Detection and Impact of Sewage Pollution on South Kohala’s Coral Reefs

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LIST OF ABBREVIATIONS AND SYMBOLS

ADCP: Acoustic doppler current profiler.

ALOG: Algal overgrowth.

BL: Bleaching.

CCA: Crustose coralline algae.

DC: Discoloration.

ESE: East-Southeast.

FIB: Fecal indicator bacteria.

GA: Growth anomaly.

IW: Injection well.

N: Refers to the element nitrogen.

OSDS: On-site sewage disposal systems.

SGD: Submarine groundwater discharge.

TL: Tissue loss.

USEPA: United States Environmental Protection Agency.

USGS: United States Geological Survey.

$\delta^{15}N$: Delta notation for the nitrogen-15 isotope. Expresses the enrichment or depletion of the nitrogen-15 isotope relative to a standard nitrogen element. Larger, positive $\delta^{15}N$ values indicate a greater proportion of the isotope. Smaller, negative $\delta^{15}N$ values indicate a lower proportion of the isotope.

ABSTRACT

Sewage pollution is a land-based stressor impacting coral reefs worldwide. In the Hawaiian Islands, On-site sewage disposal systems (OSDS) and wastewater injection wells have been associated with the pollution of inshore waters. Further offshore, OSDS and wastewater injection may be contributing to the chronic degradation of coral reefs in South Kohala, Hawaiʻi. Conducting benthic sampling and employing a multi-indicator approach, this study sought to determine the presence and impact of sewage on South Kohala's reefs. Our results suggest water motion and groundwater are diluting sewage found on South Kohala's reefs. South Kohala's reefs are dominated by turf algae, while sewage pollution may also be facilitating growth anomalies and algal overgrowth on South Kohala's reefs. With natural processes facilitating connectivity between land and sea, this study illustrates the need for improved sewage treatment and disposal near coastlines.

INTRODUCTION

Coral reefs are one of the most diverse habitats in the marine environment, providing many ecological services and economic benefits to humans (Moberg & Folke 1999). Unfortunately, coral reefs around the world are becoming increasingly degraded by land-based anthropogenic stressors (Brodie et al. 2012; Wedding et al. 2018; Lapointe et al. 2019). These stressors place an added strain on reefs already impacted by rising temperatures, disease, and ocean acidification (Hughes & Connell 1999; Ban et al. 2014). Despite this, local measures can promote reef resilience against naturally occurring and global scale stressors (Wooldrige & Done 2009; Gurney et al. 2013; Anthony et al. 2015).

Sewage is one of the most common land-based pollutants found in nearshore waters and has been identified as a major driver of reef degradation (Islam & Tanaka 2004; Wear & Vega Thurber 2015; Lapointe et al. 2017). In addition to nutrients, sewage can also contain pathogens, endocrine disruptors, suspended solids, and heavy metals (Wear & Vega Thurber 2015). Nutrients from sewage increase the severity of coral disease and can make corals more susceptible to bleaching, while pathogens found in sewage have been linked to coral disease outbreaks in the Caribbean (Bruno et al. 2003; Sutherland et al. 2010; Vega Thurber et al. 2014). Sewage pollution can also slow the recovery of bleached coral reefs, further hindering their resilience against other stressors (Carilli et al. 2009; Wear & Vega Thurber 2015). In severe cases, sewage pollution can alter the structure of benthic communities, facilitating the growth of macroalgae and filter feeding organisms while reducing the cover of calcifying organisms (Costa Jr. et al. 2008; Amato et al. 2016).

On coral reefs, the residence time and exposure to stressors can be influenced by water motion (Nakamura & van Woesik 2001; Storlazzi et al. 2004). Wind, waves, and tides are the primary forces initiating water motion, but geomorphological features such as embayments and benthic topography further influence circulation patterns (Hearn et al. 2011; Storlazzi et al. 2017). Decreased water motion has been associated with the increased presence of coral diseases (Burns et al. 2011; Lee et al. 2017). Conversely, reefs with low water motion have a higher disease prevalence and are more susceptible to sewage pollution (Couch et al. 2014b; Oberle et al. 2019).

It is estimated that there are 110,000 on-site sewage disposal systems (OSDS) throughout the State of Hawaiʻi, discharging 263 million liters of effluent per day (Whittier & El-Kadi 2014). Roughly 80% of the State's OSDS are cesspools, which allow untreated effluent to seep into the surrounding soil and groundwater (HDOH 2018). Studies conducted throughout the Hawaiian Islands have found evidence of sewage pollution in coastal waters adjacent to OSDS (Richardson et al. 2017; Abaya et al. 2018a,b; Miller-Pierce & Rhoades 2019; Oberle et al. 2019). Wastewater injection wells can also contribute to the pollution of nearshore waters, as documented on the island of Maui (Hunt 2007; Hunt & Rosa 2009; Glenn et al. 2013; Miller-Pierce & Rhoads 2016). Conclusively, the geology and hydrological processes found throughout the Hawaiian Islands facilitate connectivity between land-based pollutants and nearshore waters (Prouty et al. 2017; Swarzenski et al. 2017; Delavaux et al. 2018).

Though considerable sewage pollution research has been conducted on the Islands of Maui and Oʻahu, the majority of the State's OSDS are located on Hawaiʻi Island (Whitter & El-Kadi 2014; HDOH 2018). Here, previous studies have addressed shoreline sewage pollution (Parsons et al. 2008; Whittier & El-Kadi 2014; Wiegner et al. 2016; Abaya et al. 2018a; Wedding et al. 2018), though few have focused on coral reefs

(Couch et al. 2014a; Yoshioka et al. 2016; Abaya et al. 2018b). The South Kohala coast of Hawaiʻi Island has been identified as a priority management area by the State of Hawaiʻi, due to the threat posed by OSDS (State of Hawaiʻi 2010). Coastal resort developments in South Kohala also utilize wastewater injection wells (Aqua Engineering 2015). Reefs in South Kohala have changed considerably since the 1970's, with algal cover and coral disease outbreaks becoming more prevalent (Minton et al. 2013; Couch et al. 2014b; Walsh et al. 2018). Sewage pollution has been documented along the South Kohala shoreline, where sewage from OSDS can reach inshore waters within 9 h to 3 d (Abaya et al. 2018a). Previous studies have also found evidence of sewage pollution on South Kohala's reefs (Couch et al. 2014a; Yoshioka et al. 2016; Abaya et al. 2018b). However, these studies were limited to the southern portion of the South Kohala coast. Additionally, the proportion of benthic nitrate contributed by sewage, the role of water motion, and the association between sewage and coral reef health have not been established previously. Accordingly, this study builds upon previous sewage pollution work in South Kohala by: 1) Identifying sewage pollution hotspots on reefs throughout South Kohala, 2) Determining how water motion influences sewage pollution, and 3) Establishing if sewage is contributing to impaired coral health in South Kohala. At a global scale, this study will benefit reef scientists and managers addressing sewage pollution, while illustrating the need to implement better sewage mitigation strategies along coastlines.

METHODS

Study Site

This study was conducted in the district of South Kohala, located on the leeward coast of Hawaiʻi Island, USA. The South Kohala coastline is composed of highly permeable basalt from the Mauna Loa and Mauna Kea volcanoes (Kay et al. 1977). Lacking perrenial streams, submarine groundwater discharge (SGD) is a major source of freshwater and nutrients along this coast (Street et al. 2008; Knee et al. 2010). Average SGD in South Kohala ranges from 2083-2730 L m^{-1} h^{-1} (Paytan et al. 2006). South Kohala's fringing reef extends to a depth of 8-12 m and is backed by a 4-m deep reef flat extending from 75 to 230 m to shore (Minton et al. 2013). Twenty offshore benthic stations located throughout the South Kohala coast were sampled and surveyed in June 2018 and 2019. Stations were located on the fringing reef at distances of 50 to 250 m from shore. Each station was assigned into one of five regions based on their proximity to resort or residential developments (South Resorts, South Puakō, Middle Puakō, North Puakō, North Resorts) (Fig. 1). Development in the South Resort region spans 982 ha, which includes a golf course (202 ha) and 272 private residences. Development in the North Resorts region spans 418 ha, and consists of two golf courses (174 ha combined) and 207 private residences. The Puakō community consists of 163 homes spread along 3.5 km of coastline. Treated wastewater (R-1 treatment) is used to irrigate vegetation in the North Resorts region, while an injection well (R-2 treatment) is used in the South Resorts region (Aqua Engineering 2015; Limtiaco Consulting Group 2013). In the Puakō community, 58 houses have cesspools, 85 have septic tanks, and 12 have aerobic treatment units (Aqua Engineering 2015). Waikoloa Village is currently the only development upslope of Puakō, where 1587 homes use OSDS and the remaining 413 are connected to a sewer line (pers. comm. Hawaiʻi Water Supply).

Benthic Water Salinity, FIB, and Nutrient Analyses

Triplicate water samples were collected within 13 cm of the benthos at all 20 stations during low tide, when the proportion of SGD in coastal waters is highest (Ataie-Ashtiani et al. 2001; Robinson et al. 2007). The salinity of each sample was measured after collection using a calibrated YSI Pro 2030 handheld instrument. The fecal indicator bacteria (FIB) *Enterococcus* spp. and *Clostridium perfringens* were quantified from water samples collected at each station. Each water sample was collected just before or during sunrise, as exposure to sunlight can reduce FIB counts (Fujioka et al. 1981). *Enterococcus* spp. concentration was quantified using the IDEXX Enterolert MPN method with QuantiTray/2000 from IDEXX Laboratories (Chen et al. 1996). When no QuantiTray wells fluoresced blue, *Enterococcus* spp. concentrations were reported as 5 MPN/100 mL, one half the detection of the method after correcting for sample dilution. *C. perfringens* concentration was determined by filtering 100 mL of sample water with

0.45-µm pore size cellulose nitrate filters and membrane *C. perfringens* mCP agar (USEPA 2002). FIB samples were processed within 6 h of collection.

Seawater from one of the three samples was filtered through a pre-combusted 0.7-µm pore size glass fiber filter (Whatman™) (500° C for 6 h), then stored frozen until analysis at the UH Hilo Analytical Laboratory. Water samples were analyzed using a Pulse Technicon™ II autoanalyzer using standard methods and reference materials for NO_3^- + NO_2^- (Detection Limit (DL) 0.07 µmol L^{-1}, USEPA 353.4), NH_4^+ (DL 0.36 µmol L^{-1}, USGS I-2525), PO_4^{3-} (DL 0.03 µmol L^{-1}, Technicon Industrial Method 155-71 W), and H_4SiO_4 (DL 1 µmol L^{-1}, USEPA 366). Total dissolved nitrogen (TDN) was analyzed using high temperature combustion, followed by chemiluminescent detection of nitric oxide (DL 5 µmol L^{-1}, using a Shimadzu TOC-V, TNM-1). Total dissolved phosphorus (TDP) was analyzed using a Lachat Quikchem 8500 (DL 0.5 µmol L^{-1}, USGS I-4650-03).

Benthic Seawater Isotope Analyses

The $\delta^{15}N$ and $\delta^{18}O$ of dissolved NO_3^- were quantified in water from all 20 stations. All water samples were analyzed for $\delta^{15}N$ and $\delta^{18}O$- NO_3^- using a Thermo-Finnigan™ Delta V Advantage isotope ratio mass spectrometer with a Conflo III interface and a Costech™ ECS 4010 Elemental Analyzer at the UH Hilo Analytical Laboratory. Data were normalized to United States Geological Service (USGS) standards (USGS32, USGS34, USGS35). Isotopic signatures are expressed as standard (δ) values in units of parts per mil (‰) (Eq.1).

Eq.1 $$\delta^{15}N = \left[\frac{(Rsample - Rstandard)}{Rstandard}\right] \times 1000, where\ R = {}^{15}N/{}^{14}N$$

Unfortunately, every water sample could not be analyzed, as the NO_3^- concentrations were below instrument detection limits (2 µmol L^{-1}). Specifically, 38 of the 40 samples collected in June 2018 and 2019 were not analyzed. To increase the sample size and better understand conditions in South Kohala, isotope data from 19 benthic water samples collected in the South Resorts, South Puakō, and North Puakō regions in May and July of 2017 were used in the stable isotope mixing models. Note, results for the North Resorts region are excluded from this analysis because every sample collected within the North Resorts region in 2018 fell below instrument detection limits, and this region was not sampled in 2017.

Macroalgae Nutrient and δ^{15}N Analyses

Macroalgae were collected from each station and analyzed for δ^{15}N and percent N content (%N). Macroalgae samples were transported on ice to the laboratory, where they were rinsed with deionized water and placed in a drying oven (60^{o} C for 4 d). Prior to drying, algae were photographed and identified using identification books (Abbott 1999; Huisman et al. 2007). Samples were ground using a Wig-L-Bug grinding mill, with ~2 mg of the ground sample folded in a 4x6 mm tin capsule for stable N isotope analysis. Isotope and percent N analyses were conducted using a Thermo-Finnigan^{TM} Delta V Advantage isotope ratio mass spectrometer with a Conflo III interface and a Costech^{TM} ECS 4010 Elemental Analyzer at the UH Hilo Analytical Laboratory. Data were normalized to United States Geological Service (USGS) standard NIST 1547.

Sewage Pollution Scores

A sewage pollution score was calculated for each region using FIB and nutrient concentrations, as well as macroalgal δ^{15}N data, following the approach described in Abaya et al. (2018a). Sewage pollution score values were placed into one of three categories: low (11-17), medium (18-25) and high (26-33).

Benthic Water Motion and Temperature Measurements

Water motion was determined using clod cards and an acoustic doppler current profiler (ADCP). Clod cards were constructed of plastic resin glue (DAP Weldwood brand, 75 g) and patching compound (Fix It All brand, 212 g) mixed with 800 mL of tap water. After blending, the mixture was poured into small paper cups and placed in an oven to dry (27 °C for 48 h). Prior to deployment, clod cards were removed from the paper cups and weighed to obtain pre-deployment weights. Clod cards were then glued to ceramic tiles (three clod cards per tile) using Loctite marine adhesive. To control for dissolution not caused by water motion, three clod cards were placed into three separate 26 L containers of Instant Ocean salt water for 24 h, mixed at salinities comparable to offshore waters (28-33 salinity). After removal from the tiles, clod cards were placed in aluminum trays to air dry at room temperature for 24 h. After drying, clod cards were weighed again to obtain post-deployment weights. The difference between the initial and post-deployment clod card weights were calculated and presented as the percentage of weight lost. A total of 180 clod cards were deployed across all five regions each year. However, in 2018, one clod card from the South Resorts, Middle Puakō, and North Resorts region was missing upon retrieval. In 2019, nine of the 36 clod cards deployed in the South Resorts region were missing upon retrieval.

A Teledyne Workhorse (1200 KHz) acoustic doppler profiler (ADCP) was deployed at one station in each region (stations 16, 6, 35, 20, 31) for a period of 42-74 h. While deployed, the ADCP measured current direction and magnitude, as well as water depth and temperature. The ADCP's 6-s ping collected 300 data points that were averaged every 5 min. A 0.5-m bin range was used, with the first bin ~1 m above the seafloor and the last bin ~0.5 m below the surface. Temperature and pressure were also recorded by the ADCP 0.4-m above the benthos, while a HOBO U24 conductivity logger attached to the ADCP measured the salinity of benthic waters every five minutes. However, salinity data are only available for 2019, as the conductivity logger did not record any data in 2018.

Benthic Surveys

Benthic surveys were conducted at each station along a single 10-m transect placed on the benthos in a direction parallel to the shoreline. Benthic surveys were conducted at depths ranging from 2 to 6 m. Photo quadrats (1-m^2) were taken at 1-m intervals along the transect line using an Olympus TG-860 digital camera. To determine percent cover of coral, turf algae, macroalgae, and crustose coralline algae (CCA), pictures from each photo-quadrat were analyzed using CoralNet (Williams et al. 2019). Corals that fell within 0.5 m on either side of the transect were identified to a species level and surveyed for signs of compromised health. Compromised health conditions included algal overgrowth (ALOG), bleaching (BL), discoloration (DC), growth anomalies (GA), and tissue loss (TL). The percentage of living tissue affected by a compromised health condition was recorded. These data were then used to determine the severity (percentage of each individual coral colony surface area) and prevalence (percentage of all coral colonies encountered on a transect) of each coral condition in each region. A reef builder ratio, which quantifies the percent cover of calcifying to non-calcifying benthic organisms, was also calculated for each region (Vargas-Angel and Schumacher 2018).

Statistical Analyses

All statistical analyses were conducted using the program R (version 3.6.1). A multivariate analysis of variance (MANOVA) was used to determine if FIBs, nutrients, algal $\delta^{15}N$, algal %N, water motion, benthic cover, reef builder ratio, and coral health differed among regions. If a significant result was obtained ($\alpha = 0.05$), a Tukey's post-hoc test was used to determine which regions differed. Kruskal-Wallis statistical tests were used to compare FIB concentrations among regions, as log transformations failed to normalize these data.

Linear mixed effects models (LME) were used to determine associations among impaired coral health conditions with FIBs, nutrients, algal $\delta^{15}N$ and %N, water temperature, and water motion. The LME models were used to account for the nested sampling structure created when stations were assigned into distinct regions. The severity of each coral health condition was logit transformed, and used as model response variables. The FIBs, nutrients, algal $\delta^{15}N$ and %N, water temperature, and water motion variables were included in the models as fixed effects, while region was set as the random effect for each model. The models presented in this paper were selected using a top-down strategy, where all explanatory variables were initially included in a model as fixed components. Using maximum likelihood estimation, variables were sequentially removed until the model contained only variables that had a statistically significant relationship with the response variable. The final selected models were then analyzed using reduced maximum likelihood estimation and tested for violations of homogeneity, variance, and normality.

Stable Isotope Mixing Models

$\delta^{15}N$ and $\delta^{18}O-NO_3^-$ data were used in stable isotope mixing models to identify N sources to the benthos, and determine their relative percent contributions to the NO_3^- pool. Specifically, the stable isotope mixing model package "simmr" in the program R (version 3.6.1) was used. The simmr package uses Bayesian methods and NO_3^- concentration dependence to account for natural variation and uncertainty in the model (Parnell et al. 2013). Potential N sources used in the mixing model included OSDS sampled in the Puakō community ("Sewage", n= 7), effluent from the wastewater injection well located in the South Resorts region ("IW", n= 1), ocean water samples ("Ocean", n= 6), groundwater sampled from low elevation (14-32 m above sea level) irrigation wells ("LE-GW", n= 7), and soil collected from residential lots in the Puakō community ("Soil", n= 3). Mauna Lani effluent source data were obtained from Panelo et al. unpublished data, while all other source data were derived from samples collected by Abaya et al. (2018a).

RESULTS

Benthic Water Quality & Sewage Pollution Scores

FIB concentrations were similar among regions; *Enterococcus* spp. ($p= 0.22$) and *C. perfringens* ($p= 0.58$) (Table 1). *Enterococcus* spp. concentrations ranged from 5-6 MPN/100 mL, while *C. perfringens* concentrations ranged from 0-2 CFU/100 mL. Nutrient concentrations were also similar among regions; $NO_2^-+NO_3^-$ ($p= 0.77$), NH_4^+ ($p= 0.50$), PO_4^{3-} ($p= 0.53$), H_4SiO_4 ($p= 0.98$), TDN ($p= 0.89$), and TDP ($p= 0.69$) (Table 2). Ranges of nutrient concentrations were: $NO_2^-+NO_3^-$ (0.42-3.92 µmol/L), NH_4^+ (0.18-3.47 µmol/L), PO_4^{3-} (0.030-0.090 µmol/L), H_4SiO_4 (0.50-8.43 µmol/L), TDP (0.13-0.39 µmol/L). A total of 8 macroalgae species were collected for $\delta^{15}N$ and %N analysis during both years of the study (Appx. I.1). Algal $\delta^{15}N$ (mean ± SE) was nearly two times higher in the North Resorts region ($\delta^{15}N= 3.8 \pm 0.6$) than the Middle Puakō ($\delta^{15}N= 1.4 \pm 0.4$) and North Puakō ($\delta^{15}N= 1.7 \pm 0.3$) regions (Fig.2). The highest algal %N content (1.6% ± 0.1) was observed in the North Puakō region, which was significantly greater than the South Resorts region (1.1% ± 0.1) (Fig. 3). The highest sewage pollution score was observed in the North Resorts region (score= 25 ± 2.0), which was significantly different than North Puakō regions (score= 17 ± 1.7), which was the lowest of all five regions (Fig. 4). Although average scores for each region did not exceed the medium category, scores for individual stations within the North Resorts region fell within the high category twice. Average benthic salinity values were similar among regions, though the greatest range of salinity values were observed in the South and North Puakō regions (Table 2).

Benthic seawater $\delta^{15}N$ and $\delta^{18}O$- NO_3^- from each region fell within the range of ocean, sewage, groundwater, and soil sources (Fig. 5). Evidence of denitrification in the South Puakō region was also observed, evidenced by the increase in $\delta^{15}N$ and $\delta^{18}O$ by a nearly 2:1 ratio. Using the simmr mixing model, proportions of NO_3^- sources were determined in three regions (Fig. 6). Sewage from the OSDS and IW contributed up to 50% of the NO_3^- at some stations. Specifically, sewage contributions from OSDS to benthic NO_3^- ranged from 10.3-28.5%, with the largest proportion of sewage observed in the South Puakō region. Inputs of LE-GW were the second largest source of NO_3^- in all regions, ranging from 9.2-26.7%. Proportions of IW effluent ranged from 8.6-26.8% and were most prominent in the South Resorts region. One station in the South Puakō region (station 4) had a highly enriched $\delta^{15}N$ and $\delta^{18}O$- NO_3^- value, which fell on a line with a 2:1 ratio for $\delta^{15}N$ and $\delta^{18}O$ from the IW effluent source value. This finding suggests that the IW effluent was denitrified along its flow path to the benthic seep. The proportion of ocean water to the benthic NO_3^- pool were similar in all regions, ranging from 8.6-26.5%. Soil contributed the lowest proportion of NO_3^- in all regions, with ranges between 5.1-26.0%.

Benthic Water Motion and Temperature

The greatest clod card percent weight loss was observed in the South Puakō region (15% ± 1.4) which differed only from the North Puakō region ($p= 0.014$) (Fig. 7). Near-benthic water velocity measured by the ADCP significantly differed between the South Puakō, North Puakō, and North Resorts regions (Fig. 8) Like the clod card data, the greatest mean near-benthic water velocity (32 mm/s ± 0.6) was observed in the South Puakō region. Benthic currents moved every direction, but dominant (mode) current directions differed in each region (Appx. II.1). Currents in the South Resorts region favored an east-southeast direction, while currents in the South Puakō region favored a northern direction. In the Middle Puakō region south-southeast currents dominated, while west-southwest currents dominated the North Puakō region. Currents in the North Resorts region were dominated by northeastern currents.

Benthic water temperatures in 2018 ranged from 25.9-27.6 °C, while benthic temperatures in 2019 increased, ranging from 26.4-28.2 °C in 2019 (Appx. II. 2). Over the course of the ADCP deployment, benthic salinity values fluctuated with changes in tidal height (water depth) (Fig. 9). In all regions, the highest salinity values were generally observed during high tide, while the lowest salinity values were generally observed during low tide. Benthic salinity was most variable in the South Puakō region, where salinity values ranging from 34.5 to 35.1 were observed over the instrument's 44-h deployment. Salinity values in the South Puakō region were also lower than those recorded in the South Resorts (34.7-34.9), Middle Puakō (34.6-34.9), North Puakō (34.6-34.9), and North Resorts (34.7-34.9) regions.

Benthic Cover

Turf algae was the dominant benthic cover in all regions, followed by coral and CCA (Fig. 10). Turf algae percent cover was significantly different among regions (p= 0.0028). Percent turf cover was most prominent in the North Resorts region, which was 20-28% greater than turf cover in the South Resorts (57% ± 2.0), South Puakō (61% ± 2.5), Middle Puakō (52% ± 5.0), and North Puakō (49% ± 6.8) regions. Macroalgae cover was negligible in all five regions. Percent coral cover also significantly differed among regions (p= 0.0056). The highest coral cover was observed in the Middle Puakō region (27% ± 3.2), while coral cover in the North Resorts region (7% ± 2.6) was substantially lower than the South Resorts (23% ± 2.2), South Puakō (22% ± 1.8), Middle Puakō (27% ± 3.2), and North Puakō (22% ± 4.6) regions. A total of 19 coral species were observed during both years' benthic surveys, with *Porites lobata* being the most commonly surveyed (Appx. I.2). CCA cover was similar among regions (p= 0.22), with averages ranging between 9-17%. The reef builder ratio was also similar among regions (p= 0.11), though North Puakō was the only region with a ratio above one (ratio of 1.3) (Fig. 11). This suggests that the proportion of calcifying benthic organisms only exceeds that of non-calcifying organisms in North Puakō.

Coral Health

The impaired health conditions ALOG, BL, DC, GA, and TL were observed in every region (Fig. 12). ALOG was the most prevalent condition observed in each region, while BL was the most severe. However, there was no significant difference in the severity or prevalence of each condition among regions (Table 3). GA and ALOG were the only health conditions that exhibited statistically significant relationships with the LME predictor variables. In nearly every region, GA severity was positively associated with H_4SiO_4 concentration, with an effect size of 0.17 (Table 4, Fig. 13). This suggests that the logit value of GA severity increases by 0.17 for every unit increase in H_4SiO_4. Model output also suggests GA severity is negatively associated with elevated water temperatures, as an effect size of -0.38 was observed (Appx. III.1). With this finding, GA severity is expected to decrease by a logit value of 0.38 for every unit increase in water temperature. ALOG severity was positively associated with benthic water temperature in most regions, with an effect size of 0.14 (Table 4, Fig. 14). This indicates that ALOG severity will increase by a logit value of 0.14 for every unit increase in water temperature.

DISCUSSION

Sewage Indicators & Nutrients

Enterococcus spp. is commonly used to monitor for sewage pollution in recreational waters (Rodrigues & Cunha 2017). However, the use of *Enterococcus* spp. as a FIB has been criticized due to its natural occurrence in tropical soils (Fujoka & Byappanhalli 1996; Byappanhalli et al. 2012). *Enterococcus* spp. has also been shown to be a poor indicator of non-point source sewage pollution in Hawaiʻi, especially in areas where OSDS are used (Miller-Pierce & Rhoads 2019). *C. perfringens* has been identified as a better indicator of sewage pollution in Hawaiʻi, as this FIB cannot metabolize and replicate under aerobic conditions and has been reliably detected in both raw and treated sewage (Fujioka & Shizumura 1985; Fujioka & Byappanhalli 1996). At the time of writing, *C. perfringens* is used as a secondary FIB by the Hawaiʻi Department of Health (HDOH), with *Enterococcus* spp. being the primary FIB monitored throughout the state (HDOH 2014). Benthic FIB concentrations in this study did not exceed HDOH standards. No *Enterococcus* spp. sample exceeded the HDOH 130 MPN/100 mL statistical threshold value, and no *C. perfringens* sample fell above the recommended 5 CFU/100 mL standard (Fujioka & Byappanhalli 1996; HDOH 2014). Concentrations of *C. perfringens* also did not suggest the presence of sewage pollution from a non-point source (>10 CFU/100mL in Fung et al. 2007). Previous FIB studies at Puakō similarly observed that shoreline FIB concentrations were orders of magnitude higher than offshore, benthic FIB concentrations (Couch et al. 2014a; Abaya et al. 2018a, b). Low benthic FIB concentrations (0-41MPN/100mL for *Enterococcus* spp. and concentrations below 2 CFU/100mL for *C. perfringens*) have also been reported on reefs in the Florida Keys (Lipp & Griffin 2004; Futch et al. 2010).

Sewage pollution also contributes to eutrophication on coral reefs (Costa Jr et al. 2008; Reopanichkul et al. 2010; Lapointe et al. 2017). Elevated nutrient levels can alter the composition of benthic organisms and promote coral disease (Kaczmarsky & Richardson 2011; Redding et al. 2013; Lapointe et al. 2017). Average benthic nutrient concentrations in South Kohala varied, with no single region having the highest concentrations. Previous studies conducted in South Kohala have reported a similar range of benthic nutrient concentrations, with benthic nutrient concentrations noticeably lower than surface and shoreline waters (Knee et al. 2010; Couch et al. 2014a; Abaya et al. 2018a, b). Nutrient concentrations observed in this study were also similar to benthic nutrient concentrations reported on sewage impacted reefs around the world (Parsons et al. 2008; Lapointe et al. 2019; Oberle et al. 2019). Nutrient concentrations measured at sewage impacted reefs around the world are as follows: NO_2^-+NO_3^- (0.01-42.3 µmol/L), NH_4^+ (0.00-9.25 µmol/L), and PO_4^{3-} (0.1-11.5 µmol/L). Lower nutrient concentrations have been observed on reefs in Australia and French Polynesia: NO_2^-+NO_3^- (0.01-0.83 µmol/L), NH_4^+ (0.14-9.11 µmol/L), PO_4^{3-} (0.01-0.89 µmol/L) (Crossland & Barnes 1983; Charpy-Roubaud et al. 1990).

Analyses of macroalgae $\delta^{15}N$ and %N content have been widely used to examine the sources and availability of N on coral reefs (Risk et al. 2009; Barr et al. 2013). As macroalgae opportunistically uptake and store N from many sources in their tissue, they reflect nutrient conditions within a month’s timespan (Risk et al. 2009). Both methods have been used throughout Hawai'i to detect sewage pollution and N loading in nearshore marine waters (Dailer et al. 2010; Amato et al. 2016; Wiegner et al. 2016; Abaya et al. 2018a, b). In particular, it has been suggested that algal N content above 2% indicates elevated nutrient loading in coastal waters (Amato et al. 2016). The %N content of macroalgae tissues was elevated in the Puakō regions, which approached 2%. This suggests that N bioavailability is greatest in this region of the coast. The highest algal $\delta^{15}N$ were observed in the two Resort regions and South Puakō. However, these algal $\delta^{15}N$ did not fall within the range of sewage values specific to Puakō (+9.62 to +11.57‰ in Abaya et al. 2018a) or sewage values reported in literature (+7 to +20‰ reviewed in Wiegner et al. 2016). A comparison of our algal $\delta^{15}N$ to other Hawai'i studies (Amato et al. 2016; Abaya 2018b) suggests that sewage pollution on the reef is diluted by a combination of ocean water and SGD. The mixing of sewage with other anthropogenic and natural N sources in South Kohala is also likely, based on a conceptual model developed by Amato et al. (2016).

$\delta^{15}N$ and $\delta^{18}O$ in dissolved NO_3^- have been used previously to detect the presence of sewage and other land-based nutrient sources in coastal waters (Hunt 2007; Hunt & Rosa 2009; Wiegner et al. 2016). While algal isotope analyses are useful in identifying N inputs in aquatic environments, the use of multiple isotope data in mixing models allows for greater distinction among potential N sources, while accounting for isotope fractionation processes (Xue et al. 2009). Output from $\delta^{15}N$ and $\delta^{18}O$-NO_3^- mixing models concurs with our algal $\delta^{15}N$ analysis, suggesting that sewage diluted in groundwater and seawater is present on South Kohala's reefs. Sewage pollution is most problematic in South Puakō, as sewage from OSDS and IW comprise over 50% of the NO_3^- at some benthic stations. Sewage pollution associated with OSDS has been previously documented along the South Puakō shoreline (Couch et al. 2014a; Abaya et al. 2018a,b). Our study provides some of the first evidence that IW effluent is reaching the reefs at Puakō, as $\delta^{15}N$ and $\delta^{18}O$-NO_3^- values for one station fall along the projected line for denitrification from the IW source (Aravena & Robertson 1998). Similar results were found along the shoreline of Maui, Hawai'i, where denitrified injection well effluent was detected (Hunt 2007). A recent ruling by the U.S. Supreme Court has classified wastewater injection wells on Maui as "point sources" of pollution, requiring them to obtain permits to discharge treated wastewater (County of Maui v. Hawaiʻi Wildlife Fund, 590 U. S. ___ 2020). This ruling will affect the disposal of all sewage injection wells in the State of Hawaiʻi, including those in South Kohala.

At large spatial scales, FIB and nutrient concentrations often provide conflicting information about the location and severity of sewage pollution. In Hawaiʻi, this issue is further confounded by the natural occurrence of *Enterococcus* spp. and weather-related factors that influence the concentration and transport of FIBs through a watershed (Byappanahalli et al. 2012; Economy et al. 2019). Thus, the sewage pollution scoring method was developed by Abaya et al. (2018a) to assess sewage pollution in Hawaiian coastal waters. In this study, average pollution scores for every region fell within the medium category, though the range of scores at stations in the South Puakō and North Resorts fell within the high category twice. High and medium category sewage pollution scores have been previously documented along the South Puakō shoreline, where OSDS derived sewage pollution is being discharged (Abaya et al. 2018a). Together, this strongly suggests the presence of sewage pollution on reefs in South Puakō. High sewage pollution scores in the North Resorts region were also observed. This was not expected, as treated wastewater in this region is used for irrigation, but finding warrants further investigation.

Benthic Water Motion, Depth, Temperature, and Salinity

Physical processes play an equally important role as biological interactions in shaping coral reef communities. Water motion and circulation on coral reefs are influenced to varying degrees by oceanographic forces and geomorphologic features (Hoeke et al. 2011; Taebi et al. 2011; Reid et al. 2019). Differences in geomorphology along the South Kohala coast may explain the variability of near-benthic current velocities and directions observed in this study. Instruments tended to record greater water motion on fringing reefs exposed to the open ocean (Puakō regions) than those located within embayments (Resort regions). Additionally, water motion can influence the uptake of nutrients as well FIB concentrations, which may explain why benthic nutrient and FIB concentrations observed in this study were lower than shoreline and surface concentrations (Atkinson et al. 1992; Atkinson et al. 2001; Rippy et al. 2013).

Changes in salinity associated with changes in tidal height observed by the ADCP suggest the presence of benthic SGD. Generally, salinity values were lowest during low tides. However, different salinity patterns were observed in each region. As SGD is most pronounced during low tides, these decreased salinity values likely reflect the presence of benthic groundwater seeps on the reef (Ataie-Ashtiani et al. 2001; Robinson et al. 2007). Salinity values observed in this study are also comparable to benthic salinity values reported on reefs where SGD is present, including those in South Kohala (31.0-35.0) (Couch et al. 2014a; Abaya et al. 2018b), reefs adjacent to wastewater plumes on the Island of Maui (33.4-34.1) (Swarzenski et al. 2017), and the Philippines (33.4-33.6) (Cantanero et al. 2019). The benthic salinity data, sewage pollution scores and $\delta^{15}N$ and $\delta^{18}O$- NO_3 mixing model results, all suggest that SGD is discharging sewage-laden groundwater on the reef.

Benthic Cover and Coral Health

Coral reefs provide numerous ecosystem services but are threatened by a combination of local and global anthropogenic activities (Bishop et al. 2011; Gove et al. 2019). Currently, South Kohala's reefs are considered to be some of the least resilient in Leeward Hawai'i, and were some of the hardest hit during a Fall 2015 bleaching event, which reduced live coral cover by an average of 50% along this coast (Kramer et al. 2016). In the years prior to this bleaching event, coral made up 34-38% of the benthic substrate along the South Kohala coast (Couch et al. 2014b; Abaya et al. 2018b). In the 1970's, coral cover as high as 80% has been recorded on South Kohala's fringing reefs (Minton et al. 2012). The results of benthic surveys conducted in this study suggest limited recovery, as coral cover in the Middle and North Puakō regions are approaching values reported prior to the 2015 bleaching event. Benthic surveys also identified the North Resorts region as an area of concern. Of the five study regions, the North Resorts had the highest percent turf cover and lowest reef builder ratio value. Sewage pollution is also likely present in the North Resorts region, based on algal $\delta^{15}N$ and sewage pollution scores. Sewage polluted reefs in other parts of the world tend to be algal dominated, with little to no coral cover (Costa Jr. et al. 2008; Wear & Vega-Thurber 2015; Lapointe et al. 2019).

Coral disease outbreaks have also contributed to the global degradation of coral reefs and have increased throughout the last half century (Tracy et al. 2019). Coral diseases are also common on reefs throughout the Main Hawaiian Islands, which may further reflect the presence of localized, anthropogenic stressors (Aeby et al. 2011; Couch et al. 2014a). ALOG was the most prevalent condition on South Kohala's reefs, which can be exacerbated by anthropogenic development and nutrient enrichment (Vermeij et al. 2010; Barott et al. 2012). Thus, sewage pollution and N bioavailability on South Kohala's reefs are likely facilitating ALOG. The most severe condition frequently observed in each region was BL. Although BL is commonly associated with increased water temperatures, changes in water quality and disease can also cause BL (Jokiel 2004). Other impaired health conditions associated with anthropogenic stressors were also observed in the five study regions. An elevated prevalence and severity of GAs was observed in the South Resorts, Middle Puakō, and North Puakō regions. The abundance of GAs in these same regions were also noted by Couch et al. (2014b) and Yoshioka et al. (2016). The presence of GAs on shallow reefs have been associated with low water motion and nutrient inputs (Burns et al. 2011; Couch et al. 2014b; Caldwell et al. 2020). Our findings support this, as our clod card data indicate that benthic water motion was lowest in these three regions. TL and DC were also observed in each region, though these conditions have been associated with several potential pathogens and stressors (Weil et al. 2006; Bourne et al. 2009; Work et al. 2012; Sudek et al. 2015). Coral diseases are most notable in the Caribbean, where diseases linked to sewage pollution have been responsible for reducing coral cover by 85-88% (Sutherland et al. 2010). Sewage has also been associated with the introduction of disease-causing microbes on coral tissue, while sewage polluted SGD may be facilitating disease outbreaks on offshore reefs (Lipp et al. 2002; Futch et al. 2010).

Identifying the drivers of reef decline are crucial to managers, policy makers, and other stakeholders seeking to conserve and protect coral reefs (Jouffray et al. 2015). In this study, mixed effects models found associations between two impaired coral health conditions and environmental parameters. GA severity increased as H_4SiO_4 concentrations increased in nearly every region. A similar association between GAs and H_4SiO_4 was previously observed on South Kohala's reefs by Couch et al. (2014a).

Additional results from the model indicate GA severity is negatively associated with increased water temperatures. Elevated concentrations of H_4SiO_4 accompanied by low temperatures and salinities are characteristic of SGD in Leeward Hawai‘i, suggesting that the model reflects a relationship between GA severity and groundwater (Street et al. 2008; Knee et al. 2010). In South Kohala, groundwater is responsible for transporting sewage into shoreline and offshore waters (Couch et al. 2014a; Abaya et al. 2018a,b). Because of this, nutrients or pathogens from sewage polluted groundwater may be responsible for GAs in South Kohala. In the second model, ALOG severity increased under elevated benthic water temperatures. This finding may partially reflect the ability of algae to outcompete stressed corals, or grow on corals after they succumb to bleaching. On reefs experiencing bleaching or eutrophic conditions, corals may be more susceptible to ALOG (Diaz-Pulido & McCook 2002; Vermeij et al. 2010). Studies have also suggested that turf algae contain chemical compounds that promote coral mortality and subsequent overgrowth (Jompa & McCook 2003; Smith et al. 2006). As a chronic stressor and source of nutrients, sewage pollution may be facilitating the overgrowth and impairment of corals in South Kohala. Notably, the model also displayed a negative relationship between ALOG severity and NH_4^+ concentrations. A positive relationship between the two variables would be expected, as NH_4^+ can promote algal growth (Wear & Vega-Thurber 2015; Lapointe et al. 2017). However, the majority of benthic NH_4^+ concentrations observed in this study were near or at the analytical instrument's lowest detection limit for NH_4^+ (0.18 μmol). Measured NH_4^+ concentrations were also not significantly different among regions. Because there is little variation in the NH_4^+ data, NH_4^+ concentration values on the x-axis is clustered towards one side of the plot, resulting in regression lines that are oriented in a negative direction (Appx. III. 1).

CONCLUSION

Coral reefs provide numerous benefits to society, but are threatened by multiple stressors. Localized stressors such as sewage pollution can be effectively managed, promoting reef resilience against other stressors. Our multi-indicator approach, combined with benthic *in situ* sampling found moderate levels of sewage pollution present on South Kohala's offshore reefs from benthic seeps. Water motion appears to be mixing and diluting FIBs and nutrients at the benthos. Surveys identified turf algae as the dominant benthic substrate and observed several impaired coral health conditions throughout the five study regions. Linear mixed-effects models indicate that sewage transported through SGD is likely influencing the severity and prevalence of GA and ALOG on South Kohala’s reefs. This study illustrates the importance of using multiple indicators and studying water motion when assessing sewage pollution in coastal environments. In addition to documenting sewage pollution on coral reefs, our research also identified environmental drivers associated with impaired coral health conditions. Methods used in this study can be utilized by managers outside of Hawaiʻi to identify and reduce anthropogenic stressors to coral reefs.

TABLES

Table 1. Average ± SE and [range] of benthic *Enterococcus* spp. (MPN/100 mL) and *Clostridium perfringens* (CFU/100 mL) at five regions along the South Kohala coastline, Hawaiʻi, in June 2018 and 2019.

Region	***Enterococcus* spp.**	***C. perfringens***
South Resorts	5.0 ± 0.0 [5.0]	0.4 ± 0.2 [0-1.0]
South Puakō	6.0 ± 0.4 [5.0-8.0]	0.5 ± 0.2 [0-2.0]
Middle Puakō	6.0 ± 0.5 [5.0-7.0]	0.3 ± 0.1 [0-2.0]
North Puakō	6.0 ± 0.5 [5.0-10]	0.1 ± 0.1 [0-1.0]
North Resorts	5.0 ± 0.3 [5.0-7.0]	0.3 ± 0.2 [0-1.0]

Table 2. Average ± SE and [range] of benthic nutrient concentrations (μmol/L) and salinity values at five regions along the South Kohala coastline, Hawaiʻi, in June 2018 and 2019.

Region	NO_2^-+NO_3^-	NH_4^+	PO_4^{3-}	H_4SiO_4	TDN	TDP	Salinity
South Resorts	0.80± 0.09 [0.45-1.37]	0.59 ± 0.20 [0.18-1.73]	0.056 ± 0.006 [0.030-0.080]	3.90 ± 1.03 [0.50-8.07]	6.91 ± 1.38 [2.50-12.13]	0.19 ± 0.02 [0.13-0.25]	32.8 ± 0.4 [31.1-34.2]
South Puakō	1.01 ± 0.33 [0.42-3.92]	0.44 ± 0.12 [0.18-1.30]	0.052 ± 0.006 [0.030-0.080]	3.96 ± 0.42 [2.37-6.48]	7.13 ± 0.87 [2.50-10.03]	0.19 ± 0.02 [0.13-0.25]	32.8 ± 0.5 [30.9-34.4]
Middle Puakō	0.75 ± 0.12 [0.44-1.26]	0.86 ± 0.53 [0.18-3.47]	0.063 ± 0.008 [0.040-0.090]	4.22 ± 1.00 [1.19-8.43]	5.65 ± 1.14 [2.50-9.39]	0.22 ± 0.03 [0.13-0.29]	32.9 ± 0.6 [31.5–34.9]
North Puakō	0.76 ± 0.03 [0.60-0.89]	0.32 ± 0.06 [0.18-0.64]	0.057 ± 0.004 [0.040-0.070]	3.96 ± 0.62 [1.61-7.40]	6.17 ± 0.96 [2.50-10.63]	0.19 ± 0.02 [0.13-0.25]	32.2 ± 0.5 [30.3-34.7]
North Resorts	0.67 ± 0.08 [0.53-1.06]	0.41 ± 0.12 [0.18-0.78]	0.048 ± 0.004 [0.030-0.060]	3.44 ± 1.03 [1.55-8.38]	6.96 ± 1.49 [2.50-11.15]	0.23 ± 0.04 [0.13-0.39]	32.2 ± 0.5 [31.1-33.9]

Table 3. Results of MANOVA and Kruskal-Wallis tests comparing the prevalence (percentage of all surveyed colonies affected) and severity (percent of each individual colony affected) of impaired coral health conditions among five regions within the South Kohala coast, Hawaiʻi, in June 2018 and 2019 (α= 0.05). DF refers to degrees of freedom.

Condition Prevalence	DF	p-value	MANOVA F-value	Kruskal Wallis Chi-Squared
Algal Overgrowth (ALOG)	4	0.80	0.41	-
Bleaching (BL)	4	0.94	-	0.78
Discoloration (DC)	4	0.80	0.41	-
Growth Anomalies (GA)	4	0.13	1.9	-
Tissue Loss (TL)	4	0.44	-	3.7
Condition Severity	**DF**	**p-value**	**MANOVA F-value**	**Kruskal Wallis Chi-Squared**
Algal Overgrowth (ALOG)	4	0.40	-	7.7
Bleaching (BL)	4	0.23	-	5.5
Discoloration (DC)	4	0.32	-	4.7
Growth Anomalies (GA)	4	0.36	0.36	-
Tissue Loss (TL)	4	0.41	1.0	-

Table 4. Results of best fit mixed effects model for coral growth anomaly and algal overgrowth severity among five regions in South Kohala, Hawai'i, in June 2018 and 2019 (α= 0.05). SE stands for standard error, while DF stands for degrees of freedom.

Growth Anomaly Severity Model					
Fixed Effects	**Estimate Value**	**SE**	**DF**	**t-value**	**p-value**
H_4SiO_4	0.173	0.07	32	2.40	0.022
TDN	-0.151	0.05	32	-2.83	0.008
Benthic Water Temperature	-0.379	0.2	32	-2.12	0.042
Algal Overgrowth Severity Model					
Fixed Effects	**Estimate Value**	**SE**	**DF**	**t-value**	**p-value**
Benthic Water Temperature	0.142	0.04	33	3.35	0.002
NH_4	-0.127	0.07	33	-1.93	0.063

FIGURES

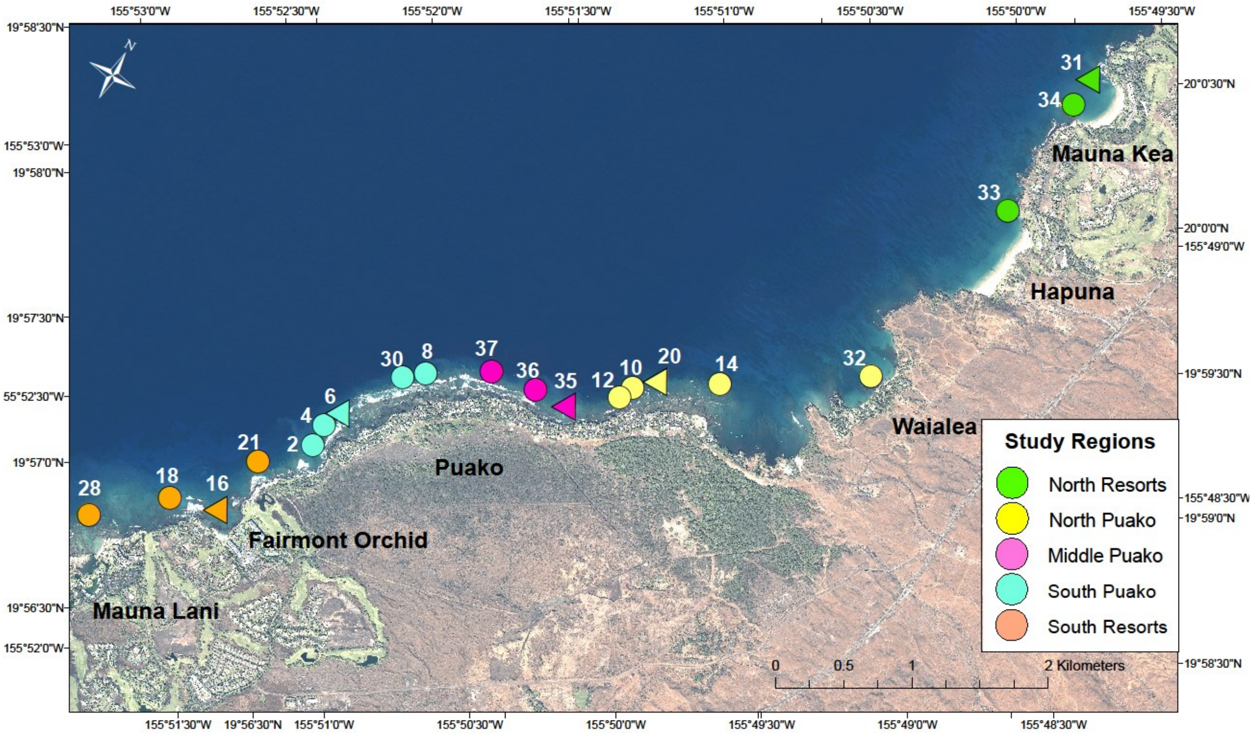


Figure 1. Map displaying benthic stations along the South Kohala coastline, Hawai'i. Stations were assigned into one of five color coded regions (South Resorts, South Puakō, Middle Puakō, North Puakō, North Resorts), based on their proximity to the resorts or the Puakō community. At all stations, water and macroalgae samples were collected, benthic surveys conducted, and clod cards deployed. Stations marked with a triangle show where an acoustic doppler current profiler was deployed. Samples, surveys, and deployments were conducted in June 2018 and 2019.

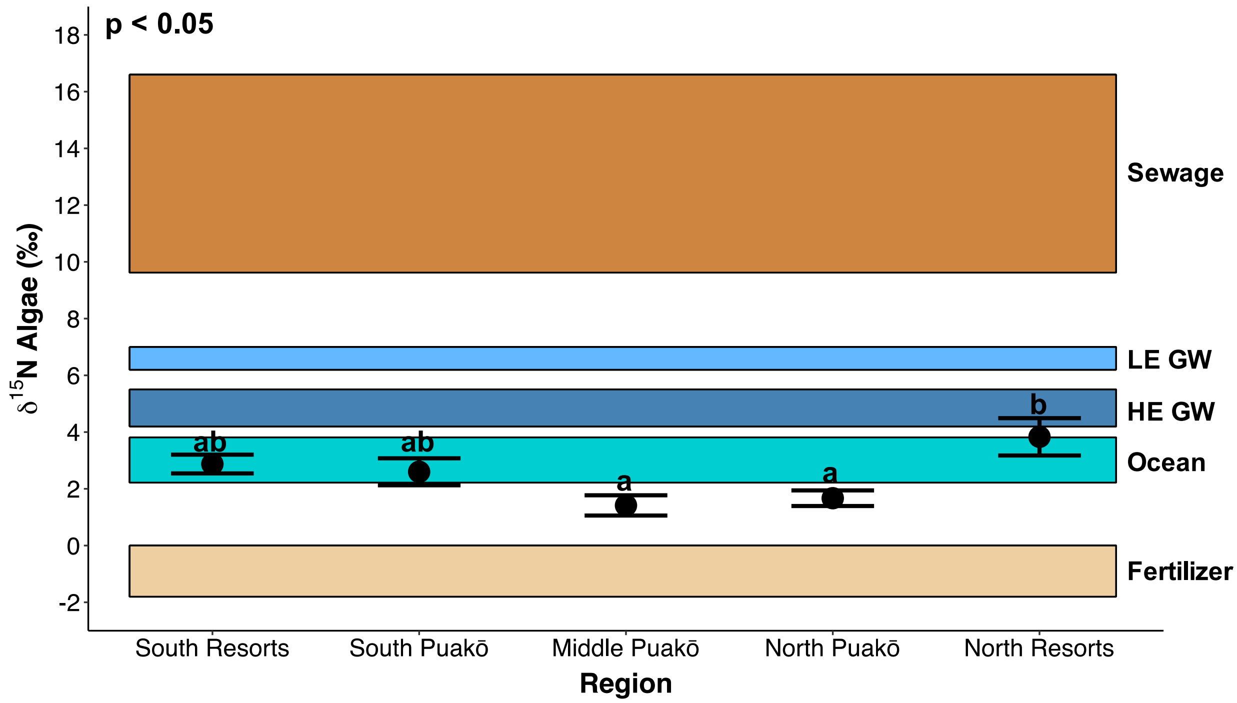


Figure 2. Average ± SE $\delta^{15}N$ of benthic macroalgae collected from South Kohala, Hawai'i, in June 2018 and 2019. Colored bars represent the range of $\delta^{15}N$ for sewage (OSDS and wastewater injection well effluent), low elevation groundwater (LE GW), high elevation groundwater (HE GW), ocean water (ocean), and fertilizer. Range of $\delta^{15}N$ for OSDS, LE GW, HE GW, ocean, and fertilizer sources were determined byAbaya et al. (2018a). Injection well effluent $\delta^{15}N$ were determined by Panelo et al. (unpublished data). Regions that do not share the same letter are significantly different from each other (MANOVA with Tukey HSD, α= 0.05).

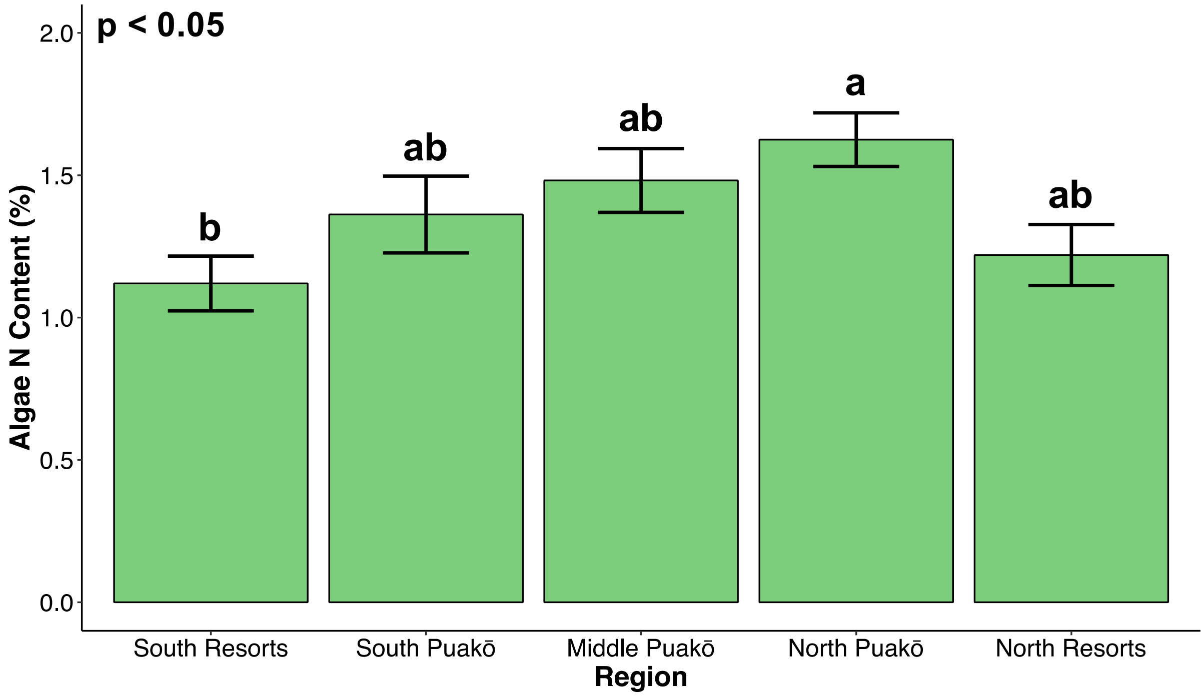


Figure 3. Average ± SE % nitrogen content of benthic macroalgae collected from South Kohala, Hawaiʻi, in June 2018 and 2019. Regions that do not share the same letter are significantly different from each other (MANOVA with Tukey HSD, α= 0.05).

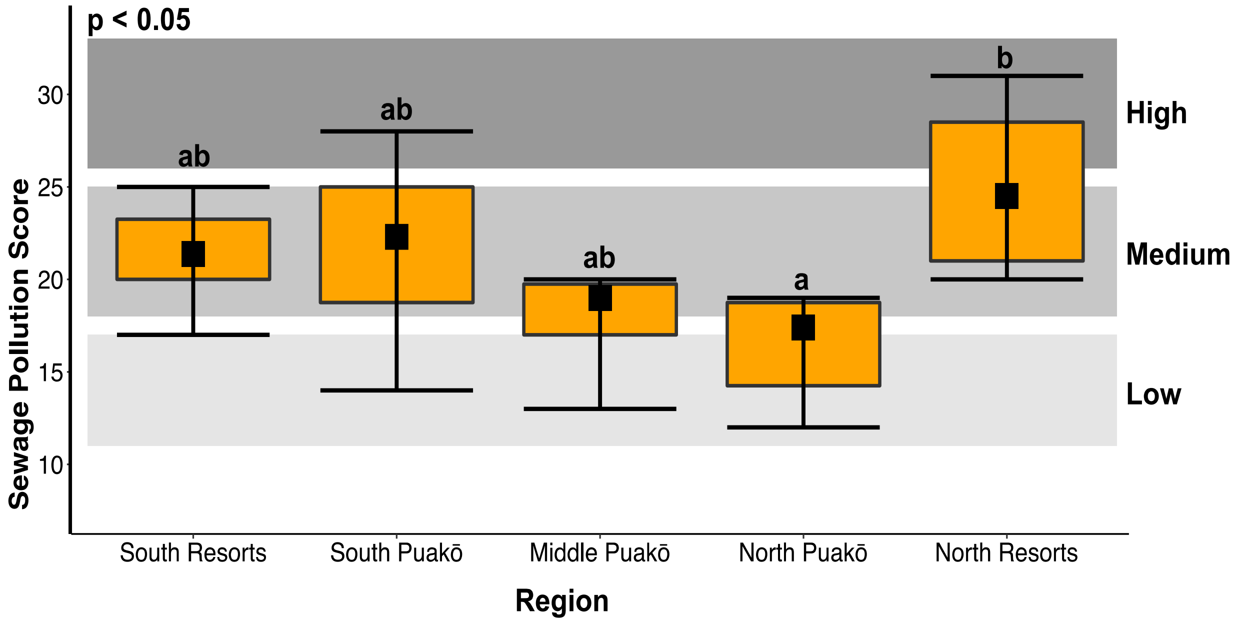


Figure 4. Average ± SE sewage pollution scores for five study regions in South Kohala, Hawai‘i, during June 2018 and 2019. Scores were calculated using the approach described in Abaya et al. (2018a). Shaded bars represent score categories: low (11-17), medium (18-25), and high (26-33). Regions that do not share the same letter are significantly different from each other (MANOVA with Tukey HSD, α= 0.05).

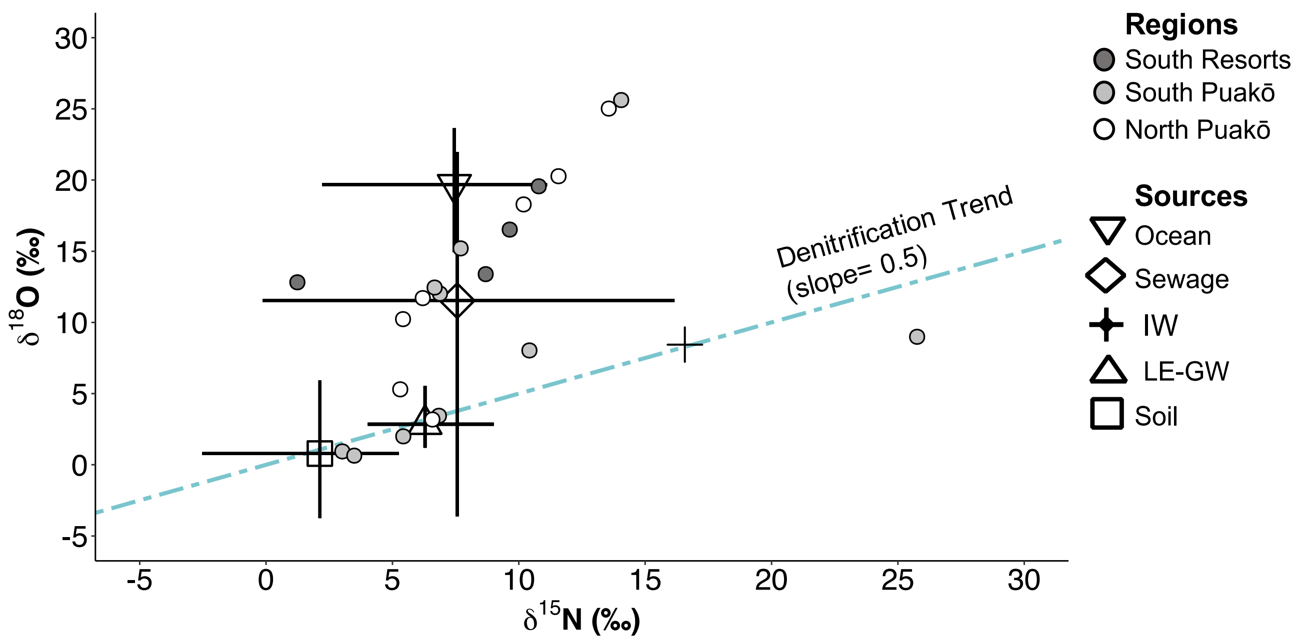


Figure 5. Biplot displaying $\delta^{15}N$ and $\delta^{18}O$-NO_3^- of N sources and benthic water samples collected from three regions along the South Kohala coastline, Hawai‘i, in May and July 2017 and June 2018. Vertical and horizonal lines illustrate the range of stable isotope values associated with each source. Dashed blue line illustrates $\delta^{15}N$ and $\delta^{18}O$ enrichment associated with denitrification.

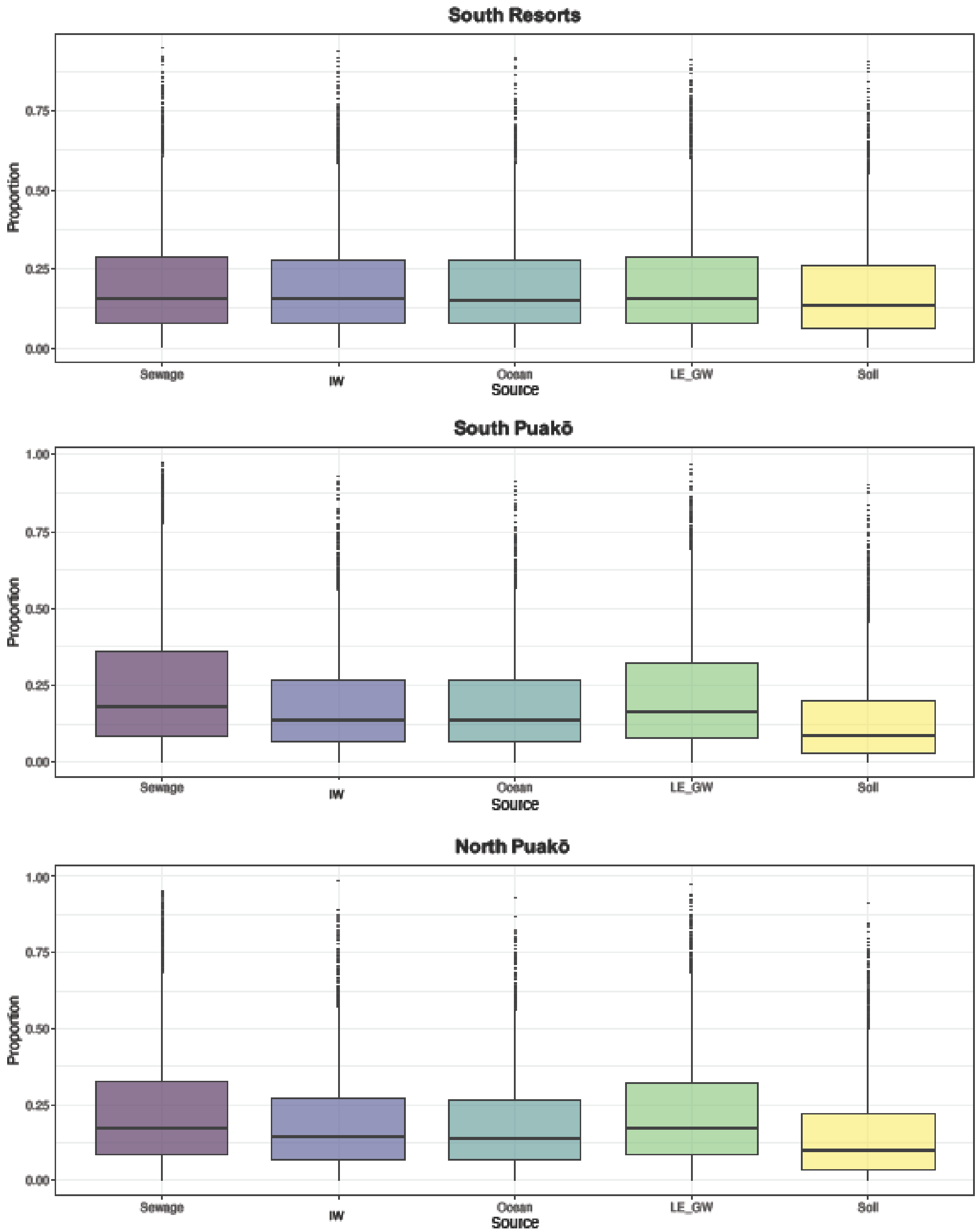


Figure 6. Simmr mixing model results displaying the proportion (%) of each N source contributed to the benthic NO_3^- pool in three study regions along the South Kohala coastline, Hawai'i, in May and July 2017 and June 2018. Sources included in the model are sewage (OSDS effluent), IW (injection well effluent), ocean (seawater), LE GW (low elevation groundwater), and soil (residential soils). Vertical bars display SE, while horizontal bars display the mean value.

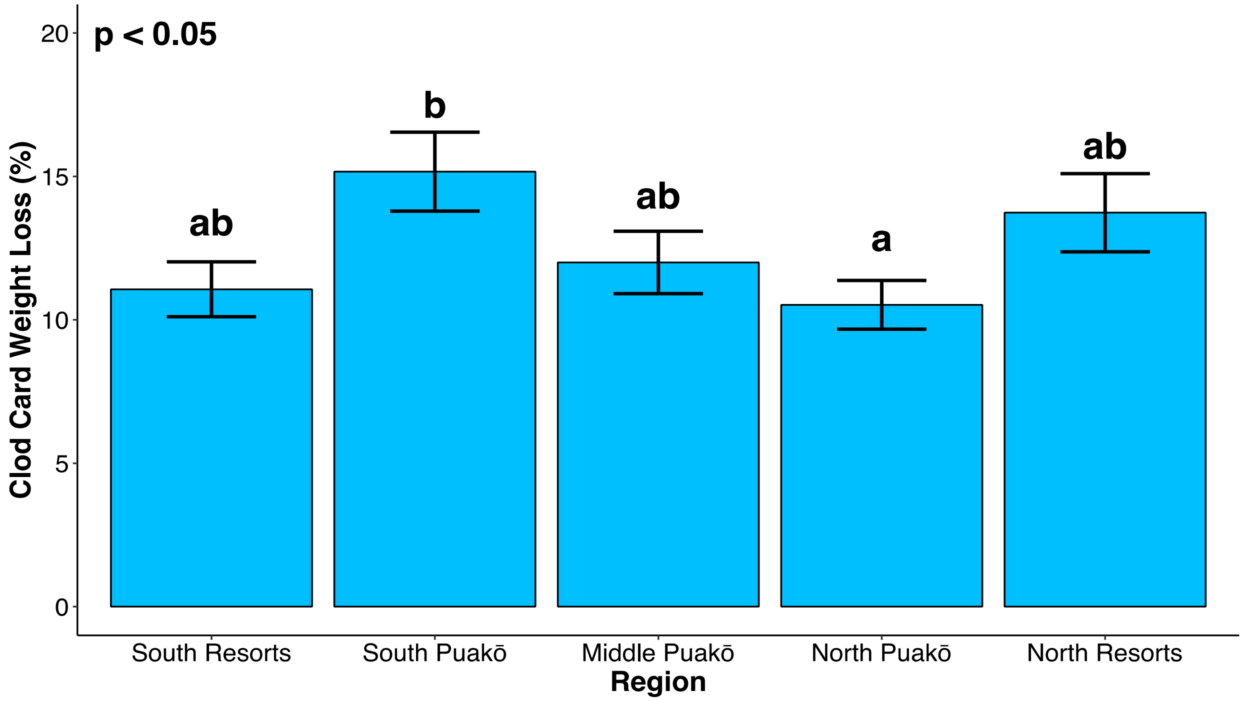


Figure 7. Average ± SE of clod card percent weight loss at five regions along the South Kohala coastline, Hawaiʻi, in June 2018 and 2019. Regions that do not share the same letter are significantly different from each other (MANOVA with Tukey HSD, α= 0.05).

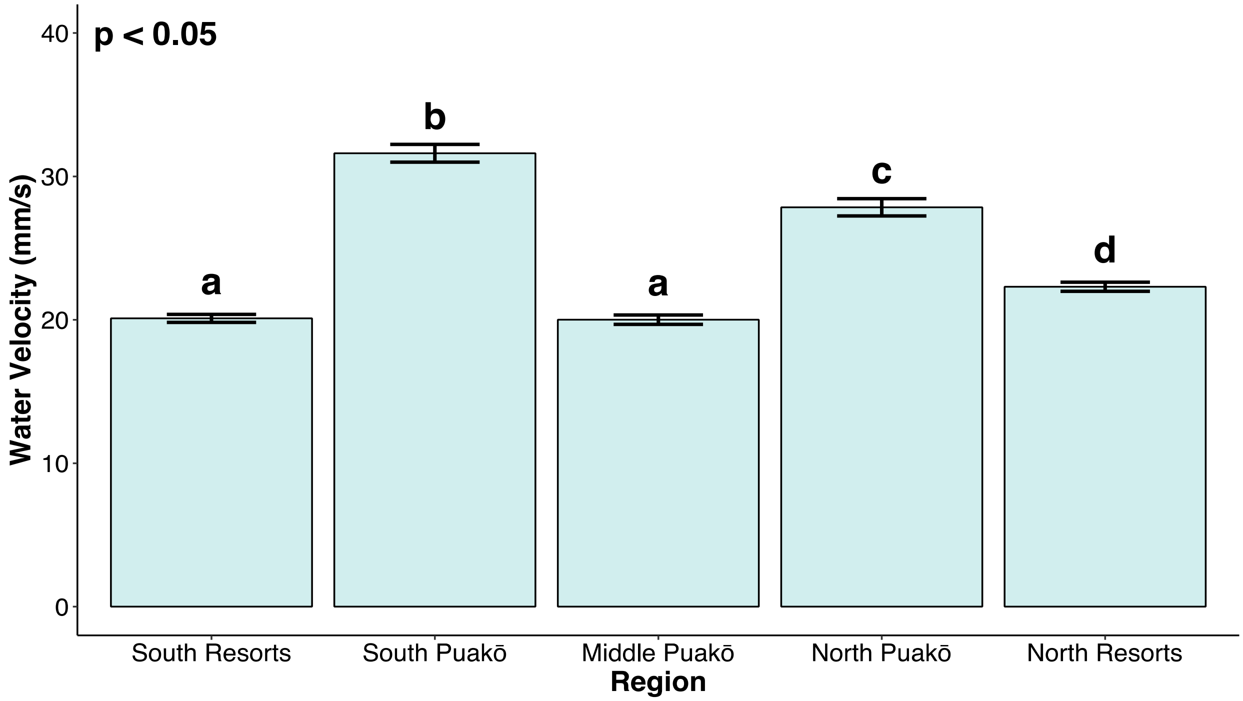


Figure 8. Average ± SE water velocity measured ~1 m above the seafloor at five regions along the South Kohala coastline, Hawai‘i, in June 2018 and 2019. Velocity was measured over a period of 42-74 h using an acoustic doppler profiler. Regions that do not share the same letter are significantly different from each other (MANOVA with Tukey HSD, α= 0.05).

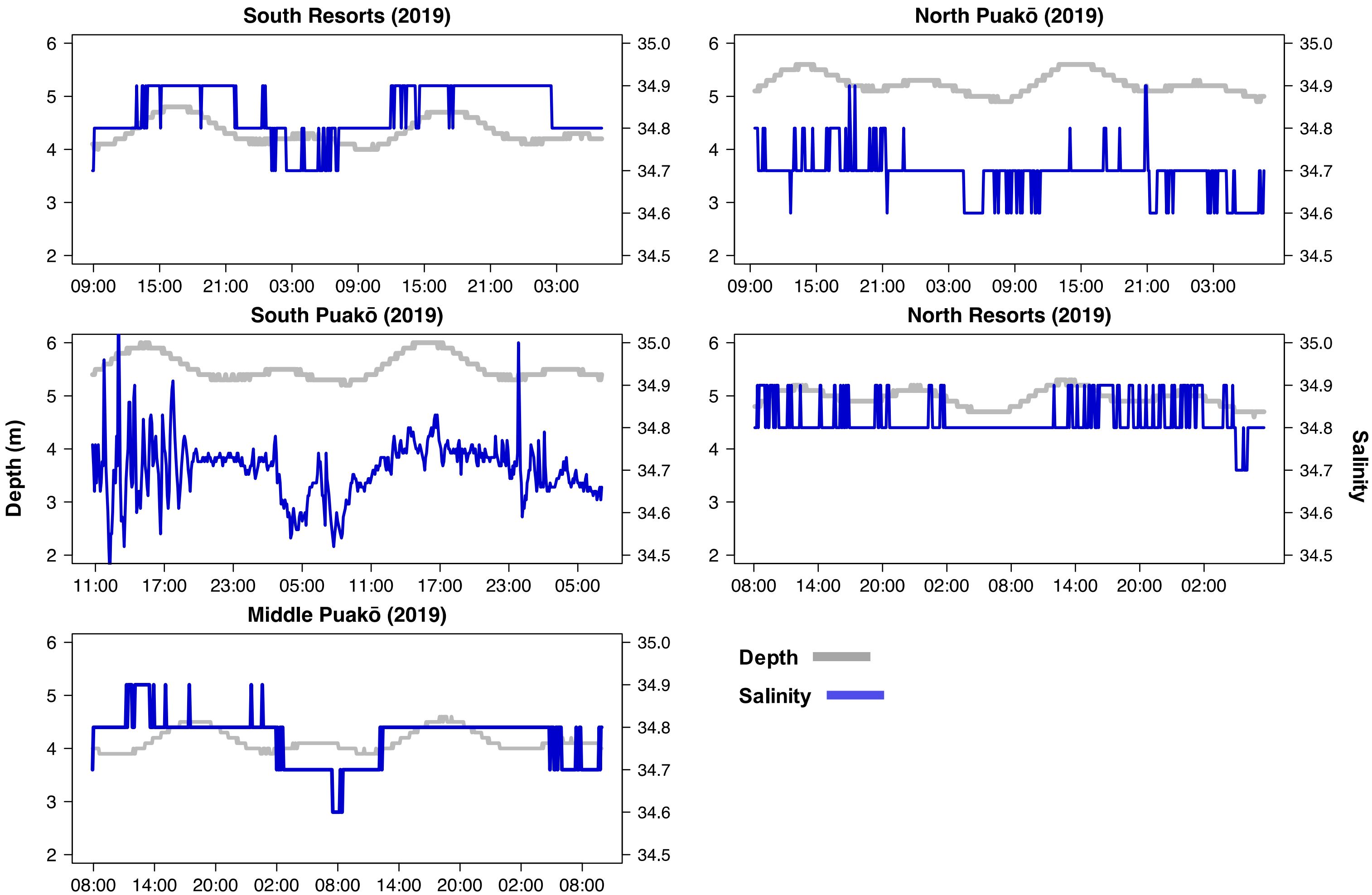


Figure 9. Water depth and benthic salinity measured at five regions along the South Kohala coastline, Hawai‘i, in June 2019. Depth was measured using an acoustic doppler current profiler, while salinity was measured using a HOBO U24 conductivity logger. Both instruments were deployed between 42-74 h.

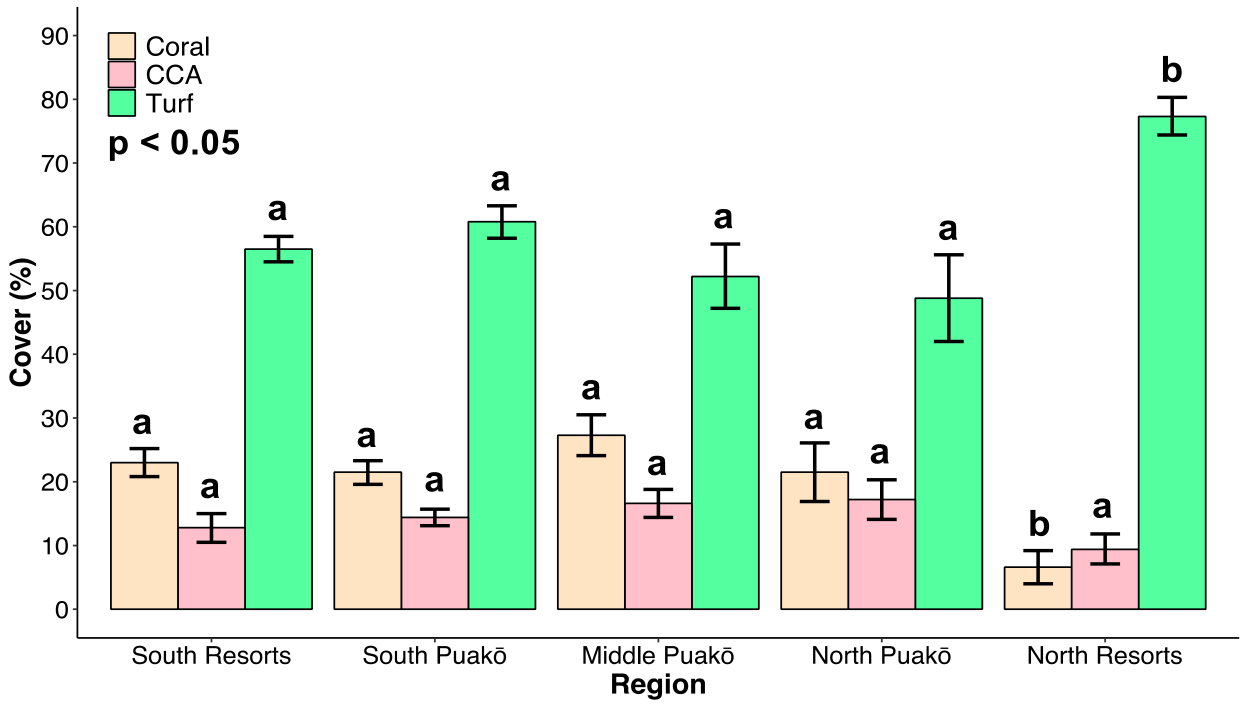


Figure 10. Average ± SE of coral, crustose coralline algae (CCA), and turf algae percent cover at five regions along the South Kohala coast, Hawaiʻi, in June 2018 and 2019. Regions that do not share the same letter are significantly different from each other (MANOVA with Tukey HSD, α= 0.05).

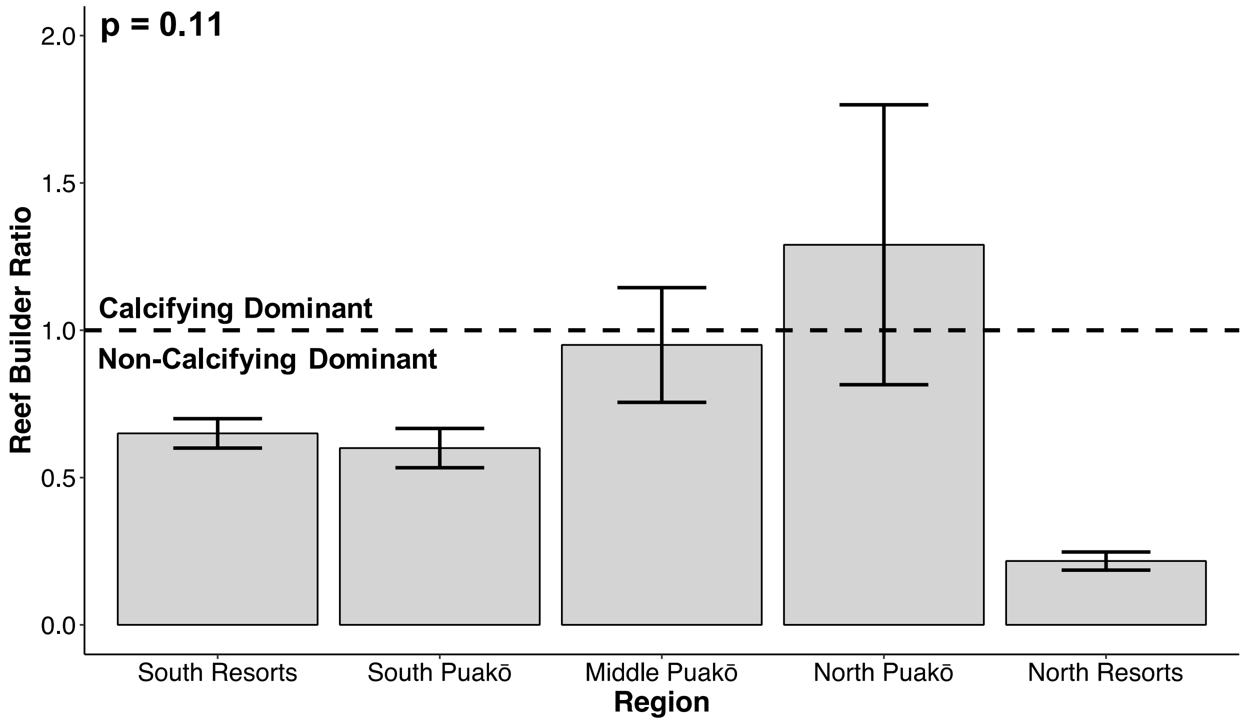


Figure 11. Average ± SE of reef builder ratio values for five regions along the South Kohala coast, Hawaiʻi, in June 2018 and 2019. The reef builder ratio compares the percent cover of calcifying organisms (coral and CCA) to non-calcifying organisms (macroalgae, turf algae, cyanobacteria). Ratio values greater than or equal to one suggest calcifying organisms make up a larger proportion of the benthic substrate. Results of an MANOVA comparing all regions are shown on the figure (α= 0.05).

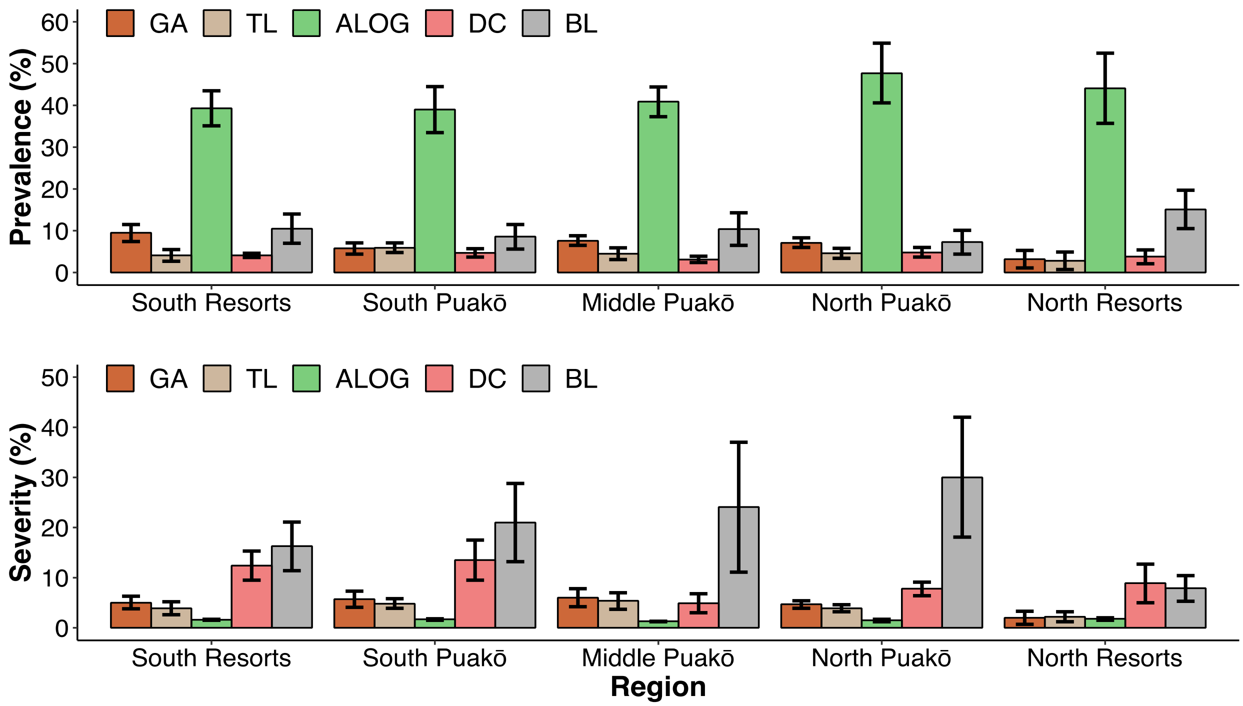


Figure 12. Average ± SE prevalence and severity of five impaired coral health conditions observed along at South Kohala, Hawaiʻi, in June 2018 and 2019. These health conditions are growth anomalies (GA), tissue loss (TL), algal overgrowth (ALOG), discoloration (DC), and bleaching (BL). Prevalence refers to the percentage of coral colonies affected by an impaired health condition. Severity reflects the percentage of a coral colony affected by an impaired health condition.

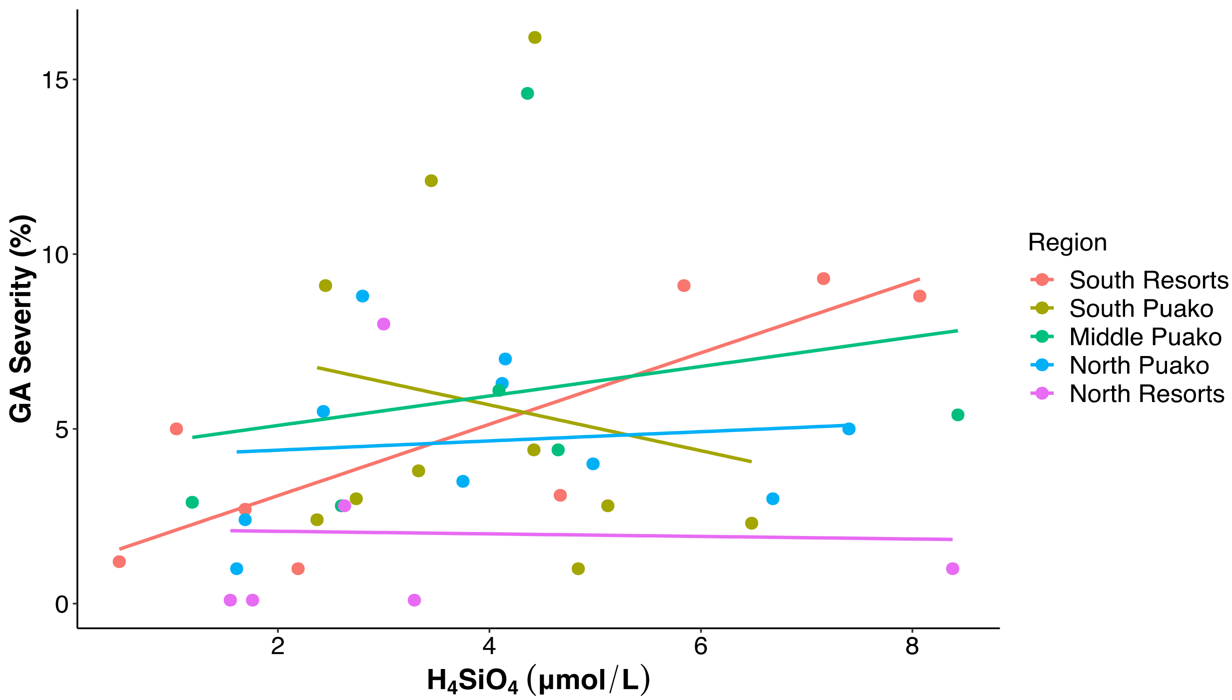


Figure 13. Association between coral growth anomaly (GA) severity and H_4SiO_4 concentrations at five regions along the South Kohala coastline, Hawai‘i, in June 2018 and 2019.

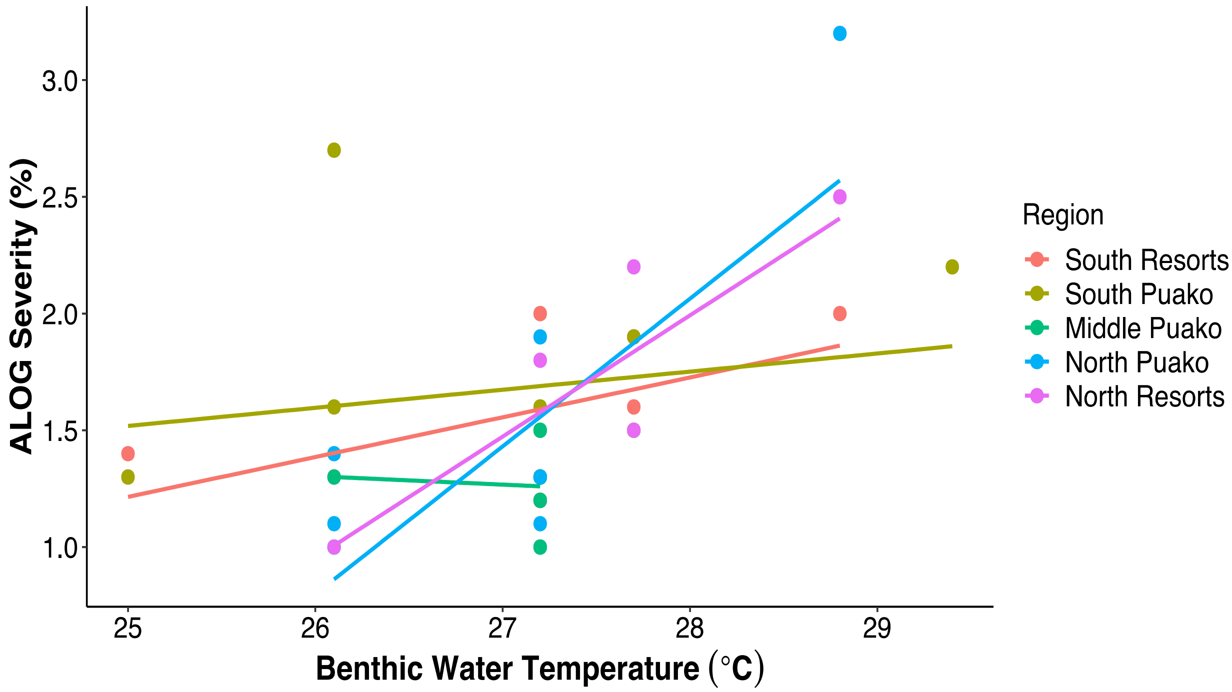


Figure 14. Association between algal overgrowth (ALOG) severity and benthic water temperature at five regions along the South Kohala coastline, Hawai‘i, in June 2019 and 2019.

APPENDIX

Appendix I: Species Observed

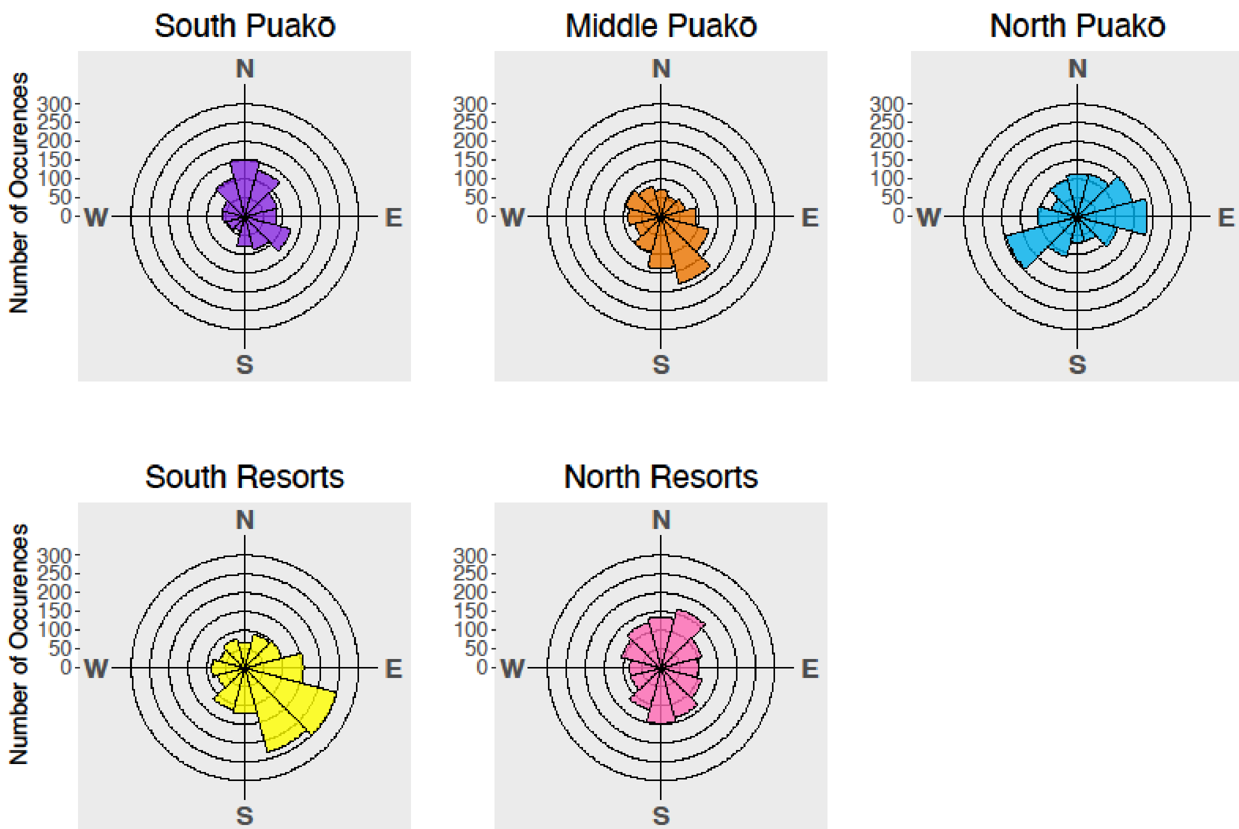
Appx. I.1 - Macroalgae collected from five regions within the South Kohala, Hawai‘i, in June 2018 and 2019. Algae were identified to the lowest taxonomic level and are listed in alphabetical order.

Algae Taxon
Amansia glomerata
Gracilaria dawsonii
Hormothamnion enteromorphoides
Leptolyngbya crosbyana
Palisada parvipapillata
Phylum *Cyanobacteria*
Pterocladiella capillacea
Symploca hydnoides

Appx. I.2 – Coral taxon documented during benthic surveys in five regions within the South Kohala, Hawai‘i, in June 2018 and 2019. Species are listed in alphabetical order.

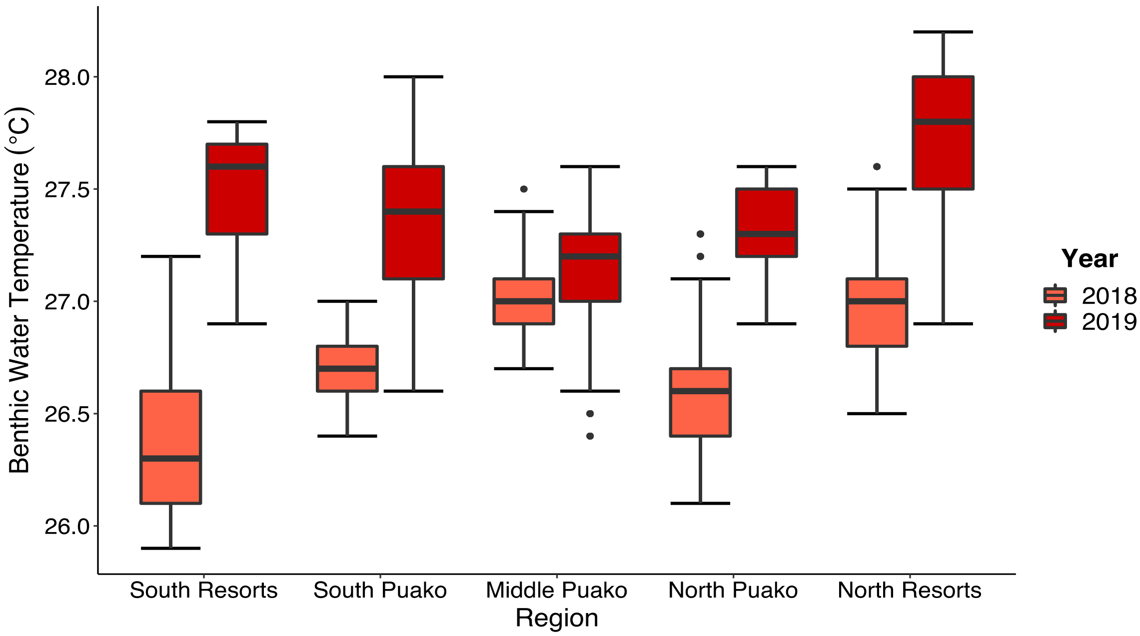
Coral Taxon
Cyphastrea ocellina
Fungia scutaria
Leptastrea bewickensis
Leptastrea purpurea
Leptastrea transversa
Montipora capitata
Montipora flabellata
Montipora patula
Palythoa caesia
Pavona varians
Pocillopora damicornis
Pocillopora meandrina
Porites brighami
Porites compressa
Porites evermanni
Porites lobata
Porites species
Psammocora nierstraszi
Psammocora stellata

Appendix II: Frequency and Direction of Near-Benthic Currents



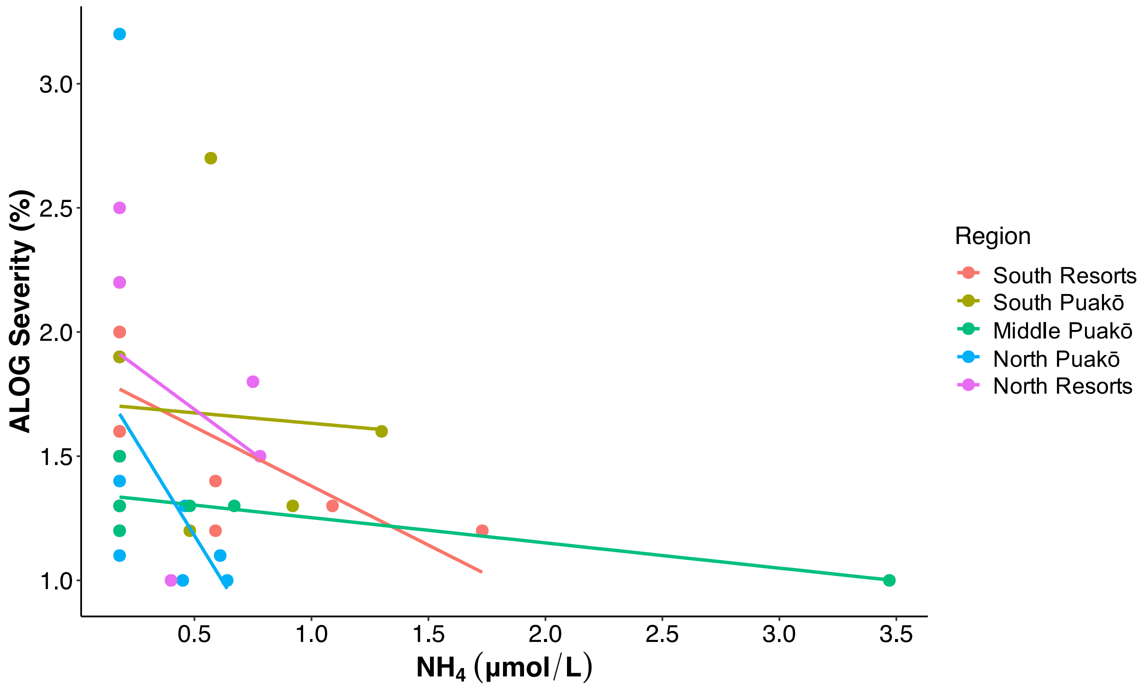
Appx. II.1 – Frequency and Direction of near-benthic currents measured at five regions along the South Kohala, Hawaiʻi, in June 2018 and 2019. Current directions were measured ~1 m above the benthos over a period of 42-74 h using an acoustic doppler profiler

Appendix II. 2 Benthic water temperatures in 2018 and 2019



Appx. II. 2 - Benthic water temperatures measured at five regions along the South Kohala coastline, Hawai‘i, in June 2018 and 2019. Temperatures were measured over a period of 42-74 h using an acoustic doppler profiler.

Appendix III: Mixed Effects Model Relationship Between ALOG Severity and NH_4^+



Appx. III. 1 - Association between algal overgrowth (ALOG) severity and benthic NH_4^+ concentrations at five regions along the South Kohala coastline, Hawaiʻi, in June 2019 and 2019.

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