nature portfolio

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Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☐	☒	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection. Where necessary, data were extracted from graphs using WebPlotDigitizer (versions: 4.3 and 4.4). The geographic location of data points were also examined in Google Earth (version: 7.3).
Data analysis	All data analysis was conducted in the software R (version: 4.0.2) using the mgcv (version: 1.9.0), mice (version: 3.14.0), FactoMineR (version: 2.8), vegan (version: 2.6-4), tidyverse (version: 1.3.2), stargazer (version: 5.2.3), lmtest (version: 0.9.40), plm (version: 2.6.2), piecewiseSEM (version: 2.1.2), and lme4 (version: 1.1.31) packages.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:
- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Our field survey data from 1990s to 2020 were compiled to create a dataset (Fig. 1, Fig. S1 and Fig S2).

The environmental factors data, such as temperature, chlorophyll a, photosynthetically active radiation, turbidity (Kd490) and Degree Heating Weeks (DHW), were obtained from NASA's Earth Observing System Data and Information System (EOSDIS) Modis-Aqua satellite database, which has an ~4 km resolution beginning through mid-2002 to December 2020 (https://oceandata.sci.gsfc.nasa.gov), and the NOAA Coral Reef Watch who conducts 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).

Typhoon impact data (2000-2020) were obtained from the China Meteorological Administration tropical cyclone database (http://typhoon.zjwater.gov.cn/).

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

The socio-economic data from 2000 to 2020, such as local human population, number of overnight visitors, the crop planting area and production, were obtained from Hainan Statistical Yearbook.

Data of mangrove forest area were extracted from published reports and literatures, and data of seagrass coverage were obtained from our field survey and published literatures.

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

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender (identity/presentation), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender	Not applicable
Reporting on race, ethnicity, or other socially relevant groupings	Not applicable
Population characteristics	Not applicable
Recruitment	Not applicable
Ethics oversight	Not applicable

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences   ☐ Behavioural & social sciences   ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	
Data exclusions	
Replication	
Randomization	
Blinding	

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	
Research sample	
Sampling strategy	
Data collection	

Timing	
Data exclusions	
Non-participation	
Randomization	

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

This study leverages two decades of systematic monitoring across 102 sites spanning 22 reefs in the northern South China Sea (SCS) to quantify multi-stressor impacts on live coral coverage (LCC) through an integrated land-sea approach. We employ panel regressions and structural equation modeling (SEM) to identify the main drivers of LCC change, including abiotic factors (e.g., sea surface temperature, turbidity, typhoon), biotic factors (e.g., fish, macroalgae coverage, CoTS abundance, coral species richness), socio-economic factors (e.g., urban sprawl, agriculture development), as well as their interactions. We then propose an Integrated Coast-Reef Management (ICRM) framework with tailored strategies to improve coral reef resilience under ocean warming. This systemic approach contributes a paradigm shift from reactive conservation to predictive, stressor-specific management in anthropogenically complex reef system. Our findings contribute to coral conservation paradigms by highlighting tailored strategies at the local level beyond globalized approaches, which offer scalable solutions for regions facing similar pressures.

Research sample

Based on an initial examination of available data we settled on these coral reef community composition indicators, including living hard coral (LCC), soft corals, dead hard coral, bleached coral, coral recruit (< 5cm diameter), crown-of-thorns starfish (CoTS), macroalgae, coral reef fish, and coral species richness.
The ecological and socio-economic factors includes typhoon exposure, temperature, turbidity, local human resident population intensity and agricultural development (agriculture N, denotes total agricultural nitrogen emissions per year to the local waters).
The reef benthos, and associated fish communities, were surveyed using underwater visual census techniques. For each coral reef, a reef check survey or simple random sample survey was conducted annually, with at least 3 sites per reef for simple random sample surveys. At each site, community substrate type was recorded by video along each ≥50m transect line, and the linear point intercept (LPI) method was used to identify organism species and calculate the percentage of reef benthos. And each coral taxon also was categorized into life-history types based on previous studies.
Within each site, the banded transect was recorded by video for 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.

Sampling strategy

Coral reef monitoring programs use Standard Operational Procedures to ensure consistent methodology through time, including line intercept, point intercept or photo quadrat transect methods. This ensures that the data we are reporting on has been collected in a consistent, rigorous way, enabling robust appraisal of any changes in reef condition indicators through time. The methods used are globally accepted by the scientific community.
Sampling strategies were determined by each data collector and often involved replicate transects stratified by depth. Each survey site consisting to 2~6 transects was deployed at a depth of 2-9 m.

Data collection

The individual data points in our dataset were mean reef level (i.e. a unique latitude and longitude) benthic community composition data. Mean reef level data were used as this was the finest resolution of data that could be reliably sourced. For example, we aggregate the LCC data by calculating the mean LCC per survey site/year, then the mean LCC per reef/year.
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.
The some environmental factors data, such as temperature, chlorophyll a, photosynthetically active radiation, turbidity (Kd490) and Degree Heating Weeks (DHW), 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), and 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).
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 (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 winds16. 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.

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.

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. 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).

Some socioeconomic indicators were selected to calculate exposure stress, including local human population, number of overnight visitors and total agriculture N per year to the water in native city. 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. A parameters-localized NUFER model was used to estimate N and P emissions.

Data about mangrove forest area and seagrass coverage extracted from published reports and literature.

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).

Timing and spatial scale	Data were collected between 1990s and 2021. The field survey data were from 2000s to 2020. The laitudinal range of the study region covered approximately 16°N~20°N (Fig. 1), including 22 reefs were monitored annually.
Data exclusions	We did not use those reef sites into our panel modeling and structural equation analysis due to the short temporal span of monitoring at some of the sites (less than 5 years).
Reproducibility	A full description of the methodolopies used is provided in the Methods. All data used in this manuscript are publicly available upon request from the corresponding author.
Randomization	Fixed site surveys, in which reef fish and benthos on the reef surface are surveyed at three sites, in a habitat that is standardised across reefs. Underwater visual survey counts were started from the beginning to the end for each transect. Ensuring each site is permanently marked helps reduce variation in the data due to sampling, and enables us to detect changes through time, which is the primary goal of monitoring. Fixed site surveys are designed to detect reef community changes in more detail and at finer taxonomic resolution than what can be provided by random surveyed points. Covariates from the environmental factors data used in this study were controlled by running a covariate correlation analysis and removing variables with a correlation coefficient of 0.70 or greater before we built our panel modeling and structural equation analysis.
Blinding	Blinding was not necessary as these were surveys of wild communities of benthic organisms and fish.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Field conditions in the sea were appropriate and allowed to conduct monitoring surveys.
Location	The study was conducted at reef sites in a standardized reef slope habitat between 2 to 9 m depth throughtur the study region covered approximately 16"N~20'N (See Map Fig. 1 in manuscript).
Access & import/export	All data collectors were responsible for obtaining the necessary permissions and permits required for underwater observations of coral reef benthic communities.
Disturbance	No disturbances were caused because data collection only required observation.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	Antibodies
☒	Eukaryotic cell lines
☒	Palaeontology and archaeology
☐	☒ Animals and other organisms
☒	Clinical data
☒	Dual use research of concern
☒	Plants

Methods

n/a	Involved in the study
☒	ChIP-seq
☒	Flow cytometry
☒	MRI-based neuroimaging

Antibodies

Antibodies used	
Validation	

Eukaryotic cell lines

Policy information about cell lines and Sex and Gender in Research

Cell line source(s)	
Authentication	
Mycoplasma contamination	
Commonly misidentified lines (See ICLAC register)	

Palaeontology and Archaeology

Specimen provenance	
Specimen deposition	
Dating methods	

☐ Tick this box to confirm that the raw and calibrated dates are available in the paper or in Supplementary Information.

Ethics oversight	

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Animals and other research organisms

Policy information about studies involving animals; ARRIVE guidelines recommended for reporting animal research, and Sex and Gender in Research

Laboratory animals	No laboratory animals were used in this study.
Wild animals	Invertebrate coral communities were sampled non-destructively using standard underwater observation protocols along transect lines,and recorded by experienced scientific divers.
Reporting on sex	Sex was not considered as part of this study.
Field-collected samples	No samples were collected.
Ethics oversight	Reef Check surveys required no ethics oversight as the study was observational.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Clinical data

Policy information about [clinical studies](#)

All manuscripts should comply with the ICMJE [guidelines for publication of clinical research](#) and a completed [CONSORT checklist](#) must be included with all submissions.

Clinical trial registration	
Study protocol	
Data collection	
Outcomes	

Dual use research of concern

Policy information about [dual use research of concern](#)

Hazards

Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

No	Yes	
☐	☐	Public health
☐	☐	National security
☐	☐	Crops and/or livestock
☐	☐	Ecosystems
☐	☐	Any other significant area

Experiments of concern

Does the work involve any of these experiments of concern:

No	Yes	
☐	☐	Demonstrate how to render a vaccine ineffective
☐	☐	Confer resistance to therapeutically useful antibiotics or antiviral agents
☐	☐	Enhance the virulence of a pathogen or render a nonpathogen virulent
☐	☐	Increase transmissibility of a pathogen
☐	☐	Alter the host range of a pathogen
☐	☐	Enable evasion of diagnostic/detection modalities
☐	☐	Enable the weaponization of a biological agent or toxin
☐	☐	Any other potentially harmful combination of experiments and agents

Plants

Seed stocks	NA
Novel plant genotypes	NA
Authentication	NA

ChIP-seq

Data deposition

☐ Confirm that both raw and final processed data have been deposited in a public database such as GEO.

☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links
May remain private before publication.

Files in database submission

Genome browser session
(e.g. UCSC)

Methodology

Replicates

Sequencing depth

Antibodies

Peak calling parameters

Data quality

Software

Flow Cytometry

Plots

Confirm that:

☐ The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).

☐ The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).

☐ All plots are contour plots with outliers or pseudocolor plots.

☐ A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

Sample preparation

Instrument

Software

Cell population abundance

Gating strategy

☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type

Design specifications

Behavioral performance measures

Acquisition

Imaging type(s)

Field strength

Sequence & imaging parameters

Area of acquisition

Diffusion MRI ☐ Used ☐ Not used

Preprocessing

Preprocessing software

Normalization

Normalization template

Noise and artifact removal

Volume censoring

Statistical modeling & inference

Model type and settings

Effect(s) tested

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference

(See Eklund et al. 2016)

Correction

Models & analysis

n/a | Involved in the study
☐ ☐ Functional and/or effective connectivity
☐ ☐ Graph analysis
☐ ☐ Multivariate modeling or predictive analysis

Functional and/or effective connectivity

Graph analysis

Multivariate modeling and predictive analysis