Linking Watershed Activities to Reef Health in American Samoa: Land-Based Sources of Pollution Impacts on Aua Coral Reefs

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January 2024

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Background

Project Goals

The overarching goals of this project were to establish a water quality and biological baseline for reefs in Aua, American Samoa, and provide managers with recommendations on how to reduce land-based sources of pollution (LBSP) in order to protect their coral reefs. Land-based sources of pollution include pollutants like sewage, enriched nutrients, and sediment that enter into coastal waters.

Project Objectives

- Confirm the presence of a water quality gradient
- Assess the coral reef responses to land-based sources of pollution
- Determine if coastal acidification impacts the reefs of Aua
- Identify bioindicators for land-based sources of pollution
- Identify efforts that managers and community leaders can implement to maintain a healthy reef

Aua Historical Context

Aua is home to the world's longest running reef survey site. It was first surveyed by Alfred Mayer from the Carnegie Institution for Science in 1917, and has been surveyed for over 100 years.

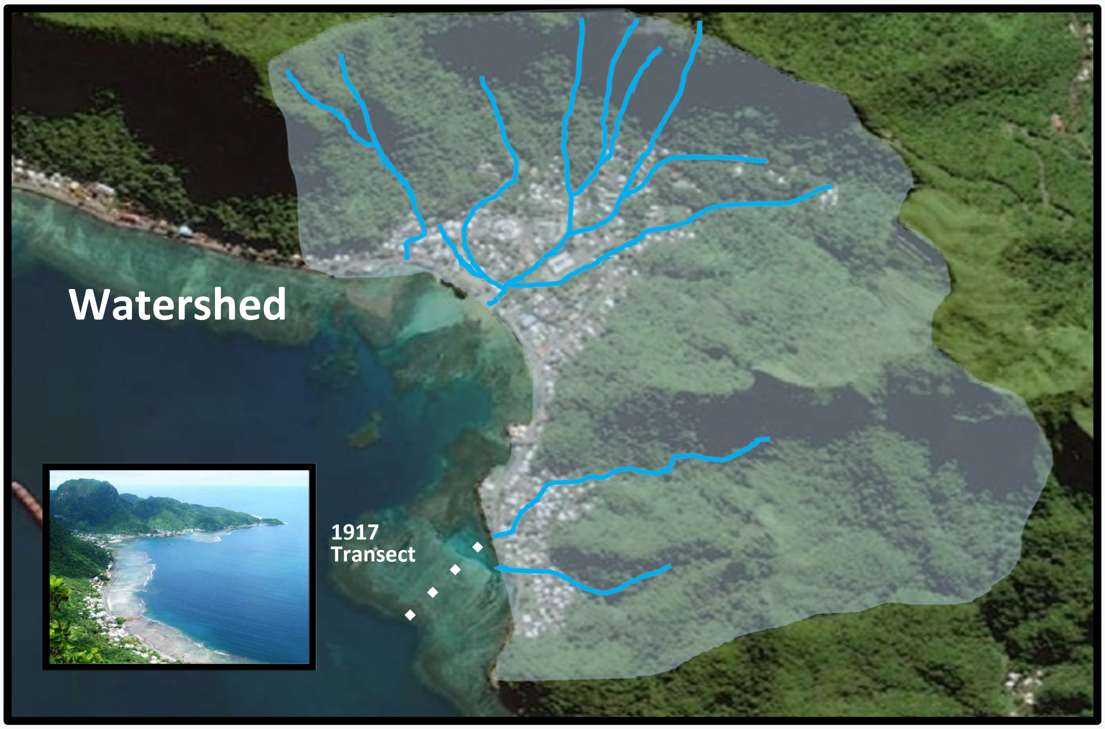
As part of the Watershed Protection Plan, both the American Samoa Environmental Protection Agency and the Coastal Zone Management Program identified Aua as a priority watershed. Protecting the watershed means first identifying resource management issues where water quality of the streams, wetlands, and oceans might be impacted. Here, we evaluate the impacts of LBSP in coastal waters on coral reef communities.

Aua Watershed

There are several streams that drain off of the mountain, flow through the village of Aua, and eventually drain into the ocean. The bulk of the water enters through streams in the north and smaller streams that enter from the east.

Multiple land-based sources of pollution impact Aua reefs. The Horsley Witten Group of Sustainable Environmental Solutions identified land-based sources of pollution of the Aua

Watershed (Horsley Witten Group 2023). Many of these can directly impact coral reefs. The primary issues that can potentially impact corals are **sedimentation** and **nutrient enrichment**.



Map of Aua Watershed. (Credit: NOAA scientist)

Example activities that contribute to increased sedimentation:

- Excavation behind water tanks
- Erosion and accumulated sediment in streams and stream mouths
- Coastal construction of sewage line installation

Example activities that contribute to increased nutrients:

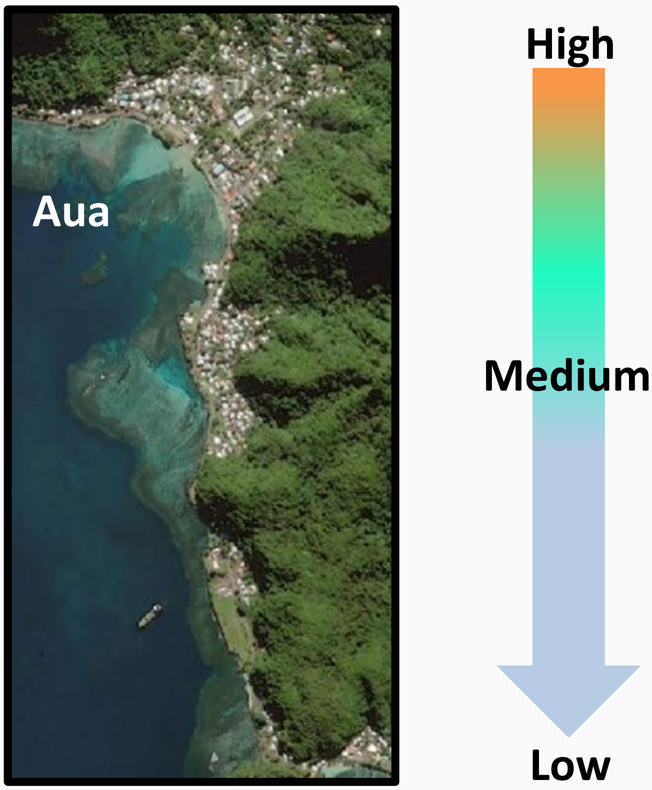
- Historical long-term impacts of raw sewage outflow into reef
- Near-stream piggeries
- Trash in streams

High levels of suspended sediments in the water column can negatively impact coral reefs (Cooper et al 2009). Sediments can smother corals and limit the ability for coral larvae to settle (Jones et al 2019, Birrell et al 2005). Reduced light also limits coral growth (Jones 2020).

Enriched nutrients can reduce coral growth, tissue thickness, density of symbionts, and increase their susceptibility to disease (Fabricius 2005, Haapkla et al 2011). They can also promote coastal productivity that can lead to coastal acidification, which would further stress corals by reducing their ability to accrete calcium carbonate (Strong et al 2014).

Chronic sedimentation and enriched nutrients can lead to long-term shifts in benthic community structure and taxonomic richness of corals (De'ath and Fabricius 2010).

One objective was to establish the presence or absence of a water quality gradient. The prediction was that total suspended sediments and nutrients would be higher near the mouth of the stream in Aua and gradually decline away from the stream mouth.



Prediction:

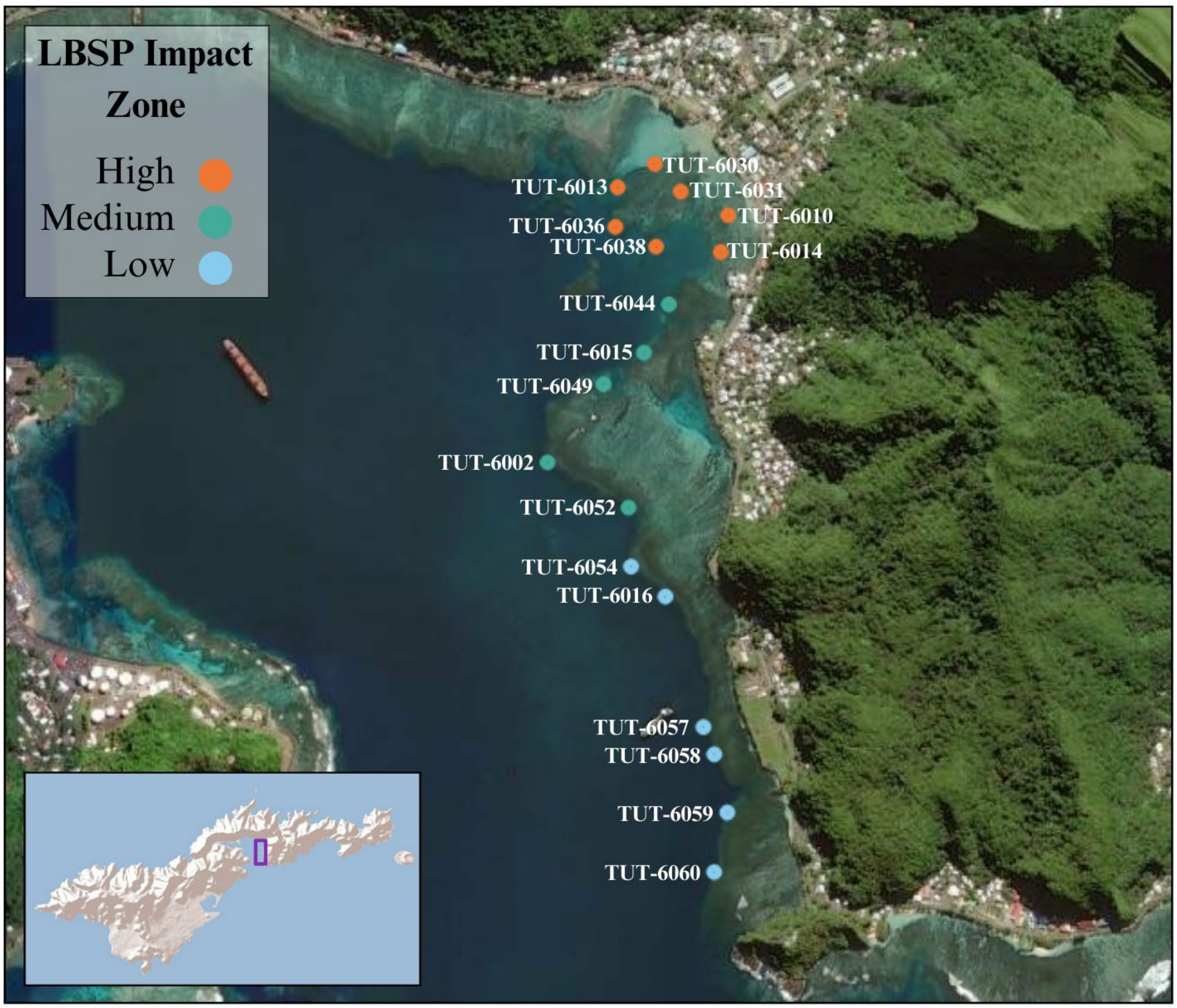
High LSBP
High Sedimentation
Enriched Nutrients
Increased Productivity
Low pH

Low LSBP
Low Sedimentation
Limited Nutrients
Decreased Productivity
High pH

Methods

In order to determine the impacts of water quality on coral reefs in Aua, NOAA scientists came to American Samoa to conduct field work from September 8-29, 2022. Eighteen sites were established along Aua reefs. Sites were categorized into the high LBSP impact zone, medium LBSP impact zone, and low LBSP impact zone based on distance from the mouth of the stream.

Water samples were collected 5 times at all 18 sites and measured for multiple water quality parameters over the course of the 3-week period. Additionally, biological surveys were conducted at all 18 sites.



Map of survey sites. Sites were categorized by LBSP impact zone (high, medium, low). (Credit: NOAA scientists)

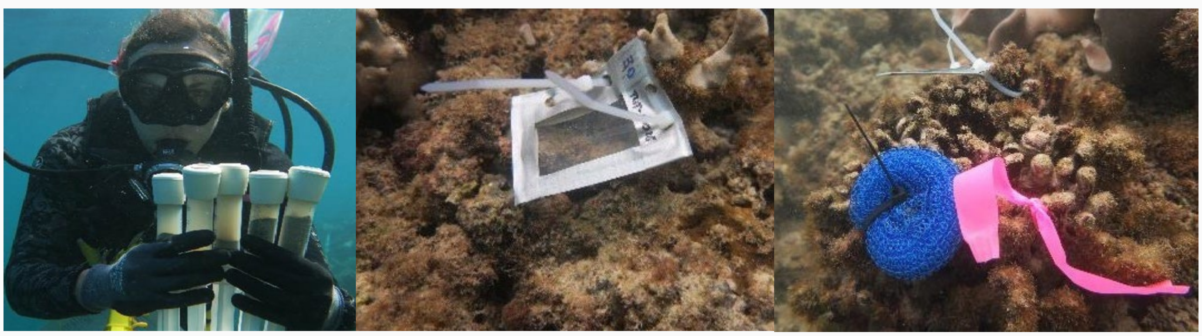
An oceanographic instrument (CTD) was used to measure the temperature, salinity, and depth at each site. A Niskin bottle was used to collect water samples. Seawater pH was measured immediately after collection. The rest of the water sample was filtered for total suspended sediments (TSS) and nutrients. These samples were shipped to a laboratory for analysis.

Conductivity-Temperature-Depth sensor was used to measure ocean temperature and salinity (top left). Scientists measure seawater pH (top right). Scientists filter water to measure total suspended sediments, and dissolved nutrients (bottom left). Scientist collects water sample (bottom right). (Photo credit: NOAA scientists).

Water samples were analyzed for water quality parameters (TSS, chlorophyll-a, dissolved nutrients) and oceanographic parameters. Total suspended sediments provide an estimate for sedimentation. Chlorophyll-a provides an estimate for ocean productivity. Dissolved nutrients, including phosphate, nitrate and nitrite, are directly absorbed by corals and used for calcification, growth, and fuel for zooxanthellae. Ammonia provides an estimate of sewage in the reef system.

Benthic surveys for reef communities were conducted at all 18 sites along the water quality gradient using NOAA's traditional National Coral Reef Monitoring Program (NCRMP) methods. Photo-quadrat surveys were conducted to identify the percent cover of the major benthic groups (e.g., coral, fleshy macroalgae, encrusting macroalgae, turf algae, sediment, crustose coralline algae). Belt transect surveys were used to determine coral diversity, as well as to count juvenile and adult coral densities.

Additional biological surveys were conducted on non-coral groups known to be strong bioindicators for poor water quality. Samples were collected at each site for benthic foraminifera, benthic microalgae, and benthic macroinvertebrates. All samples were analyzed under a microscope.



Methods in the field used to collect bioindicators for poor water quality. Scientist collects sediment samples to examine benthic foraminifera (left). Glass settlement tiles are deployed to examine benthic microalgae (middle). Scouring pads are deployed to collect macroinvertebrates (right). (Photo credit: NOAA scientists).

Benthic foraminifera picked out of sediment samples (left). Glass settlement tiles after 3 weeks of deployment are covered in benthic microalgae (middle). Scouring pads after deployment are filled with macroinvertebrates (right). (Photo credit: NOAA scientists)

Statistical Analysis

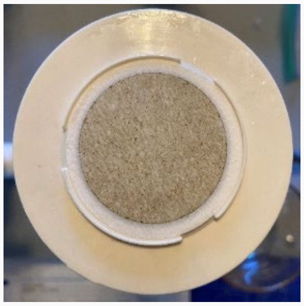
Statistical analyses were performed to analyze the water quality data and benthic community data. Specifically, generalized linear models (GLMs) were used to determine the significant difference in environmental conditions between LBSP impact zones. The results presented include the effect size (F-value) and statistical significance (p-value).

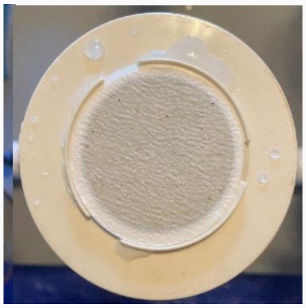
Furthermore, redundancy analysis (RDA) were used to assess the relationship between community composition (benthic groups, adult and juvenile coral densities, macroinvertebrates) and water quality and environmental variables (total suspended sediments, chlorophyll-a, phosphate, nitrate and nitrite, ammonia, temperature, salinity, seawater pH). RDAs are a multivariate, ordination technique that determines which variables significantly alter the composition of a community. Specifically, four separate RDA analysis were conducted and are presented in this report: (1) environmental variables impact on benthic composition (percent cover), (2) environmental variables impact on adult coral densities, (3) environmental variables impact on juvenile coral densities, and (4) environmental variables impact on macroinvertebrate abundances. RDA results will be presented in two ways in this report, through tables and RDA plots. The tables will present the statistical results of each environmental variable on community composition. The RDA plots show differences in community composition between LBSP impact zones. They can be interpreted by noticing that the high LBSP community (orange circle on RDA plot) does not overlap with the low LBSP community (blue circle on RDA plot). When circles on the RDA plot do not overlap, that means the communities living in each LBSP impact zone are different. The total variance (in percent) that the selected environmental variables significantly explains is indicated in parenthesis for each axis.

Results

Total Suspended Sediments

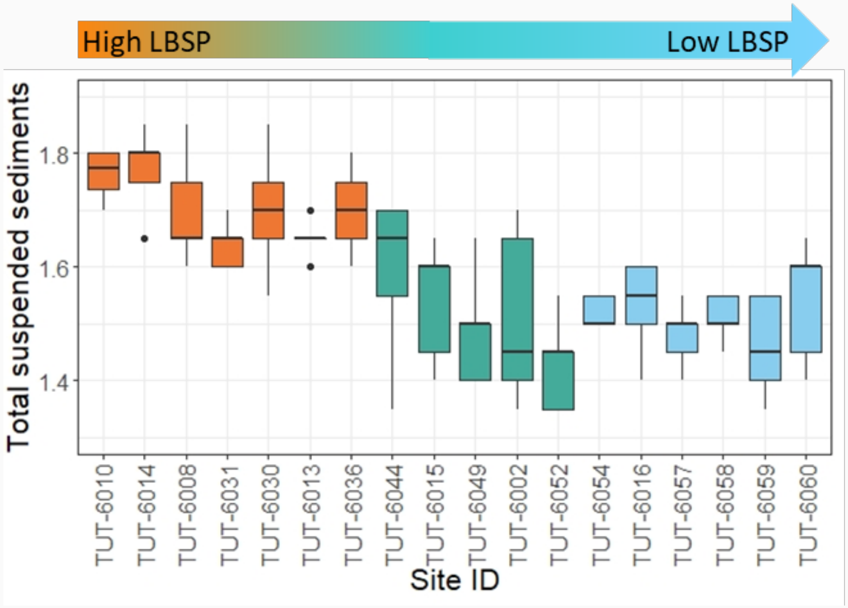
Water flows out of the stream mouth and currents carry that water eastward. Total suspended sediments (TSS) accumulate on the east side of Aua Bay. Filtered water samples show more TSS near the point source for LBSP.





Filter paper with samples of total suspended sediments. Filter on the left is from the high LBSP impact zone, filter on the right is from the low LBSP impact zone.

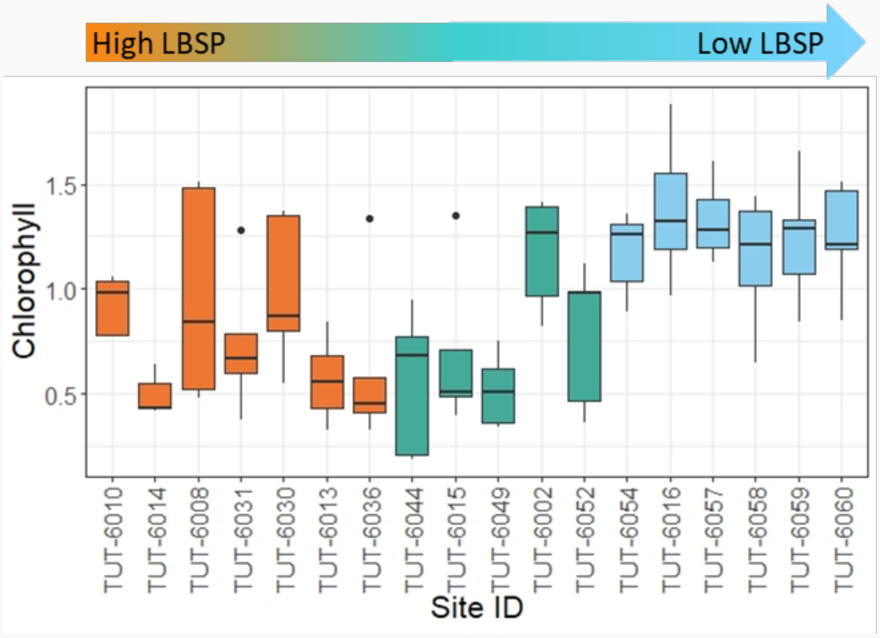
Sediment pollution was present along the water quality gradient. Total suspended sediments (TSS) exhibited a gradient from the mouth of the stream to the reefs away from it. Mean TSS was significantly different between LBSP impact zones ($F_{(2,87)}$=46.1; $p<0.001$). The range in TSS values was from 1.35 to 1.95 mg L^{-1}. The mean ± SE TSS in the high LBSP impact zone was 1.71 ± 0.02 mg L^{-1} , at the low LBSP impact zone it was 1.49 ± 0.02 mg L^{-1}. Overall, TSS was the dominant identified land-based source of pollution.



Plot of total suspended sediments (mg L^{-1}) at each site (Photo credit: NOAA Scientist).

Chlorophyll-a

Ocean productivity (measured through chlorophyll-a) had a reverse gradient from TSS and is lower in the high LBSP impact zone and higher in the low LBSP impact zone. Chlorophyll-a was significantly different between impact zones ($F_{(2,87)}=11.1$; $p<0.001$) and ranged in values from 0.19 to 1.88 µg L^{-1}. Mean ± SE chlorophyll-a in the high LBSP impact zone was 0.76 ± 0.06 µg L^{-1}, at the low LBSP impact zone it was 1.24 ± 0.06 µg L^{-1}. Variability in chlorophyll-a was high between sample times for select sites in the high LBSP impact zone, this may be due to tidal differences between sampling periods.

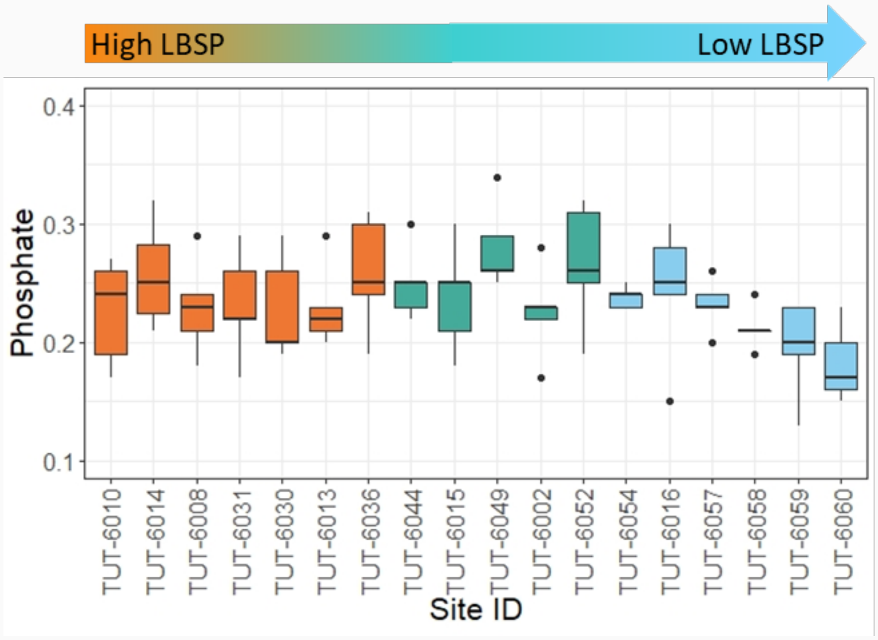


Plot of chlorophyll-a (µg L^{-1}) at each site (Photo credit: NOAA Scientist).

Dissolved Nutrients

Phosphate

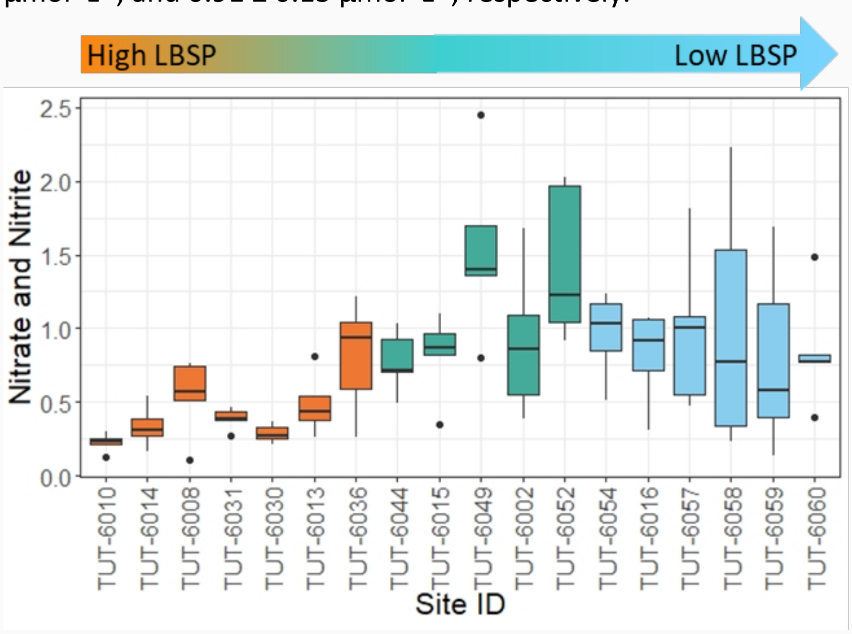
Dissolved nutrients exhibited a weak gradient and the trend differed depending on the type of analyte. Phosphate was slightly but significantly elevated at the high and medium LBSP impact zone ($F_{(2,87)}=3.5$, $p<0.05$). Phosphate ranged from 0.13 to 0.56 µmol L^{-1}. Mean ± SE phosphate values in the high, medium, and low LBSP impact zones were 0.25 ± 0.01 µmol L^{-1}, 0.25 ± 0.01 µmol L^{-1}, and 0.21 ± 0.01 µmol L^{-1}, respectively.



Plot of phosphate (µmol L^{-1}) at each site (Photo credit: NOAA Scientist).

Nitrate and Nitrite

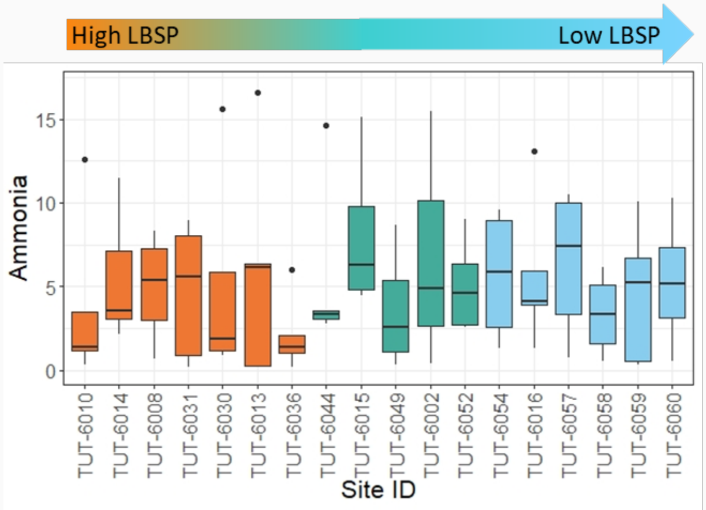
Nitrate and nitrite were significantly elevated in the medium LBSP impact zone ($F_{(2,87)}$=21.7; $p<0.001$). This nutrient enrichment was primarily localized to only a few sites (TUT-6049 and TUT-6052). Nitrate and nitrite ranged from 0.11 to 2.45 µmol L^{-1}. Mean ± SE nitrate and nitrite values in the high, medium, and low LBSP impact zones were 0.44 ± 0.04 µmol L^{-1}, 1.04 ± 0.08 µmol L^{-1}, and 0.91 ± 0.13 µmol L^{-1}, respectively.



Plot of nitrate and nitrite (µmol L^{-1}) at each site (Photo credit: NOAA Scientist).

Ammonia

Ammonia is not significantly different between LBSP impact zones ($F_{(2,87)}$=0.1; p=0.91). Mean ± SE ammonia values in the high, medium, and low LBSP impact zones were 7.13 ± 2.1 µmol L^{-1}, 7.74 ± 1.6 µmol L^{-1}, and 9.35 ± 4.5 µmol L^{-1}.

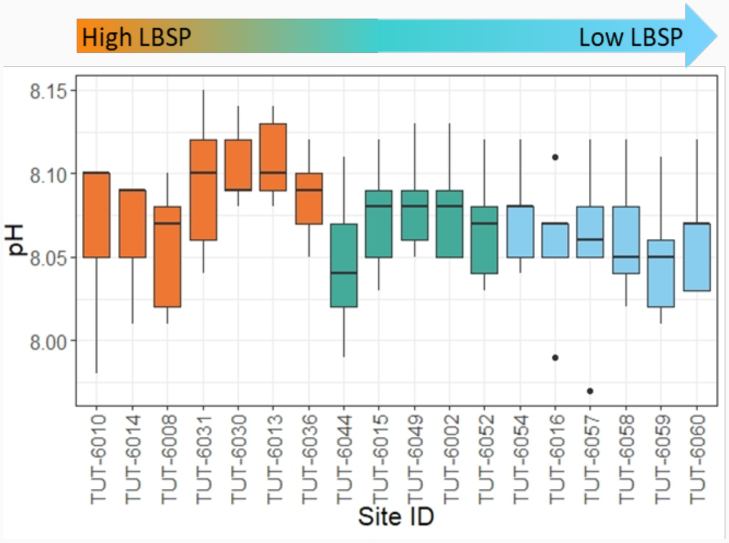


Plot of ammonia (µmol L^{-1}) at each site (Photo credit: NOAA Scientist).

Oceanographic Parameters

pH

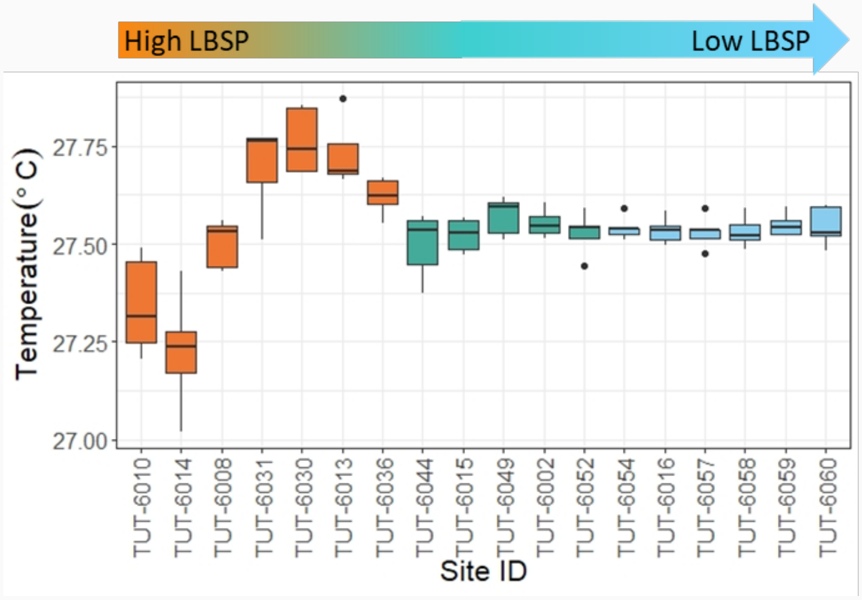
Coastal acidification was not observed nearest the stream mouth. Contrary to expectations, pH was higher in the high LBSP impact zone (mean ± SE: 8.08 ± 0.006) compared to the low LBSP impact zone (mean ± SE: 8.06 ± 0.009), and this difference in seawater pH between high and low LBSP impact zones was significant ($F_{(2,87)}$=4.5, p<0.05).



Plot of seawater pH (total scale) at each site (Photo credit: NOAA Scientist).

Temperature

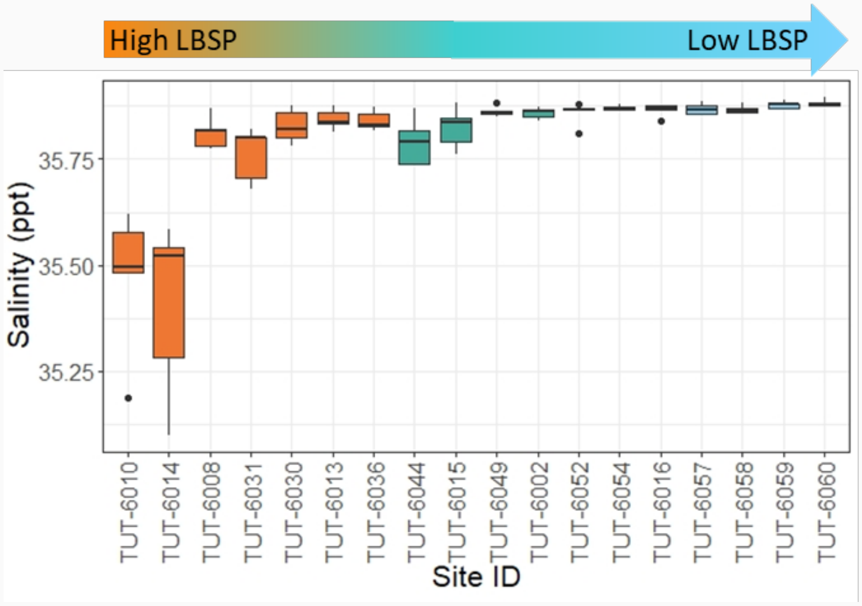
Temperature was coldest at the sites nearest the stream mouth with temperature of 27.02℃. The embayment in the high LBSP impact zone included the warmest water in shallow water and reached max values of 27.87 ℃.The mean temperature across all sites was 27.54 ± 1.4 ℃.



Plot of temperature (℃) at each site (Photo credit: NOAA Scientist).

Salinity

Salinity minimally decreased at the 2 sites closest to the stream mouth due to freshwater input (lowest salinity value was 35.1 ppt), but quickly stabilized to a mean value of 35.8 ppt.

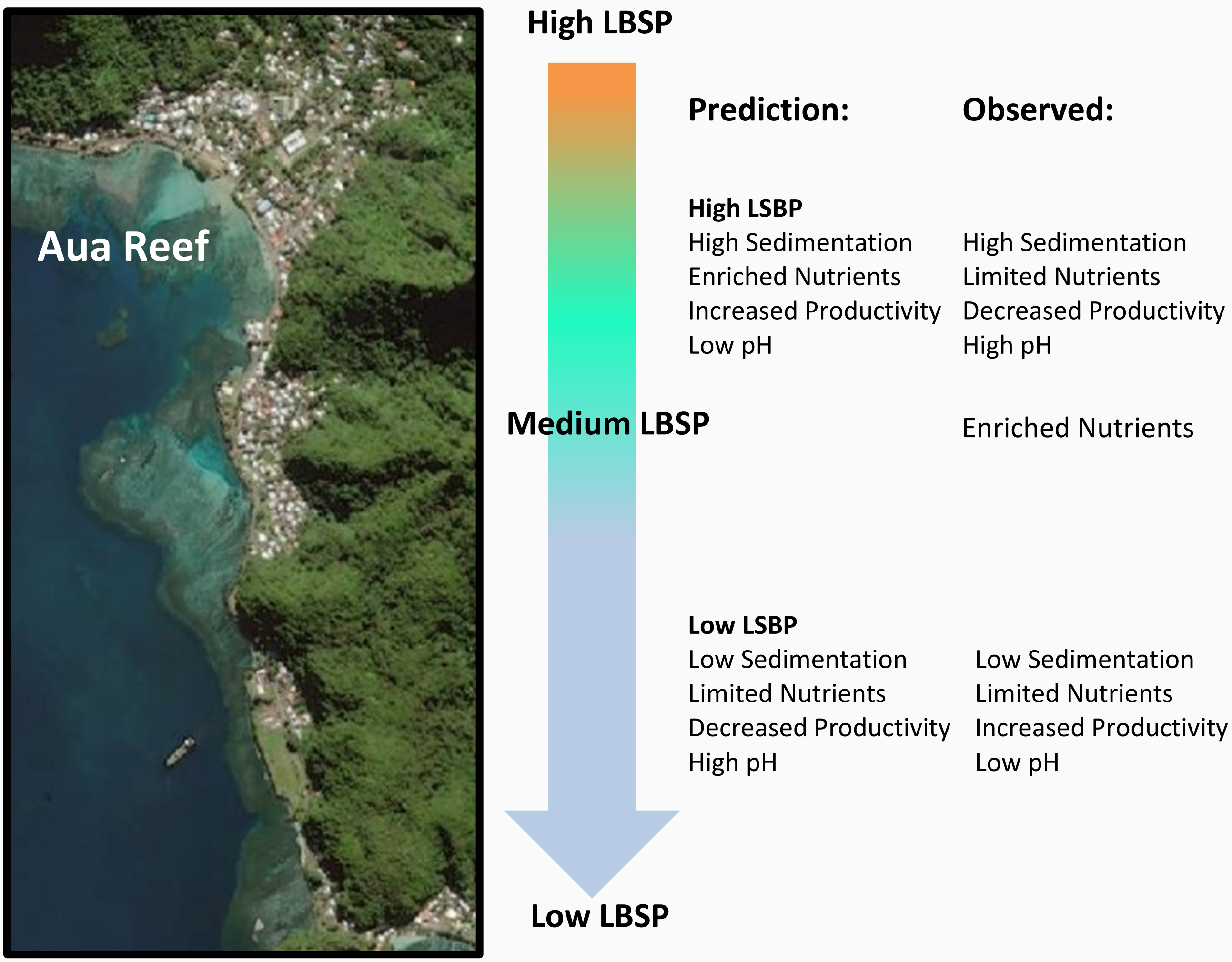


Plot of salinity (ppt) at each site (Photo credit: NOAA Scientist).

Research Objective Summary

Confirm the presence of a water quality gradient

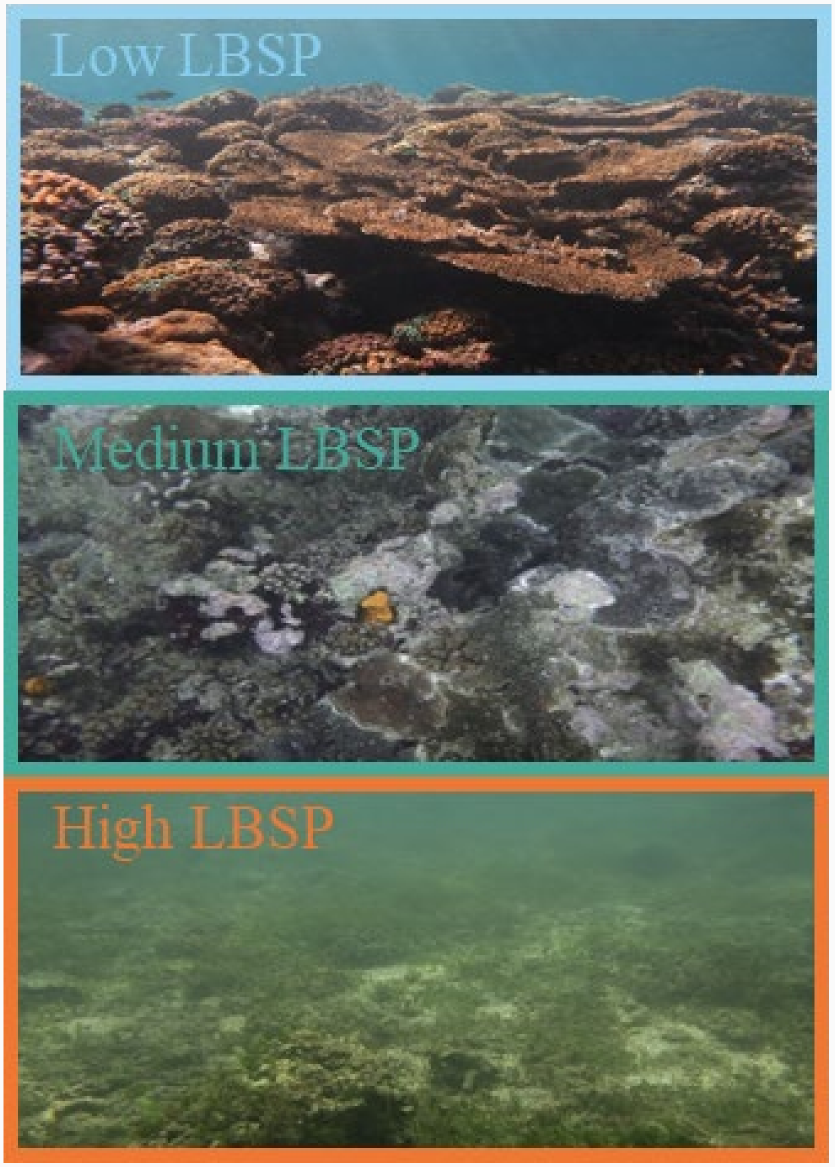
There is a water quality gradient, with total suspended sediments being the most dominant land-based source of pollution. Nutrients are slightly enriched in the medium impact zone, but this enrichment is localized and the nutrients readily absorbed. Productivity (i.e., chlorophyll-a) is higher in the low LBSP reefs. Seawater pH is slightly elevated in the high LBSP impact zone.



Comparison of predictions versus observations measured for each land-based source of pollution.

Benthic Responses

Photos from the photo-quadrat survey indicate that the high LBSP sites have more turf and sediment compared to the low LBSP sites where there is more coral and crustose coralline algae. Specifically, coral cover declined from a mean ± standard error (SE) of 30% ± 0.04 in the low LBSP impact zone to 18% ± 0.06 in the high LBSP impact zone. Crustose coralline algae (CCA) declined from a mean ± SE of 25% ± 0.02 to 7% ± 0.02. Meanwhile, mean ± SE turf cover in the low LBSP impact zone was 17% ± 0.02, and increased in the high LBSP impact zone to a mean of 50% ± 0.05. Likewise, sediment cover also increased from the low to high LBSP impact zones, from a mean ± SE of 0.01% ± 0.001 to 8% ± 0.03.



Visual representation of benthic composition from each LBSP Impact Zone. (Photo credit: NOAA scientists)

The dominant benthic groups were coral, crustose coralline algae (CCA), encrusting macroalgae (EMA), sediment (SED), turf algae, and fleshy macroalgae (FMA). The photos below provide an example of what the dominant benthic groups look like. Although they occurred less frequently (<1% cover), additional benthic groups were recorded during the benthic surveys and included soft coral (SC) and invertebrates (I).

Left: Coral, Middle: Crustose Coralline Algae, Right: Encrusting Macroalgae.

Left: Sediment, Middle: Turf algae, Right: Fleshy Macroalgae.

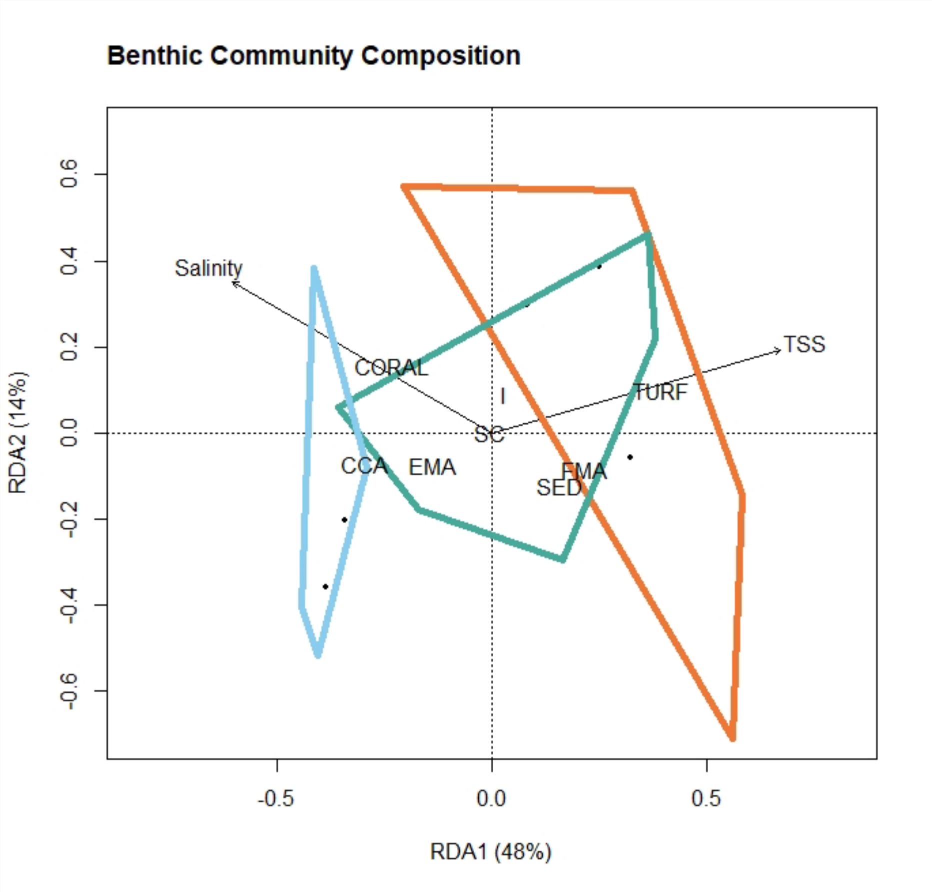
Elevated total suspended sediments (TSS) associated with altered benthic composition

Results from a redundancy analysis reveals that total suspended sediments and salinity are the two environmental variables that significantly alter benthic community composition.

Table 1. RDA results examining impact of water quality parameters on benthic community composition. (*) indicates that the particular variable significantly alters the benthic composition.

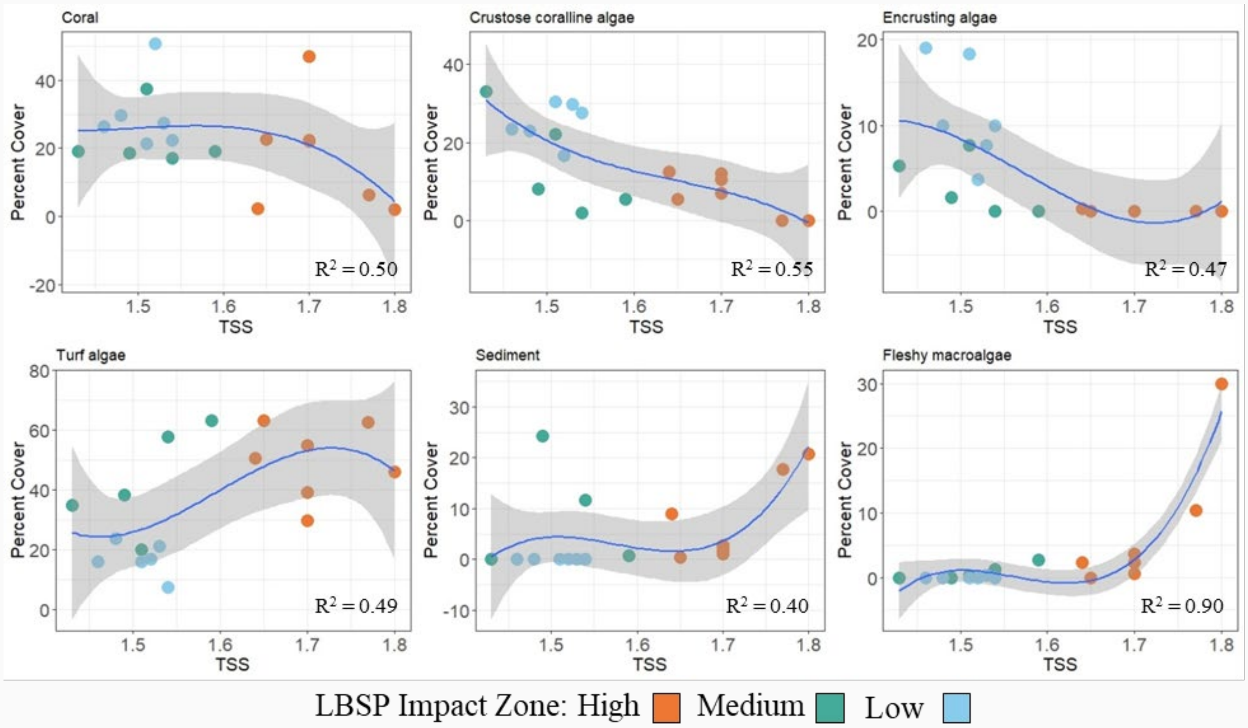
Parameter	**(df,df)**	**F-value**	**p-values**
Total suspended sediments (mg L^{-1})	(1,9)	7.8	0.001*
Chlorophyll-a (µmol L^{-1})	(1,9)	2.1	0.07
Phosphate (µmol L^{-1})	(1,9)	2.5	0.06
Nitrate and Nitrite (µmol L^{-1})	(1,9)	1.8	0.14
Ammonia (µmol L^{-1})	(1,9)	1.7	0.14
Temperature (°C)	(1,9)	1.2	0.3
Salinity (ppt)	(1,9)	3.6	0.01*
Seawater pH (total scale)	(1,9)	0.4	0.89

Furthermore, the RDA plot reveals that the benthic community at the high LBSP Impact Zone (orange) is associated with more turf and sediment and is primarily driven by changes in total suspended sediment. Note that the high LBSP sites (i.e. orange circle) do not overlap with the low LBSP sites (i.e. blue circle). No overlap in the circles signifies that the benthic communities between the two LBSP impact zones are different.



Plot from redundancy analysis reveals that the benthic communities are different between the high and low LBSP impact zones (high LBSP = orange, medium LBSP = green, low LBSP = blue).

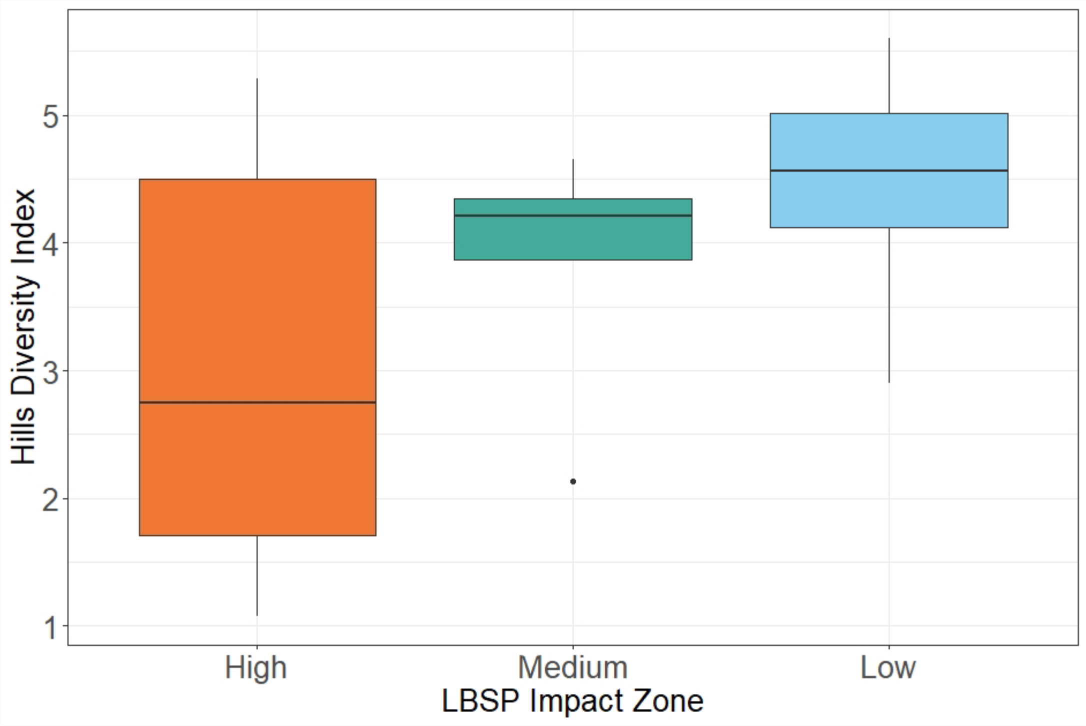
Higher total suspended sediments in the water column are associated with less coral, crustose coralline algae, encrusting macroalgae and more turf algae, sediment, and fleshy macroalgae.



Scatterplots of total suspended sediments (mg L^{-1}) in association with percent cover of major benthic groups. Plots are fitted with regression curves (solid blue line) and 95% confidence intervals (shaded gray area). R-squared values from generalized linear model outputs are included in each plot. Coral, crustose coralline algae (CCA), and encrusting algae cover (EMA) decreases with increasing total suspended sediments (TSS), while turf, sediments (SED), and fleshy macroalgae (FMA) increase. LBSP impact zones are identified by color: high LBSP (orange), medium LBSP (green), low LBSP (blue).

Decreased coral diversity with high TSS

Total suspended sediments not only impacted benthic composition (i.e. percent cover of major benthic groups), but it also influenced coral biodiversity. Hills diversity index (i.e. a measure of coral genera diversity and evenness) declined with increasing total suspended sediments. TSS was the only water quality and environmental variable that significantly impacted Hills diversity index ($F_{(1,16)}$=4.5, $p<0.05$). Ocean productivity (chlorophyll-a) and dissolved nutrients (phosphate, nitrite and nitrate, ammonia) did not impact Hills diversity index.



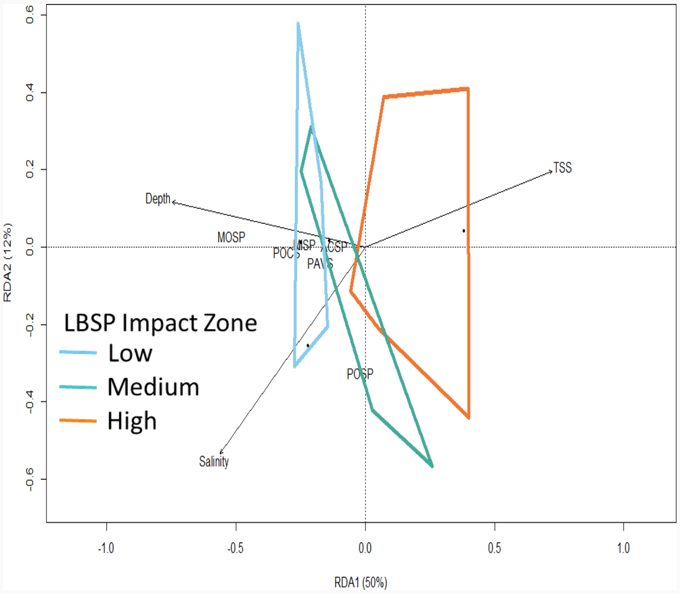
Increasing total suspended sediments is associated with lower coral biodiversity (i.e. Hills diversity index).

The dominant coral genera present were Acropora (ACSP), Millepora (MISP), Montipora (MOSP), Pavona (PAVS), Pocillopora (POCS), and Porites (POSP).

Photograph of dominant coral genera: Acropora (ACSP), Millepora (MISP), Montipora (MOSP), Pavona (PAVS), Pocillopora (POCS), and Porites (POSP) (Photo Credit: NOAA Scientists)

Decreased adult coral densities with high TSS

A redundancy analysis shows that there is a different community of adult corals between the reefs from the high and low LBSP impact zones. All of the dominant coral genera are more abundant in the low LBSP reefs compared to the reefs impacted by high LBSP.



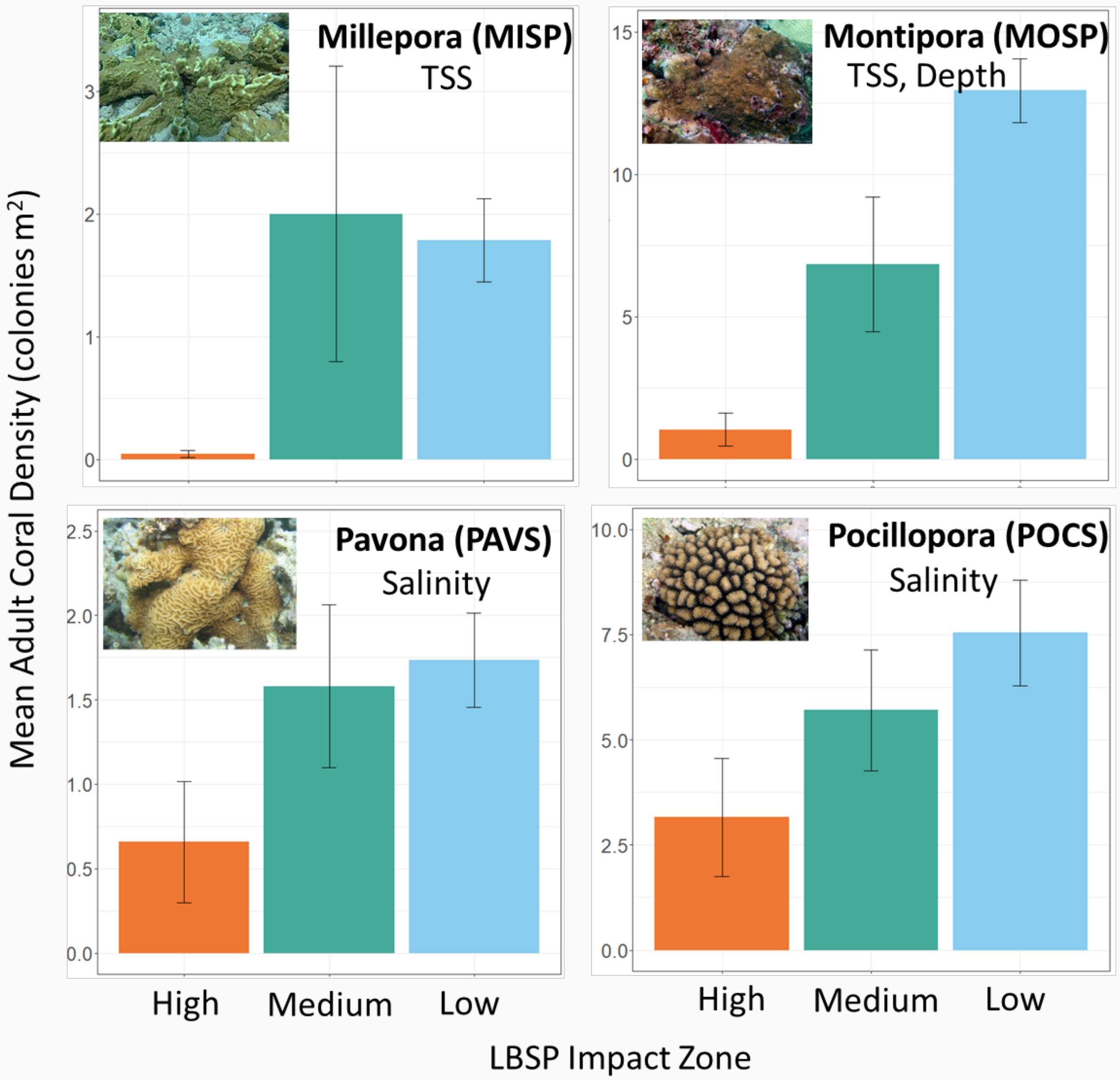
Plot from redundancy analysis indicates that the community of adult corals is different between the high and low LBSP impact zone.

Total suspended sediments (TSS), salinity, and depth significantly affected adult coral density.

Table 2. RDA results examining impact of water quality parameters on adult coral communities. (*) indicates that the particular variable significantly alters the benthic composition.

Parameter	**(df,df)**	**F-value**	**p-values**
Total suspended sediments (mg L^{-1})	(1,8)	9.2	<0.001*
Chlorophyll-a (µmol L^{-1})	(1,8)	7.9	0.16
Phosphate (µmol L^{-1})	(1,8)	0.1	0.96
Nitrate and Nitrite (µmol L^{-1})	(1,8)	0.8	0.53
Ammonia (µmol L^{-1})	(1,8)	0.2	0.93
Temperature (°C)	(1,8)	0.6	0.62
Salinity (ppt)	(1,8)	2.3	0.1
Seawater pH (total scale)	(1,8)	0.1	0.94
Depth (m)	(1,8)	3.2	0.04

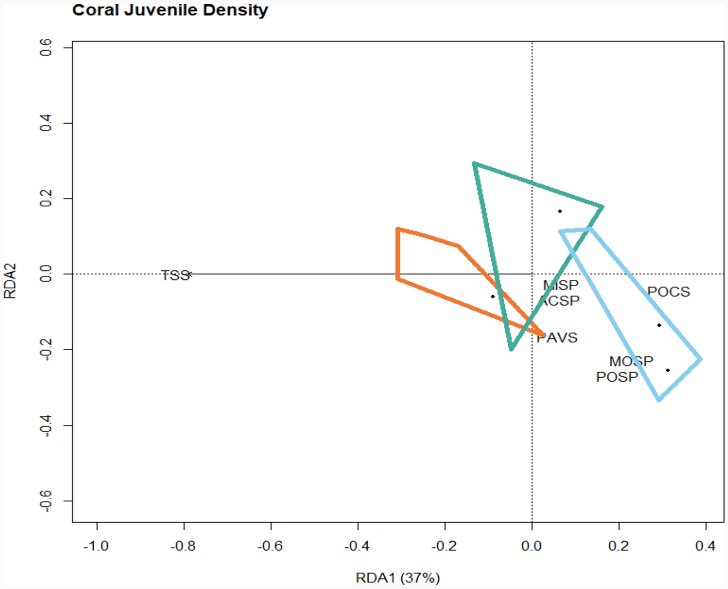
For the top six dominant coral genera, *Acropora* ($F_{(2,15)}$=0.6; p=0.57) and *Porites* ($F_{(2,15)}$=0.4; p=0.67) were not significantly different between LBSP impact zones. Adult densities were significantly reduced in the high LBSP impact zone for *Millepora* ($F_{(2,15)}$=7.7; p<0.005) and *Montipora* ($F_{(2,15)}$=18.2; p<0.001). *Millepora* adult densities were significantly impacted by TSS ($F_{(1,13)}$=23.3; p<0.001). *Montipora* was significantly impacted by TSS ($F_{(1,13)}$=6.9; p<0.05) and depth ($F_{(1,13)}$=6.4; p<0.05). Additionally, salinity significantly reduced adult densities of *Pavona* ($F_{(1,13)}$=7.1; p<0.05) and *Pocillopora* ($F_{(1,13)}$=5.4; p<0.05).



Higher adult densities of the coral genera Millepora, Montipora, Pavona, and Pocillopora were present in the healthy, low LBSP reefs.

Total suspended sediments reduce coral recruitment

All genera of juvenile corals decline under high TSS. The juvenile coral composition was different between the high LBSP and low impact zones.



*Plots of redundancy analysis reveal that juvenile coral communities are different between the high and low LBSP impact zones. There is no overlap in the coral juvenile communities between the high LBSP and low LBSP impact zones (high LBSP (orange), medium LBSP (green), low LBSP (blue))***.**

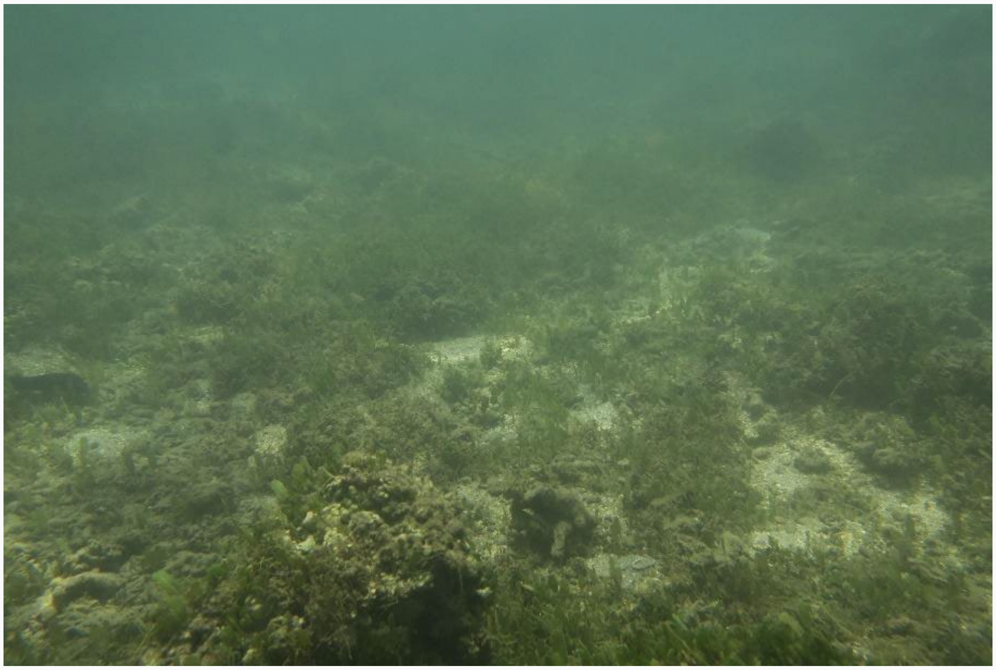
Total suspended sediments were also the only environmental driver that impacted juvenile coral density.

Table 3. RDA results examining impact of water quality parameters on juvenile coral communities. (*) indicates that the particular variable significantly alters the benthic composition.

Parameter	**(df,df)**	**F-value**	**p-values**
Total suspended sediments (mg L^{-1})	(1,9)	11.1	0.002*
Chlorophyll-a (µmol L^{-1})	(1,9)	3.5	0.05
Phosphate (µmol L^{-1})	(1,9)	2.6	0.09
Nitrate and Nitrite (µmol L^{-1})	(1,9)	0.5	0.68
Ammonia (µmol L^{-1})	(1,9)	1.5	0.22
Temperature (°C)	(1,9)	0.82	0.45
Salinity (ppt)	(1,9)	0.9	0.47
Seawater pH (total scale)	(1,9)	1.2	0.3

Total suspended sediments were the main driver influencing the benthic community. A shift occurred due to poor water quality in which corals were replaced by turf and sediment. The reefs with low LBSP had high percent cover of coral, higher abundances of the adult and juvenile corals, and high overall coral diversity. Nutrients had minimal influence on the benthic community in Aua. Reefs in Aua can be managed by controlling sediment pollution.

Aua reef in low LBSP impact zone. Credit: NOAA Fisheries

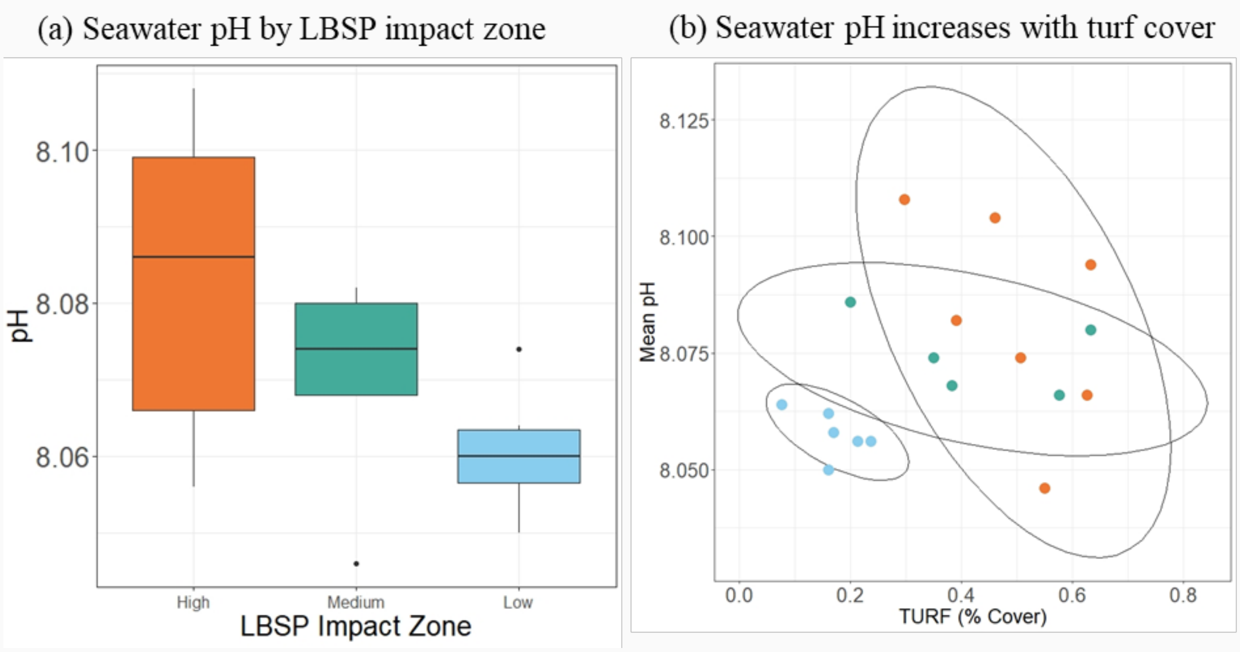


Aua reef in high LBSP impact zone. Credit: NOAA Fisheries

Determine if coastal acidification impacts the reef

In addition to determining if the benthic community responded to LBSP, an additional goal was to determine if coastal acidification was present and observe how that might also impact the benthic community. The prediction was that the high LBSP impact zone would lead to coastal acidification with lower pH. Furthermore, pH was predicted to be a driver for benthic community composition.

Coastal acidification did not impact Aua reefs. The opposite trend was observed than predicted. Seawater pH was significantly higher in the high LBSP impact zone ($F_{(2,87)}$=5.3, $p<0.05$). When benthic composition was tested as a predictor variable for seawater pH, percent cover of turf algae ($F_{(2,10)}$=279,$p<0.05$) and temperature ($F_{(2,10)}$=222,$p<0.05$) significantly impacted seawater pH. Sites with higher cover of turf algae had lower seawater pH. In other words, turf algae, which absorbs CO_2, may help buffer against coastal acidification.



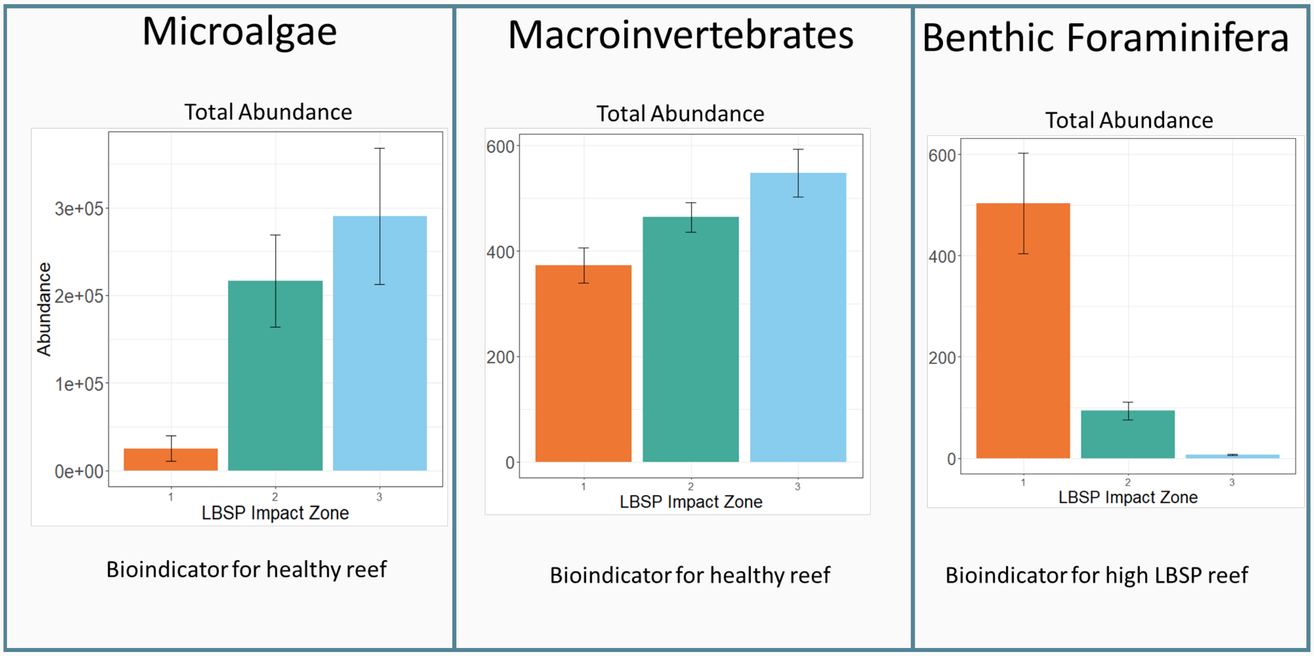
Coastal acidification is not present in Aua reefs. Seawater pH is elevated under the high LBSP impact zone and decreased in the low LBSP impact zone. Seawater pH increases with percent cover of turf. Credit: NOAA Fisheries

Identify bioindicators for LBSP

Non-coral response variables were also explored to determine their usefulness as bioindicators for LBSP. The three non-coral bioindicators explored (microalgae, macroinvertebrates, benthic foraminifera) are all known bioindicators for poor water quality in other reefs (Cooper et al 2009, Uthicke et al 2010, Fabricius et al 2012).

Microalgae are at the bottom of the food chain. Macroinvertebrates include plankton that live residential to reefs, plus larval stages of economically important groups like crabs and shrimp. Benthic foraminifera are tiny protists that live in sand.

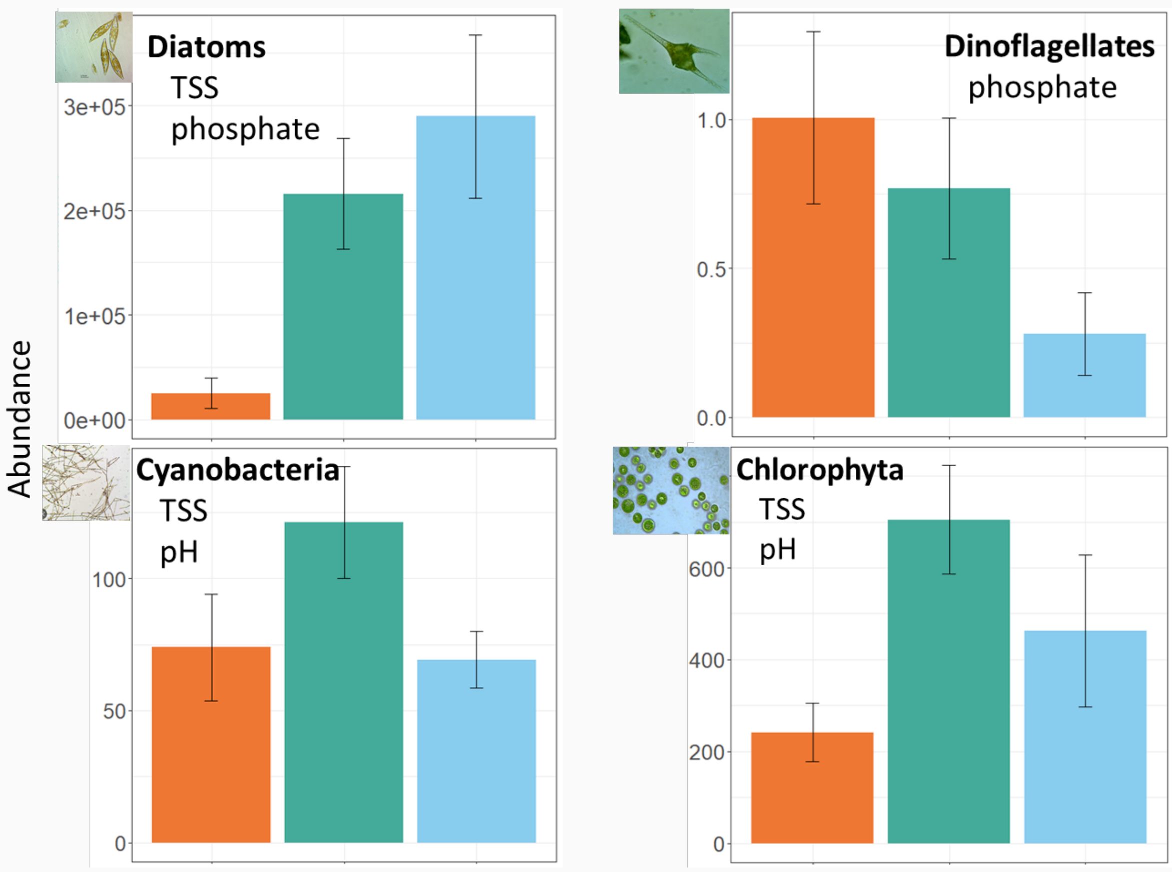
The total abundance of all microalgae and macroinvertebrates were more abundant in the healthy reefs and could be used as a bioindicator for low LBSP. Benthic foraminifera were more abundant in the high LBSP impact zone.



Plankton bioindicators respond to LBSP. Microalgae and macroinvertebrates prefer the coral reefs with low LBSP, while benthic foraminifera prefer the high LBSP impact zone.

Microalgae

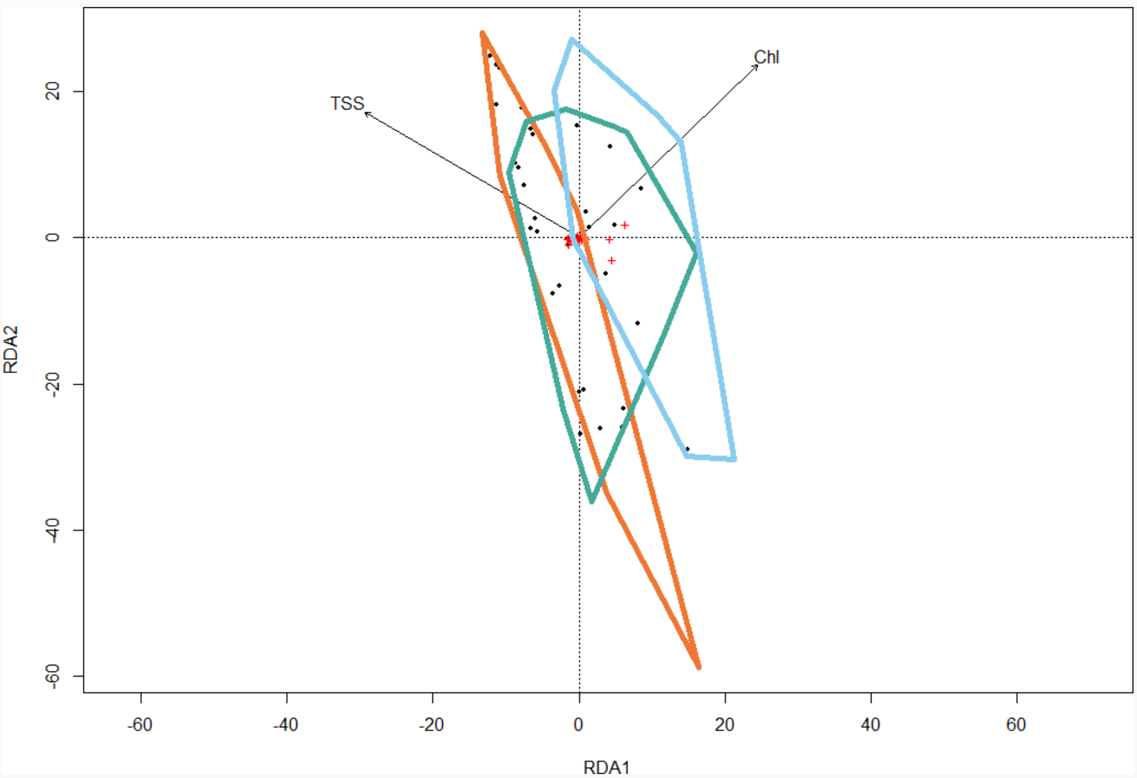
Diatoms were the most abundant type of microalgae present. Diatoms are a good bioindicator for reefs with a low LBSP impact (Desrosier et al 2013). Generalized linear models (GLMs) were used to assess if water quality parameters significantly impacted abundances of diatoms, dinoflagellates, cyanobacteria, and chlorophyta. Diatom abundance was significantly influenced by chlorophyll-a ($F_{(1,48)}=6.3$, $p<0.05$), TSS ($F_{(1,48)}=5.4$, $p<0.05$), and phosphate ($F_{(1,48)}=6.5$, $p<0.05$). Dinoflagellates have a low overall abundance but are a good bioindicator for poor water quality (Takarina et al 2021). Dinoflagellate abundance was significantly influenced by chlorophyll-a ($F_{(1,48)}=5.2$, $p<0.05$) and phosphate ($F_{(1,48)}=8.6$, $p<0.001$). Cyanobacteria was most abundant in the medium LBSP impact zone and its abundance was significantly influenced by chlorophyll-a ($F_{(1,48)}=9.0$, $p<0.01$), TSS ($F_{(1,48)}=10.4$, $p<0.01$), and pH ($F_{(1,48)}=4.5$, $p<0.05$). Chlorophyta was also most abundant in the medium LBSP impact zone and its abundance was significantly influenced by TSS ($F_{(1,48)}=13.6$, $p<0.001$) and pH ($F_{(1,48)}=4.4$, $p<0.05$). Nutrients did not significantly impact the abundance of cyanobacteria (phosphate: ($F_{(1,48)}=0.2$, $p=0.66$), nitrate and nitrite: ($F_{(1,48)}=0.7$, $p=0.40$), ammonia: ($F_{(1,48)}=0.9$, $p=0.35$)) or chlorophyta ($F_{(1,48)}=1.0$, $p=0.31$), nitrate and nitrite: ($F_{(1,48)}=3.4$, $p=0.07$), ammonia: ($F_{(1,48)}=0.24$, $p=0.63$)).



Microalgae group (diatoms, dinoflagellates, cyanobacteria, chlorophyta) responses to LBSP.

Macroinvertebrates

The macroinvertebrate community was significantly impacted by productivity of the reef, as measured through chlorophyll-a ($F_{(1,45)}$=3.5, $p<0.05$), and total suspended sediments ($F_{(1,45)}$=3.3, $p<0.05$). Dissolved nutrients and environmental parameters (temperature: $F_{(1,45)}$=1.8, p=0.15, salinity: $F_{(1,45)}$=1.6, p=0.17, pH: $F_{(1,45)}$=0.6, p=0.54) did not significantly impact macroinvertebrate communities. In total there were over 30 taxonomic groups that composed the macroinvertebrate community. The community composition between high and low LBSP impact zones were different. Some groups preferred the high LBSP reefs (e.g., ostrocods, polychaetes, nematodes), while others preferred the low LBSP impact reefs (e.g., crustacean larvae, isopods, tanaids). For all taxonomic groups combined, there were more macroinvertebrates present at the reefs with low LBSP impact compared to the high LBSP impact reefs.



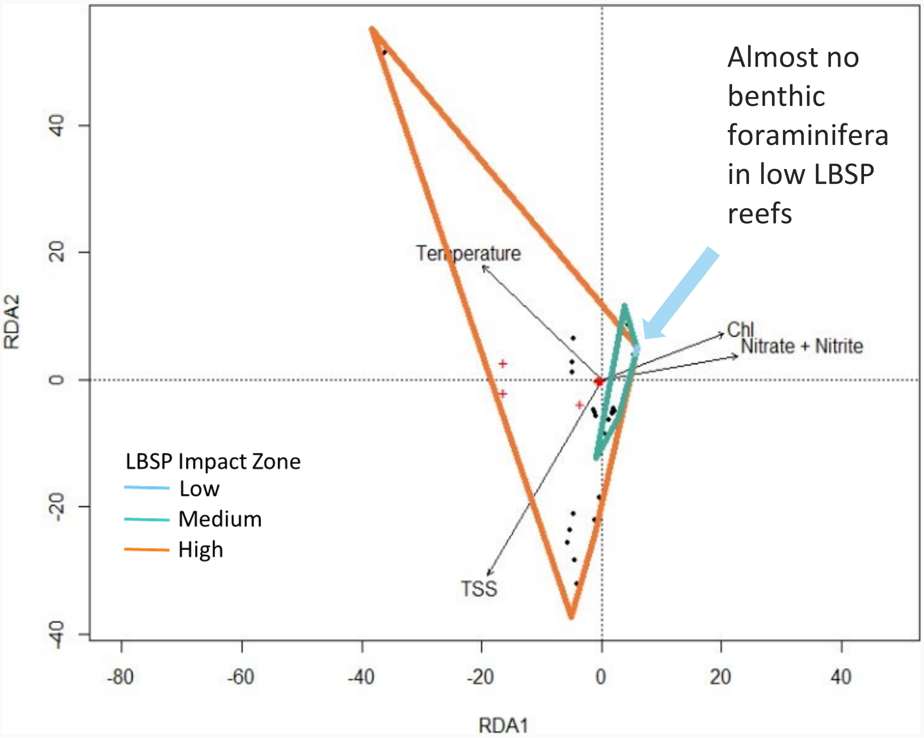
Plot from redundancy analysis reveals that the macroinvertebrate community is different between the high and low LBSP impact zones (high LBSP (orange), medium LBSP (green), low LBSP (blue)).

Benthic Foraminifera

There were 8 genera of benthic foraminifera present in the sediment samples collected at the reefs. The most dominant benthic foraminifera genera were *Baculogypsina, Calcarina*, and *Hippogrepinella*. All benthic foraminifera genera responded strongly to the water quality gradient and could be used as a bioindicator for land-based sources of pollution.

The benthic foraminifera community was influenced by total suspended sediments ($F_{(1,45)}$=5.7, $p<0.05$), chlorophyll-a ($F_{(1,45)}$=3.6, $p<0.05$), temperature ($F_{(1,45)}$=6.6, $p<0.05$), and nitrate and nitrite ($F_{(1,45)}$=4.0, $p<0.05$). Although benthic foraminifera live within sediment, interestingly their abundances were not significantly driven by percent cover of sediment.

The picture on the left provides examples of benthic foraminifera. The picture on the right shows the difference in benthic foraminifera abundance between water quality extremes (high LBSP impact zone on left, low LBSP impact zone on right).



Plot of redundancy analysis reveals that the benthic foraminifera community is different between the high and low LBSP impact zones.

All benthic plankton groups (macroinvertebrates, microalgae, benthic foraminifera) responded to changes in water quality and could be used as a bioindicator.

Using bioindicators for LBSP could be a useful tool for monitoring poor water impacts in other reef ecosystems. In order to streamline efforts, specific taxa with the strongest impacts to LBSP could be sorted from the samples. For example, bioindicators for healthy coral reefs with a low LBSP impact include diatoms, isopods, crab larvae, and amphipods. Bioindicators for reefs impacted by high LBSP include dinoflagellates, ostracods, polychaetes, shrimp larvae, and the dominant benthic foraminifera genera, *Baculogypsina*, and *Calcarina*.

Project Summary

- Sediment pollution is the dominant land-based source of pollution impacting the entire reef ecosystem from the bottom of the food chain (microalgae) to the entire benthic community.
- Sediment pollution causes a shift from a reef with high cover, diversity, and abundance of adult and juvenile corals, to a reef replaced by turf and sediment.
- Reefs where turf now exists have coral rubble underneath the turf, suggesting it used to be a thriving reef before sedimentation caused the regime shift.
- Aua reefs are not experiencing coastal acidification—due to the shift from coral to turf, turf algae may absorb CO_2 and act as a buffer against coastal acidification.
- Nutrients do not play a major role in driving changes in benthic communities in Aua. Overall nutrients are elevated compared to coral reefs away from a coastline, but there is no strong gradient in nutrients along the Aua reefs. Phosphate is slightly elevated in the high and medium LBSP impact zone. Nitrate and nitrite are slightly elevated in the medium LBSP impact zone. And ammonia remains consistent across all three LBSP impact zones.
- Similar to the coral communities, the main drivers for change in non-coral communities are total suspended sediments and chlorophyll-a – but nutrients also become important for microalgae and benthic foraminifera. High nitrate and nitrite levels in the medium LBSP impact zone directly impacts benthic foraminifera. Microalgae (specifically diatoms and dinoflagellates) readily absorb the nitrate and nitrite but become phosphate limited.
- Microalgae, macroinvertebrates, and benthic foraminifera were all bioindicators for LBSP.

Implications

- Coastal zone managers seeking to increase coral cover, diversity, abundance, and juvenile recruitment could target efforts to reduce sediment pollution into the reefs of Aua (Kroon et al 2014, Bartley et al 2014).
- Nutrients are not a strong driver of change in the benthic coral reef community (e.g. coral, crustose coralline algae), but nutrients (phosphate, nitrite and nitrate) do influence the non-coral communities (benthic foraminifera, microalgae, and macroinvertebrates).
- Benthic foraminifera, microalgae, and macroinvertebrates are all bioindicators for LBSP and could be a useful tool to determine if a reef is being impacted by poor water quality. These methods are cost effective and could target key taxonomic groups to provide a rapid method for detection of a system impacted by LBSP.
- Coastal acidification is not a stressor to corals in Aua due to a shift in the benthos related to sedimentation. However, this could change with decreased sedimentation.
- Future coral restoration in the high LBSP zone would likely not be successful unless sediment pollution is reduced.

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