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New Idea

Vacuums of the sea: Ecological function of large coral reef benthic scavengers in suppressing crown-of-thorns starfish (COTS) outbreaks

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Abstract

Despite their drastic impacts on coral reefs, outbreaks of the coral-feeding seastar crown-of-thorns starfish (COTS), *Acanthaster*, have remained a scientific enigma. Significant efforts in coral reef conservation science have been dedicated to identifying natural predators able to exert demographic control on COTS and prevent population outbreaks. These efforts are motivated by empirical evidence showing that reefs within marine protected areas are less prone to COTS outbreaks than reefs open to fishing where potential COTS predators have been reduced or removed functionally from food webs. Research findings point towards COTS' early life-stages as a major demographic bottleneck for COTS populations, with various reef fish and benthic organisms identified as predators of the seastar. Yet, no species or species groups have been clearly identified as exerting enough top-down control to influence COTS population increases or prevent outbreaks. We report the benthic scavenging behavior of eagle rays (family Myliobatidae), a large-bodied predator, feeding in coral rubble fields of Kanaky New Caledonia, critical habitats where juvenile COTS find refuge and food and accumulate to produce population outbreaks. We argue that with their effective substrate-sucking feeding behavior, similar to vacuums of the sea, eagle rays may be a hitherto unidentified predator able to exert significant control on COTS populations. Eagle rays and other large benthic scavengers were previously neglected in the search for major COTS predators. Relatively little existing data show that eagle ray populations in Kanaky New Caledonia's lagoon are more abundant inside than outside marine protected areas, which concords with the hypothesis that they could be responsible for the mitigation of COTS outbreaks as reported within reserves. We advocate for further investigations on the role of eagle rays and other large benthic scavengers in controlling COTS outbreaks, and the importance of preserving the unique ecological function of sea vacuums for coral reef conservation.

Keywords: Coral reef; *Acanthaster*; Seastar; Predator outbreak; Eagle ray; Nature-based solution.

Unresolved mystery surrounding COTS outbreaks

Outbreaks of crown-of-thorns starfish (COTS, *Acanthaster* spp.) cause mass coral mortality and are a clear threat to coral reef conservation in an era of global coral decline (Kayal et al. 2012, Pratchett et al. 2017, Condie et al. 2021). There has been a long-running debate about the mechanisms that control COTS outbreaks, which, in part, remain a scientific enigma. Two predominant hypotheses about the mechanisms exerting demographic bottlenecks for COTS populations have been proposed, both of which are supported by a relatively large body of empirical evidence (Pratchett et al. 2014). The bottom-up "nutrient enrichment hypothesis" emphasizes the importance of nutrient availability for phytoplankton blooms upon which COTS larvae feed and rely during their transition from pelagic to benthic stages: with eutrophication of reef environments, COTS populations increase due to increased recruitment and early life stage survivorship (Fabricius et al. 2010, Wooldridge and Brodie 2015, Matthews et al. 2020). The top-down "predation release hypothesis" emphasizes the role of species feeding upon the seastar in regulating their populations, a mechanism altered when reef fisheries reduce local abundances of COTS predators (Cowan et al. 2017). Recently, Deaker et al. (2020) discovered a third mechanism by showing that COTS is able to remain in an "ecologically dormant" state of herbivorous juvenile hiding in dead coral rubble, enabling the build-up of cryptic outbreak populations over years, before shifting to corallivory and full-grown adults once preferred coral prey is available (Wilmes et al. 2020a, Deaker and Byrne 2022, Neil et al. 2022). Quantitative evidence indicates that COTS outbreaks are more frequent and intense outside of marine protected areas than in reef areas protected from fishing, thereby supporting the predation release hypothesis (Dulvy et al. 2004, Sweatman 2008, McCook et al. 2010, Mellin et al. 2016, Vanhatalo et al. 2017, Westcott et al. 2020, Kroon et al. 2021). Nevertheless, the evidence to support the predation release hypothesis so far remains predominantly correlative and circumstantial, and there is need for improved understanding of the mechanisms through which protection from fishing benefits control of COTS populations. Specifically, identifying species exerting significant control on COTS populations can help define targeted management actions that support coral reef resilience.

Our hypothesis

We propose the hypothesis that foraging by eagle rays (family Myliobatidae), large-bodied bottom scavengers feeding in coral reef rubble fields, can exert significant top-down control of COTS juvenile life-stages, thereby playing a key role in regulating COTS outbreaks. Our hypothesis is based on observations of active foraging of the reef substrate in Kanaky New Caledonia by an eagle ray, moving coral rubble around and sucking up potential prey hidden in the substrate and around live corals (Figure 1). Because coral rubble fields constitute predominant habitats for COTS juvenile stages (Zann et al. 1987, Wilmes et al. 2020b), we argue that such feeding behavior, acting as a vacuum of the sea substrate, may constitute a key ecological function regulating marine benthic invertebrate populations, including COTS whose outbreaks can devastate corals at large spatial scales.

Figure 1. Photograph of an eagle ray (family Myliobatidae) foraging the shallow reef substrate in Kanaky New Caledonia. The individual was observed moving coral rubbles and sucking up potential prey from the reef substrate, a suction feeding behavior comparable to a vacuum of the sea. We believe that this ecological function may be critical for regulating invertebrate populations hiding in the substrate, such as juveniles of the coral predator crown-of-thorns starfish. See video at Kayal (2024).

Support for our hypothesis

Recent research efforts have focused on identifying COTS predators in an endeavor to improve coral reef management through the regulation of COTS outbreaks exerted by their natural predators. More than 100 species of reef fish and invertebrates have been identified as preying upon the seastar at different life stages and health conditions (Cowan et al. 2017). However, predation on early COTS life stages remains largely under-characterized, while seastar survival in the juvenile stage—that is when the small, cryptic, and coralline feeding seastars are hiding within coral rubble habitats—is considered a major demographic bottleneck for COTS populations (Wilmes et al. 2018, 2020b). In an extensive review of the scientific literature, Cowan et al. (2017) concluded that predation on newly settled starfish is predominantly exerted by benthic invertebrates associated with coral rubble fields, a hypothesis currently under intensive investigation (Desbiens et al. 2023). However, research on putative predators of juvenile COTS have hitherto largely dismissed the importance of large generalist reef predators that are able to effectively forage through coral rubble over expansive reef areas, like eagle rays. Eagle rays, like other large rays, are intensive bottom-feeders that effectively "vacuum" up invertebrate prey hidden in marine benthic substrate (Thrush et al. 1991, Hines et al. 1997, Ajemian et al. 2018, Figure 1). A large body of research conducted in the 1980's solidified how foraging by bat rays in temperate latitude regions (Hulberg and Oliver 1980, Van Blaricom 1982), and sting rays in tropical latitudes (Thistle 1981), substantially influence soft-sediment invertebrate assemblages, either directly through predation or indirectly through physical disturbance (see Lenihan and Micheli 2001 for a review). Our observation of an eagle ray foraging in coral rubble suggests that they may be a key predator able to control COTS juvenile abundance and reduce outbreaks. Indeed, coral rubble provides important recruitment substrate, refuge, and coralline-algae food for juvenile COTS (Zann et al. 1987, Wilmes et al. 2018, 2020a), and is where seastar density can build up over years leading to outbreaks (Deaker et al. 2020).

Juvenile COTS buried in coral rubble may not have many large predators (Cowan et al. 2017). Species acting as sea vacuums in rubble fields, like eagle rays, may play a unique role in controlling COTS density build-ups and the frequency and intensity of outbreaks, which typically originate in habitats dominated by coral rubble (Zann et al. 1987, Johnson et al. 1991, Kayal et al. 2012, Wilmes et al. 2020b). Relatively healthy eagle ray populations may explain the relatively constrained COTS outbreaks observed in Kanaky New Caledonia's lagoon, as compared with the neighboring regions Australia and Vanuatu, where higher fishing and shark-net impacts on rays and higher frequency and intensity of COTS outbreaks are reported (Lynch et al. 2010, Schluessel et al. 2010, Harry et al. 2011, Sumpton et al. 2011, Adjeroud et al. 2018, Sporcic et al. 2018, Laran et al. 2024). Although data limitations currently prevent quantitatively testing our hypothesis, recent investigation in Kanaky New Caledonia indicates eagle ray populations were three times more abundant inside than outside of marine reserves (Heudier et al. 2023), supporting the hypothesis that they could be responsible for the mitigation of COTS outbreaks in protected areas, as reported in other regions (Dulvy et al. 2004, Sweatman 2008, McCook et al. 2010, Mellin et al. 2016, Westcott et al. 2020, Kroon et al. 2021). Other hitherto overlooked benthic scavenger species potentially exerting significant predatory control on juvenile COTS hidden in coral rubble and with populations severely impacted by fisheries include sea cucumbers (Holothuria; Anderson et al. 2011, Purcell et al. 2013, Pierrat et al. 2022, Ahmed et al. 2023), although this is beyond the scope of the present study.

Conclusions and prospective research

Megafauna often play important roles in marine ecosystems, although their ecological functions are not always known or fully recognized, and their populations are often significantly reduced by human activities (McCauley et al. 2015, Pimiento et al. 2020). Our observations shed light on the potentially unique ecological function of eagle rays for safeguarding coral reefs from COTS outbreaks. While we currently do not possess the necessary information to test this hypothesis, future investigations may include eagle ray behavior and diet analyses to confirm or reject predation on juvenile COTS (Ajemian et al. 2012, Leray et al. 2013), and joint analysis of eagle ray and COTS populations to establish predator-prey regulation and a potential mitigation of outbreaks (Kayal et al. 2012). While diver operated COTS control efforts are costly but often considered as the best approach to reduce the impacts of their outbreaks (Westcott et al. 2020, Condie et al. 2021, Castro-Sanguino et al. 2023), coral reef resilience may significantly benefit from an increased protection of eagle ray populations and their important ecological function as vacuums of the reef.

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Response to referee

We agree with Pratchett (2025) that dedicated studies are necessary before confirming our hypothesis that eagle rays exert regulatory pressure on juvenile populations of the coral-eating seastar crown-of-thorns starfish (COTS). As stated in our original manuscript, and indicated by the journal name—*Ideas in Ecology and Evolution*—and category of article we have proposed, our hypothesis remains predominantly a *new idea* that requires further investigation. The discussion platform provided by this journal enables further debating the mechanisms underlying our hypothesis with colleagues working on the topic, and identifying ways to test them in future research. There are predominantly two lines of evidence, one mechanistic and the other correlative, pointing towards the potential role of eagle rays in regulating COTS juvenile abundance in coral reef rubble fields.

Mechanistic line of evidence: *eagle rays are large-bodied generalist vacuum feeders able to suck up large quantity of prey from coral reef rubble, which is the predominant habitat in which juvenile COTS find refuge to build up outbreaking populations*.

We agree that studies on the feeding behavior of eagle rays are necessary to confirm the commonness of our observation that eagle rays regularly prey in coral reef rubble fields, and that their feeding activity has indeed regulatory effects on COTS populations. Until such knowledge is available there is no reason to believe that our observation is an exclusive behavior (i.e. a one-time event, or that of a deviant individual), or that eagle rays' vacuum feeding in coral reef rubble would spare juvenile COTS. The eagle ray in our video is seen displacing a relatively large piece of coral rubble before scrutinizing the area and overturned rubble piece with its mouth, seemingly sucking up uncovered small prey living in the interstices (see Kayal 2024 video at 1:00-1:20). It seems probable that such feeding behavior would exert strong indiscriminate predation on meio- and macro-benthic invertebrates within the size range of a millimeter to few centimeters, including juvenile COTS (Hines et al. 1997, Ajemian et al. 2012, Deaker et al. 2020, Wilmes et al. 2020a,b). We are not stipulating that eagle rays specifically search for and actively target juvenile COTS hidden in rubble fields in a way to fully suppress their populations even at low densities, but rather that repeated eagle ray vacuum feeding in rubble fields may result in keeping COTS populations in check.

As highlighted by Pratchett (2025), few studies have reported echinoderms in eagle ray diet (Capapé 1976, Gray et al. 1997, Schluessel et al. 2010, Ajemian et al. 2012, Serrano-Flores et al. 2018), and to our knowledge there is currently no evidence that eagle rays do consume COTS juveniles. However, there is no evidence that eagle rays avoid preying upon juvenile COTS when vacuum feeding in coral reef rubble. Studies describing stomach content of eagle rays and affiliates report a diversified diet, with a large predominance of mollusks and few echinoderms, sometimes including seastars (Capapé 1976), in proportions predominantly reflecting local prey composition (Gray et al. 1997, Jardas et al. 2004, Yamaguchi et al. 2005, Schluessel et al. 2010, Serrano-Flores et al. 2018, Cahill et al. 2023). Given the described generalist predator behavior with a flexible diet adapting to various environments, one can anticipate that eagle rays' indiscriminate vacuum feeding in reef substrate infested with COTS juveniles would result in high proportions in stomach contents. Among regions where COTS is present and exhibits population outbreaks, Schluessel et al. (2010) identified only small amounts of ophiuroids (another class of echinoids) in eagle ray stomachs collected in February 2007 from Australia's Heron Island, southern Great Barrier Reef, which may have not corresponded to a time and place where high juvenile COTS densities were present in the substrate. Furthermore, visual identification of juvenile COTS in stomach contents may be challenging, as individuals are small (a millimeter to few centimeters) and lack hard structures that could facilitate identification of their remains (Deaker et al. 2020, Wilmes et al. 2020a,b, Cahill et al. 2023). As reminded by Pratchett (2025), molecular tools can complement the visual identification of prey in eagle ray stomach.

As pointed out by the referees, future research on the feeding behavior and efficiency of eagle rays may help confirm predation on juvenile COTS, provided that eagle rays and coral rubble hosting COTS juveniles are at hand, which is logistically difficult. As large coastal species inhabiting shallow lagoons and bays, eagle rays and affiliates are particularly vulnerable to fisheries and frequently caught by long- and drum-lines, nets, traps, and trawlers (Gray et al. 1997, Jardas et al. 2004, Lynch et al. 2010, Schluessel et al. 2010, Sumpton et al. 2011, Serrano-Flores et al. 2018). Therefore working with fishing communities can facilitate the acquisition of live and dead specimen for stomach content analysis and experiments. For example, patches of coral rubble hosting juvenile COTS, as identified in situ by Wilmes et al. (2020b) or cured in aquarium by Deaker et al. (2020), can be exposed to eagle ray feeding to estimate the species' efficiency in regulating juvenile COTS populations. Such enclosure-exclosure experiments can be deployed in natural eagle ray feeding grounds as identified in our video, or in aquarium (Hines et al. 1997, Kayal et al. 2011, Ajemian et al. 2012, Flowers et al. 2021). The studies would also offer the opportunity to explore the mechanisms through which eagle ray feeding impacts the juvenile seastars at different development stages through direct predation (swallowing individuals) versus indirectly through injuries from suction and coral rubble movement, or exposure to other predators (Flowers et al. 2021). In our video, a dozen fish of various sizes are seen circling around the eagle ray, seemingly to benefit from prey exposed from the feeding activity, particularly fish from the family Labridae (probably *Thalassoma jansenii*, *Thalassoma hardwicke*, and/or *Hemigymnus fasciatus*) which are commonly observed with such behavior (Figure 2; Sabino et al. 2017, Bonham and Silbiger 2024).

Figure 2 Portions of the video frames where fish following the eagle ray can be seen, seemingly to benefit from prey exposed by the feeding activity. Thanks to their movement, the fish are easier to spot in the video, which can be watched at slow motion and high quality at Kayal (2024).

Correlative line of evidence: *eagle rays are more abundant inside than outside marine protected areas, which may explain why COTS outbreaks are less preeminent in reef protected from fishing.*

There is currently limited data available in our study system of Kanaky New Caledonia to confirm that eagle ray abundances are higher inside than outside protected areas at a larger scale than that demonstrated by Heudier et al. (2023), and to test to which degree ray abundances may negatively correlate with COTS populations. What is known from the literature is that, like other megafauna inhabiting coastal waters, eagle rays are highly vulnerable to human activities and declining, particularly due to targeted and incidental catch and habitat degradation (Dulvy et al. 2021, Glaus et al. 2024). Eagle rays and affiliates are frequently caught by fishing devices and shark-nets (Gray et al. 1997, Jardas et al. 2004, Serrano-Flores et al. 2018, Broadhurst and Cullis 2020), including in tropical coral reef systems such as the Australian Great Barrier Reef (Lynch et al. 2010, Schluessel et al. 2010, Harry et al. 2011, Sumpton et al. 2011, Sporcic et al. 2018). In absence of further knowledge, it seems realistic to stipulate that eagle ray populations in the Great Barrier Reef may exhibit similar patterns than those observed in the Kanaky New Caledonian lagoon where densities were significantly (3-folds) higher inside than outside protected areas (Heudier et al. 2023). This concords with the hypothesis that eagle rays may exert some level of regulation on COTS populations as found in reefs protected from fishing (Dulvy et al. 2004, Sweatman 2008, McCook et al. 2010, Mellin et al. 2016, Vanhatalo et al. 2017, Westcott et al. 2020, Kroon et al. 2021).

Correlative studies contribute greatly to characterizing predator-prey interactions and trophic cascades that trickle down across ecosystem compartments (Myers et al. 2007, Heithaus et al. 2008, Kayal et al. 2012, Flowers et al. 2021). Where spatio-temporal data on both eagle ray and COTS is available, such analysis can help testing to which degree the abundances of the two species are (negatively) correlated. As eagle rays are hard to approach in nature and constitute a diversified species group with potentially various life histories to investigate, data acquisitions can be accelerated using aerial and underwater imagery and telemetry, citizen science, environmental-DNA, and artificial intelligence (Tagliafico et al. 2019, Araujo et al. 2020, Desgarnier et al. 2022, Glaus et al. 2024).

Conclusion

While our understanding of coral reef ecosystem functioning remains in its infancy, this is yet another example of how preserving biodiversity could help safeguard important ecological mechanisms supporting ecosystem health and associated benefits to society. We look forward to further studies on this topic, and advocate for increased protection of eagle rays and affiliate "ecological reef vacuums" as a potential nature based solution for regulating COTS populations and supporting coral reef management.

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