North Pacific Fisheries Commission

NPFC-2020-SSC BFME01-WP08

Report on VMEs and SAIs on Koko, Yuryaku, Kammu and Colahan seamounts

USA

Abstract: Two peer-reviewed papers are presented for consideration under SSC BFME 01 agenda item 6.4.2:
Baco et al. 2019. Amid fields of rubble, scars, and lost gear, signs of recovery observed on seamounts on 30- to 40-year time scales.
Baco et al. 2020. Observations of vulnerable marine ecosystems and significant adverse impacts on high seas seamounts of the northwestern Hawaiian Ridge and Emperor Seamount Chain.

These papers document the locations of VMEs and SAIs on seamounts of the NHR-ESC based on scientific research surveys. They are submitted with the intention of formally reporting these locations to the NPFC. These papers also provide background information relevant to the BFME discussions on establishing VME post-encounter protocols and a standardized approach to SAI determination and are relevant to agenda items 6.3.2, 6.3.3, and 7.3.

When SAIs are occurring on VMEs, the NPFC regulations state that it is necessary to "adopt appropriate conservation and management measures to prevent SAIs" [NPFC 2017]. Therefore, in accordance with the precautionary approach, and to "establish appropriate conservation measures" the results presented here would indicate a closure of all NHR and ESC seamounts to bottom contact fisheries until the gear being used can be proven to not cause SAIs. Additionally, since recovery is possible for these VME taxa, not only untrawled areas ('freeze the footprint type measures") should be closed, but also actively fished areas should be closed to bottom contact gear to allow them time to recover. Examples of following the precautionary approach in seamount management can be seen in the NAFO area where many features are closed to bottom-fishing due to the presences of corals and sponges [NAFO 2018]. Similar closures have already been enacted for coral-rich habitats within the NPFC on Koko Guyot and C–H seamount [NPFC 2019], thus the NPFC already has the regulatory guidelines in place to enact further closures to protect the VMEs described herein.

ECOLOGY

Amid fields of rubble, scars, and lost gear, signs of recovery observed on seamounts on 30- to 40-year time scales

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Although the expectation of lack of resilience of seamount vulnerable marine ecosystems has become a paradigm in seamount ecology and a tenet of fisheries management, recovery has not been tested on time scales >10 years. The Northwestern Hawaiian Ridge and Emperor Seamounts have experienced the highest documented fish and invertebrate seamount fisheries takes in the world. Surveys show that, despite visible evidence of substantial historic fishing pressure, a subset of these seamounts that have been protected for >30 years showed multiple signs of recovery including corals regrowing from fragments and higher abundances of benthic megafauna than Still Trawled sites. Contrary to expectations, these results show that, with long-term protection, some recovery of seamount deep-sea coral communities may be possible on 30- to 40-year time scales. The current practice of allowing continued bottom-contact fishing at heavy trawled sites may cause damage to remnant populations, which likely play a critical role in recovery.

INTRODUCTION

High-flow hard substrate areas on seamounts are generally colonized by dense assemblages of suspension feeders, which, in many areas, are dominated by deep-sea corals (*1*–*5*). With growth rates on the order of micrometers to millimeters per year, and life spans ranging from decades to millennia, the life history characteristics of deep-sea corals connote a high vulnerability to, and protracted recovery from, disturbance (*6*–*9*). Adding to this picture of protracted recovery time is research that indicates that recruitment of coral larvae is sporadic or limiting for deep-sea species, with larvae being selective of substrate type and with slow-growing recruits (*10*, *11*). These life history characteristics are the primary reasons seamount deep-sea coral communities are designated as vulnerable marine ecosystems (VMEs) and as ecologically and biologically significant areas (EBSAs) and have led to the prediction that recovery of seamount coral communities following anthropogenic disturbance likely takes decades to centuries, if recovery is even possible at all [reviewed in (*6*)]. Although the opportunities to test this hypothesis have been rare, existing studies support the lack of recovery on 5- to 10-year time scales (*12*–*14*).

Despite the lack of opportunity to test the hypothesis on longer time scales, these observations, combined with the expectation of low resilience based on life history characteristics, have resulted in wide-scale acceptance among fisheries managers and seamount ecologists of the idea of decadal to century time scales for recovery from anthropogenic disturbance (*6*). While this paradigm provides a logical argument for minimizing the expansion of bottom trawling efforts, the argument has also been flipped, with high-seas regional fisheries management organizations (RFMOs) and domestic fisheries management workshops using the lack of recovery potential as a justification to continue fishing an area. For example, in both Alaska and in the South Pacific RFMO, seafloor areas with little or no history of trawling have been closed to trawling, but areas that have already experienced high impacts have been left open to fishing, with the justification that areas that have already experienced high trawling damage are unlikely to recover (*15*–*17*). The expectation of no recovery has also been used in cost-benefit analyses of fisheries to select areas within the existing trawling footprint to prioritize for protection, with areas with higher fisheries impact considered to have reduced "benefit" to protection (*15*, *18*).

An excellent opportunity to gain additional and longer-term insights into the recovery potential of seamount deep-sea coral communities occurs in the U.S. Exclusive Economic Zone (EEZ) around the Hawaiian Archipelago and in adjacent international waters of the far Northwestern Hawaiian Ridge (NHR) and lower Emperor Seamount Chain (ESC). Heavy fishing efforts in the far NHR and ESC seamounts in the 1960s to the 1980s, concentrated at depths of 300 to 600 m, resulted in the largest amount of fish and invertebrate biomass removed from any documented seamount fishery in the world [as quantified in (*19*)]. This included two types of fisheries: trawling, which removed up to 210,000 metric tons of fishes per year, and coral tangle net fishing, which removed as much as 200,000 metric tons of deep-sea precious corals per year (*19*, *20*) (table S1). After the establishment of the U.S. EEZ in 1977, a subset of the affected sites were protected from further fishing (*21*), which has allowed those sites up to 40 years to recover, while the remaining sites experience continued but reduced bottom fisheries. To test for recovery on 30- to 40-year time scales, we conducted replicate imaging surveys at depths of 200 to 700 m on four "Recovering" and three "Still Trawled" sites with the autonomous underwater vehicle (AUV) Sentry and the Pisces IV and V submersibles in 2014 through 2017 (Fig. 1 and table S1).

RESULTS

Reflecting the documented fishing at these sites (*19*, *20*), explorations of these seamounts showed significant adverse impacts from fisheries including vast areas of barren substrate scarred by bottom-contact gear (Fig. 2A), coral rubble (Fig. 2B), coral stumps (Fig. 2C), and lost fishing gear (Fig. 2, D to F). Of the Still Trawled seamounts, 18 to 25% of images per seamount included scarred substrate (table S1).

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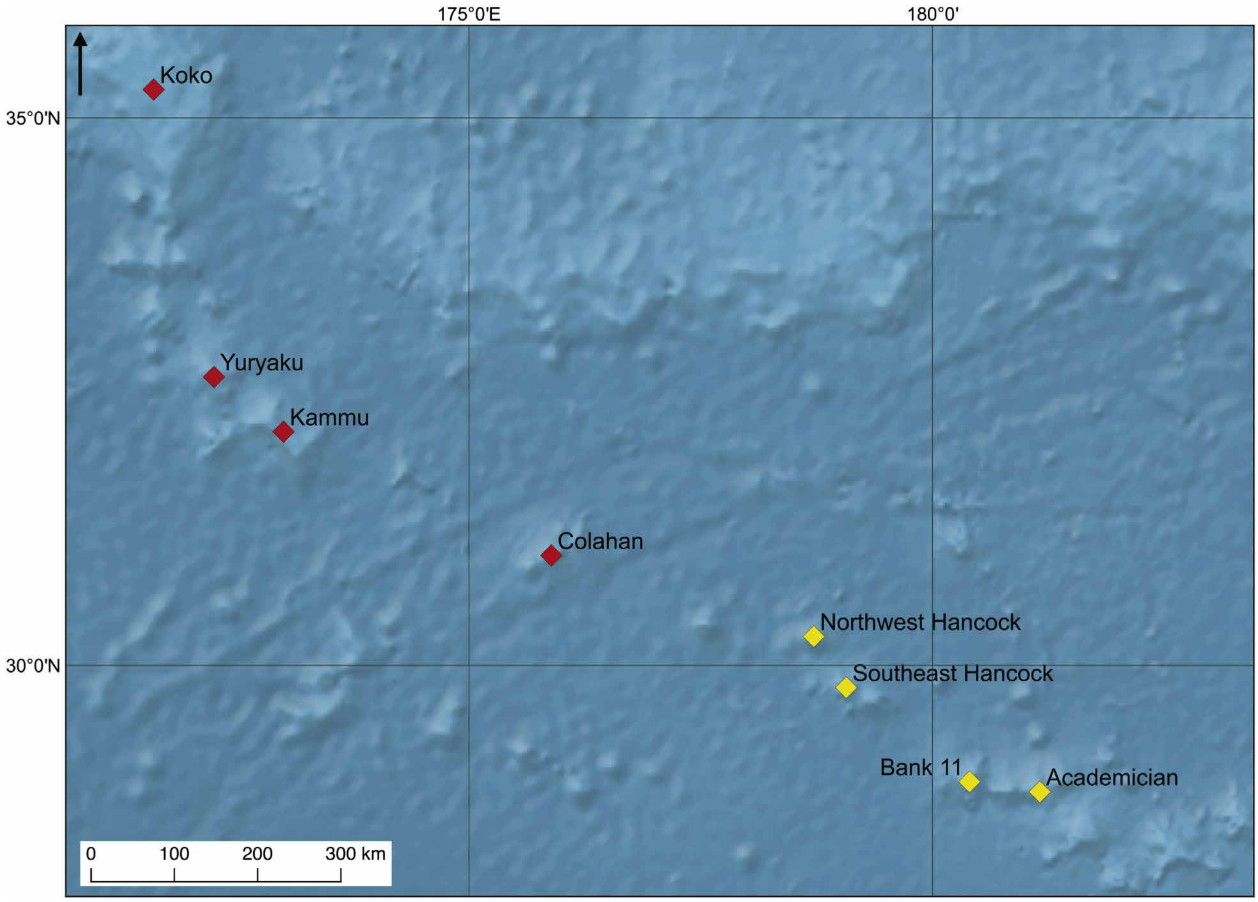

Fig. 1. Map of the study area including the northwestern end of the Hawaiian Ridge and the southern portion of the ESC. Yellow diamonds indicate the location of Recovering seamounts. Red diamonds indicate the location of Still Trawled seamounts. Map created in QGIS v. 2.18 Las Palmas (*34*) using ocean bottom layer downloaded from the Natural Earth public domain database (*35*).

However, evidence of recovery was also observed, both on the Recovering seamounts and in small pockets on the seamounts that are Still Trawled. The Recovering seamounts of Northwest (NW) and Southeast (SE) Hancock received comparable levels of historic fishing pressure to the Still Trawled seamounts in terms of total catch removed and had the highest levels of catch per unit area of any of the studied seamounts in either group (table S1) (*19*, *22*). Evidence of significant adverse impacts were still apparent on these features and included hard substrates scarred by bottom-contact gear (6 to 9% of images), coral rubble, and lost fishing gear including fishing nets, lines, and large areas of coral rubble. Despite this, there were signs of recovery on both of these seamounts. These included corals growing over areas of trawl marks (Fig. 3, A and B), the coralliid precious coral *Hemicorallium laauense*, and the reef-forming coral *Enalopsammia* regrowing from fragments in coral rubble spilling out of lost nets (Fig. 3, C and D), and healthy octocoral beds and *Solenosmilia* scleractinian reefs (Fig. 3, E and F).

Perhaps even more unexpected, given the continued trawling, were the pockets of recovering corals observed on the Still Trawled features. These include two areas of the young primnoid octocoral *Thouarella* on Kammu (Fig. 4, A and B), young *H. laauense* colonies on Yuryaku (Fig. 4C), and denser, more diverse areas that may be either recovering or remnant populations on Koko (Fig. 4, D and E). Colahan Seamount also had areas of intact scleractinian reefs not included in previous observations (Fig. 4F) (*23*). These combined with observations of scattered live polyps among the coral rubble on Yuryaku and Kammu, and bushy scleractinian colonies at several sites, suggest that elements of the original communities remain at these sites to reseed recovery on Still Trawled seamounts.

Data from replicate quantitative AUV image transects at three depths (table S2) on three Still Trawled seamounts and four Recovering seamounts also show that, at a given depth, there was a higher number of total megafaunal individuals per image on the Recovering seamounts ($P < 0.0249$) and a higher number of corals per image ($P < 0.0100$, interaction $P < 0.0076$). There was also a higher mean number of taxa observed per image on the Recovering seamounts ($P < 0.0198$) (table S3).

DISCUSSION

There is no consensus definition of the word "recovery" in the scientific literature as to whether recovery is a "process" or a "state" and, if it were a "state," whether it only applies to a state of being "fully recovered" [e.g., (*24*–*26*)]. Previous papers on recovery on seamounts have not given their definition of the term (*6*, *12*–*14*), and dictionaries include multiple definitions for the word including

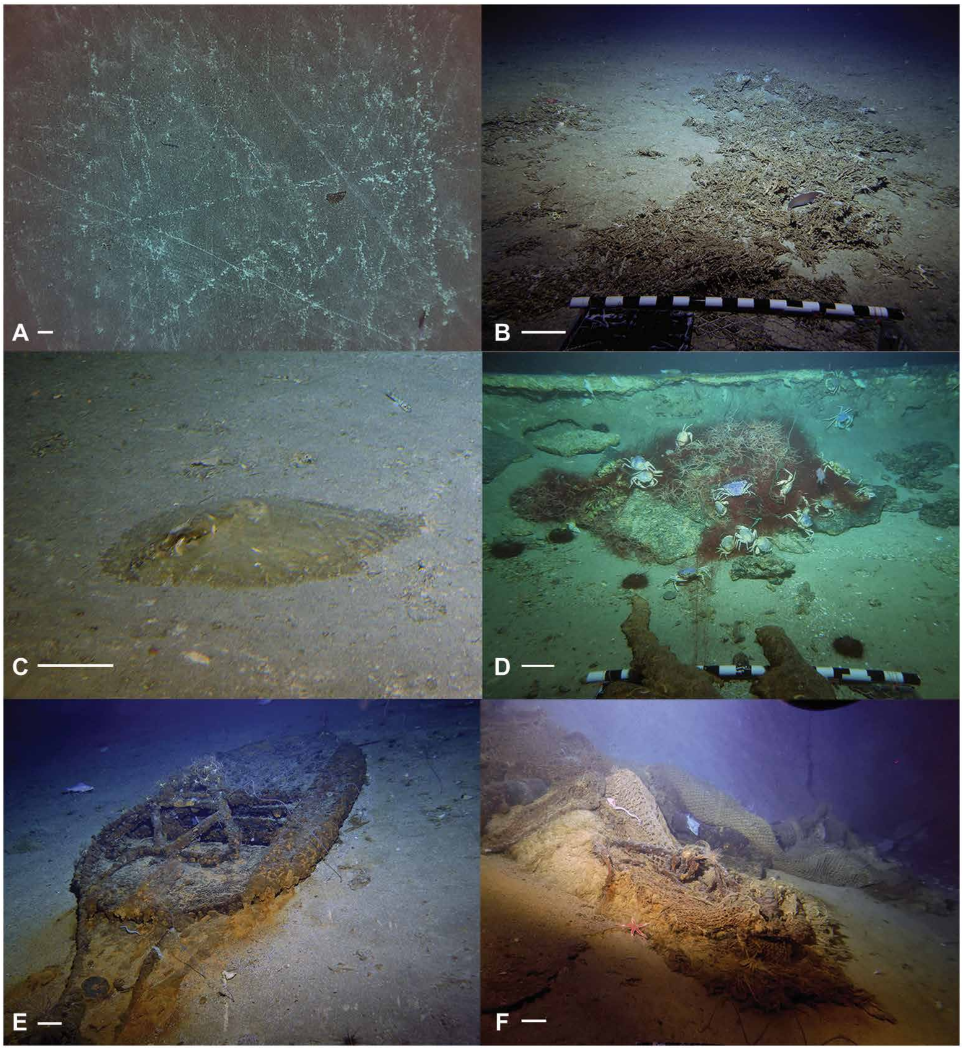

Fig. 2. Example images of adverse impacts of fisheries on seamount deep-sea coral communities. Scale bars, 10 cm. (**A**) AUV Sentry image of barren substrate with scars from bottom-contact gear on Yuryaku Seamount at 400 m. (**B**) Scleractinian reef rubble on Kammu at 600 m. (**C**) Gold coral stump on Kammu at 400 m. (**D**) Lost net with scavengers on Kammu at 400 m. (**E**) Lost trawl door on NW Hancock at 300 m. (**F**) Lost trawl net from a second location on NW Hancock at 400 m. Photo credits: (A) A. Baco-Taylor (FSU) and E. B. Roark (TAMU), NSF, AUV Sentry; (B to F) A. Baco-Taylor (FSU) and E. B. Roark (TAMU), NSF, with HURL pilots T. Kerby and M. Cremer.

both a process definition and a state definition. Westwood *et al.* (*26*) proposed that "recovery" be considered a "process" and "fully recovered" be the "state" a population or ecosystem reaches after the recovery process is complete. Here, the use of the word "recovery" aligns with this approach, with references to observations of seamounts being in the "process" of recovery, rather than in a "state" of being fully recovered.

With these definitions in mind, evidence presented here indicates that long-term protection of heavily trawled seamounts does allow for measurable recovery of seamount deep-sea coral communities on time scales of 30 to 40 years. These findings are contrary to the expectations and previous observations on seamount coral communities following disturbance (*6*, *12*–*14*), which concluded that there were not yet signs of recovery at all on seamounts: They were "effectively denuded of large sessile fauna and no longer support habitat forming corals in any significant numbers" 9 to 10 years after the secession of trawling (*12*) or had some animals but a different community and much lower abundances 5 to 10 years after trawling (*13*, *14*). Considering these conclusions, any recovery observed in a seamount community at all, even if it is partial recovery, can be considered remarkable.

Differences between these results and previous findings may be due to the longer time scales of this study, with 30 to 40 years since the end of trawling compared to 5 to 10 years. The depth range of this study was also slightly shallower, 300 to 600 m, compared to depths ranging from ~700 to 1700 m in previous recovery studies (*12*–*14*). Since food supply is expected to decrease with increasing depth [e.g., (*27*)] and available data to date suggest that deep-sea coral growth rates also decrease with increasing depth [e.g., (*28*)], recovery rate may be expected to change with increasing depth. However, at least within the narrow depth range sampled here, this prediction is not supported, since the increases in the median faunal abundance seen at 600 m (higher in recovering sites by 225%) in this study were comparable to the increases at 350 m (250% higher).

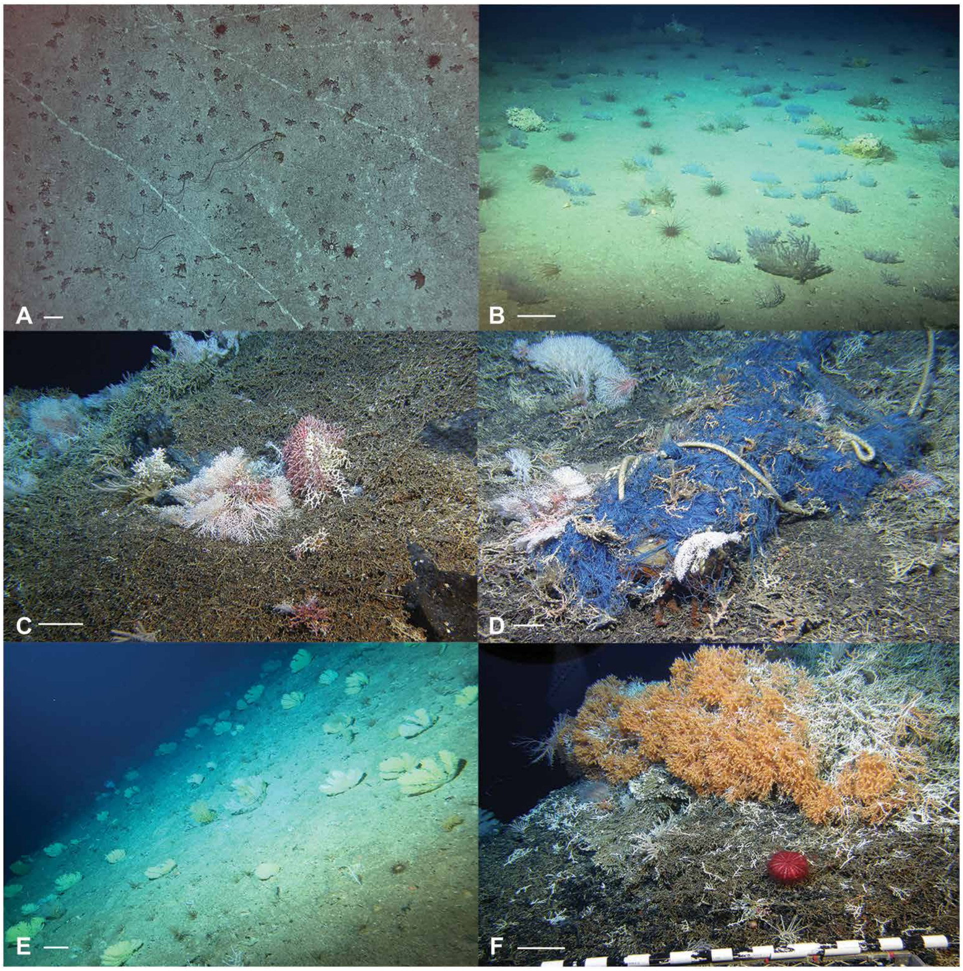

Fig. 3. Example images of recovering assemblages on the Recovering Seamounts of NW and SE Hancock. Scale bars, 10 cm. (**A**) Down-looking AUV Sentry image of soft corals growing over historic trawl scars on NW Hancock at 300 m. (**B**) Image of the same type of soft coral assemblage from the submersible on SE Hancock at 400 m (scars are not as obvious using the oblique angle of the submersible camera). (**C**) The precious red octocoral *H. laauense* and the reef-forming scleractinian *Enalopsammia* regrowing from fragments amid a field of coral rubble on SE Hancock at 600 m. (**D**) *H. laauense* regrowing from fragments pouring out of lost fishing nets on SE Hancock Seamount at 600 m. (**E**) A bed of young octocorals on SE Hancock at 600 m. (**F**) A patch of recovering scleractinian reef on SE Hancock at 650 m. Photo credits: (A) A. Baco-Taylor (FSU) and E. B. Roark (TAMU), NSF, AUV Sentry; (B to F) A. Baco-Taylor (FSU) and E. B. Roark (TAMU), NSF, with HURL pilots T. Kerby and M. Cremer.

A final source of potential difference among studies may have to do with the dominant taxa in the region. In the North Pacific, octocorals are the dominant taxon [e.g., (*4*, *29*–*31*)]; in Althaus *et al.* (*13*) and Williams *et al.* (*14*), the dominant coral taxa are scleractinians. However, in Waller *et al.* (*12*), the dominant coral taxa are also octocorals.

The level of taxonomic resolution possible with the AUV images prevents us from quantitatively determining whether the recovering communities are returning to the same communities that were present before fishing activities started or whether an alternative state is developing [e.g., (*24*)]. On the basis of published studies on the seamount fauna of the Northwestern Hawaiian Islands (NWHI) in the depth ranges of this work, we expect the predisturbance communities to have been dominated by octocorals and antipatharians, with a high abundance of coralliid and primnoid octocorals, as well as gold coral (*4*, *29*–*31*). While octocorals do dominate the Recovering sites, long-lived gold corals were nearly absent and coralliids were not among the more abundant morphotypes. Also, the soft corals that were colonizing the trawl marks near the summits of NW and SE Hancock (Fig. 3, A and B) have not been previously observed in these depth ranges in other areas. However, primnoid octocorals were common in Recovering areas (Fig. 4) and are also among the dominant families in Hawaiian coral beds in these depths (*30*). These observations suggest that the recovering communities observed contain some, but not yet all, of the elements of the predisturbance communities. Therefore, the question of whether the recovering community is an alternative community or an early community that, with successive community change, will eventually return to an assemblage similar to the predisturbance communities composed of long-lived octocorals and antipatharians is still open.

The current scientific and management literature on recovery and resilience of seamount communities do not take into account the potential for some corals to regrow from fragments, and there is minimal consideration given to the possibility of remnant or recovering populations on heavily affected sites. There are taxa that certainly would be expected to have protracted recovery times, such as reef-forming species and long-lived [decades to millennia (*7*–*9*)] species such as coralliid octocorals, some antipatharians, and zoantharian gold corals. However, these results show that both remnant populations

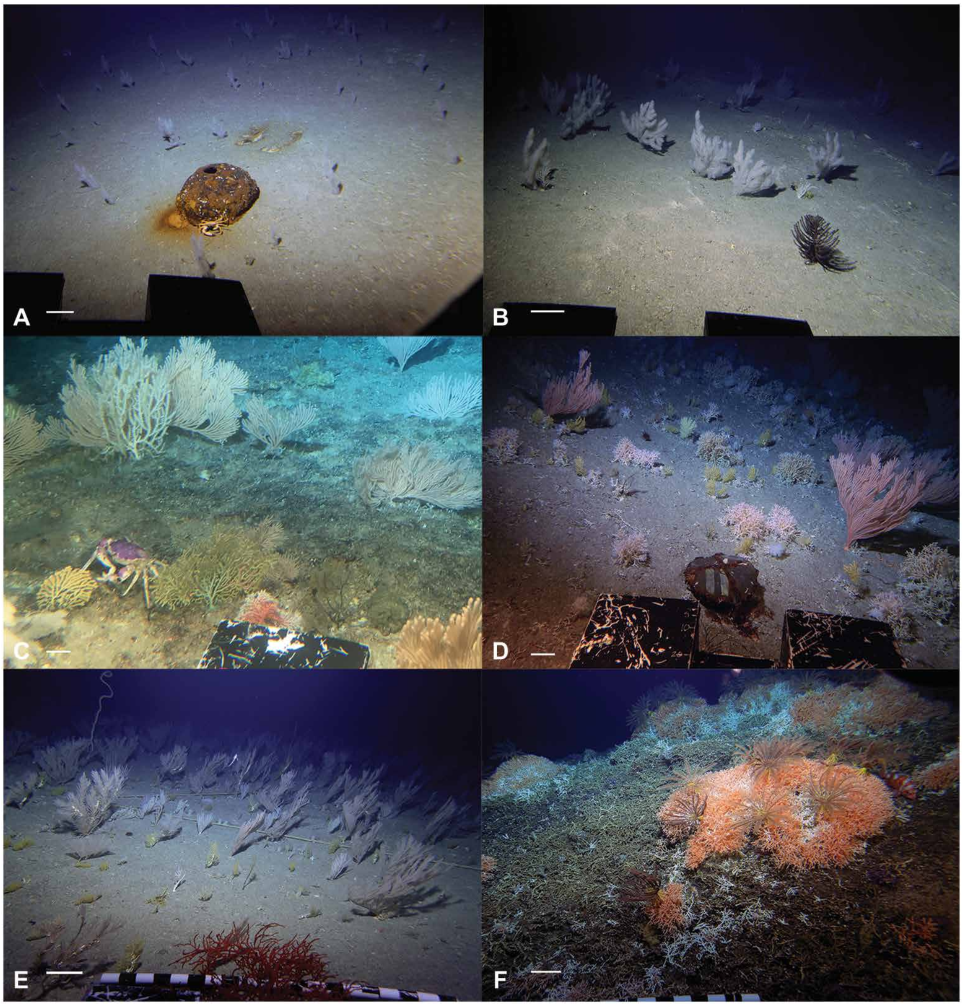

Fig. 4. Example images of recovering or remnant communities on Still Trawled seamounts. Scale bars, 10 cm. (**A**) Young colonies of the primnoid octocoral *Thouarella* on Kammu Seamount at 400 m. (**B**) Slightly older colonies of *Thouarella* with the antipatharian coral *Bathypathes* on Kammu at 500 m. (**C**) A young colony of *H. laauense* (pink colony near the center in front of the biobox) amid a bed of other octocorals on Yuryaku at 500 m. (**D**) A mixed bed of scleractinian and octocorals that appear to be recovering on Koko at 500 m. (**E**) A bed of more mature octocoral colonies with visible epifauna, amid lost fishing lines on Koko at 450 m. (**F**) An area of scleractinian reef on Colahan at 600 m. Photo credits: (A to F) A. Baco-Taylor (FSU) and E. B. Roark (TAMU), NSF, with HURL pilots T. Kerby and M. Cremer.

and regrowth from fragments may help to accelerate the recovery process and increase the probability of the community returning to the same predisturbance state, thereby increasing the resilience of seamount deep-sea coral communities.

These findings raise critical considerations for the management of seamount coral communities, both domestically and in areas beyond national jurisdiction. Domestically, the two Recovering seamounts with the highest abundance communities, Northeast and Southwest Hancock, fall into the 2016 expansion of the boundaries of the Papahānaumokuākea Marine National Monument (PMNM). The recent expansion of the PMNM has been called into review as part of the Department of the Interior's review of National Monuments established since 1996 (*32*). The presence of fragile recovering deep-sea coral communities on these seamounts should be taken into consideration in future reviews of PMNM boundaries and in any potential changes to bottom-fish fishing and trawling regulations within the PMNM.

In areas beyond national jurisdiction, management organizations should consider that the current protocol of allowing continued bottom-contact fishing at sites that have already experienced heavy trawling may cause damage to remnant VME populations. If these remnant populations are large enough to be reproductively viable, then they are likely to play a critical role in the recovery process as a source of propagules for heavily disturbed areas on seamounts, and further impacts could thereby limit the recovery process. The time scales for recovery observed on these seamounts additionally suggest that short-term "crop rotation"–type closures [e.g., (*33*)] would not allow sufficient time for affected communities to recover; instead, a long-term or even permanent closure will be needed for significant recovery to be attained on seamounts.

MATERIALS AND METHODS

Experimental design

A total of seven seamounts in the NWHI and ESC were surveyed in 2014 and 2015 using the AUV Sentry. On the basis of the trawling history, the seamounts were categorized as Recovering or Still

Trawled. Sites that were once actively trawled, but were protected with the establishment of the US EEZ in 1977 (*21*), were placed into the Recovering treatment and included Academician Berg, Bank 11, and SE and NW Hancock Seamounts. Sites that are still actively trawled, including Kammu, Yuryaku, and Koko Seamounts, were placed into the Still Trawled treatment (table S1).

AUV photo surveys with a length of ~30 to 40 km were designed to include replicate 1-km transects at depth intervals of 50 m from depths of 200 to 700 m. This survey design was then replicated on two to three sides of each seamount to reduce effects of within-seamount variability on comparisons between treatments. The depth range of 200 to 700 m was chosen to encompass the full range of depths that were part of the historic trawl and coral fisheries, which were concentrated at 300 to 600 m (*21*). The AUV flew at a height of ~5 m above the seafloor at a rate of 0.45 to 0.65 m/s, taking photos at a rate that ensured a continuous visual (photo) survey of the seafloor. Images were taken with a down-looking digital still camera, and each individual AUV image covered approximately 12 m^2 of seafloor. Observations were made from all of the >536,000 dive images, with a subset used for the quantitative analyses as described below. Additional qualitative observations and images were obtained on dives with the Pisces IV and V submersibles, which returned to the same sites in 2016 and 2017, as well as to Colahan Seamount.

Quantitative site comparisons

For quantitative comparisons, only images from depths of 350, 450, and 600 m were analyzed for each feature. Initial analyses included surveying every other image on each transect for trawl or drag marks and the proportion of soft substrate, totaling over 54,000 images analyzed. For quantitative comparisons, images along a transect that were <75% soft substrate were then used to count benthic megafauna, totaling 22,188 images analyzed. From these, all of the visible megafauna were counted in every other image to avoid duplicate counts. The primary benthic megafaunal taxa observed included cnidarians, sponges, and echinoderms. The height above the seafloor that the AUV must be flown over rough terrain and the angle of the camera make identification to the species level unreliable, so instead, we used a morphotype classification that allowed for a consistent level of resolution of the observed fauna. These categories included "wire coral," "antipatharian fan," "octocoral fan," "scleractinian fan," "scleractinian bush," "sea pen," "*Eguchipsammia*," "encrusting zoanthid," "stalked crinoid," "unstalked crinoid," "brisingid," and "sponge." Urchins were also present on most features, but the abundances made counting them time prohibitive; thus, they were not included. The gold coral, *Kulamanamana haumeaae*, common in precious coral beds in the NHWI (*4*, *29–31*), was notably absent from all included transects. By coincidence, extensive areas of live reef as shown in Fig. 4F also did not occur in the AUV images on the targeted depth transects in either treatment.

Statistical analyses

Data for each transect were standardized as number of observations of fauna divided by number of images included from that transect. A two-way crossed analysis of variance (ANOVA) was used to compare Recovering and Still Trawled sites at depths of 350, 450, and 600 m for two groups: Total Megafauna, including all of the morphotypes listed above, and Coral, which included all cnidarians except soft substrate–associated sea pens, fast-growing wire corals, and encrusting species that were difficult to accurately quantify by count methods. All statistical comparisons were performed in JMP version 13.2 (SAS).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/8/eaaw4513/DC1

Table S1. Summary of location, trawling history, and AUV data for the sites of this study listed from the NW to SE of the lower ESC and NHR.

Table S2. Raw data on morphotype counts per transect used for quantitative comparisons.

Table S3. Results of two-way crossed ANOVA for quantitative comparisons among treatments and depth groups.

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Acknowledgments: We thank the captains and crew of the *RV Sikuliaq*, *RV Kilo Moana*, and *RV Ka'Imikai-O-Kanaloa*; the pilots and crew of the AUV Sentry and Pisces IV and V submersibles; and the assistance of many volunteers at sea. The images were obtained through the professional work of the pilots, engineers, and technicians of the AUV Sentry and the Pisces IV and V submersibles. S. Goode, T. Ferguson, A. Rentz, and T. Whitehead contributed to the AUV Sentry image analyses. B. Mejia assisted with screening still images from the submersible cruises. This paper benefitted from discussions with M. Gianni and A. Rowden. **Funding:** This work was conducted through support from NSF grant numbers OCE-1334652 (to A.R.B.) and OCE-1334675 (to E.B.R.). Work in the PMNM was permitted under permit #PMNM-2014-028 and #PMNM-2016-021. **Author contributions:** A.R.B. and E.B.R. designed the research. N.B.M. and A.R.B. analyzed images. A.R.B. compiled and analyzed the datasets. All authors wrote and reviewed the manuscript. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** AUV Sentry images are archived by the Woods Hole Oceanographic Institution. Pisces dive videos are archived by the Hawaii Undersea Research Laboratory. All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 20 December 2018
Accepted 27 June 2019
Published 7 August 2019
10.1126/sciadv.aaw4513

Citation: A. R. Baco, E. B. Roark, N. B. Morgan, Amid fields of rubble, scars, and lost gear, signs of recovery observed on seamounts on 30- to 40-year time scales. *Sci. Adv.* **5**, eaaw4513 (2019).

Science Advances

Amid fields of rubble, scars, and lost gear, signs of recovery observed on seamounts on 30- to 40-year time scales

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Sci Adv **5** (8), eaaw4513.
DOI: 10.1126/sciadv.aaw4513

Marine Policy 115 (2020) 103834

Contents lists available at ScienceDirect

Marine Policy

journal homepage: http://www.elsevier.com/locate/marpol

Observations of vulnerable marine ecosystems and significant adverse impacts on high seas seamounts of the northwestern Hawaiian Ridge and Emperor Seamount Chain

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ARTICLE INFO

Keywords:
Seamounts
Vulnerable marine ecosystems
Significant adverse impacts
Deep-sea corals

ABSTRACT

The Northwestern Hawaiian Ridge seamounts (NHR) outside the US EEZ and the Emperor Seamount Chain (ESC) have some of the longest history and largest takes of bottom contact fisheries of any seamounts globally. Imaging surveys from four of these seamounts provide evidence of vulnerable marine ecosystems (VMEs) on all surveyed features including dense patches of octocorals, scleractinian reefs, and sponges. Crinoids and brisingids occurred patchily in high abundance. These results, records from precious coral fishery takes, and habitat suitability modeling collectively indicate an extremely high probability that deep-sea coral VMEs are widespread on all of the ESC-NHR seamounts.

Evidence for significant adverse impacts (SAIs) from bottom contact fisheries was also observed on all surveyed seamounts and included large areas of barren hard substrate, with scars from bottom contact gear in 19–29% of AUV images. Stumps from arborescent corals and rubble from reef-forming corals were observed. Evidence of SAIs is further supplied by many observations of coral rubble associated with lost fishing gear. Finally coralliid octocorals, once sufficiently abundant on the targeted seamounts to support the world's largest precious coral fishery, were extremely rare on all features despite the large survey area.

Based on observations of VMEs, SAIs to these VMEs, and the potential for recovery, the results presented here would indicate a closure of all NHR and ESC seamounts to bottom contact fisheries until the gear being used can be proven to not cause SAIs. Closures should include both untrawled areas and currently fished areas to allow for recovery.

1. Introduction

Under UNGA resolution 61/105, management of seamount fisheries in areas beyond national jurisdiction (ABNJ) by regional fisheries management organizations (RFMOs) requires consideration of vulnerable marine ecosystems (VMEs) [1]. Criteria to designate a site as a VME include uniqueness or rarity, functional significance, fragility, structural complexity, and life history traits "that make recovery difficult" [2]. Despite the fact that the original UNGA resolution 61/105 paragraph 83 (c) explicitly states that VMEs include seamounts and cold-water corals, which would imply that they should qualify as VMEs without a need for further discussion, significant effort has gone into defining thresholds for designating a VME and into determining encounter protocols for VME indicator taxa on seamounts and other high seas habitats [e.g. 2,3, 4].

UNGA resolution 61/105 paragraph 83(a) also calls for fisheries to be managed to "prevent" significant adverse impacts (SAIs) to those VME areas [1]. SAIs "are those that compromise ecosystem integrity (i.e. ecosystem structure or function) in a manner that: (i) impairs the ability of affected populations to replace themselves; (ii) degrades the long-term natural productivity of habitats; or (iii) causes, on more than a temporary basis, significant loss of species richness, habitat or community types." [2]. These commitments have been reinforced by the UNGA through periodic reviews of the implementation of resolution 61/105 and subsequent resolutions, most recently through the adoption of UNGA resolution 71/123 [5]. The UNGA plans another review in 2020.

Some high seas seamounts are already managed as VMEs (e.g. many in the North Atlantic [6]), but until the call for management of all seamounts within fishing depths as VMEs is heeded [7], locating VMEs on seamounts relies on fisheries observers and scientific surveys. Similarly,

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https://doi.org/10.1016/j.marpol.2020.103834
Received 8 April 2019; Received in revised form 24 January 2020; Accepted 24 January 2020
Available online 1 February 2020

determining SAIs requires knowledge of where VMEs were located and the status of the ecosystems prior to impacts. For many deep-sea habitats, especially high seas seamounts, baseline data are not available because there has not been adequate exploration to determine locations of VMEs. However, as noted by Watling and Auster [7] from their experience in the northwest Atlantic, and in over 20 years of exploration of seamounts by the authors in the northeast and central Pacific, every seamount that has been explored using visual methods in hard substrate areas, has been found to have VME indicator species present including deep-sea corals, sponges, dense crinoid beds, etc, in sufficient densities to be considered VMEs [e.g. 8-13]. Habitat suitability modeling for deep-sea corals, one of the more prominent members of seamount hard-substrate communities, also support that most seamounts provide areas of suitable habitat for deep-sea coral communities [14-18].

The seamounts of northwestern end of the Hawaiian Ridge (NHR) beyond the US EEZ, and of the Emperor Seamount Chain (ESC), are among the high seas areas managed by the North Pacific Fisheries Commission (NPFC). These seamounts have some of the longest history of bottom contact fisheries of any seamounts globally, going back to the 1960s, and some of the greatest takes of any seamount fisheries [as quantified in [19]]. These included bottom trawl and gill net fisheries for pelagic armourhead and splendid alfonsino, which removed up to 210,000 t per year of fishes and extended from the Emperor Seamounts to Bank 8 in the Northwestern Hawaiian Islands (NWHI). In the same period, there were also tangle net fisheries for precious corals, which removed as much as 200,000 kg of deep-sea precious corals per year from sites in the NWHI and Emperor Seamounts, with the highest yields from the Milwaukee Banks [reviewed in [19], [20]]. Both fisheries were concentrated at depths of 300–600 m, and peaked between the 1960s and 1980s [19,20] with significantly reduced fishing activity continuing through the present day.

Aside from data on which species were taken and the amount of biomass taken in the fishery, there is very little data on the fauna of these seamounts. Thus, the goal of this study was to explore four ABNJ seamounts in the NHR and ESC to describe the extent and distribution of benthic megafauna and VME taxa using AUV imaging survey transects. We also make notes on observations of SAIs and lost fishing gear at these same sites. These findings are then discussed in light of the regulations established by the NPFC to implement the UNGA resolutions for the purpose of managing bottom fisheries to prevent SAIs on VMEs in this region. This paper focuses on fauna and impacts, while Baco et al. [21] focuses on evidence for recovery on these and nearby features within the US exclusive economic zone.

2. Methods

As a part of a larger project to understand the recovery process on trawled seamounts [21], 4 high seas seamounts of the far northwestern end of the Hawaiian Ridge and the southern end of Emperor Seamount Chain were surveyed in 2014–2017 (Fig. 1). In 2014 multibeam and

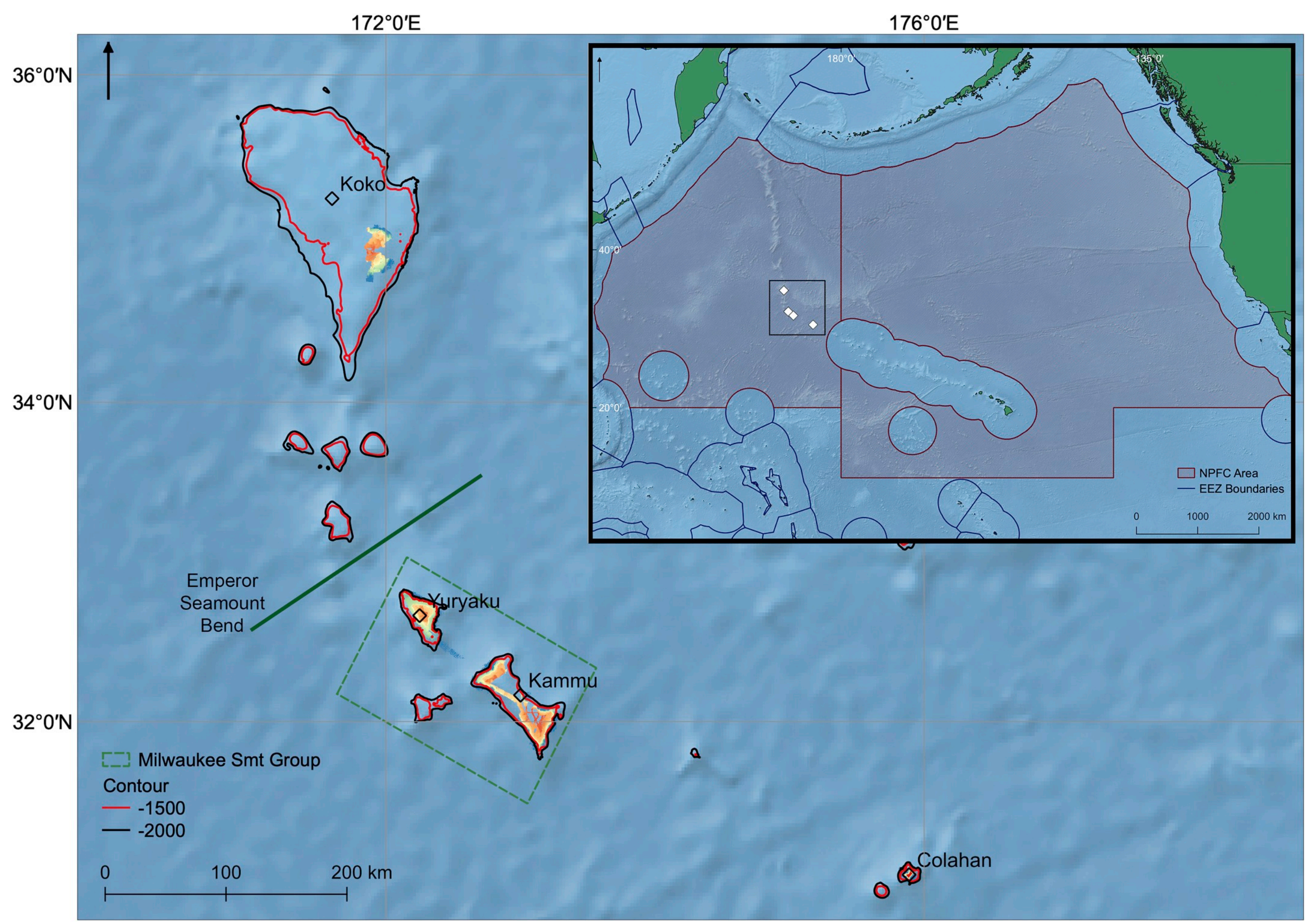

Fig. 1. Map of locations of the four seamounts of this study including available multibeam bathymetry. The Milwaukee Banks are indicated with the green dashed box. Inset shows the location of these sites, as white diamonds, in the broader Pacific with a demarcation of the NPFC management areas and EEZ boundaries. Public domain baselayers provided by Natural Earth database [43]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

backscatter data were collected for Yuryaku on the *R/V Sikuliaq* using a Kongsberg EM302 Multibeam Echosounder and was processed by Seafloor Investigations Inc. Using the CARIS Hips and Sips software package [22,23]. In 2015 multibeam bathymetry and backscatter data were collected on the other seamounts using a Kongsberg EM122 installed on the *R/V Kilo Moana*. Multibeam surveys were conducted to maximize coverage in the 200–700 m depth range on multiple sides of each seamount. Data were processed using Qimera 3D editor then loaded into Fledermaus DMagic [24] to create raster grid files.

Multibeam bathymetry and backscatter were used to design *AUV Sentry* surveys, conducted in 2014 and 2015, to focus on areas of hard substrate on multiple sides of each of 3 seamounts: Koko, Yuryaku and Kammu, with 2–3 replicate 1 km transects at 50 m depth intervals from 200 to 700 m depths, inclusive. Surveys were conducted along depth contours. Sentry flies about 5 m above the bottom with a down-looking Allied Vision Technologies Prosilica GE4000C camera, at a rate of 0.45–0.65 m/s taking photos at a rate that provided a near-continuous visual (photo) survey of the seafloor.

A total of 176,112 Sentry images were taken with Sentry on Koko, Yuryaku and Kammu (Table 1). Animals were counted on every dive image that had an altitude between 1 and 9 m above the seafloor, including those between transects, resulting in 162,534 images analyzed. Individual animals were only counted in the first image they appeared in when overlapping images occurred. To facilitate review in a finite time period, only the most abundant five taxa were counted, and were designated as Coral, Anemone, Sponge, Crinoid, or Brisingid. Urchins were also highly abundant but not counted due to time constraints. Corals and sponges are of interest due to their importance as VME taxa, as ecosystem engineers, and as the known dominant taxa in this region. Anemones, crinoids, and brisingids were of interest due to their extremely high densities in certain areas. Density levels for the target taxa were assigned as: Sparse (2–5 individuals per image), Medium (6–10 individuals per image), or Abundant (11+ per image). Images with less than 2 individuals were not counted. We also noted two specific groups when observed – octocorals in the Family Coralliidae, as an economically important fisheries species and a known component at these sites prior to the onset of fishing [reviewed in [20]]; and reef-forming scleractinian corals, which were discovered in this region as a part of these surveys [13].

Substrate was qualitatively analyzed in every other photo from the useable images, for percent coverage of soft sediment and categorized into either 0–25%, 26–50%, 51–75%, or 76–100% soft sediment. Images were also analyzed for scars from bottom contact gear in every photo from the useable image set. Images were categorized as "Few" in images with only parallel scar marks (as those could possibly all be from one trawl pass) and as "Dense" in images with scars in multiple directions. Bottom contact gear types used in the region have included fisheries trawls, coral tangle nets, long lines, bottom gill nets, and pots ([27]). For simplicity, bottom scar data are referred to as "trawl marks" throughout the paper.

Raster data from Fledermaus were imported into QGIS v.2.18 [25]. Sentry tracking files were imported into QGIS as point shapefiles and overlaid on the raster files. Distributions of animals and bottom contact scarring were then imported as point shapefiles using the georeferenced information of each image from Sentry. Those points were overlaid on the bathymetry to highlight locations of animals as well as to visually check for any relationships between animal abundances and trawl marks.

Additional observations and images made with the Pisces IV and V submersibles, which returned to the same sites along with Colahan Seamount in 2016 and 2017, were used to obtain supplementary observations and higher quality images of abundant taxa. Submersible surveys included replicate 500 m long transects at depths of 400, 500, and 600 m along with collections for voucher specimens for identification, aging, and genetics. Pisces IV and V are each equipped with an Insite Pacific MINI-ZEUS HDTV camera and still images were also collected with Nikon Coolpix L340.

3. Results

AUV images from Koko, Yuryaku and Kammu showed that overall, corals were the dominant benthic megafauna on every survey dive of the 5 taxa counted, with 58–92% of the total images with fauna per transect. Sponges were the next most common of the counted taxa, present on every dive except S344 on Koko, and constituted 0.4–42% of the faunal images. Crinoids had their highest occurrence on Koko with 10–22% of faunal images. Sponges had their highest occurrence on Yuryaku, and brisingids were unusually common on Kammu with nearly 29% of the faunal images on dive S349 (Fig. 2, Table S1). More detailed descriptions of the megafaunal assemblages observed on each seamount are provided below.

3.1. Koko Seamount

With a surface area in our target depth range of ~3874 km^2 Koko was the largest of the studied seamounts. A section of the eastern portion of the southern half of this seamount was mapped and then explored on two AUV Sentry dives (Figs. 3a and 4a). Of the three high seas seamounts surveyed with the AUV, Koko had the lowest proportional occurrence of trawl scars, with ~19% of images. Bottom contact gear scars were the densest at the shallower portions of the seamount (Figs. 3a and 4a). Koko also had the highest proportion of images with benthic megafauna at 20.7% (Table 1) with corals the most abundant of the observed fauna. Of the 57,612 useable images taken on Koko, coralliid octocorals were only

Table 1
Trawling history and summary image data for targets of this study listed from the northwest to southeast. Yuryaku and Kammu are two of the three features of the Milwaukee Banks. All positions from SBN earthref.org. *Data from Clark and Tittensor [15] and Clark et al. [19] were provided as estimates split into 1-degree latitude and longitude grid cell boxes and given as metric tons (mt). Values for each feature were taken as the grid cell they fell into. Number of images with trawl marks were determined from the full "AUV Images Analyzed" set. SA = Surface area given as area within 300–600 m depth range, ** after removing images with altitude <1 mab or >9 mab, *** - megafauna includes only the 5 focus taxa of this study and excludes urchins.

Feature Name	Posit Lat N	Posit Long E/W	Total Catch *mt	SA (km^2)	Catch (mt) per km^2	Total Linear Survey Length (km)	AUV Images Analyzed**	Number of Images with >2 megafauna*** per image	Number of Analyzed Images with Trawl Marks	Proportion of Images w > 2 megafauna per image	Proportion of Analyzed Images w trawl marks
Koko Smt	35 15.0	171 35.0	92,500	3874	24	114.94	57,612	11,954	11,078	20.75	19.23
Yuryaku Smt	32 40.2	172 16.2	63,000	72.7	867	131.00	56,153	1886	16,550	3.36	29.47
Kammu	32 10.0	173 00.0	63,000	610.3	103	104.96	48,769	4179	11,125	8.57	22.81
Colahan	30 59.0	175 55.5	92,500	15.75	5873	~17.25	7 video transects	na	na	na	na

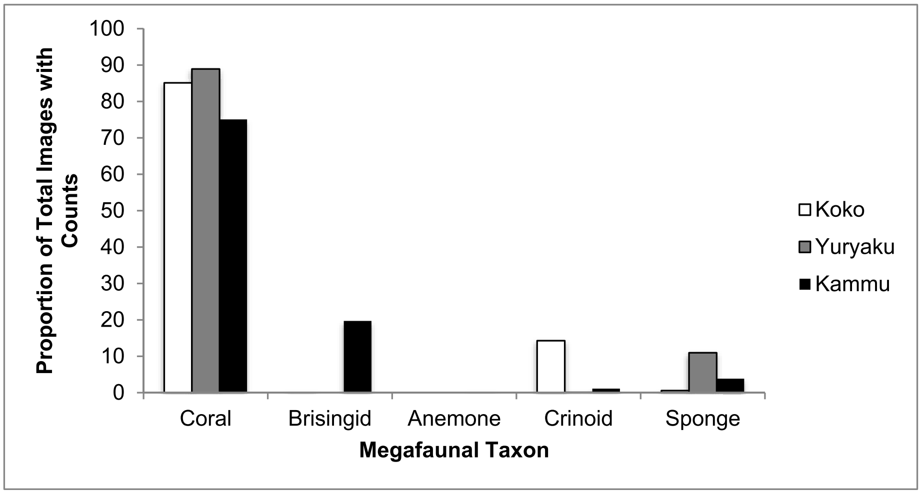

Fig. 2. Proportional abundance of each of the five major megafaunal invertebrate taxa for each seamount. Calculated by the number of images with 2 or more megafaunal individuals out of total number of images.

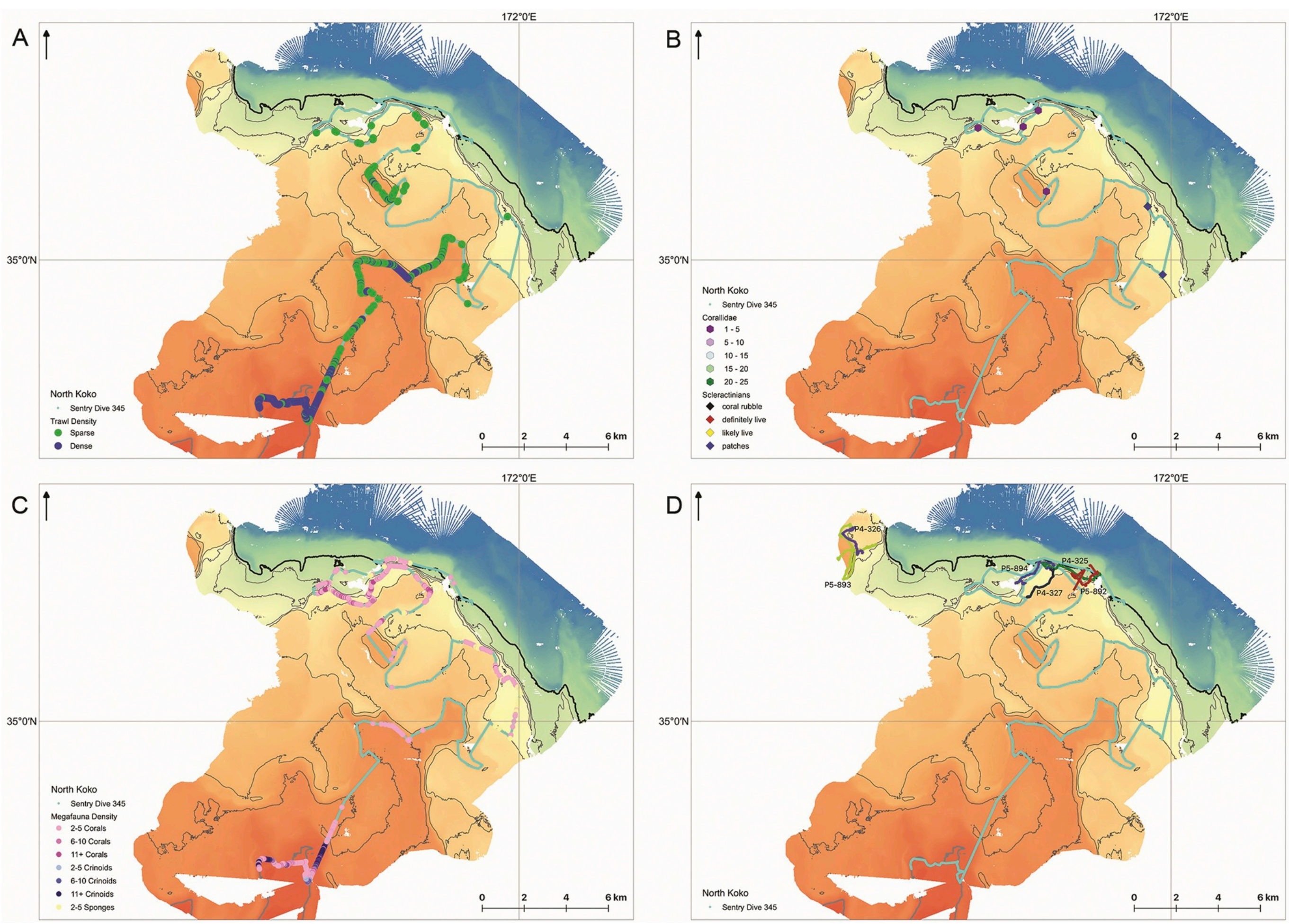

Fig. 3. Visual summary of northern AUV dive surveys on Koko Seamount, showing multibeam bathymetry from 300 to 900 m depth, contour lines from 300 to 700 m at 50 m depth intervals in gray, and AUV dive track in light blue (A) locations of scars from bottom contact gear and relative density are overlaid; (B) locations of images and approximate abundance for observations of coralliid octocorals and scleractinian corals are overlaid, (C) locations of images and abundances for observations of other megafauna are overlaid, and (D) locations of submersible dive tracks are overlaid. Each circle or diamond in panels A–C represents a single AUV image, with color coding explained in the keys for each panel. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

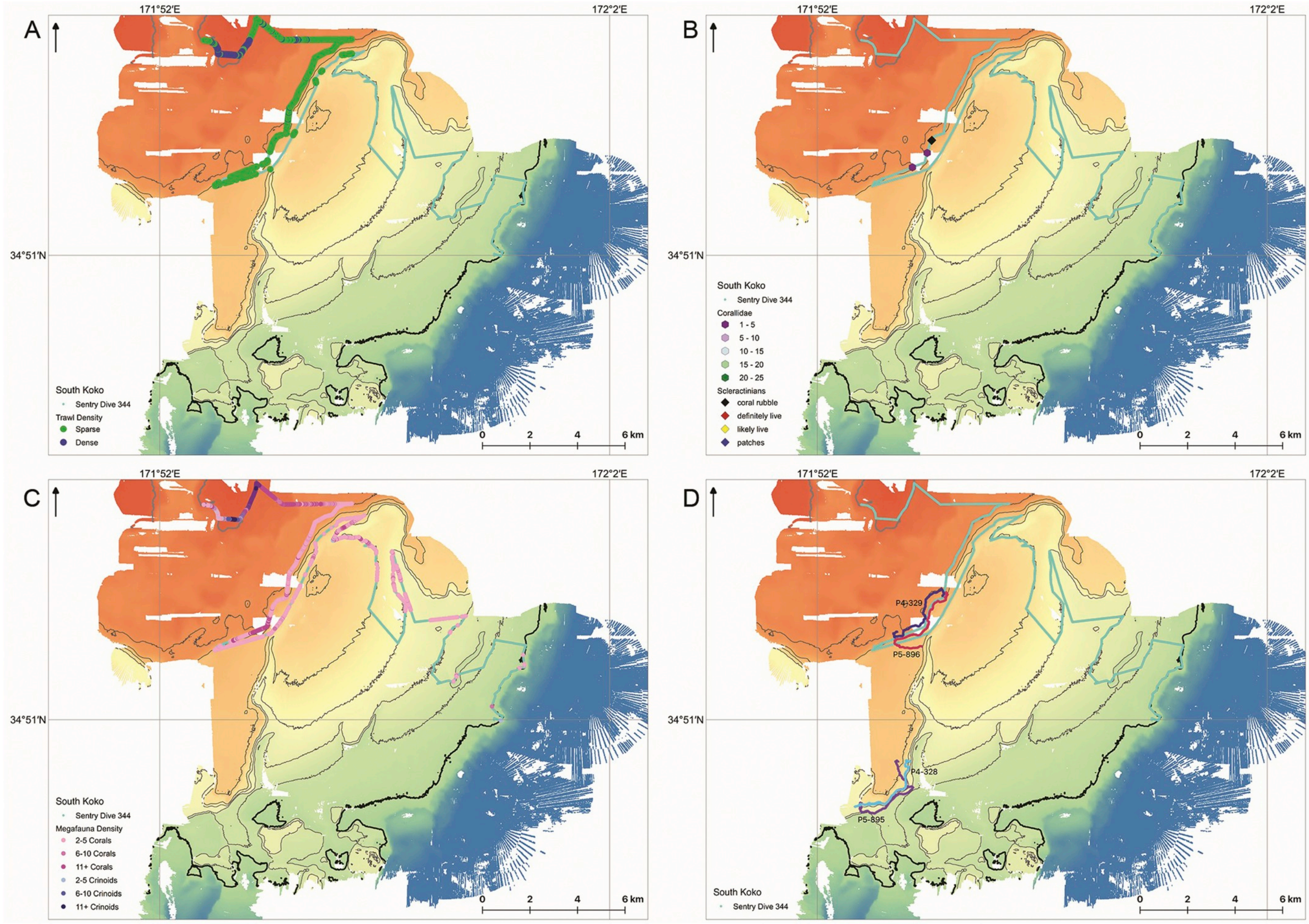

Fig. 4. Visual summary of southern AUV dive surveys on Koko Seamount, showing multibeam bathymetry from 300 to 900 m depth, contour lines from 300 to 700 m at 50 m depth intervals in gray, and AUV dive track in light blue line. (A) locations of scars from bottom contact gear and relative density are overlaid. (B) locations of images and approximate abundance for observations of coralliid octocorals and scleractinian corals are overlaid. (C) locations of images and abundances for observations of other megafauna are overlaid. (D) locations of submersible dive tracks are overlaid. Each circle or diamond in panels A–C represents a single AUV image, with color coding explained in the keys for each panel. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

observed at densities of >2 individuals per image in 6 total images, two in the northern survey area and one cluster of four images in the southern survey area (Figs. 3b and 4b). In each of these images there were fewer than 5 individuals. Scleractinian reefs were also very sparse on Koko and occurred primarily as small (<30 cm diameter) bushes resembling recovering reef patches, or as rubble with a few live polyps (Figs. 3b, 4b and 5a). These occurred in 32 AUV images on Koko, seventeen images in two clusters on the eastern slope, just to the north of the closed area and fifteen on the southern side in a cluster near one of the coralliid observations. Although reef and coralliids were not terribly abundant in the areas surveyed, many other corals were observed, primarily octocorals and antipatharians, with the most common being unbranched whip corals (Figs. 3c, 4c and 5b). The areas in both the northern dive and the southern dive with a high density of other corals overlapped with the areas of observations of coralliids. Corals were most abundant near the shallowest areas surveyed. Crinoids also occurred in significant densities near the shallowest portion of the survey (Figs. 3c and 4c). Areas with less dense trawl marks tended to have a higher abundance of benthic megafauna (Figs. 3a and 4a vs. Figs. 3c and 4c).

A total of 10 submersible dives were conducted on Koko Seamount in 2017. Corals were generally of moderate to high density (>6 corals per image) in most of the dives, but based on our experience from other areas of the NWHI, the corals were generally of small sizes. Fig. 5 provides some example images of the density and types of VME taxa that were observed. The richest communities were observed on Dives P4-328 and P5-895 on the southernmost point (Fig. 4d). This area was on a steeper portion of the slope and showed signs of dense communities that appeared, based on observations of lost lines, gear, and trawl scars, to be recovering from gear impacts. Fauna observed included octocorals and small scleractinian colonies (Fig. 5c), and occasional patches of sponges (Fig. 5d). The sizes of the corals were generally small (Fig. 5a,c), but a few areas also included larger, more mature colonies, in high densities and with visible epifauna (Fig. 5e and f).

3.2. Yuryaku Seamount

Yuryaku is one of the seamounts of the Milwaukee Banks and is a much smaller feature than Koko, thus it was able to be fully mapped and a greater percentage of its area was surveyed on four AUV dives (Fig. 6a). Yuryaku had a much higher proportion of its area showing evidence of trawling, with 29.5% of useable images including scars from bottom contact gear (Fig. 6a). Bottom contact gear scars were again the densest at the shallowest portion of the seamount (Fig. 6a), and vast areas of the seamount were barren of fauna with numerous visible scars and tumbled slabs of broken up seafloor (e.g. Fig. 7a). Not surprisingly, given the heavy gear impacts, the reefs observed on Yuryaku were

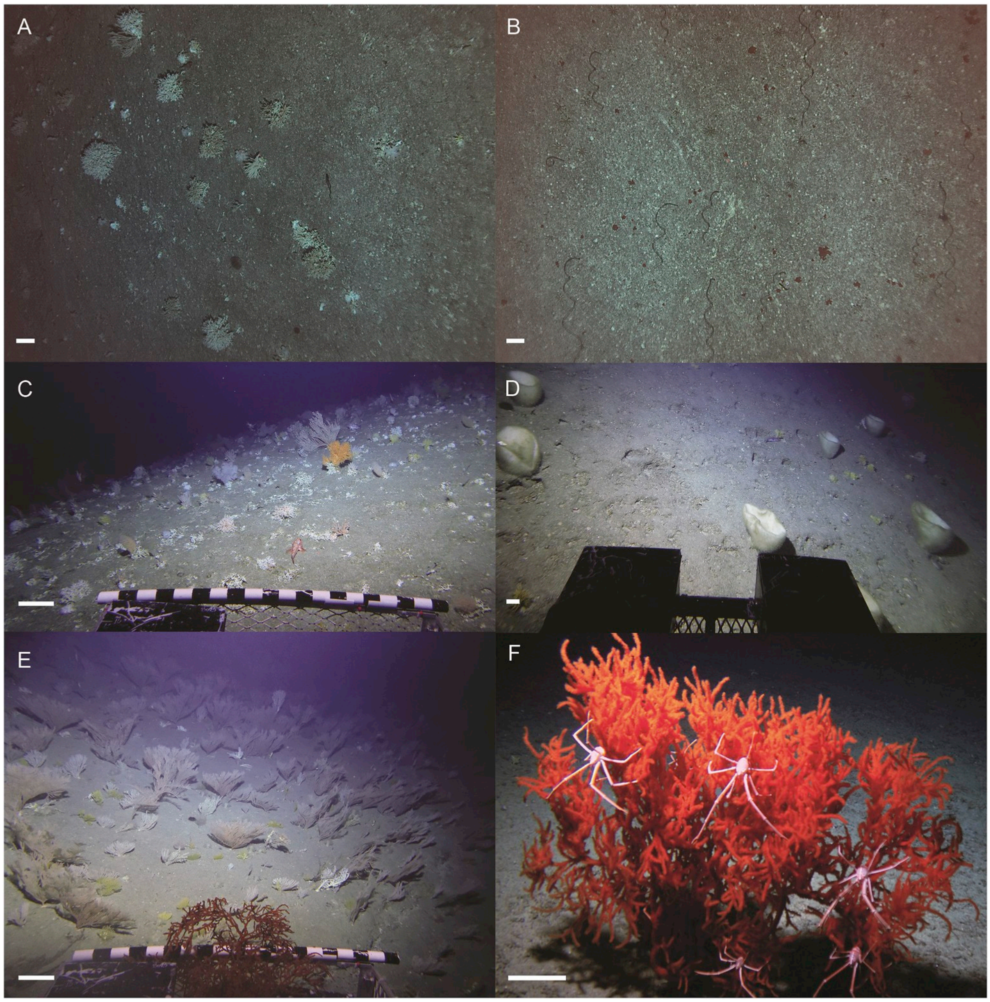

Fig. 5. Example seafloor images of megafauna from Koko Seamount. The white scale bar in each image represents 10 cm. (A) AUV image of scleractinian reef patches. (B) AUV image of whip corals common on the shallowest portions of Koko. (C) Submersible image of small octocorals and scleractinian corals. (D) Area of dense sponges. (E) Dense area of larger octocoral colonies. (F) Zoom on antipatharian colony showing associated galathaeid crabs.

largely reduced to rubble with scattered live polyps (Fig. 7b). Despite the heavy impacts, areas with evidence of reef were more widespread on Yuryaku than on Koko, particularly on the northwest and southeast corners of the seamount (Fig. 6b). These same areas also had some sparse colonies of what appeared to be young coralliids.

Other fauna were also relatively sparse on Yuryaku, present in only 3.4% of the AUV images taken. There were however, a few patches with higher densities of octocorals, and several patches with sponges. These also occurred primarily in the southeast and northwest slopes of the seamount, and covered a much broader area than the scleractinian and coralliid observations (Fig. 6c).

Due to weather constraints and competition with fishing vessels, only 1 pair of submersible dives were conducted on Yuryaku in 2016. These dives targeted the southwest corner based on the higher density corals that were observed by the AUV (Fig. 6d). This area had a steeper slope than most of the area covered by the AUV. Patches of relatively dense octocoral assemblages were observed in this area, which included larger more mature colonies of primnoid and isidid octocorals (Fig. 7c and d) along with young coralliids (Fig. 7d). Additional reef observations still only showed rubble with scattered surviving polyps, though in sheltered patches and steep walls smaller clumps of scleractinian corals could be seen.

3.3. Kammu (Kanmu) seamount

Kammu, another seamount of the Milwuakee Banks, was also a large feature with a surface area in our target depth range of over 600 km^2. Competition with fishing vessels for access to this site occurred in all 4 years of the project. As a result, mapping efforts were limited primarily to the southern half of the seamount and this portion of the feature was surveyed on two AUV Sentry dives in 2015. The observations on Kammu were very similar to Yuryaku with a high proportion (nearly 23%) of images with trawl marks and large areas of barren substrate with scarring from bottom contact gear (Fig. 8a). Out of nearly 49,000 AUV images, only 2 showed evidence of scleractinian reef (Figs. 8b and 9a), near the SE corner of the surveyed area, and not a single coralliid was observed. There were other patches of octocorals and sponges observed however, with fauna present in about 8.6% of useable images (Fig. 8c). Unexpectedly, there were two high-density patches of brisingid sea stars on the eastern facing slope at a depth of 400 m. Patches were 1.3 km and 2 km long, and included densities as high as 110 individuals per 12 m^2 image (Fig. 9b). This was the only high-density patch of brisingids observed in the ABNJ seamounts surveyed by the AUV, and such densities of brisingids have only been observed by the authors on one other seamount in the Northwestern Hawaiian Islands.

In 2016 and 2017, 6 submersible dives were conducted on Kammu (Fig. 8d). The 4 on the northeast corner of the seamount found mostly barren substrate with heavy gear scarring and occasional fauna

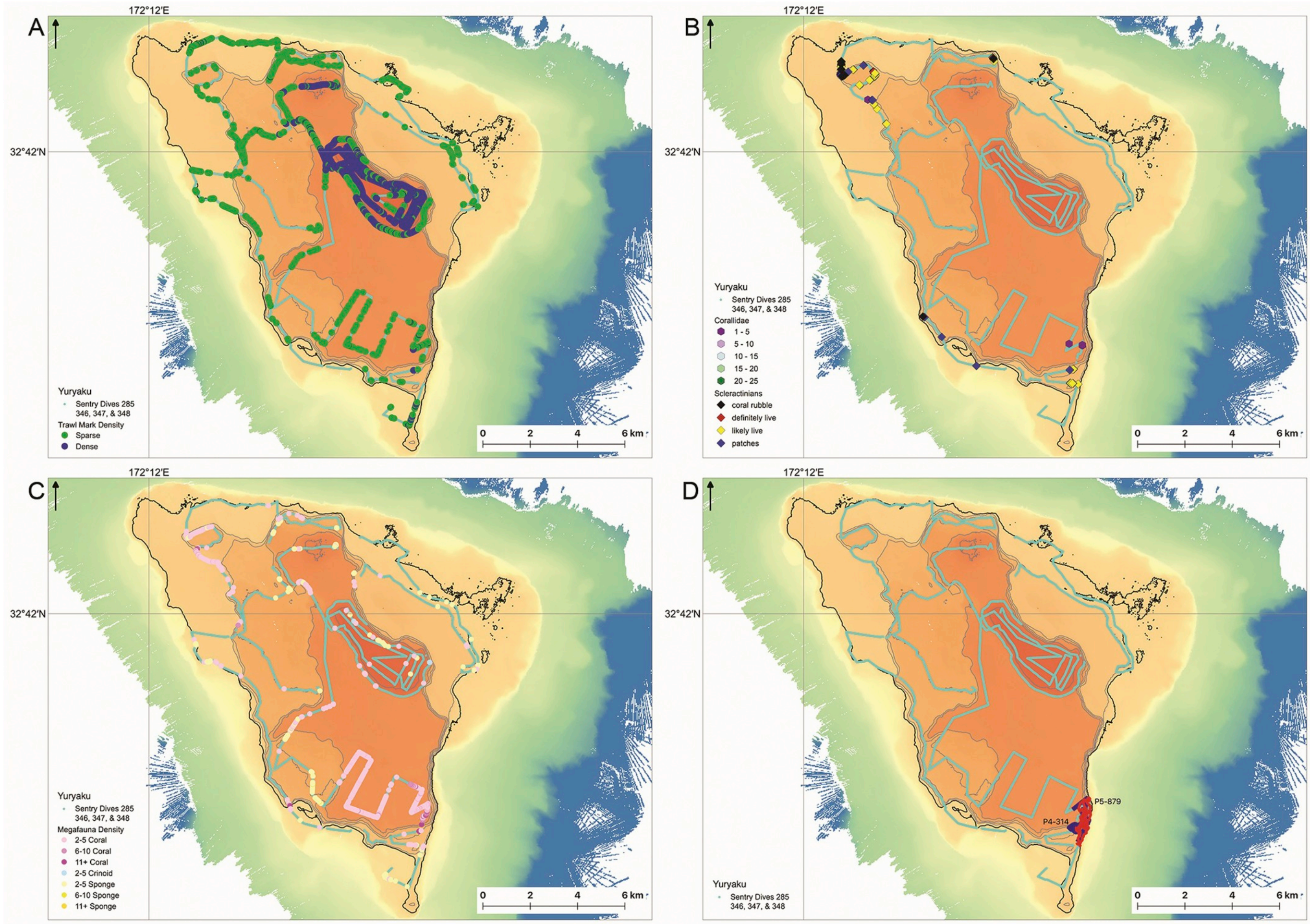

Fig. 6. Visual summary of AUV dive surveys on Yuryaku Seamount, showing multibeam bathymetry from 400 to 1500 m depth, contour lines from 400 to 700 m at 50 m depth intervals in gray, and AUV dive track in light blue line. (A) locations of scars from bottom contact gear and relative density are overlaid. (B) locations of images and approximate abundance for observations of coralliid octocorals and scleractinian corals are overlaid. (C) locations of images and abundances for observations of other megafauna are overlaid. (D) locations of submersible dive tracks are overlaid. Each circle or diamond in panels A–C represents a single AUV image, with color coding explained in the keys for each panel. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

including one small reef patch (Fig. 9c). The 2 dives on the southeastern portion visited the area where scleractinians were observed by the AUV and found that there was not much left of whatever reef had been there, (Fig. 9d). There were also areas on the southeast side with many coral stumps from large octocorals, as well as gold coral, *Kulamanamana haumeeae* stumps (Fig. 9e). The submersible also found a few young patches of the primnoid octocoral *Thouarella* (Fig. 9f), and patches of slightly older colonies of the same species (Fig. 9g). During the submersible dives, lost fishing gear was also observed, including lines, weights, and nets that may be ghost fishing (Fig. 9h).

3.4. Colahan (Calahan) seamount

Colahan seamount was not one of the original targets of this study and so was not surveyed with an AUV, however it was the best option when weather prevented diving with the submersibles further northwest and so a pair of dives were done on a ridge off of the NW corner of Colahan seamount in 2017 (Fig. 10A). Dives here were also cut short and constrained in survey area due to competition with fishing vessels. Despite this, an extensive, well-developed reef was discovered on Colahan at a depth of 620 m (Fig. 10b and c), that had not been noted in our previous descriptions of the NWHI reefs [13]. The reef was in better condition than that on any of the seamounts surveyed outside the US EEZ. There were clear associations of invertebrates and fishes with the reef structure. (Fig. 10 b,c). However, there was also evidence of significant damage to the reef with lost fishing gear, and large areas of coral rubble (Fig. 10 d). Drop camera fisheries surveys have also noted reef on the northeast ridge of Colahan, with Hayashibara and Nishida [26] noting that the reefs occur on this feature as deep as 850 m. In addition to reef, occasional colonies of large octocorals were observed, as well as an area of dense cup corals and an area of dense sponges (Fig. 10 e, f).

4. Discussion

Because of their remoteness, high seas management of fisheries in relation to the protection of VMEs on seamounts relies primarily on observations of bycatch of VME taxa in fisheries gear. However, it has been argued that the capture efficiency of VMEs by trawl gear is relatively low, and may not be representative of the true abundance and distribution of VME taxa on the seafloor [3]. An alternative approach is the use of visual surveys to determine the presence of VME taxa. The UN General Assembly resolutions [1] and the International Guidelines for the Management of Deep Sea Fisheries in the High Seas (hereinafter referred to as the FAO Guidelines) paragraph 47 [2] in fact have called on states and/or RFMOs to map an area to determine the extent of the presence of VMEs prior to authorizing bottom fisheries in the area on the

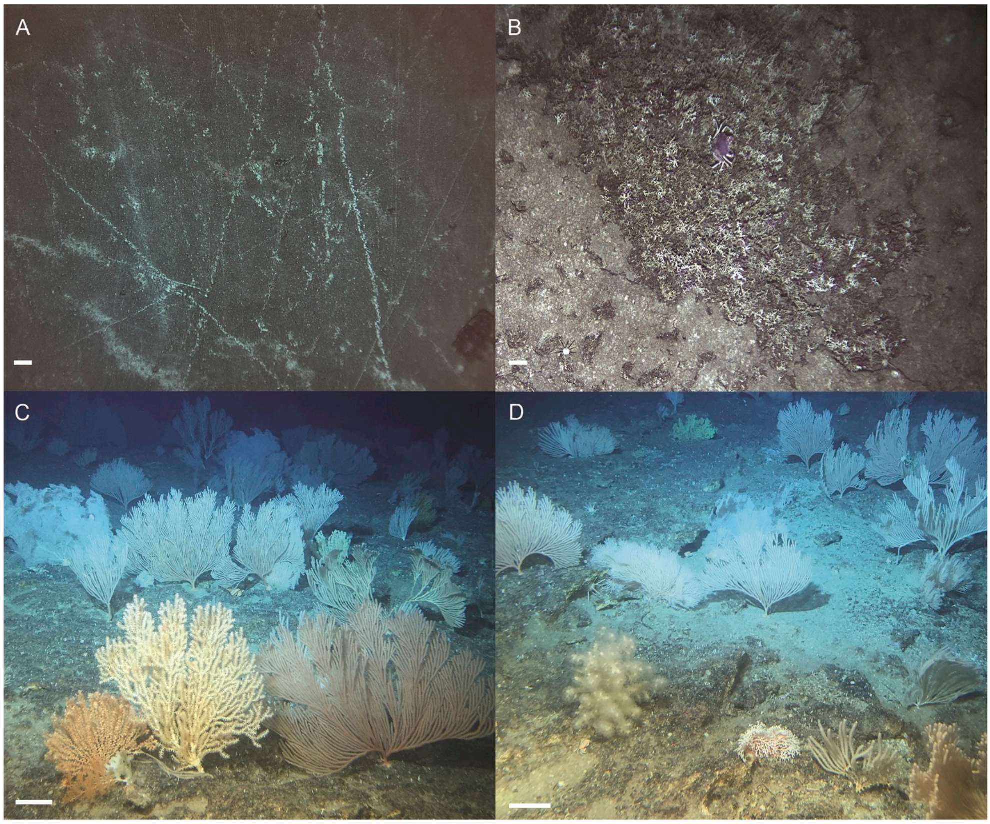

Fig. 7. Example seafloor images of megafauna from Yuryaku Seamount. The white scale bar in each image represents 10 cm. (A) AUV image showing scars from bottom contact gear. (B) AUV image of scleractinian reef rubble. (C) Dense patch of large octocorals. (D) Dense patch of octocorals with small coralliid colony.

high seas, and have reiterated and reinforced this call in 2016 as part of UNGA resolution 71/123, paragraph 180 [5]. Here we used an AUV and submersibles to survey a comparatively large area of four ABNJ seamounts in the ESC-NHR to assess the presence of VMEs and SAIs. We consider these results in the context of the guidelines in the NPFC regulations for bottom fisheries, which dictate that if "fishing activities are causing or likely to cause SAIs on VMEs or marine species, the member of the Commission is to adopt appropriate conservation and management measures to prevent such SAIs. The member of the Commission is to clearly indicate how such impacts are expected to be prevented or mitigated by the measures" [27]. This same document states that conservation and management measures should use available scientific information and be "in accordance with the precautionary approach" [28].

Based on these resolutions and guidelines and looking at any given seamount of the ESC-NHR, if *VMEs are likely to occur*, and if *bottom contact fisheries cause SAIs*, then the precautionary approach dictates that areas with likely VMEs should be shut down completely until the fishing states can prove that their gear will not cause SAIs. Also, if *recovery is possible*, then based on the precautionary approach, areas that provide suitable habitat and/or are known to have once harbored VME taxa should also be closed and allowed to recover. And these should remain closed unless it can be proven that SAIs would not occur. This is clearly called for in UNGA resolution 61/105 (and all subsequent resolutions calling for action to prevent significant adverse impacts on VMEs) in paragraph 81(c):

> "(*c*) In respect of areas where vulnerable marine ecosystems … are known to occur or are likely to occur based on the best available scientific information, to close such areas to bottom fishing and ensure that such activities do not proceed unless conservation and management measures have been established to prevent significant adverse impacts on vulnerable marine ecosystems"

4.1. VMEs are likely to occur

In this paper we provide evidence of the occurrence of VME taxa including dense patches of octocorals, scleractinian reefs, and deep-sea sponges on all four of the surveyed NHR and ESC seamounts. In many areas these taxa occur in sufficient abundance and densities to constitute reproductively viable populations and to be acting as habitat for other species of invertebrates and fishes. Out of the surveyed sites, areas that would qualify for VME designation based on these criteria include at a minimum, several locations on Koko, the southeast and northwest corners of Yuryaku, locations on Kammu, and the northwestern ridge of Colahan Seamount.

In addition to these documented observations, we can infer that VME taxa are or were present across broader areas of each of these features in significant concentrations and in areas we did not explore from a number of lines of evidence. The most obvious is the precious coral fishery, which had some of the highest takes in the world in this region. A key target of this fishery was the "Milwaukee Banks" where a "huge bed of *Corallium* (now *Pleurocorallium*) *secundum* was discovered at 400 m" in 1965. The take in this area was up to 200,000 kg of coralliids per year over the next 20 years. During this period 90% of global precious coral takes came from the NWHI/Emperor bend region [reviewed in [20]]. Both *Pleurocorallium secundum and Hemicorallium* (formerly *Corallium*) *laauense* were the target species at depths <600 m. The abundance and density of corals required to support such a large fishery for 2 decades imply a significant concentration of coralliid octocorals more than sufficient for a VME designation.

Besides the coralliid octocorals, a high diversity of other octocorals, antipatharians, gold corals, stylasterids, and non-hermatypic scleractinians occur in significant concentrations to depths of at least 2000 m at a number of other NWHI locations that have been explored [9–12, 29–32]. The species composition of these communities changes with

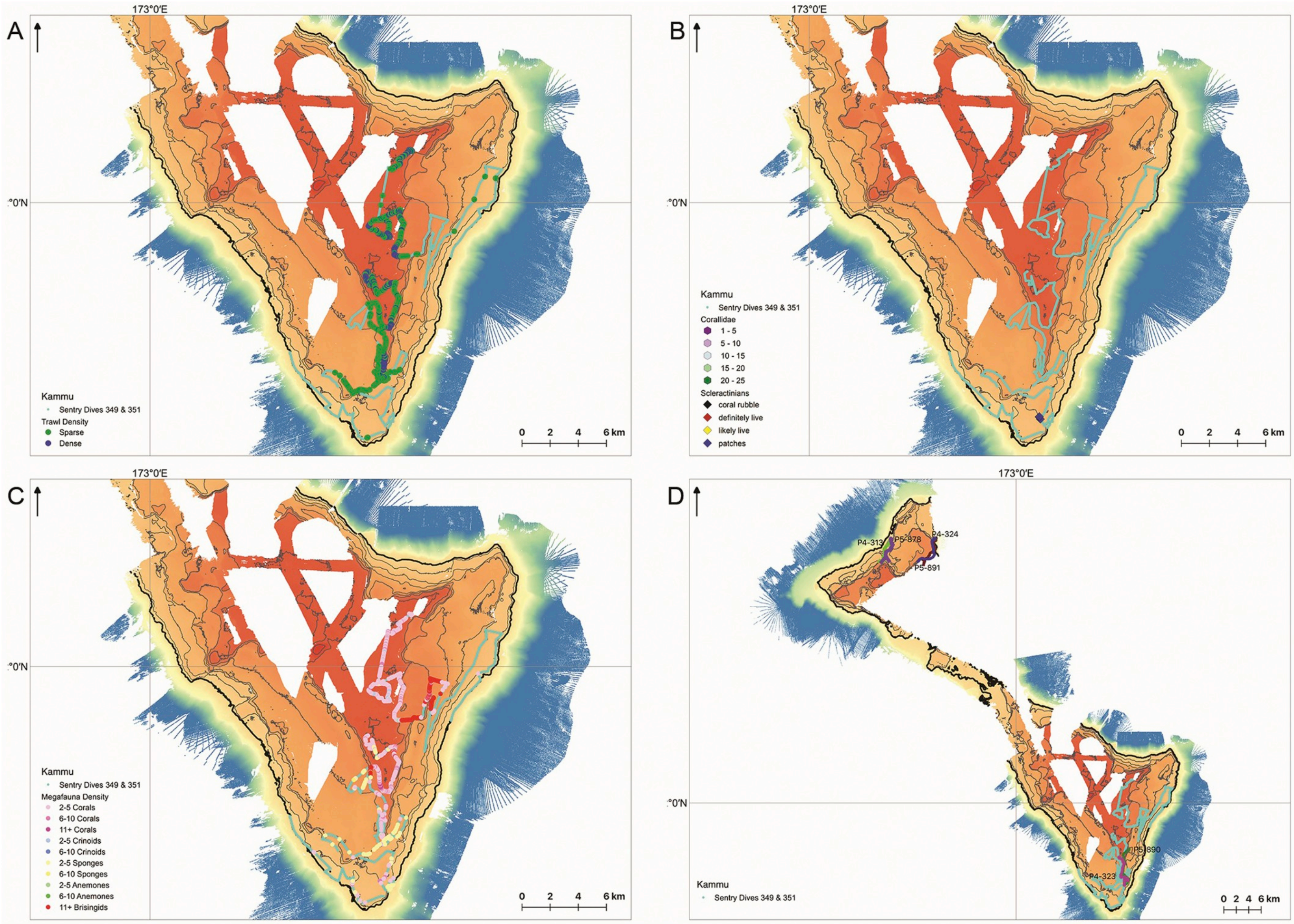

Fig. 8. Visual summary of AUV dive surveys on Kammu Seamount, showing multibeam bathymetry from 300 to 1500 m depth, contour lines from 300 to 700 m at 50 m intervals in gray, and AUV dive track in light blue line. (A) locations of scars from bottom contact gear and relative density are overlaid. (B) locations of images and approximate abundance for observations of coralliid octocorals and scleractinian corals are overlaid. (C) locations of images and abundances for observations of other megafauna are overlaid. (D) locations of submersible dive tracks are overlaid. Each circle or diamond in panels A–C represents a single AUV image, with color coding explained in the keys for each panel. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

depth and can vary within a single seamount [12,31,32]. These taxa generally occur in hard substrate areas at densities that would qualify as VMEs. Observations of coral communities, as well as octocoral and gold coral stumps on multiple seamounts documented here, support the expectation that these communities of VME taxa would also occur widely on the ABNJ seamounts. Miyamoto et al. [33] also confirmed the presence of many of these same VME taxa on ESC-NHR seamounts based on fisheries observers, beam trawls, and dredge samples.

Besides octocorals, deep-sea scleractinian reefs were discovered at depths of 530–750 m on six ESC-NHR and US EEZ NWHI seamounts, including Koko, Yuryaku and Kammu [13]. Colahan is added to that list of seamounts and had reef observed in sufficient density with visible faunal associations to be considered a VME. Additionally, rubble on Yuryaku, Kammu and Koko, with patches of live corals and recovering corals suggests these VMEs were once common on those seamounts as well.

Multiple habitat suitability modeling studies, recognizing there are some caveats to the approach [e.g. [34],[35]], corroborate the above evidence and suggest very high habitat suitability across most of the surface area of these seamounts for deep-sea corals in several taxonomic groups. Yesson et al. [17] found extremely high habitat suitability for octocorals along the entire Hawaiian Ridge and Emperor Seamount Chain. Davies and Guinotte [16] show very high to extremely high habitat suitability for structure forming scleractinians on all of the currently fished NHR and ESC seamounts, especially Koko and Kammu, but also Yuryaku and Colahan. In the highest resolution habitat suitability study, Miyamoto et al. [36] found high habitat suitability for large octocorals in a broad depth band all the way around Colahan seamount, and in patches on Koko Seamount (the focal seamounts of their study).

Collectively these lines of evidence indicate an extremely high probability that deep-sea coral VMEs are widespread on all of the ESC-NHR seamounts.

4.2. Bottom contact fisheries cause SAIs on the NHR and ESC seamounts

Assuming that VMEs are widespread in hard substrate areas of these seamounts as supported by the evidence above, then many lines of evidence for significant adverse impacts are documented here and in Baco et al. [21] for the NHR and ESC seamounts that are actively fished. 1) Large areas of hard substrate on each of the four seamounts were devoid of fauna (Figs. 7a and 8a). 2) These same areas showed numerous scars from bottom contact gear, with 19–29% of AUV survey images showing evidence of scars (Table 1). 3) Patches of coral stumps, from both gold corals and octocorals were observed (Fig. 9e). 4) Areas of coral rubble from scleractinian reefs were observed on all four seamounts (Figs. 5a and 7b,e, 8b, 9a, c, 10c). 5) Evidence of both fishing and SAIs is further supplied by presence of lost gear observed on every seamount, including

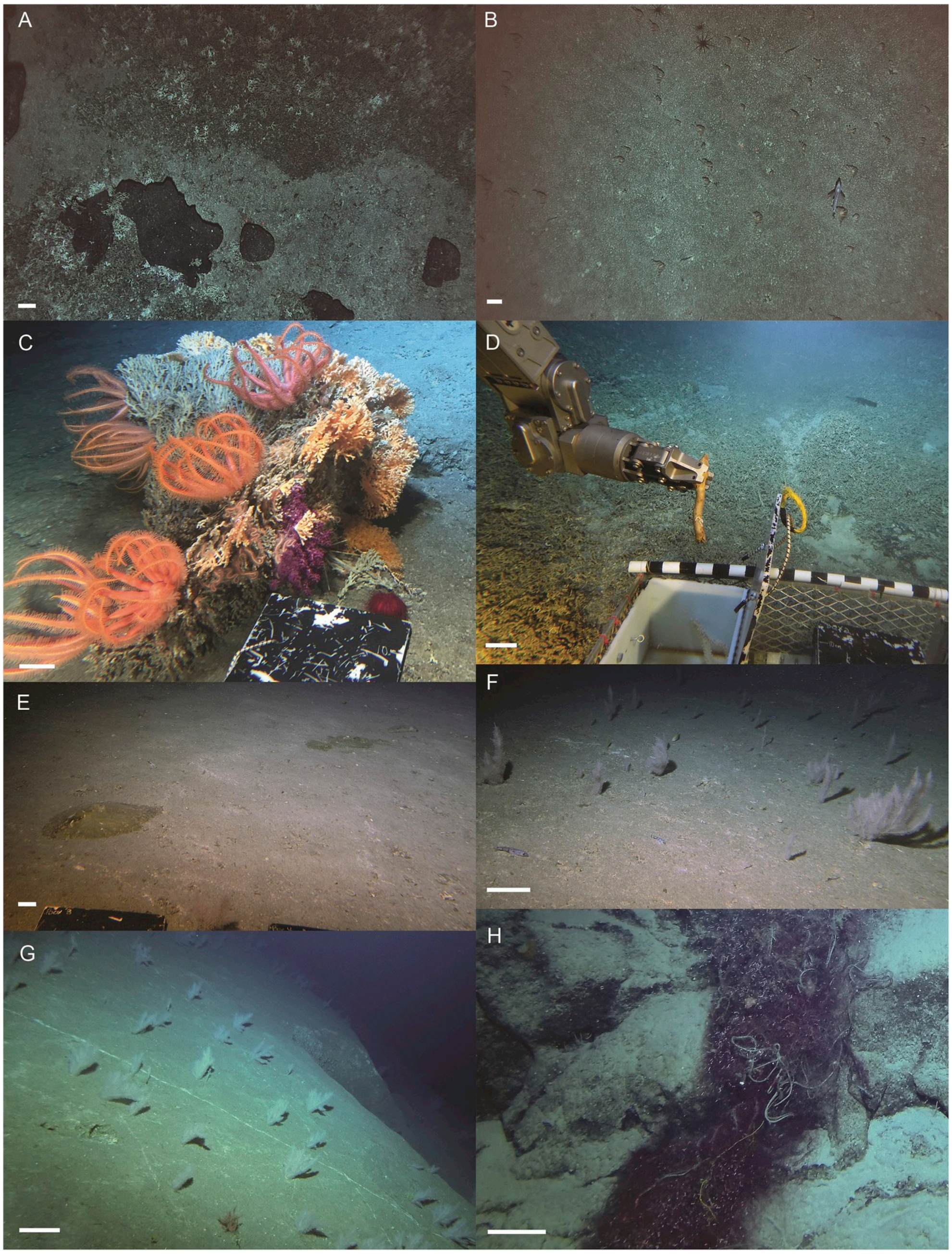

Fig. 9. Example seafloor images of megafauna from Kammu Seamount. The white scale bar in each image represents 10 cm. (A) AUV image of scleractinian rubble. (B) AUV image showing density of brisingids. (C) Solitary reef patch observed on submersible dives on northeast corner of Kammu including closeup image of brisingids. (D) Submersible image of reef rubble from southeast corner of Kammu. (E) *Kulamanamana haumeeae* stumps. (F) Patch of young *Thouarella* colonies with gear scars visible on the rock face. (G) Patch of older *Thouarella* colonies with gear scars visible. (H) Lost fishing net.

many observations of coral rubble in or around the nets, lines, floats, etc entangled in corals or laying across the coral beds (Figs. 9 h, 10D, and [21]).

We can also infer evidence of SAIs on these seamounts from the extremely low abundances of coralliid octocorals. To have supported the high levels of and duration of coralliid harvest in this region (1960–1980s), coralliids likely were present in comparable or greater abundances to other high-density coralliid beds in the Hawaiian Archipelago. Based on data from Parrish [30], we can estimate densities of coralliids of 30–50 ind per 100 m^2 in hard substrate areas on the Milwaukee Banks, with substantial abundances likely on the extensive hard substrate areas of most of the other NHR and ESC seamounts at depths <600 m as well. Kammu, the larger of the Milwaukee Banks, had only 1 coralliid observed on 6 sub dives and two 30-h AUV dives (>100 h total bottom time, and well over 100 km of linear distance surveyed). Coralliids were also rare on the other surveyed seamounts, with *P. secundum* nearly absent from all 4 seamounts studied (1 individual on Yuryaku and few on Koko) and *H. laauense* only found as small colonies in protected pockets. A density and abundance of coralliid octocorals which could support a documented fishery for over 2 decades clearly qualifies as a VME, and findings of few to no coralliids on those same seamounts 40 years after the peak of the fishery, cannot be defined as anything other than a significant adverse impact, across a significant spatial extent, to a VME taxon.

Therefore, with the evidence that indicates an extremely high probability that VMEs were widespread on all of the ESC-NHR seamounts prior to the fisheries detailed above, the observations outlined here (as well as in numerous other studies in other seamount coral beds in other parts of the world (e.g. [37–41]) collectively indicate that bottom contact fisheries cause significant adverse impacts to VMEs on the NHR and ESC seamounts.

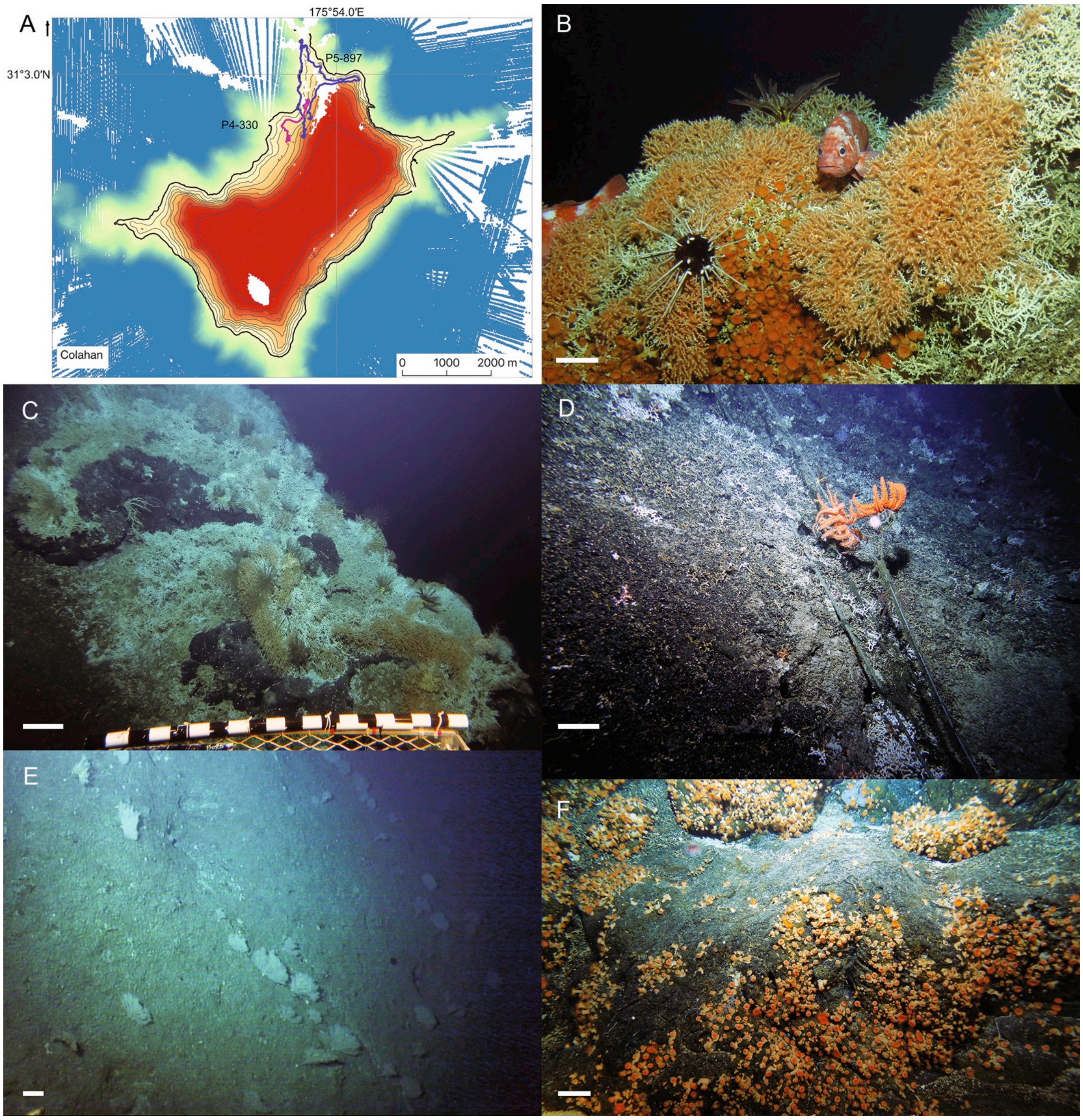

Fig. 10. (A) Bathymetry of Colahan Seamount showing location of submersible dives. Example submersible images from Colahan of: (B) Close up of scleractinian reef showing associated fish and invertebrates. (C) Overview of scleractinian reef with associated crinoids. (D) Lost fishing gear with scleractinian rubble. (E) Octocoral colonies. (F) Dense cup corals. The white scale bar in images B–F represents 10 cm.

4.3. Resilience and recovery of VME taxa on the NHR and ESC seamounts

In a separate analysis we have outlined the potential for recovery of deep-sea coral VME taxa on the seamounts of the NHR and ESC [21]. In that paper, evidence for recovery following protection of seamounts included colonization of corals over areas with visible gear scars, coralliid and reef-forming scleractinians regrowing from fragments among the coral rubble surrounding and spilling out of lost nets, and counts of megafauna from replicated, quantitative AUV image tracks that show higher levels of megafauna overall and higher levels of corals, on recovering seamounts in the US EEZ when compared the sites which are still trawled on the NHR and ESC.

The current analysis provides additional images of remnant and/or recovering VME populations on all four currently fished seamounts. Koko and Colahan have the best developed coral communities with pockets of significant concentrations of VME taxa remaining. Kammu and Yuryaku are more heavily impacted, but have patches that suggest recovery is possible if protections are put into place. Observations included larger more mature octocoral colonies in areas with lost lines, gear and gear scars (Fig. 5f and g, 7c, and [21]), observations of dense stands of remnant or recovering populations of octocorals on Koko Seamount; rare but observed images of young *Thouarella* (a primnoid octocoral) on Kammu; pockets of corals on Yuryaku; and pockets of healthy reefs on Colahan.

Collectively these observations provide evidence that recovery of deep-sea coral VME taxa may be possible if protections are put into place. Also, pockets of remnant VME populations exist on the currently impacted seamounts that may help to speed the recovery process at those sites.

5. Conclusions and management implications

Based on the evidence provided here, VMEs were observed on all four seamounts and are likely to occur extensively on NHR and ESC seamounts. Historic and current bottom contact gear fisheries have caused and continue to cause SAIs to these VMEs. The UNGA has called on states and RFMOs to close areas to bottom fishing where VMEs are known or likely to occur, unless fishing in the area can be managed to "prevent" SAIs on VMEs. When SAIs are occurring on VMEs, the NPFC regulations state that it is necessary to "adopt appropriate conservation and management measures to prevent SAIs" [28]. Therefore, in accordance with the precautionary approach, and to "establish appropriate conservation measures" the results presented here would indicate a closure of all NHR and ESC seamounts to bottom contact fisheries until the gear being used can be proven to not cause SAIs. Additionally, since recovery is possible for these VME taxa, not only untrawled areas ('freeze the footprint type measures") should be closed, but also actively fished areas should be closed to bottom contact gear to allow them time to recover. Examples of following the precautionary approach in seamount management can be seen in the NAFO area where many features are closed to bottom-fishing due to the presences of corals and sponges [6]. Similar closures have already been enacted for coral-rich habitats within the NPFC on Koko Guyot and C–H seamount [42], thus the NPFC already has the regulatory guidelines in place to enact further closures to protect the VMEs described herein.

Funding

This work was conducted through support from NSF grant #s OCE-1334652 to ARB and OCE-1334675 to EBR. Work in the adjacent Papahānaumokuākea Marine National Monument was permitted under permit #PMNM-2014-028 and #PMNM-2016-021.

Declaration of competing interest

The authors have no competing interests to declare.

CRediT authorship contribution statement

Amy R. Baco: Conceptualization, Methodology, Formal analysis, Funding acquisition, Resources, Investigation, Writing - original draft, Visualization, Data curation, Writing - review & editing, Supervision, Project administration. **Nicole B. Morgan:** Investigation, Visualization, Methodology, Data curation, Writing - review & editing. **E. Brendan Roark:** Funding acquisition, Supervision, Investigation, Data curation, Writing - review & editing, Project administration.

Acknowledgments

The authors would like to thank the captains and crew of the RV Sikuliaq, RV Kilo Moana and RV Ka'Imikai – O - Kanaloa as well as the pilots and crew of the AUV Sentry and Pisces IV and V submersibles, as well as the assistance of many volunteers at sea. Savannah Goode, Travis Ferguson, Alexis Rentz and Tyler Whitehead contributed to the AUV Sentry image analyses. Discussions with Matthew Gianni improved this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpol.2020.103834.

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