Remote sensing monitoring and future change assessment of coral reefs in the South China Sea

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Purposes:

Coral reefs are primarily composed of carbonate skeletons and symbiotic coral polyps. Not only do corals directly participate in biogeochemical cycles, but they also offer protection to marine organisms, provide medicinal value, and so on. Hundreds of islands and reefs distribute in the South China Sea, covering about 37,000 km^2 of coral reefs. Unfortunately, similar to corals in other global regions, those in the SCS have experienced varying degrees of degradation in recent years, facing multiple threats to their survival. Existing coral survey data indicates a consistent decline in live coral cover in most areas of the SCS since 2004. Multiple factors contribute to coral degradation, with rising sea surface temperature (SST) being a crucial factor, along with ocean acidification, low oxygen levels, and microplastics. Therefore, monitoring and assessing coral reefs are essential.

Remote sensing technology, with its advantages of fast speed and wide monitoring range, is widely used in coral monitoring. The development of species distribution modeling (SDM) technology also supports the simulation of species' suitable ranges and reveals the corresponding relationships between species and the environment. Therefore, the main research objective of this project is to explore the distribution of coral reefs in the SCS using remote sensing technology, quantitatively analyze their temporal and spatial changes in recent years, acquire the ecological niche information for corals, determine the key environmental factors influencing their survival, and ultimately evaluate the risk of coral degradation under future climate conditions.

Methods:

(1) Coral reef remote sensing monitoring:

We downloaded Landsat 8 satellite data from the USGS for 2013-2021 and preprocessed these images. Then we established a coral substrate classification system, comprising six types: coral colony, patch reefs, reef flat, forereef slope, sandbanks, and vegetation and buildings. Subsequently, we extracted spectral and texture information for these six substrate types from remote sensing images, improved existing spectral indices, and constructed a decision tree classification model (Fig. 1).

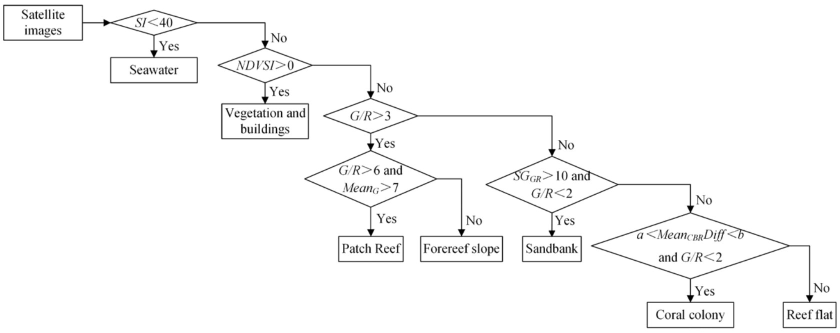

Fig.1 Decision tree for coral reef sediment classification

(2) Ecological niche information acquiring

We obtained coral distribution data in SCS from UNEP-WCMC and downloaded commonly used marine environmental data from multiple public datasets, including biochemical, physical parameters of seawater, and meteorological parameters. Perform preprocessing on these data to construct a species distribution model. The model then generated predictive maps for coral distribution, and assessed the impact of environmental variables on coral distribution. This allowed us to identify key environmental factors affecting coral survival and the suitable environmental range for coral habitats.

(3) Exposure risk evaluation under future environmental changes

Based on CMIP6 data, two representative scenarios, SSP245 and SSP585, representing moderate and high emission scenarios respectively, were selected. The change-factor method was employed to calculate future data for key environmental factors. Combining the previously defined coral suitable environmental range, coral exposure risk levels were defined: future data within the suitable range were considered “no risk”, while those exceeding the range were classified into “low risk”, “moderate risk”, “superior risk”, and “highest risk” based on quartiles. The total exposure risk map was generated by summing up all exposure risk of key factors.

Results:

(1) Coral reef remote sensing monitoring:

After verification, the decision tree classification model proposed in this study achieved a classification accuracy of 77.33%, approximately 7% higher than that of traditional supervised classification methods. Subsequently, we applied this model to various islands. The classification results for the Yongle Atoll in the Xisha Islands (Fig. 2) indicated an overall increase in the area of corals by around 1.69 km^2. However, the change in each island varied. Yinyu and Jinyin Island showed a continuous recovery of coral colony, while Jinqing, Quanfu, Coral Island, and Lingyang Reef experienced significant degradation, with a reduction in coral colony by about 0.3 to 0.9 km^2.

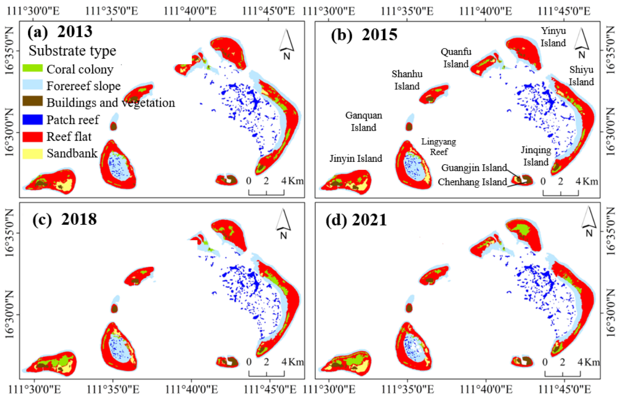

Fig.2 Coral information of Yongle Atoll in Xisha Islands at different periods

The coral colony in Huangyan Island also showed serious degradation, with a reduction of about 3 km^2 compared with the beginning of the study. The northeastern colony was heavily degraded, while the western corals showed signs of recovery.

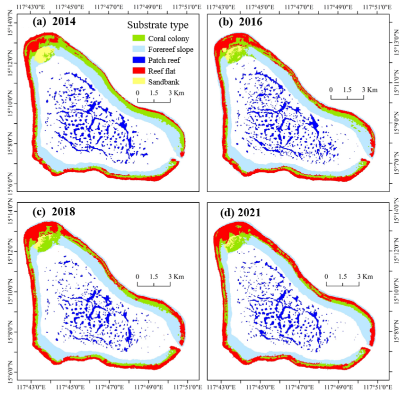

Fig.3 Coral information of Huangyan Island at different periods

The coral changes of Nansha Islands were similar to those of Yongle Atoll. In general, the area of coral colony had decreased by about 1.5 km^2, among which the Pearson Reef recovered first and then degraded. The corals of Alison Reef and Cornwallis South Reef continued to degrade, with the area decreased by 0.97 km^2. Most of the coral changes at Pearson Reef occurred in the south. Coral degradation at Cornwallis South Reef and Alison Reef occurred mainly in the south and north, respectively.

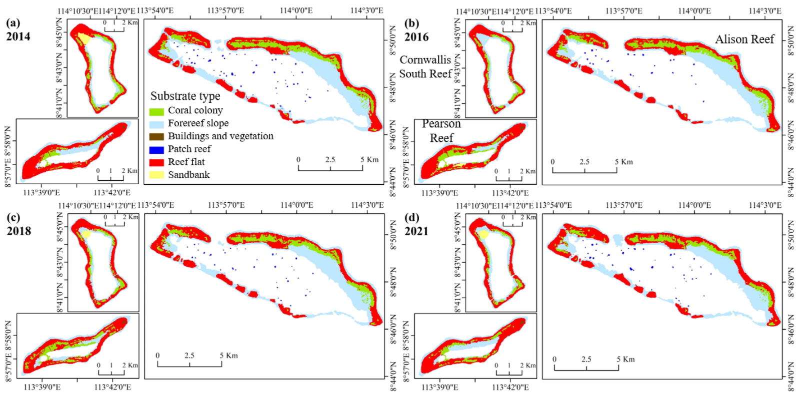

Fig.4 Coral information of three islands in Nansha Islands at different periods

(2) Ecological niche information acquiring

The MaxEnt model had a good predictive effect on the distribution of corals in the SCS (Fig. 5), and its AUC could reach 0.856. Coral high suitability areas were mainly concentrated in the north of 10° N latitude and the southeast of Nansha, including Yongle Atoll and Xuande Atoll in Xisha, Zhongsha atoll, Huangyan Island and the north of Nansha, covering an area of about 31,360 km^2.

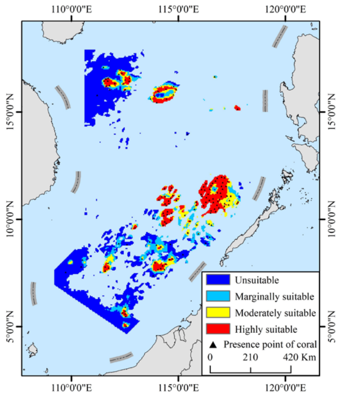

Fig.5 Suitable regions for coral reef predicted by MaxEnt model

The importance results were showed in Fig. 6. Among the factors considered, seawater velocity–Mean had the highest percentage contribution of 52.4%, followed by nitrate–Lt. Min (6.3%) and cloud cover (4.6%), and their cumulative contribution was greater than 62%. The top three variables with high permutation importance (Fig. 6b) were seawater velocity–Mean (23.7%), SST–Mean (13.5%), and PAR—Mean (12.1%). In summary, velocity, DO, SST and PAR had the significant impact on coral presence.

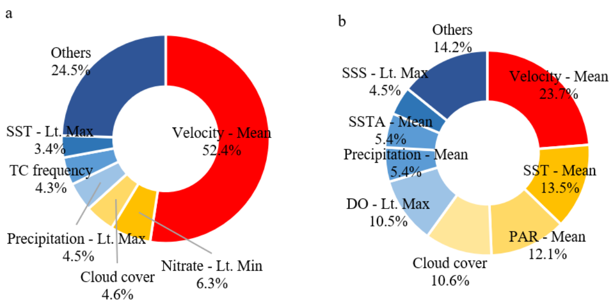

Fig.6 Percent contribution(a) and permutation importance(b) of the environmental variables to MaxEnt model

The optimum range of velocity was below 0.27 m·s^{-1}(Fig. 7a). Annual mean SST had a unimodal distribution (Fig. 7b). It appeared that corals displayed a preference for slightly warmer seawater, and the range for optimal SST was approximately 28 °C to 29.2 °C. PAR–Mean and DO–Lt. Max had bimodal distributions (Fig. 7c and 7d). The optimal average annual PAR range was 42.5 to 45 E·m^{-2}·day^{-1}. For DO–Lt. Max, two distinct peaks were observed, occurring at approximately 6.55 mg·L^{-1} and 6.88 mg·L^{-1}.

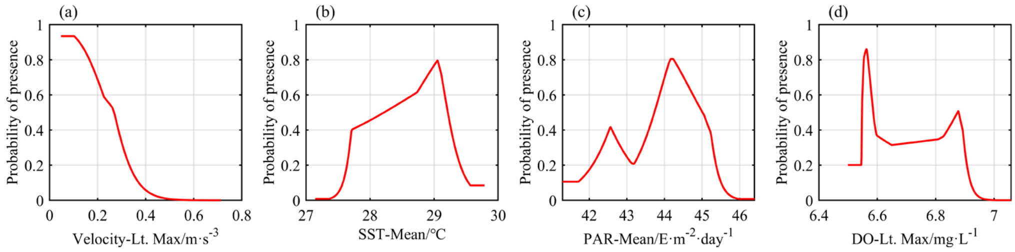

Fig.7 Response curves between key environmental variables and presence probability

(3) Exposure risk evaluation

Under future climate scenarios, the majority of environmental variables underwent significant changes, especially under high forcing conditions such as SSP585. Notably, SST, precipitation, nitrate, and DO exhibited dramatic variations. The alterations in each environmental variable within the southern Nansha Islands surpassed the low risk level, signifying that this region was particularly vulnerable to environmental shifts. As time progressed and forcing scenarios intensified, the exposure risk in the SCS continued to escalate (Fig.8). In the most extreme scenario (SSP585-2090s), more than 67% of corals would confront the highest risk, predominantly concentrated in the Nansha Islands, while the coral reefs in the Xisha Islands and Zhongsha Atoll consistently faced lower exposure risks.

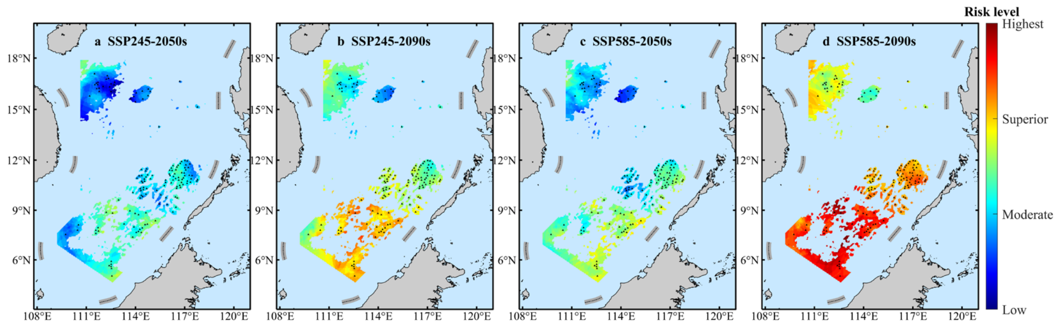

Fig.8 Distribution of exposure risk for coral survival

Future challenges:

(1) The decision tree classification model needs to be simplified to ensure its applicability to other satellite data.

(2) For future risk assessment, multi-model aggregation is needed to improve the accuracy and spatial resolution of future environmental data.

Attachment:

The article, published on Ecological Indicators, is attached.