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An Update on Recent Research and Management of Hawaiian Black Corals

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AN UPDATE ON RECENT RESEARCH AND MANAGEMENT OF HAWAIIAN BLACK CORALS

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I. Introduction

Antipatharians, commonly known as black corals, are a little studied order of anthozoan hexacorals that currently encompasses over 235 described species (Cairns 2007, Daly et al. 2007, Bo 2008). Black corals occur worldwide in all oceans from polar to tropical regions, and have a wide depth distribution ranging from 2-8,600 m (reviewed by Wagner et al. 2012a). Despite this wide bathymetric range, black corals are primarily found in deeper waters below the photic zone, with over 75% of known species occurring exclusively below 50 m (Cairns 2007). At these depths, antipatharians are often abundant and dominant faunal components, and create habitat for a myriad of associated organisms (reviewed by Wagner et al. 2012a).

In Hawai'i black corals are particularly important, not just from an ecological perspective, but also from an economic and cultural one. First, black corals are the predominant habitat-forming species on Hawaiian deep reefs that are exposed to strong currents (50-150 m; Grigg 1965, Grigg 1976, Chave & Malahoff 1998, Parrish & Baco 2007). Second, Hawai'i is the only place in the United States, and only one of a few places in the world, where black coral is harvested commercially for the precious coral jewelry industry, a multi-million dollar business that employs close to 650 people in manufacturing facilities and retail stores statewide (Grigg 2001, Parrish & Baco 2007, Grigg 2010). Third, black corals are important culturally as they

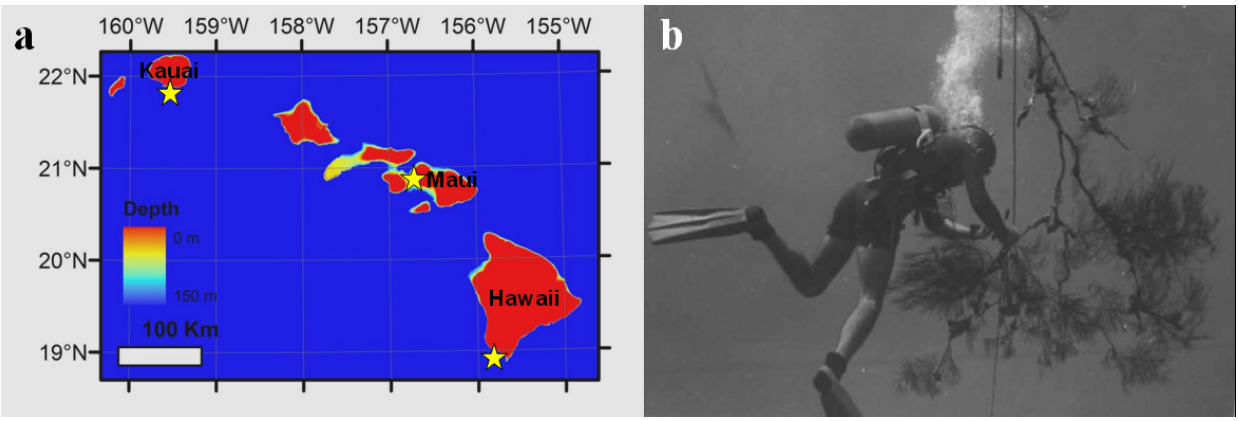

Figure 1. *(a) Map showing the geographic locations of the three largest commercially valuable black coral beds in Hawai'i. (b) Diver attaching black coral colony to an anchor line so it can be lifted to the surface (Photo by R. Grigg).*

represent the official gemstone of the State of Hawai'i, and were traditionally used in Hawaiian culture for medicinal purposes (Kaaiakamanu & Akina 1922, Chun 1994). 'Ēkaha kū moana, as black coral is known in the Hawaiian language, has for a long time been cherished by native Hawaiians for its presumed therapeutic effects against lung diseases and mouth sores (Kaaiakamanu & Akina 1922, Chun 1994).

Despite the fact that native Hawaiians have used black corals for several centuries, Hawaiian antipatharians were only discovered by western scientists at the beginning of the 20th century. In 1902, the scientific expedition by the U.S. Fish Commission Steamer *Albatross* was the first to sample black corals from the Hawaiian Archipelago (Bayer 1961). Through the use of deep-sea trawls and tangle nets, the *Albatross* sampled black corals in Hawaiian waters at depths exceeding 2,000 m, although the majority of antipatharian specimens were collected at depths shallower than 500 m (Bayer 1961). Black coral specimens collected by the Albatross were deposited in the National Museum of Natural History, where they remained largely unexamined until recent reexaminations of these collections led to the description of numerous new antipatharian species including several from Hawaiian waters (Opresko 2002, 2003c, 2005). In 1928, Verrill was the first to formally describe Hawaiian black coral species, when he described *Antipathes grandis* and *Antipathes irregularis* (Verrill 1928), the latter of which was later identified as a gorgonian (Grigg & Opresko 1977). In 1958, large aggregations of black corals were discovered off Maui (Gage 1962, Grigg 1964), a discovery which eventually lead to the development of a local black coral fishery (Grigg 2001), as well as to numerous studies on this group of corals. Scientists, resource managers and fishermen have collaborated closely throughout the history of the fishery (Grigg 2001), and as a result, Hawaiian antipatharians are some of best studied on the globe (Etnoyer & Morgan 2005, Wagner et al. 2012a). The purpose of this article is to briefly summarize these collaborations, with an emphasis on black coral research and management activities that have occurred since the last synthesis on the state of the deep-sea ecosystems in Hawai'i (Parrish & Baco 2007).

II. The History of the Hawaiian Black Coral Fishery

Since its inception in 1958, the Hawaiian black coral fishery has been supplied by SCUBA divers that collect the coral at depths between 40-70 m, primarily in the Au'au Channel between the islands of Maui and Lāna'i, and to a lesser extent off the islands of Kaua'i and Hawai'i (Figure 1; Oishi 1990, Grigg 2001, Parrish & Baco 2007). Harvesting methods have remained essentially unchanged since start of the fishery, and involve fishermen descending to black coral beds using SCUBA, severing colonies from the substrate using axes or sledges, and then bringing coral trees back to the surface via lift bags or anchor lines (Figure 1; Oishi 1990, Grigg 2001). Three black coral species have been reported as being targeted by the Hawaiian precious coral fishery, and include *Antipathes griggi* Opresko, 2009 (formerly A. *dichotoma*), *Antipathes grandis* Verrill, 1928, and *Myriopathes* cf. *ulex* (Ellis & Solander, 1786) (formerly *Antipathes ulex*) (Figure 2; Grigg 1976, NOAA 1983, Oishi 1990, DLNR 1999, Grigg 2001, Parrish & Baco 2007, Grigg 2010). However, close to 90% of the coral harvested in Hawaiian waters consists of *A. griggi*, with *A. grandis* and *M.* cf. *ulex* representing 10% and 1% of harvested black coral, respectively (Oishi 1990).

III. Black Coral Fishery Management

The vast majority of commercially valuable black coral beds lie in waters that fall under the jurisdiction of the State of Hawai'i (<3 nautical miles from shoreline), with a much lesser degree found in federal waters (3-200 nautical miles from shore) (Figure 1; Grigg 2001, Parrish & Baco 2007, Grigg 2010). The fishery is therefore managed through both state and federal regulations, which are set by the Hawai'i Department of Land and Natural Resources (DLNR), and NOAA's National Marine Fisheries Service (NMFS) in consultation with the Western Pacific Regional Fishery Management Council (WPRFMC), respectively (NOAA 1983, DLNR 1999, NOAA 2002, DeMello 2006, NOAA 2007, 2008). State regulations came into effect in 1981 (DLNR 1999). Since then, all harvesters of black corals in Hawaiian state waters are required to purchase a state commercial marine license, and submit catch reports if the coral is sold (Oishi 1990). In 1999, the State of Hawai'i added size limits by which it prohibited harvesting of colonies with a base diameter of less than 1.905 cm (DLNR 1999), which corresponds to a colony height of 90 cm (Boland & Parrish 2005), or an age of 14-15 years using growth rate estimates (6.12-6.42 cm/yr; Grigg 1976). Federal regulations on the fishery became effective in 1983, which mandated domestic fishermen to report their catches in federal waters (NOAA 1983). In 2002, federal regulations added size harvesting limits, which prohibited harvesting of colonies with a base diameter of less than 2.54 cm or a colony height lesser than 122 cm (NOAA 2002). Additionally, the 2002 federal rule provided persons that had reported black coral landings between 1997 and 2002 the option to apply for an exemption, that allowed harvesting using the minimum base diameter of 1.905 cm (NOAA 2002). This exemption was removed in 2007, thereby effectively prohibiting all federal harvesting of colonies lesser than 122 cm in height or 2.54 cm in width (NOAA 2007). In 2008, a harvesting quota of 5,000 kg/2 years was established for the Au'au Channel bed (Figure 1), where the vast majority of black corals have been harvested since 1980 (Parrish 2006, NOAA 2008). In 2012, an annual catch limit of 2,500 kg/year was set for the Au'au Channel bed

(NOAA 2012). While this annual catch limit applies to the entire Au'au Channel bed, which extends through both state and federal waters, it is currently only enforced in federal waters (NOAA 2012). Additionally, the 2012 revisions set an annual catch limit of 1,000 kg/year for all precious corals in the Hawai'i exploratory area (NOAA 2012). This catch limit applies to all precious corals found in federal waters anywhere else outside the Au'au Channel bed in Hawai'i, and includes pink, red, bamboo, gold (currently under moratorium) and black corals (NOAA 2012).

IV. Recent Research

The recent revisions of fishery regulations (NOAA 2007, 2008, 2012), were the results of a number of deep-water surveys (40-110 m) that indicated a decline in the biomass of commercially valuable black corals (Grigg 2001, 2004). Surveys performed in the Au'au Channel in 1975 and 1998, showed similar colony size-frequency distributions, and thereby suggested a long-term stability in the recruitment and growth of black coral populations (Grigg 2001). In contrast, subsequent surveys performed in 2001, revealed a downward shift towards smaller sized colonies, as well as a 25% decline in the biomass of black corals since 1998 (Grigg 2004). Likely causes for these declining patterns included both increases in harvesting pressure, and overgrowth of black corals by the invasive octocoral *Carijoa* sp. (initially identified as *Carijoa riisei*) (Grigg 2003, 2004, Kahng & Grigg 2005). Together, these developments raised questions about whether fishery regulations needed to be redefined in order to maintain a sustainable harvest (Grigg 2004). To address these concerns, the WPRFMC held a workshop to review the state of the Hawaiian black coral fishery and to identify future research priorities (WPRFMC 2006). The workshop highlighted the need for studies on the (1) growth, (2) reproduction, (3) recruitment, (4) mortality, (5) fishing, and (6) geographical distributions of Hawaiian antipatharians (WPRFMC 2006). Motivated in large part by these recommendations, several studies have recently examined various aspects of the taxonomy, biology and ecology of commercially valuable Hawaiian black corals, and are briefly reviewed below.

Taxonomy

In 1977, Grigg and Opresko (1977) published a taxonomic survey of Hawaiian antipatharians based on colony branching pattern. Since that study, skeletal spine morphology has become increasingly important in antipatharian taxonomy (Opresko 2001, 2002, 2003c, 2004, 2005, 2006, and references therein), because this character is thought to be largely independent of environmental cues, as compared to other more plastic morphological characters (Lapian et al. 2007, Wagner et al. 2010). Recent taxonomic studies using skeletal spine morphology have led to more detailed descriptions of several Hawaiian species, as well as to revisions of the species names that had previously been used in the literature (Opresko 2009, Wagner et al. 2010, Wagner 2011, Wagner et al. 2011a, Opresko et al. 2012). While these recent revisions have provided better insights into what species are present in Hawaiian waters and how they compare to species found elsewhere, systematics of the entire antipatharian order are still in a state of revision.

Prior to recent revisions, the Hawaiian species *Antipathes griggi* (Figure 2) was known as *A. dichotoma* Pallas, 1766, a species originally described from off Marseilles in the Mediterranean Sea (Pallas 1766). Subsequent comparisons between Hawaiian and Mediterranean specimens revealed substantial

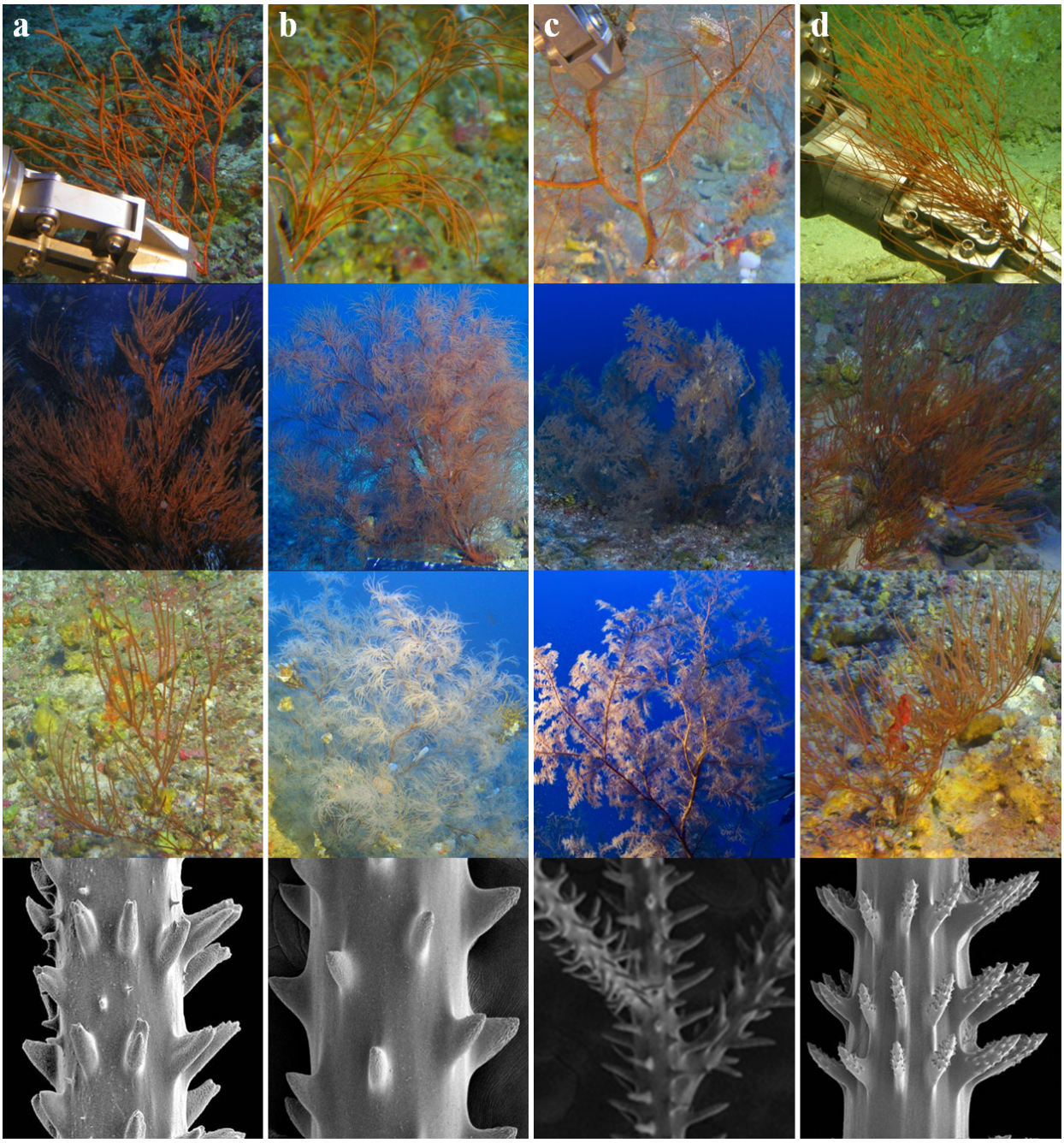

Figure 2. *Hawaiian antipatharian species (a) Antipathes griggi, (b) Antipathes grandis, (c) Myriopathes cf. ulex, and (d) Aphanipathes verticillata (scale bars = 200 μm). NOTE: With the exception of M. cf. ulex, species cannot be reliably differentiated based on colony morphology alone, and typically require microscopic examination of skeletal spines (bottom row). Photos courtesy of the Hawaiian Undersea Research Laboratory (HURL).*

morphological differences (Opresko 2003a). As a result, the Hawaiian "*A. dichotoma*" was assigned the new name of *Antipathes griggi* and formally described (Opresko 2009).

Even though *Antipathes grandis* (Figure 2) was the first antipatharian species to be described from Hawai'i (Verrill 1928), the original species description was very brief and the type material remained unexamined for a long period. Therefore, Wagner et al. (2010) redescribed *A. grandis* using morphological and molecular characters, in conjunction with *in situ* observations. These examinations revealed that *A. grandis* colonies can exhibit three different color morphotypes, at least one of which may have been confounded with *A. griggi* in the past (Figure 2).

Grigg (1964) presented the first published account of *Myriopathes* cf. *ulex* (Figure 2) from Hawai'i (as *Antipathella* sp.), and Grigg and Opresko (1977) later identified this species as *Antipathes ulex* Ellis and Solander, 1786. In 2001, Opresko reassigned *A. ulex* to the newly established antipatharian family *Myriopathidae* and the new genus *Myriopathes*, resulting in the name *Myriopathes ulex*. The original species description of *M. ulex* is rather brief (Ellis & Solander 1786), and the type material has been lost (Opresko 2001). Thus, positive identification of *M. ulex* cannot be made until a neotype is designated. Pending such a taxonomic revision, the name *Myriopathes* cf. *ulex* is used here and elsewhere to refer to the species that is targeted by the Hawaiian black coral fishery (Wagner 2011, Wagner et al. 2012f).

Besides these three species that had been known to exist in areas where black corals have been harvested in Hawai'i (*A. griggi*, *A. grandis* and *M.* cf. *ulex*), recent surveys have discovered a fourth species, *Aphanipathes verticillata* Brook, 1889 (Figure 2), which was previously unknown from Hawaiian waters (Opresko et al. 2012). While gross observations suggest that the skeleton of this species is suitable to manufacture jewelry and may therefore have been targeted by the fishery, all known records of Hawaiian *A. verticillata* come from depths that are slightly deeper (88-130 m) than the harvesting depth zone (40-70 m; Opresko et al. 2012). It is therefore unknown if, and to what extent, *A. verticillata* has been commercially harvested in Hawai'i (Opresko et al. 2012).

Geographic and depth ranges

Surveys for *A. griggi* have been particularly frequent in Hawai'i, because it is the main fishery species. Based on field observations using colony morphology, *A. griggi* has been reported throughout the Hawaiian Archipelago to depths of 159 m (Chave & Malahoff 1998). However, recent taxonomic studies have shown that *A. griggi* can easily be misidentified as the sympatric species *A. grandis* or *Aphanipathes verticillata* (Figure 2). These recent taxonomic studies raise questions about the validity of many previous reports of *A. griggi* (as *A. dichotoma*), especially those at depths below 100 m. Additionally, colonies with similar morphologies to *A. griggi*, identified as *A. dichotoma*, have been reported from various Indo-Pacific locations including the Philippines, Indonesia, Palau, China, Guam and Johnston Atoll (Van Pesch 1914, Grigg 1975, Zhou & Zou 1984, Zou & Zhou 1984, Zhou & Zou 1992, Chave & Malahoff 1998, Paulay et al. 2003, Rogers et al. 2007, Qi et al. 2009). These locations all lie outside the range of *A. dichotoma*, which is only known from the Mediterranean and East Atlantic (Opresko 2003a, Bo 2008). Like the previous misidentification of *A. dichotoma* from Hawai'i, these misidentified *A. dichotoma* records may also be *A. griggi*. However, detailed taxonomic

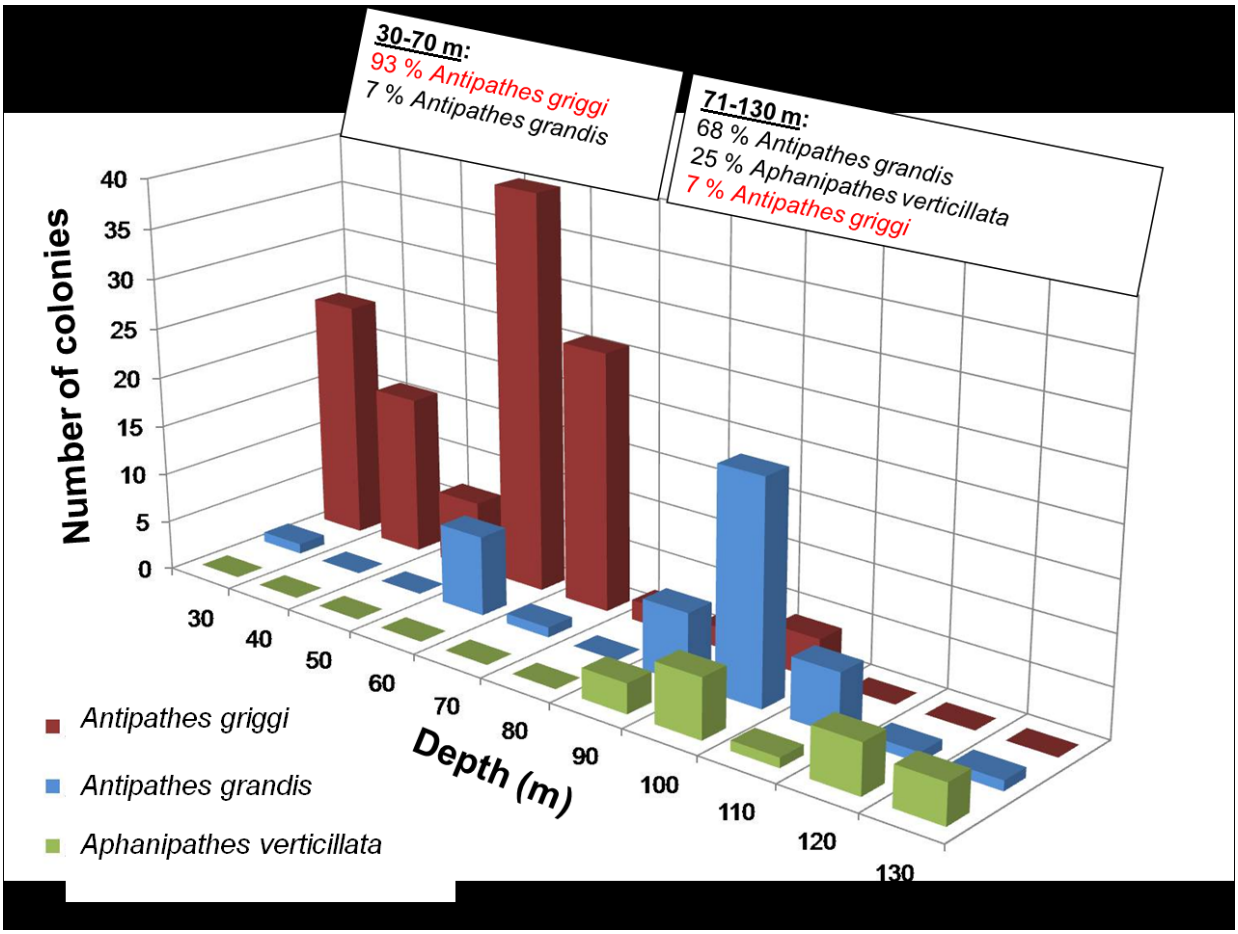

Figure 3. *Depth distribution by species for 250 black coral colonies sampled at depths between 30-130 m in the Au'au Channel.*

investigations of specimens from these Indo-West Pacific locations will have to be undertaken to confirm this. To date, specimens identified as *A. griggi* using all available diagnostic characters, have only been reported from the Hawaiian Archipelago from the islands of Hawai'i to Laysan at depths ranging between 10-110 m (Opresko 2009, Wagner 2011, Wagner et al. 2011a, Wagner 2015).

A. grandis was originally described from a specimen collected off Maui (Verrill 1928), and subsequently reported throughout the Main Hawaiian Islands from Hawai'i to Ni'ihau at depths between 27-127 m (see Wagner et al. 2010). Additionally, there are two reports of this species from off China (Zhou & Zou 1984, Zou & Zhou 1984); however, these records cannot be confirmed until specimens from that locality are examined.

Myriopathes ulex was initially described from Indonesia (Ellis & Solander 1786), but subsequently reported throughout the Indo-West Pacific at depths ranging between 25-364 m (Blainville 1834, Gray 1857, Brook 1889, Van Pesch 1914, Grigg & Opresko 1977, Chave & Malahoff 1998, Parrish & Baco 2007, Rogers et al. 2007, Bo 2008, Moon & Song 2008). However, a thorough taxonomic investigation is needed to verify whether these records all correspond to the same species that is present

in Hawaiian waters. In the Hawaiian Islands, *Myriopathes* cf. *ulex* has been confirmed from Hawai'i Island to Pearl and Hermes Atoll at depths ranging between 41-326 m (Wagner 2011, Wagner et al. 2011a, Wagner 2015).

Up to now the black coral fishery has been managed under the presumption that a harvesting depth refuge exists; however recent studies have shown that there is no such depth refuge (Wagner et al. 2012f). Due to logistical constraints of SCUBA diving, fishermen have traditionally harvested black corals at depths between 40-70 m. However, dense black coral populations exist in the Main Hawaiian islands to depths of at least 110 m (Grigg 2001, Parrish & Baco 2007). It had previously been thought that colonies below the harvesting depth zone (>70 m) provided a depth refuge from the fishery and were capable of reseeding fished populations in shallower water (<70 m; Grigg 1976, 2001). However, recent surveys indicate that the majority of black corals below 70 m consist of *A. grandis* (68%) and *Aphanipathes verticillata* (25%), with *A. griggi* accounting for only 7% (Figure 3; Wagner et al. 2012f). Thus, the population size below the harvesting depth zone has been overestimated in the past and there is no real depth refuge from harvest (Wagner et al. 2012f).

Sexual reproduction and histological studies

As many other aspects of the antipatharian biology (see Wagner et al. 2012a), information on the sexual reproduction is scarce, and is mostly limited to brief notes accompanying taxonomic descriptions (reviewed by Wagner et al. 2011h). Recent histological examinations of eight Hawaiian species, including the commercially valuable *A. griggi* and *A. grandis*, have revealed that there are several similarities in the sexual reproduction of black corals, even among distantly related species (Wagner et al. 2011h, Wagner et al. 2012a). First, of the six primary mesenteries only the two in the transverse plane bear gametes. Second, entire colonies are generally either female or male, although sequential hermaphroditism cannot be ruled out in most cases. Third, there is no evidence for internal fertilization within antipatharians, indicating that fertilization and larval development likely occur externally in the water column and not internally within polyps. Additionally, a more detailed study on the sexual reproduction of *A. griggi* has demonstrated that this species (1) is gonochoric with a 1:1 sex ratio, (2) has an annual reproductive cycle, and (3) spawns in multiple successive events with greatest intensities between November and December (Wagner et al. 2012f). Furthermore, this study revealed that ~80% of colonies meeting the state harvesting limit (90 cm) are sexually mature, whereas ~90% of colonies meeting the federal limit (122 cm) are sexually mature (Wagner et al. 2012f).

Apart from providing insights into the sexual reproduction of antipatharians, recent histological investigations have uncovered endosymbiotic algae of the genus *Symbiodinium*, also known as zooxanthellae, within a large proportion of Hawaiian black coral species (Wagner et al. 2011d). Due to the predominant occurrence of antipatharians in low-light environments that do not support photosynthesis (>50 m, Cairns 2007), the absence of *Symbiodinium* within black corals has generally been inferred rather than empirically demonstrated, and the whole taxonomic order has been considered azooxanthellate (see Wagner et al. 2011d). That said, close to a century ago several scientists noted round structures within the tissues of several black coral species, which they interpreted as symbiotic algae (Brook 1889, Van Pesch 1914, Buchner

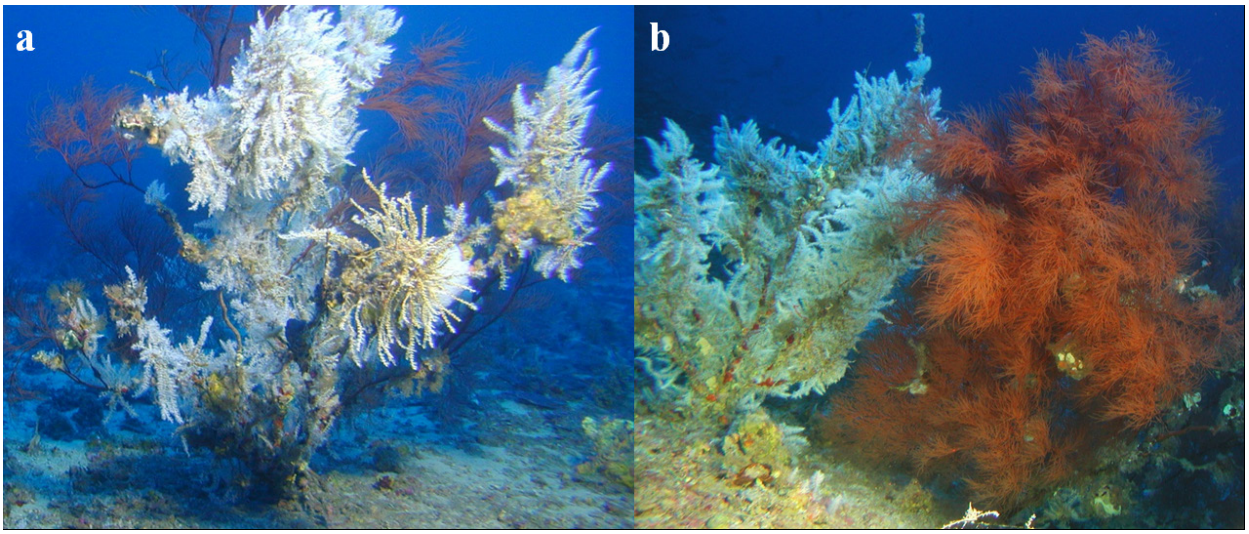

Figure 4. *(a-b) Commercially valuable Hawaiian black corals, overgrown by the invasive octocoral Carijoa sp. in the Au'au Channel. Photos courtesy of HURL.*

1921). However, these early reports have been largely overlooked or dismissed as questionable. Supporting the tentative nature of these reports, numerous more recent studies using histological techniques (Grigg 1964, 1976, Goenaga 1977), chlorophyll measurements (Shick & Dykens 1985, Santiago-Vazquez et al. 2007) and molecular techniques (Santiago-Vazquez et al. 2007) have failed to detect *Symbiodinium* within antipatharians. In contrast, Wagner et al. (2011d) detected very low densities (0–92 cells/mm3) of endosymbiotic *Symbiodinium* within the majority of black coral species from Hawai'i, and down to a maximum depth of 396 m. While the physiological role of the endosymbiotic cells were not determined, their low densities coupled with the extreme depths at which they were recorded, argue that they do not provide their antipatharian hosts with photosynthetic products and thus suggest an either parasitic or commensal association with black corals (Wagner et al. 2011d).

Overgrowth by *Carijoa* sp.

The alcyonacean octocoral *Carijoa* sp. was first observed in Hawai'i in 1966 (Kahng et al. 2008) and the first published record of this species was in 1972, when it was discovered within the fouling community of Pearl Harbor, O'ahu (Evans et al. 1974). In 2001, black coral surveys in the Au'au Channel recorded *Carijoa* sp. overgrowing a large percentage of commercially valuable Hawaiian black corals at depths between 70-110 m (Figure 4; Grigg 2003). Due to the concerns about the effects of this invasion on the Hawaiian black coral fishery, several studies were initiated to characterize and monitor the impacts of *Carijoa* sp. on black corals (Kahng & Grigg 2005, Kahng et al. 2008, Concepcion et al. 2010, Kahng 2010). Initial surveys in the Au'au Channel indicated that over 75% of the number of *A. grandis* and *A. griggi* colonies were overgrown by the octocoral at depths between 80-110 m (Kahng & Grigg 2005). However, subsequent monitoring efforts in the channel suggested that the impact of the *Carijoa* sp. invasion was not worsening with time, and that while still widespread and

serious, the invasion was less severe than previously thought (Kahng 2010). These more recent surveys have determined that ~33% of black corals >40 cm have *Carijoa* sp. overgrowth, with ~25% of colonies being completely overgrown and ~8% being partially overgrown (Kahng 2010). Furthermore, *Carijoa* sp. appears to settle on portions of black coral colonies where the bare skeleton is exposed, which can be created by abrasion or senescence (Kahng and Grigg 2005). There are no known natural predators of Hawaiian black corals (Wagner et al. 2012b), and therefore it is unknown whether predation facilitates *Carijoa* sp. overgrowth.

V. Future Management Directions and Implications for Other Coral Fisheries

While the latest surveys on the effects of *Carijoa* sp. on commercially valuable black corals indicate that the impacts are less severe than first assumed (Kahng 2010), recent studies also indicate that there is no depth refuge from harvest (Wagner et al. 2012f). Consequently, the biomass of commercially valuable black corals will likely continue to decline if no corrective management actions are undertaken (Grigg 2004). Specifically, three revisions in the management regulations should be pursued, including (1) increasing both the state and federal harvesting size limits to 130 cm to ensure that more colonies have a chance to reproduce before being exposed to fishing mortality, (2) setting aside no take areas to allow more colonies to continuously reproduce and reseed fished populations, and (3) limiting the entry of new fishermen. While there are only three permitted vessels in the Hawaiian black coral fishery (NOAA 2007), advances in diving technologies may attract more people into collecting black coral in the near future. Traditionally, diving for black corals has been a hazardous occupation due to the many inherent risks associated with deep SCUBA diving (Grigg 2001, 2010). However, as new diving technologies such as mixed-gas technical diving and closed-circuit rebreathers become more readily available, there will likely be an increased incentive for people to enter the fishery. Fetching over $25/lb., harvesting black corals can be a lucrative enterprise (Grigg 2001). With novel technologies making black coral harvesting a safer practice, there will likely be a future increase in the fishing pressure on black corals. Thus, limiting the number of people entering the fishery should be pursued now before the resource becomes too depleted. Furthermore, creating no take areas may allow for the reseeding of fished populations. With the exception of black corals found in federal waters around Hawai'i, there is currently no limit on the amount of black coral that can be harvested in Hawai'i. As black coral populations in federal waters get progressively depleted, fishermen might be pushed towards exploring black coral beds closer to shore. Without any other regulations, these beds are currently vulnerable to becoming overexploited, especially if new diving technologies attract more people to enter the fishery and allow for more efficient harvesting.

Besides Hawai'i, black corals have been commercially harvested in several other regions around the globe including throughout Asia, South America, the Caribbean, the Mediterranean and the Red Sea (Grigg 1975, Noome & Kristensen 1976, Castorena & Metaca 1979, Olsen & Wood 1980, Kenyon 1984, Grigg 1993, Romero 1997, Padilla & Lara 2003, Deudin et al. 2010, Tsounis et al. 2010). However, in contrast to the Hawaiian fishery, antipatharian fisheries

in most other locations have remained largely unmanaged and thus exhibited a cyclic pattern of discovery of a population, exploitation, depletion, followed by exploration for new harvesting grounds, a boom and bust cycle that resembles strip mining more than a fishery (Noome & Kristensen 1976, Castorena & Metaca 1979, Grigg 1993, Romero 1997, Padilla & Lara 2003, Tsounis et al. 2010). In contrast, the Hawaiian black coral fishery has had a comparatively long history and serves as a commendable example of what can be achieved through close collaborations between resource managers, scientists and fishermen. Through continued research partnerships between different fishery stakeholders, black coral populations in Hawai'i have become some of the best studied in the world, and it is imperative that adaptive management strategies continue to be pursued as new scientific information becomes available.

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