Rapid Response to three species of Invasive Corals in Kāneʻohe Bay, Oʻahu, Hawaiʻi

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WHITE PAPER

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Executive Summary

On May 13, 2020 the Aquatic Invasive Species (AIS) Program with the Division of Aquatic Resources (DAR) received a report from Hiʻilei Kawelo of non-native corals found on a patch reef in Kāneʻohe Bay within the National Estuarine Research Reserve (NERR) boundaries. Her father, Gabby Kawelo, first saw the corals around 2018. The AIS Program visited the site seven days after the original report and found twelve colonies that appeared to be non-native and comprised of three species. Dr. Robert Toonen from the Hawaiʻi Institute for Marine Biology (HIMB) facilitated taxonomic identification of the species by Dr. Douglas Fenner from the National Oceanic and Atmospheric Administration (NOAA). Dr. Fenner identified two of the species as *Montipora foliosa, Montipora digitata,* and the third species as either *Montipora stellata* or *Monitipora carinata*. A non-native anemone, believed to be *Anemonia manjano,* was also found. All three corals could be designated as invasive since they were seen overgrowing native corals and could serve as a vector of disease for native corals. The AIS program collaborated with multiple agencies, developed a response plan, and initiated the removal of the corals on July 29, 2020. The corals were removed by the AIS Program, Hiʻilei Kawelo, Josh Maxwell from the Waikīkī Aquarium, and staff from NERR at Heʻeia. Follow-up surveys were performed by the AIS Program in October 2020. Coral fragments were removed or coated with Z-SPAR A-788 Splash Zone Two Part Epoxy Compound. The AIS team continues to monitor the site for regrowth of the invasive corals.

Introduction

Marine invasive species have the potential to negatively impact native marine species, native ecosystems, the economy and human well-being (Bax et al. 2003). The Hawaiian Islands are one of the most remote places on earth, leaving them extremely susceptible to invasion due to a lack of natural predators and a year-round growing season (Davidson et al. 2014). Over 463 marine species in Hawaiʻi are of foreign origin or their origin cannot be determined, and the level of marine invasion in Hawaiʻi ranks as high as anywhere of comparable size in the world (Davidson et. al. 2014, Carlton and Eldredge 2015).

The State of Hawaiʻi Aquatic Invasive Species (AIS) Program in the Division of Aquatic Resources (DAR) is responsible for AIS management, covering all aspects of prevention, early detection, rapid response, and control. Rapid response refers to quickly responding to a report of non-native species before they spread and proliferate. The more widespread and established a non-native species becomes, the more difficult it is to eradicate or control. Non-native species have the potential to become invasive, a key example in Hawaii is invasive macroalgae (Neilson et al. 2018). Species that are not considered invasive elsewhere, like Mangroves and the Marquesan Mullet, have proven to cause negative impacts in Hawaiʻi (Allen 1998, Schemmel et. al 2019).

On May 13, 2020, the AIS Program received a report of a non-native coral that a community member had discovered on a patch reef in Kāneʻohe Bay, Oʻahu within the National Estuarine Research Reserve (NERR). Hiʻilei Kawelo, the Executive Director of Paepae o Heʻeia, was out with her father, Gabby Kawelo, who had first observed the unusual corals around 2018. The Kawelo ʻOhana is a Native Hawaiian family who are skilled watermen and have generational knowledge of the Bay. Hiʻilei immediately recognized that these corals were likely not native. She and her sister Kapua Kawelo reached out to members of the scientific community and natural resource managers. Pictures of the corals were circulated to experts familiar with Hawaiian corals, none of whom identified the species as native. Dr. Robert Toonen, a professor at Hawaiʻi Institute of Marine Biology (HIMB), informed the AIS Program of this sighting and facilitated communication with the Kawelo ʻOhana.

This report prompted rapid response procedures and the AIS Program staff did their first site inspection, accompanied by Hiʻilei, seven days after the initial report. A management assessment was completed, including a multiagency collaborative removal of the corals on July 29, 2020.

Site Inspection and Species Identification

On May 20, 2020, members of the AIS team joined Hiʻilei to do an initial site inspection of the unusual corals. The non-native coral was located on patch Reef 8 or "Bank Reef" in Kāneʻohe Bay just north of HIMB's research facility at Moku o loʻe. This reef is within the National Estuarine Research Reserve (NERR) at Heʻeia which is an Indigenous Community and Conserved Area (ICCA) (Figure 1). The NERR at Heʻeia coalesces conventional and indigenous resource management and science (Winter et al. 2020). Various non-governmental organizations, state, and federal agencies comanage the NERR at Heʻeia including but not limited to the Hawaiʻi Institute of Marine Biology (HIMB), the Department of Land and Natural Resources (DLNR), Paepae o Heʻeia, and the National Oceanic and Atmospheric Administration (NOAA).

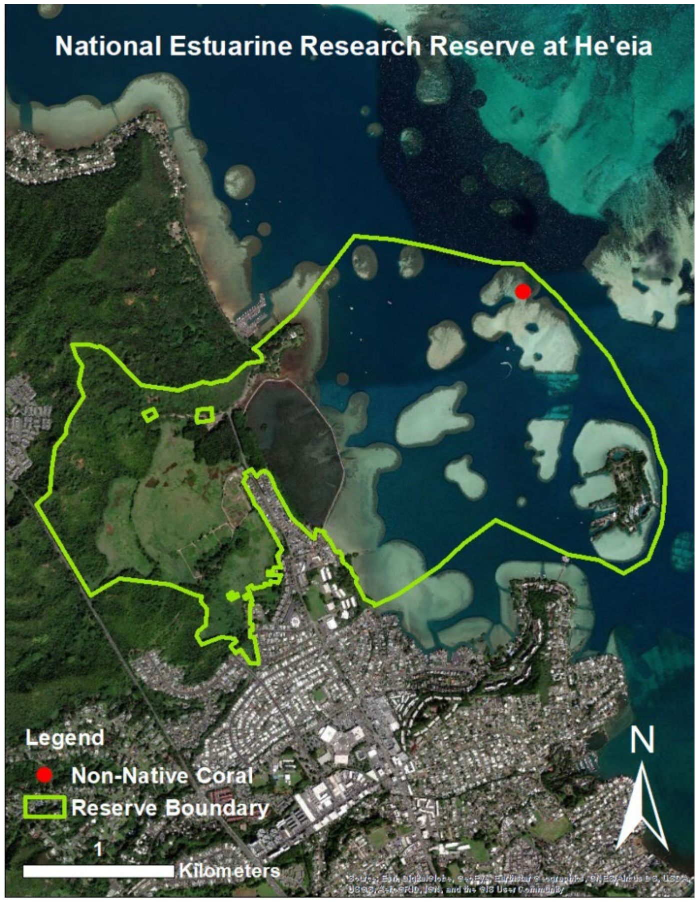

Figure 1: Non-native coral location within the National Estuarine Research Reserve at He‘eia.

Upon *in situ* investigation via snorkel, twelve colonies comprised of three species appeared to be non-native. The colonies ranged from 17 cm to 1.25 m in diameter. There was an orange coral with foliose formation not typically observed in local Montiporids, as well as not having the characteristic tubercule formation of native Montiporids. A purple branching coral was observed that was unlike any native branching corals the AIS biologist had observed in the Main Hawaiian Islands. The last species was of plate and pillar formation similar to local Montiporids, but with green polyps and slightly different pillar morphology.

Samples were collected from each suspected species and sent to Dr. Doug Fenner, a Coral Biologist with the National Oceanic and Atmospheric Administration (NOAA), for taxonomic identification. Samples were also submitted to Dr. Toonen for future genetic analysis and to Bishop Museum for their collection. On June 1, 2020, DAR received word that Dr. Fenner identified the orange foliose coral as *Montipora foliosa*, the purple branching coral as *Montipora digitata* and the green polyp plate and pillar coral as either *Montipora stellata* or *Monitipora carinita* (Figure 2, Appendix B). The footprint of the area with the non-native coral colonies was approximately 2.2 m x 2.9 m (Figure 3).

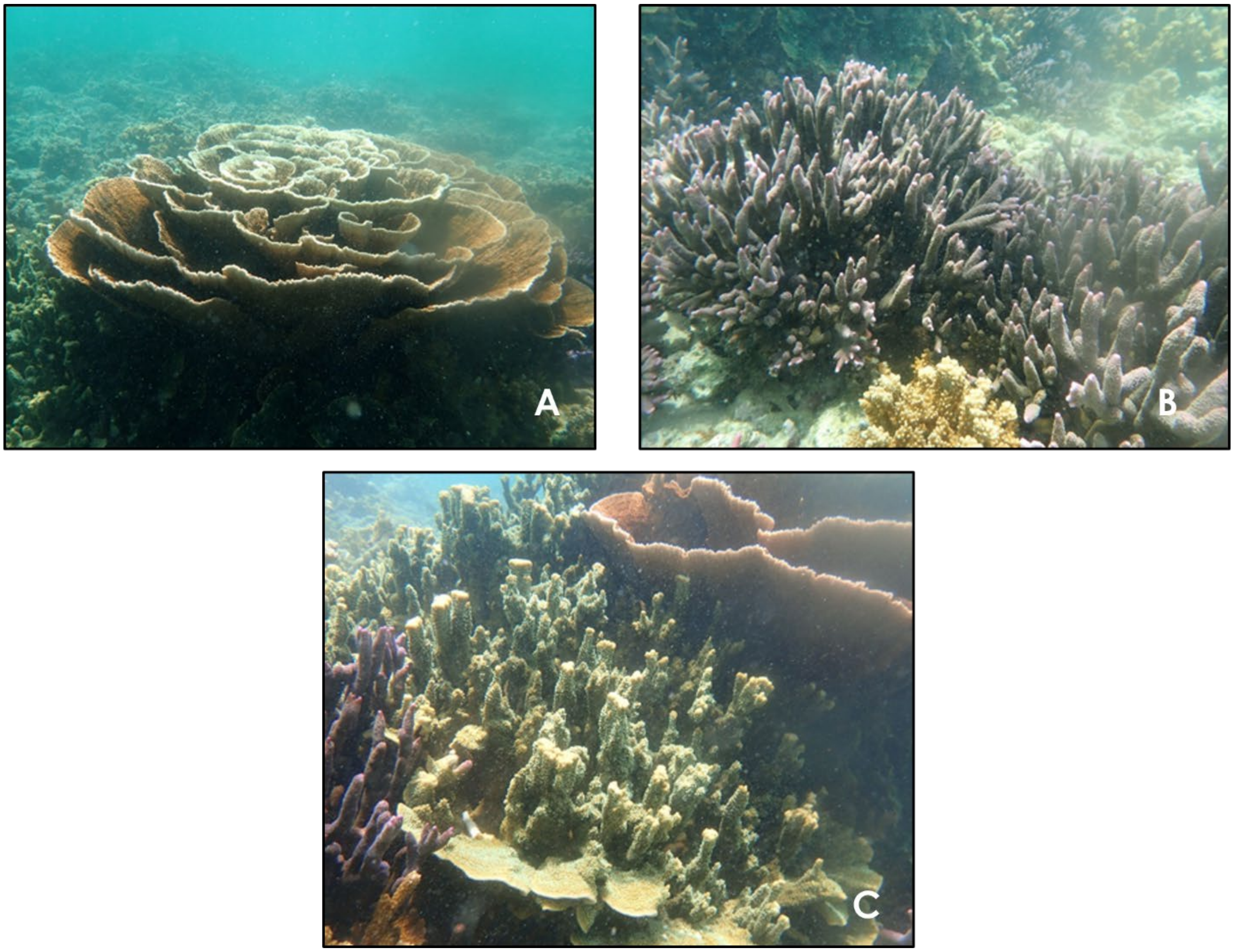

Figure 2: Photos of three non-native coral species found in Kāneʻohe Bay: A) Orange foliose coral identified as *Montipora foliosa* B) Purple branching coral identified as *Montipora digitata* C) Green polyp plate and pillar coral suspected to be either *Montipora stellata* or *Monitipora carinita* in the middle of the three species seen.

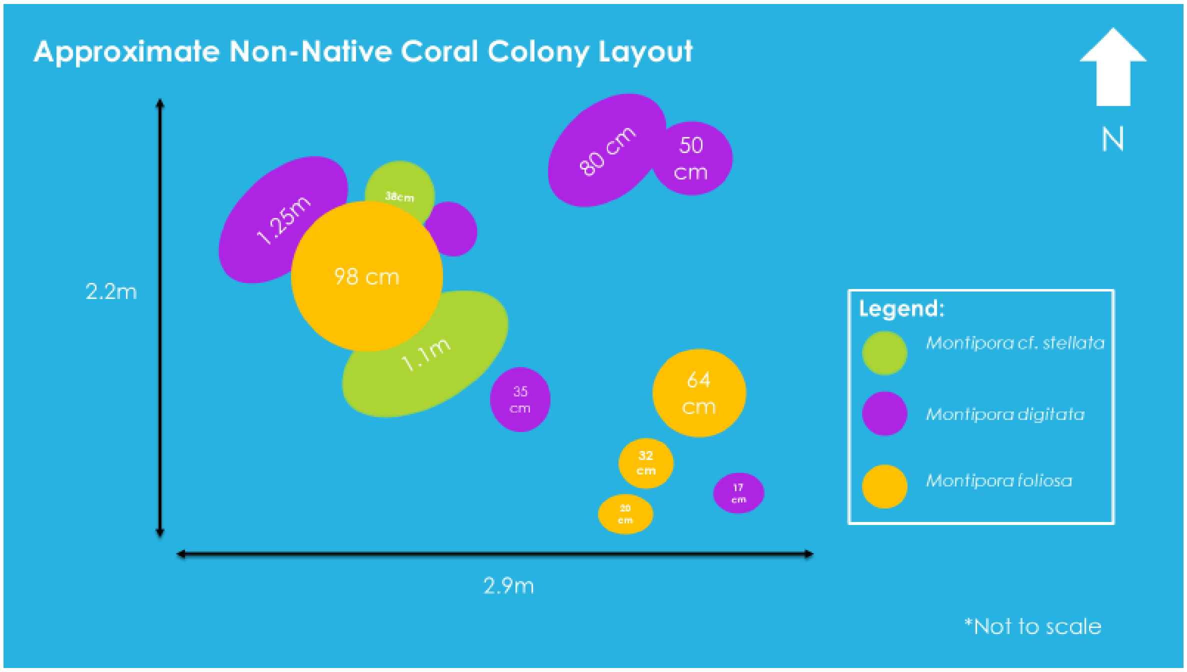

Figure 3: Approximate Non-Native Coral Colony Layout: Colored circles represent coral colonies found at the site. The approximate footprint and the measured diameter of coral colonies is noted.

Figure 4: Photo-mosaic of the non-native coral footprint: Created by Dr. Anthony Montgomery (USFWS).

As coral identification can sometimes prove difficult, the AIS program further built the case for the corals being non-native by consulting experts at partner organizations. Pictures were circulated and expert opinions were gathered on species identification from the United States Fish and Wildlife Service (USFWS), Bishop Museum, the Waikīkī Aquarium, Paepae o Heʻeia, Heʻeia National Estuarine Research Reserve (NERR), NOAA and HIMB. Dr. Anthony Montgomery from the USFWS Ecological Services visited the site on July 16, 2020 and gathered images of the footprint, which he processed into a photo mosaic (Figure 4). All partners consulted agreed the corals appeared to be non-native and deferred to Dr. Fenner as the taxonomic coral expert in the region.

A suspected non-native anemone was also found in subsequent site visits (Figure 5). The anemone was found in the largest *M. foliosa* colony and in the crevices of adjacent native *Montipora capitata.* Josh Maxwell, the coral biologist with the Waikīkī Aquarium, believes them to be *Anemonia manjano*, a nuisance species in the aquarium hobby. The anemones were removed, and samples were given to Bishop Museum for further taxonomic and genetic work.

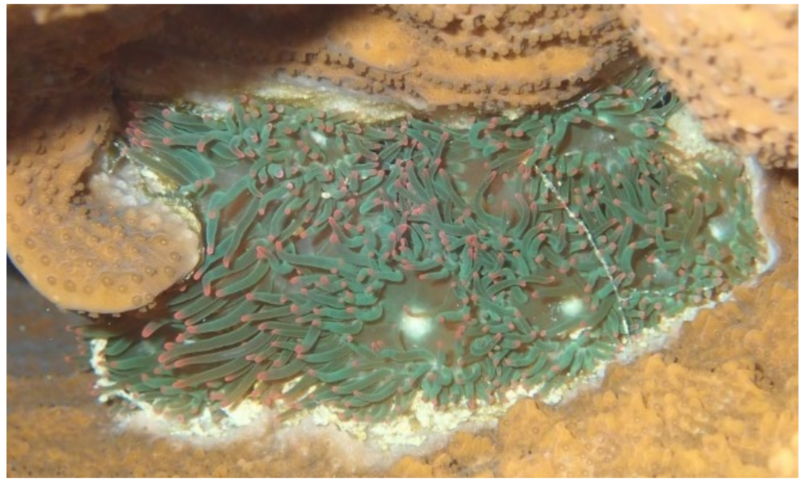

Figure 5: Suspected *Anemonia manjano* anemones found in a *Montipora foliosa* colony.

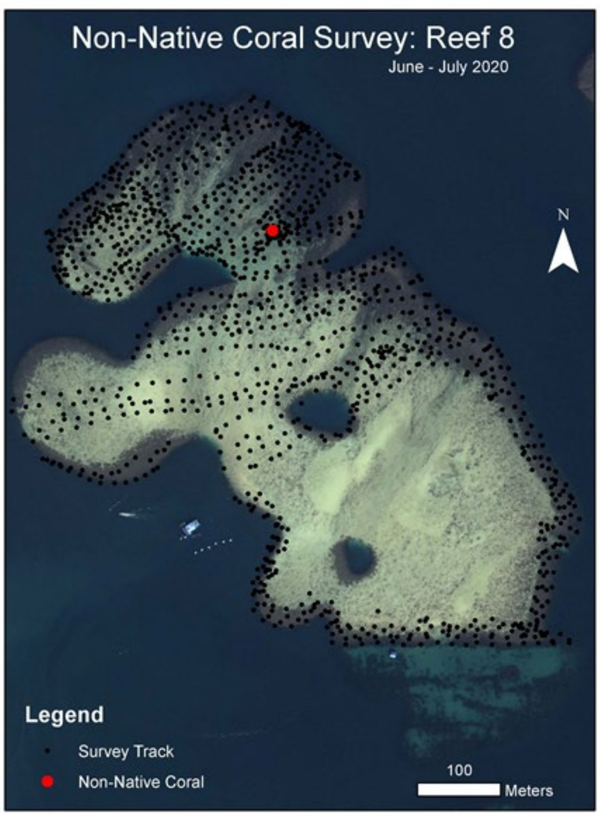

Figure 6: Non-native coral distribution map

The distribution of the corals on Reef 8 was investigated throughout June and July of 2020 (Figure 6). No specimens of non-native coral were found on the same reef except at the location they were originally discovered. The AIS program completed annual invasive algae monitoring the week of July 15, 2020 and did not see any other non-native coral colonies on the reefs surveyed (Appendix A).

The layout of the three non-native coral species in close proximity (Figure 3 & 4) indicates that they were likely from a reef tank that was dumped on the reef or were purposely out-planted. The introduced coral species identified are popular in the aquarium trade. The contrasting colors of the corals adjacent to each other is common in aquarium aesthetic design. The varying diameters of the colonies adjacent to one another could lend to the idea that if reproduction was occurring before this investigation, it was likely via asexual reproduction in the form of fragmentation.

Reproductive Assessment

The community was concerned with the sexual reproduction of the non-native corals overlapping with local Hawaiian corals that spawn during summer months. Literature indicates that *Montipora foliosa* and *Montipora digitata* spawn in October and November in their natural range (Babcock et al. 1986; Richmond & Hunter 1990). *Montipora stellata* has been recorded to spawn in February, March, April and September (Penland et al. 2003; Penland et al. 2004). *Montipora carinata* has been documented to spawn in March (Penland et al. 2003). According to the literature, it did not appear likely that most of the corals would spawn in June or July. However, it is possible that spawning could take on a different cycle in the coral's non-native range.

On July 2, 2020, the AIS program took coral gamete scientist Mike Henley, a PhD candidate in Dr. Mary Hagedorn's lab at HIMB, to sample the corals. Mr. Henley sampled the corals to determine if there were viable gametes present, both in the field and in the lab, although histology was not performed. Three samples were taken from the largest colonies of each species. In the field, colored eggs that would indicate sexual maturity were not observed (Henley 2020, personal communication). The samples were then taken back to the lab and inspected under a dissection scope, where again no eggs were immediately observed.

Mr. Henley decalcified and stained the samples, making it easier to identify if eggs were present. After inspection of the processed samples, Mr. Henley found immature eggs in the *M. digitata* and *M. foliosa* fragments. No eggs were found in the coral identified as either *M. stellata* or *carinita*. The eggs found were 200-300 µm and probably at least a few months from spawning, as the normal spawning size is 400-450 µm. The eggs also lacked color, which indicated their immaturity as they often are a pale yellow-orange color when ready to spawn (Henley 2020, personal communication). Further processing methods and a summary of findings compiled by Mr. Henley in a PowerPoint presentation can be seen in Appendix C.

Designation of Corals as Invasive

Multiple agencies and representatives were consulted to identify the coral species and the consensus was that they are non-native. DAR colleagues, experts from partner organizations (NOAA, USFWS, Bishop Museum, the Waikīkī Aquarium, NERR, HIMB, Paepae o He'eia) and the Native Hawaiian Kawelo 'Ohana were consulted on their opinion of if removal should occur. They generally agreed or advocated that the corals should be removed. However, there were external concerns about prioritizing action on this population of non-native corals. One argument was that corals are slow growing and unlikely to become invasive. Another argument was that any coral adds to the diversity of reefs and can still serve important ecosystem functions, regardless of origin. In order to justify removal, the AIS Program addressed these points.

The non-native coral species were seen overgrowing and, in some cases, smothering adjacent native corals (Figure 7). There was also disease observed in non-native *Montipora digitata* and *Montipora foliosa* that was similar to disease observed in native *Montipora capitata* (Figure 8). While the disease may or may not have originated with the introduced corals, disease presence indicates the ability to serve as a vector of disease. The corals adjacent to the non-native corals were comprised primarily of *M. capitata*, but endemic *Porites compressa* colonies were also present. Additional native coral species observed on Reef 8 were *Cyphastrea ocellina*, *Leptastrea purpurea*, *Monitipora flabellata, Montipora* *patula,* and *Pocillipora damicornis.* The overgrowth of native corals and potential to serve as a vector for disease indicates that the non-native corals do in fact have invasive qualities.

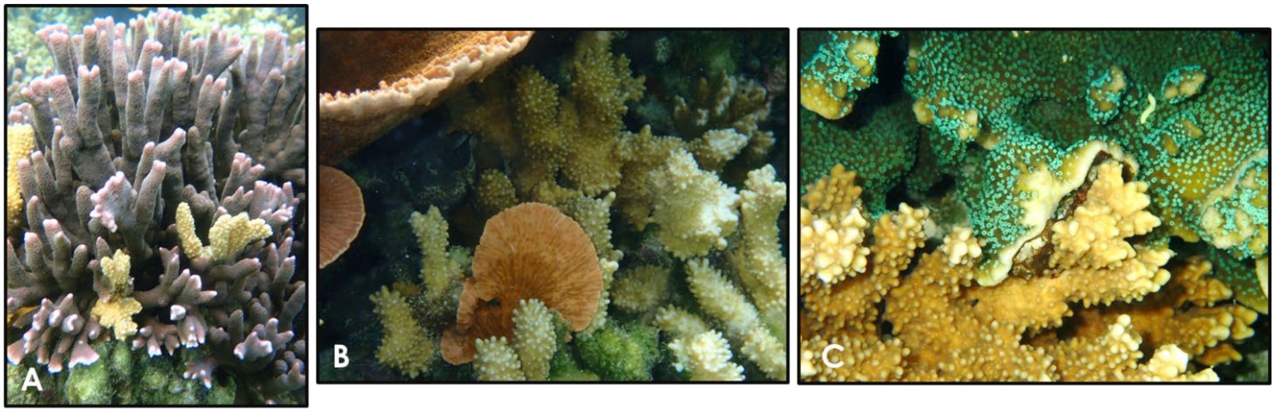

Figure 7: Non-native corals overgrowing native corals: A) Introduced *M. digitata* (purple) smothering native *M. capitata* (orange). B) Introduced *M. foliosa* (plating) colonizing and overgrowing native *M. capitata* (paler orange pillars). C) Introduced *Montipora carinata* or *stellata* (green polyps) overgrowing native *M. capitata*.

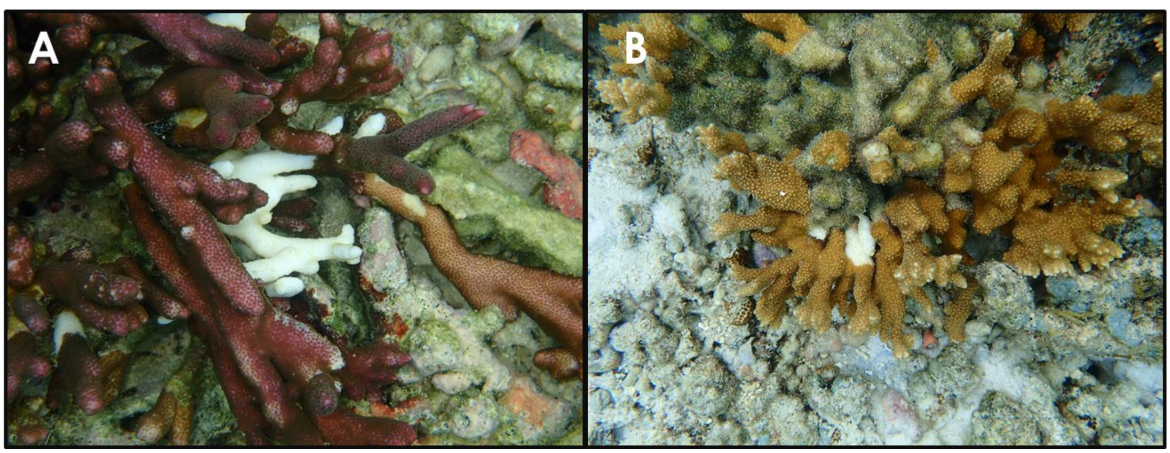

Figure 8: Coral disease: White sections on coral indicate disease and were observed in A) non-native *M. digitata* and B) native *M. capitata*

In situ documentation of negative impacts on native species was coupled with a literature review exploring the qualities and growth rates of the non-native corals (Appendix D). The literature indicates that *M. digitata, M. stellata,* and *M. foliosa* are known to grow quickly and reproduce easily via fragmentation (Gomez et al. 1985; Heyward & Collins 1985; Tkachenko et al. 2007). Anecdotal accounts have described *M. digitata* as a weedy species and indicated that the *M. digitata* beds in its natural range can be monocultures. Compared to other tropical Pacific coral species, Hawaiian corals tend to have slower growth rates (Rodgers et al. 2003; Jokiel et al. 2008).

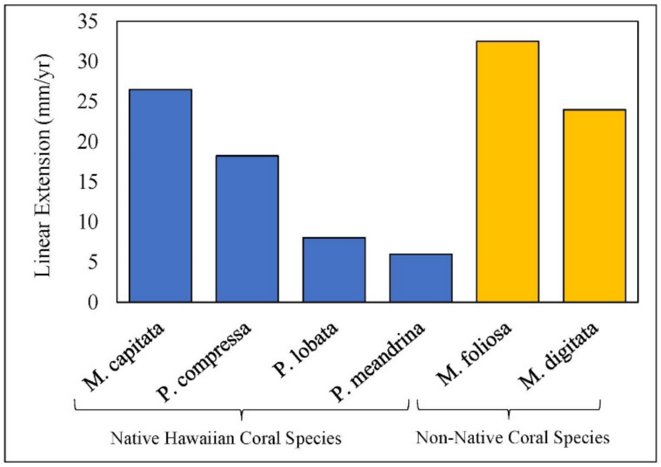

Figure 9: Mean linear extension rates of four common native Hawaiian coral species and two non-native tropical Pacific coral species (Gomez et al. 1985; Heyward & Collins 1985; Rodgers et al. 2003).

Due to the slower growth rates of Hawaiian species, there is concern that introduced species with faster growth rates could out compete native species. The average growth rates of four common native Hawaiian species (*M. capitata, P. compressa, P. lobata and P. meandrina*) and two non-native coral species (*M. foliosa* and *M. digitata*) were compared (Figure 9). Though *M. digitata* does not have a higher growth rate than *M. capitata*, *M. digitata* grows quicker than the other three native species and was seen smothering *M. capitata in situ* (Figure 7). *M. foliosa* is the fastest growing coral species, with a linear extension that is 6 mm/yr. greater than the linear extension for *M. capitata.* Given the fast growth rates of the non-native corals and their ability to reproduce via fragmentation, there is evidence for their ability to be invasive. However, the growth rates compared from non-native species are from their native range and thus may vary in Hawaiian waters.

The introduced corals may serve as habitat for native species, as juvenile fish and an eel were observed inhabiting a large colony of *M. foliosa*. The risk of detrimental impact to native coral species, however, likely outweighs the observed introduced coral ecosystem functions as native coral and other natural structure can serve as habitat for those species.

The introduced corals qualify as invasive since they overgrow native corals and harbor disease which are clear threats to the native ecosystem, but there also is evidence for negative social impact. From an Indigenous standpoint, corals have cultural significance. Native Hawaiian cosmogonic chants view corals as the first lifeform created, and coral reefs are an important habitat for constitutionally protected traditional and customary practices of Native Hawaiians (e.g., fishing and gathering) that are upheld by the State. Not surprisingly, the Native Hawaiians who discovered that found the introduced corals advocated for their speedy removal, not wanting the native coral habitat that they have stewarded for generations to be forever changed.

Invasive Coral Removal

The decision to control non-native species with limited resources depends on three things:

1) Distribution –is the area of the non-native species widespread or is it an incipient population with a small enough footprint to manage?

2) Impact –is there evidence that the non-native species could be designated as invasive and negatively impact the native species and ecosystems, the economy or human well-being? If the community is impacted, they are more likely to support control.

3) Control actions available –is there enough manpower, funding, and are there the correct tools and technologies that could be used to control the non-native species?

Luckily, the footprint of the introduced corals was relatively small (2.9 m x 2.2 m). Even though the non-native corals are invasive in Hawaiʻi, the corals are still valuable reef builders elsewhere. Thus, the AIS program partnered with the Waikīkī Aquarium to remove the corals in a manner that they could be used for future educational display.

On July 29, 2020, a collaborative removal of the invasive corals was undertaken by the AIS program, Hiʻilei Kawelo, NERR and the Waikīkī Aquarium. Josh Maxwell, from the Waikīkī Aquarium directed the removal of the colonies so they could remain as intact as possible or be fragmented at ideal places. Three to five snorkelers removed the corals by hand using chisels, hammers, and cutters. The colonies and fragments were placed in large plastic bags to reduce the spread of fragments during transit. Snorkelers swam the bagged coral approximately 10 m to the AIS program's 12' mini-barge (Figure 10).

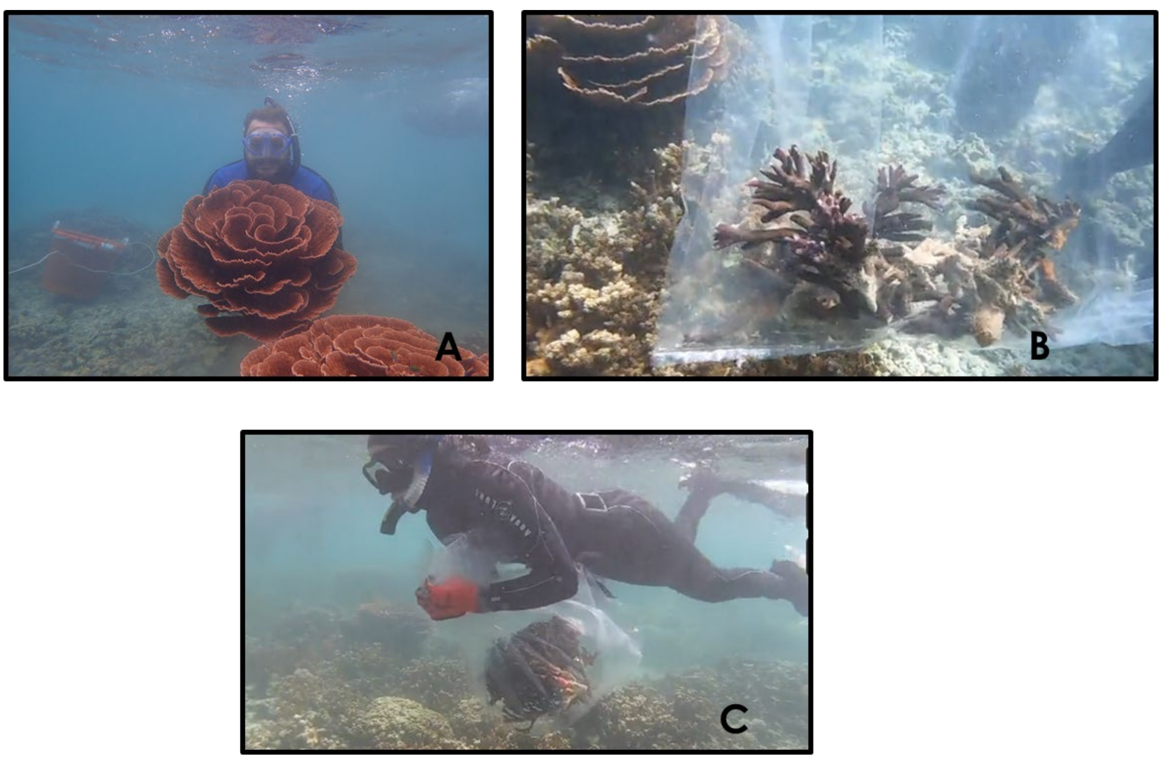

Figure 10: In situ pictures of the invasive coral removal: A) Josh Maxwell from the Waikīkī Aquarium holding a colony of *Montipora foliosa* that he removed. B) Bagged *Montipora digitata* C) Diver transiting bagged invasive corals to mini-barge.

Two staff were stationed at the mini-barge and lifted the bagged coral into large totes on the barge. The staff changed the water in the totes for coral health as needed. When the mini-barge totes were full, the staff stationed on the mini-barge swam it over to the edge of the reef near a deeper keyhole. The AIS program 22’ Force then met the mini-barge in the keyhole to tow it to the larger barge (33’) stationed on a mooring on the west side of the reef (Figure 11). Two additional AIS staff served as vessel support during the operations on the Force and 33’ barge. The corals were then transferred from the totes on the mini-barge to the totes stationed on the 33’ barge by hand. The mini-barge was then towed back to the keyhole by the 22’ Force to be reloaded with additional corals.

Figure 11: Locations on Reef 8 of the non-native coral, keyhole and 33’ barge mooring area.

Most corals were able to fit into bags to reduce risk of fragments spreading, but a few large colonies could not be bagged (Figure 12). For the colonies too large to bag, snorkelers followed the person carrying the colony and picked up any fragments that may have been dropped on the way to the mini-barge. The participants were also careful to not allow fragments to fall into the water when moving corals across vessels or totes.

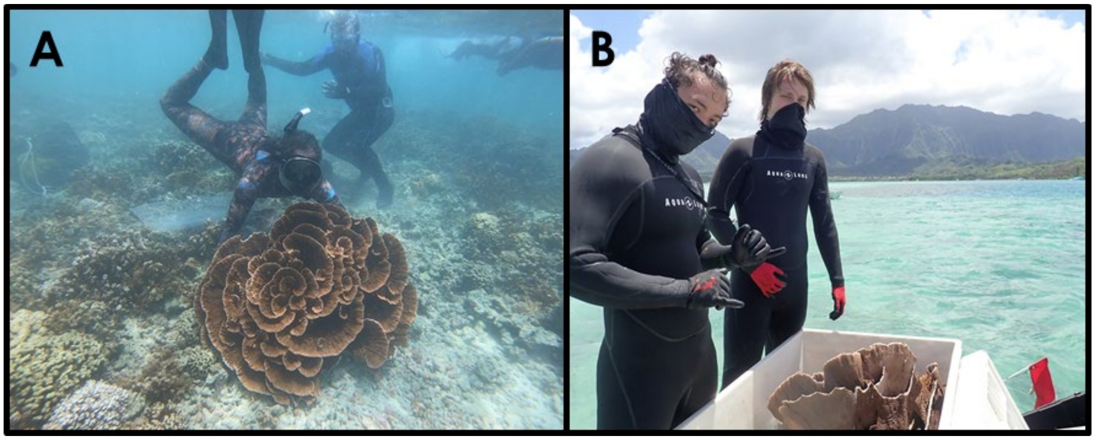

Figure 12: ***M. foliosa*** **that was too large to bag**: A) Hiʻilei Kawelo holding large *M. foliosa* colony after it had been removed. Photo credit: Fred Reppun, NERR. B) *M. foliosa* that was too large to bag in tote next to DAR AIS staff.

After all the corals were loaded on the 33’ barge, the vessel transited to the loading dock at Heʻeia Pier. The largest *M. foliosa* colony (~1 m in diameter) was towed in a tote on the mini-barge with the 22’ Force due to spatial restrictions and to reduce the risk of fragmentation spread by multiple transfers. All corals were then transferred to two state trucks by hand. The loaded trucks transited to the Waikīkī Aquarium where the corals were unloaded into quarantine tanks.

The water that the corals were held in was bleached or strained before disposal to reduce the risk of the invasive corals spreading. All unwanted or diseased fragments of the invasive coral were bleached completely white before disposal.

One colony of the *Montipora stellata* or *carinita* had to be removed the following day, July 30, 2020, by the AIS team due to time constraints. The AIS team also assessed the area of the removal site that day and removed any additional fragments.

Continued Monitoring of the Invasive Coral Removal Site

The AIS team conducted an initial check-up on the area around two months after the removal on October 5, 2020. Around 30 fragments of the invasive corals ranging in size from <1 cm to almost 6 cm were detected. The loose invasive coral fragments were removed by hand, bagged, and bleached completely white before disposal. Some fragments were attached to other corals or large pieces of live rock and could not be removed by hand.

The AIS program followed up again on October 23, 2020. The remaining attached invasive coral fragments were smothered with Z-SPAR A-788 Splash Zone Two Part Epoxy Compound (Figure 13). The team found additional loose invasive coral fragments and removed them as before (Figure 13). A few suspected *Anemonia manjano* were found in a hole near the original removal site and were also smothered with Z-SPAR.

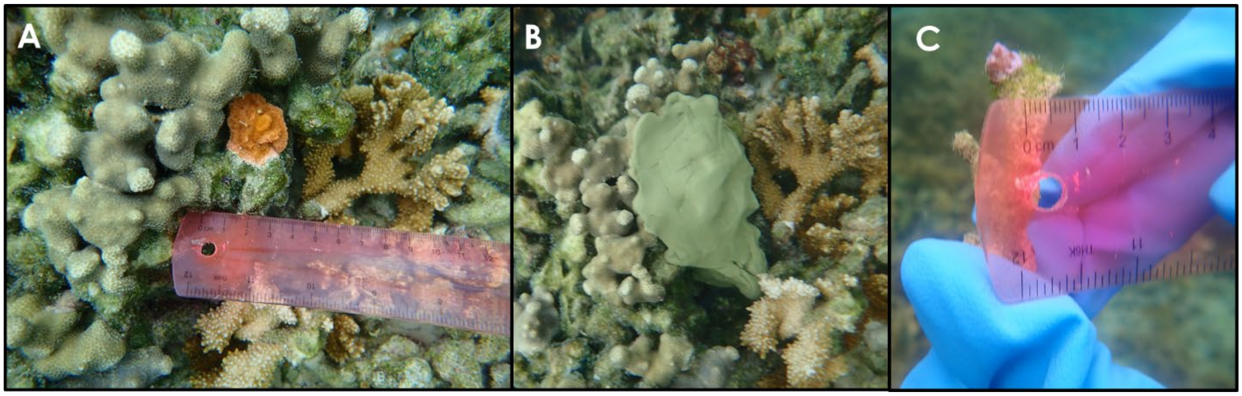

Figure 12: Invasive Coral Fragments: A) Fragment of *M. foliosa* attached to live rock and adjacent to endemic and native corals. B) Same fragment of *M. foliosa* as in A, smothered with ZSPAR C) Small loose fragment of *M. digitata* <1cm in diameter.

Although the area was thoroughly inspected for fragments multiple times, it is easy to miss fragments due to their size and the complex benthic habitat. At a minimum, annual monitoring of the area is necessary to inspect for regrowth of the invasive corals.

Conclusion

Although the primary vector of marine introduced species is through the shipping industry in the form of ballast water and biofouling, release is also a vector of marine introductions in Hawaiʻi (Carlton and Eldredge 2009). Release can entail individual rogue actors intentionally releasing aquaculture, aquarium, or food species into natural waterways, and historic stocking of desirable species by government agencies. Unintentional release is also a vector, as exhibited by smothering seaweed spreading from experimental pens onto adjacent reefs and ultimately across Kāneʻohe Bay (Russel 1983). At least 30 non-native marine fish, invertebrates and algae have become established and spread throughout Hawaiʻi from the vector of release, some of them being destructive invasive species (Carlton and Eldredge 2009).

Prevention is the most cost and time effective form of invasive species management. Introductions like these invasive corals highlight the need for continued education and enforcement of illegal activity in Hawaiʻi. According to Hawaiʻi State statute § 187A-6.5 “No person shall release any live non-native fish or other live non-native aquatic life being held in an aquarium or other confinement for scientific study, exhibition, display, sale, or for any other purpose, into any waters of the State.” Where prevention is not possible, rapid response is ideal. The AIS Program recognizes the vital need for an efficient form of communication with water users, as they must serve as our eyes across our archipelago. Without community and colleague reporting, many incipient invasive populations of aquatic invasive species may go unmanaged by the AIS Program. Please visit our website at <http://dlnr.hawaii.gov/ais/> and contact us at dar.ais@hawaii.gov to report novel non-native aquatic species in our natural waterways. This multi-agency collaborative effort is an ideal model for how we should manage threats to our native ecosystems, economy, and human well-being.

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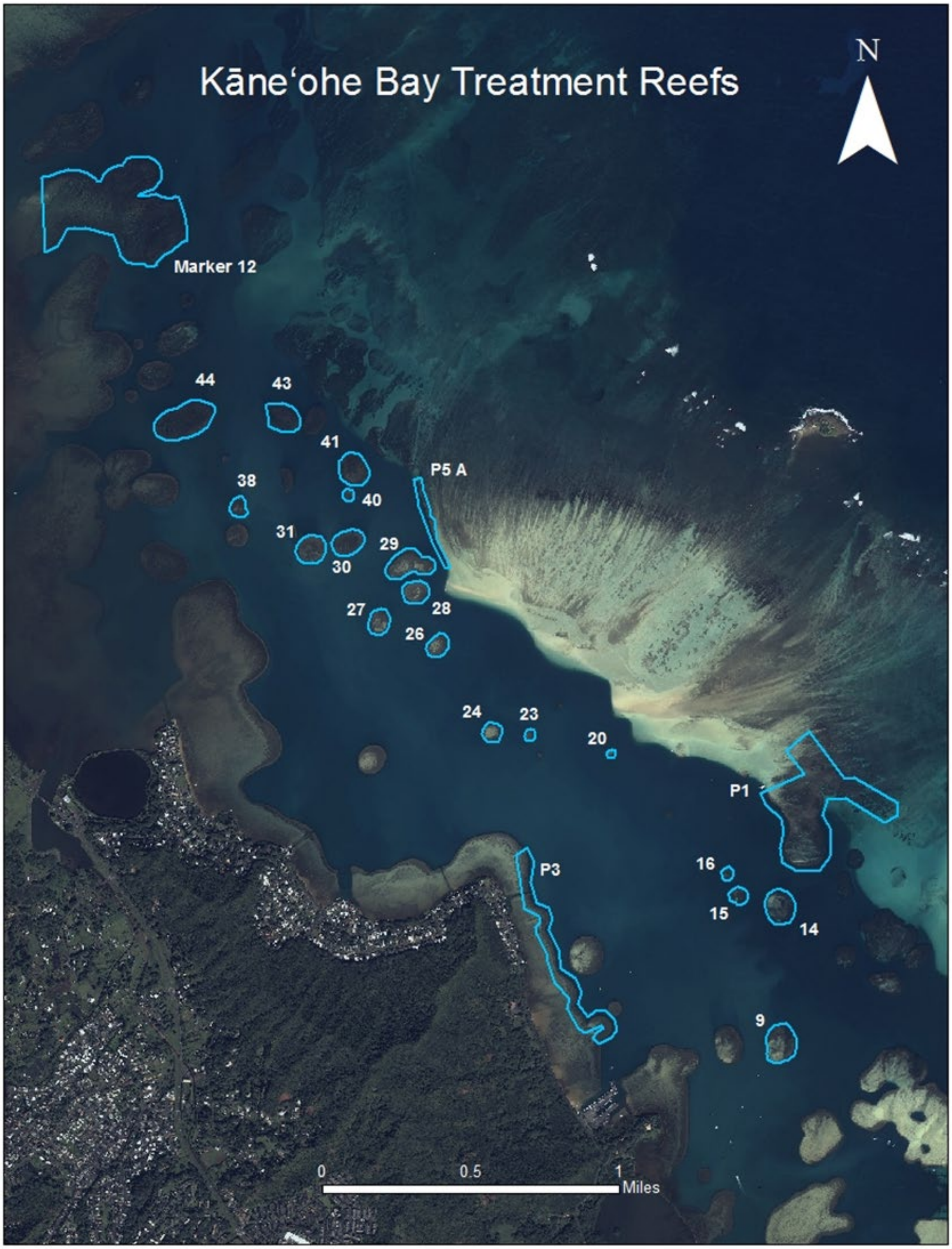
Winter, K B, Rii YM, Reppun FAWL, DeLaforgue Hintzen K, Alegado RA, Bowen BW, Bremer LL, Coffman M, Deenik JL, Donahue MJ, Falinski KA, Frank K, Franklin EC, Kurashima N, Kekuewa Lincoln N, Madin EMP, McManus MA, Nelson CE, Okano R, Olegario A, Pascua P, Oleson KLL, Price MR, Rivera MJ, Rodgers KS, Ticktin T, Sabine CL, Smith CM, Hewett A, Kaluhiwa R, M. Cypher, B. Thomas, J.-A. Leong, K. Kekuewa, J. Tanimoto, K. Kukea-Shultz, A. Kawelo, K. Kotubetey, B. J. Neilson, T. S. Lee, and R. J. Toonen. 2020. Collaborative research to inform adaptive comanagement: a framework for the He'eia National Estuarine Research Reserve. Ecology and Society 25(4):15. https://doi.org/10.5751/

Appendix A: Reefs Surveyed in July 2020



Reefs Surveyed in the July 2020 for annual invasive algae surveys. No non-native corals were found.

Appendix B: Taxonomic Identification of Non-native Corals by Dr. Doug Fenner

Three Newly Discovered Corals in Hawaii

Douglas Fenner June 16, 2020

Corals collected from Kaneohe Bay.

Montipora digitata "Purple branching"

The purple branching colony is *Montipora digitata*, as expected. Clearly not *M. samarensis* or *M. altasepta* which are similar in colony shape but have bumps or lower lips, which it doesn't have.

The skeleton is 16 cm long, with cylindrical branches 8-12 mm diameter. Corallites are flush with the surface, and the coenosteum has no papilli, or ridges or lower lips of the corallites or any other ornamentation. Corallites are about 0.6 mm diameter, and are about 2 diameters apart. A theca is visible for most corallites. First cycle septa some to all present up to 2/3 R. A few second cycle septa may be present up to about 1/3 R. The coenosteum is fairly coarse.

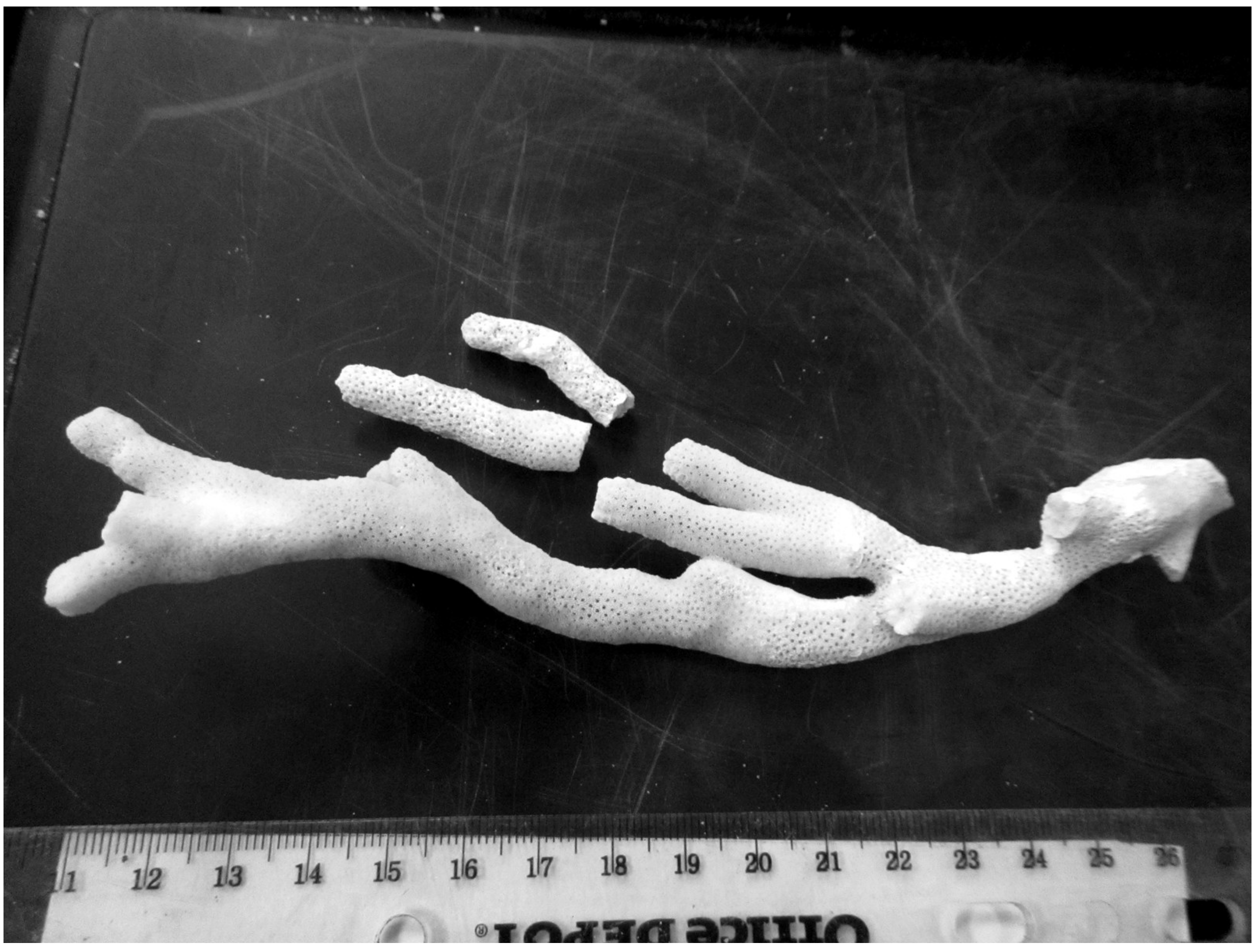


Figure 1. *Montipora digitata*, "purple branching."

Figure 2. Closer view of *Montipora digitata* “purple branching”.

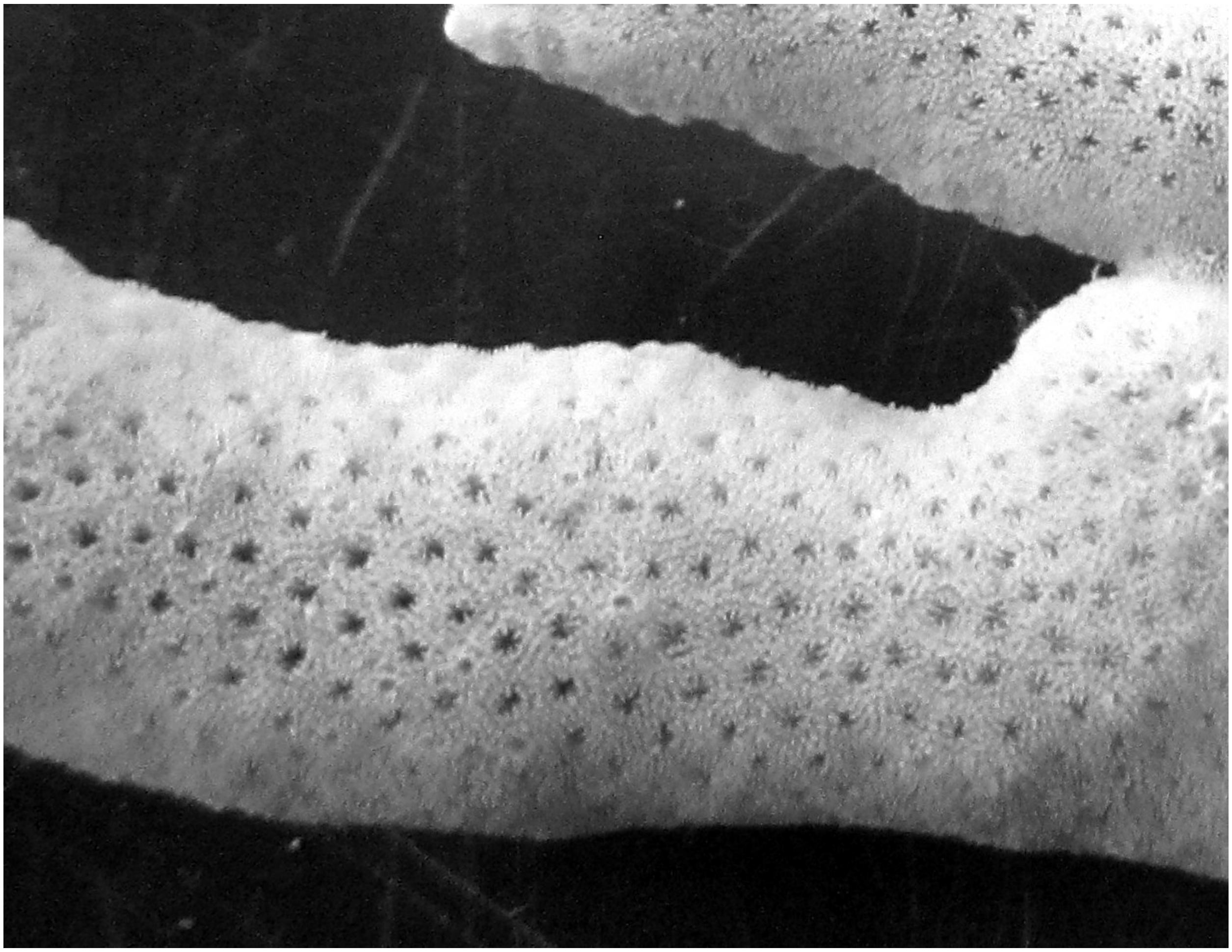


Fig. 3. Closeup photo of *Montipora digitata*.

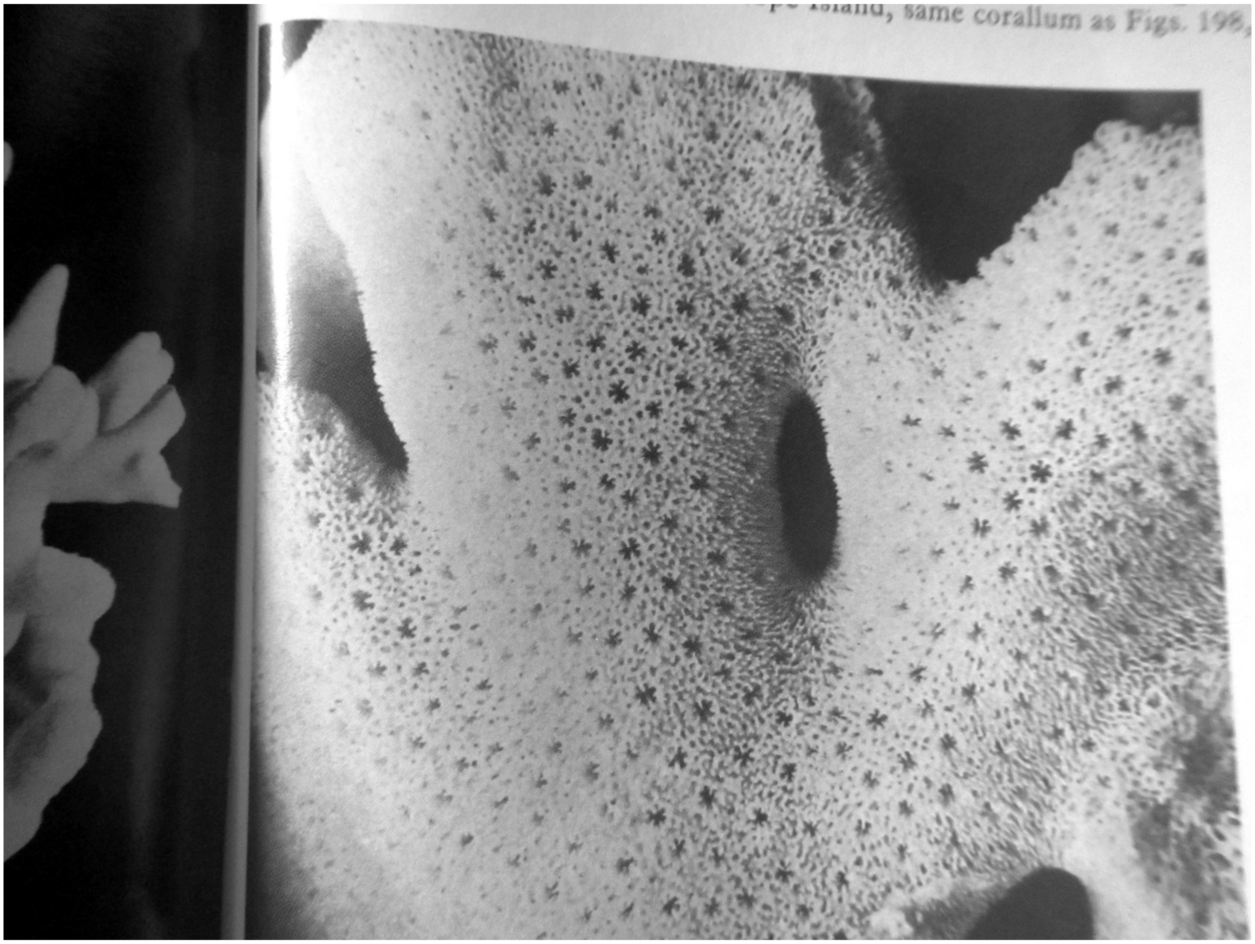


Figure 4. Closeup photo of *Montipora digitata* from Veron and Wallace (1984).

***Montipora* sp.** “green columns and plates”

The green colony with columns and plates is clearly NOT *M. digitata* or anything like it. It is closest to *Montipora stellata* and *M. carinata* (=*M. hirsuita*). But it is distinct from them. *M. stellata* has 4 synonyms that Veron & Wallace (1984) list. It could be one of those or an unnamed species. From what Veron says, the synonyms don't appear to be hot leads. I'll see if I can check any of them.

The skeleton is branching, 13 cm long, with irregular shapes that range from nodules to branches. Nodules are about 3-4 mm diameter and most are short. There are three branch ends, each oval, up to 4 X 15 mm wide, and flat ended. Nodular areas are covered with fine papillae, and the branches have very thin, long ridges running their length. There are both thecal and coenosteal papillae, which are not clearly differentiated. Papillae are composed of fused spinules, with a filigree arrangement of spinules on their tips. The branches have long, thin, raised striations running lengthwise, that appear to be thin ridges to the naked eye, and surfaces have papillae much like the nodules have. Corallites are about 0.6-0.8 mm diameter. First cycle septa complete, up to ¾ R, second cycle incomplete, up to 1/3 R. First cycle septa vary in thickness. Corallites on the branches are very superfical. The coenosteum is coarse, on the branches most of the elements run lengthwise in places. The plate is 5-7 mm thick on the central edge, 6 cm from the edge of the plate. The plate has coarse coenosteum with lighter calcification that the branches, so larger holes. There are fewer corallites on the upper surface, and only a few small corallites on the under surface.

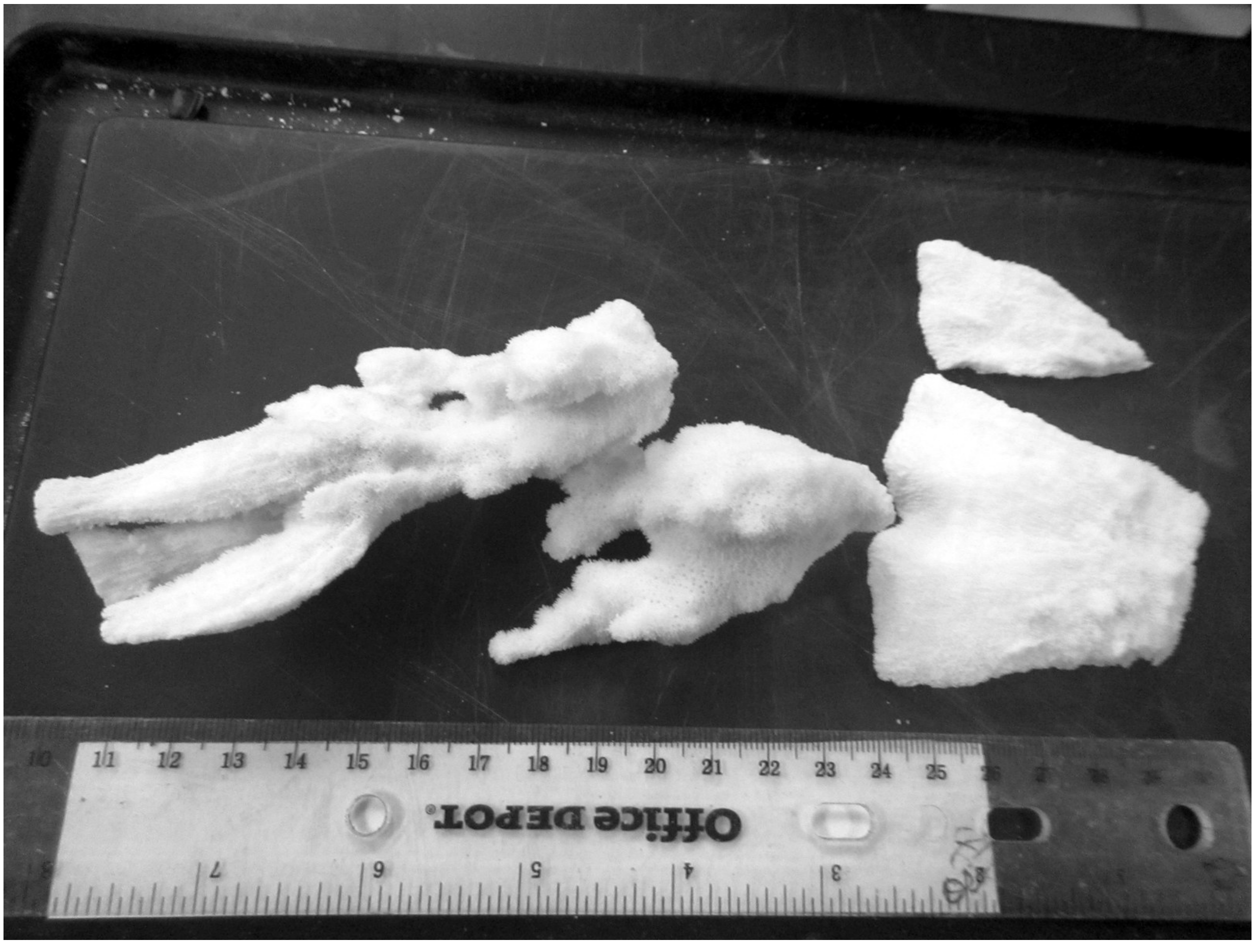


Fig 5. *Montipora* sp. “green columns and plates.” The pieces on the right are the plate pieces, the piece that extends from the left to the center is the columnar piece.

Figure 6. Branch end, *Montipora* sp.

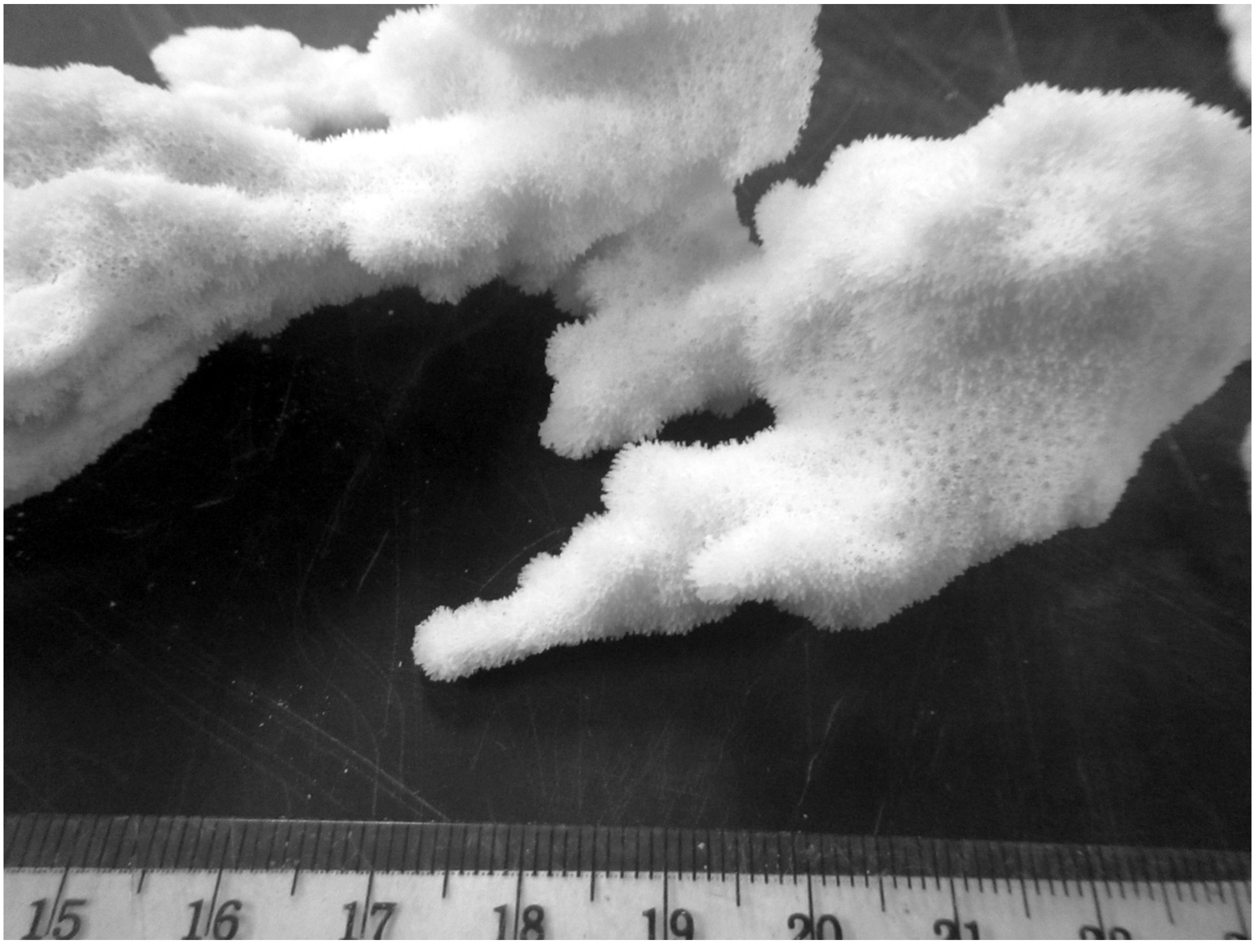


Figure 7. Nodular portion of column, *Montipora* sp. Notice the fine spines.

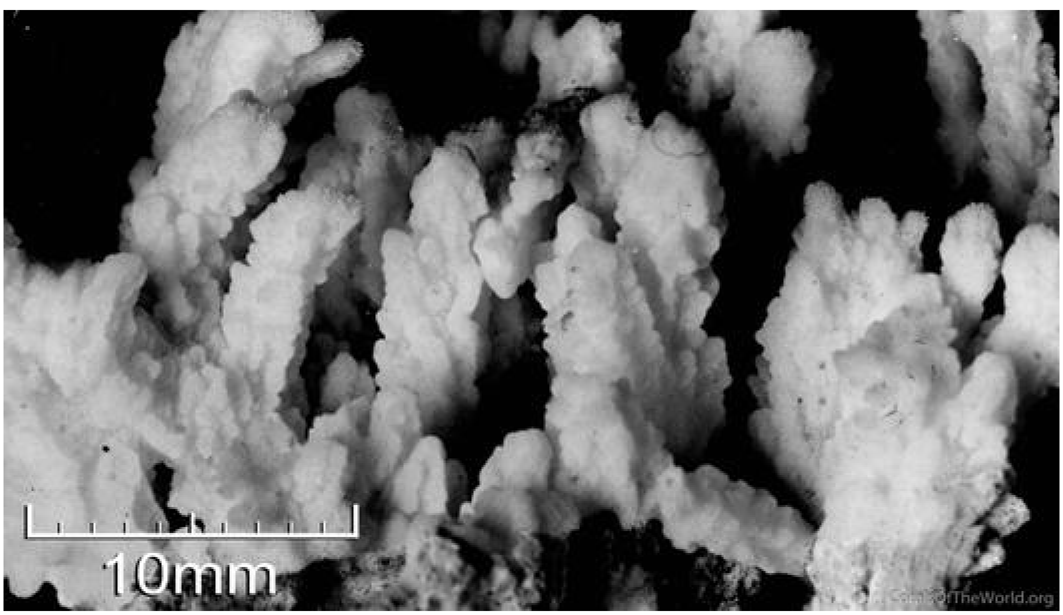


Figure 8. *Montipora stellata* from Veron et al 2000 (www.coralsoftheworld.org) Notice the large bumps.

Montipora foliosa, "orange plates in whorls"

The orange foliose colony appears to fit with *Montipora foliosa* pretty closely. It is clearly not *M. delicatula*, *M. mactanensis*, or *M. cebuensis*. It is very different from *M. capricornis*, which does not have radiating ridges. I conclude it is *Montipora foliosa*. There appears to be a fair bit of variation within *Montipora foliosa*.

Photographs of the living colonies show orange plates in whorls, with radiating thin ridges. The skeleton pieces are up to 7 by 7 cm (clearly small pieces from the edge of a colony) which are about 5 mm thick 7 cm from the outer edge of the colony. The outer edge is relatively thick, about 3-4 mm thick, and smooth. The upper surface of the coral has many long, thin, compact ridges which radiate and are parallel with little anastomosing. The underside is much smoother, with low rounded radiating ridges. Ridges are rounded and about 1 mm wide and tall, with spaces between them about 1 mm wide. Centrally, some ridges reach 2-3 mm tall, and have narrower, more serrated edges. Corallites are located only between ridges, there is only one row of corallites between ridges, corallites are slightly raised, and about 0.6-0.8 mm diameter. First cycle septa some to all present, up to 2/3 R. Second cycle septa absent or some present up to ¼ R. Coenosteum is coarse.   The underside has a very fine coenosteum, with small corallites about 0.3 mm diameter, widely spaced, about 0.5 to 3 mm apart.

Figure 9. Pieces of *Montipora* orange foliose.

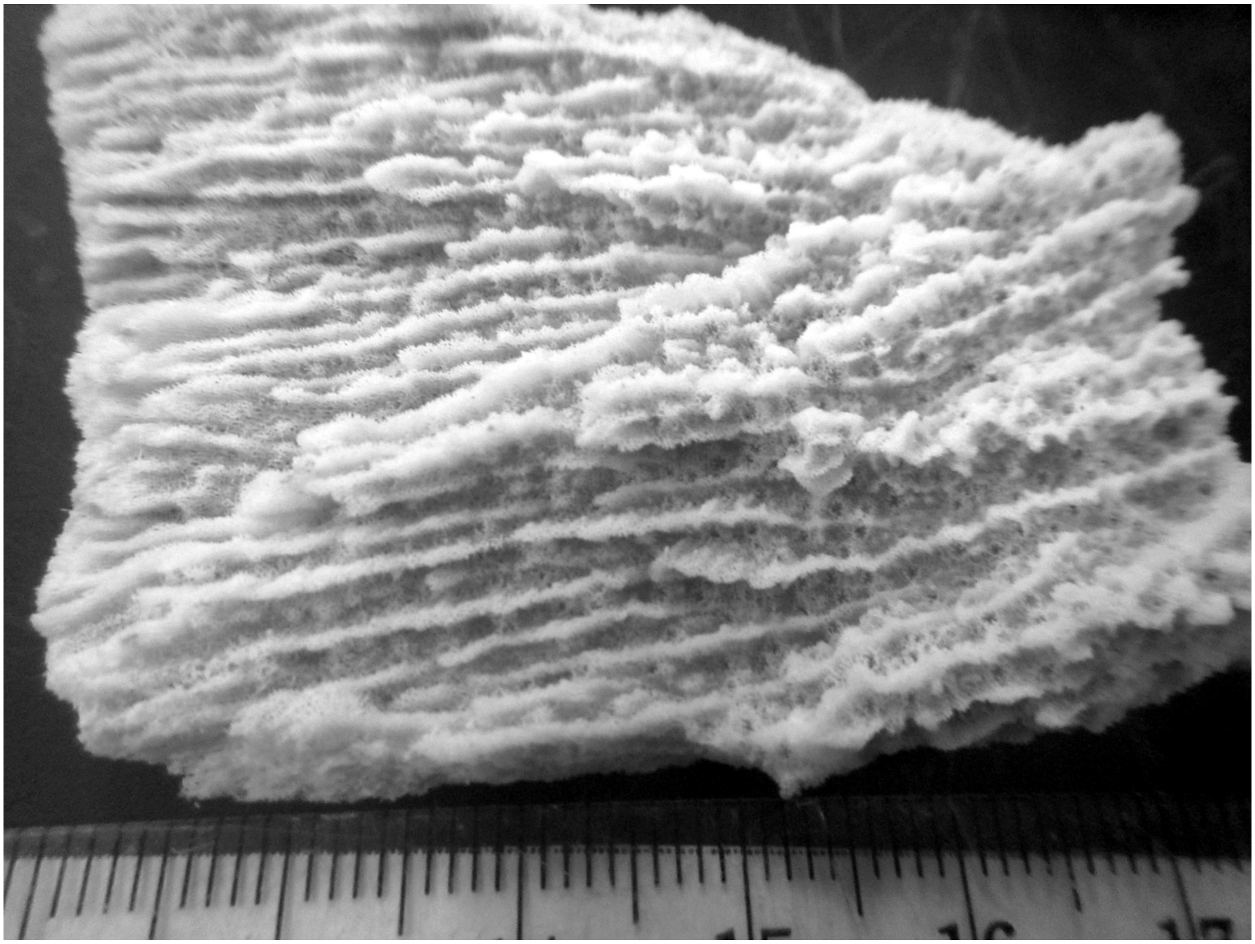


Figure 10. Closer photo of orange foliose *Montipora*.

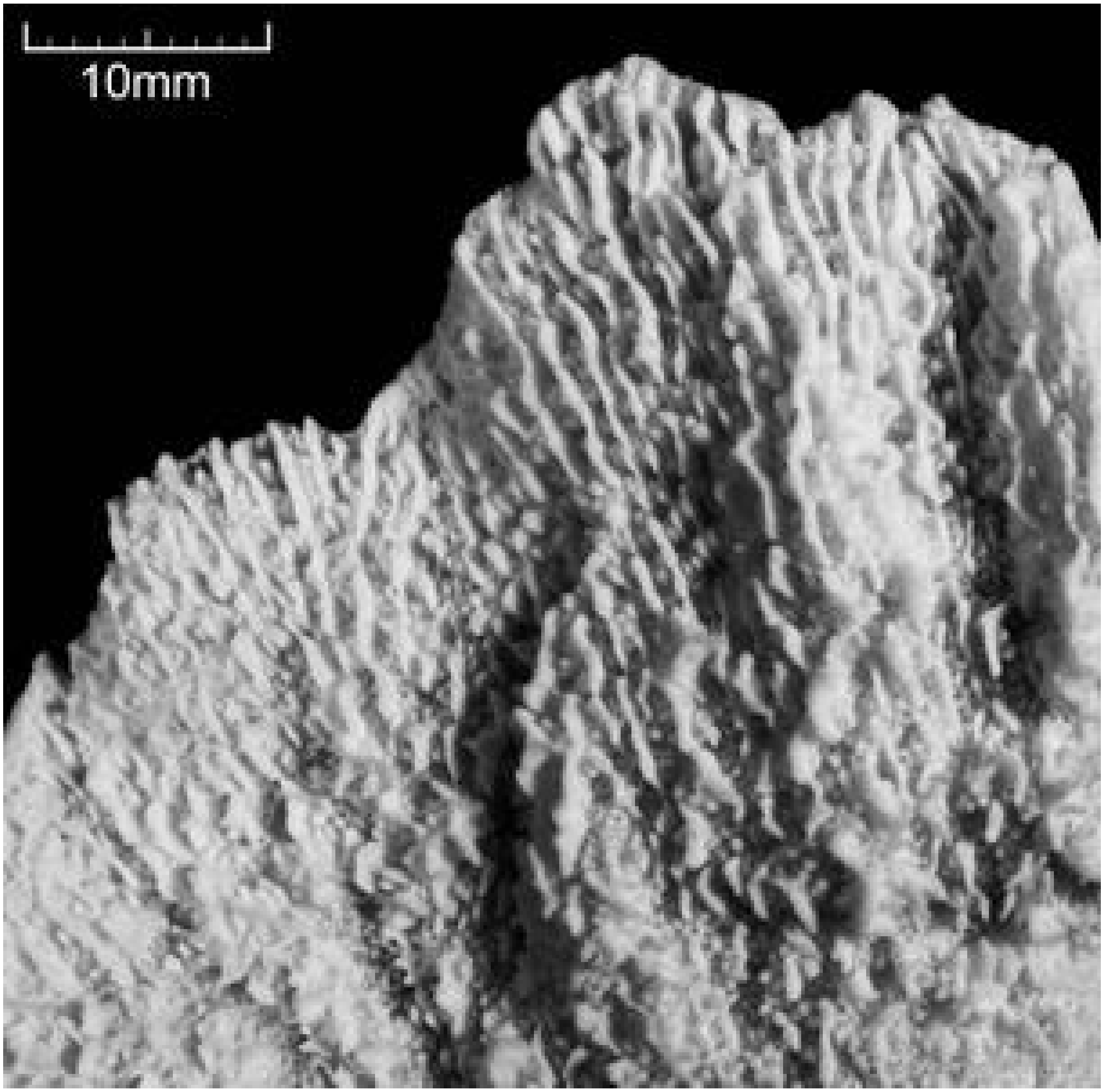


Figure 11. *Montipora foliosa*, from Veron et al (2020: www.coralsoftheworld.org).

Figure 12. A closeup photo of *Montipora foliosa* from Veron and Wallace, 1984.

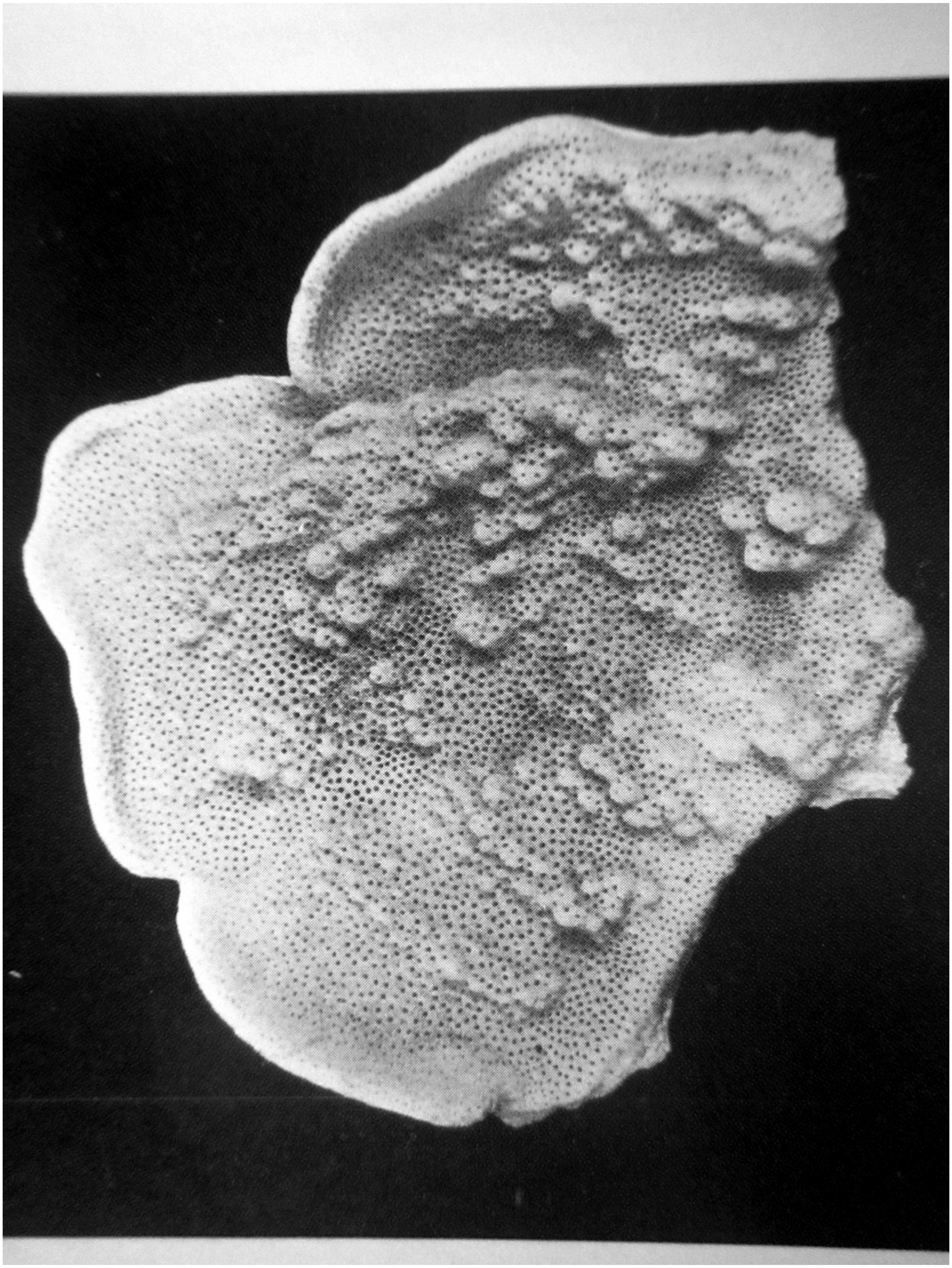


Figure 13. A whole colony photo of *Montipora capricornis* from Veron and Wallace, 1984.

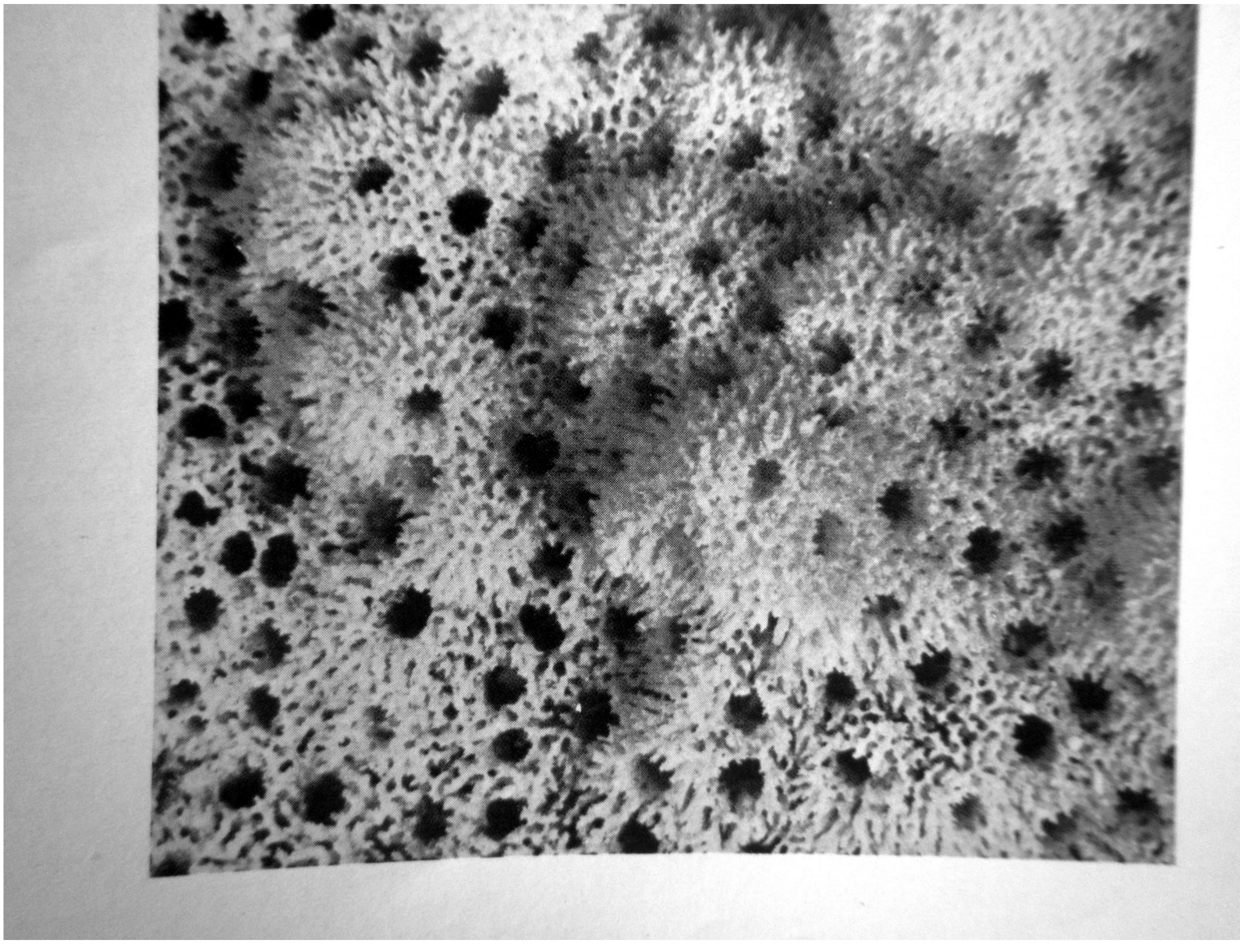


Figure 14. A closeup photo of *Montipora capricornis.*

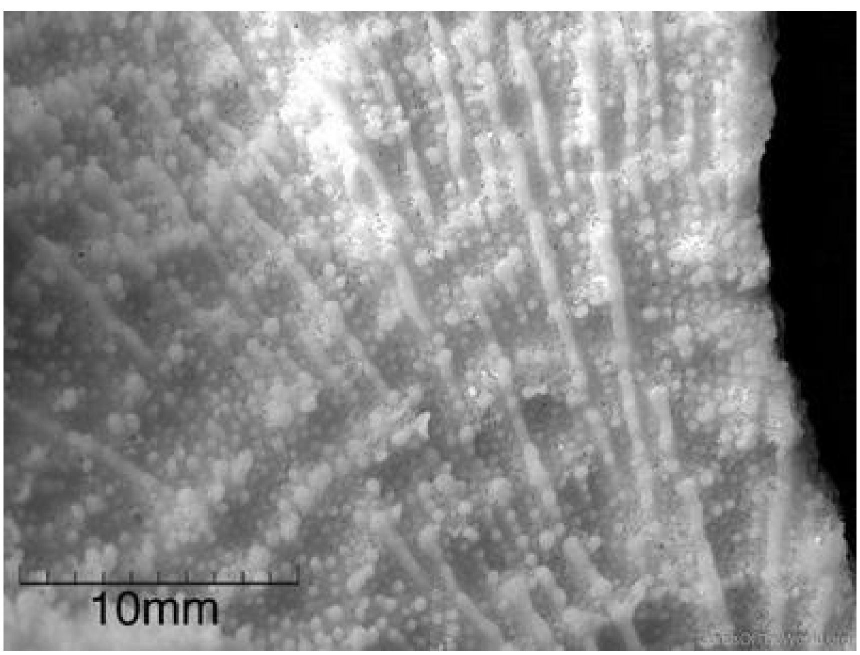


Figure 15. A closeup photo of *Montipora delicatula* from Veron et al (2020; www.coralsoftheworld.org).

Appendix C: Non-native Coral Reproductive Assessment: PowerPoint by Mike Henley

Non-native Montipora spp.
Kāneʻohe Bay
2-July-2020

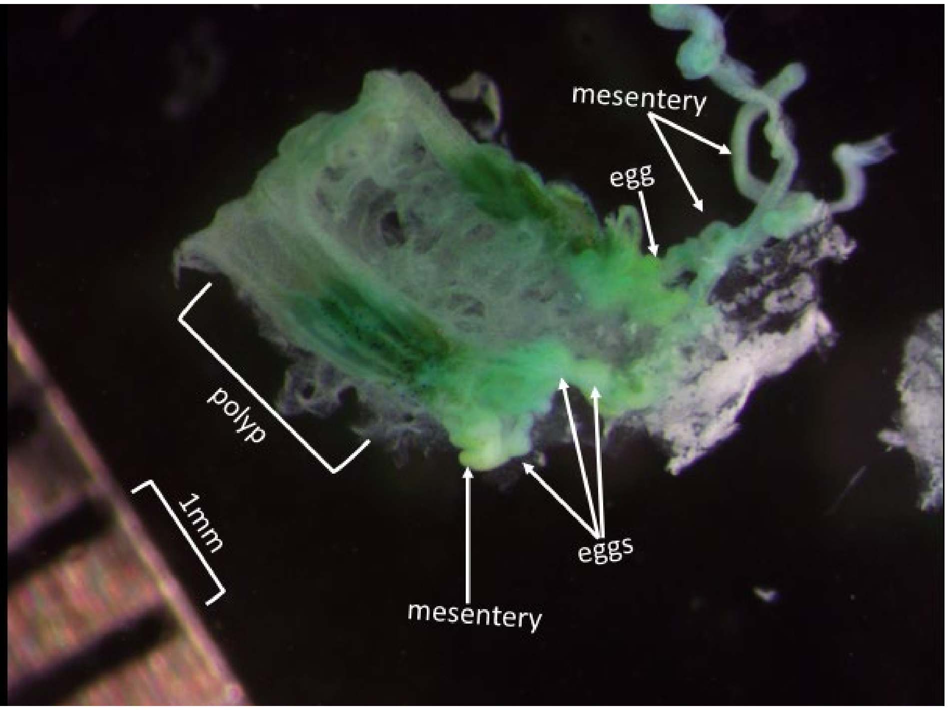
Mike Henley
Doctoral Candidate: Hawai'i Institute of Marine Biology

Non-native Montipora spp.

- Fragments were fixed for 48 hours in 4% paraformaldehyde (PFA) with filtered seawater (FSW)
- Fragments were then decalcified for 24 hours in Cal-Ex decalcifier
- After decalcification, fragments were rinsed in fresh water for about 2 hours
- After rinsing, tissue was placed in 1% methylene blue solution for about 10 seconds and then rinsed in fresh water
- Fragments then stored in 70% EtOH
- Scale bars in photos are 1mm

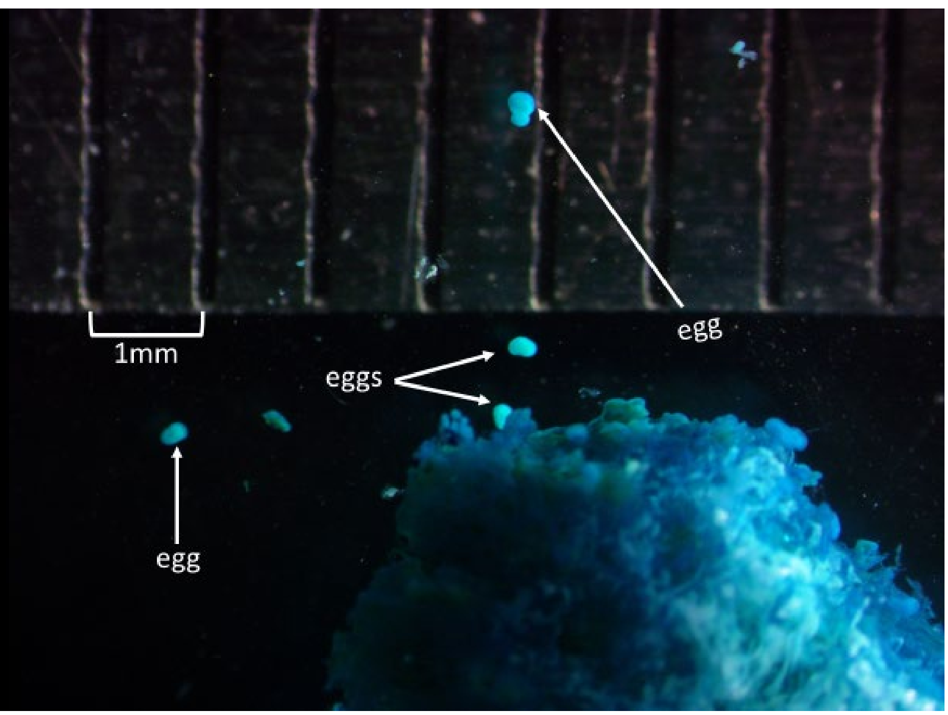
Montipora digitata

- Coral is not yet stained
- Eggs are bound and coiled with mesentery



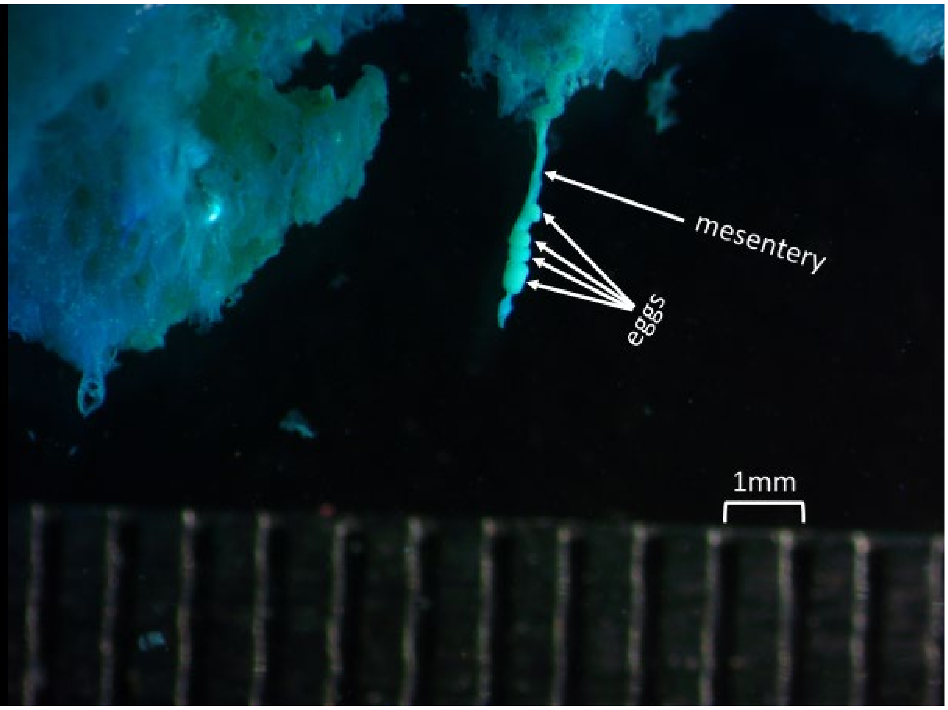
Montipora digitata

- Coral is stained with Methylene Blue
- The free eggs here were shaken loose from the mesenteries as I was peeling back the decalcified tissues
- Eggs appear to be about 200µm



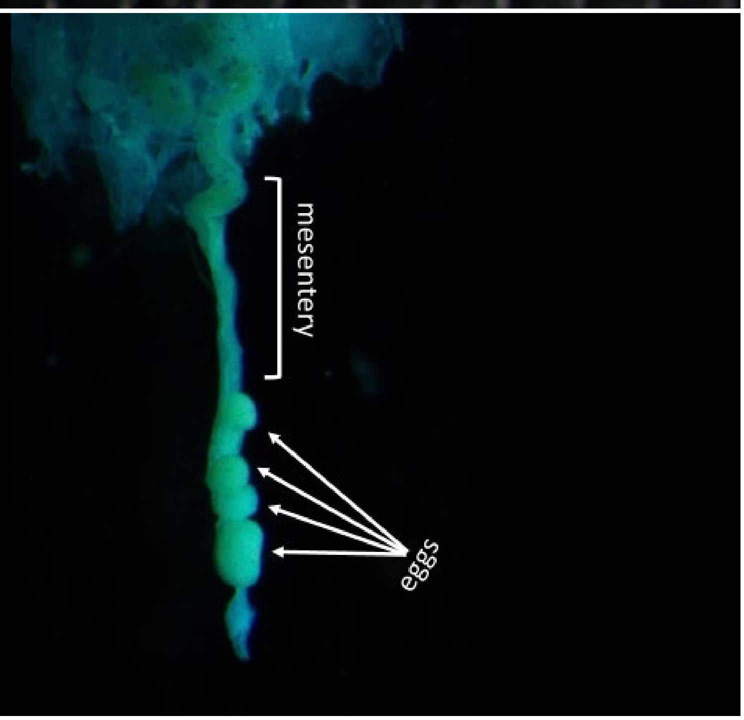
Montipora foliosa

- Coral is stained with Methylene Blue
- Eggs in the characteristic line along the mesentery



Montipora foliosa

- Closer look at eggs and mesentery
- No scale bar present
- Possibly *Symbiodinium sp.* present in the eggs (brown speckles) but would need higher magnification to confirm



Non-native *Montipora spp.*

- Eggs are present in *M. digitata* (purple branching) and *M. foliosa* (orange plating)
- Did not find any eggs present in *Montipora sp.* (possibly *M. stellata* or *M. carinata*)
  - However, as time permits, might need to decalcify another section to confirm
- The eggs in the other two species seem to be in the 200-300µm range
  - Spawning size is typically 400-450µm
  - **Probably a few months away from spawning**

Introduced coral species discovered in Kāneʻohe Bay 2020: a brief review

Jon Ehrenberg

Hawaiʻi Coral Reef Initiative, Division of Aquatic Resources, Ānuenue Fisheries Research Center, Sand Island, Honolulu, Hawaiʻi 96819, USA

Abstract

This literature review provides background information on coral species that were discovered in Kāneʻohe Bay by local community members. The first two species; *Montipora foliosa* and *Montipora digitata*, were positively identified. There is still uncertainty regarding a positive ID for the third coral species. The two species that closely resemble the unidentified coral are *Montipora stellata* and *Montipora carinata*. All four of these coral species are not naturally occurring within the Hawaiian Archipelago and are hypothesized to have been introduced. It is unknown where these colonies originated from; however, estimates place their ages between 2 to 50 years. With growing concerns from community members, these introduced corals are scheduled to be removed from Kāneʻohe Bay and placed in the custody of the Waikiki Aquarium.

Montipora foliosa (Pallas, 1766)

GENERAL DESCRIPTION

Montipora foliosa colonies grow in plates that form whorls or tiers (Veron et al. 2016). A distinguishing feature of this species is the coenosteum ridges that run perpendicular to the colony’s growing edge (Veron et al. 2016). Colors range from a brown/cream hue to pink (Veron et al. 2016).

NATIVE RANGE

Montipora foliosa are widespread throughout the Indian, western and central Pacific Oceans (Cairns et al. 1999). This widespread species is found in: American Samoa, Australia, the Red Sea, the southwest, northwest and northern Indian Ocean, Indo-Pacific, South-east Asia, Japan, Palau, Philippines, Marianas, the East China Sea, and other coastal reef areas in these regions (DeVantier et al. 2014). *Montipora foliosa* is commonly found on protected upper reef slopes within its native range (Veron et al. 2016). It is a popular species in the aquarium trade and is exported and grown internationally (DeVantier et al. 2014). There are no previous records of this species in the main Hawaiian Islands.

ICUN Red List Status

Near Threatened (DeVantier et al. 2014).

REPRODUCTION

This plating and scrolling coral generally spawns in November during a full moon lunar phase (Babcock et al. 1986; Richmond & Hunter 1990). *Montipora foliosa* are hermaphroditic, slow release, broadcast spawners (Babcock et al. 1986). Colonies were observed spawning two days after the full moon and approximately two and a half hours after sunset (Babcock et al. 1986). This species can reproduce asexually via fragmentation (Richmond & Hunter 1990). It is possible that the colonies discovered in Kāneʻohe Bay were introduced as fragments, which subsequently broke to produce the multiple colonies observed today. However, this is not confirmed and the origin of the colonies located in Kāneʻohe Bay is still unknown.

GROWTH RATE

Over a three year observation period, transplanted *M. foliosa* colonies in the Philippines had linear growth rates of 3.25 centimeters/year (cm/yr) or 2.71 millimeters/month (mm/month)

(Gomez et al. 1985). If the growth rate of the colony in Kāneʻohe was similar to that observed by Gomez et al. (1985), the largest colony with a diameter of about 1 meter (m) could be approximately 15 years old. This is assuming the linear growth rate out from the center is 3.25 cm/yr and the radius of the colony is 50 cm. For a more accurate estimate, the area of the entire colony could be compared to the measured rate of 83.3 cm^2/yr (Gomez et al. 1985).

***Montipora foliosa* in reef restoration**

Transplantation of *M. foliosa* fragments has been used in coral reef restoration efforts in the Philippines; however, the survival rates of the transplanted fragments was 5.9% over a 10 month monitoring period (Yuyang et al. 2016). The small newly established fragments were affected by sedimentation and a cyclone during the monitoring period (Yuyang et al. 2016). Compared to the four other coral species used, *M. foliosa* was not as tolerant to less than optimal conditions (Yuyang et al. 2016). Researchers determined that *M. foliosa* was not a suitable option for reef restoration in areas where stressors would affect the survivability of fragments (Yuyang et al. 2016). If *M. foliosa* is to be used in restoration efforts, potential stressors should be identified and addressed before transplantation.

Montipora digitata (Dana, 1846)

GENERAL DESCRIPTION

Montipora digitata colonies are described as forming digitate upright branches (Veron et al. 2016). The color of the colony can vary from hues of brown to a cream complexion and in some cases, polyps can present as a pink, purple, or blue (Veron et al. 2016).

NATIVE RANGE

Montipora digitata are widespread throughout the Indian, western and central Pacific Oceans (Cairns et al. 1999). They are found in shallow reef environments and have been recorded as the dominant species in certain shallow mud flats (Veron et al. 2016). The lower depth limit for *M. digitata* is approximately 5 m (DeVantier et al. 2008). This widespread species has been recorded in Australia, the British Indian Ocean Territory, Cambodia, Comoros, Chagos Archipelago, Eastern Africa, Micronesia, the Marshall Islands, the Solomon Islands, South-east Asia, southern

Japan, Sri Lanka, Palau, Philippines, Papua New Guinea, Vanuatu, and other shallow reef areas in these regions (DeVantier et al. 2008). *Montipora digitata* is a popular species in the aquarium trade and is grown and exported internationally (DeVantier et al. 2008). There is anecdotal evidence that this species has been previously recorded in the main Hawaiian Islands.

ICUN Red List Status

Least Concern (DeVantier et al. 2008).

REPRODUCTION

This branching Montiporid coral species generally spawns from October to November during full moon lunar phases (Babcock et al. 1986; Richmond & Hunter 1990). *Montipora digitata* are hermaphroditic broadcast spawners with tan colored gametes (Babcock et al. 1986; Richmond & Hunter 1990; Penland et al. 2003). In 2002, *M. digitata* was observed spawning on coral reefs in Palau 1-2 days after a full moon (Penland et al. 2003). *Montipora digitata* in Palau spawned in February from 1930-2030 (24 hour clock), March from 1915-2045, April from 1910-1945, and September from 1930-2030 (Penland et al. 2003).

GROWTH RATE

In Queensland, Australia, colony growth rate for *M. digitata* has been measured by recording linear branch extension and ranged from 1.9 - 3.1 mm/month (Heyward & Collins 1985). In 1981, the highest growth rates were observed between the months of August and May, while the lowest growth rates were measured from September to October (Heyward & Collins 1985). These growth rates were the average of 25 branches from 15 colonies and large variations were observed among colonies (Heyward & Collins 1985). Over a 329 day experimental period, Heyward & Collins (1985) extrapolated an average linear branch extension rate of 24 mm/yr. In a more recent study conducted in 2007, radial growth rates of transplanted fragments were 0.3 ± 5.1 mm/month (Gomez et al. 2011). With such large variations in growth rates and methodologies for measuring growth in *M. digitata* it is difficult to find agreement on an average growth rate.

Montipora digitata in reef restoration

Due to the fast growth rates of *M. digitata*, reef restoration projects have used this species where appropriate. In 2007, researchers in the Philippines used *M. digitata* fragments to test the feasibility of using this species for coral reef restoration (Gomez et al. 2011). Fragments were transplanted into a lagoon area near the island of Santiago, which is an area commonly affected by typhoons and anthropogenic stressors such as sedimentation and dynamite fishing (Gomez et al. 2011). Groups of fragments in high and low densities were monitored every 3-6 months over a 21 month experimental period (Gomez et al. 2011). Multiple environmental parameters were monitored to observe their effects on the fragments; however, water turbulence had the greatest impact on the survival and growth of fragments (Gomez et al. 2011). Presence of other species near the fragments were recorded and statistically compared to the survival rates of the groups (Gomez et al. 2011). In general, fragments had to compete with turf algae and sponges growing nearby (Gomez et al. 2011). Low density groups had survival rates of approximately 75% and colony height increased to 3.1-8.2 mm/month (Gomez et al. 2011). The lowest survival rate of approximately 20% was recorded for the high-density groups, which also had colony height increases ranging from 0.8-5.8 mm/month (Gomez et al. 2011). Gomez et al. (2011) determined *M. digitata* could be used for coral restoration in areas where it does not normally occur, but fragments should be planted at a lower density for better survival and growth.

Montipora stellata Bernard, 1897

GENERAL DESCRIPTION

Montipora stellata colonies generally are small and form tall upright branches (Veron et al. 2016). Colony branches are lined with irregular white ridges (Veron et al. 2016). Colony color can be cream, brown, and hues of blue (Veron et al. 2016).

NATIVE RANGE

Montipora stellata is found on coral reef ecosystems in the Indian and western and central Pacific Oceans (Cairns et al. 1999). This Montiporid has been observed in Australia, Bahrain, China, Egypt, Fiji, Indonesia, Japan, Malaysia, New Caledonia, Palau, Papua New Guinea, Philippines, Singapore, Solomon Islands, Taiwan, Thailand, Viet Nam, and other reef areas in these regions (DeVantier et al. 2008). *Montipora stellata* is common within its native range and can be the dominant species in shallow reefs, but it has been found at depths up to 20 m (DeVantier et al. 2008; Veron et al. 2016). *Montipora stellata* is not native to the Hawaiian Archipelago and has not been previously recorded in the islands.

ICUN Red List Status

Least Concern (DeVantier et al. 2008)

REPRODUCTION

Montipora stellata is a hermaphroditic broadcast spawner, which has been recorded spawning 1-3 days after a full moon (Penland et al. 2003; Penland et al. 2004). In 2002, colonies were recorded spawning in February from 1930-2030, March from 1915-2030, April from 1910-1945, and September from 1900-2010 (Penland et al. 2003; Penland et al. 2004). Gametes observed were tan on all occasions during spawning (Penland et al. 2003).

GROWTH RATE

Montipora stellata has been noted as a fast-growing coral species (DeVantier et al. 2008; Veron et al. 2016). If *M. stellata* was present in reef areas where live coral cover was negatively affected by natural disasters, the recovery of live coral cover in these areas was greater than areas without *M. stellata* (Tkachenko et al. 2007). From 2003-2005, *M. stellata* out competed *Acropora spp.* on reefs affected by hurricanes in the area due to its ability to reproduce and grow quickly via fragmentation (Tkachenko et al. 2007). There is limited research on growth rates for) *M. stellata* and most growth rate information is anecdotal. *Montipora stellata* is a popular species in the aquarium hobby and online aquarium hobbyist blogs put growth rates of *M. stellata* less than *M. foliosa*.

Montipora carinata Nemenzo, 1967

(Synonym: *Montipora hirsuta* Nemenzo, 1967)

GENERAL DESCRIPTION

Montipora carinata, also referred to as *Montipora hirsuta*, is a common species within its native range (DeVantier et al. 2008; Veron et al. 2016). Similar to *M. stellata*, *M. carinata* forms branching colonies with flat tips and irregular shapes, extending upward (Veron et al. 2016). Compared to *M. stellata*, *M. carinata* has smaller branches and corallites (Veron & Hodgson 1989). Colonies generally range from cream to brown in color, with the ends of branches a white or blue hue (Veron et al. 2016). Irregular ridges form at the branch tips from fused Coenosteum papillae (Veron et al. 2016).

NATIVE RANGE

The native range of *M. carinata* is limited to coral reefs in the western and central Pacific (Cairns et al. 1999). Reef areas that contain *M. carinata* within this region are located in Australia, Indonesia, Japan, Malaysia, Micronesia, Palau, Papua New Guinea, Philippines, Singapore, Solomon Islands, Taiwan, Thailand, and Vietnam (DeVantier et al. 2008). Colonies are commonly found in shallow reef areas with a lower depth limit of 15 m (DeVantier et al. 2008; Veron et al. 2016). Colonies provide shelter and habitat to fish and invertebrate species. *Montipora carinata* is a popular coral species in the aquarium trade and is harvested from the wild for exportation and sale (DeVantier et al. 2008). However, *M. carinata* has not been previously recorded or identified in the Hawaiian Archipelago and it is not native to the area.

ICUN Red List Status

Near Threatened (DeVantier et al. 2008)

REPRODUCTION

Montipora carinata are hermaphroditic broadcast spawners that generally spawn at night during or following a full moon (Penland et al. 2003). On reefs in the Palau, *M. carinata* was observed spawning in March 2002, one day after a full moon, and between 1930-2045 (Penland et al. 2003).

GROWTH RATE

Further research on growth rates of wild populations of *M. carinata* is required. Anecdotal accounts of growth rates in an aquarium setting put growth rates slower than *M. foliosa*.

Discussion

Compared to other tropical Pacific coral species, Hawaiian corals tend to have slower growth rates (Rodgers et al. 2003; Jokiel et al. 2008). The growth rates of four common Hawaiian coral species range from 6.00 to 26.52 mm/yr (Rodgers et al. 2003). Due to the slow growth rates of Hawaiian species, there is concern that introduced species with faster growth rates could out compete native species. In Table 1. and Fig 1. the average growth rates of four common native Hawaiian species and two non-native coral species are listed. Though *M. digitata* does not have a higher growth rate than *M. capitata*, *M. digitata* grows quicker than the other three native species. *Montipora foliosa* is the fastest growing coral species, growing 6 mm/yr more than *M. capitata*. Given the fast growth rates of the non-native corals and their ability to reproduce via fragmentation, there is some concern that they could become invasive in certain situations.

Table 1. The locations and mean linear extension rates of four common native Hawaiian coral species and two non-native tropical Pacific coral species (Gomez et al. 1985; Heyward & Collins 1985; Rodgers et al. 2003).

Species	Locality	Mean Linear Extension Rates (mm/yr)
M. capitata	Kāneʻohe Bay, Hawaiʻi	26.52
P. compressa	Kāneʻohe Bay, Hawaiʻi	18.24
P. lobata	Kāneʻohe Bay, Hawaiʻi	8.04
P. meandrina	Kāneʻohe Bay, Hawaiʻi	6.00
M. foliosa	Dumaguete, Philippines	32.52
M. digitata	Townsville, Queensland, Australia	24.00

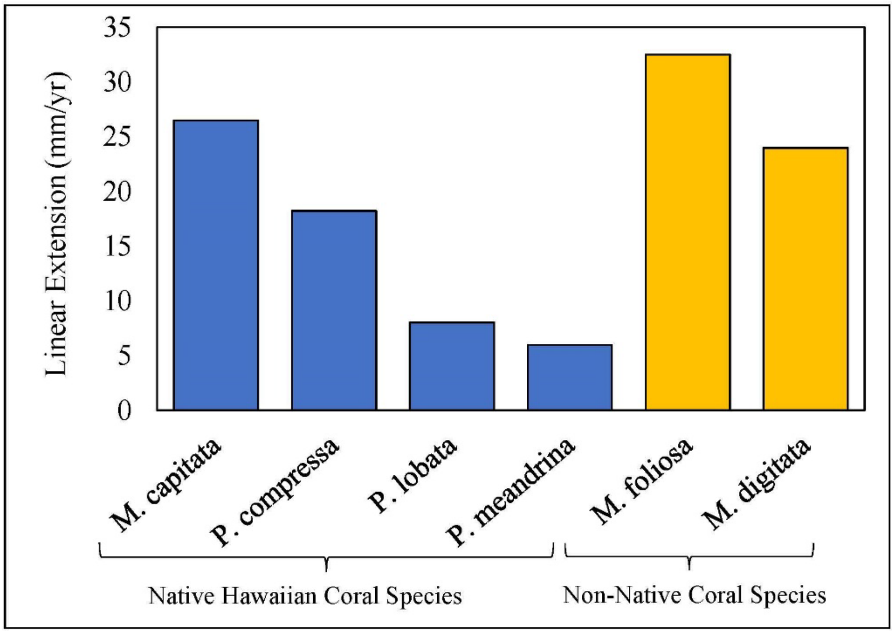


Fig 1. Mean linear extension rates of four common native Hawaiian coral species and two non-native tropical Pacific coral species (Gomez et al. 1985; Heyward & Collins 1985; Rodgers et al. 2003).

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