Seascape Solutions LLC

Pūpūkea-Waimea MLCD Coral and Fish Assessment: 2010 - 2019

Prepared for:
Mālama Pūpūkea-Waimea

October 2019

Pūpūkea-Waimea Marine Life Conservation District Coral and Fish Assessment: 2010-2019

Prepared by:
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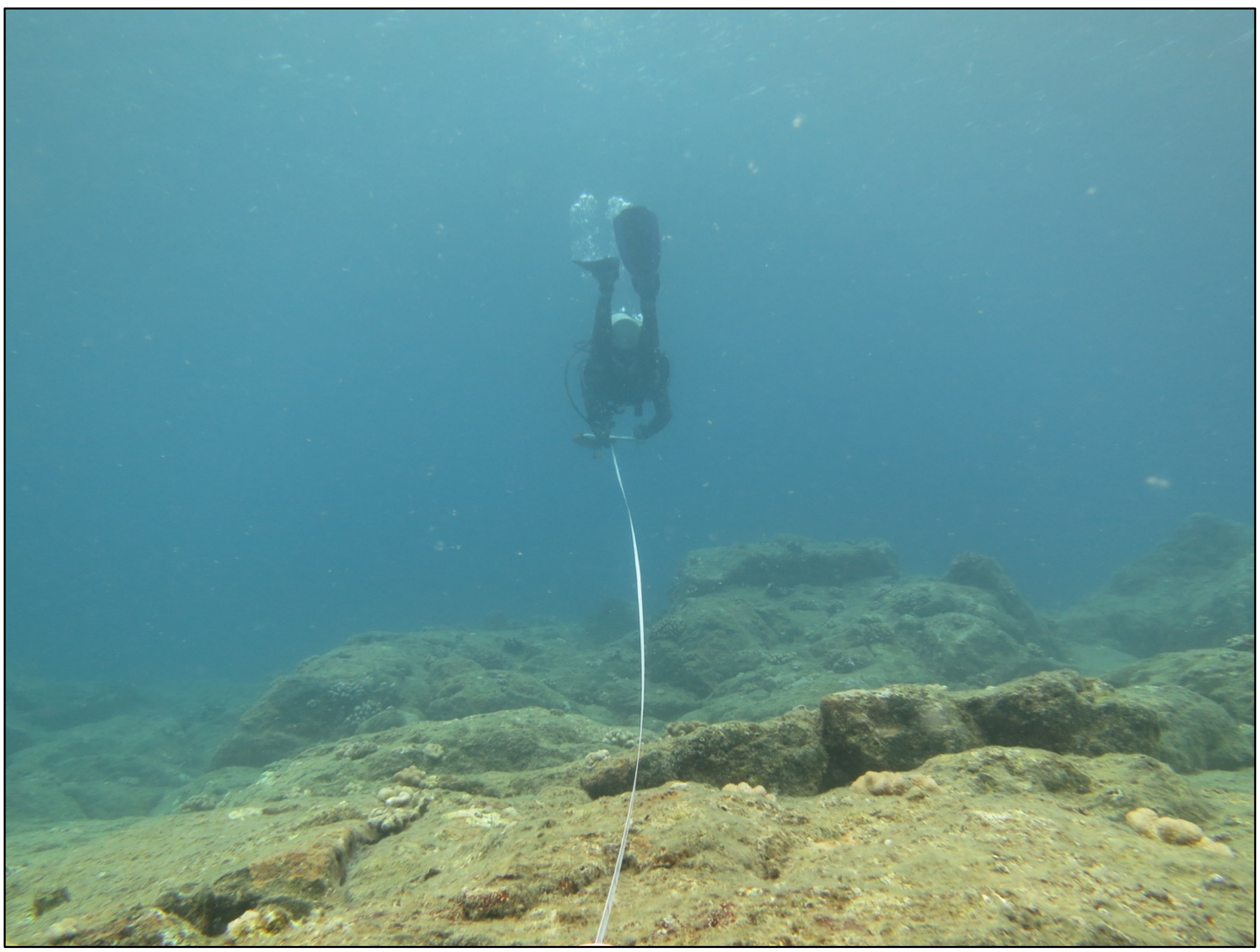

Figure i. Diver conducting a fish survey at Pūpūkea on June 5th, 2019.

Executive Summary

- Benthic cover was similar between 2010 and 2019 surveys in shallow and mid-depth areas. In deeper areas, average coral cover declined significantly from 10% to 6% with a corresponding increase in turf cover.
- Overall abundance (numbers), biomass (weight), and species richness (number of species) of fishes declined significantly between surveys across all depth zones.
- These declines were significant for both resource (fished) and non-resource (un-fished) species, except for the decline in resource fish species richness.
- The greatest declines in resource fish abundance were found in shallow sites while the greatest declines in non-resource fish abundance were found predominately in deeper areas.
- The largest declines in resource fish biomass were found in deeper sites and the largest declines in non-resource fish biomass were found across all depth zones.
- The greatest decline for resource species was the Convict Tang (manini), which showed a 91% decrease equivalent to 555 fishes per hectare.
- Some resource species increased, notably the Bluefin Trevally (omilu) which was 8 times more abundant in 2019 compared to 2010 equivalent to a gain of 35 fishes per hectare.
- The greatest decline for non-resource species was the Blackfin Chromis, which showed a 72% decrease equivalent to 3,474 fishes per hectare. Some non-resource species increased including four species of butterflyfish.
- Overall human use doubled between 2010 and 2019. In-water human use increased tenfold in the zone outside of Sharks Cove to Kulaloa point. Shore-based human use tripled in the tidepool area.

Introduction

The State of Hawaii created the Pūpūkea-Waimea Marine Life Conservation District (MLCD) on the north shore of the island of Oʻahu in 1983 to conserve the unique ecological resources of the area and to allow for public interaction with the marine environment. During the MLCD development process, concerns were raised by several user groups that resulted in the designation of a relatively small protected area (11 ha) that allowed for a number of extractive uses. In 2002, the area under protection was expanded by 645% (71 ha) and harvest restrictions were greatly increased through a largely community-driven process. The increase in total protected area size resulted in an increase in habitat diversity, depth and structural complexity (Friedlander et al. 2010). Fishing is currently prohibited except for shore fishing in Waimea Bay only, with no more than two rods per person. In addition, seasonal surround net fishing is permitted in Waimea Bay for two coastal pelagic species (opelu – August and September; akule – November and December). Malama Pūpūkea-Waimea (MPW) is a non-profit community organization that conducts education and outreach activities as well as human use and ecological surveys of the marine protected area (Stamoulis and Friedlander 2013). This organization plays a key role in raising awareness of the MLCD's fragile marine life and protected status and conducts a range of stewardship and advocacy projects and activities.

Scientific monitoring of fish and benthic communities in the Pūpūkea-Waimea MLCD has occurred over the years since its expansion with comprehensive surveys conducted in 2003, 2006, 2007, and with fish surveys only in 2008 at 24 locations on hard-bottom habitats inside the MLCD (Friedlander et al. 2010). A later survey effort occurred in 2010 which utilized the similar methods but different survey locations, with 40 locations on hard-bottom habitats inside the MLCD (Stamoulis and Friedlander 2013). At the request of the MPW organization, in June 2019, Seascape Solutions LLC replicated the 2010 surveys of Stamoulis and Friedlander (2013) at 29 locations inside the MLCD in order to 1) evaluate changes in coral cover and 2) quantify changes in coral reef fish assemblages over time at Pūpūkea-Waimea MLCD.

Methods

Benthic surveys

Underwater surveys were conducted by scientists on SCUBA at 29 pre-determined locations in Pūpūkea-Waimea MLCD (Figure 1). 25 m transect lines were laid out in the same location and position – based on GPS start points and compass bearings – as 2010 surveys (Stamoulis and Friedlander 2013). Methods were identical to those used in 2010 where photo-quadrats were collected every 2 m for a total of 12 per transect using a 0.5 m rod connected to the camera housing to standardize distance from the substrate and thus quadrat size. In addition, rugosity (3D structure) was measured on each transect using the chain and tape method whereby a fiberglass measuring tape was carefully contoured along the reef surface directly beneath the transect (Risk 1972). Benthic cover was calculated for each transect using the CPCe image analysis software (Kohler and Gill 2006), using 15 random points per photo. Benthic cover was identified to five major cover categories under each point for a total of 180 points per transect.

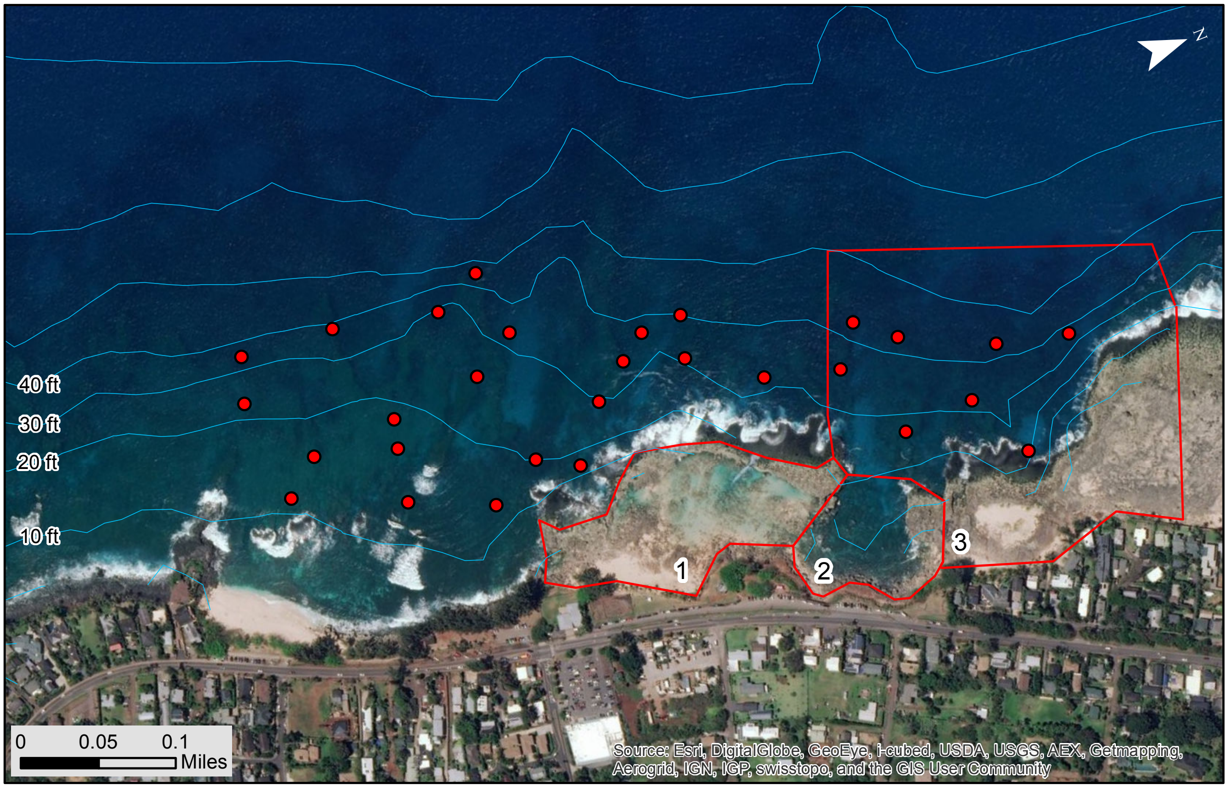

Figure 1. Sites surveyed in 2010 and re-surveyed in 2019. Human use survey zones shown in red: (1) tidepool area, (2) Sharks Cove inside, (3) Sharks Cove outside.

<u>Fish surveys</u>

Underwater coral reef fish surveys were conducted by scientists on SCUBA at the same 25 pre-determined locations in Pūpūkea-Waimea MLCD (Figure 1), immediately preceding the proposed benthic surveys. A diver swam slowly along the 25 m transect at a constant speed and identified to the lowest possible taxon all fishes visible within 2.5 m to either side of the center line. Survey duration varied from 10 to 15 min, depending on habitat complexity and fish abundance. Total length of fishes were estimated to the nearest centimeter (Bell et al. 1985, Friedlander and Parrish 1998). Length estimates of fishes were be converted to weight using the standard weight-length relationship and species-specific fitting parameters. Biomass estimates were converted to grams per square meter and abundance converted to numerical density (number per square meter) to enable comparison with previous studies. Fishes were grouped depending on if they are locally targeted by fishers with targeted species referred to as 'resource fishes' and non-targeted species referred to as non-resource fishes.

Data Analysis

Coral cover and rugosity

Change in coral cover and rugosity between the 2010 and 2019 surveys were each evaluated using a two-way ANOVA with Year and Depth as factors. The distribution of coral cover by site was first examined and found to conform to a normal distribution, thus satisfying the assumptions of the test with no transformation necessary. Rugosity by site was transformed using a square-root transformation to conform to assumptions of normality. Coral cover, turf cover, and rugosity by depth were compared by survey year using a one-way ANOVA. Results were visualized with bar charts of overall benthic cover, coral cover, turf cover, and rugosity by depth and year. Coral cover by site was examined using maps of coral cover in 2010 and 2019 as well as change in coral cover by site.

Fishes

Change in fish assemblages between the 2010 and 2019 surveys were evaluated using a one-way ANOVAs of total fish abundance, biomass and species richness; resource fish abundance, biomass and species richness; and non-resource fish abundance, biomass and species richness. Fish abundance is reported in number per square meter, biomass in grams per square meter and richness in number of species. Change in abundance was also evaluated at the species level in terms of number of individuals per hectare and percent difference. Number of individuals per hectare was used to provide more meaningful values. As a spatial reference, the area of Sharks Cove is approximately one hectare. The distribution of each response variable was examined and transformed as necessary to conform to statistical assumptions of normality. Abundance was transformed using fourth-root transformation, biomass was transformed using an $\ln(x+1)$ transformation, and species richness did not require transformation. Results were visualized using bar charts of each variable by depth and year. Abundance, biomass, and species richness of fishes by site were examined using maps of 2010 and 2019 values as well differences by site.

Humans

Human use data was provided by MPW for 2010 and 2019. Counts were made 2-5 times per month, typically in the middle of the day. The recent dataset focused on the tidepool area, inside of Sharks Cove, and outside the cove to Kulaloa Point (Figure 1). Data for these three zones was extracted from the 2010 dataset for comparison and each dataset was subset for the months May-September when usage of the MLCD is highest. Swimming, snorkeling, and SCUBA diving were combined to provide a single measure of in-water human use and beach / shore, reef walk, and rock walk were combined to form a single measure of shore-based human use. The sum of these categories was considered overall human use. Change in human use was evaluated using a two-way ANOVA with Year and Zone as factors. Values were transformed using a square-root transformation to conform to statistical assumptions of normality.

Results

Coral Cover

Overall benthic cover was similar between 2010 and 2019 surveys for shallow (10-20') and mid-depth (20-30') areas (Figure 2).

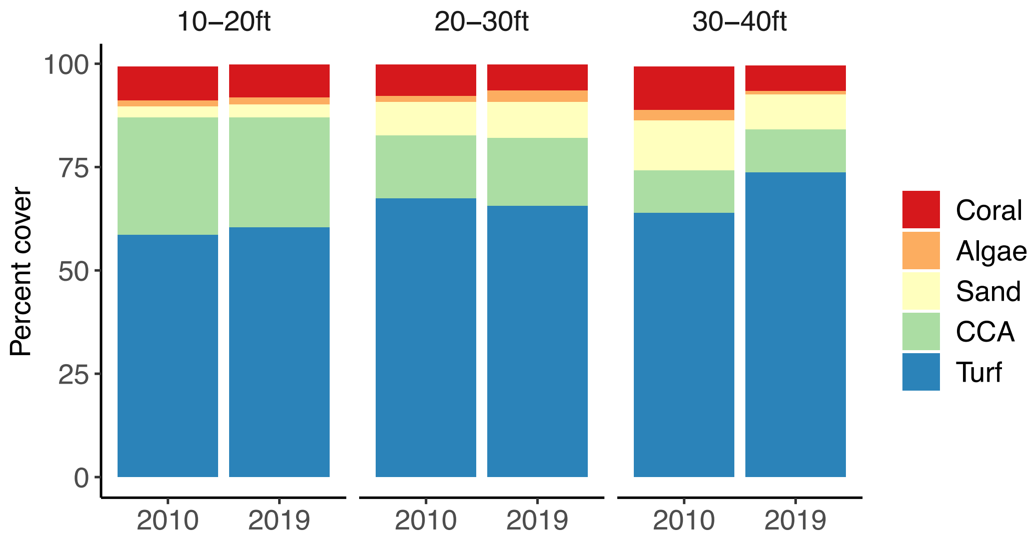

Figure 2. Combined percent benthic cover in 2010 and 2019 by depth zone.

Coral cover in these areas averaged 6-8% in both years. In contrast, deeper (30-40') areas showed a significant decline in average coral cover from 10.4% (± 3.2) to 6.2% (± 2.9) on average ($F=7.8$, $p<0.05$, Figure 3).

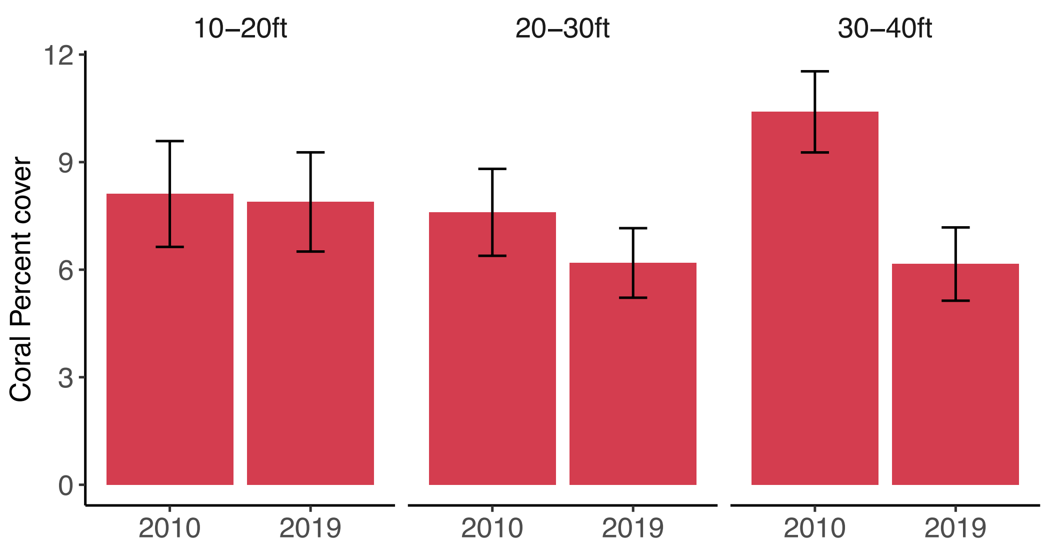

Figure 3. Coral percent cover in 2010 and 2019 by depth zone. Error bars represent standard error of the mean.

Correspondingly, turf cover increased from 64.0% (± 6.9) to 73.8% (± 8.2) on average (F=6.6, p<0.05, Figure 4). Rugosity showed no significant differences for any depth zone during the survey interval (Figure 5). Specific sites in deeper areas showed coral cover decreases of up to 9%, though other sites showed increases of 1-3%. (Figure 6). In contrast, several sites in shallow areas showed coral cover increases of 3-6% (Figure 6).

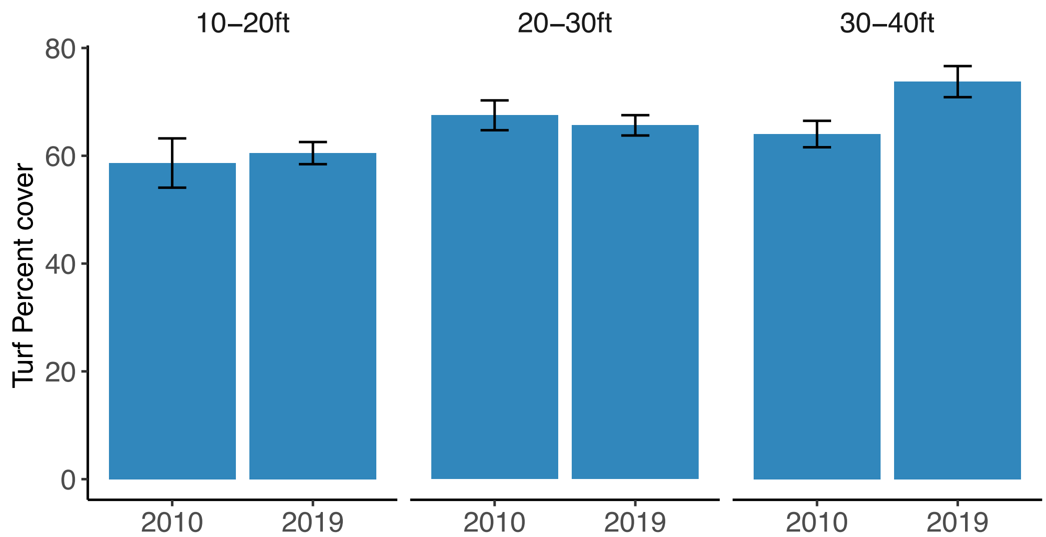

Figure 4. Turf percent cover in 2010 and 2019 by depth zone. Error bars represent standard error of the mean.

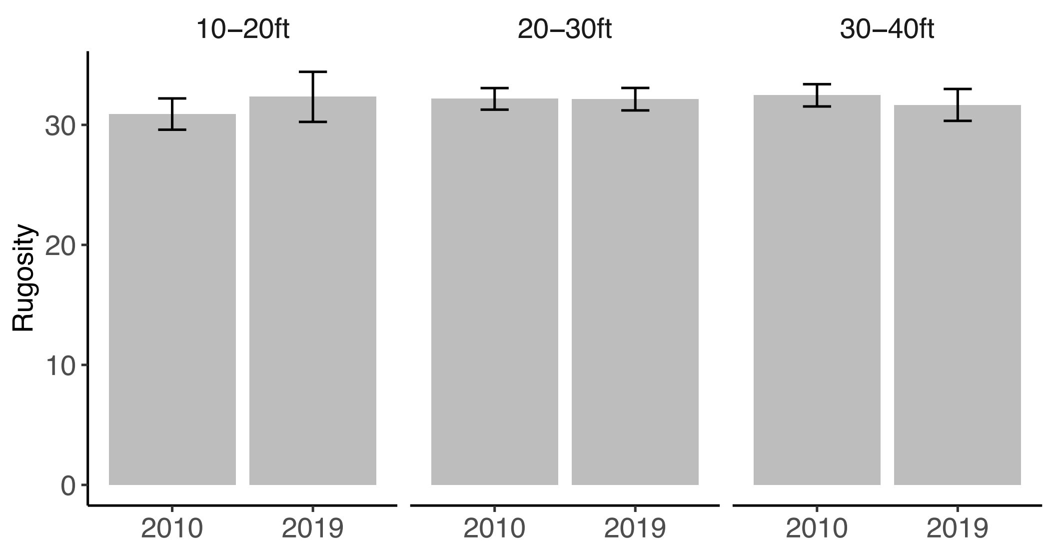

Figure 5. Rugosity in 2010 and 2019 by depth zone. Error bars represent standard error of the mean.

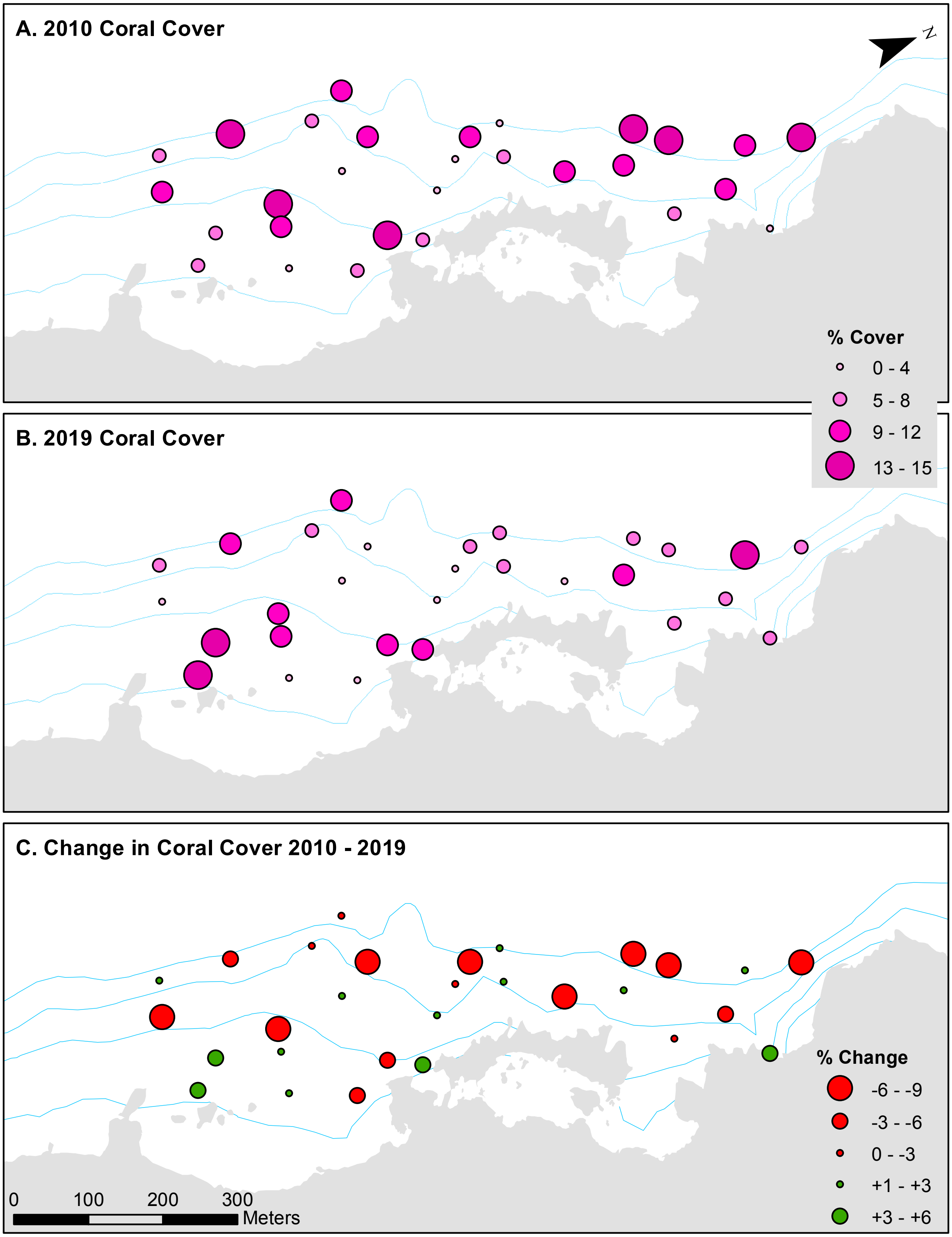

Figure 6. A) Coral cover by site in 2010. B) Coral cover by site in 2019 shown on the same scale. C) Change in coral cover by site between 2010 and 2019.

Fishes

Overall abundance (F=67.6, p<0.001, Figure 7), biomass (F=21.3, p<0.001, Figure 8), and species richness (F=12.6, p<0.001, Figure 9) of fishes declined significantly between surveys across all depth zones (Table 1). A significant decline was found for resource fish abundance (F=11.1, p<0.01) and biomass (F=14.1, p<0.001), though not richness (F=3.5, p>0.05). Non-resource fish declined significantly in terms of abundance (F=48.2, p<0.001), biomass (F=21.1, p<0.001), and richness (F=12.6, p<0.001).

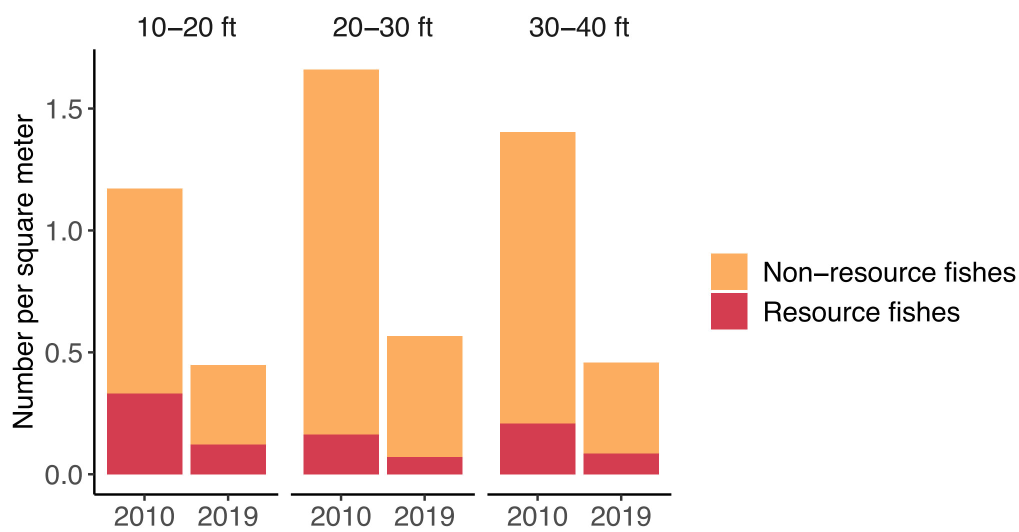

Figure 7. Fish abundance (number/m^2) in 2010 and 2019 by depth zone.

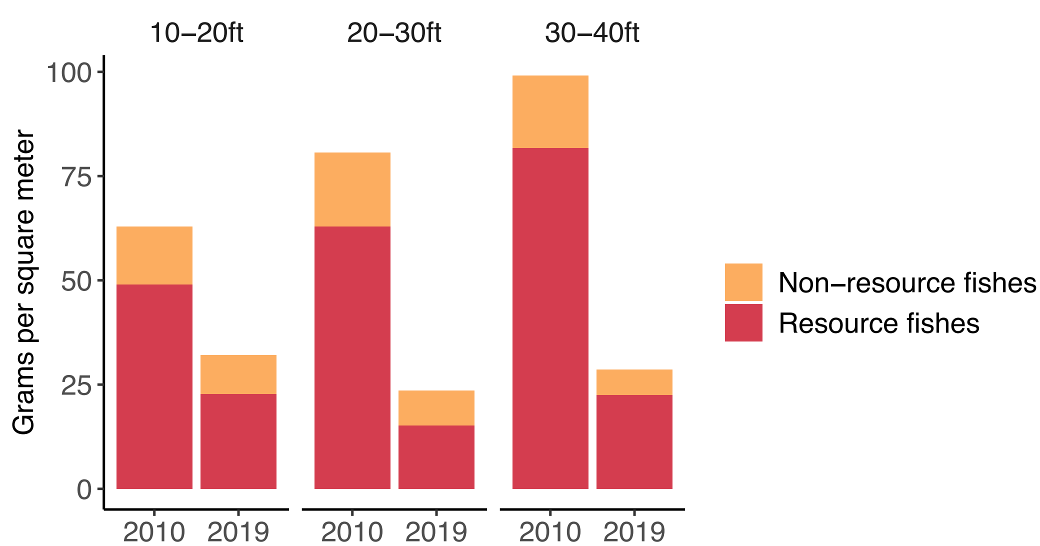

Figure 8. Total fish biomass (g/m^2) in 2010 and 2019 by depth zone.

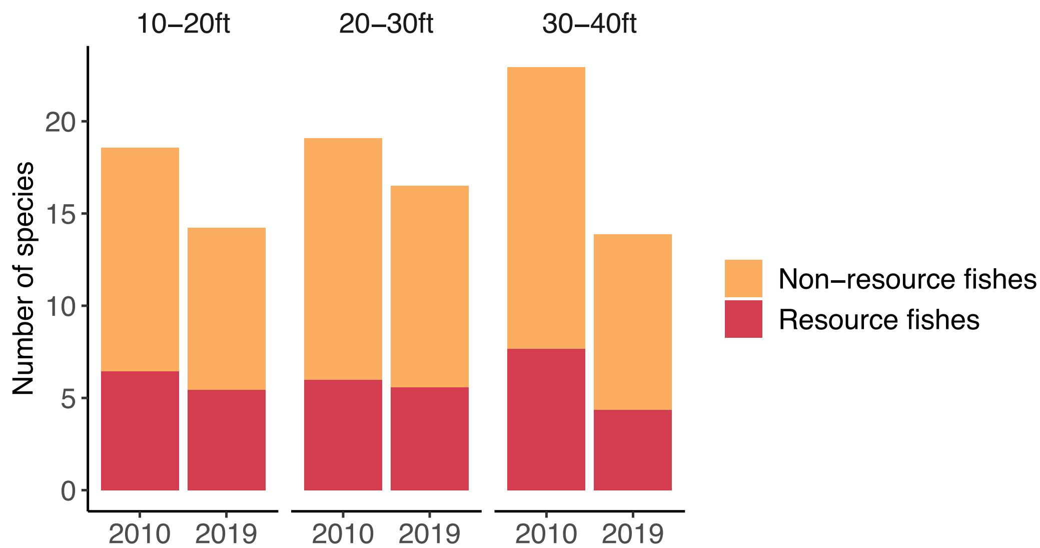

Figure 9. Total fish species richness in 2010 and 2019 by depth zone.

Table 1. Average and standard deviation (sd) of fish species abundance (number per square meter), total fish biomass (grams per square meter), and fish species richness (number of species) in 2010 and 2019.

	Abundance		Biomass		Richness	
Year	**num/m²**	**± (sd)**	**g/m²**	**± (sd)**	**number**	**± (sd)**
2010	1.4	0.7	80.2	71.6	20.0	5.9
2019	0.5	0.2	27.6	19.8	15.1	4.5

The greatest declines in resource fish abundance were found in shallow sites (Figure 10) while the greatest declines in non-resource fish abundance were found predominately in deeper areas (Figure 11). The largest declines in resource fish biomass were found in deeper sites (Figure 12) and the largest declines in non-resource fish biomass were found across all depth zones (Figure 13). The greatest declines in resource fish richness were also found mainly at deeper sites (Figure 14) and the greatest declines in non-resource fish richness were found at both shallow and deeper sites (Figure 15).

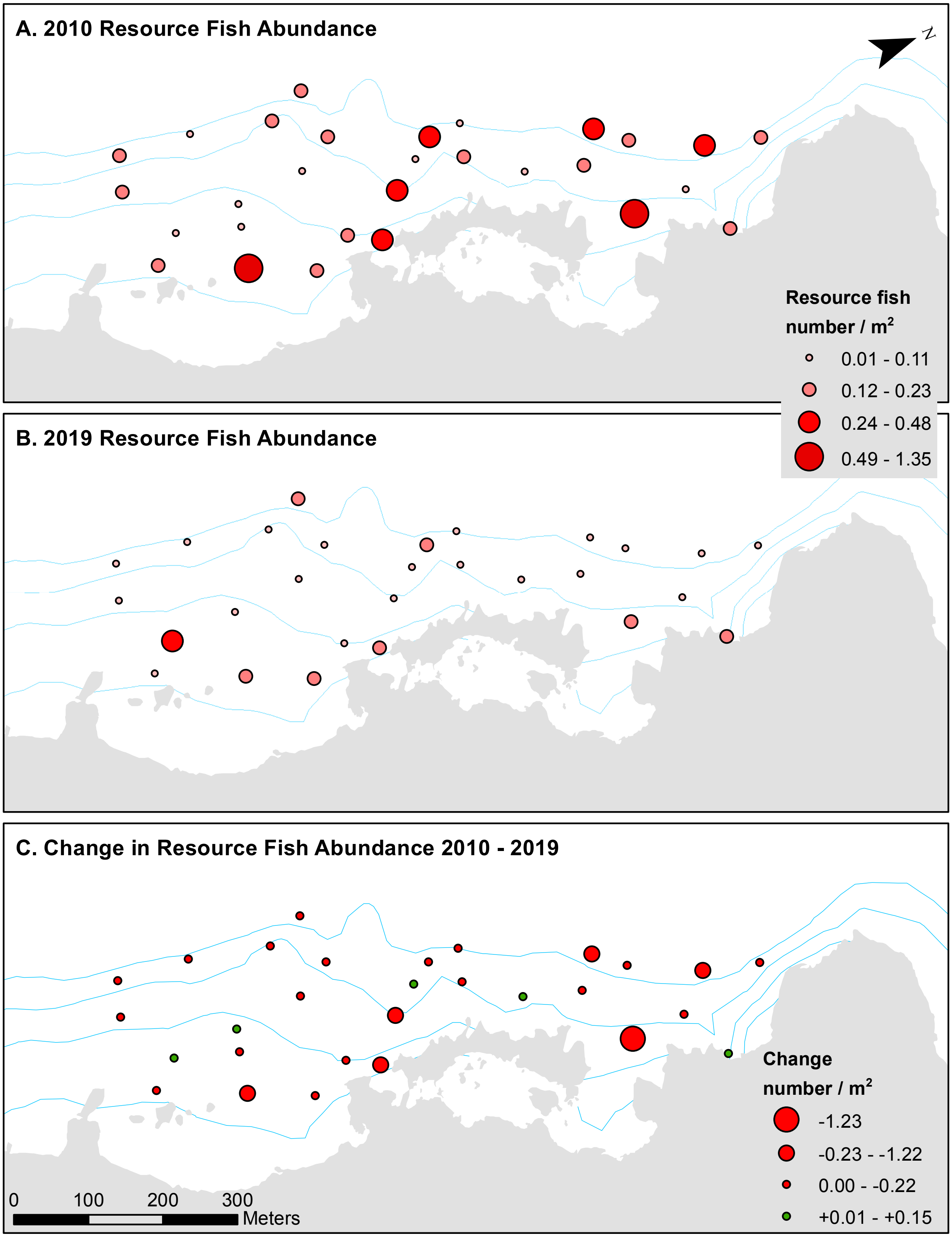

Figure 10. A) Resource fish abundance by site in 2010. B) Resource fish abundance by site in 2019 shown on the same scale. C) Change in resource fish abundance by site between 2010 and 2019.

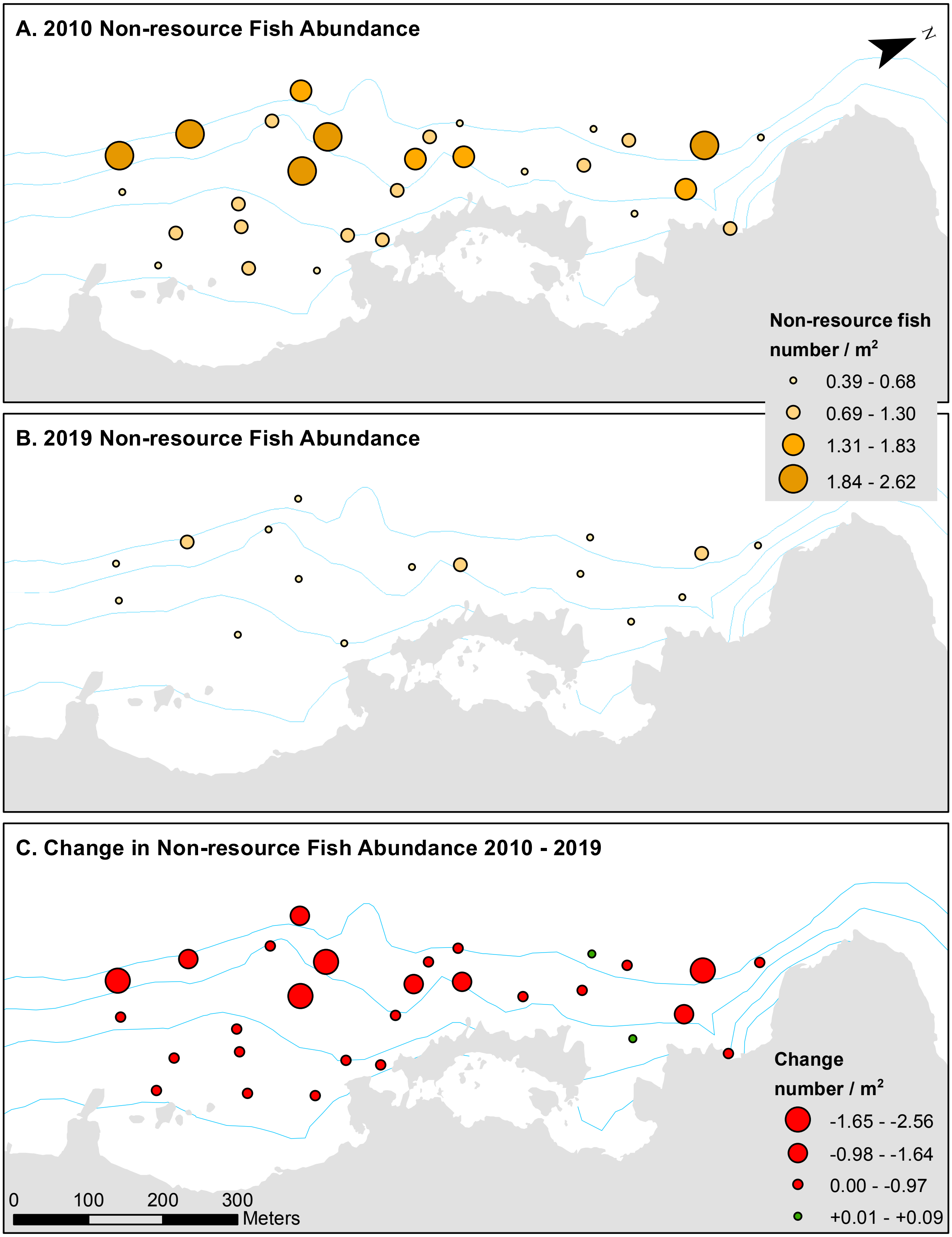

Figure 11. A) Non-resource fish abundance by site in 2010. B) Non-resource fish abundance by site in 2019 shown on the same scale. C) Change in non-resource fish abundance by site between 2010 and 2019.

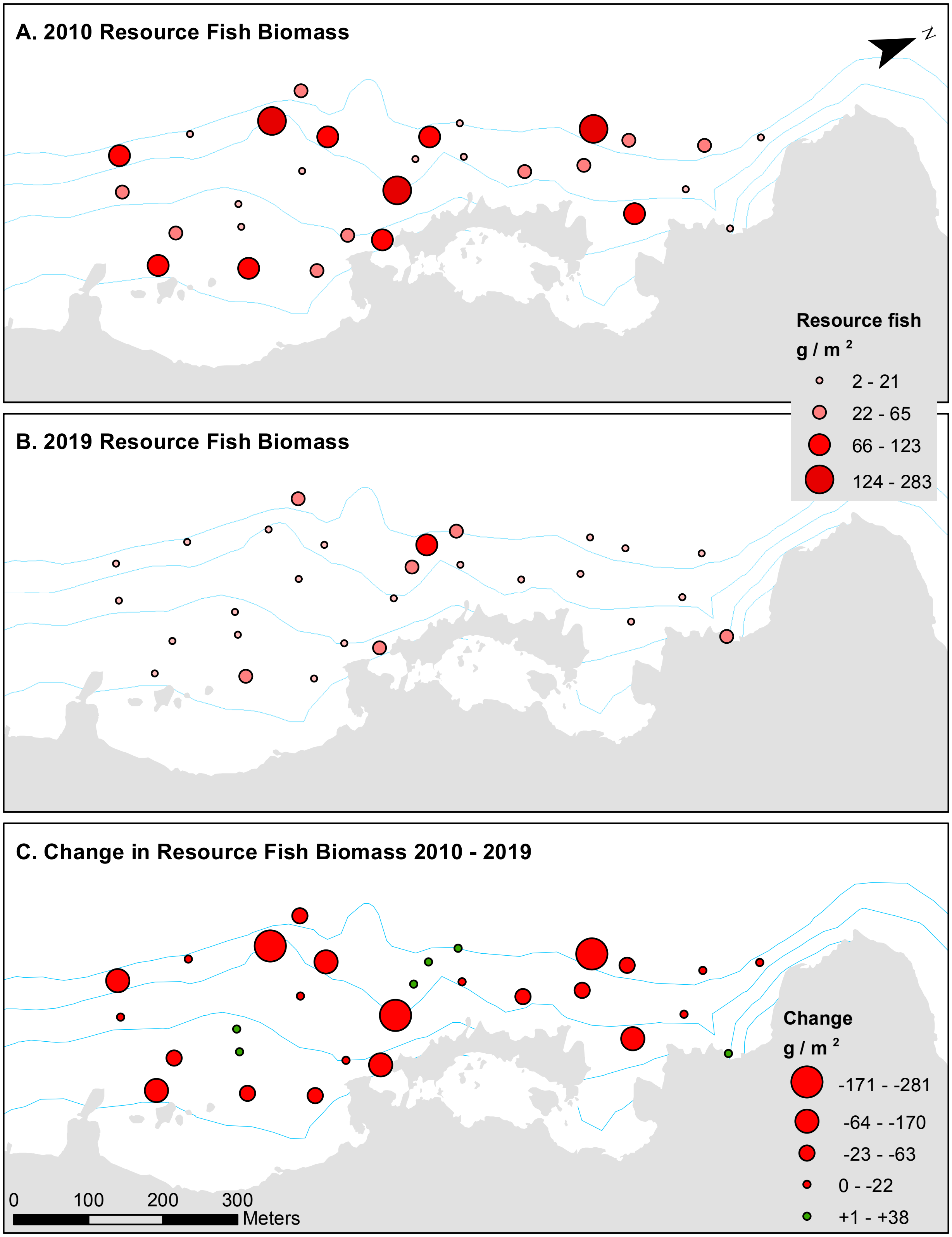

Figure 12. A) Resource fish biomass by site in 2010. B) Resource fish biomass by site in 2019 shown on the same scale. C) Change in Resource fish biomass by site between 2010 and 2019.

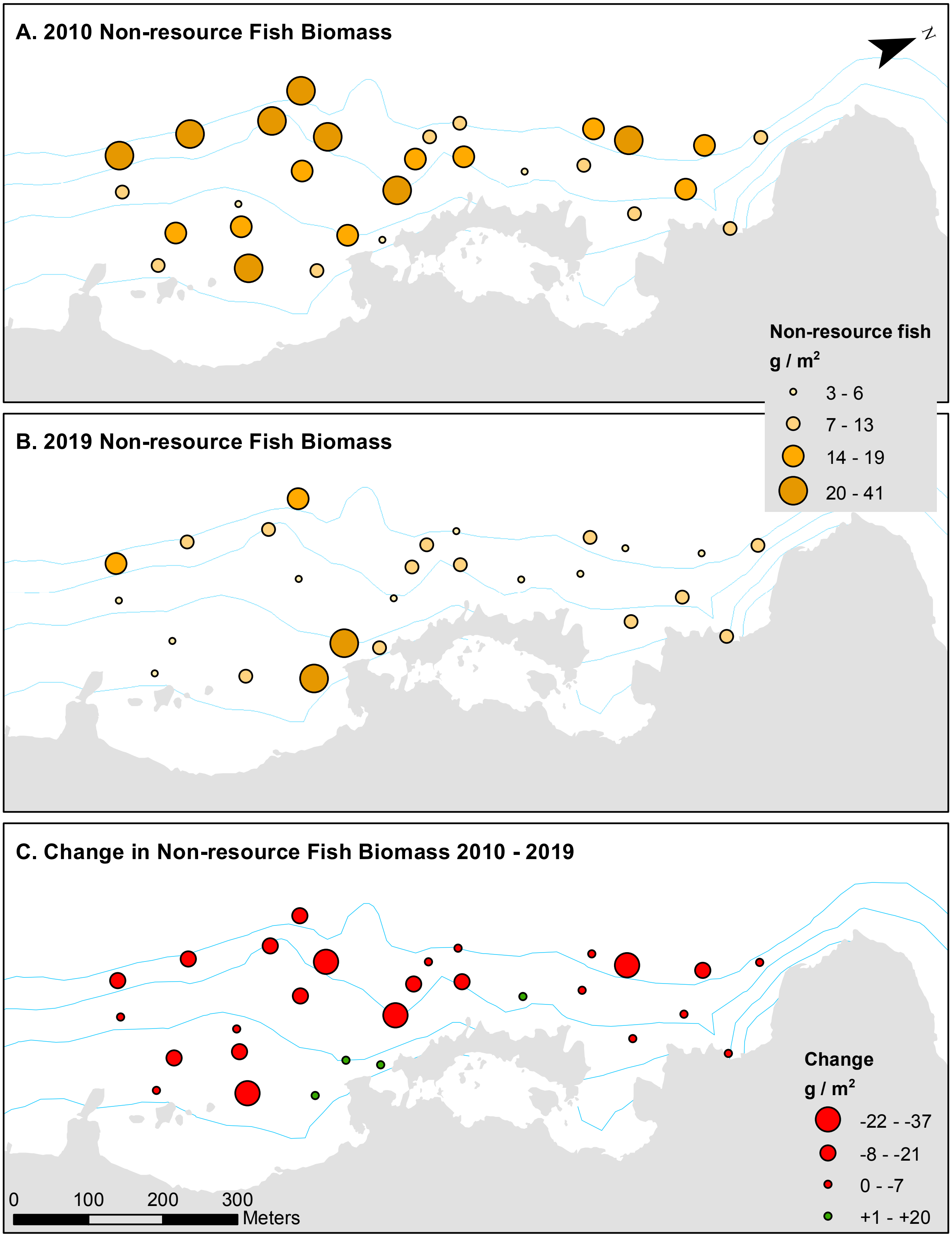

Figure 13. A) Non-resource fish biomass by site in 2010. B) Non-resource fish biomass by site in 2019 shown on the same scale. C) Change in Non-resource fish biomass by site between 2010 and 2019.

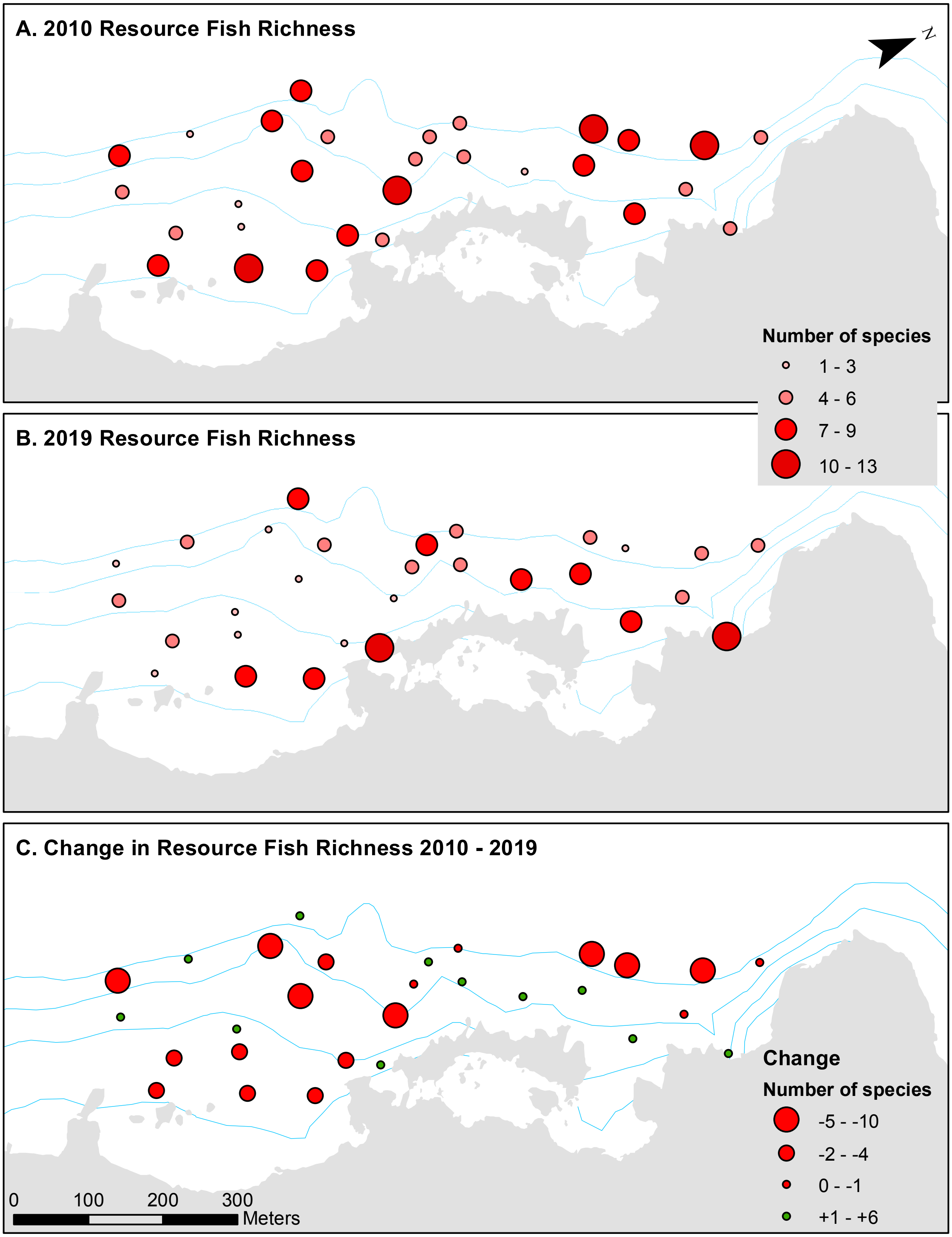

Figure 14. A) Resource fish richness by site in 2010. B) Resource fish richness by site in 2019 shown on the same scale. C) Change in Resource fish richness by site between 2010 and 2019.

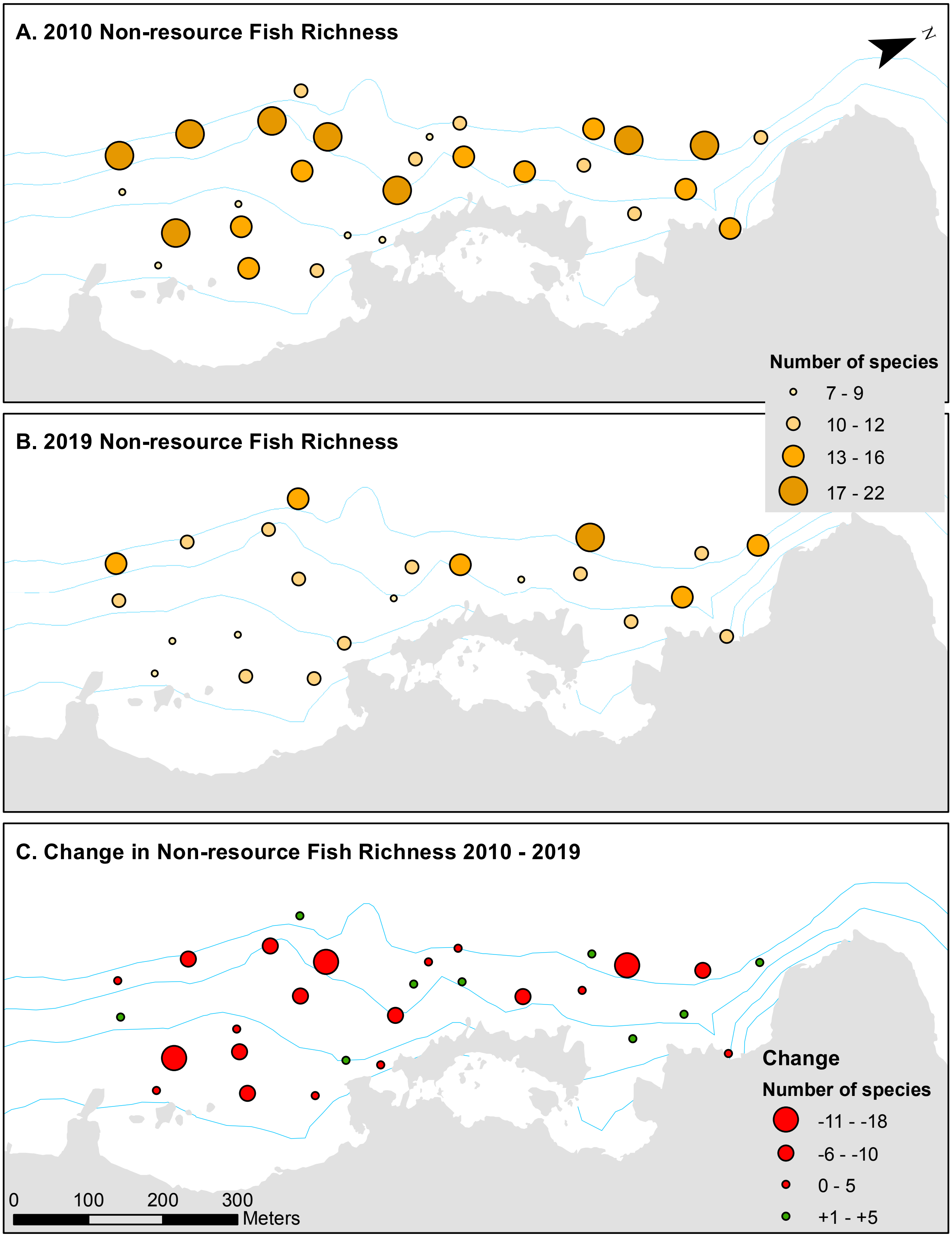

Figure 15. A) Non-resource fish richness by site in 2010. B) Non-resource fish richness by site in 2019 shown on the same scale. C) Change in Non-resource fish richness by site between 2010 and 2019.

Over 70% of the overall observed decline in abundance of resource fishes was explained by five species (Table 2). The greatest decline was for the Convict Tang (manini), which showed a 91% decrease equivalent to a loss of 555 fishes per hectare; followed by the Whitebar Surgeonfish (maikoiko), Manybar Goatfish (moano), Redlip Parrotfish (uhu palukaluka), and Mackeral Scad (opelu) (Table 2).

Table 2. Average resource fish species abundance (number per hectare) in 2010 and 2019, absolute difference, and percent difference for species showing decline. Species are ordered by scale of decline.

Common name	Scientific name	num/ha 2010	num/ha 2019	num/ha Diff.	% Diff.
Convict tang	*Acanthurus triostegus*	612.4	57.9	-554.5	-91
Whitebar Surgeonfish	*Acanthurus leucopareius*	412.4	279.3	-133.1	-32
Manybar Goatfish	*Parupeneus multifasciatus*	185.5	59.3	-126.2	-68
Redlip Parrotfish	*Scarus rubroviolaceus*	98.6	20.7	-77.9	-79
Mackerel Scad	*Decapterus macarellus*	75.2	0.0	-75.2	-100
Hawaiian Hogfish	*Bodianus albotaeniatus*	42.1	0.0	-42.1	-100
Goldring surgeonfish	*Ctenochaetus strigosus*	67.6	26.2	-41.4	-61
Yellowfin Goatfish	*Mulloidichthys vanicolensis*	51.0	13.8	-37.2	-73
Eye-stripe Surgeonfish	*Acanthurus dussumieri*	39.3	2.8	-36.6	-93
Chub	*Kyphosus sp.*	65.5	33.8	-31.7	-48
Sergent Major	*Abudefduf abdominalis*	42.8	11.7	-31.0	-73
Pearl wrasse	*Anampses cuvier*	33.1	2.8	-30.3	-92
Bluespine Unicornfish	*Naso unicornis*	26.2	3.4	-22.8	-87
Peacock Grouper	*Cephalopholis argus*	26.9	5.5	-21.4	-79
Ringtail Wrasse	*Oxycheilinus unifasciatus*	10.3	0.0	-10.3	-100
Leatherback	*Scomberoides lysan*	9.7	0.0	-9.7	-100
Stareye parrotfish	*Calotomus carolinus*	8.3	0.0	-8.3	-100
Yellowstripe coris	*Coris flavovittata*	6.9	0.0	-6.9	-100
Black Surgeonfish	*Ctenochaetus hawaiiensis*	6.9	0.0	-6.9	-100
Ringtail Surgeonfish	*Acanthurus blochii*	12.4	5.5	-6.9	-56
Achilles Tang	*Acanthurus achilles*	20.7	13.8	-6.9	-33
Doublebar Goatfish	*Parupeneus insluaris*	29.7	24.8	-4.8	-16
Whitesaddle Goatfish	*Parupeneus porphyreus*	2.8	0.0	-2.8	-100
Sidespot Goatfish	*Parupeneus pleurostigma*	7.6	5.5	-2.1	-27
Yellowfin Surgeonfish	*Acanthurus xanthopterus*	1.4	0.0	-1.4	-100
Bullethead parrotfish	*Chlorurus spilurus*	1.4	0.0	-1.4	-100
Greater Amberjack	*Seriola dumerili*	1.4	0.0	-1.4	-100
Blacktail Wrasse	*Thalassoma ballieui*	1.4	0.0	-1.4	-100
Blue Goatfish	*Parupeneus cyclostomus*	4.1	3.4	-0.7	-17

Some resource species increased, notably the Bluefin Trevally (omilu) which was 8 times more abundant in 2019 compared to 2010 (Table 3). This is equivalent to an increase of 35 fishes per hectare (Table 3).

Table 3. Average resource fish species abundance (number per hectare) in 2010 and 2019, absolute difference, and percent difference for species showing increase. Species are ordered by scale of increase.

Common name	Scientific name	num/ha 2010	num/ha 2019	num/ha Diff.	% Diff.
Bluefin Trevally	*Caranx melampygus*	4.1	38.6	34.5	833
Orangeband surgeonfish	*Acanthurus olivaceus*	94.5	115.9	21.4	23
Surge Wrasse	*Thalassoma purpureum*	6.2	18.6	12.4	200
Yellowstripe Goatfish	*Mulloidichthys flavolineatus*	3.4	9.0	5.5	160
Pinktail Durgon	*Melichthys vidua*	2.8	8.3	5.5	200
Bigeye Emperor	*Monotaxis grandoculis*	1.4	6.2	4.8	350
Blackspot sergent	*Abudefduf sordidus*	0.0	2.8	2.8	100
Black Durgon	*Melichthys niger*	0.0	2.8	2.8	100
Hawaiian Bigeye	*Priacanthus meeki*	0.0	2.8	2.8	100
Sailfin tang	*Zebrasoma veliferum*	0.0	2.8	2.8	100
Blacktail Snapper	*Lutjanus fulvus*	4.8	5.5	0.7	14
Bluelined Surgeonfish	*Acanthurus nigroris*	8.3	9.0	0.7	8
Whitespotted Surgeonfish	*Acanthurus guttatus*	2.8	2.8	0.0	0
Orangespine Unicornfish	*Naso lituratus*	59.3	59.3	0.0	0

The decrease in abundance of non-resource fishes was driven primarily by the Blackfin Chromis, followed by the Oval Chromis, Brighteye Damselfish, Pacific Gregory, and the Saddle Wrasse (Table 4).

Table 4. Average non-resource fish species abundance (number per hectare) in 2010 and 2019, absolute difference, and percent difference for species showing decline. Species are ordered by scale of decline.

Common name	Scientific name	num/ha 2010	num/ha 2019	num/ha Diff.	% Diff.
Blackfin chromis	*Chromis vanderbilti*	4856.6	1382.8	-3473.8	-72
Oval chromis	*Chromis ovalis*	1006.2	168.3	-837.9	-83
Brighteye Damselfish	*Plectroglyphidodon imparipennis*	1075.9	381.4	-694.5	-65
Pacific Gregory	*Stegastes marginatus*	684.8	69.7	-615.2	-90
Saddle Wrasse	*Thalassoma duperrey*	1126.9	530.3	-596.6	-53
Brown Surgeonfish	*Acanthurus nigrofuscus*	982.8	623.4	-359.3	-37
Elegant coris	*Coris venusta*	262.8	5.5	-257.2	-98

Ornate Wrasse	*Halichoeres ornatissimus*	189.7	40.0	-149.7	-79
Shortnose Wrasse	*Macropharyngodon geoffroy*	144.1	9.0	-135.2	-94
Blue-eye Damselfish	*Plectroglyphidodon johnstonianus*	104.1	8.3	-95.9	-92
HI Whitespotted toby	*Canthigaster jactator*	104.8	21.4	-83.4	-80
Redbar Hawkfish	*Cirrhitops fasciatus*	85.5	21.4	-64.1	-75
Lei Trigger	*Sufflamen bursa*	125.5	71.0	-54.5	-43
Belted Wrasse	*Stethojulis balteata*	204.1	150.3	-53.8	-26
Psychadelic Wrasse	*Anampses chrysocephalus*	52.4	0.0	-52.4	-100
Scarface Blenny	*Cirripectes vanderbilti*	44.1	0.0	-44.1	-100
Chocolate-dip	*Chromis hanui*	35.9	2.8	-33.1	-92
HI Cleaner	*Labroides phthirophagus*	40.0	9.0	-31.0	-78
Arc-eye Hawkfish	*Paracirrhites arcatus*	109.7	84.8	-24.8	-23
Reef triggerfish	*Rhinecanthus rectangulus*	71.7	48.3	-23.4	-33
Cornetfish	*Fistularia commersonii*	21.4	2.8	-18.6	-87
Christmas Wrasse	*Thalassoma trilobatum*	21.4	5.5	-15.9	-74
Scale-eating Blenny	*Plagiotremus goslinei*	15.2	0.0	-15.2	-100
Squaretail filefish	*Cantherhines sandwichiensis*	11.7	0.0	-11.7	-100
Crown Toby	*Canthigaster coronata*	20.0	9.0	-11.0	-55
Whitemouth Moray	*Gymnothorax meleagris*	13.8	2.8	-11.0	-80
Smalltail Wrasse	*Pseudojuloides cerasinus*	11.0	0.0	-11.0	-100
Twospot Wrasse	*Oxycheilinus bimaculatus*	10.3	0.0	-10.3	-100
Yellowtail coris	*Coris gaimard*	31.0	21.4	-9.7	-31
Blackside Hawkfish	*Paracirrhites forsteri*	17.9	9.0	-9.0	-50
Bird wrasse	*Gomphosus varius*	16.6	9.0	-7.6	-46
Fourline Wrasse	*Pseudocheilinus tetrataenia*	12.4	5.5	-6.9	-56
Threadfin butterflyfish	*Chaetodon auriga*	5.5	0.0	-5.5	-100
Spotted Boxfish	*Ostracion meleagris*	4.8	0.0	-4.8	-100
Hawaiian dascyllus	*Dascyllus albisella*	4.1	0.0	-4.1	-100
Eightline Wrasse	*Pseudocheilinus octotaenia*	4.1	0.0	-4.1	-100
Multiband butterflyfish	*Chaetodon multicinctus*	17.2	13.8	-3.4	-20
Yellowmargin Moray	*Gymnothorax flavimarginatus*	6.9	3.4	-3.4	-50
Cigar Wrasse	*Cheilio inermis*	2.8	0.0	-2.8	-100
Shortbodied Blenny	*Exallias brevis*	5.5	2.8	-2.8	-50
Disappearing Wrasse	*Pseudocheilinus evanidus*	2.8	0.0	-2.8	-100
Devil Scorpionfish	*Scorpaenopsis diabolus*	2.8	0.0	-2.8	-100
Yellow Tang	*Zebrasoma flavescens*	2.8	0.0	-2.8	-100
Bluestripe butterflyfish	*Chaetodon fremblii*	4.8	2.8	-2.1	-43
Potter's Angelfish	*Centropyge potteri*	4.1	2.8	-1.4	-33
Dwarf moray	*Gymnothorax melatremus*	1.4	0.0	-1.4	-100
Bridled Trigger	*Sufflamen fraenatus*	6.9	5.5	-1.4	-20

Lizardfish	*Synodus sp.*	1.4	0.0	-1.4	-100
Teardrop butterflyfish	*Chaetodon unimaculatus*	4.1	3.4	-0.7	-17

Some non-resource fishes showed an increase in abundance including four species of butterflyfish (Table 5).

Table 5. Average non-resource fish species abundance (number per hectare) in 2010 and 2019, absolute difference, and percent difference for species showing increase. Species are ordered by scale of increase.

Common name	Scientific name	num/ha 2010	num/ha 2019	num/ha Diff.	% Diff.
Ornate butterflyfish	*Chaetodon ornatissimus*	6.2	18.6	12.4	200
Fourspot butterflyfish	*Chaetodon quadrimaculatus*	19.3	31.7	12.4	64
Stocky Hawkfish	*Cirrhitus pinnulatus*	1.4	9.0	7.6	550
Moorish Idol	*Zanclus cornutus*	21.4	26.9	5.5	26
Milletseed butterflyfish	*Chaetodon miliaris*	4.1	8.3	4.1	100
Forcepsfish	*Forcipiger flavissimus*	2.8	6.2	3.4	125
Ewa Blenny	*Plagiotremus ewaensis*	9.7	12.4	2.8	29
Trumpetfish	*Aulostomus chinensis*	0.0	2.8	2.8	100
Agile Chromis	*Chromis agilis*	0.0	2.8	2.8	100
Racoon butterflyfish	*Chaetodon lunula*	0.0	2.8	2.8	100
Titan Scorpionfish	*Scorpaenopsis cacopsis*	0.0	2.8	2.8	100
Whitetip shark	*Triaenodon obesus*	0.0	2.8	2.8	100
Ambon Toby	*Canthigaster amboinensis*	7.6	9.0	1.4	18
Barred Filefish	*Cantherhines dumerilii*	2.8	2.8	0.0	0

Humans

Humans in the MLCD averaged 70.3 (± 54.0) in 2010 and 151.0 (± 87.6) in 2019 and differed significantly between years ($F=134.8$, $p<0.001$) and zones ($F=188.2$, $p<0.001$). The increase was greatest in the tidepool area, with an additional 132 people on average. Average in-water human use was greater in all three zones, but especially outside the cove where it was nearly 10 times higher (Figure 16). Average shore-based human use doubled inside Sharks Cove and was nearly three times higher in the tidepool area (Figure 17).

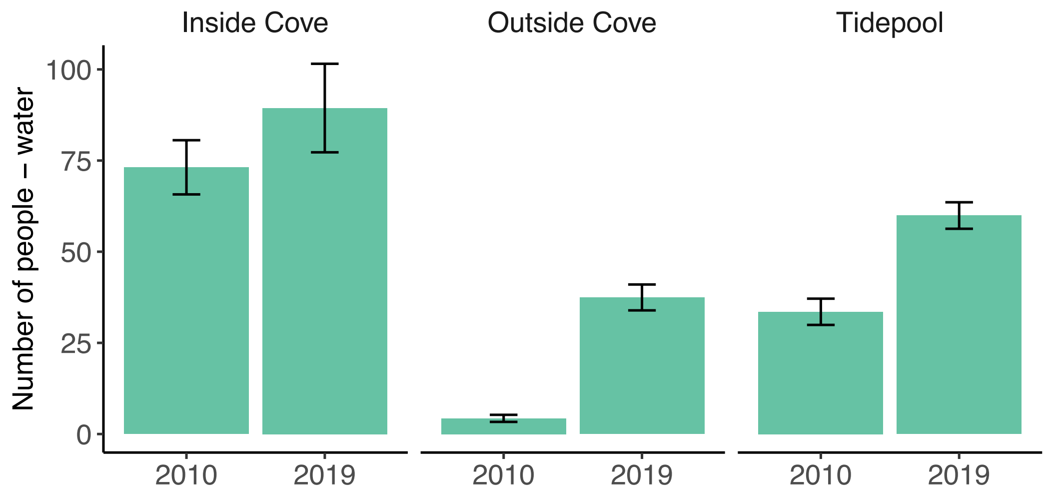

Figure 16. Average in-water human use by year (May-Sept) inside of Sharks Cove, outside of Sharks Cove, and at the tidepool area.

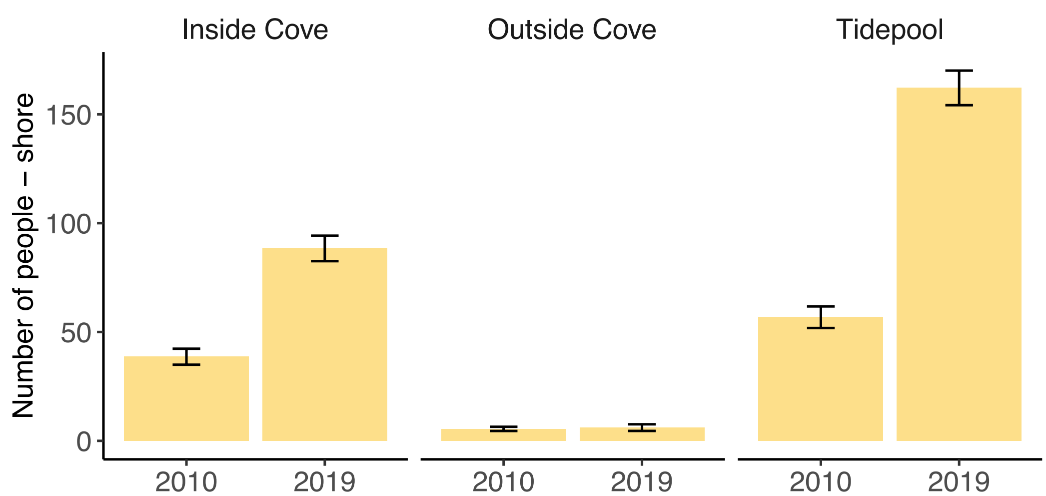

Figure 17. Average shore-based human use by year (May-Sept) inside of Sharks Cove, outside of Sharks Cove, and at the tidepool area.

Discussion

Coral Cover and Rugosity

Coral cover was found to be 6-8% in 2010 and 2019 in shallow and mid-depth areas of Pūpūkea-Waimea MLCD, while deeper (30-40') areas showed a significant decline from 10% to 6%. These patterns are within the range of variability measured by Friedlander et al. (2010) for average percent coral cover in the MLCD which ranged from 6% in 2003 to 13% in 2006. One reason for the decline in coral cover in deeper areas over the last 10 years could be the series of abnormally large NW swells which impacted the north shore of Oʻahu during that time frame. These mega-swells have waves with larger periods that affect the benthos at greater depths (Storlazzi et al. 2002). In more shallow waters on the north shore, the coral reef community is adapted to the seasonal wave disturbance (Jokiel 2006). However, the coral community in deeper waters may be shifting in response to these larger swells and coral cover could have decreased as a result of wave induced sand-scouring, where sand moved around by waves abrades and buries corals (Mumby 1999).

The decline in coral cover in these deeper areas corresponded with a significant increase in turf cover. Turf algae (or "algal turfs") are dense, mixed-species assemblages of filamentous benthic algae and cyanobacteria that are typically less than 1 cm in height. Turf algae are resistant to physical stress caused by wave-induced water turbulence (Cheroske et al. 2000) and grazing (Steneck and Dethier 1994) and are the dominant benthic cover on the north shore of Oʻahu and similar environments. Compared to macro algae, turf algae also occupy newly available space faster and quickly colonize bleached and dead corals (Diaz-Pulido and McCook 2002).

Rugosity did not change over time in Pūpūkea-Waimea MLCD. In environments with low water turbulence, coral can create significant structure on coral reefs (Dollar 1982). However, in wave-dominated environments such as the north shore of Oʻahu where the MLCD is located, coral communities are dominated by encrusting and mounding corals (Jokiel 2006). Furthermore, the MLCD has high physical structure due to the underwater rock formations that form a complex of canyons and caves. This structure, as measured by rugosity, is not likely to change due to changes in the overlying benthic community.

Fishes and Humans

Combined abundance, biomass, and species richness of all fishes declined significantly across all depth zones between 2010 and 2019. Average abundance declined from an all-time high of 1.4 individuals per square meter in 2010 to an all-time low of 0.5 in 2019, a 65% decrease. Previous surveys recorded a range of 1.2 in 2006 to 0.75 individuals per square meter in 2007 (Friedlander et al. 2010). Average biomass decreased from 80.2 grams per square meter in 2010 to 27.6 in 2019, a decline of 66%. For comparison, Friedlander et al. (2010) reported an increase of 75 grams per square meter in 2003 to 86 in 2008. Average number of species dropped from 20 in 2010 to 15 in 2019, a 25% decrease. Previous to 2010, average richness was stable at around 20 species (Friedlander et al. 2010). Resource fishes declined more in terms of biomass (weight), and non-resource fishes declined more in terms of abundance (numbers). Species richness of resource fishes did not decline between the two survey years.

The decline in numbers and weight of both resource and non-resource fishes suggests a combination of factors. It is possible that illegal fishing is partly responsible for the declines in resource fishes (Stamoulis and Friedlander 2013), though would not explain the decrease in non-resource fishes. Human in-water use of the MLCD has increased significantly over the 9-year interval between survey rounds, especially in the tidepool and the deeper areas of the MLCD. This may be a contributing factor as some research has shown displacement impacts on fish assemblages from in-water tourist activities (Ilarri et al. 2008, Albuquerque et al. 2014).

Another potential factor is land-based source pollution (LBSP). Suspended sediments have been shown to result in decreased abundance of key coral reef fish functional groups including herbivores such as the Convict Tang (manini) and Whitebar Surgeonfish (maikoiko) and planktivores such as the Blackfin and Oval Chromis (Delevaux et al. 2018a, Moustaka et al. 2018). Elevated nutrients from surface runoff and groundwater inputs are known to have indirect effects on fish communities through habitat impacts (Delevaux et al. 2018b). Marine Research Consultants, Inc. (2017) documented elevated nearshore nutrient and turbidity (sediment) levels in Sharks Cove and the tidepool area. We did not find a decrease in coral cover or increase in algae and/or turf in shallow areas, however, our surveys locations were all > 3m deep, not directly adjacent to shore. The large tidepool, which likely acts as a nursery area for many reef fish species (Goodell et al. 2018), may be impacted by LBSP and/or increased human use. Rosinski (2012) documented a high abundance of Convict Tang (manini) in the Sharks Cove tidepool which is one of the species showing the greatest decline. If the nursery function of the tidepools has been compromised, it would impact the fish community in the surrounding area (Nagelkerken et al. 2012, 2017).

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Appendix

Table A1. Site metadata.

Transect	Latitude	Longitude	Bearing	Depth (ft)	Depth zone
03	21.65381	-158.06350	200	39	3
05	21.65169	-158.06399	200	25.5	2
06	21.65306	-158.06254	250	17.5	1
08	21.65274	-158.06322	200	21	2
09	21.65048	-158.06508	200	40.5	3
10	21.64982	-158.06486	200	26.5	2
11	21.65008	-158.06506	200	34.5	3
12	21.65038	-158.06466	200	22	2
13	21.64910	-158.06404	200	22.5	2
15	21.64883	-158.06622	200	29.5	2
16	21.64872	-158.06426	200	19.5	1
17	21.64637	-158.06583	200	23	2
19	21.64763	-158.06514	200	17.5	1
42	21.65231	-158.06409	200	40	3
43	21.65205	-158.06317	200	15	1
44	21.65100	-158.06419	200	26	2
45	21.64822	-158.06397	200	13	1
46	21.64849	-158.06525	200	23.5	2
47	21.64837	-158.06599	200	36	3
48	21.64739	-158.06622	200	26	2
49	21.64747	-158.06432	200	10.5	1
50	21.64680	-158.06509	200	15	1
62	21.65314	-158.06367	200	34.5	3
63	21.65196	-158.06438	200	37.5	3
66	21.64948	-158.06457	200	29	2
67	21.64893	-158.06554	200	34.5	3
68	21.64646	-158.06478	200	11.5	1
69	21.64756	-158.06486	200	14.5	1
70	21.64650	-158.06629	200	28	2

Table A2. Benthic cover (% cover) by transect.

Year	Transect	Coral	Algae	Turf	CCA	Sand
2010	03	12.8	3.9	74.4	6.1	2.8
2010	05	10.6	3.9	61.7	15.6	8.3
2010	06	1.7	0.6	66.1	24.3	2.9
2010	08	11.2	0.6	78.2	7.3	2.8
2010	09	3.9	0.6	52.2	4.4	38.9
2010	10	4.5	2.2	65.3	23.5	4.4
2010	11	11.7	3.3	70.6	4.4	10.0
2010	12	5.2	1.7	63.4	20.9	8.9
2010	13	5.6	0.0	84.4	2.8	7.2
2010	15	9.6	0.6	70.4	18.9	0.6
2010	16	12.9	1.1	62.5	20.6	2.9
2010	17	10.6	0.0	75.0	11.7	2.8
2010	19	15.0	0.0	42.3	42.7	0.0
2010	42	13.5	1.1	66.9	7.3	11.3
2010	43	7.8	6.1	31.3	51.5	3.3
2010	44	10.1	1.1	50.8	22.5	15.6
2010	45	8.3	1.7	75.9	13.5	0.6
2010	46	2.3	0.6	59.4	18.9	18.9
2010	47	7.8	2.9	60.4	20.5	5.6
2010	48	14.6	0.6	64.5	17.0	2.8
2010	49	1.7	0.0	68.6	28.6	0.6
2010	50	7.8	1.1	59.6	23.7	6.2
2010	62	9.7	5.1	62.2	6.2	16.9
2010	63	12.3	2.3	65.9	10.0	8.4
2010	66	0.0	3.9	60.6	10.0	24.4
2010	67	11.7	1.7	59.8	22.4	3.3
2010	68	7.9	1.8	63.3	20.3	6.7
2010	69	10.0	0.6	58.5	30.4	0.6
2010	70	7.2	1.7	76.7	13.9	0.6
2019	03	5.6	1.7	83.7	4.5	4.5
2019	05	11.2	3.9	67.4	7.3	10.1
2019	06	5.9	3.5	54.1	17.1	19.4
2019	08	7.8	5.6	66.1	18.9	1.7
2019	09	6.1	0.0	59.8	14.5	19.6
2019	10	4.4	2.2	58.3	33.9	1.1
2019	11	5.1	0.0	77.5	13.5	3.9
2019	12	6.8	2.8	66.1	23.2	1.1

2019	13	9.5	3.4	59.8	19.0	7.8
2019	15	8.9	3.3	74.4	12.2	0.0
2019	16	9.0	2.8	64.4	23.2	0.6
2019	17	2.2	0.6	76.4	20.2	0.6
2019	19	8.5	0.6	70.1	20.3	0.0
2019	42	6.1	0.6	76.5	5.0	10.1
2019	43	4.5	2.3	64.2	23.9	4.5
2019	44	1.1	2.8	55.0	2.2	38.3
2019	45	4.0	0.6	59.1	35.2	1.1
2019	46	2.8	3.9	66.3	7.3	19.1
2019	47	7.3	2.2	64.2	22.9	2.2
2019	48	8.9	0.0	70.9	20.1	0.0
2019	49	1.7	0.6	65.5	30.5	1.7
2019	50	14.0	3.4	56.4	26.3	0.0
2019	62	12.3	1.1	77.1	8.9	0.6
2019	63	4.5	1.7	80.1	11.4	2.3
2019	66	2.8	1.1	59.4	12.2	24.4
2019	67	2.2	0.0	71.1	2.8	23.9
2019	68	12.4	0.6	60.1	26.4	0.6
2019	69	11.1	0.6	50.6	36.7	0.0
2019	70	7.8	3.4	67.6	21.2	0.0

Table A3. Fish data by transect. Abundance in number m^{-2} (Abun), biomass in grams m^{-2} (Bio), and species richness in number of species (Rich) for resource fish (Res) and non-resource fish (NR). Values for all fishes are the sum of resource fish and non-resource fish.

Year	Tran#	Abun-Res	Abun-NR	Bio-Res	Bio-NR	Rich-Res	Rich-NR
2010	03	0.14	0.59	17.5	12.9	5	11
2010	05	0.15	0.99	36.1	9.5	7	11
2010	06	0.13	0.94	16.6	9.8	5	13
2010	08	0.11	1.82	14.5	14.3	5	13
2010	09	0.09	0.49	12.1	7.8	6	10
2010	10	0.04	1.76	8.8	14.6	4	12
2010	11	0.27	0.77	75.2	9.5	5	9
2010	12	0.13	1.74	19.6	18.5	5	14
2010	13	0.47	0.84	122.9	6.0	6	9
2010	15	0.22	1.67	49.5	23.1	8	11
2010	16	0.16	0.96	29.7	17.4	7	9
2010	17	0.14	0.68	33.3	10.6	5	7
2010	19	0.01	0.77	1.9	2.9	1	7
2010	42	0.12	0.84	38.0	27.4	9	17
2010	43	1.35	0.39	94.2	10.0	8	10
2010	44	0.08	0.56	39.6	3.3	3	13
2010	45	0.15	0.49	65.1	9.2	9	12
2010	46	0.08	2.16	21.4	17.4	7	16
2010	47	0.23	1.15	205.8	23.8	8	20
2010	48	0.03	2.24	15.1	28.0	3	19
2010	49	0.83	1	101.3	30.7	13	16
2010	50	0.11	1.12	49.6	16.8	6	19
2010	62	0.34	2.62	30.1	16.2	12	18
2010	63	0.32	0.5	186.9	17.2	12	15
2010	66	0.33	1.08	283.4	41.1	13	17
2010	67	0.16	2.6	88.5	23.8	6	22
2010	68	0.21	0.58	80.4	12.2	7	8
2010	69	0.04	1.3	2.2	15.2	3	15
2010	70	0.18	2.42	112.0	25.7	7	17
2019	03	0.08	0.44	1.9	8.0	4	13
2019	05	0.06	0.67	5.1	5.8	7	10
2019	06	0.23	0.21	54.5	8.7	10	10
2019	08	0.08	0.58	13.5	8.8	5	14
2019	09	0.08	0.22	30.4	5.6	5	6
2019	10	0.11	0.62	30.8	7.0	4	12
2019	11	0.16	0.24	80.9	6.2	7	6

2019	12	0.07	0.76	11.1	9.5	6	14
2019	13	0.16	0.18	48.5	7.1	11	6
2019	15	0.12	0.49	26.7	14.9	9	15
2019	16	0.08	0.45	11.8	19.2	3	10
2019	17	0.06	0.44	19.5	6.0	6	10
2019	19	0.03	0.16	5.3	1.0	3	5
2019	42	0.04	0.1	9.8	4.5	2	6
2019	43	0.12	0.44	14.2	6.3	9	12
2019	44	0.09	0.15	14.6	3.4	8	7
2019	45	0.15	0.2	13.4	28.8	7	10
2019	46	0.04	0.52	2.7	4.5	2	10
2019	47	0.08	0.6	10.7	7.3	2	12
2019	48	0.03	0.97	5.3	10.0	4	11
2019	49	0.16	0.3	60.7	8.1	9	10
2019	50	0.26	0.31	9.1	4.0	4	7
2019	62	0.09	0.75	12.3	3.3	6	10
2019	63	0.08	0.59	15.6	12.2	5	19
2019	66	0.03	0.17	2.4	4.5	3	9
2019	67	0.07	0.04	18.2	1.6	4	4
2019	68	0.06	0.38	16.0	5.3	3	8
2019	69	0.008	0.48	20.2	2.4	1	7
2019	70	0.01	0.39	3.3	18.1	2	13