Title

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Dive beyond the surface: Revealing the past and the future of coral reefs in southern Taiwan with large-area imaging technology

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Abstract

Coral reefs are facing unprecedented threats due to climate change and local stressors, necessitating a better understanding of their responses and resilience mechanisms regionally. This study examines the impacts of the 2020 mass bleaching event on coral reef dynamics in Kenting National Park, Taiwan, using large-area imaging (LAI) technology. Four sites were analyzed, revealing insights into coral abundance, planar area, size distribution, and survival rates of two common coral taxa, corymbose *Pocillopora* and massive *Porites*. While restricted in scope, our findings highlight the resilience and adaptability of coral species in the face of environmental stressors. Despite limitations, our study underscores the importance of LAI data in providing detailed insights into coral reef demography and dynamics, serving as both a scientific analysis tool and a means of effective science communication. Further research is needed to fully understand underlying mechanisms and ensure the long-term sustainability of coral reef ecosystems in Kenting National Park.

Introduction

Coral reefs are highly complex and dynamic ecosystems, continually influenced by various disturbances, including local and global threats such as local water pollution, fishing, and recreational activities, as well as the impacts of global warming and ocean acidification.[1] In recent years, these threats have significantly challenged coral reef survival. Coral reefs' responses vary across regions due to their dynamic nature, with distinct behaviors and adaptation strategies observed in various coral species globally. Instances of coral resilience amidst climate change and pollution stressors emphasize the need to understand regional changes. This understanding is crucial for developing precise local management policies to preserve and safeguard coral reef ecosystems.

Unraveling the Impact of 2020 Mass Bleaching:

Kenting National Park (KNP), the oldest national park encompassing both terrestrial and marine areas, is located in a tropical region at the southern tip of Taiwan. Recognized as the area with the highest marine biodiversity in Taiwan, KNP has faced multiple natural disturbances including bleaching events, typhoons, escalating human activities, and increasing tourism, leading to a decline in coral coverage and alterations in benthic community composition.[2] Furthermore, the most severe coral bleaching event on record occurred in 2020, resulting in an estimated loss of one-third of coral colonies in KNP's

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[1] Anthony, R. N. (2016). Coral Reefs Under Climate Change and Ocean Acidification: Challenges and Opportunities for Management and Policy. https://doi.org/10.1146/annurev-environ-110615-085610

[2] Kuo, C.-Y., Yuen, Y. S., Meng, P.-J., Ho, P.-H., Wang, J.-T., Liu, P.-J., Chang, Y.-C., Dai, C.-F., Fan, T.-Y., Lin, H.-J., Baird, A. H., & Chen, C. A. (2012). Recurrent disturbances and the degradation of hard coral communities in Taiwan. *PLoS ONE*, 7(8). https://doi.org/10.1371/journal.pone.0044364

marine areas.[3] These disturbances prompt urgent questions about the long-term resilience and adaptability of coral species in the region. Despite global awareness of the challenges coral reefs face, a critical knowledge gap exists concerning the specific responses of coral species in the Kenting area to the 2020 mass bleaching event, impeding effective conservation and management efforts.

Understanding coral species' post-bleaching response and assessing the ecosystem's overall impact are crucial for effective conservation and management. Limited studies have tracked these demographic changes after the 2020 mass bleaching event in the region comprehensively. Bridging this gap is essential for informed decision-making and raising awareness within local communities. Large-area imaging (LAI) is a valuable technology to fill this gap.

Gaps in Community Awareness and Communication in Coral Reef Conservation Efforts:

Due to the limited accessibility to the underwater world, many people in Taiwan have never had the opportunity to experience coral reefs firsthand. Their primary source of information is from mass media, which often emphasizes the negative narrative of coral reef degradation, further constraining public understanding of the complex and dynamic nature of the coral reef ecosystem. Understanding the past and future of coral reefs should extend beyond the scientific community. It is crucial to translate scientific findings into information that can be comprehended and utilized by management entities and local communities, whose livelihoods depend on this ecosystem, for advocacy and improved local management.

Furthermore, the management information published by the National Park Administration is not easy to access and interpret for the local community. During the planning of the protected zones process, there was insufficient communication with the residents, and as a result, widespread support from the public was not obtained. Most residents might be unaware of the zoning plan for the marine areas of KNP.[4] Community involvement can enhance conservation area management, fostering understanding and acceptance of park measures.

The role of Large-Area Imaging technology:

LAI has great potential to monitor and visualize changes in benthic ecosystems over time. By co-registering images of the same environment at various intervals, researchers can gain valuable insights into changes at both the organism and community levels, revolutionizing the documentation of ecosystem recovery or decline for researchers and management

[3] Chen, C. L. (2022). Long-Term Ecological Monitoring Project of Coral Reefs in the Marine Areas of Kenting National Park. Construction and Planning Agency, Ministry of the Interior, Kenting National Park Administration.

[4] Dai, C. F. (2000). Review and Recommendations for Zoning in the Marine Areas of Kenting National Park. Construction and Planning Agency, Ministry of the Interior, Kenting National Park Administration.

entities.[5] This study seeks to address these gaps by employing innovative LAI technology, offering a high-resolution and comprehensive approach to monitoring changes in coral demographics and growth rates. Bridging these knowledge gaps is paramount for developing targeted conservation strategies and fostering community involvement in coral reef protection. Further, this project aims to utilize LAI data, 3D fly-through videos of coral reef changes, and the current state of local management to narrate a comprehensive story of the coral reefs ecosystem management in the Kenting area.

Methodology

Study Taxa

To examine the response and recovery of different characteristic species, two regionally common coral taxa were selected: corymbose *Pocillopora* and *Porites* massive. These taxa are easily identifiable and exhibit different morphologies; corymbose Pocillopora is a grouping of two branching species (*P. meandrina* and *P. verrucosa*), while Porites massive is a species complex of three massive species (*P. arnaudi*, *P. lobata*, and *P. lutea*). Previous studies have shown that massive corals have higher density and lower susceptibility to thermal stress compared to branching forms.[6] Additionally, a synoptic study of coral functional traits has classified these taxa into distinct life history strategies, with *Pocillopora* categorized as weedy or ruderal and *Porites* as stress-tolerant.[7] These two taxa provide a valuable basis for exploring the response and recovery of coral reefs in this region.

Study Sites

Four 100 m^2 reef plots were chosen within Kenting National Park, each experiencing varying environmental conditions. From north to south and west to east, these sites are: (1) Wanlitong, (2) Dinbaisha, (3) Tiaoshi, and (4) Siangjiao Bay *(See Table 1 and Figure 1)*. Wanlitong and Dinbaisha are located on the west coast of the Kenting Peninsula. The coral reefs in this region observed a relatively high bleaching response during the 2020 mass bleaching event.[8] Tiaoshi and Siangiao Bay are located in Nanwan, the bay area. This area

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[5] McCarthy, O. S., Contractor, K., Figueira, W. F., Gleason, A. C., Viehman, T. S., Edwards, C. B., & Sandin, S. A. (2023). Closing the gap between existing large-area imaging research and marine conservation needs. Conservation Biology, 38(1). https://doi.org/10.1111/cobi.14145

[6] Wooldridge, S. A. (2014). Differential thermal bleaching susceptibilities amongst coral taxa: Re-posing the role of the host. Coral Reefs, 33(1), 15–27. https://doi.org/10.1007/s00338-013-1111-4

[7] Darling, E. S., Alvarez-Filip, L., Oliver, T. A., McClanahan, T. R., & Côté, I. M. (2012). Evaluating life-history strategies of reef corals from species traits. Ecology Letters, 15(12), 1378–1386. https://doi.org/10.1111/j.1461-0248.2012.01861.x

[8] Chen, Y.-J., Cai, Y.-L., & Zhang, Q.-H. (2017). Long-term ecological monitoring project of coral reefs in Kenting National Park marine area (No. 109) [PDF document]. Retrieved from https://ws.ktnp.gov.tw/Download.ashx?u=LzAwMS9VcGxvYWQvMjQ1L3JlbGZpbGUvNjczMi8xMTI3MzMvMTg5NTNjYmMtNzk2ZC00YzI0LTliMGUtOTlmYmQ5OWRjMjFlLnBkZg%3d%3d&n=MTA55bm05bqm5aK%2b5LiB5ZyL5a625YWs5ZyS5rW35Z%2bf54%2bK55Ga56SB6ZW35pyf55Sf5oWL55uj5ris6KiI55WrLnBkZg%3d%3d&icon=.pdf

experiences a unique phenomenon caused by tidal variations, leading to periodic upwelling. This brings colder, nutrient-rich, lower pH, and lower dissolved oxygen water masses from the deep sea to the surface, constantly alternating with warmer shallow water masses. During periods of abnormal ocean warming, the cold water masses from the upwelling create a temperature fluctuation effect, similar to a sauna, which helps alleviate the damage caused by sustained high temperatures on the corals.[9]

Table 1. Location and sampling metadata for each island included in the analysis.

Sites	Latitude	Longtitude	Depth	Sampling month, t_0	Sampling month, t_1
Wanlitong	21.9944	120.70108	10m	Jul 2018	Oct 2022
Dinbaisha	21.94785	120.71084	10m	Jul 2018	Jan 2023
Tiaoshi	21.95319	120.76891	10m	Jul 2018	Sep 2022
Siangjiao Bay	21.92394	120.82922	10m	Jul 2018	Sep 2022

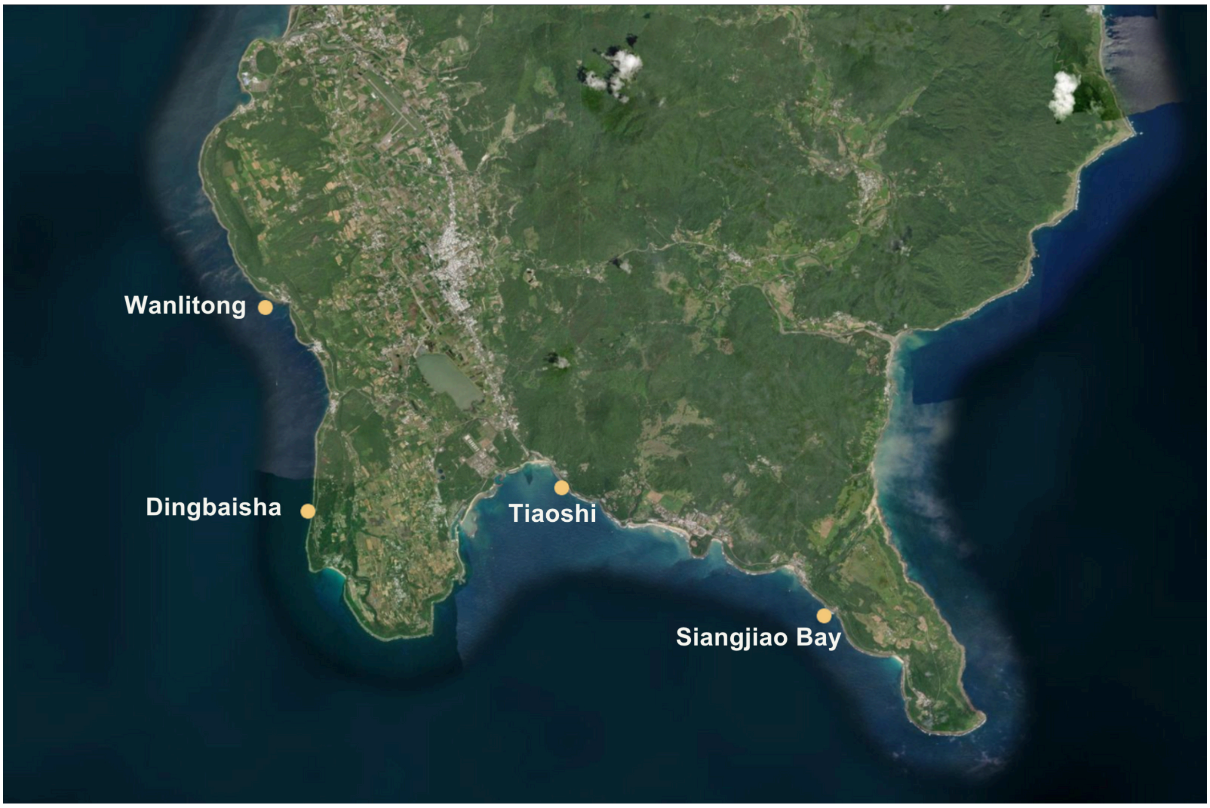

Figure 1. Maps of the sites included in the analysis.

[9] Fan, T.-Y., & Fang, L.-H. (January 2010). Environmental adaptability of coral reefs in Kenting. Science Development, 445(1). Retrieved from https://ejournal.stpi.narl.org.tw/sd/download?source=9901/9901-03.pdf&vlId=87009A25-CF08-4F43-B87D-F65E5DC370E8&nd=0&ds=0

Data Collection

Large-area imagery of the study sites was collected by Stuart Sandin's lab and local partners in 2018 and 2022 as part of the 100 Island Challenge. To analyze the LAI data, we used the software *Agisoft Metashape* to build 3D models of each site. After constructing the 3D models in *Metashape*, we imported them into the custom software *Viscore*. In *Viscore*, we scaled the 3D models, oriented them with respect to the sea surface, and spatially co-registered the 3D models of the same site collected in different years using a semi-automated co-registration workflow. We then exported high-resolution, 2D orthoprojection of the models for further data extraction.[10]

Data Extraction

To obtain detailed information on the percent cover changes of benthic organisms, including live coral and algae, we utilized the Virtual Point Intercept (VPI) tool in *Viscore*. This tool allowed us to drop 2,500 stratified random points on each 10 × 10 m site, where we then identified each point to the finest taxonomic resolution possible, down to the genus level. The VPI tool enhances the accuracy of identification by allowing us to examine single random points using all reference raw images collected in the field that are matched to that point in the 3D model reconstruction.

To acquire precise data on the changes in size and fate of each individual colony under study, we utilized *TagLab* to assist in the segmentation and annotation processes. While the segmentation is predominantly manual, it is supported by semi-automated tools within *TagLab*. *TagLab* allows us to trace live coral tissue with maps from different time points side by side. After initially annotating all coral colonies at each time point, the annotator then links colonies from each time point to the nearest consecutive time point. Subsequently, all linked colonies are manually checked to ensure accuracy. Due to the potential visual ambiguities present in 2D orthoprojections, our methodology incorporated a workflow that combines the use of *TagLab* with *Viscore*. Similar to the application of the VPI tool, integrating *Viscore* allowed us to correlate the coral tracing efforts with the original raw images. This approach mitigates the resolution limitations of 2D orthoprojections and provides more accurate reference data.

Analytical Methods

All data were extracted from *TagLab* and *Viscore* as .csv files for processing and analysis in R. The output from *TagLab* includes colony abundance and planar area (cm^2) for both taxa at two time points, as well as the fate of matched and unmatched colonies. If matched colonies

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[10] Edwards, C. B., Viehman, T. S., Battista, T., Bollinger, M. A., Charendoff, J., Cook, S., Combs, I., Couch, C., Ferrari, R., Figueira, W., Gleason, A. C. R., Gordon, S., Greene, W., Kuester, F., McCarthy, O., Oliver, T., Pedersen, N. E., Petrovic, V., Rojano, S., Runyan, H., Sandin, S. A., & Zgliczynski, B. J. (2023). Large-area imaging in tropical shallow water coral reef monitoring, research, and restoration: A practical guide to survey planning, execution, and data extraction. NOAA National Ocean Service, National Centers for Coastal Ocean Science. NOAA Technical Memorandum NOS NCCOS 313. https://doi.org/10.25923/5n6d-kx34

have a larger planar area at the second time point, they are categorized as "grow." Conversely, if matched colonies have a smaller planar area at the second time point, they are categorized as "shrink." Additionally, we removed coral colonies from the analysis that moved due to physical disturbances between the two study time points.

Science communication

To leverage the findings of this study for more effective management policies and to increase public awareness of coral reef conservation in the region, the outcomes of this study include the development of a StoryMap. This StoryMap will integrate geographic maps, narrative text, and multimedia content, encompassing the study results and visual content of the LAI model. This interactive and dynamic platform aims to present the research findings and information in a meaningful way. To ensure the relevance and completeness of the content, interviews with local management entities and stakeholders, including representatives from the tourism industry and non-governmental organizations (NGOs) were conducted throughout the study. These interviews will be instrumental in identifying and addressing potential information gaps, contributing to a more comprehensive and well-rounded presentation of the coral reef situation and management conditions in the Kenting area.

The final version of StoryMap: https://storymaps.arcgis.com/stories/85e3e2f908e74065bd8fd8ce10d4ccff

Results

a) Change in Abundance and Planar Area

A total of 863 coral colonies were included in this study, with 164 colonies of *Pocillopora*, 485 colonies of *Porites* in 2018, and 145 colonies of *Pocillopora*, 510 colonies of *Porites* in 2022 (*See Table 2*). In general, there are more *Porites* than *Pocillopora* in the region, with higher abundance of both taxa on the west coast of the peninsula than in Nanwan. The abundance of *Pocillopora* has declined in most sites, with Tiaoshi experiencing the most significant decrease at 51.7% (*See Figure 2A*). This decline aligns with expectations, as *Pocillopora* is known as a thermally-sensitive taxon. In contrast, the change in *Porites* massive populations has been more stable, with the highest decline in abundance recorded at 14.1% (*See Figure 2B*), indicating *Porite*s' greater thermal tolerance compared to *Pocillopora*.

Regarding the change in planar area, both taxa have generally increased in most sites, particularly *Pocillopora* (*See Figure 2C*). The exception is *Pocillopora* in Wanlitong, which experienced a modest loss of 5%, while *Porites* exhibited a positive increase across all sites, with the highest increase recorded at 46%. (*See Figure 2D*). When combined with the abundance data, it appears that most sites in the Kenting area have either experienced a slight decrease or increase in abundance alongside an increase in planar area.

Notably, both taxa at Siangjiao Bay have exhibited an increase in colony numbers and planar area. *Pocillopora* increased by 340% in abundance and 363.3% in planar area, while *Porites* increased by 40.8% in abundance and 12.9% in planar area.

Pocillopora

Sites	Colony abundance, 2018	Colony abundance, 2022	Planar area, 2018 (cm^2)	Planar area, 2022 (cm^2)	Median area, 2018 (cm^2)	Median area, 2022 (cm^2)
Wanlitong	54	42	7,242	6,881	18	62
Dingbaisha	71	45	12,837	13,080	61	181
Tiaoshi	29	14	949	1,880	27	141
Siangjiao Bay	10	44	703	3,260	53	28

Porites

Sites	Colony abundance, 2018	Colony abundance, 2022	Planar area, 2018 (cm^2)	Planar area, 2022 (cm^2)	Median area, 2018 (cm^2)	Median area, 2022 (cm^2)
Wanlitong	139	157	12,188	14,282	23	23
Dingbaisha	163	140	9,905	14,464	25	34
Tiaoshi	107	106	30,103	37,534	46	50
Siangjiao Bay	76	107	43,650	49,264	13	16

Table 2. Summary of traced colonies numbers, abundance, planar area and median colony size between 2018 and 2022

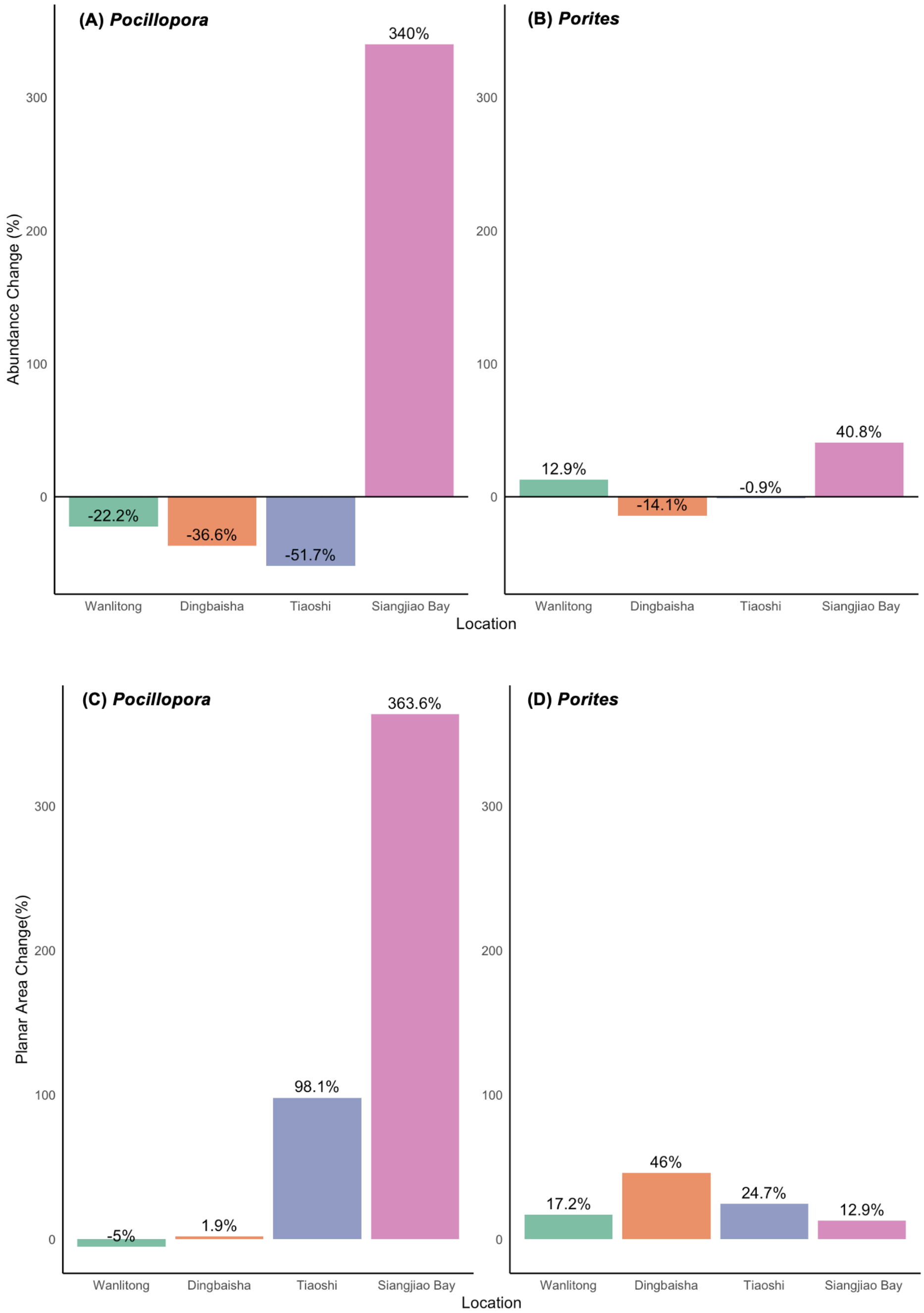


Figure 2. Changes in abundance and planar area of two studied coral taxa across all sites. (A) Percentage change in abundance of *Pocillopora*. (B) Percentage change in abundance of *Porites*. (C) Percentage change in planar area of *Pocilloporas.* (D) Percentage change in planar area of *Porites.*

b) Change in Size Distribution

A log scale for the x-axis and a standard scale for the y-axis were used to better examine the change in size distribution. The mean size of colonies for both taxa has either remained the same or increased in most sites. *Pocillopora* shows a more pronounced change (*See Figure 3A*), whereas *Porites* exhibits a more subtle variation (*See Figure 3B*). In general, for both taxa there has been a reduction in the abundance of small colonies, coupled with an increase in the abundance of larger colonies, as evidenced by the rise in median colony size in most locations. An exception to this trend is *Pocillopora* in Siangjiao Bay (*See Figure 3A*), which has seen high recruitment of smaller colonies.This pattern aligns with predictions, as smaller colonies tend to have a higher risk of whole colony mortality due to bleaching events. Notably, *Pocillopora* in Tiaoshi and Dinbaisha show an obvious decrease in the abundance of smaller colonies compared to other sites.

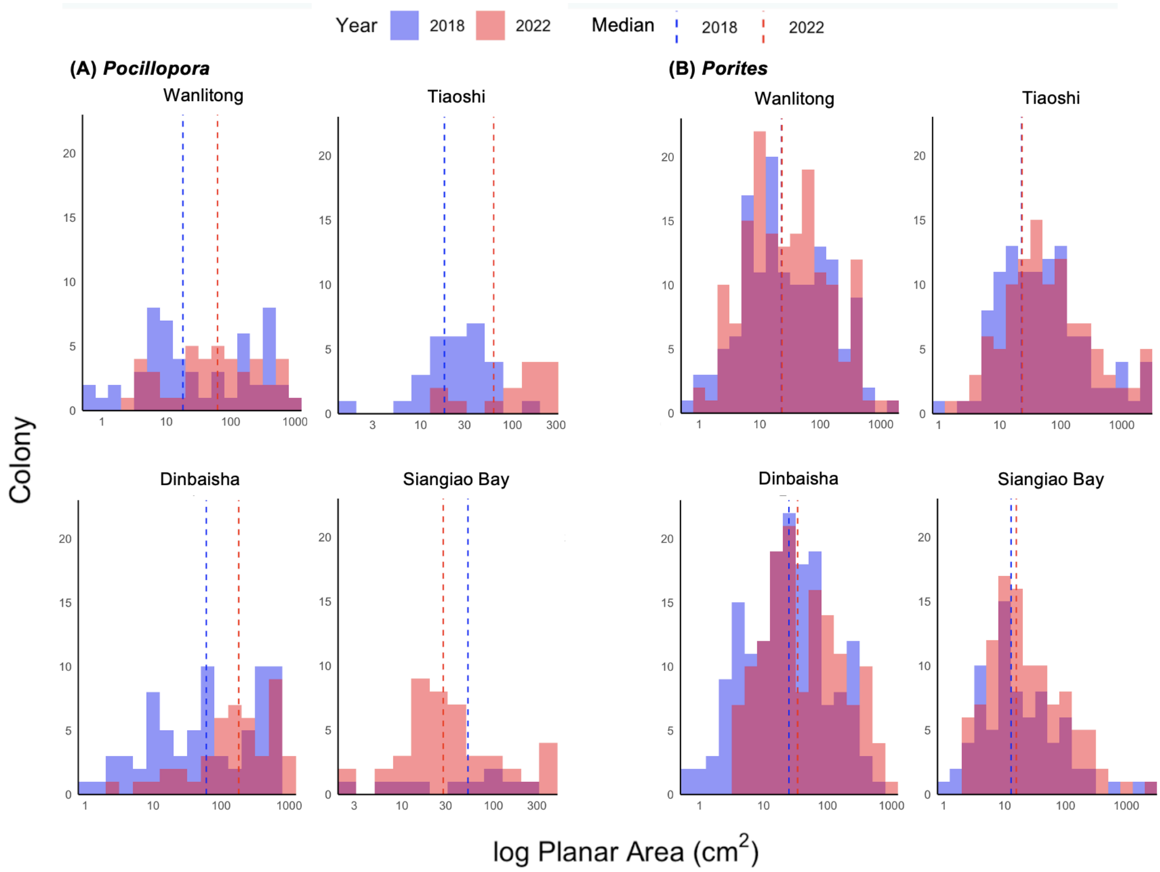


Figure 3. Changes in the colony size structure and median colony size of two studied coral taxa across all sites. The color bars indicate the colony size structure, while the dashed line represents the median colony size at the first time point (blue, 2018) and the second time point (red, 2022) for both *Pocillopora* and *Porites* at the four studied sites. (A) Change in the colony size structure of *Pocillopora*. (B) Change in the colony size structure of *Porites*.

c) Change in Colony-Level Live Coral Tissue Area

We focused on tracking the fate of corals by checking if the same colony was present in both time points. If colonies of the same taxa were present in the same location at both time points, they were considered to be the same colony; if not, the colonies were not matched and therefore not included in the colony specific change in live coral tissue area analysis. Corals can be displaced by external factors such as typhoons and large waves. In this study, any colonies that underwent large-scale coral movement were removed from analysis.

In general, most colonies either experienced complete mortality or survived and grew into larger colonies(*See Figure 4*). Complete mortality was more common in *Pocillopora* (*See Figure 4A*), while a greater proportion of *Porites* colonies avoided total mortality (*See Figure*

4B) with few portions experiencing partial mortality. This likely reflects the impact of mass bleaching events in Kenting in 2020.

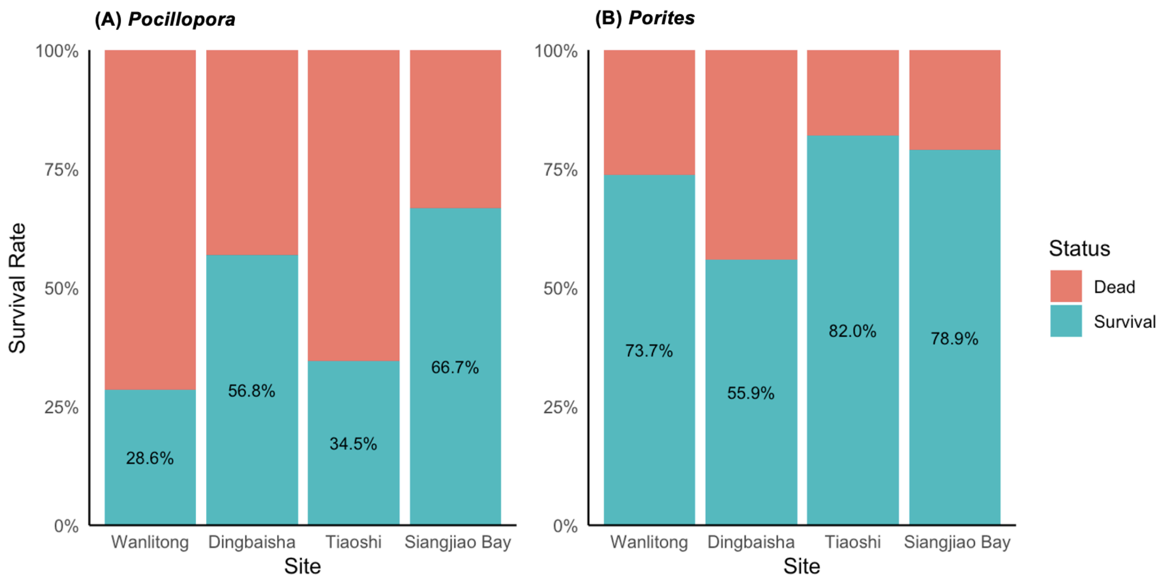
Figure 4. Colony-specific changes in the live tissue area of two studied coral taxa across all sites. (A) *Pocillopora* change in colony-level size across all sites. (B) *Porites* change in colony level size across all sites. The red dashed line represents the 1:1 line, indicating no change between 2018 to 2022.

d) Survival and Recruitment Rate Site Comparison

Due to the four-year interval between data points, we tracked individual corals at two distinct time points. If a coral individual was absent at the first time point but present at the second, it was classified as "born". This classification was used to calculate recruitment, without considering size or dimensions.

In general, *Pocillopora* has lower survival rates (average 46.64%), especially in Wanlitong and Tiaoshi, with the highest survival rate found in Siangjiao Bay (*See Figure 5A*). *Porites* has higher survival rates (average 72.6%) compared to *Pocillopora* (*See Figure 5B*).

The *Pocillopora* taxon is known for its relatively high growth rates and recruitment success. In particular, in Wanlitong and Siangjiao Bay, over 65% of the *Pocillopora* colonies are new, indicating a robust recruitment process. Conversely, in Dinbaisha and Tiaoshi, recruitment rates are significantly lower. This discrepancy suggests that certain factors are inhibiting the settlement of new colonies in these areas.



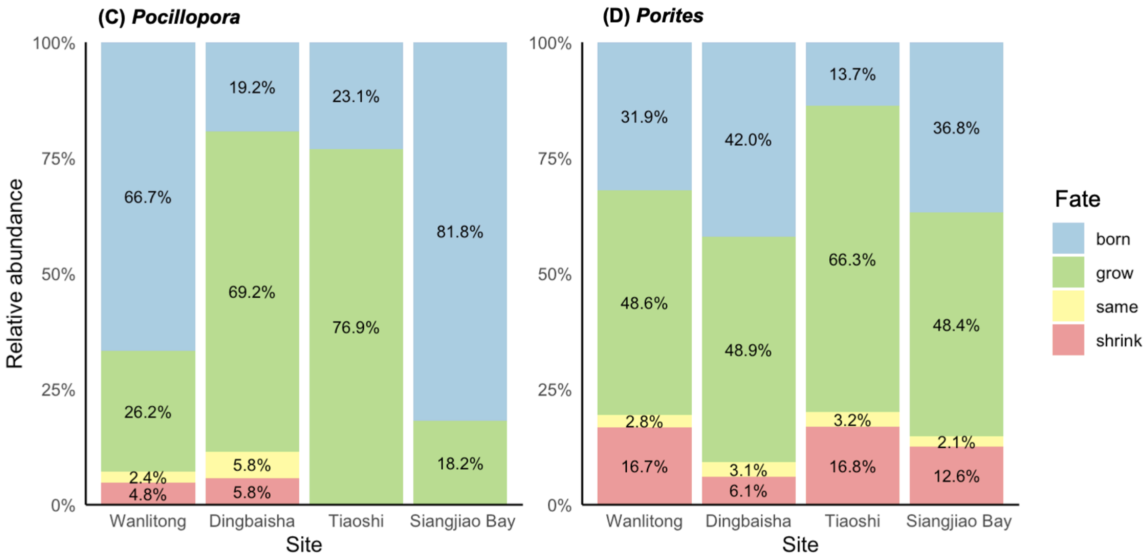


Figure 5. Survival rate and relative abundance of fate at t1 of two studied coral taxa across all sites. (A) Survival rates of *Pocillopora* at t0. (B) Survival rates of *Porites* at t0. (C) Fate of *Pocillopora* at t1. (C) Fate of *Porites* at t1.

Discussion

In this study, we found evidence of the potential resilience of the coral reefs in the Kenting region. Most sites in this area have either experienced a slight decrease or increase in abundance alongside an increase in planar area. This might suggest that the majority of both taxa in the area may either be resistant to bleaching events or have the potential for recovery afterward. The shift of size distribution towards larger colonies in most sites may suggest greater recovery capacity within these coral populations.

In Wanlitong, *Pocillopora* experienced a significant loss of colonies between the survey intervals. However, with high recruitment rates, *Pocillopora* was able to replace the individuals lost after the mass bleaching event. Surviving colonies continued to grow into larger colonies. Therefore, overall, there was not a substantial change in the size distribution in both taxa. This does indicate the impact of the mass bleaching event; however, this site's capacity for recovery allowed the size distribution to remain similar.

In Tiaoshi, *Pocillopora* experienced the most significant decline in abundance. Nevertheless, surviving individuals displayed accelerated growth rates, leading to nearly double the expansion in planar area. This phenomenon could be attributed to the predominance of smaller-sized individuals within this population, facilitating rapid growth.[11] Further analysis

[11] Madin, J. S., Baird, A. H., Baskett, M. L., Connolly, S. R., & Dornelas, M. A. (2019). Partitioning colony size variation into growth and partial mortality. Biology Letters, 15(9), 20190727. https://doi.org/10.1098/rsbl.2019.0727

is needed to understand the underlying mechanisms driving these dynamics and to assess the long-term implications for coral population dynamics in this area.

A noteworthy observation pertains to *Pocillopora* in Dinbaisha and Tiaoshi, where there is a reduced proportion of new coral recruits and a conspicuous absence of small-sized coral individuals. These findings suggest an environment potentially unsuitable for coral larval settlement and early growth phases. One potential reason could be the already high density of existing coral in these regions, which might limit the availability of suitable substrate for larvae to attach to.[12] Another possible factor could be high algae cover, which also reduces suitable spaces for coral larvae settlement.[13] In contrast, *Pocillopora* populations in Wanlitong and Siangjiao Bay might be adopting a different strategy, prioritizing energy investment in reproduction over the growth of large colonies. This reproductive focus could contribute to the higher recruitment rates observed in these areas. Our study underscores the importance of continued monitoring and management efforts to safeguard coral reefs in the Kenting region. Further research is required to elucidate the underlying causes of these patterns. In light of these findings, future management strategies may need to include targeted interventions, such as local algae suppression initiatives, monitoring regimes for herbivorous fish and invertebrates, and comprehensive water quality assessments. These measures aim to mitigate competition between algae and corals, thereby enhancing coral recruitment and overall reef resilience.

Regarding the observations for *Porites*, we found that in all sites, *Porites* increased in planar area even after experiencing the largest bleaching event on record. However, we also observed that in Dinbaisha, despite *Pocillopora* having a relatively higher survival rate, *Porites* exhibited a relatively lower survival rate. This finding could be due to other environmental factors affecting the survival of *Porites*, which requires further research to identify these factors.

Another significant finding is in Siangjiao Bay, both taxa have increased in abundance and planar area, with the highest increase in abundance of all sites. Both taxa also have relatively higher survival rate and higher recruitment rate compared to all sites. The observation shows the potential of resilience in this site. Compared to other study sites, Siangiao Bay has the longest history of the highest level of protected area. While our study results suggest a potential correlation between the observed outcomes and the established history of the protected area, further investigation is needed to establish a definitive relationship. Nevertheless, our findings strongly indicate that the environmental conditions within this area

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[12] Giyanto, R., Dewi, R., & Azkiyah, B. U. (2021). Coral recruitment and its relationship to hard coral cover in the Derawan Islands, East Kalimantan. IOP Conference Series: Earth and Environmental Science, 1137(1), 012001. https://doi.org/10.1088/1755-1315/1137/1/012001

[13] Hughes, T. P., Rodrigues, M. J., Bellwood, D. R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchett, M. S., Steneck, R. S., & Willis, B. L. (2007). Phase shifts, herbivory, and the resilience of coral reefs to climate change. Current Biology, 17, 360–365. https://doi.org/10.1016/j.cub.2006.12.049

enhance the resilience capacity of corals in this region. Therefore, it is imperative that policies remain in place to consistently maintain and monitor this area.

Conclusion

The study provides a detailed examination of coral reef responses to the 2020 mass bleaching event in Kenting National Park, Taiwan. Our findings shed light on the resilience and adaptability of coral species in the face of environmental stressors and underscore the importance of effective conservation strategies in safeguarding coral reef ecosystems.

However, due to the project's timescale restrictions, our analysis was limited to four out of the 12 survey sites surveyed by the 100 Island Challenge. While our results may not fully represent all sites in the region, they offer a snapshot of a more dynamic, complex picture. This highlights the importance of utilizing LAI data to provide more detailed insights into coral reef demography and dynamics. LAI technology not only serves as a valuable scientific analysis tool but also as a powerful means of science communication.

In conclusion, our study provides valuable insights into coral reef dynamics following the 2020 mass bleaching event. However, further research is essential to fully understand the underlying mechanisms driving these dynamics and to ensure the long-term sustainability of coral reef ecosystems in Kenting National Park. Continued monitoring and research efforts are crucial for informing effective conservation and management strategies to preserve these invaluable marine ecosystems for future generations.

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