Catchment to sea connection: impacts of terrestrial run-off on benthic ecosystems in American Samoa

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Abstract:

Variation in water quality can directly affect the composition of benthic assemblages on coral reefs. Yet, few studies have directly quantified nutrient and suspended particulate matter (SPM) to examine their potential impacts on benthic community structure, especially around high oceanic islands. We assessed the spatio-temporal variation of nutrients and SPM across six sites in American Samoa over a 12-month period and used exploratory path analysis to relate dissolved inorganic nutrients, land use, and natural and anthropogenic drivers to benthic assemblages on adjacent shallow reefs. Multivariate analyses showed clear gradients in nutrient concentrations, sediment accumulation and composition, and benthic structure across watersheds. Instream nutrients and land uses positively influenced reef flat nutrient concentrations, while benthic assemblages were best predicted by wave exposure, runoff, stream phosphate and dissolved inorganic nitrogen loads. Identifying locality-specific drivers of water quality and benthic condition can support targeted management in American Samoa and in other high islands.

Keywords:

Water quality, suspended particulate matter, nutrients, sedimentation, land use, coral reefs, high islands, ridge-to-reef

1 | INTRODUCTION

Growing human populations in tropical coastal areas and the associated coastal development and changes in land use have caused declines in water quality (increased nutrients and suspended sediments) in nearshore environments, with these declines in water quality being linked to changes in benthic communities on nearshore coral reefs (Brodie et al., 2012; Brown et al., 2019; Fabricius et al., 2012; Oliver et al., 2011). Increased dissolved nutrients, such as inorganic and organic forms of nitrogen and phosphorus from agriculture, can result in increases in turf and macroalgae abundance and/or benthic hetetrotrophic filter feeding taxa (Fabricius, 2005; Littler et al., 2006; Szmant, 2002). Additionally, increased inputs of suspended particulate matter (SPM) can reduce light penetration and hence photosynthetic efficiency of corals and algae, while increases in fine terrigenous sediments (< 20 μm) can smother corals and inhibit coral settlement, leading to changes in the assemblage structure, composition, and cover of coral assemblages (Bainbridge et al., 2018; Weber et al., 2006). Declining water quality, together with increasing seawater temperatures, is one of the most significant stressors affecting the health and functions of coastal reef ecosystems, and provisioning of ecosystem services (Burke et al., 2011; De'ath and Fabricius, 2010; Wooldridge, 2009). There is a clear need to identify the key pollutants that impact water quality at localized coral reef sites so they can be better managed.

Across tropical Pacific island countries, growing coastal populations, agriculture, coastal development, and varying land uses have led to substantial and sustained declines in water quality flowing into coastal marine environments (Falkland, 1999). Indeed, coastal development has been estimated to threaten about 20% of reefs in the region, with another 25% of reefs being impacted by watershed-based pollution (Burke et al., 2011). Given the tight coupling of watershed condition, nearshore water quality, and coral reef health, a growing number of studies have focused on integrated ridge-to-reef approaches to simultaneously address and manage upstream activities and downstream ecological conditions (Adam et al., 2020; Comeros-Raynal et al., 2019; Delevaux et al., 2018; Houk et al., 2020; Rodgers et al., 2012; Rude et al., 2016; Wenger et al., 2020). Despite improved understanding of the effects of declining water quality on reef condition in the Pacific region, our understanding of the relative effects of enriched nutrients and suspended particulate matter in influencing the composition of benthic assemblages on nearshore reefs, particularly in high islands, remains limited. Despite catchments on high islands being generally smaller than those found on continents (Jupiter et al., 2017; Ruddle et al., 1992), high volcanic islands are especially vulnerable to land use and land cover modifications due to their lithology (erosive andesite soils) and steep topography (Verbist et al., 2010). The strong land-sea connection and intrinsic vulnerability of high volcanic islands warrants expansion of research efforts in island communities (Carlson et al., 2019).

Tropical high islands present an opportunity to examine the effects of increasing nutrients and sediment loads on the composition of benthic assemblages on nearshore reefs due to a combination of complex geomorphology, strong seasonal precipitation patterns, coastline configuration comprising replicate bays and fringing reef systems, and the varied distribution of human populations and land use activities. Moreover, many high islands, such as Tutuila, American Samoa, are large enough to provide a series of spatially distinct sampling sites, and are nested within similar oceanographic and meteorological regimes. Concentrated human populations in the coastal plains, and associated soil erosion from disturbance to vegetation highlight the predisposed vulnerabilities of nearshore coral reefs to the negative impacts of human land uses in watersheds (Holst Rice et al., 2016; Houk et al., 2010; Messina and Biggs, 2016; Shuler et al., 2019; Vargas-Angel and Huntington, 2020; Whitall et al., 2019). Tutuila is located in the South Pacific Convergence Zone where there is abundant rainfall (Kennedy, 1987; Shuler and El-Kady, 2017) potentially leading to higher transport rates of nutrients and sediments to nearby coral reefs from watersheds with highly modified landscapes.

Here, we quantified water quality across six watersheds spanning a gradient in anthropogenic impact on Tutuila, and relate this to variation in benthic assemblages on adjacent shallow coral reefs. Specifically, we quantified total and dissolved nutrient concentrations from streams and adjacent reef flats, and the accumulation rate, composition, and particle size of sediments captured in sediment traps at 3-monthly intervals for one year. We examined the spatial groupings of nutrients and sediments, and the composition of the benthos to determine if clustering followed local watershed classifications. Lastly, we used exploratory path analyses to simultaneously examine the relationships between natural (e.g., surface runoff, wave exposure), and anthropogenic drivers (intensive land use, DIN load, stream and reef flat nutrients) and benthic cover. Monitoring terrestrial run-off and relating its influence on benthic condition at sampling units relevant to management can help support integrated scientific and management approaches in American Samoa and potentially can be adapted to other oceanic high islands where ridge-to-reef approaches are implemented.

2 | METHODS

2.1 | Study Location

American Samoa has five main volcanic high islands (Tutuila, Aunu'u, Ofu, Olosega, and Ta'u) and two atolls (Rose and Swains), and is the southernmost U.S. Territory in the South Pacific at 14.27°S, 170.13°W. Our study was conducted on Tutuila, the largest of the main high islands in American Samoa with an area of 138 km^2 and the most populous with a population of 55,000 (US Census Bureau, 2014). Tutuila is an extensively eroded volcanic island comprised of a central ridge of steep mountains which lead sharply to a narrow coastline (Atkinson and Medeiros, 2005; Craig et al., 2010). Tutuila has a tropical climate with uniform temperatures between 26 and 28 °C and high humidity throughout the year. The mean annual rainfall on Tutuila is 3,810 mm/year with peak rainfall during the wet season from October to April and lower rainfall occurring in the dry season from May to September (Izuka et al., 2005; Wong, 1996). Precipitation on the islands generally increases with elevation and ranges from 2,388 mm/year at the shorelines to 6,350 mm/year at ~480 m above sea level elevation (Meyer et al., 2017).

Land Use and Land Cover

Over 65% of Tutuila is natural forest while agriculture and development combined covers 24% of the island and is concentrated on the south-western coast (Meyer et al., 2017). From 2004 to 2010, there has been a 4.8% increase in developed land and a 6.8% rise of impervious surfaces, while agriculture has increased by 17% (NOAA, 2020).

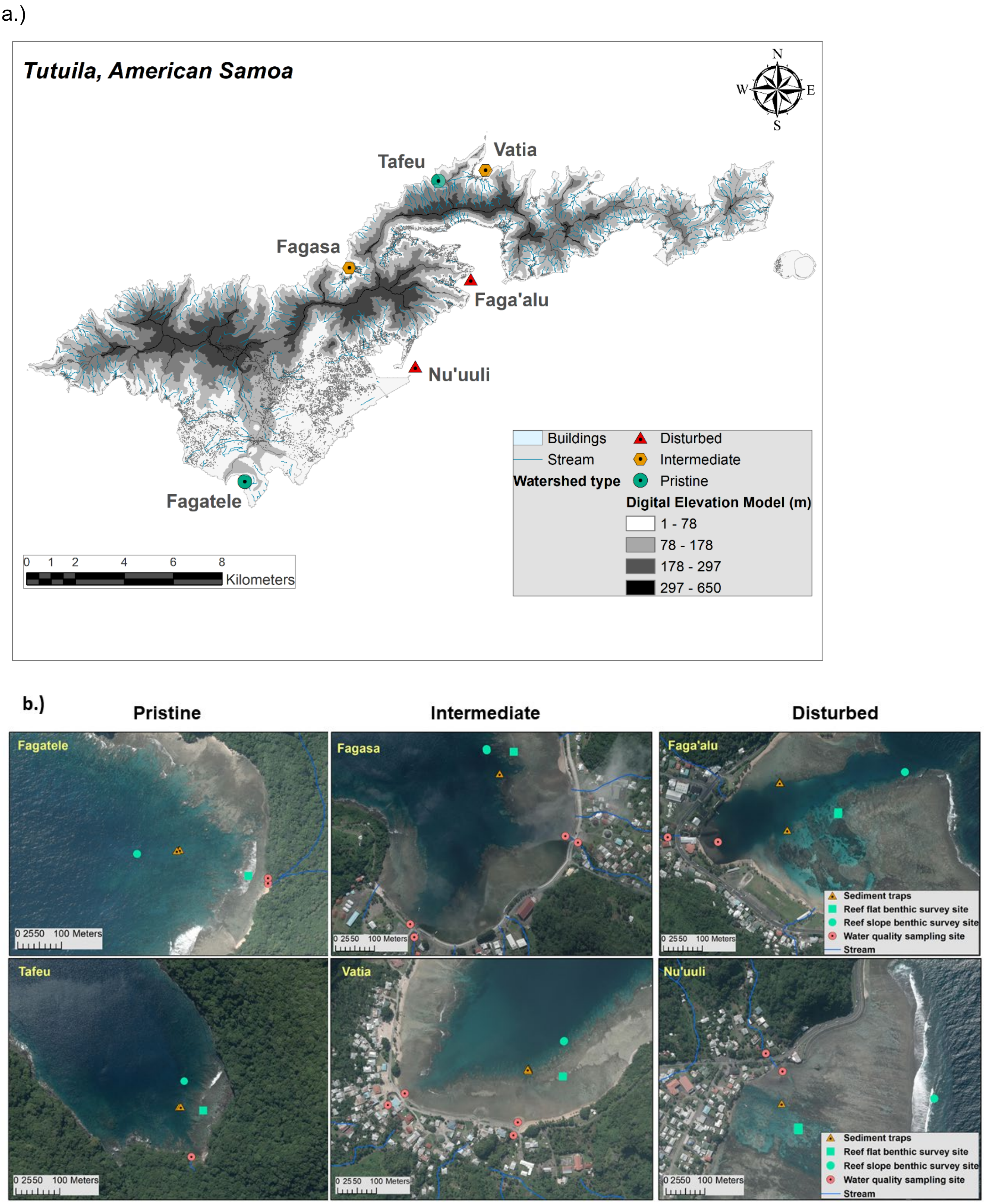


Figure 1. Map of Tutuila, American Samoa showing the location of the six study sites. (a) Map of Tutuila showing the location of two study sites within each of three watershed types as classified by the American Samoa Environmental Protection Agency (AS-EPA). Red triangles: disturbed; orange

hexagon: intermediate; green circle: pristine. (b) Satellite images of the six sites showing the approximate location of data collection sites for water quality, sediments, and benthic surveys.

2.2 | Study design

Water quality and benthic assemblage data were collected from six sites that spanned a gradient of anthropogenic impact in the adjacent watersheds (Fig. 1). Specifically, we selected two sites within each of three watershed classifications (pristine, intermediate, and extensive) characterized by the American Samoa Environmental Protection Agency (DiDonato, 2004; Tuitele et al., 2016). For clarity, the term 'disturbed' is used hereafter when referring to extensive watersheds, and is classified as having a human population density of >290 individuals km^{-2}. Disturbed watersheds (Nu'uuli and Faga'alu) had large watershed areas (i.e., >2.33 km^{-2}) and were characterized by greater proportions of disturbed land (28% and 13% of the total watershed area, respectively). Similarly, intermediate watersheds (Fagasa and Vatia) had large watershed areas and low to moderate proportions of disturbed land (7% and 5%, respectively). Pristine watersheds (Fagatele and Tafeu) had the smallest watershed sizes (i.e., <1.55 km^{-2}) and low human population density of <0.38 individuals km^{-2}. However, the Fagatele watershed includes the major landfill on Tutuila, and had the highest agroforest and cultivated land percent cover (Table 1).

2.4 | Biological surveys

Benthic composition was quantified along four replicate 50 m point-intercept transects within each of two habitats, the reef flat (1 – 4 m depth) and reef slope (5 – 9 m depth), at each of the six sites in May 2019. The substratum directly under the transect tape was recorded at 50cm intervals along each transect (n=101 points per transect). Benthic categories were recorded as crustose coralline algae (CCA), turf algae (primarily filamentous algae <10mm in height), macroalgae (>10 mm in height), and hard coral. Hard coral and macroalgae were identified to genus. Transects were laid along the reef profile with a minimum of 10 m between adjacent transects.

2.3 | Environmental data

To evaluate the relationships of terrestrial run-off on nearshore shallow reef habitats, water quality data were collected at 3-monthly intervals for 12 months across the six watersheds to account for baseflow conditions and storm events over the two rainfall seasons in American Samoa: rom June through September representing the drier winter season, and from October through May, representing the wetter summer season (Izuka et al., 2005). The major streams in each watershed were sampled, with a single stream sampled in Faga'alu, Fagatele, Nu'uuli and Tafeu, and two streams in Vatia (Gaoa and Faatafe) and Fagasa (Leele and Agasii). Water samples were collected every 3 months from August 2018 – May 2019, and included two sampling periods in the wetter summer months: November 2018 and February 2019; and in the drier winter months: August 2018 and May 2019. Water samples were collected from the mouth of each stream at approximately 1 m above sea level during low tide to minimize mixing of coastal water during each sampling period. Upstream land use distance to stream mouth varied, with some point-source/cleared areas within 1 km of the sampling site. Stream mouth distance to the reef flat and reef slope sampling sites varied across sites (50-550 m) due to inherent differences in reef geomorphology and stream locations across sites. Sediment samples were collected using SediSampler® patented traps deployed on the reef slope at depths of 5-7 m.

Water samples were taken from the surface waters of the stream and reef flat by rinsing 500 ml and 60 ml polyethylene bottles three times with sample water prior to filling. Samples were placed on ice after collection and returned to the laboratory. Samples in 60 ml bottles were immediately frozen (unfiltered samples for total nitrogen and total phosphorus analysis), and the samples in 500 ml bottles were filtered using 0.7 µm GF/F Whatman filters, and the filtrate stored frozen until analysis. Filtration was conducted to remove most bacteria and other microorganisms that could affect the stability of filtered nutrient constituents.

The frozen water samples were then sent to the University of Hawaii's SOEST Laboratory for Analytical Biogeochemistry (S-LAB) for analysis of dissolved nutrients: sum of nitrate and nitrite (N+N; and ammonium (NH^{4+}), hereafter referred to as dissolved inorganic nitrogen (DIN)), ammonium (NH^{4+}), phosphate (PO_4^{3-}), silicate (SiO_4^{4-}); and Total Nitrogen (TN), and Total Phosphorus (TP) (Armstrong et al., 1967; Grasshoff et al., 1983; Kérouel and Aminot, 1997; Murphy and Riley, 1962). Subsequent analysis of stable isotope of dissolved nitrate was conducted by the Biogeochemical Stable Isotope Facility at the University of Hawaii using the denitrifier method on a Thermo Finnigan MAT 252 Mass Spectrometer using a continuous flow GC-interface with a Triplus autosampler (McIlvin and Casciotti, 2010; Sigman et al., 2001).

Suspended particulate matter

To quantify suspended particulate matter (SPM) matter (i.e. sediments and associated particulate matter), we deployed three SediSampler® patented traps (Integral Aqua Pty Ltd) on the reef slope at each site in 5-7 m depth (Figure 1b). Each trap was attached to a steel bar driven into the substratum so that the mouth of the trap was positioned approximately 1 m above the substratum (refer to Lewis et al. 2020). The sediment traps were deployed at the time of the water sampling (i.e., November 2018, February 2019, May 2019, and September 2019) and collected after ~3 months. An additional three SediSampler® traps were placed at the mouth of the stream in Faga'alu to account for the previously reported differences in the spatial distribution of sediments at this site (Holst Rice et al., 2016; Messina, 2016; Messina and Biggs, 2016). After three months deployment on the reef, the 1 L sample bottles were carefully removed from the SediSampler® traps and the bottles capped underwater to avoid loss of sediments. The sample bottles were placed on ice within 10 minutes of collection and transferred to a refrigerator until sample processing.

In the laboratory, each 1 L sediment trap sample bottle from each site was transferred to individual containers that had been pre-rinsed with distilled water, and the samples were well mixed for two minutes to ensure even distribution of particles prior to subsampling. 21 aliquots (each 30 ml) were collected from each sample for Total Suspended Solids (TSS) analysis (APHA et al., 2012). The 21 aliquots for TSS analysis were then placed in a refrigerator and the remaining sample (~370 ml) prepared for salt removal. Similar to SPM, TSS includes both terrestrially-derived and marine-derived organic matter and mineral sediment. Thus, we refer to TSS as SPM from here on. The remaining wet sediment samples from each sediment trap were transferred to individual 1 L plastic beakers, and left for 24-48 hours to allow sediment particles to settle. The supernatant was then decanted, taking care to ensure sediment particles were not lost. Distilled water (900 ml) was then added to each sample, agitated for two minutes to ensure mixing, allowed to settle for 24 hours and the supernatant carefully decanted as described above. This process of rinsing in distilled water, settling, and decanting was repeated until salinity was < 200 µs/cm (i.e., 3-4 rinses). The three sediment trap samples from each site were then combined in a pre-rinsed container and agitated for 2 minutes. Seven 30ml aliquots were collected from the combined sample for particle size analysis.

The remaining bulk sample from the combined trap sediment samples were left to settle for 24 hours, decanted, and transferred to a 1 L beaker. Samples were then dried in an oven at 60°C for 24-48 hours with approximately 7 individual bags per deployment for sediment composition analysis. A total of 28 wet samples (30 ml tubes) and 7 dried samples from each deployment were then transported to Australia and analyzed at the TropWATER Laboratory, James Cook University (JCU) for Suspended Particulate Matter and Loss on Ignition (LOI), and the School of Earth and Environmental Science laboratory, JCU for particle size analysis.

The Loss on Ignition method was used to determine proportions of mineral, organic, and carbonate content by consecutively weighing the dried sediment samples after heating at suitable temperatures (Heiri et al., 2001). Sample organic matter content was determined using Standard Method 2540E (APHA et al., 2012). Briefly, a crucible containing a pre-weighed quantity of each sediment trap sample (dried at 105°C to remove moisture) was ignited in a Carbolite (AAF1100) ashing furnace at 550°C for 4 to 5 hours, and reweighed. The weight lost during ignition represents the total volatile solids, an approximation of the organic matter content of each sample (weight % LOI, 550°C) (Bainbridge et al., 2012). To determine marine sediment trap carbonate content, the sample crucibles were returned to the ashing furnace and heated at 950°C for at 2 hours, with the weight lost on ignition representing carbon dioxide released from calcium carbonate (Bainbridge et al., In review).

The TSS method was used to measure the sediment accumulation within each sediment trap (n=21 per deployment). Briefly, we pipetted 1ml of wet sample from each sediment trap with-salt aliquot, into a filtering manifold which was prefilled with 250 ml of RO water, and filtered the measured volume through a pre-weighed Whatman GF/C (1.2 μm pore size) filter paper (Lewis et al., 2020). The filter paper was then dried for ~24 hours at 105°C and weighed again to measure the weight of total suspended solids (mg/L). This concentration was then converted to accumulation rate per day per cm^2 using the length of each deployment and the internal cross-sectional area (21.52 cm^2) of the sediment trap head (i.e. $mg/cm^2/day$).

Particle size distributions from salt removed wet samples were determined using the Malvern Mastersizer 3000, a laser diffraction particle-size analyzer following the parameterization method of Sperazza et al. (2004) and Bainbridge et al. (2012). This analysis was conducted on a sub-sample of collected trap material, and includes mineral, organic and carbonate components. Particle sizes were reported as percentage distributions D10, D50, and D90. For example, D50 refers to median size particles, where the diameter of a sphere at which 50% of the particles in the sample is smaller.

Environmental and land use variables

We quantified land use, environmental (i.e., rainfall and wave energy), and anthropogenic (surface runoff, and Dissolved Inorganic Nitrogen (DIN) load) factors for each of the six sites. We used ArcMap 10.4 to calculate percent cover of land that was forest, agroforest, cultivated, developed and other land-use types using high resolution and LIDAR remote sensing habitat maps produced by the American Samoa Department of Marine and Wildlife Resources (Meyer et al., 2017). Monthly modeled average discharge rates (rainfall and surface runoff) for each of the six watersheds were estimated using an open-source water budget model for Tutuila (Shuler et al., 2021). Wave energy for each site was calculated using 10-year average wind speeds for Tutuila using the Wave Energy tool in ArcGIS (Jenness and Houk, 2014). DIN loads exported from each watershed were taken from Shuler and Comeros-Raynal (2020).

2.5 | Data analysis

We used principal component analyses (PCA) to visualize variation in (i) benthic assemblages, (ii) nutrient concentrations, and (iii) suspended sediment characteristics among sampling locations. PCA were conducted using the “vegan” package (Oksanen et al., 2019) in R version 4.0.2. Analysis of benthic assemblages were based on the correlation matrix of the transect level data of each of the benthic categories, for water quality data based on quarterly collections, and for suspended sediments based on 3-month trap deployments. Separate PCA were performed for each of the two habitats (reef flat and reef slope) for benthic assemblages, and each of two sampling locations (stream and reef flat) for water quality.

We used path analysis to explore the potential influences of both natural and anthropogenic variables relating to the catchment and wave exposure and dissolved nutrient concentrations on benthic cover in shallow coastal reef flats. Natural variables comprised of wave energy, watershed size and discharge rates, while anthropogenic variables included percent cover disturbed land area (% cover of developed, cultivated and agroforest land uses), and a proxy of human population density from DIN loads of onsite disposal systems and piggeries (kg.day^{-1}). Of the water quality parameters quantified, DIN and phosphate concentrations were used as explanatory variables as they are highly bioavailable and are known indicators of anthropogenic nutrient loading on shallow reef systems. Benthic cover was partitioned into two groups: turf and macroalgae, and hard coral and CCA as we expected that responses to nutrient enrichment will vary between these different benthic components. Importantly, hard corals together with CCA play key roles in CaCO3 accretion into the reef matrix, and form desirable reef health indicators from a management perspective (Houk et al., 2015; Littler and Littler, 2007).

Path analysis is a multivariate technique which uses a series of structured linear regression equations to test the specified relationships between measured variables (Pedhazur, 1997). The relationships are displayed in a path diagram where variables are linked by straight arrows indicating the direction of the relationship between the variables (Streiner, 2005). In a path diagram, variables are represented as rectangles and are either exogenous or endogenous (Lleras, 2005). The direct effects of an independent variable on a dependent variable are expressed as path coefficients. Coefficients are positive where an increase in the independent variable causes an increase in the dependent variable when other causal variables are held constant, or negative where an increase in the causal variables decreases the dependent variable. Model fit was assessed using four tests: X^2, Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA) and Standardized Root Mean Square Residual (S)RMR (Kline, 1998; Lleras, 2005). Assumptions of the linear models were validated using the *gvlma* package (Peña and Slate, 2006). All linear regressions performed met model assumptions.

3 | RESULTS

The PCA of both reef flat and reef slope benthic assemblages revealed a clear partitioning among watershed types. For the reef flat, the first two principal components explained 41.1% and 33.5% of the total variation, respectively, with sites within pristine watersheds being separated from intermediate and disturbed watersheds along PC1, and intermediate and disturbed watersheds being differentiated along PC2 (Figure 2a). Reef flat benthic assemblages within pristine watersheds were represented by a relatively high percent cover of live coral, CCA, and turf algae, whereas those in intermediate and disturbed watersheds were represented by a higher percent cover of macroalgae and rubble, respectively (Figures 2a, S1). For the reef slope, the first two principal components explained 58% and 18% of the total variation, respectively, with sites within pristine watersheds being represented by relatively high cover of hard coral cover and CCA and separated from intermediate watersheds that were represented by a high cover of macroalgae and rubble along PC1 (Figures 2b, S1). There were considerable variations in reef slope benthic assemblages between the two disturbed sites with Fagaalu being characterized by a relatively high cover of macroalgae and rubble, while Nu'uuli was defined by a high cover of CCA (Fig 2b).

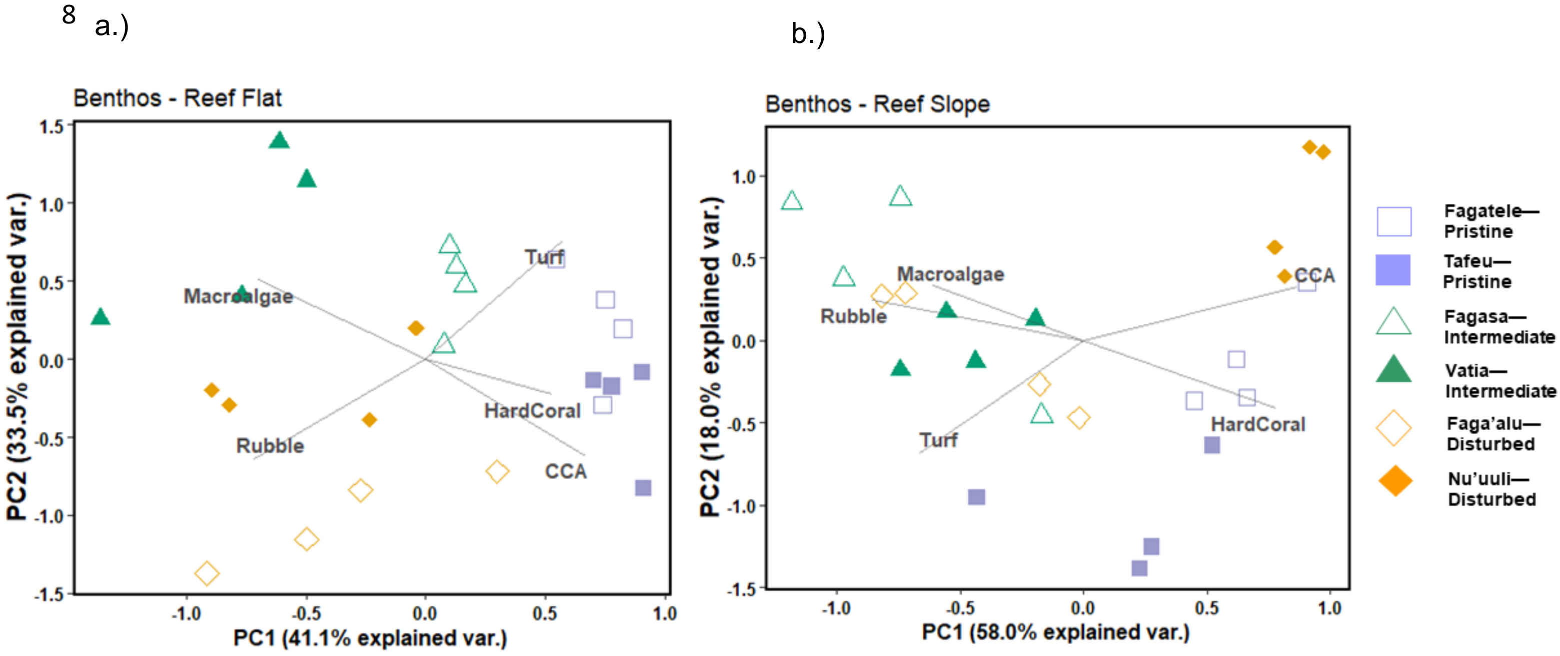


Fig 2. Principal Component Analysis (PCA) showing variation in benthic assemblages on (a) the reef flat, and (b) the reef slope among watershed types (pristine, intermediate, disturbed), and six reef sites around Tutuila, American Samoa. Analyses are based on the cover of benthic categories along four 50 m point-intercept transects within each habitat at each site. Vector lengths are proportional to correlation strengths with the primary PCA axes.

3.1 | Water quality

Nutrients

The PCA's of nutrient concentrations from stream and reef flat samples revealed a clear partitioning between pristine and intermediate watersheds (Figure 3). Nutrient concentrations exhibited spatial structure across watershed types with higher concentrations found in the intermediate and disturbed watersheds (Fig. S2) and a general trend of higher nutrient concentrations during the drier winter (August 2018) season (Fig. S3). For example, DIN stream concentrations were more variable across sites compared to reef flat DIN but in general had the highest average concentrations in disturbed watersheds, Nu'uuli and Faga'alu, in streams from 7.8 to 8.5 μmol/L and reef flats from 4.0 to 6.7

μmol/L, respectively. From the stream samples, the first two principal components explained 36.1% and 23.2% of the total variation, respectively, with samples from pristine watersheds being differentiated from intermediate watershed samples along PC2 due to lower concentrations of total DIN and, ammonium, and lower values of $\delta^{15}N$ (Figure 3a).

For nutrients on reef flats, the first two principal components explained 59.9% and 12.8% of the total variation, respectively. Samples from pristine watersheds were largely differentiated from disturbed watersheds along PC1, with samples from disturbed sites characterized by higher concentrations of all nutrients than those from pristine sites (Figure 3b). Samples from intermediate watersheds were separated from pristine watersheds along PC2, and were characterized by a higher DIN load than pristine sites.

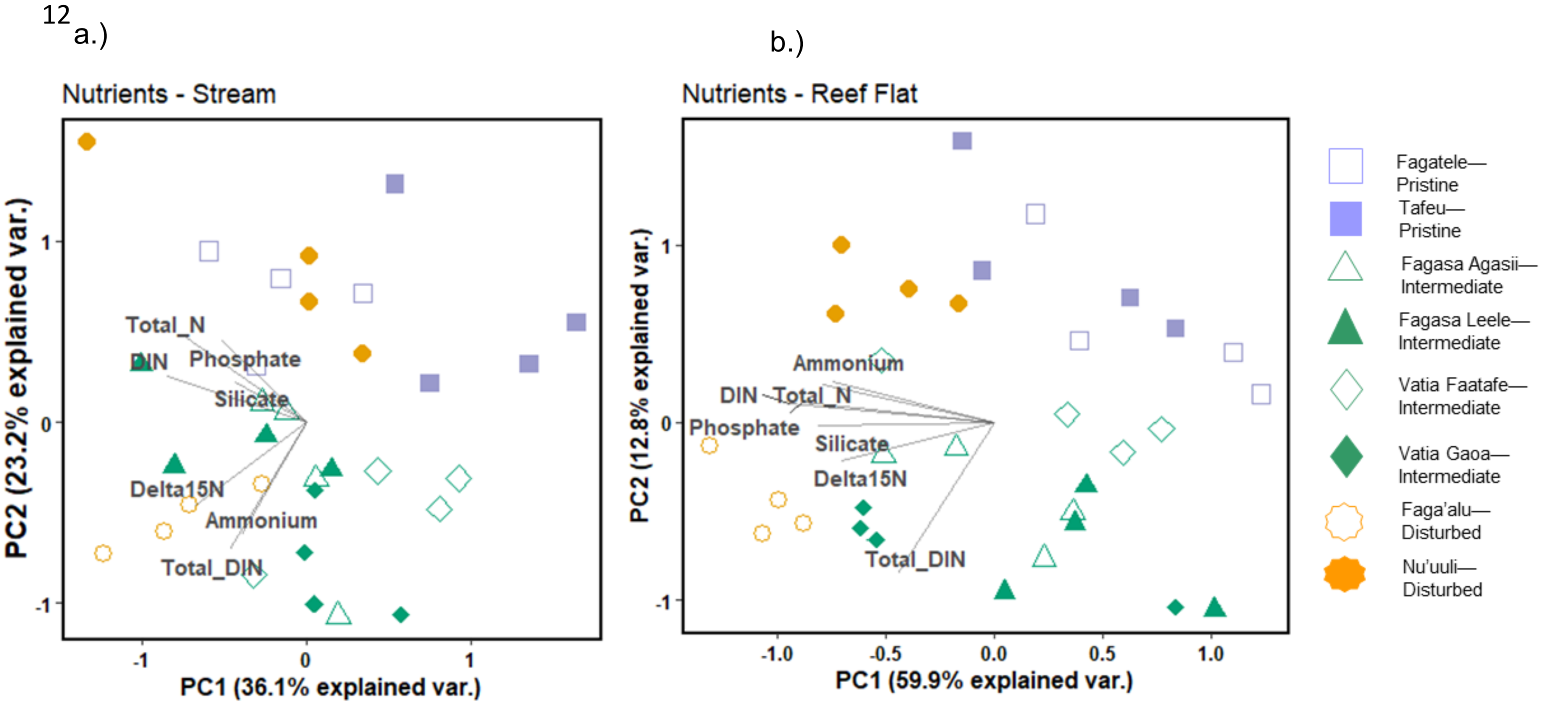


Figure 3. Principal Component Analysis (PCA) showing variation in nutrient concentration on (a) the stream, and (b) the reef flat among watershed types (pristine, intermediate, disturbed), and eight stream sites around Tutuila, American Samoa. The two major streams in Vatia (Gaoa and Faatafe) and Fagasa (Leele and Agasii) were sampled. Analyses are based on nutrient concentrations collected from quarterly sampling within each habitat at each site. Vector lengths are proportional to correlation strengths with the primary PCA axes.

Sediments

For suspended particulate matter, the first two principal components explained 51.4% and 23% of the total variation, respectively (Figure 4). The pristine watershed samples were closely clustered and characterized by a larger median particle size (means: 48 – 70 µm), and greater carbonate content (79%) than samples from intermediate or disturbed watersheds (Figure 4; Table 2). There was greater variability in sediment characteristics among samples from the intermediate and disturbed watershed sites, with the intermediate sites having higher sediment trap accumulation rates (i.e. >18 mg/cm^2/day), and with DIN load, DIN and mineral composition being generally higher in disturbed samples (Figure 4).

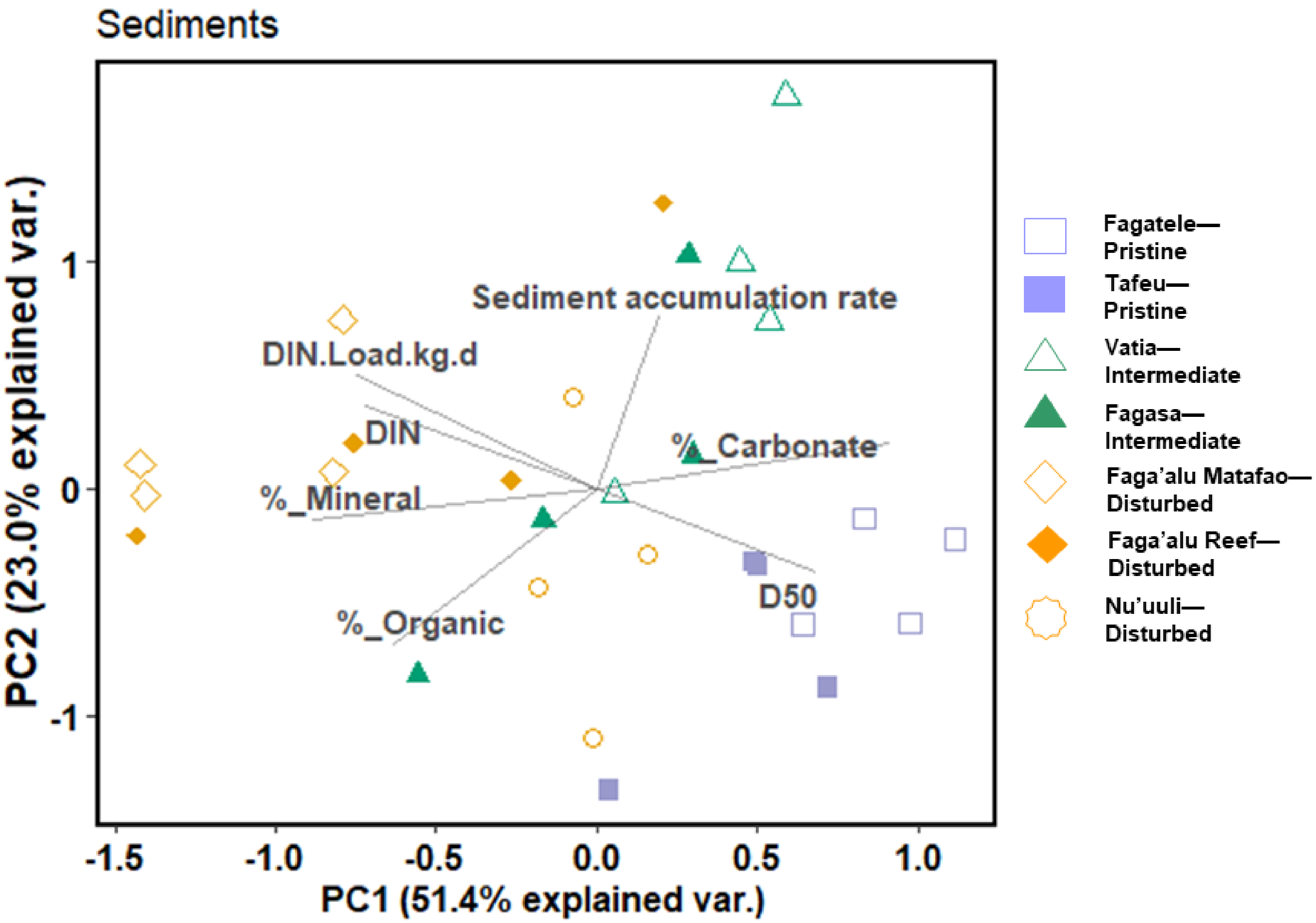
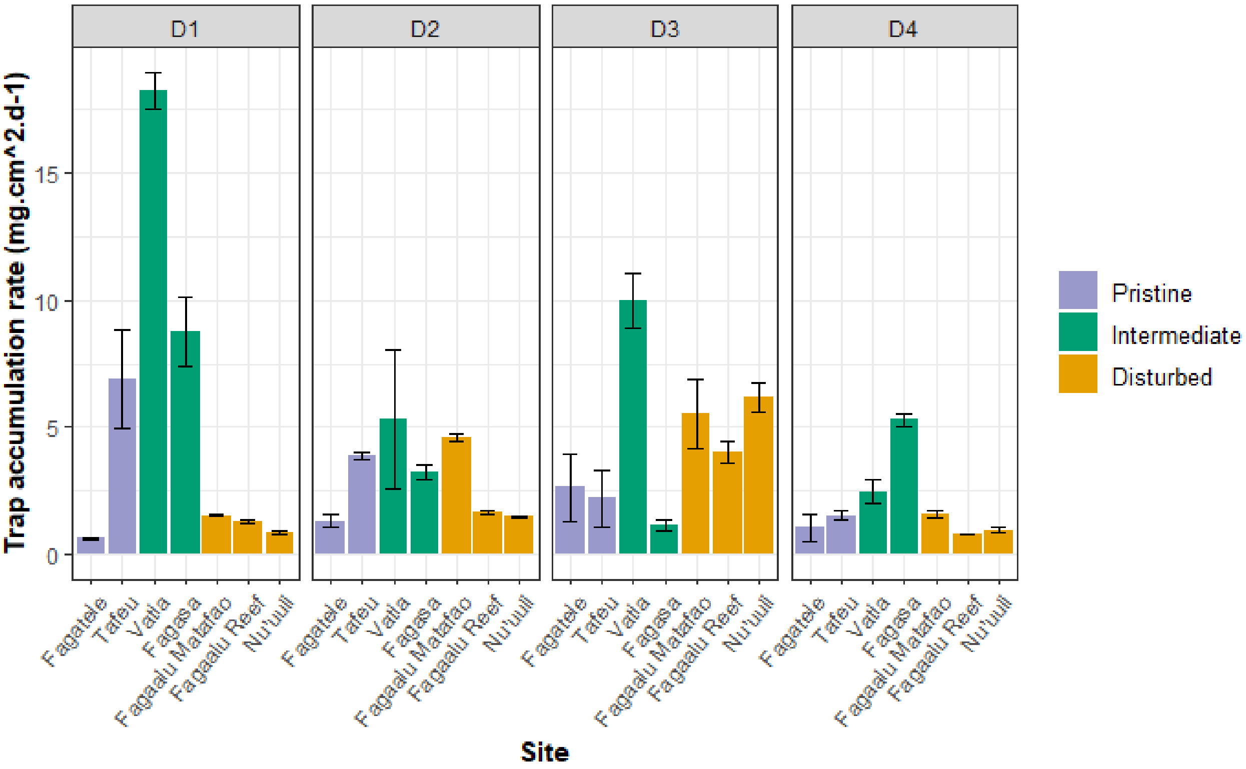


Figure 4. Principal Component Analysis (PCA) showing variation in sediment accumulation rate, carbonate, mineral, and organic content, DIN concentrations and DIN load (kg.d^{-1}) among watershed types (pristine, intermediate, disturbed), and seven sediment traps sites around Tutuila,

American Samoa. Analyses are based on samples collected from quarterly sampling at each site. Vector lengths are proportional to correlation strengths with the primary PCA axes.

Sediment trap accumulation rates varied seasonally with higher rates during the wet deployments (Nov-18 – Feb-19; Feb-19 – May-19) and lower accumulation during the dry season (May-19 – Sep-19; Sep-19 - Nov-19) (Fig. 4a). Both intermediate watersheds and Tafeu had the highest sediment accumulation rates during the first wet season deployment (Nov-18 – Feb-19). Disturbed watersheds had more uniform sediment accumulation rates across sites and across deployments. In pristine watersheds, sediment accumulation was higher in Tafeu during the two wet season deployments (Nov-18 – Feb-19; Feb-19 – May-19) compared to Fagatele. Trap sediments were comprised predominantly of carbonate material (Fig. S4), comprising 34 to 79% of the total sample across all sites and deployments. The organic and mineral composition varied across deployments, with the highest (terrigenous) mineral component measured in the two wet season deployments (Fig. 4b). Average particle size range was largest for the pristine sites (8.1 to 298 µm and 10.5 to 349 µm, respectively for Fagatele and Tafeu) and disturbed site Nu'uuli (7.2 to 552 µm) (Table 2). Relatively uniform percentile rank grain size distribution was measured across the remaining intermediate and disturbed watersheds. Median particle size (i.e. D50) varied across sites but was smaller in the disturbed watersheds (Table 2).

a)


D1
D2
D3
D4
Trap accumulation rate (mg.cm^2.d-1)
0
5
10
15
Fagatele
Tafeu
Vatia
Fagasa
Fagaalu Matafao
Fagaalu Reef
Nu'uuli
Site
Pristine
Intermediate
Disturbed

b)

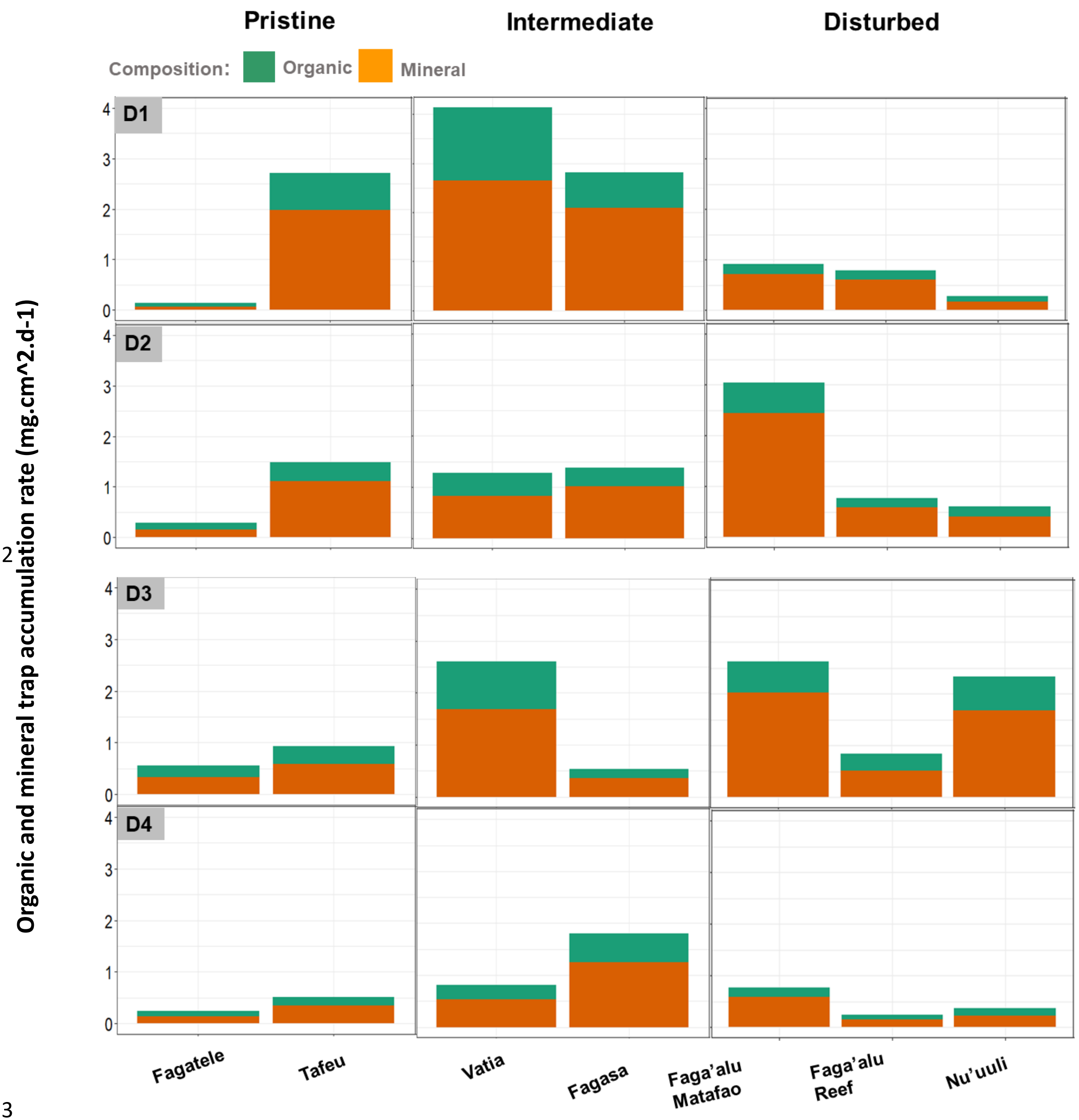


Figure 4. Trap accumulation rate (mg.cm^2.d^{-1}) by watershed type. (a) Total trap accumulation rates (unit) by seasonal deployments. Error bars represent total trap accumulation standard error. (b) The terrigenous composition of each sample (organic and mineral sediment) is represented within each bar. D1 and D2 represent wet season deployments (Nov-18 – Feb-19; Feb-19 – May-19); D3 and D4 represent dry season deployments (May-19 – Sep-19; Sep-19—Nov-19).

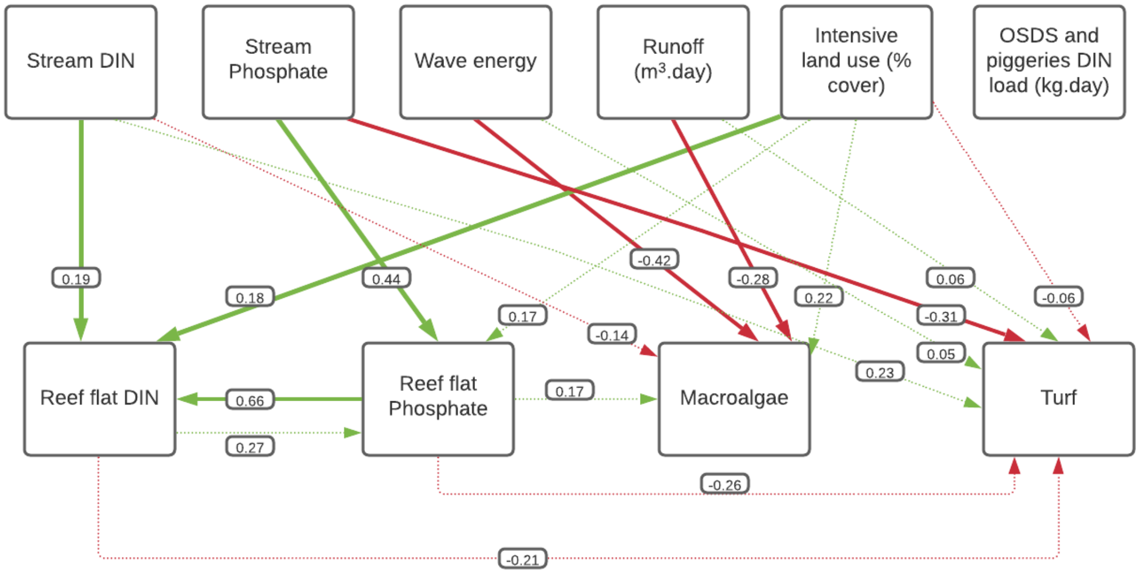
3.3 | Path Analysis

Path analysis revealed a direct and positive link between stream DIN and intensive land use with reef flat DIN, and positive links between stream phosphate, reef phosphate and reef DIN (Fig. 5; Table 3).

Macroalgal cover on the reef flat was best predicted by wave energy and surface runoff, both having a significant negative effect on macroalgal cover (Figure 5a). Interestingly, there was little evidence to support any effect of nutrients, intensive land uses, or DIN loads from piggeries and On-Site Disposal Systems on macroalgal cover, while the cover of turf algae was negatively associated to stream phosphate concentrations (Fig 5a; Table 3).

Hard coral cover was positively related to surface runoff and DIN load from On-Site Disposal Systems and piggeries (path coefficient 0.28 and 0.32, respectively) (Fig 5b; Table 3). Nutrient concentrations in the stream and reef flat, wave energy, and intensive land uses did not have direct significant effects on hard coral cover. CCA cover was positively influenced mainly by surface runoff.

a)



b)

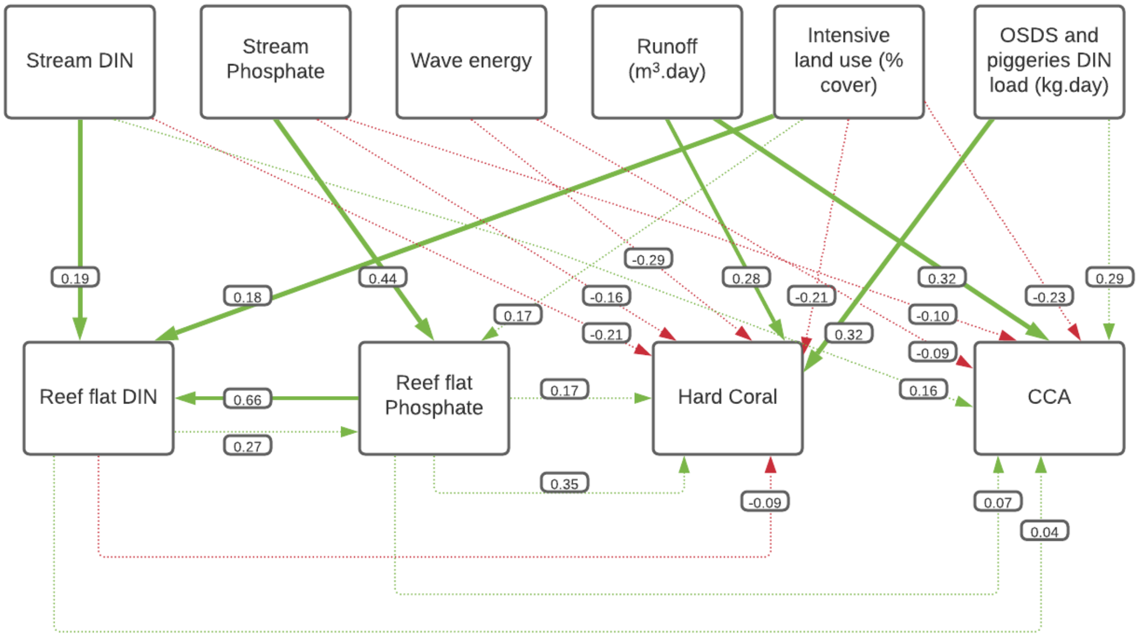


Fig. 5. Path analysis showing pathways through nutrients, wave, runoff, intensive land uses and DIN loads affect (a) macroalgal and turf, and (b) hard coral and CCA cover on the reef flat. The two models represent the two groupings of benthic assemblages (see Methods for more details). Arrows in red and green with grey text boxes represent negative and positive path coefficients respectively. The bold straight line arrows represent significant (p-value < 0.05) path coefficients, broken lines represent non-significant path coefficients.

4 | DISCUSSION

Water quality parameters and the composition of shallow water benthic reef communities exhibited distinct differences among watershed types on Tutuila, American Samoa, with sites adjacent to pristine watersheds generally characterized by lower nutrient concentrations and sediment accumulation rate, and higher cover of hard coral and CCA cover. In contrast, sites adjacent to intermediate and disturbed watersheds had higher nutrient concentrations and sedimentation, and higher cover of macroalgae, turf algae, and rubble. These findings are largely consistent with previous studies linking patterns of land use and water quality to benthic composition on coral reefs (Brodie and Pearson, 2016; Brown et al., 2017; Ennis et al., 2016; Oliver et al., 2011; Rodgers et al., 2012; Wenger et al., 2020). Further, the exploratory path analyses highlighted the linkage between land use and water quality which showed positive associations between intensive land uses and DIN concentrations in both stream and reef flat waters, the analyses also revealed some unexpected findings. The positive relationships between surface runoff and DIN load with hard coral cover was unexpected because these drivers are generally thought to be detrimental to coral condition.

Conversely, factors generally thought to contribute to macroalgal growth and/or cover (i.e., nutrients) were negatively correlated or absent in the path analysis, rather, incident wave energy was identified as the most important driver of macroalgal cover. The results of the path analysis, although exploratory, highlight the potential complexities of the processes shaping benthic communities on coral reefs, and the need to consider multiple factors (including nutrient concentrations, sedimentation, light, space availability and physical forces) simultaneously.

4.1 | Drivers of algal cover

The positive effects of nutrient availability on macroalgal growth and cover are widely accepted, with numerous studies reporting correlations between nutrients and macroalgal cover (De'ath and Fabricius, 2010; Fabricius et al., 2012) and elevated growth of macroalgae following nutrient-enrichment (Lapointe, 1997; Larned, 1998; Littler et al., 1991). While the highest macroalgal cover in the present study was at sites with the highest DIN and $\delta^{15}N$, the path analysis suggested that macroalgal cover was primarily influenced by wave exposure and surface runoff. Macroalgal responses to nutrient enrichment can vary among taxa. For example, the species cover and richness of red and green macroalgae (i.e., Rhodophyta and Chlorophyta, respectively) on inshore reefs of the Great Barrier Reef, Australia was shown to have a negative relationship with good water quality, yet the cover and richness of brown macroalgae (i.e., Phaeophyceae) showed no relationship to water quality (Fabricius, 2005; Fabricius and De'ath, 2004). While increased discharge rates can lead to higher nutrient concentrations and increased macroalgae growth and cover, reduced salinity from freshwater discharge and increased sedimentation can also potentially negatively affect macroalgae photosynthesis and respiration, recruitment, growth, and survival (Kirst, 1990; Umar et al., 1998). The negative relationship between wave exposure and percent cover of macroalgae in our study contrasts with findings from inshore reefs within the Great Barrier Reef Marine Park, which showed a positive effect of wave exposure on macroalgal cover (Ceccarelli et al., 2020), and in Palau where wave exposure was attributed to macroalgal growth and dominance following disturbance from a super typhoon (Roff et al., 2015). However, multiple factors influence the abundance and growth of macroalgae including nutrient availability, light, surface availability and physical forces, and these drivers can interact with each other leading to site-specific composition and abundance patterns (Besterman et al., 2020). Further, wave exposure can enhance macroalgal productivity in shallow environments (Leigh et al., 1987) but high exposures can also cause disturbance and inhibit macroalgal stabilization and accumulation (Williams et al., 2013). While wave energy has been shown to be a major predictor of benthic assemblage structure across regional (Jouffray et al., 2019) and local scales (Ceccarelli et al., 2020), the strong influence of wave energy and its potential interaction with terrestrial run-off warrants further consideration. For instance, higher wave energy can flush terrestrial run-off away from sites exposed to strong waves and currents which can reduce the vulnerability of exposed sites to terrestrial run-off (Rodgers et al., 2012), while low wave energy can lead to retention of nutrients and sediments, increasing residence time and exposure to watershed-derived materials (Storlazzi et al., 2018). The potential decoupling of watershed drivers (e.g., nutrients) and macroalgal cover in the present study could relate to the influence of localized water movement in the transport of, and exposure to, terrestrial run-off.

The highest cover of turf algae around Tutuila was at sites adjacent to intermediate and pristine watersheds on the northern aspect of the island (Tafeu, Vatia and Fagasa). Although these sites had relatively high DIN and $\delta^{15}N$ concentrations, the path analysis suggested the cover of turf algae was negatively related to phosphate concentration in stream waters. The lack of a positive relationship between nutrients and turf algae cover is perhaps not surprising as numerous studies have linked the cover of algal turfs with the spatial availability on the reef benthos, and in particular, recent coral mortality (e.g., (Diaz-Pulido and McCook, 2002; Hughes et al., 2018), whereas the productivity and biomass of turf algae may be more closely linked to nutrients (den Haan et al., 2016; Karcher et al., 2020; Lapointe et al., 2019).

4.2 | Drivers of hard coral and CCA cover

The cover of CCA and hard coral was generally highest at the two sites adjacent to the pristine watersheds (i.e., Fagatele and Tafua), and is consistent with previous studies on Tutuila (Birkeland et al., 2003; Green, 1996; Green et al., 1999; Sudek and Lawrence, 2016). While such patterns of higher coral and CCA cover adjacent to pristine watersheds may be interpreted as a positive effect of higher water quality, the path analysis suggested hard coral and CCA cover were positively related to surface runoff. Somewhat similar results were recently reported for the U.S. Virgin Islands where coral diversity and reef rugosity were positively related to sedimentation (Oliver et al., 2018). Terrestrially-derived organic matter in the SPM can comprise both light fraction particulate organic matter, comprised of animal material and plants, and heavy-fraction organic matter, attached to mineral sediment particles. The different fraction compositions likely interact with surface water nutrient concentrations and influence bioavailable nutrient loads (Bainbridge et al., 2018). While sediment accumulation rate was not included in the analysis due to potential interactions with nutrient concentrations, the analysis was able to examine the direct effects of natural and anthropogenic drivers on benthic cover. Runoff is one of a suite of factors affecting the transport of sediment and nutrients into nearshore reef areas and is used as a proxy for potential sources of pollutants and contaminants from the watersheds. However, terrestrial run-off is influenced by the changes in the frequency, duration, and intensity of discharges via stream, river or groundwater into coastal environments (Alvarez-Romero et al., 2013; Bainbridge et al., 2018; Messina and Biggs, 2016; Oliver et al., 2011; Rodgers et al., 2012). Water flow can modulate the delivery of nutrients and sediment to the reef, and as such further investigations on how discharge rates interact with tidal and wave forcing are needed to better understand the effects of surface runoff on hard coral and CCA cover. Another unexpected finding was the significant and positive effect of DIN load (kg/day) from piggeries and On-Site Disposal Systems on hard coral cover, a surprising finding also shared between coral diversity and proximity to impaired water quality sites in the US Virgin Islands (Oliver et al., 2018). Although increased nutrients negatively affect corals for the most part, positive correlations does not always necessarily infer causality. Elevated dissolved inorganic nutrients have also been attributed to increased zooxanthellae density and photosynthetic rates (Fabricius, 2005).

4.3 | Links between land use, stream nutrients and reef nutrients, and suspended particulate matter

The spatial pattern of nutrient concentrations followed local watershed classifications, where higher nutrient concentrations characterized intermediate and disturbed sites while lower concentrations characterized pristine watersheds (Fig. S2). Path analysis further supports this relationship between intensified land uses and stream DIN concentrations and the strong positive influence of stream nutrient concentrations on reef flat nutrients. Disturbed sites had higher average concentrations of reef flat nutrients, while pristine sites had lower average nutrient concentrations. Though there was more spatial variability in the streams, disturbed sites also had higher average nutrient concentrations (Fig. S2). For instance, phosphate concentrations (which dominated total phosphorus) were much higher for disturbed sites. The higher nutrient concentrations in sites adjacent to disturbed watersheds were similar to spatial patterns of DIN quantified at monthly intervals across 26 watersheds in Tutuila (Comeros-Raynal et al. 2019), and broadly comparable to a baseline study of nutrient concentrations around Vanuatu, another South Pacific high island (Devlin et al., 2020). Interestingly, the DIN concentrations in stream waters for the pristine site, Fagatele, in the present study were higher than those reported by Comeros-Raynal et al. (2019). This discrepancy could be attributed to the difference in precipitation at the time of sampling, or potentially higher groundwater discharge in streams as baseflow during sample collection.

Together with the spatial variation in nutrient concentrations, nutrient concentrations were generally greater during the drier winter season (Fig. S3).Concordant with our findings, temporal patterns from Comeros-Raynal et al. (2019) showed that DIN concentrations were higher during the drier winter months (July – September), and were lowest during months with relatively low rainfall. We note that four sampling points taken over a period of one year may not fully capture the temporal pattern in nutrient concentrations, given other potential sources of variation. For instance, nutrient concentrations may vary based on streamflow quantity and the hydrograph stage of sample collection. Integrated, event-based sampling approaches that can account for the particular point in time when the sample is taken from the hydrograph, is desirable because the timing of sampling, at the beginning of a storm after a dry period as opposed to sampling as the storm progresses, will affect nutrient concentrations. Further, nutrient concentrations can be impacted by varying stream flow rates or submarine groundwater discharge (SGD), and thus, our sampling regime may not characterize the true impact of terrestrial discharge into nearshore reef environments (Shuler and Comeros-Raynal, 2020). Nutrient loading, estimated by multiplying nutrient concentration and water discharge rate, , can potentially be a more effective indicator of nutrient impacts on coastal waters. However, local water quality standards in surface waters are typically reported as nutrient concentrations, thus our results can be directly compared to American Samoa's water quality standards for nitrogen and phosphorus concentrations in freshwaters (e.g., streams) and embayments (e.g., reef flats), and can be used to help establish nutrient thresholds (Houk et al., 2020).

Suspended Particulate Matter

Multiple factors affect the transport of sediments into nearshore reef environments including precipitation patterns, land uses, topography, soil type, watershed size, shape, river network pattern, and discharge rates (Devlin and Brodie, 2005; Lewis et al., 2020; Messina and Biggs, 2016). Higher sediment accumulation rates recorded during the wet season (October to April) followed a temporal trend for intermediate watersheds, Vatia and Fagasa. The pristine watershed, Tafeu, also had a higher sediment accumulation rate at 6.9 mg.cm^2.d^{-1} during the wet season (Fig S4). In addition to high rainfall events, northern winds typical of the wet season from October to April could have influenced the resuspension of large volumes of sediments at these three sites. The pattern of higher sediment accumulation rates in the traps from flood events was similarly observed in inshore areas of the Great Barrier Reef (Lewis et al., 2020) suggesting the important role of discharge in driving increased suspended particulate matter on nearshore reefs. The reverse temporal trend, however, was observed in the disturbed watershed, Faga'alu with the highest sediment trap accumulation rate recorded during the dry season (May 2019 deployment).The high mountains in Faga'alu obstruct the northerly winds from October to April during the wet season, and is instead exposed to dry season south-easterly trade winds from May to September (Craig, 2009). The calm conditions during the wet season coinciding with high rainfall events transporting sediments, nutrients and contaminants can increase exposure of corals to contaminants and elevate their vulnerability to terrestrial run-off (Storlazzi et al., 2018).

Sediment type in the traps was dominated by carbonate across all deployments and across all sites. The islands of American Samoa are comprised mostly of basalt without carbonate rocks (Birkeland et al., 2008), therefore, the predominance of carbonate sediment point to a marine provenance. Grain size analysis from Messina (2016) of larger-sized particles comprised mostly of carbonate material in more exposed reef sites support our findings. Terrigenous sediments (terrestrially-derived particulate organic matter and mineral) comprised a smaller component of total sediment composition. However, percent mineral content was higher than organic content across all sites and deployments. The higher mineral and organic composition in Faga'alu Matafao compared to Faga'alu Reef support previous work in Faga'alu that showed higher terrigenous sediment on the inner reef attributed to calmer hydrodynamic conditions compared to the more exposed southern reef site (Messina, 2016). Although the sediment composition at our six sites contrasts with sediment types at seven inshore sites in the Great Barrier Reef, with higher proportions of mineral content (Lewis et al., 2020), the difference in composition is not surprising because oceanic island lithology differs from continental shelves. Further, land uses, catchment sizes, topography, and seasonal and hydrodynamic patters vary among the two locations.

Sediment particle size affects rates of sedimentation and water clarity, and can also determine responses of the benthic biota to sedimentation. Finer-grained sediments (<63 µm) are more an issue for corals because these sediments are easily resuspended and can remain in the water column longer, reducing the light essential for photosynthesis in zooxanthellate corals (Storlazzi et al., 2015). Land uses can significantly influence the fractions of organic matter. For instance, forested watershed often have higher fractions of light fraction particulate matter, while intensive land uses such as agriculture can affect the proportions of terrestrially-derived particulate organic matter transported from streams (Bainbridge et al., 2018). Across sites, Tafeu had the highest percent cover of forested area (90%) while Nu'uuli had the lowest at 52% (Table 1). Fagatele, a pristine watershed, had 58% forest cover and the highest percent cover of cultivated land and agroforest, 11% and 10%, respectively. The larger sediment grain size measured in sediment traps at both pristine and one disturbed (Nu'uuli) watershed sites potentially reflect the variability in space and time in the amount of organic material delivered to streams (Table 1). Future work that can characterize and determine the origin of particulate organic matter will improve our understanding of SPM properties and its consequent impacts on nearshore reef environments.

4.4 | Limitations of the study

In fringing reefs adjacent to steep watersheds, tidal, wind, and wave forcing, and geomorphic controls act in concert to influence the speed and, direction of currents, and residence times over the reef flats influencing exposure of benthic assemblages to terrestrial run-off (Messina, 2016). Thus, our exploratory path analysis provides at best, a simplified approximation of the ridge-to-reef continuum, and should be interpreted with caution. The unexpected associations between surface runoff and hard coral and CCA cover, in particular, warrant further examination because of the important role of discharge in driving increased suspended particulate matter on nearshore reefs. Corals' response to increased sedimentation is dependent on sediment transport and the level of exposure to this stressor. Critical threshold values for deposited and suspended sediment on coral reefs range between 10 and 300 mg/cm^2/d or mg/l (Erftemeijer et al., 2012). However, adverse effects, including mortality, can occur at lower sediment concentrations; 1 mg/cm^2/d for deposited sediment and as low as 3.2 mg/L for suspended sediment concentrations (Tuttle and Donahue, 2020). Sediment trap accumulation rates of below 10 mg/cm2/d across all sites, could potentially negatively affect coral growth and abundance. Future research efforts should be expanded to include sedimentation rates in path analysis or similar analysis examining causal relationships. Further, additional sites along the wave exposure gradients should be considered to examine variation due to inherent environmental exposure and from anthropogenic influence, and the interactions between these drivers. Laboratory and field experiments which quantify sedimentation rates, sediment type, grain size, and coral responses should be expanded and locality-specific environmental regimes and taxa predisposed to sedimentation stress should be considered as well as additive/synergistic effects from nutrient enrichment. Because coral percent cover is the most widely used indicator of coral reef health and is commonly available, our results can be used to compare to other sites that use integrated ridge-to-reef management approaches. However, coral cover may be more sensitive to disturbances compared to coral metrics such as evenness, heterogeneity, skewness, and size-class distribution. Integrating terrestrial run-off information with coral demography data from local and national-level coral reef monitoring programs in American Samoa could potentially help further understand the impacts of terrestrial runoff in nearshore reef environments. While the exploratory path analysis focused on direct effects and did not include indirect effects, it highlighted connection strengths between land condition and drivers of benthic cover; and while exploratory, is expandable to emerging datasets (e.g., precipitation projections, future % change of land use, fish recruitment, etc.), thus, can be used as baseline for future ridge-to-reef investigations.

5 | Conclusions

The tight coupling between land and sea is an important factor in the health and functioning of nearshore reef habitats. The quantification of nutrient concentrations and suspended particulate matter across an environmental gradient, is the first study on Tutuila, American Samoa to simultaneously examine the relative effects of two major contributors of terrestrial run-off on adjacent reefs, and is also among the first in the South Pacific to use specifically-designed traps (SediSampler®) to quantify SPM. Our findings build on a growing body of ridge-to-reef literature that have linked patterns in land use to water quality and biological communities on adjacent shallow water reefs (Delevaux et al., 2018; Oliver et al., 2011; Rodgers et al., 2012), and contributes to the baseline for volcanic high island communities in the South Pacific. The increased coverage in islands can potentially enable comparisons of water quality thresholds, compare benthic responses to increased nutrients and sediments, and provide opportunities to scale up locality-driven findings to similar island configurations in the Pacific region.

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References:

Adam, T.C., Burkepile, D.E., Holbrook, S.J., Carpenter, R.C., Claudet, J., Loiseau, C., Thiault, L., Brooks, A.J., Washburn, L., Schmitt, R.J., 2020. Landscape-scale patterns of nutrient enrichment in a coral reef ecosystem: implications for coral to algae phase shifts. Ecological Applications n/a, e2227.

Alvarez-Romero, J.G., Devlin, M., Teixeira da Silva, E., Petus, C., Ban, N.C., Pressey, R.L., Kool, J., Roberts, J.J., Cerdeira-Estrada, S., Wenger, A.S., Brodie, J., 2013. A novel approach to model exposure of coastal-marine ecosystems to riverine flood plumes based on remote sensing techniques. J Environ Manage 119, 194-207.

APHA, Association, A.W.W., Federation, W.E., 2012. Standard Methods for the Examination of Water and Waste Water 22nd ed. American Water Works Association.

Armstrong, F.A.J., Stearns, C.R., Strickland, J.D.H., 1967. The measurement of upwelling and subsequent biological process by means of the Technicon Autoanalyzer® and associated equipment. Deep Sea Research and Oceanographic Abstracts 14, 381-389.

Atkinson, C.T., Medeiros, A.C., 2005. Trip Report: Pilot Study of Factors Linking Watershed Function and Coastal Ecosystem Health in American Samoa. USGS Pacific Island Ecosystems Research Center, p. 34.

Bainbridge, Z., Lewis, S., Bartley, R., Fabricius, K., Collier, C., Waterhouse, J., Garzon-Garcia, A., Robson, B., Burton, J., Wenger, A., Brodie, J., 2018. Fine sediment and particulate organic matter: A review and case study on ridge-to-reef transport, transformations, fates, and impacts on marine ecosystems. Marine Pollution Bulletin 135, 1205-1220.

Bainbridge, Z., Lewis, S., Stevens, T., Petus, C., Lazarus, E., Gorman, J., Smithers, S.G., In review. Measuring sediment grain size across the catchment to reef continuum: Improved methods and environmental insights Marine Pollution Bulletin.

Bainbridge, Z.T., Wolanski, E., Álvarez-Romero, J.G., Lewis, S.E., Brodie, J.E., 2012. Fine sediment and nutrient dynamics related to particle size and floc formation in a Burdekin River flood plume, Australia. Marine Pollution Bulletin 65, 236-248.

Besterman, A.F., McGlathery, K.J., Reidenbach, M.A., Wiberg, P.L., Pace, M.L., 2020. Predicting benthic macroalgal abundance in shallow coastal lagoons from geomorphology and hydrologic flow patterns. Limnology and Oceanography n/a.

Birkeland, C., Craig, P., Fenner, D., Smith, L., Kiene, W.E., Riegl, B.M., 2008. Geologic Setting and Ecological Functioning of Coral Reefs in American Samoa, in: Riegl, B.M., Dodge, R.E. (Eds.), Coral Reefs of the USA. Springer Netherlands, Dordrecht, pp. 741-765.

Birkeland, C.E., Randall, R.H., Green, A.L., Smith, B., Wilkins, S., 2003. Changes in the coral reef communities of Fagatele Bay NMS and Tutuila Island (American Samoa), 1982-1995, Technical Report Submitted to the Fagatele Bay National Marine Sancturary, Pago Pago, American Samoa

Brodie, J., Pearson, R.G., 2016. Ecosystem health of the Great Barrier Reef: Time for effective management action based on evidence. Estuarine, Coastal and Shelf Science 183, 438-451.

Brodie, J.E., Kroon, F.J., Schaffelke, B., Wolanski, E.C., Lewis, S.E., Devlin, M.J., Bohnet, I.C., Bainbridge, Z.T., Waterhouse, J., Davis, A.M., 2012. Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses. Marine Pollution Bulletin 65, 81-100.

Brown, C.J., Jupiter, S.D., Albert, S., Anthony, K.R.N., Hamilton, R.J., Fredston-Hermann, A., Halpern, B.S., Lin, H.-Y., Maina, J., Mangubhai, S., Mumby, P.J., Possingham, H.P., Saunders, M.I., Tulloch, V.J.D., Wenger, A., Klein, C.J., 2019. A guide to modelling priorities for managing land-based impacts on coastal ecosystems. Journal of Applied Ecology 56, 1106-1116.

Brown, C.J., Jupiter, S.D., Albert, S., Klein, C.J., Mangubhai, S., Maina, J.M., Mumby, P., Olley, J., Stewart-Koster, B., Tulloch, V., Wenger, A., 2017. Tracing the influence of land-use change on water quality and coral reefs using a Bayesian model. Sci Rep 7, 4740.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at Risk Revisited. Word Resources Institute, Washington, D.C., USA, p. 114.

Carlson, R.R., Foo, S.A., Asner, G.P., 2019. Land Use Impacts on Coral Reef Health: A Ridge-to-Reef Perspective. Frontiers in Marine Science 6, 562.

Ceccarelli, D.M., Evans, R.D., Logan, M., Mantel, P., Puotinen, M., Petus, C., Russ, G.R., Williamson, D.H., 2020. Long-term dynamics and drivers of coral and macroalgal cover on inshore reefs of the Great Barrier Reef Marine Park. Ecological Applications 30, e02008.

Comeros-Raynal, M.T., Lawrence, A., Sudek, M., Vaeoso, M., McGuire, K., Regis, J., Houk, P., 2019. Applying a ridge-to-reef framework to support watershed, water quality, and community-based fisheries management in American Samoa. Coral Reefs 38, 505–520.

Craig, P., 2009. Natural History Guide to American Samoa, Third ed. National Park Service, p. 134.

Craig, P., Didonato, G., Fenner, D., Hawkins, C., 2010. The State of Coral Reef Ecosystems of American Samoa.

De'ath, G., Fabricius, K., 2010. Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. Ecological Applications 20, 840-850.

Delevaux, J.M.S., Whittier, R., Stamoulis, K.A., Bremer, L.L., Jupiter, S., Friedlander, A.M., Poti, M., Guannel, G., Kurashima, N., Winter, K.B., Toonen, R., Conklin, E., Wiggins, C., Knudby, A., Goodell, W., Burnett, K., Yee, S., Htun, H., Oleson, K.L.L., Wiegner, T., Ticktin, T., 2018. A linked land-sea modeling framework to inform ridge-to-reef management in high oceanic islands. PLOS ONE 13, e0193230.

den Haan, J., Huisman, J., Brocke, H.J., Goehlich, H., Latijnhouwers, K.R.W., van Heeringen, S., Honcoop, S.A.S., Bleyenberg, T.E., Schouten, S., Cerli, C., Hoitinga, L., Vermeij, M.J.A., Visser, P.M., 2016. Nitrogen and phosphorus uptake rates of different species from a coral reef community after a nutrient pulse. Scientific Reports 6, 28821.

Devlin, M., Smith, A., Graves, C.A., Petus, C., Tracey, D., Maniel, M., Hooper, E., Kotra, K., Samie, E., Loubser, D., Lyons, B.P., 2020. Baseline assessment of coastal water quality, in Vanuatu, South Pacific: Insights gained from in-situ sampling. Marine Pollution Bulletin 160, 111651.

Devlin, M.J., Brodie, J., 2005. Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behavior in coastal waters. Mar Pollut Bull 51, 9-22.

Diaz-Pulido, G., McCook, L., 2002. The fate of bleached corals: patterns and dynamics of algal recruitment. Marine Ecology Progress Series 232, 115-128.

DiDonato, G.T., 2004. Developing an Initial Watershed Classification for American Samoa, Report to the American Samoa Environmental Protection Agency, Pago Pago, American Samoa. American Samoa Environmental Protection Agency, p. 14.

Ennis, R.S., Brandt, M.E., Wilson Grimes, K.R., Smith, T.B., 2016. Coral reef health response to chronic and acute changes in water quality in St. Thomas, United States Virgin Islands. Mar Pollut Bull 111, 418-427.

Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., Todd, P.A., 2012. Environmental impacts of dredging and other sediment disturbances on corals: A review. Marine Pollution Bulletin 64, 1737-1765.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar Pollut Bull 50, 125-146.

Fabricius, K.E., Cooper, T.F., Humphrey, C., Uthicke, S., De’ath, G., Davidson, J., LeGrand, H., Thompson, A., Schaffelke, B., 2012. A bioindicator system for water quality on inshore coral reefs of the Great Barrier Reef. Marine Pollution Bulletin 65, 320-332.

Fabricius, K.E., De'ath, G., 2004. IDENTIFYING ECOLOGICAL CHANGE AND ITS CAUSES: A CASE STUDY ON CORAL REEFS. Ecological Applications 14, 1448-1465.

Falkland, T., 1999. Water resources issues of small island developing states. Natural Resources Forum 23, 245-260.

Grasshoff, K., Ehrhardt, M., Kremling, K., 1983. Methods of Seawater Analysis Verlag Chemie.

Green, A.L., 1996. Status of the Coral Reefs of the Samoan Archipelago. Department of Marine and Wildlife Resources, American Samoa p. 126.

Green, A.L., Birkeland, C.E., Randall, R.H., 1999. Twenty Years of Disturbance and Change in Fagatele Bay National Marine Sanctuary, American Samoa. Pacific Science 53, 376-400.

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25, 101-110.

Holst Rice, S., Messina, A., Biggs, T., Vargas-Angel, B., Whitall, D., 2016. Baseline Assessment of Faga'alu Watershed: A Ridge to Reef Assessment in Support of Sediment Reduction Activities and Future Evaluation of their Success, NOAA Technical Memorandum CRCP. NOAA Coral Reef Conservation Program, Silver Spring, Maryland, p. 44.

Houk, P., Camacho, R., Johnson, S., McLean, M., Maxin, S., Anson, J., Joseph, E., Nedlic, O., Luckymis, M., Adams, K., Hess, D., Kabua, E., Yalon, A., Buthung, E., Graham, C., Leberer, T., Taylor, B., van Woesik, R., 2015. The Micronesia Challenge: Assessing the Relative Contribution of Stressors on Coral Reefs to Facilitate Science-to-Management Feedback. PLOS ONE 10, e0130823.

Houk, P., Comeros-Raynal, M., Lawrence, A., Sudek, M., Vaeoso, M., McGuire, K., Regis, J., 2020. Nutrient thresholds to protect water quality and coral reefs. Marine Pollution Bulletin 159, 111451.

Houk, P., Musburger, C., Wiles, P., 2010. Water quality and herbivory interactively drive coral-reef recovery patterns in American Samoa. PLoS One 5, e13913.

Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Dietzel, A., Eakin, C.M., Heron, S.F., Hoey, A.S., Hoogenboom, M.O., Liu, G., McWilliam, M.J., Pears, R.J., Pratchett, M.S., Skirving, W.J., Stella, J.S., Torda, G., 2018. Global warming transforms coral reef assemblages. Nature 556, 492-496.

Izuka, S.K., Giambelluca, T.W., Nullet, M.A., 2005. Potential Evapotranspiration on Tutuila, American Samoa, USGS Scientific Investigations Report 2005-5200. U.S. Geological Survey Department of the Interior, p. 40.

Jenness, J., Houk, P., 2014. UOGML Wave Energy ArcGIS Extension. University of Guam Marine Laboratory.

Jouffray, J.-B., Wedding, L.M., Norström, A.V., Donovan, M.K., Williams, G.J., Crowder, L.B., Erickson, A.L., Friedlander, A.M., Graham, N.A.J., Gove, J.M., Kappel, C.V., Kittinger, J.N., Lecky, J., Oleson, K.L.L., Selkoe, K.A., White, C., Williams, I.D., Nyström, M., 2019. Parsing human and biophysical drivers of coral reef regimes. Proceedings of the Royal Society B: Biological Sciences 286, 20182544.

Jupiter, S.D., Wenger, A., Klein, C.J., Albert, S., Mangubhai, S., Nelson, J., Teneva, L., Tulloch, V.J., White, A.T., Watson, J.E.M., 2017. Opportunities and constraints for implementing integrated land–sea management on islands. Environmental Conservation 44, 254-266.

Karcher, D.B., Roth, F., Carvalho, S., El-Khaled, Y.C., Tilstra, A., Kürten, B., Struck, U., Jones, B.H., Wild, C., 2020. Nitrogen eutrophication particularly promotes turf algae in coral reefs of the central Red Sea. PeerJ 8, e8737-e8737.

Kennedy, J., and Chilton Consulting Engineers, 1987. Groundwater contamination study Tafuna-Leone Plain Tutuila Island, Final report for the Environmental Quality Commission, Office of the Governor, Tutuila, American Samoa, p. 168.

Kérouel, R., Aminot, A., 1997. Fluorometric determination of ammonia in sea and estuarine waters by direct segmented flow analysis. Marine Chemistry 57, 265-275.

Kirst, 1990. Salinity tolerance of eukaryotic marine algae. Annual review of plant physiology and plant molecular biology 41.

Kline, R., 1998. Principles and Practices of Structural Equation Modeling. Guilford Press, New York

Lapointe, B.E., 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnology and Oceanography 42, 1119-1131.

Lapointe, B.E., Brewton, R.A., Herren, L.W., Porter, J.W., Hu, C., 2019. Nitrogen enrichment, altered stoichiometry, and coral reef decline at Looe Key, Florida Keys, USA: a 3-decade study. Marine Biology 166, 108.

Larned, S.T., 1998. Nitrogen- versus phosphorus-limited growth and sources of nutrients for coral reef macroalgae. Marine Biology 132, 409-421.

Leigh, E.G., Paine, R.T., Quinn, J.F., Suchanek, T.H., 1987. Wave energy and intertidal productivity. Proceedings of the National Academy of Sciences 84, 1314.

Lewis, S., Bainbridge, Z., Stevens, T., Garzon-Garcia, A., Chen, C., Bahadori, M., Burton, J., Rezaei Rashti, M., James, C., Smithers, S.G., Olley, J., 2020. What's really damaging the Reef?: Tracing the origin and fate of the environmentally detrimental sediment and associated bioavailable nutrients, Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns, p. 248.

Littler, M.M., Littler, D.S., 2007. Assessment of coral reefs using herbivory/nutrient assays and indicator groups of benthic primary producers: a critical synthesis, proposed protocols, and critique of management strategies. Aquatic Conservation: Marine and Freshwater Ecosystems 17, 195-215.

Littler, M.M., Littler, D.S., Brooks, B.L., 2006. Harmful algae on tropical coral reefs: Bottom-up eutrophication and top-down herbivory. Harmful Algae 5, 565-585.

Littler, M.M., Littler, D.S., Titlyanov, E.A., 1991. Comparisons of N- and P-limited productivity between high granitic islands versus low carbonate atolls in the Seychelles Archipelago: a test of the relative-dominance paradigm. Coral Reefs 10, 199-209.

Lleras, C., 2005. Path analysis. Encyclopedia of social measurement 3, 25-30.

McIlvin, M.R., Casciotti, K.L., 2010. Fully automated system for stable isotopic analyses of dissolved nitrous oxide at natural abundance levels. Limnology and Oceanography: Methods 8, 54-66.

Messina, A., 2016. Terrigenous sediment dynamics in a small, tropical, fringing reef embayment, Department of Geography. Dissertation for San Diego State University/UC Santa Barbara Joint-Doctoral Program.

Messina, A.M., Biggs, T.W., 2016. Contributions of human activities to suspended sediment yield during storm events from a small, steep, tropical watershed. Journal of Hydrology 538, 726-742.

Meyer, R., Seamon, J., Fa'aumu, S., Lalogafuafua, I., 2017. Classification and Mapping of Wildlife Habitat in American Samoa. An object-based approach using high resolution orthoimagery and LIDAR remote sensing data, Report to the American Samoa Department of Marine and Wildlife Resources Department of Marine and Wildlife Resources p. 140.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27, 31-36.

NOAA, 2020. CCAP Land Cover Atlas. NOAA.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2019. vegan: Community Ecology Package.

Oliver, L.M., Fisher, W.S., Fore, L., Smith, A., Bradley, P., 2018. Assessing land use, sedimentation, and water quality stressors as predictors of coral reef condition in St. Thomas, U.S. Virgin Islands. Environmental Monitoring and Assessment 190, 213.

Oliver, L.M., Lehrter, J.C., Fisher, W.S., 2011. Relating landscape development intensity to coral reef condition in the watersheds of St. Croix, US Virgin Islands. Marine Ecology Progress Series 427, 293-302.

Pedhazur, E., 1997. Structural Equation Models with Observed Variables: Path Analysis, Multiplpe Regression in Behavioral Research Explanation and Prediction, Third Edition ed. Christopher P. Klein, USA, pp. 765-841.

Peña, E.A., Slate, E.H., 2006. Global Validation of Linear Model Assumptions. Journal of the American Statistical Association 101, 341-354.

Rodgers, K.S., Kido, M.H., Jokiel, P.L., Edmonds, T., Brown, E.K., 2012. Use of integrated landscape indicators to evaluate the health of linked watersheds and coral reef environments in the Hawaiian islands. Environ Manage 50, 21-30.

Roff, G., Chollett, I., Doropoulos, C., Golbuu, Y., Steneck, R.S., Isechal, A.L., van Woesik, R., Mumby, P.J., 2015. Exposure-driven macroalgal phase shift following catastrophic disturbance on coral reefs. Coral Reefs 34, 715-725.

Ruddle, K., Hviding, E., Johannes, R.E., 1992. Marine Resources Management in the Context of Customary Tenure. Marine Resource Economics 7, 249-273.

Rude, J., Minks, A., Doheny, B., Tyner, M., Maher, K., Huffard, C., Hidayat, N.I., Grantham, H., 2016. Ridge to reef modelling for use within land–sea planning under data-limited conditions. Aquatic Conservation: Marine and Freshwater Ecosystems 26, 251-264.

Shuler, C., Brewington, L., El-Kadi, A.I., 2021. A participatory approach to assessing groundwater recharge under future climate and land-cover scenarios, Tutuila, American Samoa. Journal of Hydrology: Regional Studies 34, 100785.

Shuler, C.K., Comeros-Raynal, M., 2020. Ridge to Reef Management Implications for the Development of an Open-Source Dissolved Inorganic Nitrogen-Loading Model in American Samoa. Environmental Management.

Shuler, C.K., D.W., A., V., G., Baker, L., Olguin, A.N., Dulai, H., C.M., S., Alegado, R.A., 2019. Assessment of Terrigenous Nutrient Loading to Coastal Ecosystems along a Human Land-Use Gradient, Tutuila, American Samoa. Hydrology 6, 18.

Shuler, C.K., El-Kady, A.I., 2017. Provisional Hydrogeologic Data and Recommendations for Sustainable Groundwater Management Tutuila, American Samoa, December 2017 Draft. Prepared in Cooperation with

American Samoa Environmental Protection Agency through a US EPA Region IX Making a Visible Difference Project Project No. C00543. University of Hawaii Water Resources Research Center, p. 77.

Sigman, D.M., Casciotti, K.L., Andreani, M., Barford, C., Galanter, M., Böhlke, J.K., 2001. A Bacterial Method for the Nitrogen Isotopic Analysis of Nitrate in Seawater and Freshwater. Analytical Chemistry 73, 4145-4153.

Storlazzi, C.D., Cheriton, O.M., Messina, A.M., Biggs, T.W., 2018. Meteorologic, oceanographic, and geomorphic controls on circulation and residence time in a coral reef-lined embayment: Faga’alu Bay, American Samoa. Coral Reefs 37, 457-469.

Storlazzi, C.D., Norris, B.K., Rosenberger, K.J., 2015. The influence of grain size, grain color, and suspended-sediment concentration on light attenuation: Why fine-grained terrestrial sediment is bad for coral reef ecosystems. Coral Reefs 34, 967-975.

Streiner, D.L., 2005. Finding Our Way: An Introduction to Path Analysis. Canadian Journal of Psychiatry 50, 115-122.

Sudek, M., Lawrence, A., 2016. American Samoa Coral Reef Monitoring Program Progress Report FY13/14, Report to the Department of Marine and Wildlife Resources, Coral Reef Advisory Group and NOAA. Department of Marine and Wildlife Resources p. 51.

Szmant, A.M., 2002. Nutrient enrichment on coral reefs: Is it a major cause of coral reef decline? Estuaries 25, 743-766.

Tuitele, C., Tuiasosopo, J., Faaiuaso, S., 2016. Watershed Classification Update for American Samoa American Samoa Environmental Protection Agency, Pago Pago, American Samoa p. 12.

Tuttle, L.J., Donahue, M.J., 2020. Thresholds for Sediment Stress on Corals: A systematic review and meta-analysis. NOAA Fisheries Pacific Islands , Pacific Islands Regional Officec, Habitat Conservation Division, Honolulu, Hawaii, p. 76.

Umar, M.J., McCook, L.J., Price, I.R., 1998. Effects of sediment deposition on the seaweed Sargassum on a fringing coral reef. Coral Reefs 17, 169-177.

US Census Bureau, 2014. 2010 Census of Population and Housing, American Samoa, Demographic Profile Summary File: Technical Documentation.

Vargas-Angel, B., Huntington, B., 2020. Status and Trends Assessments for Land-based Sources of Pollution Impacts on Benthic Reef Communities in Faga'alu Bay, American SAmoa, NOAA Technical Memorandum NMFS-PIFSC-109, p. 38.

Verbist, B., Poesen, J., van Noordwijk, M., Widianto, Suprayogo, D., Agus, F., Deckers, J., 2010. Factors affecting soil loss at plot scale and sediment yield at catchment scale in a tropical volcanic agroforestry landscape. CATENA 80, 34-46.

Weber, M., Lott, C., Fabricius, K.E., 2006. Sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, organic and geochemical properties. Journal of Experimental Marine Biology and Ecology 336, 18-32.

Wenger, A.S., Harris, D., Weber, S., Vaghi, F., Nand, Y., Naisilisili, W., Hughes, A., Delevaux, J.M.S., Klein, C.J., Watson, J., Mumby, P.J., Jupiter, S.D., 2020. Best-practice forestry management delivers diminishing returns for coral reefs with increased land-clearing. Journal of Applied Ecology n/a.

Whitall, D., Curtis, M., Mason, A., Vargas-Angel, B., 2019. Excess Nutrients in Vatia Bay, American Samoa: Spatiotemporal Variability, Source Identification and Impact on Coral Reef Ecosystems, NOAA Technical Memorandum NOS NCCOS 266. NOAA Silver Spring, MD, p. 69.

Williams, G.J., Smith, J.E., Conklin, E.J., Gove, J.M., Sala, E., Sandin, S.A., 2013. Benthic communities at two remote Pacific coral reefs: effects of reef habitat, depth, and wave energy gradients on spatial patterns. PeerJ 1, e81.

Wong, M.F., 1996. Analysis of Streamflow Characteristics for Streams on the Island of Tutuila, American Samoa. U.S. Geological Survey, Honolulu, Hawaii, p. 173.

Wooldridge, S.A., 2009. Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. Marine Pollution Bulletin 58, 745-751.

Table 1. Site attributes including watershed area, percent land use, number of On-Site Disposal System units and pigs.

		Natural Land Use		Intensive Land Use				
Site	**Total Watershed Area (sqm)**	**% Forest**	**% Agro-forest**	**% Cultivated**	**% Develop Land**	**% All other land use (barren land, shrub/scrub land, grass/herbaceous land)**	**Total number of Onsite Disposal System units (cesspools, septic tanks)**	**No. of pigs**
Fagatele	1,917,759	58%	10%	11%	5%	15%	0	0
Tafeu	1,669,015	90%	0%	0%	0%	10%	0	0
Fagasa	3,483,148	78%	5%	5%	7%	6%	117	118
Vatia	3,574,377	79%	4%	3%	5%	9%	100	152
Nu'uuli	17,170,233	52%	5%	8%	28%	7%	65	221
Fagaalu	2,476,211	71%	4%	2%	13%	11%	124	132

Table 2. Mean percentile rank of grain size distribution (in µm) of suspended particulate matter (SPM) for each site across all seasonal deployments.

Site	**Watershed Type**	**D10 (mean ± 1 SD)**	**D50 (mean ± 1 SD)**	**D90 (mean ± 1 SD)**
Fagatele	Pristine	8.15 ± 1.5	48.4 ± 10.4	298 ± 94
Tafeu	Pristine	10.5 ± 1.7	69.6 ± 15.9	349 ± 109
Vatia	Intermediate	6.00 ± 0.75	32.7 ± 4.9	138 ± 19
Fagasa	Intermediate	6.94 ± 0.50	40.1 ± 6.6	188 ± 19
Fagaalu Matafao	Disturbed	6.32 ± 0.88	28.0 ± 5.2	114 ± 5
Fagaalu Reef	Disturbed	6.64 ± 0.99	34.3 ± 9.8	195 ± 80
Nu'uuli	Disturbed	7.17 ± 0.92	36.4 ± 5.5	552 ± 773

Table 3. Path analysis model outputs. We used the default estimator in the lavaan package, maximum likelihood. Standard error (SE) is based on the expected information matrix, and the z-value represents the ratio of the parameter to the standard error. P-value <0.05 represents significant parameters. Path coefficients are standardized versions of linear regression weights. R-squared values reflect the proportion of variance in the dependent variables accounted for by the equation.

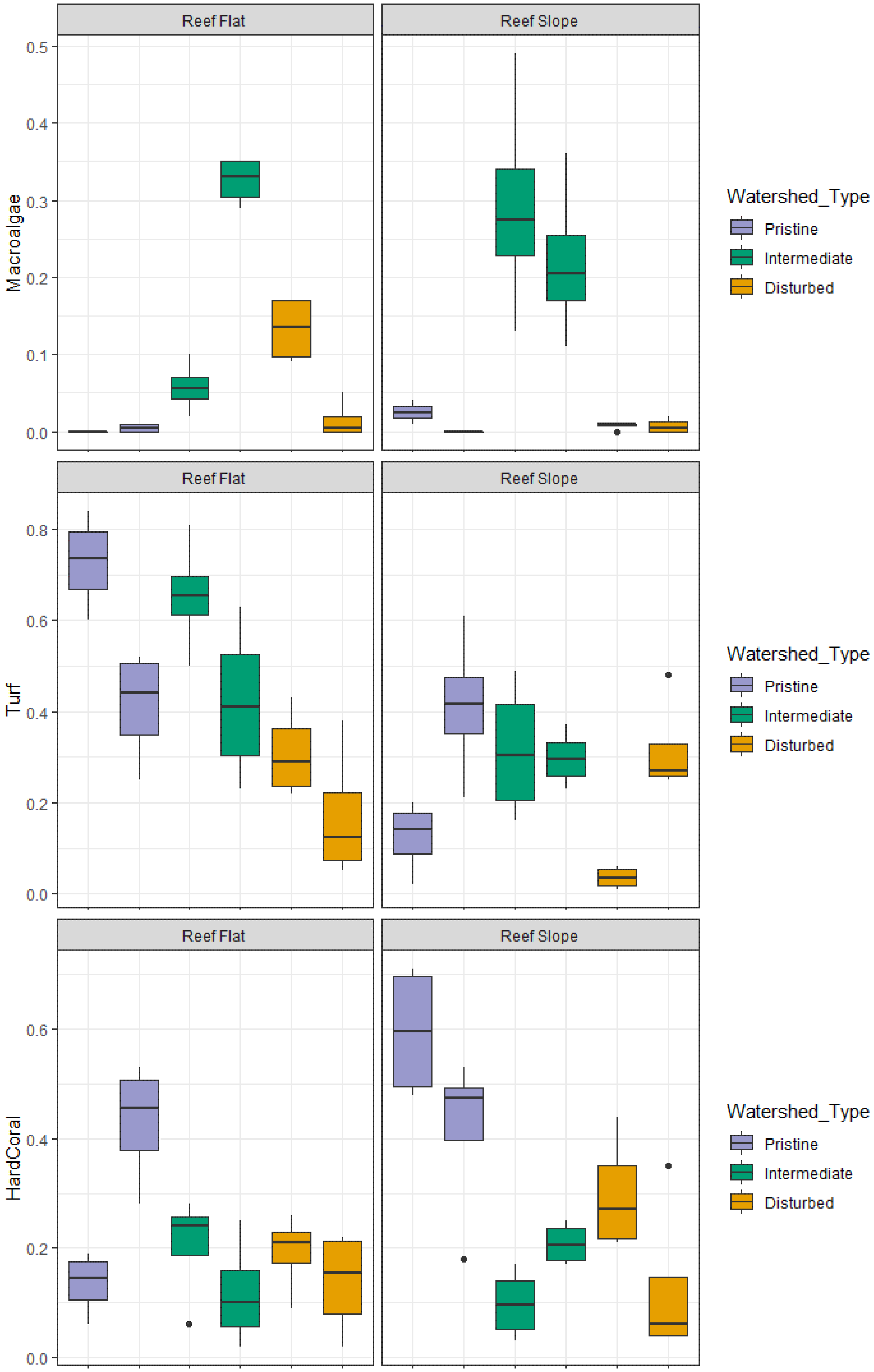
	Estimate	Std.Err	z-value	P(>|z|)	Std.all	R^2
Macroalgae Reef Flat ~						40%
Wave	-0.01	0.00	-3.49	0.00	-0.42	
Reef flat DIN ~						73%
Stream DIN	0.15	0.06	2.58	0.01	0.19	
Intensive land use	0.73	0.32	2.30	0.02	0.18	
Reef flat PO_4	1.01	0.18	5.53	0.00	0.66	
Reef flat PO_4~						61%
Stream PO_4	0.55	0.14	3.90	0.00	0.44	
Intensive land use	0.44	0.26	1.71	0.09	0.17	
Reef Flat DIN	0.17	0.12	1.40	0.16	0.27	
Macroalgae Reef Flat ~						40%
Stream DIN	-0.04	0.03	-1.25	0.21	-0.14	
Reef flat PO_4	0.08	0.05	1.56	0.12	0.17	
Runoff	-0.10	0.04	-2.54	0.01	-0.28	
Intensive land use	0.29	0.15	1.90	0.06	0.22	
Turf reef Flat ~						43%
Stream DIN	0.05	0.02	1.99	0.05	0.23	
Stream PO_4	-0.16	0.06	-2.60	0.01	-0.31	
Reef Flat DIN	-0.06	0.05	-1.16	0.25	-0.21	
Reef flat PO_4	-0.11	0.08	-1.36	0.17	-0.26	
Intensive land use	-0.07	0.12	-0.55	0.58	-0.06	
Wave energy	0.00	0.00	0.46	0.64	0.05	
Runoff	0.02	0.03	0.58	0.56	0.06	
Reef Flat DIN ~						73%
Stream DIN	0.15	0.06	2.58	0.01	0.19	
Intensive land use	0.73	0.32	2.30	0.02	0.18	
Reef flat PO_4	1.01	0.18	5.53	0.00	0.66	
Reef flat PO_4~						61%
Stream PO_4	0.55	0.14	3.90	0.00	0.44	
Intensive land use	0.44	0.26	1.71	0.09	0.17	
Reef flat DIN	0.17	0.12	1.40	0.16	0.27	
Hard coral reef flat ~						20%
Stream DIN	-0.04	0.03	-1.49	0.14	-0.21	
Stream PO_4	-0.07	0.06	-1.07	0.28	-0.16	

Reef flat DIN	-0.02	0.05	-0.43	0.67	-0.09	
Reef flat PO_4	0.12	0.08	1.53	0.13	0.35	
Wave energy	0.00	0.00	-1.59	0.11	-0.29	
Runoff	0.07	0.03	2.12	0.03	0.28	
Intensive land use	-0.19	0.13	-1.52	0.13	-0.21	
DIN Load (OSDS + pigs) kg/day	0.06	0.03	2.10	0.04	0.32	
CCA Reef Flat ~						23%
Stream DIN	0.03	0.02	1.15	0.25	0.16	
Stream PO_4	-0.04	0.06	-0.69	0.49	-0.10	
Reef flat DIN	0.01	0.05	0.17	0.87	0.04	
Reef flat PO_4	0.02	0.08	0.32	0.75	0.07	
Wave energy	0.00	0.00	-0.49	0.63	-0.09	
Runoff	0.08	0.03	2.48	0.01	0.32	
Intensive land use	-0.20	0.12	-1.68	0.09	-0.23	
DIN Load (OSDS + pigs) kg/day	0.05	0.03	1.96	0.05	0.29	

Supplementary Information:

Table S1. Ridge and Reef site attributes

	Ridge					***Reef***	
Site	**Watershed type**	**Human population density (pop/km^2)**	**Average monthly rainfall (m3/day)**	**Average monthly runoff (m3/day)**	**DIN load (kg/day)**	**Mean wave exposure (joules/m^2)**	**Sediment trap depth (m)**
Fagatele	Pristine	0	2264.57	344	0.34	19.3	5- 7
Tafeu	Pristine	0	4840.26	1322.57	0.33	100.34	5- 7
Fagasa	Intermediate	831	3724.96	1079.06	3.3	230.63	5- 7
Vatia	Intermediate	640	4670.99	1159.68	2.65	220.35	5- 7
Nu'uuli	Extensive	3955	17375.57	3856.21	0.68	985.63	5- 7
Faga'alu	Extensive	910	2616.27	761	6.71	1663.78	5- 7


Reef Flat
Reef Slope
Macroalgae
0.0
0.1
0.2
0.3
0.4
0.5
Watershed_Type
Pristine
Intermediate
Disturbed
Reef Flat
Reef Slope
Turf
0.0
0.2
0.4
0.6
0.8
Watershed_Type
Pristine
Intermediate
Disturbed
Reef Flat
Reef Slope
HardCoral
0.0
0.2
0.4
0.6
Watershed_Type
Pristine
Intermediate
Disturbed

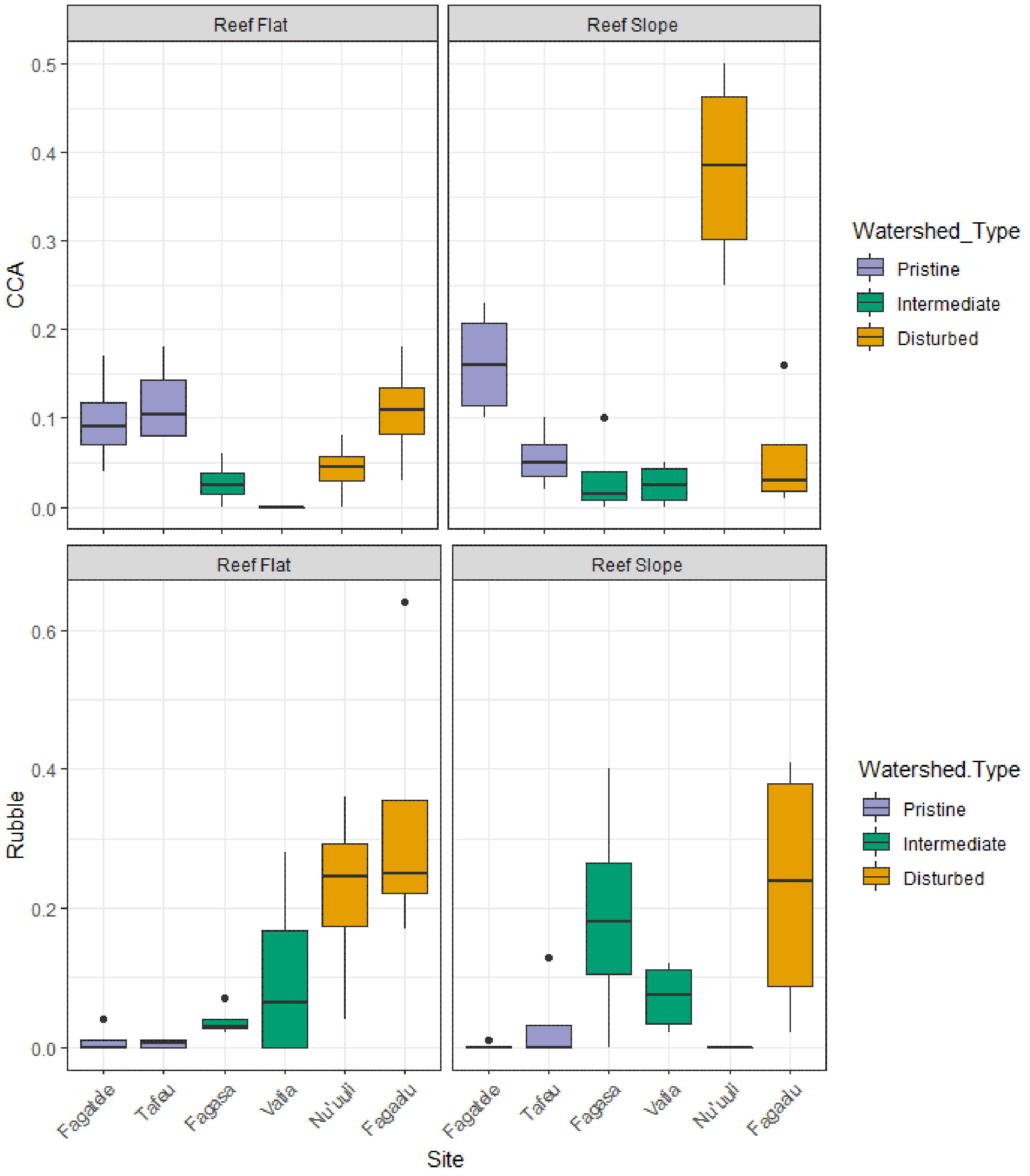
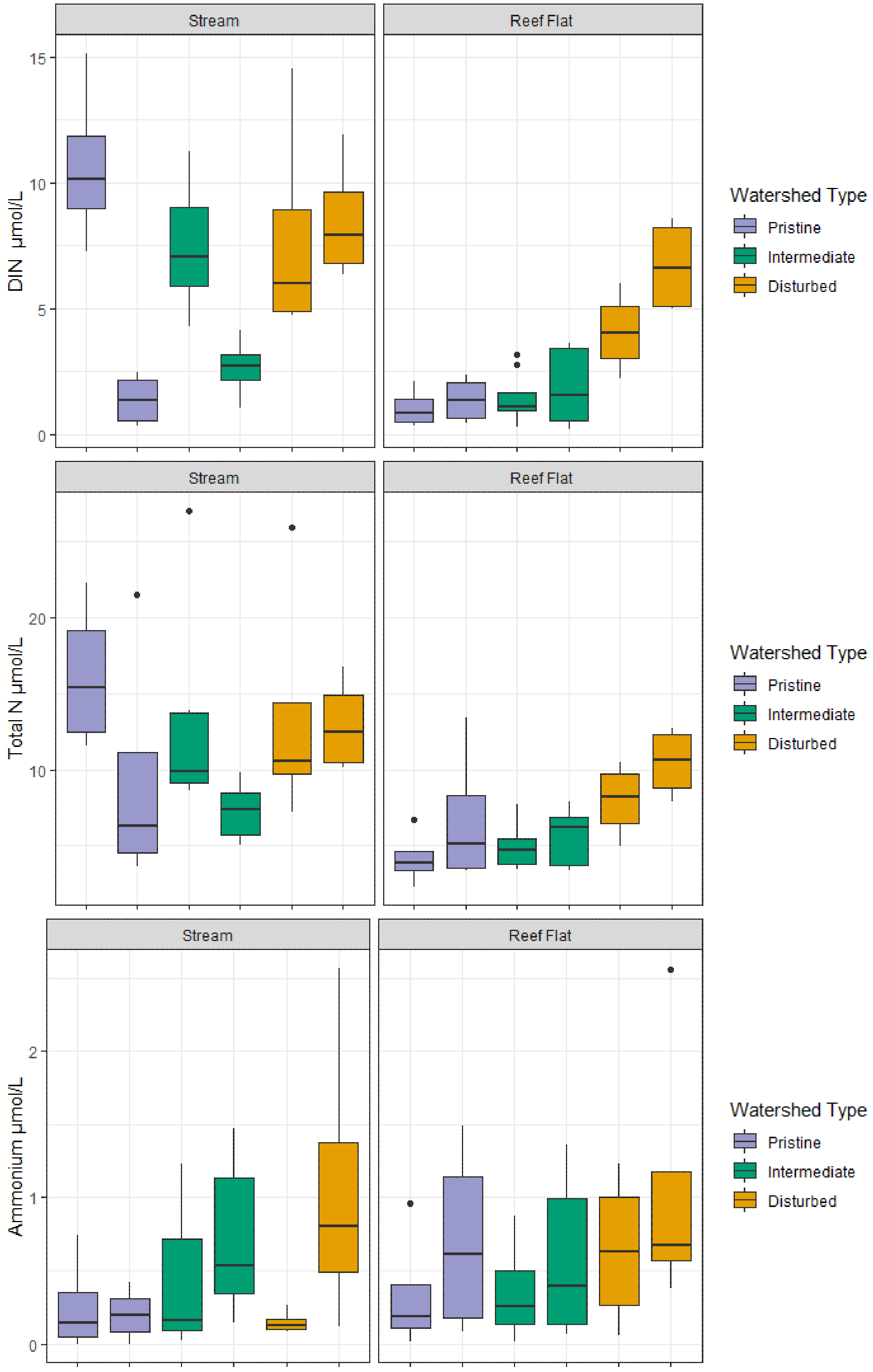
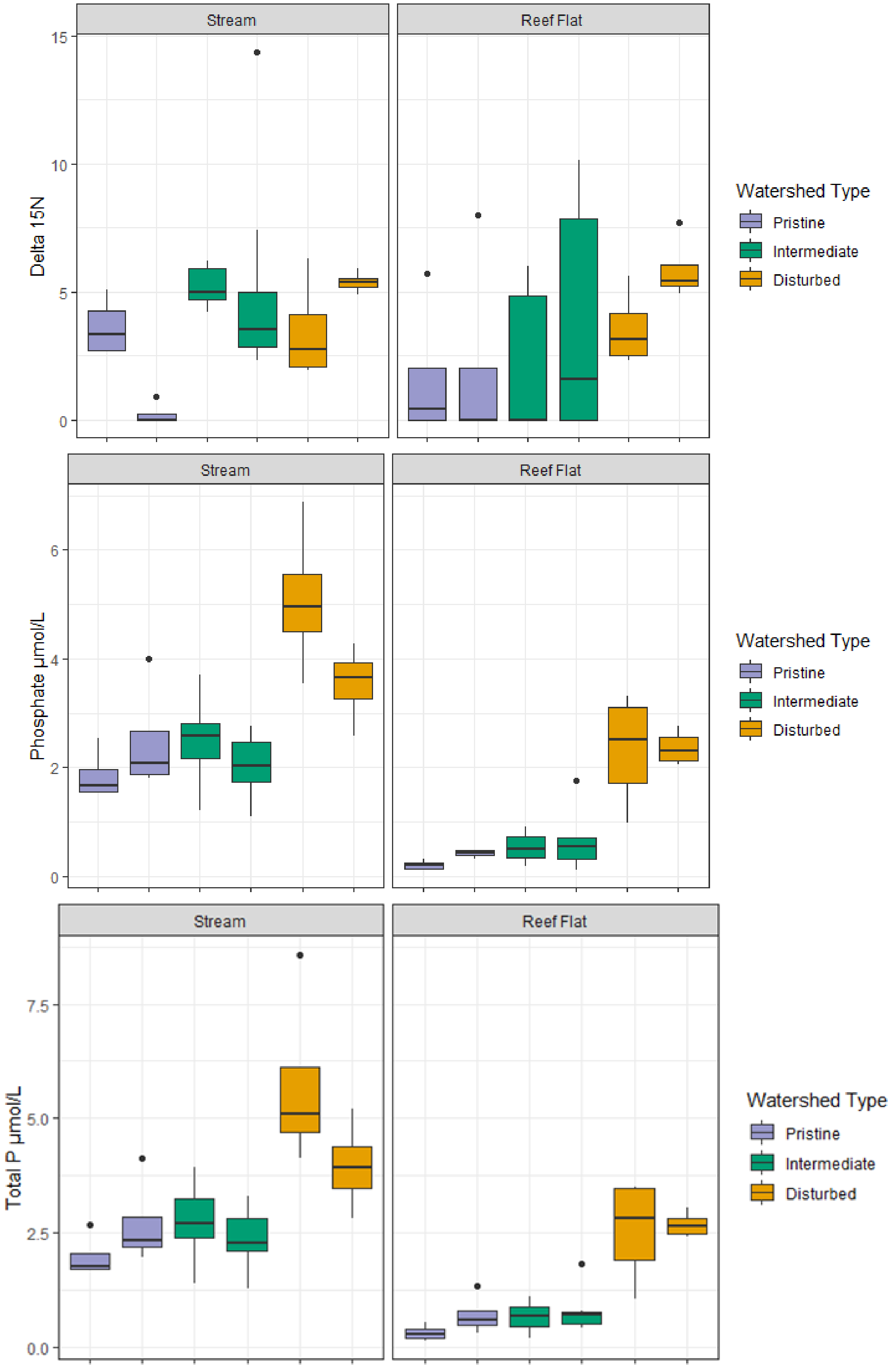


Figure S1. Percent cover of benthos across reef locations with black lines showing median values, boxes showing 25th and 75th percentile, and line showing 5th and 95th percentile of the data.


Stream
Reef Flat
DIN µmol/L
15
10
5
0
Watershed Type
Pristine
Intermediate
Disturbed
Stream
Reef Flat
Total N µmol/L
20
10
Watershed Type
Pristine
Intermediate
Disturbed
Stream
Reef Flat
Ammonium µmol/L
2
1
0
Watershed Type
Pristine
Intermediate
Disturbed


Stream
Reef Flat
Delta 15N
15
10
5
0
Watershed Type
Pristine
Intermediate
Disturbed
Stream
Reef Flat
Phosphate µmol/L
6
4
2
0
Watershed Type
Pristine
Intermediate
Disturbed
Stream
Reef Flat
Total P µmol/L
7.5
5.0
2.5
0.0
Watershed Type
Pristine
Intermediate
Disturbed

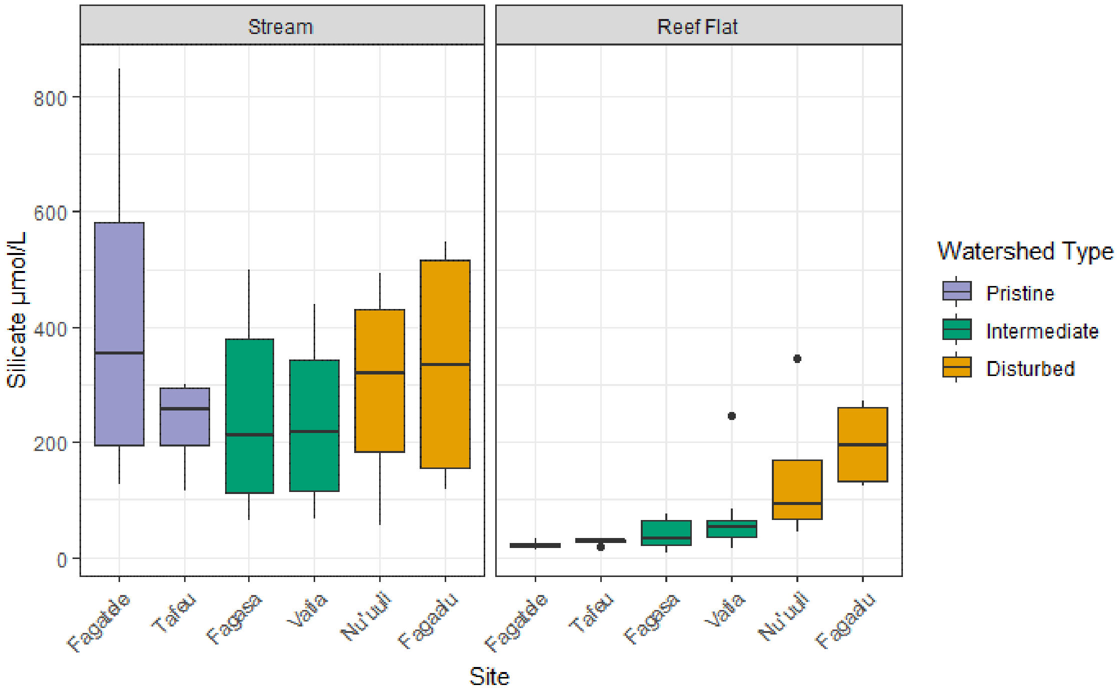
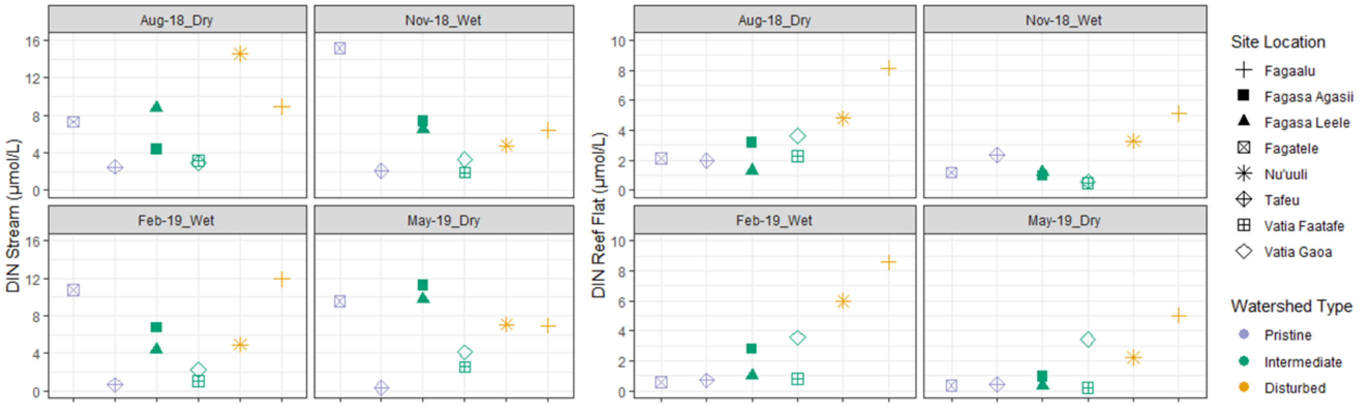
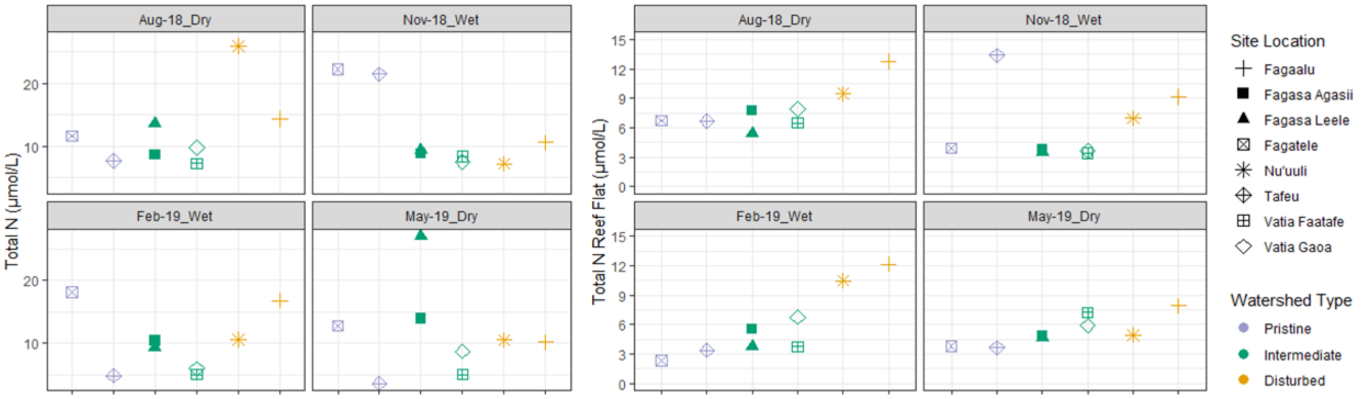


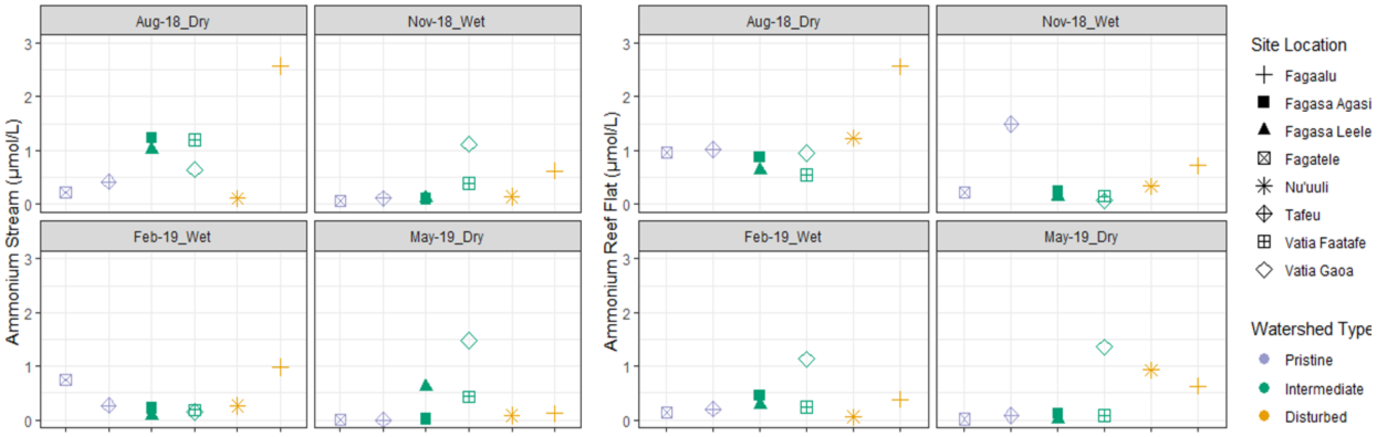
Figure S2. Nutrient concentrations (µmol/l) across all deployments by sampling location, with black lines showing median values, boxes showing 25th and 75th percentile, and line showing 5th and 95th percentile of the data.


DIN Stream (µmol/L)
Aug-18_Dry
Nov-18_Wet
Feb-19_Wet
May-19_Dry
0
4
8
12
16
DIN Reef Flat (µmol/L)
0
2
4
6
8
10
Site Location
Fagaalu
Fagasa Agasii
Fagasa Leele
Fagatele
Nu'uuli
Tafeu
Vatia Faatafe
Vatia Gaoa
Watershed Type
Pristine
Intermediate
Disturbed

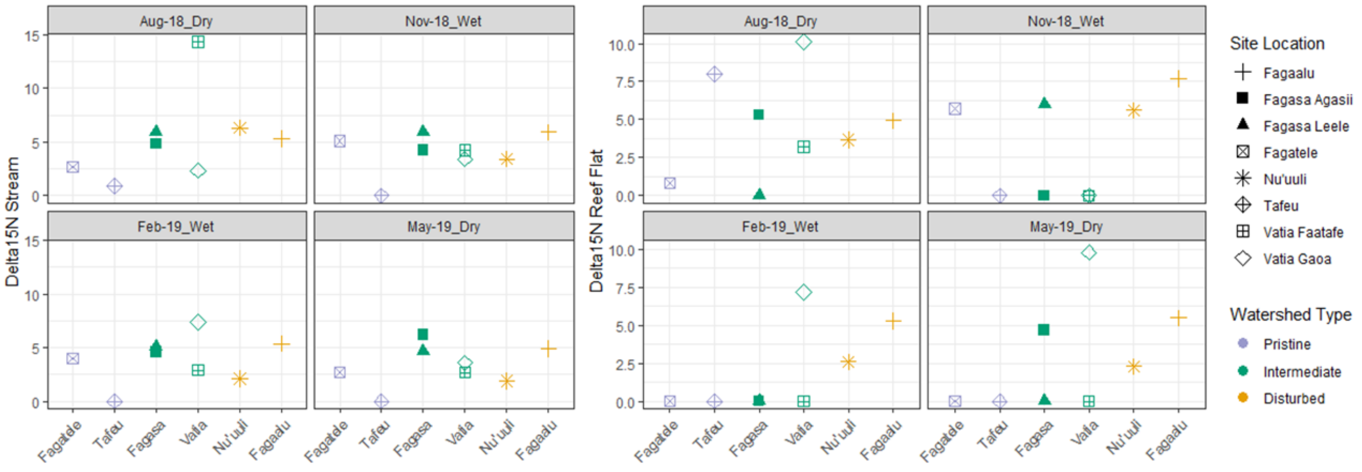
1


Total N (µmol/L)
Aug-18_Dry
Nov-18_Wet
Feb-19_Wet
May-19_Dry
10
20
Total N Reef Flat (µmol/L)
0
3
6
9
12
15
Site Location
Fagaalu
Fagasa Agasii
Fagasa Leele
Fagatele
Nu'uuli
Tafeu
Vatia Faatafe
Vatia Gaoa
Watershed Type
Pristine
Intermediate
Disturbed

2


Ammonium Stream (µmol/L)
Aug-18_Dry
Nov-18_Wet
Feb-19_Wet
May-19_Dry
0
1
2
3
Ammonium Reef Flat (µmol/L)
Site Location
Fagaalu
Fagasa Agasi
Fagasa Leele
Fagatele
Nu'uuli
Tafeu
Vatia Faatafe
Vatia Gaoa
Watershed Type
Pristine
Intermediate
Disturbed

3


Delta15N Stream
Aug-18_Dry
Nov-18_Wet
Feb-19_Wet
May-19_Dry
0
5
10
15
Fagatele
Tafeu
Fagasa
Vatia
Nu'uuli
Fagaalu
Delta15N Reef Flat
0.0
2.5
5.0
7.5
10.0
Site Location
Fagaalu
Fagasa Agasii
Fagasa Leele
Fagatele
Nu'uuli
Tafeu
Vatia Faatafe
Vatia Gaoa
Watershed Type
Pristine
Intermediate
Disturbed

4

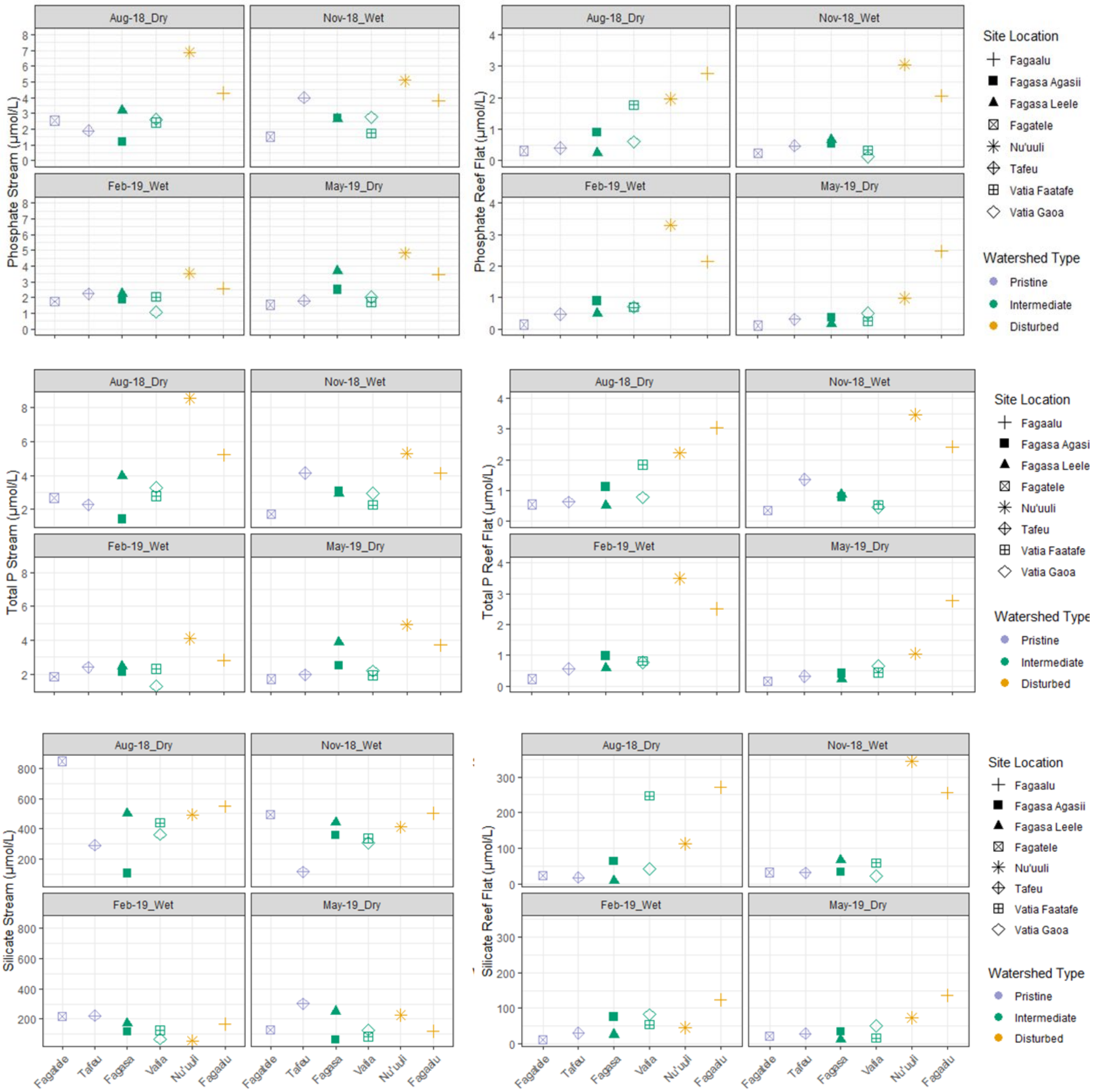


Figure S3. Nutrient concentrations for each sampling period collected from stream and reef flat locations.

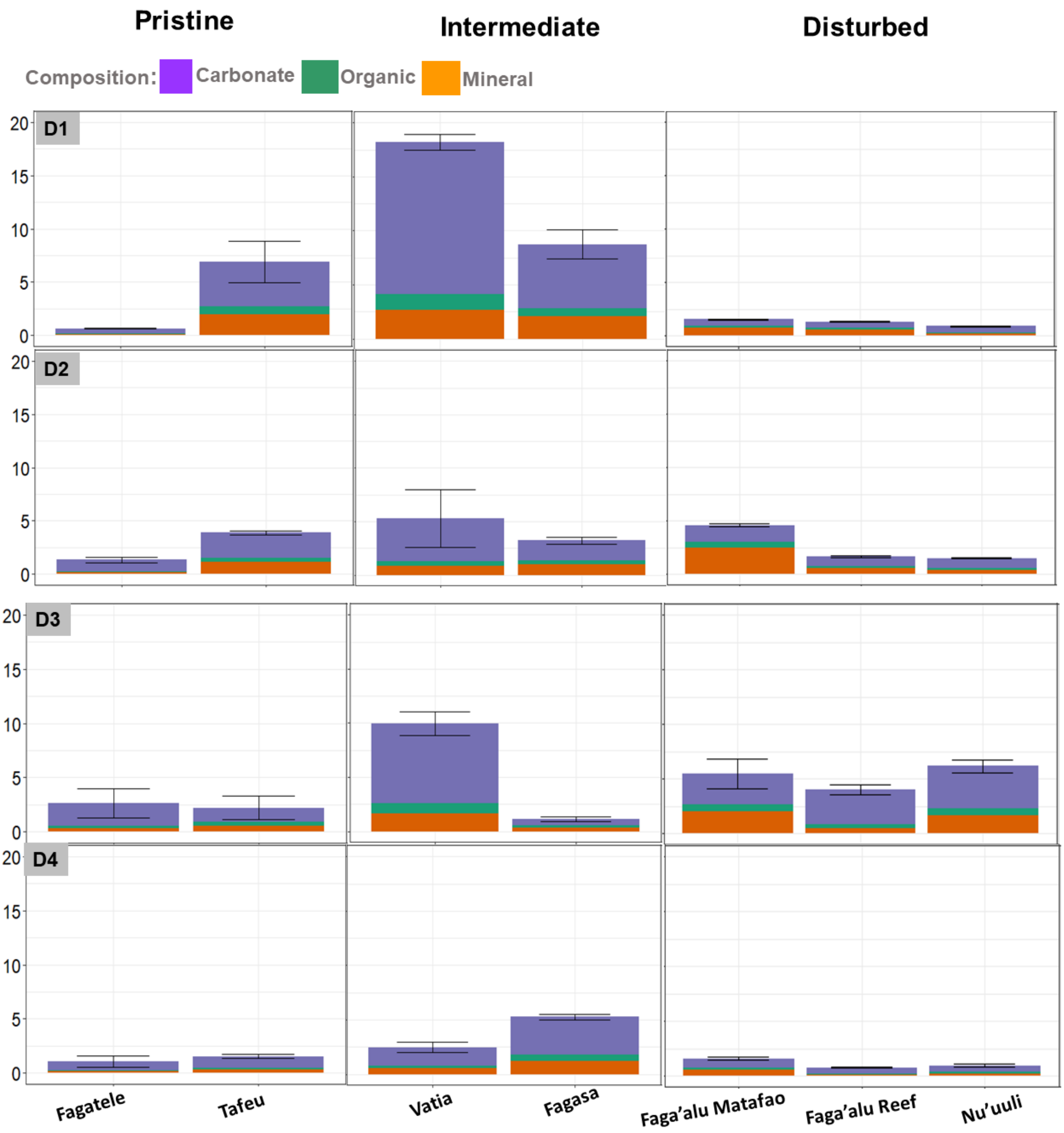


Figure S4. Pooled samples of carbonate, organic and mineral sediment composition is represented within each bar. D1 and D2 represent wet season deployments (Nov-18 – Feb-19; Feb-19 – May-19); D3 and D4 represent dry season deployments (May-19 – Sep-19; Sep-19—Nov-19).