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Post-Tsunami monitoring of the introduced Banggai cardinalfish (*Pterapogon kauderni*) population in Palu Bay

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Abstract. Post-disaster recovery of marine ecosystems and species is still poorly understood. The Banggai cardinalfish (*Pterapogon kauderni*) is an ornamental fish endemic to the Banggai Archipelago and a few nearby islands. Classified as Endangered in the IUCN Red List, this fish has limited protected status under Indonesian law. Introduced to several sites in Palu Bay in the early 2000's, two populations had become established by 2006. Until the triple disaster (earthquake, tsunami, liquefaction) in September 2018, these populations were used for research and education as well as the aquarium trade. The tsunami devastated habitat and microhabitat at the Mamboro site; a census in 2019 found 10 surviving juvenile Banggai cardinalfish in one sea anemone. Monitoring in June 2021 revealed signs of ecosystem recovery, especially seagrass. Despite limited microhabitat with few corals and a lack of *Diadema* sea urchins, there was a substantial increase in Banggai cardinalfish abundance with all life stages present. New recruits were observed in sea anemones and upside-down jellyfish (*Cassiopea* sp.). These sites present a natural laboratory for *P. kauderni* population and post-tsunami ecosystem recovery. Lessons learned can be used to inform conservation management of depleted *P. kauderni* populations in the endemic range of this endangered fish.

1. Introduction

Natural disasters related to tectonic activity such as tsunamis are often unpredictable and generally unavoidable. For humans, mitigation and adaptation generally relate to preparedness and risk management to improve survival and promote recovery [1]. Coastal ecosystems can be severely impacted, including their biotic and abiotic components [1–4]; recovery may occur naturally or, in some cases, may be assisted by human efforts. However, data and information on post-tsunami recovery of tropical shallow-water ecosystems and specific taxa are limited [4]. Tectonic activity related to the Palu-Koro fault in Central Sulawesi, Indonesia resulted in a triple disaster with earthquakes, liquefaction and tsunamis on 28 September 2018 [5]. The tsunamis within Palu Bay seem to have resulted from several submarine landslides triggered by the earthquakes and cause massive but uneven destruction along the coast, both on land and underwater [5,6].

Sites severely impacted by tsunamis included Mamboro and Kadongo on the eastern coast of Palu Bay within the boundaries of Palu City [7][8], with a wave height of around 5 m at Mamboro [8]. These sites had been used for research and educational purposes since 2000 [9–13]. Originally the focus was on the coastal ecosystems, especially the coral reefs, with coral restoration activities from 2007 to

2012 [10] and ecosystem monitoring under various programmes. In 2006 an introduced population of the Banggai cardinalfish (*Pterapogon kauderni*, Koumans 1933) was discovered [14] with a further *P. kauderni* population found at Kadongo shortly thereafter. These *P. kauderni* populations have been monitored or used in several research or conservation activities since 2006 [7,15,16,16–20] .

The Banggai cardinalfish *P. kauderni* is a small but highly attractive apogonid with a very limited endemic range in the Banggai Archipelago and a few small islands off western Taliabu [21]. Like most apogonids, *P. kauderni* is a paternal mouthbrooder, but has the unusual trait of direct development, where the larvae remain in the male parent's mouth after hatching until they are nearly fully developed [22]; new recruits look like miniature adults albeit with proportionally longer fins compared to their body size. Banggai cardinalfish are highly dependent on protective microhabitat, especially sea urchins (all sizes), sea anemones and anemone-like animals (mainly recruits and juveniles) and some hard corals (mainly adults) [17,19,21,23,24]. Recruits are especially vulnerable to predation, including cannibalism by adult conspecifics [15,17] and microhabitat loss is considered a major threat to *P. kauderni* populations [21,25,26].

Traded as an ornamental fish since the late 1990's [27,28], *P. kauderni* is considered Endangered under IUCN Red List criteria [29] and was twice proposed for listing under CITES Appendix II [25]. A National Plan of Action for Banggai cardinalfish conservation (NPA-BCF) was promulgated in 2016 [30], with one component being monitoring of endemic and introduced populations. Furthermore, in 2021 *P. kauderni* was designated as the Indonesian National Ornamental Fish Mascot [31]. Several endemic *P. kauderni* populations have been severely depleted due to overexploitation and/or sharp declines in protective microhabitat, especially diadematid sea urchins, prompting calls for both passive active interventions to aid their recovery [24,25,32,33]. The fine-scale genetic structure of the endemic *P. kauderni* population with an estimated 20-30 putative Evolutionarily Significant Units (ESUs) means that "re-stocking" should only be done with fish from the same ESU [25,26,34,35]. The "BCF Garden" concept for *in-situ* recovery is to promote *P. kauderni* reproductive success through increasing microhabitat availability [25,34,36]. Despite positive results in controlled conditions [36], testing in the field is needed to validate this concept.

The tsunami in 2018 destroyed the Central Sulawesi Provincial Marine and Fisheries Service Hatchery at Mamboro, along with many homes on or close to the shore and other infrastructure. A tectonic disaster in 2000 in the Banggai Archipelago had minimal impact on *P. kauderni* populations [37]. However, a survey in 2019 found only 10 *P. kauderni* at Mamboro in the one remaining sea anemone in a devastated habitat [18]. Chunks of broken terrestrial infrastructure were sparsely scattered across plains of featureless sediment. All coral reef restoration modules and all but a few scattered juvenile corals were gone, as well as the seagrass beds, very few benthic or pelagic organisms visible. Monitoring at both sites in 2020 showed early signs of recovery, although the *P. kauderni* populations were still low and microhabitat very scarce [7].

This research was conducted to evaluate the recovery of the Mamboro and Kadongo *P. kauderni* populations along with their microhabitat and ecosystem almost three years after the tsunami disaster. The results will add to knowledge on post-tsunami recovery as well as contributing to the targets of the NPA-BCF. In addition, the data will serve as a baseline for planning, monitoring and evaluating a pilot trial of the "BCF Garden" concept in Palu Bay.

2. Methods

2.1. Study sites and data collection

The study sites in Palu Bay, Palu City, Central Sulawesi Province, Indonesia were Mamboro (00° 47′ 53″ S; 119° 52′ 20″ E) and Kadongo (00° 47′ 01″ S; 119° 51′ 32″ E). The data were collected using the belt transect method described in the Indonesian Government manual for monitoring Banggai Cardinalfish (*Pterapogon kauderni*) populations [38]. The central transect line (20 m) was laid using a builder's roll-up tape measure and observations were made 2.5 m each side of the line, giving 20 m x 5 m (100m^2) transect (Fig. 1). Two observers using basic diving gear (snorkelling equipment) collected data on Banggai cardinalfish by size class as well as the microhabitat with which they were associated. Three age/size class were based on standard length (SL): Recruits: < 18 mm SL; Juveniles: 18-35 mm SL; Adults: > 35 mm SL. Microhabitat types were: sea urchins (*Diadema* sp., number of urchins); sea anemones; hard corals (by genus); soft corals; seagrass; other (describe). Belt transects were laid purposively wherever *P. kauderni* groups were found at each site to approach census data as closely as possible. The distance between transects was at least 5 m in all directions.

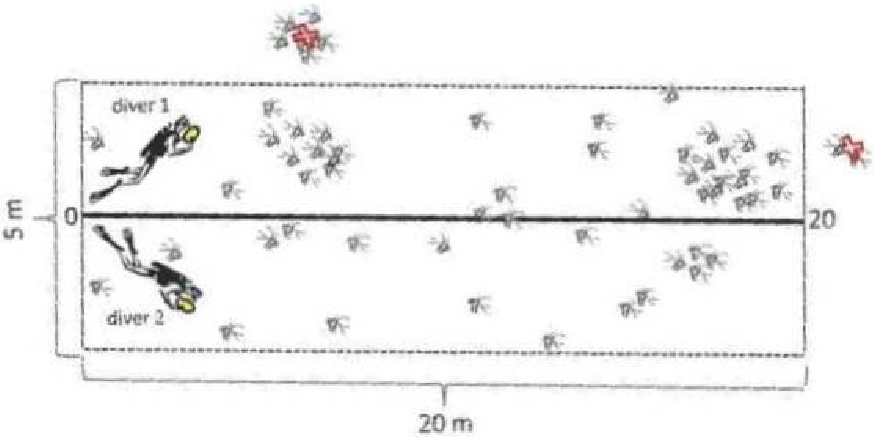


Figure 1. Belt transect (20 m x 5 m) for Banggai cardinalfish monitoring [39]

2.2. Data analysis

The data were analysed descriptively using quantitative and qualitative approaches. Quantitative data on *P. kauderni* and microhabitat organisms within the transects were tabulated and analysed graphically in Microsoft Excel 2010. These data were evaluated with reference to historical data and the scientific literature. Qualitative data were compared with visual records, i.e. photographs and videos taken by the authors at the two sites since 2006.

3. Results and Discussion

3.1. Transect data and P. kauderni population recovery

The belt transect data for Mamboro and Kadongo (Table 1) show that there were around 3.6 times as many *P. kauderni* at the Mamboro site than at the Kadongo site where only 3 transects with *P. kauderni* groups could be laid. This difference may have been related to pre-tsunami conditions as well as the current status of the ecosystems and microhabitat. While the Mamboro population was abundant, the Kadongo population was reported severely depleted in 2017, apparently due to ecosystem degradation related to a reclamation project [18]. However, compared to historical data the observed *P. kauderni* populations were low in both abundance and density. For example, in 2007 the average density (fish/100m^2) was 188 at Mamboro [19], while unpublished data from Kadongo (A. M Moore and S. Ndobe, 2008-2013) show similar densities, many times higher than the 27 (Mamboro) or 20 (Kadongo) fish/100 m^2 in 2021 (Table 1). Furthermore, the area inhabited by *P. kauderni* was greatly reduced, especially at Kadongo.

No sea urchins or soft corals were present in the transects, therefore these microhabitats are not shown in Table 1. Only one transect (Mamboro 8) had *P. kauderni* associated with more than one type of microhabitat. Recent recruits were only observed in one transect (Mamboro 4) and all were associated with upside down jellyfish (*Cassiopea* sp.) as microhabitat. These jellyfish were most likely *C. ornatus*, but may have been one of the cryptic or unresolved species revealed by genetic (DNA) studies [40]. At Mamboro, juveniles were associated with sea anemones and adult *P. kauderni* were associated with sea anemones, hard corals (small colonies of branching forms of *Acropora* and

Pocillopora) and seagrass (*Enhalus acoroides*). This is in contrast to associations noted in 2017, where around half of the *P. kauderni* were associated with diadematid urchins (64% *D. savignyi*) [18]. At Kadongo, all *P. kauderni* observed (juveniles and adults) were associated with sea anemones. Again, this contrasts with 2017, where all *P. kauderni* at the Kadongo site were associated with diadematid urchins (82% *D. setosum*) [18].

Table 1. Banggai cardinalfish belt transect data 2021

Transect Number	Banggai cardinalfish				Microhabitat			
	Recruit	Juvenile	Adult	Total	Anemone	Hard coral	Seagrass	Other
				Mamboro				
1		23	30	53	X			
2		2	60	62	X			
3			16	16			X	
4	11			11				X
5			2	2			X	
6			7	7			X	
7			37	37	X		X	
8		11	14	25	X	X	X	
Total	11	36	166	213		Proportion of transects		
%	5.16	16.90	77.93	100.00	50%	12.5%	62.5%	12.5%
density /100m^2	1.4	4.5	20.8	26.6				
				Kadongo				
1		5	39	44	X			
2			2	2	X			
3		4	9	13	X			
Total	0	9	50	59		Proportion of transects		
%	0.00	15.25	84.75	100	100%	0%	0%	0%
density /100m^2	0	3	16.7	19.7				

3.2. Ecosystem condition and recovery

The visual record shows that the seagrass ecosystem at Mamboro had recovered a similar mix of species compared to pre-tsunami conditions (Fig. 2A, left), with the canopy visually dominated by the large leaves of *Enhalus acoroides* by 2020 (Fig. 2C). Seagrass density and extent had increased by 2021, together with understory vegetation such as the calcareous alga *Halimeda* (Fig. 2D, left). However, recovery of corals was minimal, as shown by the centre photographs in Fig. 2A and 2D.

A. Mamboro in 2017 (left) and May 2018 (centre, right), prior to the tsunami

B. Mamboro in June 2019 C. Mamboro in 2020

D. Mamboro in June 2021. Left to right: *P. kauderni* with seagrass, hard coral, sea anemone

Photograph credits: A M Moore (A, B). D Wahyudi and A I M Salanggon (C, D)

Figure 2. Examples of ecosystem condition at Mamboro before and after the tsunami

3.3. P. kauderni microhabitat recovery

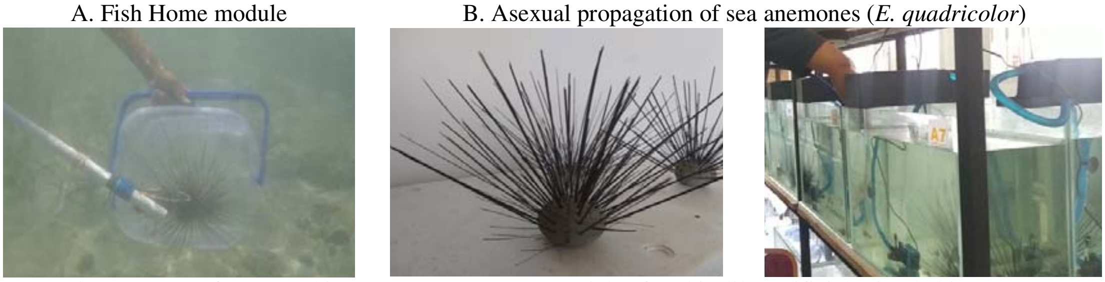
With respect to the benthic organisms known to serve as *P. kauderni* microhabitat, recovery levels varied between types. Long-spined sea urchins, mainly *Diadema setosum* and *D. savignyi* but also *Echinothrix diadema* and *E. calamares*, were previously common at both sites [11,16,18]. At Kadongo, the fire urchin *Astropyga radiata* was also frequently observed, and can provide microhabitat for recruits and small juveniles as in the endemic distribution of *P. kauderni* [41,42]. Sea urchin populations appear to have been extirpated and showed no signs of recovery after 3 years, with one *D. setosum* seen at Mamboro and 2 at Kadongo, both outside the areas where *P. kauderni* were present.

This condition makes the Palu Bay sites ideal candidates for BCF Garden trials, specifically the re-introduction of diadematid urchins once donor populations have been identified. The recovering seagrass beds at Mamboro and the rubble encrusted with algae and other organisms at Kadongo should provide suitable habitat for adult *Diadema* [43]. However, the lack of three-dimensional hard substrate relief and hence nooks and crannies for shelter may preclude successful introduction of *Echinothrix.* This lack may also be a barrier to natural recruitment (post-larval settlement and metamorphosis) and juvenile survival and growth for all sea urchins, whether the propagules originate from nearby populations and/or re-stocked adults.

In addition to promoting or directly increasing the availability of natural microhabitat through live sea urchin re-stocking, the artificial microhabitat technology being trialled by Universitas Tadulako students [44] may be an option to accelerate *P. kauderni* population recovery. The units resemble *Diadema* sea urchins; the spines are made from add species palm coir fibres and stuck into bodies made from a 1:1 mix of sand and cement. While *ex-situ* trials in aquaria showed promise, the stability of these artificial units *in-situ*, their attractiveness to *P. kauderni* recruits and juveniles, and their effectiveness in deterring predation from adult *P. kauderni* as well as other predators still need to be determined.

Sea anemones previously reported from Mamboro and/or Kadongo include *Actinodendron sp., Heteractis crispa*, *H. magnifica*, *H. malu, H. aurora, Stichodactyla gigantea, S. haddoni*, *Macrodactyla doreensis* and *Entacmaea quadricolor* [10,16,19]. In 2020, almost all *P. kauderni* were associated with the few sea anemones present [7]. In 2021 sea anemone abundance was still low at both sites, with 0 to 2 individuals per transect. This slow recruitment may be due to a lack of competent larvae, possibly related to the low density at these sites and/or other potential larval source sites around Palu Bay. Lack of suitable substrate for attachment may also be a factor. Similar to coral reef restoration where hard substrate has been lost [45], artificial substrate may be needed. The "Fish Home" artificial reef modules deployed at the two sites, especially Mamboro (Fig. 3 A), attracted sea anemones as well as corals [10]. To trial the BCF Gardens approach by accelerating sea anemone population recovery through transplantation and/or asexual propagation (Fig. 3B) [36], the low density of sea anemones present indicates the need to seek potential donor sites where *P. kauderni* hosting sea anemones of the species currently or formerly present are still abundant.

A. Fish Home module B. Asexual propagation of sea anemones (*E. quadricolor*)



C. *Diadema setosum* for re-stocking D. *In-situ* trials of urchin-like artificial microhabitat

Photograph credits: A M Moore (A, B [36], C); S Ndobe (D)

Figure 3. Examples of potential habitat and microhabitat restoration activities

The coral reefs at both sites had experienced repeated degradation and at least partial recovery over the period 2000-2018. Hard corals recorded from these and nearby sites are listed in Table 2. Most taxa were identified to the genus level using the Indo-Pacific Coral Finder [46] but some corals were identified to species level, for example the anemone-like *Heliofungia actiniformis*, a known microhabitat of *P. kauderni* recruits and juveniles.

Very few of the taxa in Table 2 were present at the Mamboro site in 2019; only a few isolated colonies, mostly large-polyped with just one or two polyps, were observed in the sediment (A M Moore, unpublished data). Based on [46] and [47], the genera identified were *Fungia*, *Trachyphyllia*, *Lobophyllia,* and *Acropora*. Only one small Acropora colony (branching form) was seen, attached to concrete debris. However, there were very few juvenile colonies visible even on the hard substrate offered by such post-tsunami debris. There are three key processes in coral recruitment as the basis recovery following severe disturbances such as typhoons or tsunamis: larval supply, settlement, and post-settlement survival [48]. Substantial reductions in coral cover can lead to a sharp reduction in larval supply and recruitment due to the loss of potential broodstock; remaining colonies might be in poor condition, inhibiting spawning or be too far from conspecifics to enable fertilisation [49]. Furthermore, a lack of cues from adult habitat may inhibit competency and hence settlement [50]. Comparison with the Fish Home modules at the study sites, where substantial recruitment was visible after a few months [10], this lack of coral recruits and juvenile colonies may indicate a lack of larval supply and/or a lack of cues to induce competent planula to settle as well as limited suitable substrate.

Table 2. Coral taxa recorded from Mamboro and Kadongo in Palu Bay

Family	Genus or species	Source	Family	Genus or species	Source
Acroporidae	*Acropora (branching)*	[10],a	Merulinidae	*Echinopora*	a
	Acropora (other forms)	[10],a		*Favites*	a
	Alveopora	a		*Goniastrea*	a
	Montipora	a		*Hydnophora*	a
Agariciidae	*Leptoseris*	a		*Pectinia*	a
	Pavona	a	Meandrinidae	*Platygyra*	a
Caryophylliidae		[10]	Milleporidae	*Millepora*	[10]
Dendrophyllidae	*Tubastrea*	[10],a	Montastraeidae	*Montastraea*	a
Euphylliidae	*Euphyllia*	a	Mussidae	*Lobophyllia*	[10],a
	Galaxea	a		*Symphyllia*	[10],a
Faviidae	Favia	[10],a	Plerogyridae	*Plerogyra*	a
Fungiidae	*Ctenactis*	a	Pocilloporidae	*Pocillopora*	[10],a
	Fungia	[10],a		*Seriatopora*	a
	Halomitra	a		*Stylophora*	a
	Heliofungia actiniformis	[10]	Poritidae	*Goniopora*	a
	Herpolitha	a		*Porites* (branching)	[10],a
	Polyphyllia	a		*Porites* (other forms)	[10],a
Merulinidae	*Caulastraea*	a	Tracgyphylliidae	*Trachyphyllia geoffroyi*	a

[a] Ndobe and Moore (2011) unpublished survey data. Family data revised based on the World Register of Marine Species (WoRMS) (http://www.marinespecies.org/, accessed 31 October 2021)

The 2020 monitoring reported severe damage to corals with very little recovery [7]. This study also found very few live scleractinian corals. However, some colonies of the genera *Acropora* and *Pocillopora* were seen, including colonies associated with *P. kauderni* (Table 1), although due to their small size the amount of protection offered by this microhabitat must have been limited. These genera are widely reported as relatively short-lived taxa, frequently among the first to colonise the skeletons of dead corals [51] and commonly used in restoration efforts [52,53]. The adoption of these colonies by larger juvenile and adult *P. kauderni* indicates that coral restoration could contribute to *P. kauderni* recovery by providing microhabitat for these larger size classes. The corals planted could both increase total microhabitat availability and potentially reduce competition for microhabitat more suited to *P. kauderni* recruits and small juveniles, especially sea anemones.

4. Conclusion

Monitoring at two *P. kauderni* introduced population sites in Palu Bay nearly three years after the 2018 tsunami revealed signs of recovery at the ecosystem level. In particular the seagrass beds at the Mamboro demonstrate the potential for natural post-disaster recovery of seagrass communities. At the species level, recovery of invertebrate taxa suitable as microhabitat for the Banggai cardinalfish *Pterapogon kauderni* was limited at both Mamboro and Kadongo. Diadematid sea urchins seem to have been ecologically extirpated, while sea anemones and coral colonies were still sparse with few taxa present. Despite the limited microhabitat available, there was a substantial increase in Banggai cardinalfish abundance, with all life stages present. New recruits were only observed in one out of 11 transects, all sheltering in upside-down jellyfish (*Cassiopea* sp.); this apparently low reproductive success most likely indicates high mortality from predation, including cannibalism. At both sites, small juveniles were all associated with sea anemones, while some larger juvenile and adult *P. kauderni* also associated with the seagrass *Enhalus acoroides* and the few branching coral colonies present. These sites present a natural laboratory for *P. kauderni* population and post-tsunami ecosystem recovery. Given the slow recovery of *P. kauderni* microhabitat taxa, these sites seem ideal for trials of the BCF Garden concept of promoting *P. kauderni* recovery through increasing microhabitat availability. Lessons learned can be used to inform conservation management of depleted Banggai cardinalfish populations in the endemic range of this endangered fish

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