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Dynamic of coral recruits in the Karimunjawa National Park, Central Java, Indonesia

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Abstract. *Tarigan SAR, Munasik, Wijayanti DP, Muhidin, Rohman EA, Pardede S. 2024. Dynamic of coral recruits in the Karimunjawa National Park, Central Java, Indonesia. Biodiversitas 25: 869-880.* After a disturbance event, coral reefs can recover naturally by recruiting new corals. These can be affected by environmental factors like the substrate's physical and biological structure, predation, and accidental mortality of recruits by grazers, as well as the number and size of parent corals supplying larvae. This study examined the connection between newly recruited corals and biological factors such as sea urchin density, herbivorous fish abundance, and hard coral coverage. The study was monitored changes in coral cover, juvenile coral density, herbivore abundance, and hard coral coverage at 43 locations and two depths (shallow; 2-3 m) and deep (8-10 m) from 2013 to 2022. The locations were distributed across six different zone systems: the core zone, protection zone, tourism zone, traditional fisheries zone, aquaculture zone, and rehabilitation zone. Multiple Linae Regression, ANOVA test, and Principal Component Analysis were employed to assess the relationship between coral recruitment and other variables. Results indicated that the coral recruitment density was not significantly different when comparing different zoning systems (two-way ANOVA test, P-value>0.05). Based on the PCA analysis, we found that in 2013 and 2019, excavator, sea urchin, browser, and hard coral have a positive relationship with coral recruitment, which implies that coral recruitment would increase as sea urchin, browser, and hard coral increase. Meanwhile, in 2019 and 2022, coral recruitment has a negative relationship with scraper, and also with hard coral growth (although only in 2022), implying that coral recruitment would decrease if scraper and hard coral increase. The study recommends restoring the role of herbivorous species in Karimunjawa National Park (KNP) by prioritizing them in conservation efforts and managing their populations.

Keywords: Conservation efforts, coral reef, disturbance event, herbivorous grazers, population management, recruiting new corals

INTRODUCTION

Since the early 1980s, climate change and human activities have led to increased coral mortality worldwide (A. El-Naggar 2021; Hughes et al. 2018). Before the first major coral bleaching in 1998, global hard coral cover was high and stable at over 30%. Following a dramatic decrease due to the bleaching events, after a decade, it recovered to pre-1998 levels (33.3% in 2009). However, between 2009 and 2018, there was a gradual loss of 14% of the world's coral reefs (Souter et al. 2020). Climate change and anthropogenic event led to loss of symbionts from coral tissues can have direct effects on the coral reefs through the loss of photosynthetic energy and can lead to starvation, disease, reproductive failure, and a loss of competitive ability relative to other organisms on the coral reef (Hoegh-Guldberg et al. 2017; Adjeroud et al. 2018). The recovery of coral reefs after disturbances involves several natural mechanisms and processes. Environmental factors, such as physical and biological surface structure of the substrate, predation and accidental mortality of coral recruits by grazers, and number of parent corals supplying larvae, size of parent corals. These factors could also influence the recovery process (Mumby et al. 2014).

Coral recovery is typically initiated by coral recruitments, which is an important factor in assessing coral reef ecosystems after experiencing anthropogenic or climate change disturbances (Gilmour et al. 2013). Moreover, coral recruitment is also considered as an indicator for resilience based management that promotes recovery coral reef ecosystem (Mcleod et al. 2019). The recruitment process involve three key phases: propagule supply, settlement, and post-settlement survival (Gouezo et al. 2020). During coral recruitment process, the biotic factor, namely fish herbivores, play vital roles in preparing reefs for coral recovery and resilience (Adam et al. 2015; Seraphim et al. 2020). Three groups of herbivorous reef fish—excavator/bioeroders, scrapers, browsers and grazers—contribute to both the resilience and vulnerability of reefs during changes.

Green and Bellwood (2009) explained that large excavators, such as the larger parrotfish species (e.g. *Bolbometopon, Chlorurus microrhinos, C. frontalis, and Cetoscarus bicolour*) engage in bioerosion. They take larger bites, dig deeper, and remove more substrate with each bite, playing a key role in bioerosion. Small excavators, such as the smaller parrotfish species (e.g., Chlorurus) also engage in bioerosion but take smaller bites, dig shallowly, and remove less substrate with each bite compared to large excavators. This function helps in eliminating algae and ensuring coral communities to be in competition with macroalgae which eventually will help to create space for coral recruits to settle in the coral reef ecosystem. Meanwhile, browsers consistently consume macroalgae, selectively choosing algal elements and eliminating only the algae and its associated epiphytic material. These browsers play a crucial role in mitigating coral overgrowth and shading caused by macroalgae, and they can significantly contribute to reversing transitions between coral and algal dominance phases (Green and Bellwood 2009). Grazers reduce seaweed, preventing coral overgrowth and shading by macro-algae (Isdianto et al. 2023). In Bonaire, Dutch Caribbean, herbivores were found to graze coral reef ecosystem giving positive impact on the abundance of adult and juvenile corals, and a decrease in macroalgae abundance (Steneck et al. 2019). Higher biomass of herbivorous fish will reduce the harmful effects of macroalgae on juvenile corals (Dajka et al. 2019). This was also supported by a study on the relationship between herbivore fish abundance with coral recruitment in Indonesia which revealed that the abundance of herbivorous fish was positively correlated with the density of young coral (Wibowo et al. 2016). Meanwhile, sea urchins, acted as primary grazers that promote coral reef recoveries (Nozawa et al. 2020) and control algal abundance (Do Hung Dang et al. 2020).

Given herbivore species crucial ecological role on coral recruitment and coral resilience (Chung et al. 2019), we aim to conduct a comprehensive assessment of the coral recruitment, to test the zoning system on coral recruitment in Karimunjawa National Park (KNP) in monitoring years of 2013, 2016, 2019 and 2022. Additionally, we aim to quantify the relationship between herbivory and coral recruitment. Karimunjawa National Park (KNP) is a Marine Protected Area (MPA) that managed by a national park authority under Ministry of Environment and Forestry (MoEF) Indonesia, located in the administrative Sub-district of Karimunjawa in Jepara District, Central Java Province. This area became habitat for marine biota such as reef fish, lobster, giant clam, and sea cucumber (Wijayanto et al. 2021). Considering the importance of the potential coastal resources within the area, looking at the dynamic of coral recruitment and their interaction with herbivore species will provide new insights which might benefit management of coral reef ecosystems in KNP.

MATERIALS AND METHODS

Study area

This research was conducted in Karimunjawa National Park (KNP), located in the south-central Java Sea, 83 km north of Java Island, in Jepara District, Central Java Province, Indonesia. The Karimunjawa archipelago consists of 22 main islands inside the KNP. The management of MPA in KNP is divided into six zones: core zone, protection zone, tourism zone, traditional fisheries zone, aquaculture zone, and rehabilitation zone. The remaining zones are open access which are not managed by the national park (Figure 1).

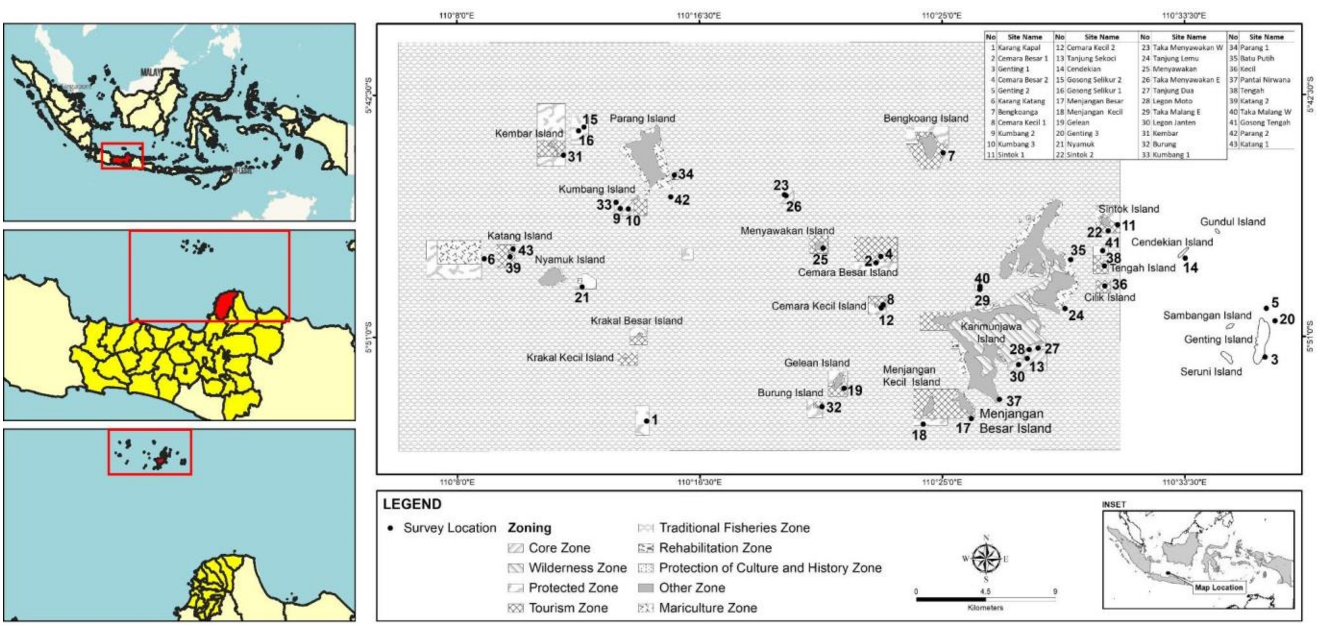

Figure 1. Map of study site in Karimunjawa National Park, Jepara District, Central Java Province, Indonesia

Data collection

We monitored 43 sites that are representative of zoning system in period 2013, 2016, 2019 and 2022 at two observation depths (deep (8-9 m) and shallow area (2-3 m) in the same season among the year (Figure 1; Table 1). In this study, we examined the density of juvenile corals (<5 cm in diameter) as a response variable and six other factors that would influence juvenile coral densities: hard coral coverage, the abundance of herbivorous fish within different functional group including grazer, browser, excavator, scraper and sea urchin density. The depth of the transects for assessing the variables (juvenile coral densities, hard coral, fish abundances and sea urchin densities are the same.

To count the number of juvenile corals (coral recruit) that are less than 5 centimeters wide, we used transect quadrats 50 x 50 cm. Quadrats were positioned on the coral reef at intervals of 10 meters along belt transects of fish, totaling 24 replications at the area observation (shallow and deep). Juvenile corals in each quadrat were counted and photographed for taxonomic identification at the genus level. We also captured images of the juvenile corals alongside a scale included in the photographs to aid in identification (Veron and Stafford-Smith 2000). The density of juvenile corals (No.m^{-2}) was calculated by dividing the sum of juvenile coral with the total area of transect.

Hard coral coverage is observed using the Point Intercept Transect (PIT) method by recording 100 substrate points along a 50-m transect (Hill and Wilkinson 2004). Three replicates of a 50-m line were placed haphazardly along hard substrate at each site. We identified hard coral on the genera level (Veron and Stafford-Smith 2000).

The abundance of herbivorous fish was estimated using the modified belt transect method (Hill and Wilkinson 2004). To ensure the identification of herbivores at the species level, caution is advised when interpreting results as recent studies have indicated that many taxa in such groups are not entirely herbivores species. With the result that, protocol for herbivorous reef fishes was used to assist identification of functional groups, namely scraper, grazer, browser and excavator (Table 1; Green and Bellwood 2009). The observation of herbivore fish abundance was conducted using three replicated transects along a length of 150 meters. The observation belt width for reef fish was 5 meters (for fish larger than 10 cm) and 2 m (for fish with a size of ≤10 cm). The density of sea urchins was observed within three replications (50 x 2 m total area of belt transect for one replication; total replications are four replications at each depth area). A scuba diver swam along a 50-meter line in the water and counted the sea urchins that were more than 1 centimeter in size. We counted the sea urchins on both sides (1 meter) along of the 50-meter line. We also captured images of the sea urchins alongside a scale included in the photographs to aid in identification. The methodology and data analysis are shown in Table 2.

Statistical analysis

Analysis impact of the zoning system on coral recruitment in Karimunjawa National Park (KNP)

We used One Way ANOVA to compare the average of fish abundance and sea urchin density across the survey period (2013, 2016, 2019, 2022). In instances where the data did not exhibit a normal distribution, as determined by the Kolmogorov-Smirnov test, we opted for the Kruskal-Wallis test instead.

Two-Way ANOVA was used to compare mean coral recruit among the monitoring period (2013, 2016, 2019, 2022), and zoning system (core, protection, tourism, aquaculture, traditional fisheries and open access). In addition, two-Way ANOVA was used to compare mean coral recruit among the monitoring period (2013, 2016, 2019, 2022) and depth area (shallow and deep). We tested the assumptions for parametric test, by testing the distribution of the populations, ensuring equal variances of the populations, and whether the samples are independent from each good (Ernst and Albers 2017).

Table 1. Families, genera and species within each functional group of herbivorous reef fishes (Green and Bellwood 2009)

Functional group	Family	Common name	Genera and species
Scrapers	Labridae (Scarini)	Parrotfishes	All *Scarus* and *Hipposcarus;* All *Bolbometopon*, *Cetoscarus*
Large excavators/ bioeroders	Labridae (Scarini)	Parrotfishes	All *Bolbometopon*, *Cetoscarus* and *Chlorurus*
Grazers/ detritivores	Acanthuridae	Surgeonfishes	All species except those that are planktivores (*A. albipectoralis, A. mata, A. nubilus, A. thompsoni* and *P. hepaticus*) or detritivores (*Ctenochaetus* spp.)
	Siganidae	Rabbitfishes	All species except *S. canaliculatus*
	Pomacanthidae	Angelfishes*	All *Centropyge* species
Browsers	Kyphosidae	Rudderfish	All species Family Kyphosidae
	Siganidae	Rabbitfishes	*S. canaliculatus*
	Acanthuridae	Unicornfishes	All *N. brachycentron, N. elegans, N. lituratus, N. tonganus* and *N. unicornis*
			Juveniles (<20cm) of *N. annulatus, N. brevirostris, N. maculatus, N. mcdadei*, and *N. vlamingii*
	Ephippidae	Batfishes	All species
	Labridae (Scarini)	Parrotfishes	All *Calotomus* and *Leptoscarus* species

Table 2. Methodology for data analysis of coral recruit dynamic study

Area observation	Data component	Methodology	Data analysis	Measure unit
Shallow (1-3 m); Deep (8-10 m)	Hard coral coverage	Point Intercept Transect (Hill and Wilkinson 2004)	$\frac{\sum Category\ point}{Number\ of\ point} x100\%$	%
Shallow (1-3 m); Deep (8-10 m)	Coral recruit	Quadrate Transect (Hill and Wilkinson 2004)	$\frac{\sum Genus\ colony-i}{m^2} X4$	$No.m^{-2}$
Shallow (1-3 m); Deep (8-10 m)	Fish herbivore abundance (grazer, scraper, excavator, browser)	Underwater Visual Census (Hill and Wilkinson 2004)	$\frac{\sum Number\ of\ fish}{Total\ Area}$	$No.ha^{-1}$
Shallow (1-3 m); Deep (8-10 m)	Sea urchin density	Belt Intercept Transect (Hill and Wilkinson 2004)	$\frac{\sum Number\ of\ Sea\ Urchin}{Total\ Area}$	$No.ha^{-1}$

Analysis of the relationship between herbivores species and coral recruitment

We examined factors that would influence the density of juvenile corals using multiple linear regression analysis. In the model, six predictor variables were considered: herbivores functional group abundance including (1) browser, (2) excavator, (3) grazer and (4) scraper, (5) sea urchin density, and 6) coral cover. To meet the underlying assumptions of multiple linear regression analysis, we applied data transformation for our collected data. For coral reef data, as it is in percentage form, an Angular/Arcsin transformation is performed. On the other hand, other indicator data related to fish abundance, sea urchin density, and recruitment used logarithmic transformation, which is used when data do not meet the assumption of additivity. Because many original data points show a distribution of values less than 10 or values close to zero, a Log(X + 1) transformation is used (John 2014).

In this case, the dependent variable, coral recruitment, is associated with independent variables such as hard coral cover, macroalgae cover, the overall abundance of herbivorous fish, the abundance of scrapers or small excavator fish, the abundance of large excavator/bioerodes fish, the abundance of grazers/detritivores fish, the abundance of browser fish, and sea urchin density. In conducting multiple linear regression analysis, we ensure fulfilling several conditions, which are: (i) the errors or residuals are normally distributed, (ii) there is no multicollinearity, (iii) there is no heteroskedasticity, and (iv) there is no autocorrelation (Ernst and Albers 2017).

Principal Component Analyses (PCA) were used to investigate variation in the benthic community composition and herbivorous fish assemblages among sites and period. The analyses were based on the covariance matrix of the mean proportion of each variable, namely herbivores functional group abundance (browser, excavator, grazer and scraper), sea urchin density, hard coral coverage and water depth in each habitat within each site, respectively. Overall research diagram flow is shown in the Figure 2.

RESULTS AND DISCUSSION

Coral recruit density

In general, we found a significant decrease of coral recruitment density from 2013 to 2022 (two-way ANOVA test, $F_{(3,5)} = 20.558$, $p = 0.000$). Coral recruit density was significantly different between the years 2013-2019, 2013-2022, 2016-2019, and 2016-2022. Overall, the highest average recruitment value was found in 2013 compared to all other observation periods. In 2013, the average recruitment value decreased from 5.67± 0.30 SE ($no.m^{-2}$) to 4.24 ± 0.21 SE ($no.m^{-2}$) in 2016. Meanwhile, coral recruitment density in 2019 also decreased from 3.37 ± 0.23 SE ($no.m^{-2}$) to 3.09 ± 0.20 SE ($no.m^{-2}$) in 2022. Observations based on zoning systems found that coral recruitment density showed dynamic pattern in each observation year.

Coral recruit density decreased significantly in several zones between period 2013 and 2016, such as the core zone, tourism zone, rehabilitation, traditional fishing zone, and outside area. The only exception was for the outside area, which experienced an increase in coral recruit density in 2016. Between period 2019 and 2022, there was a slight increase in the density of coral recruitment. Rehabilitation and protection zones showed a slight increase in coral recruit density, while in contrast, traditional fisheries and tourism zones showed slight decrease of coral recruit density. Meanwhile, coral recruit density remained steady in the core zone. Two-way ANOVA results indicated that the coral recruitment density was not significantly different between the zoning system (two-way ANOVA test, $F_{(3,5)} = 0.490$, $p = 0.784$). Meanwhile, differences in coral recruitment density between depths showed that coral recruitment density in deeper waters had a significantly higher value than in shallow depths (two-way ANOVA test, $F_{(3,1)} = 16.64$, $p = 0.000$; Figure 3).

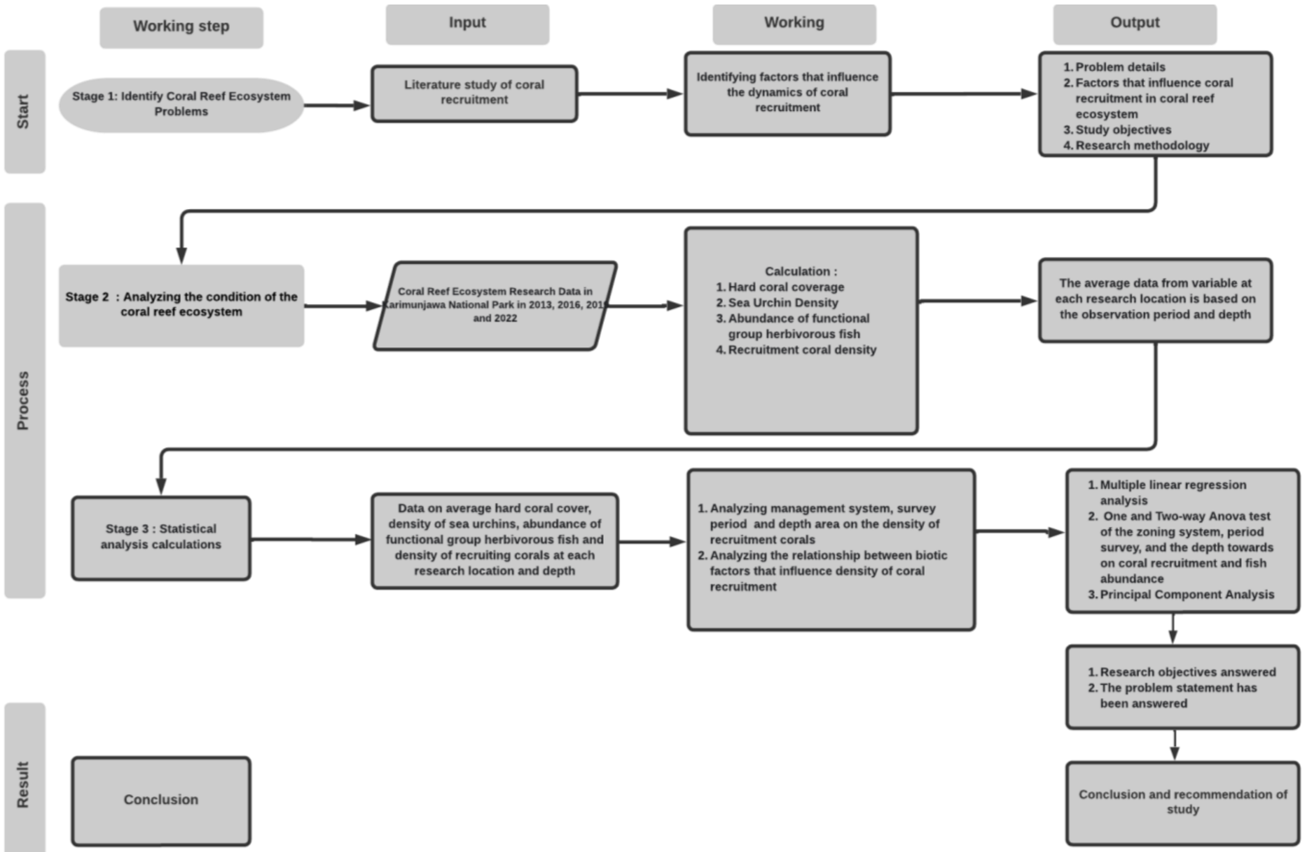

Figure 2. Research flow diagram of dynamic of coral recruit in Karimunjawa National Park, Jepara District, Central Java, Indonesia

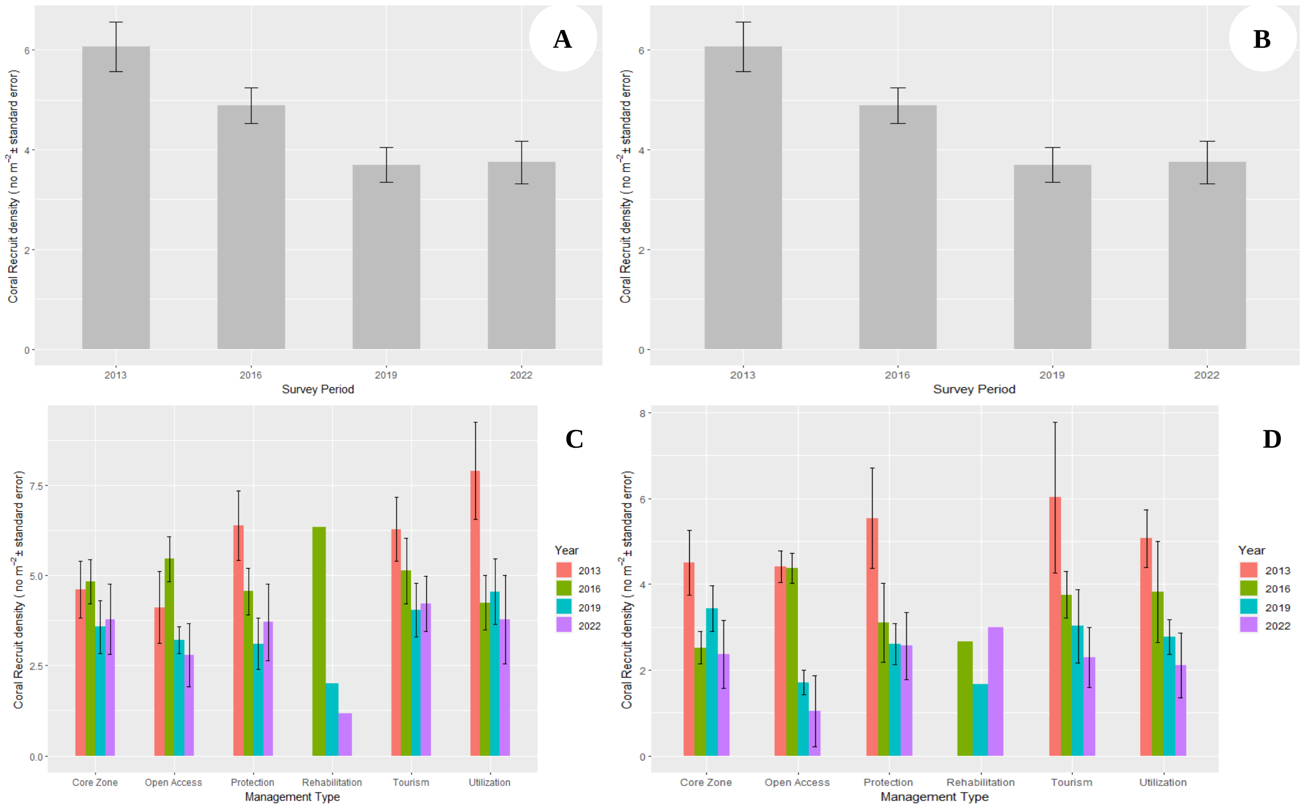

Figure 3. Coral recruit density based on survey period (A: Deep; B: Shallow) and zoning system (C: Deep; D: Shallow) in Karimunjawa National Park, Jepara District, Central Java Province, Indonesia

Fish herbivore abundance and sea urchin density

In Karimunjawa, the predominant functional groups within herbivorous fish community are followed by scraper, excavator, and browser groups. Scraper abundance accounting for the shallow area were 1345.5 ± 244.27 SE ($no.ha^{-1}$), 840 ± 123.10 SE ($no.ha^{-1}$), 474.63 ± 69.99 SE ($no.ha^{-1}$), and 317.72 ± 57.04 SE ($no.ha^{-1}$) in the periods of 2013, 2016, 2019, and 2022, respectively, with significant decrease between the period 2013-2022, 2016-2022 and 2019-2022 (one way ANOVA test, $F_{(3,159)}$=10.29; p=0.000). Meanwhile in the deeper area, scraper abundance were 302.06 ± 58.28 SE ($no.ha^{-1}$), 247.13± 39.10 SE ($no.ha^{-1}$), 200.62 ± 4.84 SE ($no.ha^{-1}$) and 199.84 ± 37.77 SE ($no.ha^{-1}$) in the periods of 2013, 2016, 2019, 2022, respectively with no significant difference among the periods (one way ANOVA test, $F_{(3,159)}$=0.656; p=0.581). These fish groups were decreasing in all of the zoning system and in the shallow area across survey period. Browser group abundance in the shallow area were 139.16 ± 27.89 SE ($no.ha^{-1}$), 94.79 ± 13.81 SE ($no.ha^{-1}$), 179.18 ± 33.94 SE ($no.ha^{-1}$), and 252.19 ± 76.13 SE ($no.ha^{-1}$) for years 2013, 2016, 2019, and 2022, respectively with no significant difference between the survey period (one-way ANOVA test, $F_{(3,159)}$=0.625; p =0.6).

Meanwhile, browser abundance in the deep area were 116.82 ±38.88 SE ($no.ha^{-1}$), 148.37 ± 103.54 SE ($no.ha^{-1}$), 139.53 ± 47.50 SE ($no.ha^{-1}$) and 135.96 ± 29.04 SE (no.ha) respectively with no significant difference across the survey period (one-way ANOVA test, $F_{(3,159)}$=1.533; p = 0.208). Excavator group abundance in the shallow area were 311.83 ± 40.59 SE ($no.ha^{-1}$), 223.57 ± 20.64 SE ($no.ha^{-1}$), 204.71 ± 29.12 SE ($no.ha^{-1}$) and 146.34 ± 18.13 SE (no.ha) respectively, both with significant decrease in the periods of 2013-2019 and 2013-2022 (one-way ANOVA test, $F_{(3,159)}$=5.619; p =0.001). Meanwhile, excavator abundance in the deeper area was 139.16 ± 25.47 SE ($no.ha^{-1}$), 101.70 ± 26.40 SE ($no.ha^{-1}$), 179.18 ± 18.43 SE ($no.ha^{-1}$) and 114.10 ± 12.17 SE ($no.ha^{-1}$) respectively, with a significant decrease between the periods of 2013-2016 (one way ANOVA test, $F_{(3,159)}$ = 3.391; p = 0.019). The results of the grazing group due to its low abundance in this study were excluded from the research results. Overall, the abundance of those groups, namely scraper and excavator are decreasing after 2016, especially in shallow area, in contrast with the abundance of browser group which shows an increase especially in shallow area after 2016 (Figure 4).

The sea urchin density in shallow waters were 476.87 ± 136 SE ($no.ha^{-1}$), 1566.25 ± 567.94 SE ($no.ha^{-1}$), 1241.63 ± 430.71 SE ($no.ha^{-1}$), 1375 ± 465.25 SE ($no.ha^{-1}$), respectively (2013-2022) with significant increase between period 2013-2019 (one way ANOVA test, $F_{(1,154)}$ = 5.619; p = 0.007). Meanwhile, the sea urchin density in deeper waters were 130.95 ± 48.31 SE ($no.ha^{-1}$), 211.62 ± 109.62 SE ($no.ha^{-1}$), 190.11 ± 42.52 SE ($no.ha^{-1}$), and 168.02 ± 51.39 SE ($no.ha^{-1}$) respectively (2013-2022) with significant increase between period 2013-2019 and 2016-2019 (one way ANOVA test, $F_{(1,157)}$ = 7.119; p = 0.008). We also found a higher density of sea urchins in shallow depths compared to deeper depths throughout the observation period. In general, we found the highest of fish abundance for two fish herbivores groups, namely scraper and excavator, in 2013. In contrast, the abundance of browser and the density of sea urchin were the lowest in this year. In the next period, the decline in scraper and excavator groups remains consistent across all zones, especially within shallow areas during the survey period. However, the browser group shows stability throughout most of the survey period. Concurrently, there is a noteworthy trend of increasing sea urchin population observed in the last survey period especially in the shallow area (Figure 4).

Dynamics of coral recruits

In 2013, in the shallow depths, the relationship was expressed as Y(coral recruit) = (-0.24) + 0.01(browser) + 0.25(excavator) + 0.01(grazer) - 0.021(scraper) + 0.43(hard coral) + 0.06(sea urchin). This indicates that if the excavator group increases by 1%, recruitment density will increase by 0.25, assuming that other independent variables remain constant. Similarly, if the sea urchin variable increases by 1%, recruitment density will also increase by 0.06. The relationship for hard coral cover was also observed, where if hard coral cover increases by 1%, recruitment density will increase by 0.43, although this relationship is minimal based on the analysis. Projection of the variables on the factor plane revealed that the 1st and the 2nd axes of the PCs explained 26.9 and 23.4%, meanwhile the 3rd axes of the PCs explained 18.4% of the total variance. The correlation analysis showed the positive relationship among the variables of coral recruitment with excavator fish abundance (0.25), hard coral coverage (0.28) and sea urchin density (0.23) (Figure 5).

In 2019, in the shallow depths, only the scraper group provided a negative predictor for recruitment density (p <0.1). The relationship was expressed as Y (coral recruit) = 0.73 - 0.0001(browser) + 0.017(excavator) + 0.04(grazer) - 0.14(scraper) + 0.07(hard coral) + 0.009 (sea urchin). This indicates that if the scraper group increased by 1%, recruitment density will decrease by 0.14, assuming that other independent variables remain constant. Projection of the variables on the factor plane revealed that the 1st and the 2nd axes of the PCs explained 35.7 and 18%, meanwhile the 3rd axes of the PCs explained 13.8% of the total variance. The correlation analysis axis showed the negative relationship between scraper abundance with coral recruitment (-0.34) (Figure 6).

In 2022, in the shallow depth, the hard coral group provided a negative predictor (p <0.01) for recruitment density in both shallow and deeper depths. The relationship was expressed as Y (coral recruit) = (1.32) + 0.06(browser) - 0.006(excavator) + 0.01(grazer) - 0.08(scraper) - 0.93(hard coral) + 0.01(sea urchin). This indicates that if the hard coral cover group increases by 1%, recruitment density will decrease by 0.93, assuming that other independent variables remain constant. Projection of the variables on the factor plane revealed that the 1st and the 2nd axes of the PCs explained 27.2 and 20.7%, meanwhile the 3rd axes of the PCs explained 17.3% of the total variance. The correlation analysis axis showed the negative relationship between hard coral variable with coral recruitment (-0.42) (Figure 7).

In 2022, in the deeper depths, the hard coral group provided a negative predictor (p <0.01) for recruitment density, and the browser group provided a positive predictor for recruitment density (p <0.1). The relationship was expressed as Y (coral recruit) = (1.64) + 0.15(browser) - 0.13(excavator) - 0.04(grazer) - 0.09(scraper) - 0.92(hard coral) + 0.006(sea urchin). This indicates that if the hard coral cover group increases by 1%, recruitment density will decrease by 0.92, assuming that other independent variables remain constant, while if the browser group increase by 1%, recruitment density will increase by 0.15. Projection of the variables on the factor plane revealed that the 1st and the 2nd axes of the PCs explained 26.5% and 22.3%, meanwhile the 3rd axes of the PCs explained 16.2% of the total variance. There was a negative correlation between coral recruitment with hard coral coverage (-0.48) and positive correlation between coral recruitment with browser fish abundance (0.18) (Figure 8). Overall, the positive relationships among the variables towards coral recruitment were observed for the excavator species group, hard coral coverage and sea urchins which we found in shallow area, in 2013. In addition, other positive correlation was also observed for the browser group which we found in deeper area in 2022. In contrast, the negative relationships among the variables towards coral recruitment were observed for the scraper group, which we found in shallow area in 2019 and hard coral coverage which we found in both shallow and deep area in 2022. Meanwhile we found no relationship among the variables on coral recruit in period 2016 (Tables 3 and 4).

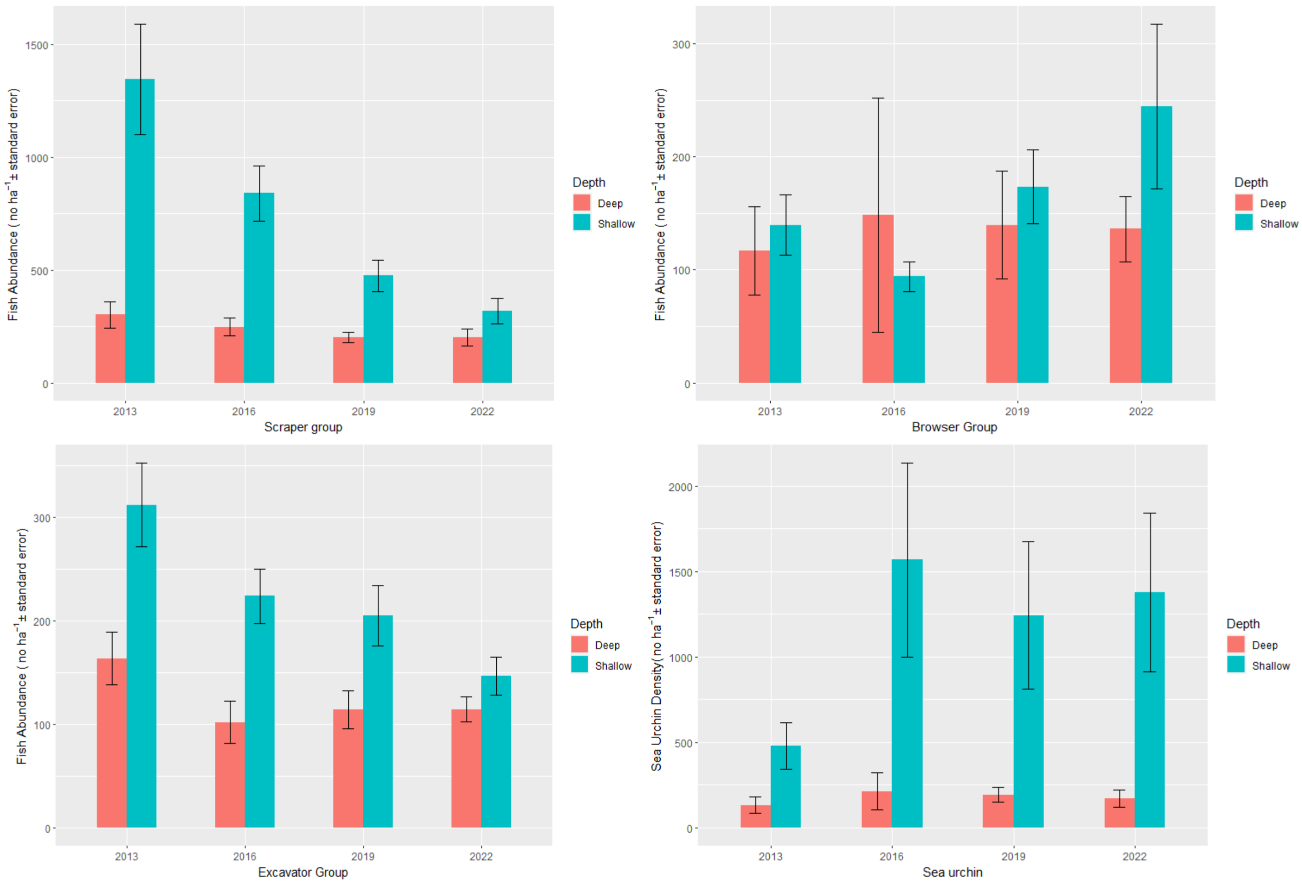

Figure 4. Herbivore fish abundance groups and urchin density based on depth area in period 2013-2022 in Karimunjawa National Park, Jepara District, Central Java Province, Indonesia

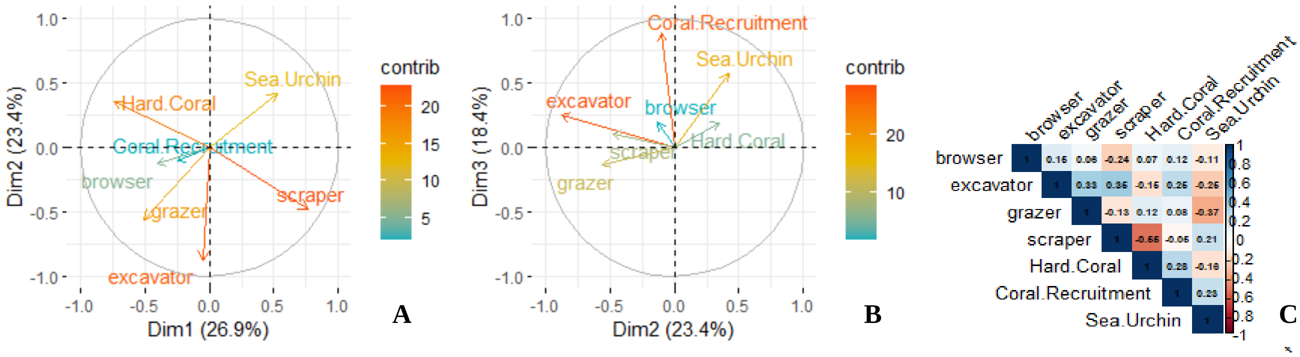

Figure 3. Ordination plot of PCA (A-B) and correlation factor (C) in shallow area for period 2013

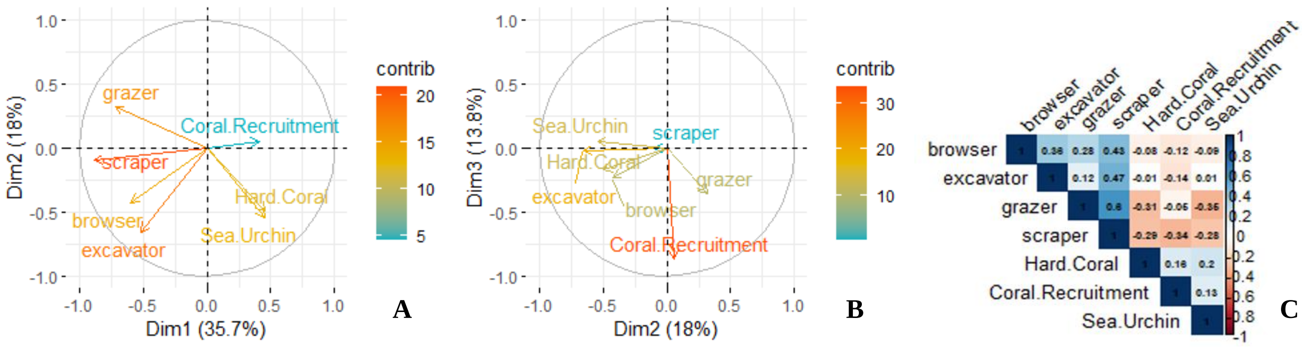

Figure 4. Ordination plot of PCA (A-B) and correlation factor (C) in shallow area for period 2019

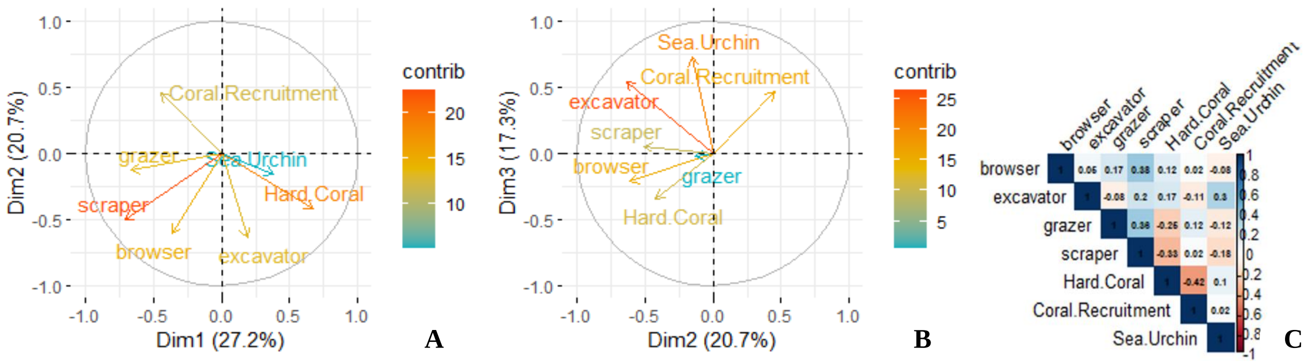

Figure 5. Ordination plot of PCA (A-B) and correlation factor (C) in shallow area for the period 2022

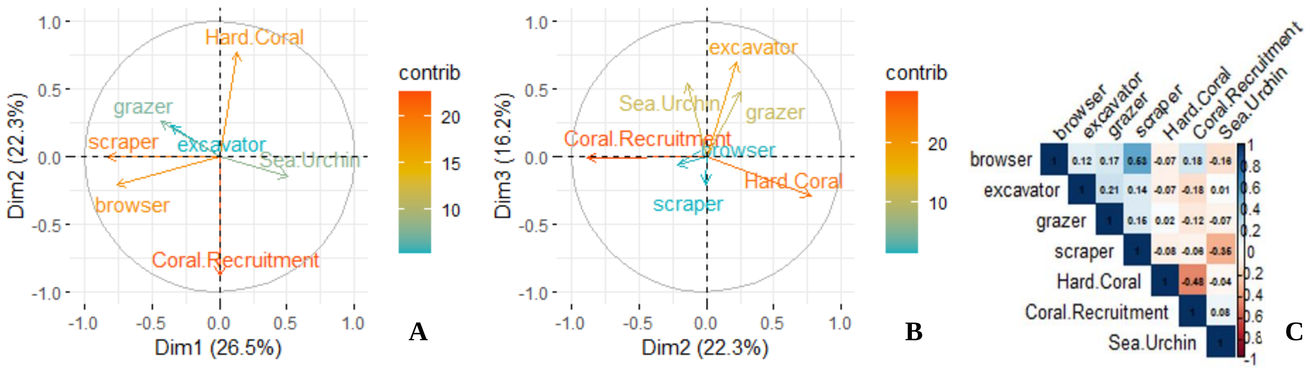

Figure 8. Ordination plot of PCA (A-B) and correlation factor (C) in deep area for period 2022

Table 3. Results of multiple linear regression analysis between the independent variables of groups of herbivorous fish, sea urchins and hard corals on the response variable of coral recruits from period 2013 to 2022 in shallow area

Variables	2013		2016		2019		2022	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
Browser	0.015	NS	-0.006	NS	-0.000	NS	0.067	NS
Excavator	0.250	***0.034 ****	-0.122	NS	0.017	NS	-0.006	NS
Grazer	0.013	NS	-0.048	NS	0.049	NS	0.017	NS
Scraper	-0.026	NS	-0.082	NS	-0.144	***0.068.***	-0.081	NS
Hard coral	0.433	***0.057.***	0.034	NS	0.077	NS	-0.937	***0.006*****
Sea urchin	0.067	***0.016 ****	-0.017	NS	0.009	NS	0.013	NS

Note: Signif. codes: <0 '***' <0.001 '**' <0.01 '*' <0.05 '.' <0.1 ' ' NS = Not significant

Table 4. Results of multiple linear regression analysis between the independent variables of groups of herbivorous fish, sea urchins and hard corals on the response variable of coral recruits from period 2013 to 2022 in deep area

Variables	2013		2016		2019		2022	
	Estimate	p	Estimate	p	Estimate	p	Estimate	p
Browser	-0.011	NS	-0.027	NS	0.008	NS	0.151	***0.069*** .
Excavator	-0.075	NS	-0.044	NS	0.062	NS	-0.134	NS
Grazer	-0.049	NS	-0.038	NS	-0.067	NS	-0.042	NS
Scraper	0.085	NS	-0.067	NS	-0.062	NS	-0.096	NS
Hard Coral	-0.187	NS	-0.095	NS	0.062	NS	-0.922	***0.000 ******
Sea Urchin	-0.024	NS	-0.002	NS	0.027	NS	0.006	NS

Note: Signif. codes: <0 '***' <0.001 '**' <0.01 '*' <0.05 '.' <0.1 ' ' NS = Not significant

Discussion

Coral recruit density

The present study demonstrated that coral recruit density exhibited an elevated presence in deeper waters compared to shallower depths between 2013 and 2022. Furthermore, there is a discernible decreasing trend in coral recruit density over the monitored period. This finding begs the question whether the shift of the coral recruit density might be influenced by tourism activities and coral bleaching event. Several studies have reported that direct contact of tourist such as stepping, and standing on coral reef had negative impact by damaging coral reef ecosystem especially in the shallow area (Aldyan et al. 2023; Wijaya et al. 2021; Satya et al. 2023) In the context of the impact of tourism activities, according to a study which assessed the coral damage in year 2016, coral damage was significantly higher in 2016 compared to 2020, when tourism was closed due to the pandemic (Rimayanti et al. 2020). Meanwhile, in 2016, el Nino event in the Pacific Ocean, could affect the Karimunjawa and Kemujan islands. In May 2016, the sea surface temperatures on the islands rose by 2° C, resulting coral bleaching in Karimunjawa, with the *Acropora* genus being the most severely affected. Approximately 26% experienced mortality, 29% underwent bleaching, and 44% turned pale (Elvan Ampou et al. 2017; Trihatmoko et al. 2024; Pardede et al. 2016). Furthermore, other research found that in 2016 the analysis showed a slight decrease in the average coral cover from 29.2 ± 0.12% SD in 2014 to 26.3 ± 0.10% SD in 2018, before and after coral mass bleaching event (Kennedy et al. 2020).

In the last period of monitoring in 2022, coral recruitment tend to be stable both in shallow and deep area compared with 2019. This finding suggest that there is a potential recovery of coral reef ecosystems within KNP. A case study in Amitori Bay, Iriomote Island, Japan reported that after a bleaching event, coral reef ecosystem has a potential for rapid recovery which is driven by a combination of larval supply from other populations, increased numbers of reproductive adults, increased spawning rates, and increased larval retention due to wind conditions (Nakamura et al. 2022). While the zoning system has not yet had an impact on the protection of coral recruits, it serves as a note to strengthen and build specific regulations for the protection of coral recruits, especially in no take areas or area supply larva of coral within KNP, as an effort and mitigation for safeguarding against the threats from climate change and anthropogenic activities.

Fish herbivore abundance and sea urchin density

Scraper and excavator abundance appear to be highest in 2013 and then continue to decrease until 2022. Meanwhile, browser group abundance and sea urchin density showed an increased over the monitoring period, especially in shallow area. During 2013, in the management context, there was a change in the rules governing Karimunjawa National Park. The practice of large-net fishing, or known as *muroami* fishing, which was known to harm coral reef ecosystems because it involved fishermen walking on top of coral reefs, was discontinued in 2010. The decision to stop *muroami* fishing was linked to a decrease in fish catches for handline-caught groupers decreased between 2003 and 2011, from 6.9 (SE 2.8) to 0.8 (SE 0.1) kg trip^{-1} and increased law enforcement efforts by Karimunjawa National Park, aimed at promoting sustainable fishing practices (Campbell et al. 2013; Yulianto et al. 2015). After 2016, scraper and excavator decreased in shallow area, but browser tend to be increasing in shallow area (Pardede et al. 2016).

A study has reported that in Karimunjawa, the stock status of herbivore fish especially from parrot fish species, *Scarus niger*, is in fully moderate condition, *Chlorurus sordidus* is in under exploited condition, while the utilization status of parrot fish species *Bolbometopon muricatum* is in over exploited condition (Pangestu 2021). This fishing pressure might be a reason for the decrease of those groups, namely scraper and excavator after 2016. Meanwhile, The dominance of browser group was due to *Siganus* sp., which is not a target fishing activities in KNP (Marliana et al. 2022). During the period 2013 to 2022, sea urchin density tend to be increasing. Several environmental factors such as water temperature, food availability, nutrient levels, ecosystem sustainability, and other factors can influence the sea urchin population. Studies on the relationship between sea urchin abundance and water nutrient levels, such as nitrate and phosphate, in Karimunjawa, revealed a strong correlation (r=0.64) (Suryanti et al. 2018). The increase in nutrient enrichment activities from the land is identified as one of the factors contributing to the higher density of sea urchins in Karimunjawa, especially in shallow area. Overall, the zoning system has not yet had an impact on the protection of herbivore fishes. In general, only browser group showed an increase of abundance in the shallow area especially in the core, utilization and tourism zones in the last period of monitoring. This finding suggests that strengthening specific regulation to promote fishing regulation of these herbivore groups as a mitigation strategy to also address climate change and anthropogenic event in the future.

Dynamics of coral recruits

The results of this study highlights the importance of fisheries management within MPA in maintaining herbivory dynamics and regulating ecosystem processes to facilitate coral recruitment in KNP. Specifically, in 2013, the results were linked to the grazer assemblages found when the management was successful to manage their ecosystem and conservation target within KNP through law enforcement and increasing the community participation. Following these regulations, the abundance of herbivore fish species doubled compared to 2012 and remained high in 2013 in all management systems (Bejarano et al. 2019). This finding also supported by the research in Kenya that found fisheries management played a crucial role in shaping herbivory dynamics, which, in turn, regulates key ecosystem processes such as algal biomass, primary production, and competition among benthic organisms like algae and corals. The primary herbivores in this context are sea urchins and herbivorous fishes (scrapers, grazers, browsers). Their grazing activities significantly impacted the dynamics and dominance of corals and macroalgae that eventually will prevent macroalgal phase shifts which ultimately provide space for coral recruitment mechanisms (Humphries et al. 2014). A study by Dang et al. (2020) in Taiwan found a positive relationship between sea urchin density and coral recruitment. In this study, sea urchin responded to the availability of food sources and the absence of competitors and predators in the coral reef ecosystem, as herbivorous fish occupy the same ecological niche in that ecosystem. Meanwhile, other studies found that low density of sea urchin tends to positively contribute to coral resilience; conversely, at high densities, sea urchin can erode much of the live coral and dead coral framework, which ultimately has a negative impact on coral recruitment (Ditzel et al. 2022). These findings seem to provide an explanation for our research results, where sea urchin density in 2013 was the lowest density compared to other periods of survey monitoring.

The positive relationship between coral recruitment and the coverage of hard coral found is believed to be due to the abundance of coral larvae that settle on the coral reefs (Couch et al. 2023). Based on research conducted in the Northwest Philippines (Harrison et al. 2021), coral cover significantly increased in the larva-supplied plot compared to the control plot, especially through the recruitment and growth of *A. tenuis*. The relationship between adult acroporid corals and their recruits seems to be influenced by the dispersal range and pre-competency period of the larvae, exhibiting a density-dependent pattern. This implies that the relationship between the number of acroporid adults and recruits is influenced by the density of individuals in the population (Muhammad Faiz et al. 2017). This is supported by the evidence that KNP is one of the important locations for the multi-species *Acropora* coral spawning, which is the dominant species based on the composition of coral recruit species (Wijayanti et al. 2019).

In 2019, a negative correlation was observed not only for scrapers but also for browsers and excavators, although the associations were notably weak. During this period, the study reported that coral bleaching events predominantly lead to a decline in coral reproductive capacity. Colonies that had recovered exhibited significantly lower energy reserves compared to those resilient to damage. Moreover, coral bleaching impacted their reproductive capabilities, with recovered colonies having a lower likelihood of containing gametes (reproductive cells) and producing fewer offspring per polyp (an individual part of a coral's body) (Leinbach et al. 2021). Typically, changes in benthic community structure post-coral bleaching events are characterized by substantial coral loss and an increase in algae. The findings revealed a consistent pattern of increased herbivorous fish, but with the ongoing reduction in hard coral coverage and the loss of structural complexity, the abundance of herbivorous fish is expected to decline in the long run. Post-bleaching events often show both increases and decreases in algae, along with a decrease in sea urchin density across reef locations (Elma et al. 2023). Meanwhile, it was also discovered that when herbivorous fish biomass and diversity are relatively low, macroalgal communities can evade herbivore control by experiencing increased growth (Doropoulos et al. 2013). This situation aligns with the monitoring results of the coral reef in KNP in 2016, indicating a decrease in herbivorous species from the scraper group, a reduction in hard coral coverage, and a decline in sea urchin density. In contrast, there was an increase in algal coverage (Pardede et al. 2016). The information clearly answer the negative relationship between scraper and coral recruitment which we found in this study.

In 2022, a negative correlation was observed between coral recruitment density and hard coral cover in both shallow and deep waters. A study conducted in Derawan, Kalimantan revealed a negative relationship between hard coral coverage and coral recruitment. Coral recruitment density was high at stations with low coral coverage. Conversely, coral recruitment density was low at stations with high hard coral coverage. In areas with high coral coverage, juvenile corals that attached to the substrate must compete for space and nutrients with other organisms in the coral reef ecosystem, including competition with the hard corals themselves (Giyanto et al. 2023). Our findings were consistent with the study, as we speculate that the hard coral cover was recorded at 65.43% (±2.08 SE) in deep depths and 64.70% (±2.35 SE) in shallow depths during the 2022 period. This contrasts with the positive correlation observed in 2013 at shallow depths, where the average hard coral cover was 50.26% (±2.60 SE) (Muhidin et al. 2022). We suspect that this negative relationship results in reduced coral damage, indicated by an increase in hard coral coverage, consequently reducing the available space for coral recruitment. We also speculate that this cause is attributed to the decreased tourism activities, as during the period of 2020-2021, tourism was halted due to the COVID-19 pandemic. Meanwhile, the positive relationship occurred between coral recruit and abundance of browser group. This is supported by study at Kenyan Reef that found that browse group namely unicorn fishes (*Naso spp.)* and scraping parrotfishes as the main contributors to macroalgae removal (Knoester et al. 2023).

According our research, the zoning system has not yet had an impact on the protection of coral recruitment. Meanwhile, coral recruitment dynamics were positively influenced by the presence of herbivore species in shallow areas in 2013 and deep areas in 2022. However, this relationship was not always the dominant factor affecting coral recruitment. Anthropogenic activities and climate change could also have a significant impact on coral recruitment dynamics in KNP. The long-term survival of coral communities depends on their ability to recover and rebuild after disturbances. This relies on two crucial factors: continuous addition of new coral individuals through larval recruitment, and availability of suitable surfaces for young corals to settle on and grow. In this context, herbivorous species that control macroalgal growth are vital for supporting process of recruitment coral. Interestingly, sea urchin also contribute positively to coral recruitment in KNP. This species provides benefits in the efficiency of conservation efforts, considering that species like *Diadematidae* are often not the target of fishing activities. However, more information is needed to realize the full potential of sea urchin to support recruitment process in coral reef management. We suggest that managers and stakeholders develop a conservation strategy focused on protecting herbivorous fish species by incorporating them as conservation targets, conducting surveys to monitor these species, and implementing fisheries regulations for herbivore species within the zoning system and strengthening collaboration between government authorities, local communities and academics.

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REFERENCES

Adam TC, Burkepile DE, Ruttenberg BI, Paddack MJ. 2015. Herbivory and the resilience of Caribbean coral reefs: Knowledge gaps and implications for management. Mar Ecol Prog Ser 520: 1-20. DOI: 10.3354/meps11170.

Adjeroud M, Kayal M, Iborra-Cantonnet C, Vercelloni J, Bosserelle P, Liao V, Chancerelle Y, Claudet J, Penin L. 2018. Recovery of coral assemblages despite acute and recurrent disturbances on a South Central Pacific reef. Sci Rep 8 (1): 1-8. DOI: 10.1038/s41598-018-27891-3.

Aldyan RA, Budiastuti MTSS, Warto W, Wiwik W. 2023. Impact of coral reef damage due to tourism activities in Karimunjawa National Park. E3S Web Conf 448: 03063. DOI: 10.1051/e3sconf/202344803063.

Bejarano S, Pardede S, Campbell SJ, Hoey AS, Ferse SCA. 2019. Herbivorous fish rise as a destructive fishing practice falls in an Indonesian marine national park. Ecol Appl 29 (8): e01981. DOI: 10.1002/eap.1981.

Campbell SJ, Kartawijaya T, Yulianto I, Prasetia R, Clifton J. 2013. Co-management approaches and incentives improve management effectiveness in the Karimunjawa National Park, Indonesia. Mar Policy 41: 72-79. DOI: 10.1016/j.marpol.2012.12.022.

Chung AE, Wedding LM, Green AL, Friedlander AM, Goldberg G, Meadows A, Hixon MA. 2019. Building coral reef resilience through spatial herbivore management. Front Mar Sci 6: 98. DOI: 10.3389/fmars.2019.00098.

Couch CS, Oliver TA, Dettloff K, Huntington B, Tanaka KR, Vargas-Ángel B. 2023. Ecological and environmental predictors of juvenile coral density across the central and western Pacific. Front Mar Sci 10. DOI: 10.3389/fmars.2023.1192102.

Dajka J-C, Wilson SK, Robinson JPW, Chong-Seng KM, Harris A, Graham NAJ. 2019. Uncovering drivers of juvenile coral density following mass bleaching. Coral Reefs 38: 637-649. DOI: 10.1007/s00338-019-01785-w.

Dang VDH, Cheung P-Y, Fong C-L, Mulla AJ, Shiu J-H, Lin C-H, Nozawa Y. 2020. Sea urchins play an increasingly important role for coral resilience across reefs in Taiwan. Front Mar Sci 7: 581945. DOI: 10.3389/fmars.2020.581945.

Ditzel P, König S, Musembi P, Peters MK. 2022. Correlation between coral reef condition and the diversity and abundance of fishes and sea urchins on an East African Coral Reef. Oceans 3 (1): 1-14. DOI: 10.3390/oceans3010001.

Do Hung Dang V, Fong CL, Shiu JH, Nozawa Y. 2020. Grazing effects of sea urchin *Diadema savignyi* on algal abundance and coral recruitment processes. Sci Rep 10 (1): 1-9. DOI: 10.1038/s41598-020-77494-0.

Doropoulos C, Hyndes GA, Abecasis D, Vergés A. 2013. Herbivores strongly influence algal recruitment in both coral- and algal-dominated coral reef habitats. Mar Ecol Prog Ser 486: 153-164. DOI: 10.3354/meps10325.

Elma E, Gullström M, Yahya SAS, Jouffray JB, East HK, Nyström M. 2023. Post-bleaching alterations in coral reef communities. Mar Pollut Bull 186: 114479. DOI: 10.1016/j.marpolbul.2022.114479.

Elvan Ampou E, Johan O, Menkes CE, Niño F, Birol F, Ouillon S, Andrefouet S. 2017. Coral mortality induced by the 2015-2016 El-Niño in Indonesia: The effect of rapid sea level fall. Biogeosciences 14 (4): 817-826. DOI: 10.5194/bg-14-817-2017.

El-Naggar HA. 2021. Human impacts on coral reef ecosystem. Natural Resources Management and Biological Sciences. IntechOpen. DOI: 10.5772/intechopen.88841.

Ernst AF, Albers CJ. 2017. Regression assumptions in clinical psychology research practice-a systematic review of common misconceptions. PeerJ (5): 1-16. DOI: 10.7717/peerj.3323.

Gilmour JP, Smith LD, Heyward AJ, Baird AH, Pratchett MS. 2013. Recovery of an isolated coral reef system following severe disturbance. Science 340 (6128): 69-71. DOI: 10.1126/science.1232310.

Giyanto, Dewi R, Azkiyah BU. 2023. Coral recruitment and its relationship to hard coral cover in the Derawan Islands, East Kalimantan. IOP Conf Ser: Earth Environ Sci 1137: 012001. DOI: 10.1088/1755-1315/1137/1/012001.

Gouezo M, Olsudong D, Fabricius K, Harrison P, Golbuu Y, Doropoulos C. 2020. Relative roles of biological and physical processes influencing coral recruitment during the lag phase of reef community recovery. Sci Rep 10: 2471. DOI: 10.1038/s41598-020-59111-2.

Green AL, Bellwood DR. 2009. Monitoring functional groups of herbivorous reef fishes as indicators of coral reef resilience a practical guide for coral reef managers in the Asia Pacific Region. IUCN working group on Climate Change and Coral Reefs. IUCN, Gland, Switzerland.

Harrison PL, dela Cruz DW, Cameron KA, Cabaitan PC. 2021. Increased coral larval supply enhances recruitment for coral and fish habitat restoration. Front Mar Sci 8: 750210. DOI: 10.3389/fmars.2021.750210.

Hill J, Wilkinson C. 2004. Methods for ecological monitoring of coral reefs. In Australian Institute of Marine Science, Townsville. DOI: 10.1017/CBO9781107415324.004.

Hoegh-Guldberg O, Poloczanska ES, Skirving W, Dove S. 2017. Coral reef ecosystems under climate change and ocean acidification. Front Mar Sci 4: 158. DOI: 10.3389/fmars.2017.00158.

Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Baird AH, Baum JK, Berumen ML, Bridge TC, Claar DC. 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359 (6371): 80-83. DOI: 10.1126/science.aan8048.

Humphries AT, McClanahan TR, McQuaid CD. 2014. Differential impacts of coral reef herbivores on algal succession in Kenya. Mar Ecol Prog Ser 504: 119-132. DOI: 10.3354/meps10744.

Isdianto A, Kurniawan A, Wicaksono AD, Marhaendra QNI, Putri BM, Fathah AL, Asadi MA, Luthfi OM, Pratiwi DC, Harahab N. 2023. Observation of coral reef and macroalgae competition in the Sempu Strait, Malang. J Ecol Eng 24 (10): 174-184. DOI: 10.12911/22998993/170246.

John HM. 2014. Handbook of Biological Statistics (Third Edit). Sparky House Publishing Baltimore, Maryland, U.S.A.

Kennedy EV, Vercelloni J, Neal BP, Ambariyanto, Bryant DE, Ganase A, Gartrell P, Brown K, Kim CJ, Hudatwi MA, Hadi A. 2020. Coral reef community changes in Karimunjawa National Park, Indonesia: Assessing the efficacy of management in the face of local and global stressors. J Mar Sci Eng 8 (10): 760. DOI: 10.3390/jmse8100760.

Knoester EG, Plug VE, Murk AJ, Sande SO, Osinga R. 2023. Fisheries restrictions and their cascading effects on herbivore abundance and macroalgae removal at Kenyan coral reefs. J Exp Mar Bio Ecol 559: 151850. DOI: 10.1016/j.jembe.2022.151850.

Leinbach SE, Speare KE, Rossin AM, Holstein DM, Strader ME. 2021. Energetic and reproductive costs of coral recovery in divergent bleaching responses. Sci Rep 11 (1): 1-10. DOI: 10.1038/s41598-021-02807-w.

Marliana I, Nur A, Gunar F, Tarigan SAR, Pardede ST, Kartawijaya T. 2022. Technical report: monitoring catch data collection in Karimunjawa National Park (2017 - 2022). Wildlife Conservation Society, Bogor. [Indonesian]

Mcleod E, Anthony KR, Mumby PJ, Maynard J, Beeden R, Graham NA, Heron SF, Hoegh-Guldberg O, Jupiter S, MacGowan P, Mangubhai S. 2019. The future of resilience-based management in coral reef ecosystems. J Environ Manag 233: 291-301. DOI: 10.1016/j.jenvman.2018.11.034.

Muhammad Faiz MH, Saad S, Mukai Y, Ahmad Z. 2017. Relationship between adult abundance and successive coral recruitment density in the Tioman Island Marine Park, Malaysia. Zool Ecol 27 (3-4): 328-334. DOI: 10.1080/21658005.2017.1396793.

Muhidin, Rizki PH, Pardede S. 2022. Karimunjawa Coral Reef Ecosystem Monitoring Brief Report 2022. Wildlife Conservation Society, Bogor. [Indonesian]

Mumby PJ, Flower J, Chollett I, Box SJ, Bozec YM, Clare Fitzsimmons JF, Gill D, Griffith-Mumby R, Oxenford HA, Peterson AM, Stead SM, Turner, RA, Townsley PB, PJH van, Williams SM. 2014. Towards reef resilience and sustainable livelihoods. In A Handbook for Caribbean Coral Reef Managers. University of Exeter, UK.

Nakamura M, Murakami T, Kohno H, Mizutani A, Shimokawa S. 2022. Rapid recovery of coral communities from a mass bleaching event in the summer of 2016, observed in Amitori Bay, Iriomote Island, Japan. Mar Biol 169 (8): 1-9. DOI: 10.1007/s00227-022-04091-2.

Nozawa Y, Lin C-H, Meng P-J. 2020. Sea urchins (diadematids) promote coral recovery via recruitment on Taiwanese reefs. Coral Reefs 39 (4): 1199-1207. DOI: 10.1007/s00338-020-01955-1.

Pangestu HA. 2021. Spawning potential ratio approach for estimating the status of cockatoo fisheries utilisation in Karimunjawa Waters. [Dissertation]. IPB University, Bogor. [Indonesian]

Pardede S, Tarigan SAR, Setiawan F, Muttaqin E, Muttaqin A. 2016. Technical report: Monitoring coral reef ecosystem of Karimunjawa National Park. Wildlife Conservation Society Indonesia Program, Bogor

Rimayanti R, Tarigan SAR, Muttaqin A, Rohman EA, Nurcahyadi M, Muttaqin E, Kartawijaya T, Pardede S, Jamaludin, Pingkan J. 2020. Assessment of the impact of maritime tourism and the supportability of maritime tourism sites in Karimunjawa National Park. Wildlife Conservation Society Indonesia Program, Bogor. [Indonesian]

Seraphim MJ, Sloman KA, Alexander ME, Janetski N, Jompa J, Ambo-Rappe R, Snellgrove D, Mars F, Harborne AR. 2020. Interactions between coral restoration and fish assemblages: Implications for reef management. J Fish Biol 97 (3): 633-655. DOI: 10.1111/jfb.14440.

Satya ED, Sabdono A, Wijayanti DP, Helmi M, Widiaratih R, Suryoputra AAD, Handoyo G, Puryajati AD. 2023. Mapping coral cover using Sentinel-2A in Karimunjawa, Indonesia. Biodiversitas 24 (2): 827-836. DOI: 10.13057/biodiv/d240219.

Souter D, Planes S, Wicquart J, Logan M, Obura D, Staub F. 2020. Status of Coral Reefs of the World: 2020. DOI: 10.59387/WOTJ9184.

Steneck RS, Arnold SN, Boenish R, De León R, Mumby PJ, Rasher DB, Wilson MW. 2019. Managing recovery resilience in coral reefs against climate-induced bleaching and hurricanes: A 15 year case study from Bonaire, Dutch Caribbean. Front Mar Sci 6: 265. DOI: 10.3389/fmars.2019.00265.

Suryanti S, Ain C, Latifah N. 2018. Mapping of nitrate, phospat and zooxanthelae with abundance of sea urchins on massive coral reef in Karimunjawa Island. IOP Conf Ser: Earth Environ Sci 116: 012086. DOI: 10.1088/1755-1315/116/1/012086.

Trihatmoko E, Nurlinda N, Darussalam A, Purwitaningsih S, Sartohadi J, Banowati E, Naibaho BB, Husna VN, Juhadi J, Aji A. 2024. Preserving coastal ecosystem through micro-zonation analysis of Karimunjawa, Indonesia. Environ Monit Assess 196: 88. DOI: 10.1007/s10661-023-12257-8.

Veron JEN, Stafford-Smith M. 2000. Corals of the world. Townsville: Australian Institute of Marine Science.

Wibowo K, Abrar M, Siringoringo RM. 2016. Trophic Status of Coral Fishes and the Relationship of Herbivorous Fishes with Coral Recruitment in Pari Island Waters, Jakarta Bay. Oseanologi dan Limnologi di Indonesia 1 (2): 73. DOI: 10.14203/oldi.2016.v1i2.85. [Indonesian]

Wijaya A, Pramono SE, Melati IS, Zamzuri NH, Hanafiah MH. 2021. Ecological problem behind marine tourism in Karimunjawa: A threat to local community? Proc 6th Intl Conf Educ Soc Sci (ICESS 2021) 578: 43-46. DOI: 10.2991/assehr.k.210918.009.

Wijayanti DP, Indrayanti E, Wirasatriya A, Haryanto A, Haryanti D, Sembiring A, Fajrianzah TA, Bhagooli R. 2019. Reproductive seasonality of coral assemblages in the Karimunjawa Archipelago, Indonesia. Front Mar Sci 6: 195. DOI: 10.3389/fmars.2019.00195.

Wijayanto A, Munasik, Farasara FP, Fadlilah YN, Windiyana AN, Meiliana S, Haryanti D. 2021. Coral reef coverage and reef fish abundance in Menyawakan Island, Karimunjawa. IOP Conf Ser: Earth Environ Sci 750: 012057. DOI: 10.1088/1755-1315/750/1/012057.

Yulianto I, Hammer C, Wiryawan B, Palm HW. 2015. Fishing-induced groupers stock dynamics in Karimunjawa National Park, Indonesia. Fish Sci 81 (3): 417-432. DOI: 10.1007/s12562-015-0863-x.