs and Tridacna	The Standing Committee of the People's Congress of Hainan Provincial, China	
2016	Opinions on the Comprehensive Establishment and Implementation of the Marine Ecological Red Line System ([2016] No.4)	State Oceanic Administration,China	
2016	The 13th Five-Year Plan for National Ecological Reef Projects	State Oceanic Administration,China	
2017/1	13th Five-Year Plan for National Island Protection	State Oceanic Administration,China	
2021	**China's List of State-Protected Wildlife under State Priority Conservation prohibited exploitation of stony corals, giant clams, the giant triton snail (*Charonia tritonis*), and other reef animals such as sea turtles and the humphead wrasse (*Cheilinus undulatus*)**	Ministry of Agriculture,China	

2024	Notice on Strengthening the Protection and Restoration of Coral Reefs	Ministry of Natural Resources of the People's Republic of China	
Time(yyyy)	**Nature Reserve Names**	**Area (ha)**	
1983	Southwest Zhongsha Islands Aquatic Resources Provincial Nature Reserve	2400000	
1987	Hainan Wanning Marine Ecology National Nature Reserve	7000	
1990	Sanya Coral Reef National Nature Reserve	8500	
Time(yyyy)	**Institution of Non-Governmental public welfare organizations**		
2012	Hidden Love for Dapeng		NGO
2007	Blue Ribbon Ocean Conservation Society		NGO
2017	The Endless Dark Blue		NGO
2018	Coral Branch, Pacific Society of China		

Note: The abbreviation for Non-Governmental Organization is NGO.

Table S2. Variance inflation factor (VIF) scores for continuous covariates.

Covariate	VIF
Coral species (CS)	1.280
Dead coral coverage (DCC)	1.226
Fish	1.789
CoTS	1.477
Macroalgae	2.094
Chl_a	1.484
Suspended solids (SS)	1.396
SST_RS	1.827
DO	1.264
COD	1.317
Salinity	1.209
Typhoon	1.155
Turbidity (K_d490)	3.020

Note: A set of 13 covariates was included in the statistical models, whereby all pairwise correlations tolerance are ＞0.1 and all variance inflation factors are ＜5, indicating that multicollinearity is not a serious concern.

Table S3. Panel model analysis of ecological factors affecting live coral coverage in different subregions.

Independent variables	Dependent variable Live coral coverage (LCC) (E+SE)		
subregion	HNE	HNS	HNXS
Fish	0.733***	0.345***	0.523**
	(0.111)	(0.056)	(0.163)
Macroalgae	-0.212*	-0.481**	-0.024***
	(0.099)	(0.089)	0.003
CoTS	-	-	-0.246***
	-	-	(0.039)
Turbidity	0.078	-0.180	0.003
	(0.035)	(0.035)	(0.168)
SST	-0.136***	-0.248***	0.070
	(0.023)	(0.050)	(0.253)
Typhoon	0.029**	-0.008	-0.046
	(0.011)	(0.022)	(0.101)
Coral Species	0.090*	0.140***	0.097*
	(0.038)	(0.041)	0.030
N	49	106	64
SD	0.053	0.050	0.142
Adjusted R^2	0.604	0.667	0.383
F Statistic	5.398*** (df = 10; 36)	9.359*** (df = 10; 90)	7.481*** (df = 10; 50)
Method	FEP	FEP	FEP

Note:* indicates $p < 0.05$，** indicates $p < 0.01$, *** indicates $p < 0.001$.

Table S4. Parameter estimates and standardized coefficients for the best SEM model.

HNE	Response	Predictor	Estimate	SE	DF	P Value	Std. Coef
	K_d490_RS	Agriculture N	0.541	0.164	46	0.002	0.524**
	K_d490_RS	POP	-0.375	0.493	46	0.451	-0.120
	Macroalgae	Agriculture N	0.008	0.083	44	0.925	0.016
	Macroalgae	POP	-0.576	0.227	44	0.015	-0.385*
	Macroalgae	K_d490_RS	0.225	0.068	44	0.002	0.469**
	Macroalgae	Fish	-0.441	0.260	44	0.096	-0.213
	LCC	K_d490_RS	0.053	0.096	42	0.584	0.071
	LCC	Macroalgae	-0.604	0.195	42	0.003	-0.390**
	LCC	SST_RS	-0.154	0.100	42	0.132	-0.176
	LCC	Fish	1.361	0.345	42	0.000	0.423***
	LCC	Agriculture N	-0.229	0.113	42	0.049	-0.298*
	LCC	POP	0.469	0.311	42	0.139	0.202
	~~Macroalgae	~~K_d490_RS	0.446	-	49	0.000	0.446***
	~~POP	~~Agriculture N	0.566	-	47	0.000	0.566***
	Fisher's C = 3.563, P-value = 0.736, df = 6						
	AIC = 39.563, BIC = 73.616						

HNS	Response	Predictor	Estimate	SE	DF	P Value	Std. Coef
	K_d490_RS	Agriculture N	0.148	0.240	102	0.539	0.065
	K_d490_RS	POP	-0.136	0.048	102	0.005	-0.306**
	K_d490_RS	Fish	-0.138	0.062	102	0.030	-0.213*
	Macroalgae	Agriculture N	-0.008	0.116	101	0.493	-0.070
	Macroalgae	Fish	-0.094	0.031	101	0.003	-0.291**
	Macroalgae	K_d490_RS	0.039	0.048	101	0.421	0.077
	Macroalgae	POP	0.054	0.024	101	0.026	0.245*
	LCC	K_d490_RS	-0.063	0.119	99	0.597	-0.032
	LCC	Macroalgae	-0.720	0.248	99	0.005	-0.182**
	LCC	SST_RS	-0.106	0.118	99	0.371	-0.072
	LCC	Fish	0.659	0.080	99	0.000	0.516***
	LCC	Agriculture N	-1.245	0.288	99	0.000	-0.277***
	LCC	POP	-0.176	0.080	99	0.030	-0.201*
	~~Macroalgae	~~K_d490_RS	0.080	-	106	0.208	0.080
	~~POP	~~Agriculture N	0.446	-	104	0.000	0.446***
	Fisher's C = 3.696, P-value = 0.449, df = 4						
	AIC = 41.696, BIC = 92.301						

HNXS	Response	Predictor	Estimate	SE	DF	P Value	Std. Coef
	CoTS	Fish	-0.263	0.115	61	0.026	-0.264*
	CoTS	SST_RS	0.281	0.0968	61	0.005	0.336**
	K_d490_RS	Fish	0.321	0.099	61	0.002	0.385**
	K_d490_RS	POP	0.082	0.094	61	0.384	0.104
	Macroalgae	Fish	1.778	1.593	61	0.269	0.139
	Macroalgae	SST_RS	3.333	1.337	61	0.015	0.309*
	LCC	K_d490_RS	0.143	0.152	57	0.352	0.098
	LCC	Fish	0.540	0.133	57	0.000	0.444***
	LCC	SST_RS	-0.069	0.112	57	0.540	-0.068
	LCC	POP	-0.074	0.117	57	0.529	-0.065

LCC	CoTS	-0.282	0.139	57	0.047	-0.231*
LCC	Macroalgae	-0.023	0.010	57	0.023	-0.238*
~~POP	~~Fish	-0.120	-	62	0.343	-0.120
~~POP	~~CoTS	0.279	-	64	0.013	0.279*
~~Macroalgae	~~Fish	0.142	-	64	0.134	0.142
~~Macroalgae	~~CoTS	0.117	-	64	0.180	0.117
Fisher's C = 12.069, P-value = 0.440, df = 12						
AIC = 52.069, BIC = 95.247						

Note:* indicates $p < 0.05$，** indicates $p < 0.01$, *** indicates $p < 0.001$.

Table S5. The Multi-paths integration restoration of coral reef based on Integrated Coast-Reef Management (ICRM) framework. Check marks indicate conservation approaches that are being piloted locally.

Typical case	Path	Option
HNE (Agriculture regions)	·Establishment of Coral Noah's Ark	☐**Conservation of coral germplasm resources** □Assisted evolution of "winner" coral under climate change
	·Water quality improvement	☑**Realizing zero discharge aquaculture wastewater through industrial upgrading** and strict wastewater treatment (eg. Shellfish/Fish+algae-specific systems, water recycling techniques) □Reducing crop nutrient emissions by precision fertilization and wetland buffers □Establishing integrated animal-plant livestock farming systems (eg. Chickens/ducks-trees)
	·Coral reef adjacent ecosystems restoration	☑**Conservation and restoration of mangrove by returning ponds to forest** □Conservation and restoration of seagrass beds by wetland buffers
	·Coral transplant restoration	☑**Building the coral nursery garden in the field** □Coral transplantation using gardening methods in line with local circumstances (eg: coral tree_epoxy/ ropes, artificial reefs, iron nails, iron frames)
HNS (Tourism regions)	·Coral transplant restoration	☑**Building the coral nursery garden in the field** □Coral transplantation using gardening methods in line with local circumstances (eg: coral tree_epoxy/ ropes, artificial reefs, iron nails, iron frames)
	·Water quality improvement	☑**Establishing strict and effective treatment of domestic sewage** □No non-public permanent structures shall be constructed within a buffer zone of 200 meters inland from the shoreline □Reducing agricultural nutrient emissions by industrial upgrading □Reducing sediment to the sea by restriction of constructive land use and eco-friendly in coastal engineering
	·Fishing control & Food web recovery	☑ **Replenishment and release of fish seed** ☑**Establishing strategic no-take zones or closed periods.** ☑**Reducing the overall catch of fish** and building modern Marine Ranching

HNXS (Remote islands)	·Fishing control & Food web recovery	☑**Establishing strategic** no-take zones or **closed periods.** ☑**Reducing the overall catch of fish** and building modern Marine Ranching □Cultivation of the endangered species in the food chain (eg: *Charonia tritonis*) ☑**Exploring the checks and balances of invasive species.** (eg: *Acanthaster planc, Drupellarugos*)
	·Coral transplant restoration	☑**Building the coral nursery garden in the field** □Coral transplantation using gardening methods in line with local circumstances (eg: coral tree_epoxy/ ropes, artificial reefs, iron nails, iron frames)

Note: The bolded option indicates that this measure is being implemented in some reefs in the subregion.

Table S6. Parameter estimates from the scenario analysis of local reef management based on ICRM framework.

Scenario analysis	Paths	Evaluation index					
HNE		**Min**	**1st Qu.**	**median**	**mean**	**3rd Qu.**	**Max**
Actual trends	· Fishing ban since 2015	3.00	4.50	8.25	11.86	19.41	31.00
HC1: Land-based	· Reducing agriculture nutrients emissions into water (0.4)	**6.79**	**10.14**	**13.00**	**15.05**	18.78	33.37
HC2: Sea-based	· Increasing fisheries resource (2)	-9.02	0.84	6.70	9.36	**14.55**	**44.31**
HC3: Integrated land-sea	· Reducing agricultural nitrogen emissions into water · Increasing fisheries resource	**12.02**	**15.11**	**22.43**	**26.44**	**34.11**	**63.34**
Scenario analysis	**Paths**	**Evaluation index**					
HNS		**Min**	**1st Qu.**	**median**	**mean**	**3st Qu.**	**Max**
Actual trends	· Fishing ban since 2015	1.50	7.125	21.00	18.04	24.60	43.00
HC1: Land-based	· Reducing agriculture nutrients emissions into water	**2.01**	**9.01**	15.56	17.25	22.92	46.86
	· Controlling the rate of urban expansion (-100000)	-	-	--	-	-	-
HC2: Sea-based	· Increasing fisheries resource (2)	-25.72	-11.11	1.54	5.33	**15.42**	**63.36**
HC3: Integrated land-sea	· Reducing agriculture nitrogen emissions into water · Increasing fisheries resource	**3.97**	**15.76**	**24.44**	**31.17**	**41.30**	**87.51**
	· Controlling the rate of urban expansion · Reducing agricultural nitrogen emissions into water · Increasing fisheries resource	**-**	**-**	**-**	**-**	**-**	**-**
Scenario analysis	**Paths**	**Evaluation index**					
HNXS		**Min**	**1st Qu.**	**median**	**mean**	**3st Qu.**	**Max**
Actual trends	· Fishing ban since 2015 and hunting the crown-of-thorns starfish in 2018	1.15	2.36	4.00	5.15	6.47	21.25
HC1: Sea-based	· No outbreak for the crown-of-thorns starfish during 2011-2020	-0.23	2.88	**6.01**	**6.49**	**8.22**	**26.46**
HC2: Sea-based	· Increasing fisheries resource (2)	-2.39	3.14	**8.62**	**10.61**	**14.88**	**52.45**
HC3: Sea-based	· Increasing fisheries resource (＞250)	**15.15**	**23.74**	**28.24**	**28.08**	**32.39**	**37.73**

Note: The live coral coverage in the different hypothetical cases HC1, HC2, and HC3 for the period 2011-2020. There are low (less than the 1st Quarter percentile), moderate (more than the 1st Quarter and less than the 3rd Quarter percentile) and high (more than the 3rd Quarter percentile) live coral cover category. The description of the hypothetical cases is in Methods. The gray shades reflect the probability density of actual live coral cover in each subregion since 2010, while the blue parts reflect the probability density of adjusted live coral cover by reducing nutrients (agriculture nitrogen) emissions into river, increasing fisheries resource, and hunting the crown-of-thorns starfish.

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