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Report to the American Samoa Department of Commerce

Eutrophication comparison of coral reefs in Ofu and Olosega



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Ofu-Olosega nutrient study

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Background

Degradation of nearshore habitats is a serious problem in some areas of American Samoa, such as in Pago Pago Harbor on Tutuila Island, and is a smaller but chronic problem in other areas. Sedimentation, pollution, nutrient enrichment from surface runoff or groundwater, and trampling are the major factors causing the changes (Peshut and Brooks, 2005). The outer islands of Ofu and Olosega (Manu'a Islands; Fig. 1) have no perennial streams and a small and declining human population (approximately 500 residents), yet there is an interesting contrast between relatively pristine lagoon habitats not far from comparatively degraded lagoon habitats. To'aga lagoon on the southeast

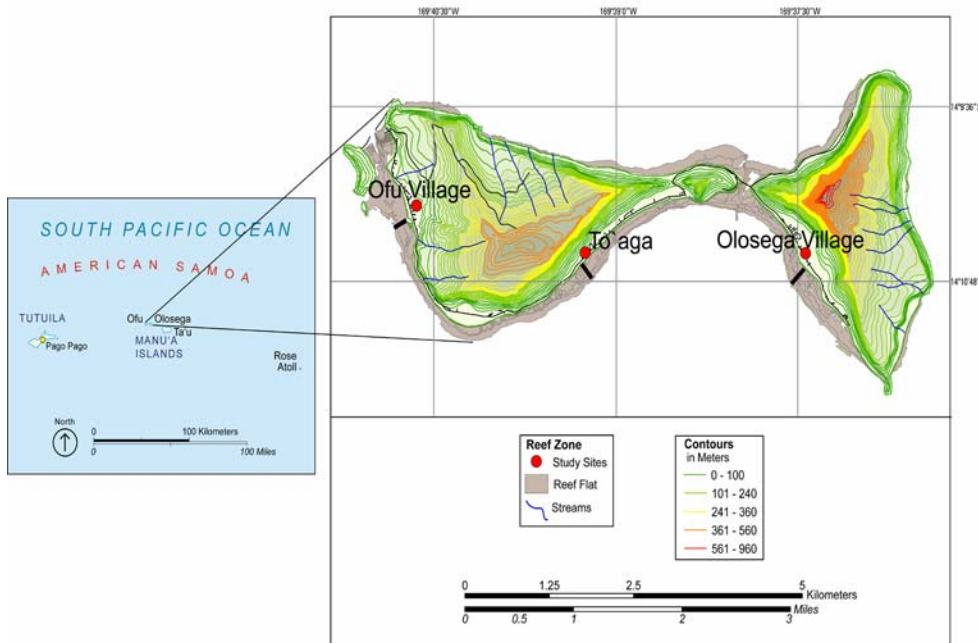


Figure 1. Map of American Samoa with inset map of Ofu and Olosega islands with elevation contours. Location of Ofu Village, Olosega Village, and the To'aga site indicated with red dots. Location of sampling transect at each site indicated by thick black line. Lagoon/reef-flat area, including reef-crest, appears in brown. (Graphic: L. Travers, USGS).

side of Ofu Island (Fig. 1) has clear waters, a high diversity of corals and fishes, no human habitations, and an undeveloped watershed with no streams. To'aga lagoon is within the boundaries of the National Park of American Samoa (NPAS) and is the site of long-term research on coral reef resilience and global climate change. Only 3 km to the east is a degraded lagoon that fronts Olosega Village. Olosega Village lagoon is similar in size but has significantly less live coral than To'aga, and blooms of filamentous algae have been reported to cover the Olosega lagoon/reef-flat bottom (unpublished data, P.

Craig, 2005; Fig. 2). Local factors operating on the scale of a kilometer or less are thought to be driving the differences observed between lagoons, because the islands are influenced by the same regional-scale and biogeochemical regimes, and both are remnants of a single volcanic caldera (Craig, 2005). Land disturbance is limited to a road linking the villages, the clearing of vegetation for buildings, and two village dump sites located on the narrow strip of land between the steep slopes of the islands and the shoreline; there is no industry or associated pollution on either island. Cesspools are used for sewage disposal. Nutrient enrichment (from cesspools) of groundwater and the lagoon, as well as trampling during gleaning of reef organisms, are possible factors affecting the spatial relief and benthic composition of the lagoons. A pristine lagoon site (To'aga) and two that may be influenced by adjacent human populations (Ofu and Olosega villages) were selected for study.



Figure 2. Filamentous algal bloom (most likely a blue-green alga) in Olosega lagoon, nine days after Hurrigan Olaf (January 2005). Image: P. Craig, NPAS.

Analysis of nutrients in lagoon waters is not the most effective method for detecting nutrient influx because of the rapid removal and recycling of nutrients from seawater by plankton and macroalgae (also known as seaweeds; e.g., Atkinson, 1988). Unlike some marine organisms and plants, macroalgae are known to incorporate nutrients directly from the water column and store excess nutrients in their tissues, providing an integrated record of nutrient influx (Fong and others, 1994). Thus, macroalgae may better provide a history of nutrient influx to a site compared to other organisms. For example, cyanobacteria can directly fix nitrogen (Howarth and others, 1988); rooted plants such as sea grasses primarily take up nutrients from sediments and interstitial water and not directly from the water column (Paling and McComb, 1994; Erftemeijer and

Middleburg, 1995); and coral reef organisms incorporate nutrients from symbionts or ingested plants and/or other organisms (Mills and others, 2004).

To investigate the relative differences in nutrient influx to each of the lagoons, we analyzed tissue from the two most common species of macroalgae for nitrogen content. To determine the source of nutrients to each of the lagoons, we examined the nitrogen isotope content of the macroalgae found on the reef flats in front of both villages (Olosega and Ofu, Fig. 1) and compared those sites with the relatively pristine lagoon/reef flat in front of To'aga (Fig. 1). Biological processes usually result in fractionation of the isotopes of elements (such as nitrogen and carbon) incorporated by organisms and plants (Minagawa and Wada, 1984). The ratio of ^{15}N to ^{14}N {more specifically the $\delta^{15}\text{N}$ (in ‰) = $[(^{15}\text{N}/^{14}\text{N} \text{ sample}) / (^{15}\text{N}/^{14}\text{N} \text{ atmospheric nitrogen}) - 1] \times 1000$ } in tissue has been reported to be effective in distinguishing between sources of nitrogen (e.g., atmospheric deposition, fertilizer, nitrogen fixation, and animals or plants; Peterson and Fry, 1987) and trophic level (the higher the trophic level, the greater the $\delta^{15}\text{N}$; e.g., Minagawa and Wada, 1984). Atmospheric deposition and fertilizers have relatively low $\delta^{15}\text{N}$ values (-12 to +5‰ and -3 to +3‰, respectively; Kreitler and Browning, 1983; Russell and others, 1998). $\delta^{15}\text{N}$ values of +5 to +22 ‰ are reported to indicate that nitrogen from animals may be present, with highest values (+10 to +22‰; Kreitler and Browning, 1983; Aravena and others, 1993) associated with septic and wastewater systems. Distinguishing between multiple animal and human sources is not as well defined.

Methods

Study sites

This study was conducted at Ofu and Olosega islands (in the Manu'a island group), which are located 96 km ENE of Tutuila, American Samoa (Fig. 1). Three study sites were selected: two reef flats off Ofu Island (one seaward of Ofu Village and the other at a "pristine" site with no human settlement, To'aga); and a reef flat off Olosega Island seaward of Olosega Village (Fig. 1). Sampling transects ran from shore to the reef-crest at each of the three locations and were sited to avoid proximity to openings in the reef and associated strong currents (Fig. 1). The width of the reef flat at low tide determined the transect length at a site (Table 1).

Ofu Village and reef flat (hereafter "Ofu") are located on the western shore of Ofu Island (Fig. 1). Ofu Village lagoon is influenced by open-ocean swells from the north, west, and south and has two openings in the reef ("avas"). Two ephemeral streams empty into Ofu Village lagoon. Approximately 250 people live in Ofu Village and use cesspools for sewage disposal. Soils are sandy with relatively low organic-carbon content.

To'aga is on the southeastern shore of Ofu Island (Fig. 1). To'aga is most influenced by swells from the east, south and southwest and has one small pass in the reef and a channel on the eastern end of the island. To'aga has an undeveloped watershed with no streams; a garbage dump is sited on land approximately 1.3 km northeast (and downcurrent) of the To'aga site.

Table 1. Transect length, depth range, salinity (parts per thousand, ppt), distance from shore to sampling stations at each site; location of sites.

Site	Shore-to-reef-crest transect meters	Depth (m) range low tide	Mean salinity (ppt ± sd)	Distance (m) from shore to sampling stations	Latitude/longitude
To'aga	170	0.3 – 3.5	36.7±0.4	1, 27, 86, 128, 173	14°10'45"S, 169°39'10"W
Ofu	111	0.1- 1.0	35.9±0.7	5, 29, 56, 84, 111	14°10'30"S, 169°40'48"W
Olosega	186	0.1 – 1.2	36.8±0.3	3, 48, 94, 140, 186	14°10'48"S, 169°37'25"W

Olosega Village and reef flat (hereafter “Olosega”) are on the western shore of Olosega Island (Fig. 1). Olosega lagoon is most often influenced by swells from the southeast to northwest and has one ava in front of the village and a channel past the west end of the island. No streams discharge into Olosega Village lagoon. Approximately 250 people live in Olosega Village. Sewage is disposed of using cesspools sited in sandy soils with relatively low organic carbon content.

Large swells from the open Pacific break on the reef-crests at all sites, delivering large quantities of water to the relatively shallow reef flats. Strong currents are created as these large masses of ocean water are pushed along the shore and out to sea via small openings in the reef. Ocean waters continually flush the reef flats even during low tide, when lower volumes of water break over the reef-crest, resulting in less forceful currents.

Of the 60 species of green algae reported from American Samoa (Skelton, 2003), only two, *Dictyosphaeria versluysii* Weber-van Boese (Fig. 3A) and *Halimeda* sp. (Fig. 3B), were common at all study sites. The green filamentous alga, *Chlorodesmis fastigata* (C. Agardh) Drucker (Fig. 3C), was occasionally observed at To'aga, but rarely along the Ofu or Olosega transects. A blue-green alga (possibly *Lyngbya* sp.; Fig. 3D) was infrequently observed at To'aga and Olosega and not observed along the Ofu transect.



Figure 3 A: *Dictyosphaeria versluysii*

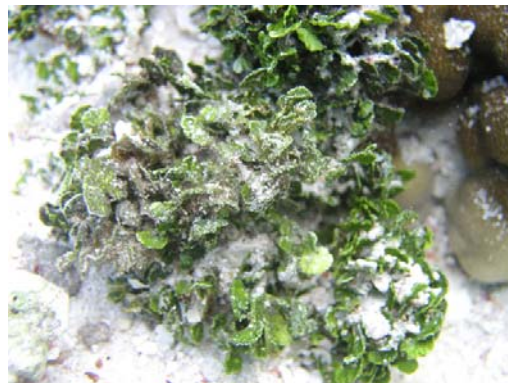


Figure 3B. *Halimeda* sp.

Field sampling

Five replicate samples of the two most common species of macroalgae (*Halimeda* sp. and *Dictyosphaeria versluysii*) were collected at each of five stations located on each transect: 3 m from shore; at distances $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of the transect length, and at the shoreward edge of the reef-crest (Table 1). No samples were collected from forereef sites due to the lack of macroalgae at those stations. Whole algal organisms (without rhizoids or holdfasts) were collected by hand using disposable gloves, cleaned of detritus and invertebrates, and immediately placed in individual Ziploc bags with seawater. All macroalgae and water samples were collected during periods of low tide between 24 May and 4 June 2006. A water sample for salinity testing was collected concurrently with each seaweed sample. Additional water samples were collected at each of the sites and from freshwater wells at Olosega and Ofu villages for nutrient analysis [nitrate, ammonia, dissolved inorganic nitrogen (DIN) and phosphate].



Figure 3C. *Chlorodesmis fastigata*



Figure 3D. Unidentified blue-green alga

Benthic cover

Benthic cover along each transect was quantified and a coral species list created using the point intercept method (Loya, 1972). One individual (DF) identified the substrate, to the lowest taxon for organisms, at 0.5-m intervals along each transect (Fig. 4 A, B).

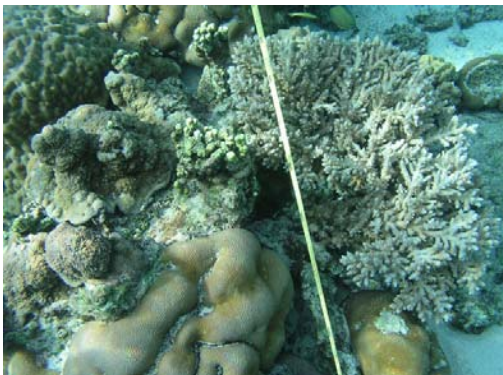


Figure 4A. Transect tape in place on transect



Figure 4B. Diver identifying substrate on sea-bottom

Laboratory

More than 200 macroalgae samples were further cleaned of sand and fouling organisms in the lab, rinsed with fresh water, placed in aluminum weighing boats, and dried at 60°C until constant weight. Individual samples were ground into a fine powder, transferred to scintillation vials and placed in a desiccator. A 5 to 9-mg subsample of each powdered *Halimeda* sp. sample was transferred into a tin capsule, weighed and sealed for $\delta^{15}\text{N}$ analysis. Because single *D. versluysii* samples did not provide the minimum weight needed for stable-isotope analysis, five replicates per station were pooled, mixed thoroughly, and three 5 to 9-mg subsamples were transferred into tin capsules, weighed, and sealed for $\delta^{15}\text{N}$ analysis. The limited number of green filamentous and blue-green algae samples was pooled by species and site, mixed thoroughly, transferred to tin capsules, weighed, and sealed for $\delta^{15}\text{N}$ and for $\delta^{13}\text{C}$ analyses. Replicate *Dictyosphaeria* samples from each station were subsampled, subsamples pooled, weighed in tin capsules, and sealed for $\delta^{13}\text{C}$ analysis. Replicate *Halimeda* sp. samples from each station were subsampled, subsamples pooled, placed in scintillation vials, a few drops of concentrated HCl added, and placed in a desiccator overnight. Inorganic C in the samples was released as CO_2 , leaving the organic C. Treated samples were dried at 60°C to remove HCl, 1 to 4 mg of sample weighed in tin capsules, and capsules sealed for $\delta^{13}\text{C}$ analysis. Macroalgae samples were analyzed for $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ at the University of California at Davis Stable Isotope laboratory specializing in isotope-mass ratio spectrometry. Nutrient concentrations in water samples ($\text{NO}_3^- + \text{NO}_2^-$, PO_4^{3-} , NH_4^+) were analyzed by colorimetric techniques (Lachat QuickChem 8000 autoanalyzer, Woods Hole Oceanographic Institution, Nutrient Analytical Facility). Nitrate and nitrite were not separately quantified, and in this report their sum is referred to as “ NO_3^- .” Total dissolved nitrogen (TDN) was measured using persulfate digestion (D’Elia and others, 1977). Dissolved organic nitrogen (DON) concentration was calculated as $\text{DON} = \text{TDN} - \text{NO}_3^- - \text{NH}_4^+$. Salinity of water samples was determined using a refractometer. ANOVA statistical analysis was used to test for differences in $\delta^{15}\text{N}$ values of *Halimeda* sp. and *Dictyosphaeria versluysii* among stations and sites.

Results

Overall, macroalgal cover was noticeably low at all lagoon sites (Fig. 5), with *Halimeda* sp. and *Dictyosphaeria versluysii* the predominant species and *Chlorodesmis fastigata* a distant third. Living coral cover was lowest on the Olosega (6.47%) and Ofu (10.05%) transects and highest at To’aga (22.81%; Fig. 5). A greater number of coral species occurred directly on the To’aga transect (10) than the Ofu and Olosega transects (6 species each; Table 2).

The $\delta^{15}\text{N}$ values of the individual macroalgae samples ranged from -0.4 to +5.5‰ (Table 3), indicating sites that seem to be most influenced by oceanic and/or atmospheric and not anthropogenic sources. Salinity measurements did not show a significant freshwater influence at any sites or stations sampled (Fig. 6). However, salinity was slightly lower, but not significantly so, in samples from the station nearest to shore in Ofu lagoon, most likely due to a freshwater stream that emptied into Ofu lagoon (Fig. 1).

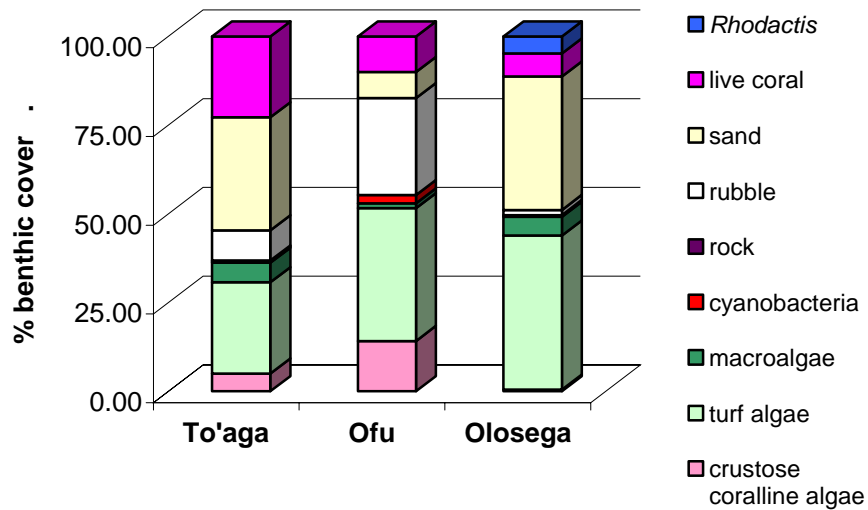


Figure 5. Percent benthic composition along the sampling transect at each site.

Table 2. Percent live coral of each reef-crest-to-shore transect, by species and overall.

% of benthic cover on transect	To'aga	Ofu	Olosega
<i>Acropora akajimensis</i>	0.29		
<i>Acropora aspera</i>		6.39	0.24
<i>Acropora pulcra</i>		0.46	
<i>Goniastrea edwardsi</i>	1.75		
<i>Goniastrea retiformis</i>	1.75		
<i>Leptoria phrygia</i>	0.58		
<i>Montipora encrusting</i>	2.34		
<i>Montipora mushroom</i>			0.24
<i>Pavona frondifera</i>	1.17		1.92
<i>Pavona venosa</i>	0.29		
<i>Porites annae</i>		0.91	
<i>Porites cylindrica</i>		1.37	3.36
<i>Porites massive</i>	2.63		
<i>Porites sp.</i>	10.53		0.48
<i>Porites sp. 2</i>	1.46	0.46	0.24
<i>Psammocora contigua</i>		0.46	
Total % live coral on transect	22.81	10.05	6.47
% live coral per meter	0.13	0.09	0.03

Halimeda sp. $\delta^{15}\text{N}$ values appeared to be quite different from *Dictyosphaeria versluysii* (3-5‰ in *Halimeda* sp. and 0-1‰ in *D. versluysii*), indicating differences in assimilation and biochemistry (Table 3). $\delta^{15}\text{N}$ values for *Chlorodesmis fastigata* (4 -5‰) were similar to those for *Halimeda* sp. (Table 3). There was no correlation between $\delta^{15}\text{N}$ values for *D. versluysii* or *Halimeda* sp. and distance from shore (Fig. 7). The lack of *Chlorodesmis fastigata* samples from Ofu and Olosega transects precluded analysis of $\delta^{15}\text{N}$ and distance from shore.

Table 3. Comparison of $\delta^{15}\text{N}$, total nitrogen, and carbon-to-nitrogen content of macroalgae by species. The number of *C. fastigata* samples from all sites were not equal.

	$\delta^{15}\text{N}$ (‰)	%N	C:N
	all sites	all sites	all sites
	mean±sd	mean±sd	mean±sd
<i>Dictyosphaeria versluysii</i>	1.03±0.66	0.88±0.17	12.58±3.12
<i>Halimeda</i> sp.	3.81±0.59	0.62±0.15	13.78±7.36
<i>Chlorodesmis fastigata</i>	4.75±0.41	3.97±0.53	9.65±1.10

Dictyosphaeria versluysii

There was no significant difference in *Dictyosphaeria versluysii* $\delta^{15}\text{N}$ values among the three sites ($p=0.44$; Table 4). There was a significant difference in $\delta^{15}\text{N}$ values among stations at Ofu ($p = 0.002$) with highest values near the reef-crest (Fig. 7); a highly significant difference among stations at Olosega ($p=0.000025$; Table 4); and no significant difference among stations at To'aga ($p= 0.025$; Table 4). At Olosega, highest $\delta^{15}\text{N}$ values occurred at nearshore and reef-crest stations (Fig. 7).

Table 4. Macroalgae $\delta^{15}\text{N}$ (‰) differences among stations and among sites by species. SD= standard deviation; s =statistically significant; ns = not statistically significant ($\alpha = 0.05$).

<i>Dictyosphaeria versluysii</i>	mean	sd	p	
To'aga (among stations)	1.306	0.289	0.0246	s
Ofu (among stations)	0.993	0.925	0.0021	s
Olosega (among stations)	0.789	0.539	0.000025	s
Among sites	1.029	0.662	0.4405	ns
<i>Halimeda</i> sp.	mean	sd	p	
To'aga (among stations)	4.45	0.48	0.014	s
Ofu (among stations)	3.47	0.41	0.06	ns
Olosega (among stations)	3.61	0.38	0.022	s
Among sites	3.81	0.59	0.0004	s

Halimeda sp.

There was a significant difference in *Halimeda* sp. $\delta^{15}\text{N}$ values among sites ($p=0.0004$), with To'aga (4.45 ± 0.48) greater than Ofu (3.47 ± 0.41) and Olosega (3.61 ± 0.38 ; Table 4). There was no significant difference in $\delta^{15}\text{N}$ among stations at Ofu ($p = 0.0598$); and a significant difference among stations at Olosega ($p=0.022$) and To'aga ($p = 0.014$; Table 4), with values generally increasing from shore to the reef-crest (Fig. 7).

Chlorodesmis fastigata

The green filamentous alga, *Chlorodesmis fastigata*, contained a relatively higher percent of nitrogen (mean = 3.97 ± 0.53) than *Dictyosphaeria versluysii* (0.88 ± 0.17), which exceeded that of *Halimeda* sp. (0.62 ± 0.15 ; Table 3). Nutrient data for the three macroalgae species could not be compared statistically because of fewer and unequal numbers of samples of *C. fastigata* from the three sites. Replicate samples of *C. fastigata* could be collected only at To'aga because the species was rarely observed at Ofu and infrequently seen at Olosega. Thus, the number of samples per site varied greatly (1-25). Carbon-to-nitrogen ratios in all species of macroalgae (no replicate C samples) were much lower than typical Redfield ratios reported from the open ocean (C:N = 6.625; Table 3).

Water samples

Nitrate, ammonia, and DIN levels were low in lagoon-water samples from all sites and not considered high for well/groundwater samples (Table 5). Phosphate levels in well water were higher in Olosega than Ofu samples. Similarly, phosphate concentrations in lagoon-water samples were highest from Olosega (Table 5). High silica concentrations in groundwater were most likely from the volcanic rock that forms the islands.

Table 5. Concentrations (μM) of ammonium (NH_4^+), silicate (SiO_4^{4-}), phosphate (PO_4^{3-}), nitrate (NO_3^-), dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), and total dissolved nitrogen (TDN) in water collected from Ofu and Olosega May/June 2006. There are no replicates for water samples due to logistical problems shipping volumes of frozen water.

	NH_4^+ μM	SiO_4^{4-} μM	PO_4^{3-} μM	NO_3^- μM	DIN μM	DON μM	TDN μM
To'aga mid-lagoon	0.6	1.9	0.1	0.1	0.7	5.1	5.8
Ofu mid-lagoon	0.7	7.9	0.2	0.3	1.0	6.5	7.5
Olosega mid-lagoon	0.1	2.8	1.7	<0.05	0.1	4.8	4.8
Olosega nearshore lagoon	0.3	4.4	2.7	0.3	0.5	7.7	8.2
Ofu well (fresh)	0.2	469.0	2.1	7.5	7.6	3.6	11.2
Olosega well (fresh)	0.2	302.0	4.5	26.1	26.3	8.5	34.8

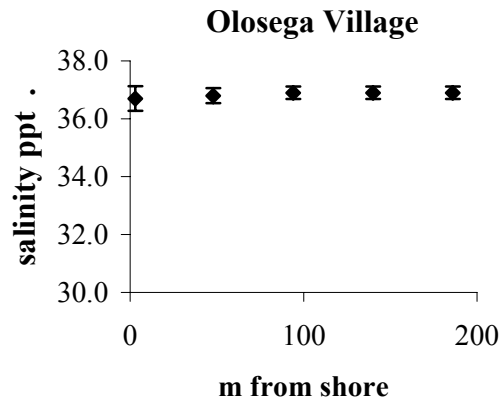
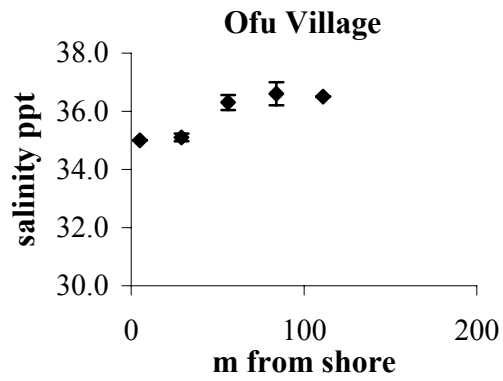
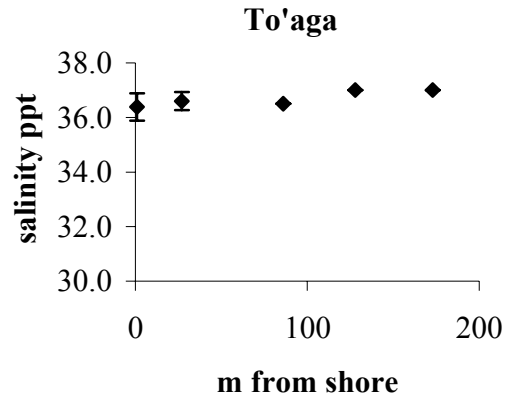
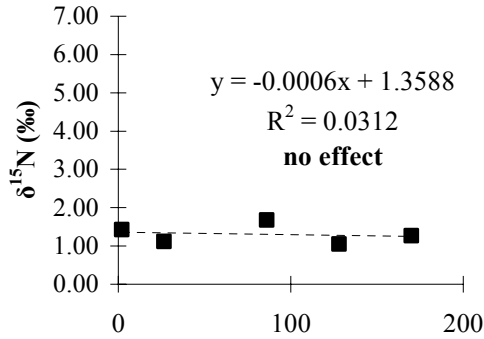
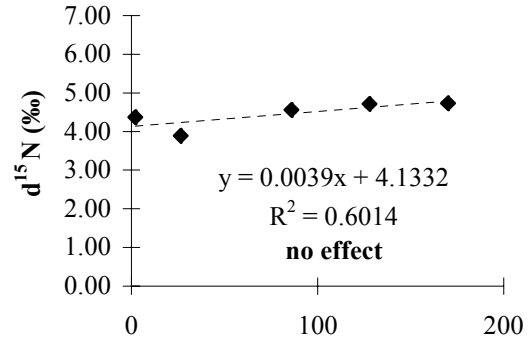


Figure 6. Mean salinity values (parts per thousand, ppt) with distance from shore at the three lagoon sites, May/June 2006.

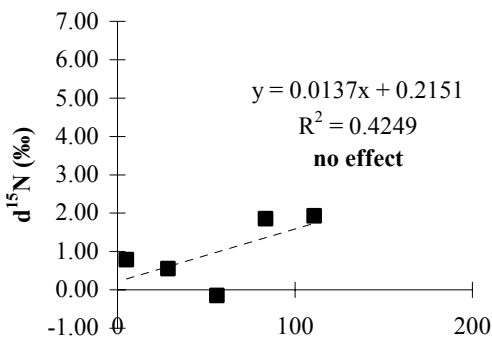
To'aga *Dictyosphaeria versluysii*



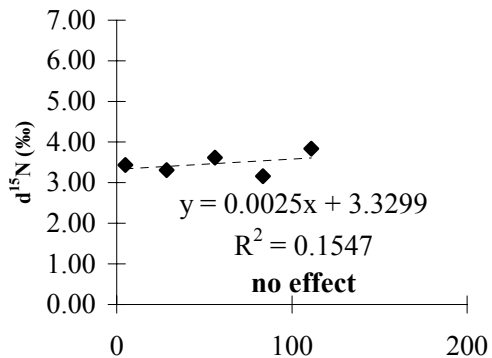
To'aga *Halimeda*



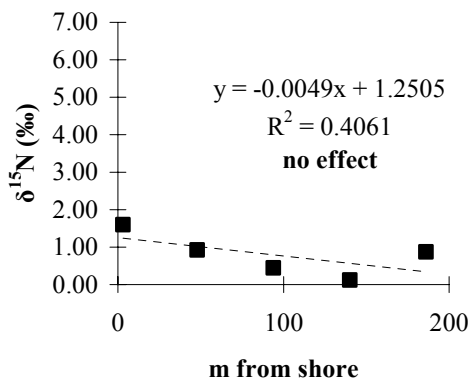
Ofu Village *D. versluysii*



Ofu Village *Halimeda*



Olosega Village *D. versluysii*



Olosega Village *Halimeda*

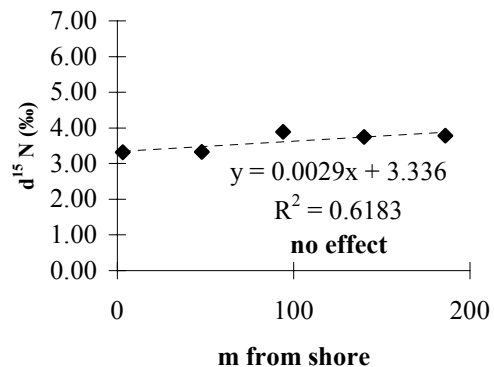


Figure 7. $\delta^{15}\text{N}$ values of *Dictyosphaeria versluysii* (left column) and *Halimeda* sp. (right column) with distance from shore at the three lagoon sites May/June 2006. Linear regression lines (dashed), equations, and correlation coefficients (r^2) show no significant effect of distance from shore on $\delta^{15}\text{N}$ values.

Discussion

The nitrogen content (percent total nitrogen, concentration of the heavier nitrogen isotope ^{15}N , and $\delta^{15}\text{N}$ values) of macroalgae varies by species (due to physiology and biochemical processes), light regime, temperature, and availability of nitrogen and ^{15}N content of the water (e.g., Heikoop and others, 1998; Cohen and Fong, 2006). Values of $\delta^{15}\text{N}$ in this study (Table 3) were close to or lower than those reported for oligotrophic suspended particulate matter (4-5‰; Waser and others, 2000), pelagic and coastal marine seaweeds (5-8‰; Minagawa and Wada, 1984), and euphotic layer DIN (7-10‰; Minagawa and Wada, 1986). The low $\delta^{15}\text{N}$ values of the macroalgae, the low nutrient concentrations of lagoon waters, the lack of correlation between $\delta^{15}\text{N}$ values and distance from shore, and the low concentrations of nutrients in well-water samples indicate that the major sources of nutrients to the three Ofu-Olosega lagoons at the time of this study were most likely oceanic/atmospheric, and not animal/anthropogenic in origin. In contrast to this study, Umezawa and others (2002) found an inverse linear or curvilinear decrease in $\delta^{15}\text{N}$ values of macroalgae with distance from shore in the Ryuku Islands, Japan. This pattern was attributed to multiple sources of nitrogen, including terrestrial and human. Cohen and Fong (2006) reported $\delta^{15}\text{N}$ in macroalgae decreased with distance from the head of estuaries in California during the dry season, due to a greater $\delta^{15}\text{N}$ content of DIN from the watershed than oceanic sources. Similarly, the $\delta^{15}\text{N}$ in rooted macroalgae (not free-floating) was found to increase significantly with increased influx of sewage-nitrogen to estuaries in the northeastern U.S. (Cole and others., 2005).

In the lagoons of Ofu and Olosega islands, high volumes of oceanic waters and strong currents flush the lagoons daily and would be expected to dilute nutrient input from land rapidly. Under high-flow regimes, oligotrophic waters are able to provide sufficient nutrients for algal growth, but storage of nutrients in algal tissues is limited due to both low residence time and low nutrient concentrations of the water (Larned and Atkinson, 1997). When high concentrations of nutrients are available, from episodic pulses to sustained high concentrations, some macroalgae store nutrients in their tissues (Wheeler and North, 1980; Lapointe and Duke, 1984; Fong and others, 1994). However, Fong and others (2003) found there is not a direct correlation between nutrient concentrations in water and macroalgae tissue. The nutrient content of tropical marine algae affects the organism's response to N and P influx, be it growth or storage. Thus, the history of available nutrients combined with the biochemistry of the macroalgae species drive the responses observed in the field (Fong and others, 2003). Whereas some macroalgae incorporate nutrients only from the water column, others can access nutrients in sediments, from adjacent heterotrophs (such as the scleractinian corals to which *Dictyosphaeria versluysii* attaches; Larned and Stimson, 1996), or, in the case of some cyanobacteria, from fixation of nitrogen (Howarth and others, 1988). *Halimeda* and *Dictyosphaeria* (Division Chlorophyta) are rhizophytic algae and can access nutrients from the water as well as from sediment via holdfasts (Littler and Littler, 1990). Larned and Stimson (1996) found that *D. cavernosa*, closely related to *D. versluysii*, has low N storage capacity and needs a continual supply of DIN. The close attachment of *D. cavernosa* (and presumably *D. versluysii*) to the substrate creates space between the alga and live coral wherein ammonium concentrations are two-fold, and nitrate+nitrite

concentrations are 10-fold greater than that of the water column (Larned and Stimson, 1996). The lack of stored nitrogen (%) in *Dictyosphaeria* was evident in the data from this study (Table 3).

The molar C:N ratio in most phytoplankton is 106:16 (or 6.6; Redfield and others, 1963) when nutrients are not limiting. In tropical epilithic macroalgae in Atlantic oligotrophic waters that are N limited, the C:N ratio is reported to range from 14-28 and to vary by species (Lapointe and others, 1992). The C:N and %N data in this study may indicate that *Dictyosphaeria* and *Halimeda* are more N limited than *Chlorodesmis* at all sites (Table 3). Alternatively, the observed difference between species could be due to: a higher structural C content in *Dictyosphaeria* and *Halimeda*; and/or, the enhanced ability of *Chlorodesmis* to assimilate nitrogen from the environment or to store nitrogen than *Dictyosphaeria* or *Halimeda*. The C:N ratio was consistently, but not significantly, higher at the To'aga site for the three macroalgae species, which could be due to a lower supply of DIN at the site.

Ofu and Olosega well-water nutrient levels from this study (Table 5) were within the range of American Samoa EPA values for Oct 2001, Jan and Dec 2003 samples (< 0.2 - 8.7 μM Ofu; <0.2 - 43 μM Olosega). Other than relatively high phosphate levels in the well-water samples, well-water nutrient levels were within normal groundwater concentrations, at the time of this study. Other sources of nutrients to the lagoons include episodic intense rainfall events that could flush nutrients from the upland watersheds and from reservoirs (such as cesspools) in the sandy soil into the lagoons. Hurricanes produce high seas and battering waves that can inundate the coast for tens of meters inshore and wash nutrients from the sandy soil into the lagoons. Nearshore marine communities adjacent to villages with cesspools, pig farms, and other domestic animals would be expected to receive a concentrated pulse of nutrients that could be quickly utilized by filamentous algae that can rapidly take up nutrients from the water and grow quickly. If lagoon substrate was exposed by removal of sand or turf algae, as often occurs during storms, an opportunistic filamentous alga could colonize, grow rapidly, and produce a "bloom". Hurricanes and other strong storms produce oceanic upwelling, where deep, cooler, nutrient-rich waters are brought to the surface (Babin and others, 2004). Storm-induced upwelling in conjunction with tidal pumping and surface runoff from land could provide a considerable source of nutrients to the nearshore waters. All of these mechanisms could fuel algal blooms nearshore. During a hurricane damage survey conducted by the National Park of American Samoa nine days after Hurricane Olaf, a filamentous alga bloom was observed in Olosega lagoon (P. Craig.; Fig. 2, January 2005). Yet no macroalgae blooms were observed off To'aga or on the north side of Ofu at that time. It is probable that an influx of nutrients flushed from the adjacent village via intense rainfall, tidal pumping, and inundating storm waves stimulated the bloom. However, data from this study, conducted 18 months later, do not support or refute this speculation. To determine the specific drivers for this system, nutrient influx from land and from upwelling, as well as the role of space availability will need to be examined.

Identifying the drivers of macroalgae blooms is often not straightforward. For example, a large-scale macroalgae bloom has been reported on coral reefs over a wide geographic area in the northern Great Barrier Reef and 15 to 20 km from known anthropogenic sources (Burgess, 2006). Is this the result of nutrient influx, loss of herbivores/changes in trophic structure, a predator outbreak that opens substrate to

colonization, changes in physiology that alter algae-coral dynamics, or a combination of factors? Are nutrient sources atmospheric, oceanic, from groundwater, rivers, or point sources? Our understanding of the major factors driving macroalgal blooms on coral reefs is far from complete.

We suggest that the lagoons in front of Ofu and Olosega Villages may have less live coral and fewer species than the lagoon at To'aga because:

- reef-walking for gleaning and fishing occurs more frequently in front of the villages, causing chronic physical damage to the coral;
- episodic, heavy rains periodically flush nutrients from the land and cesspool contents into the lagoon, resulting in filamentous algae blooms that compete for space and/or periodically smother live coral;
- the relatively shallower lagoons fronting the villages may never have supported as abundant and diverse a coral growth as is found in To'aga. We consider this unlikely because numerous shallow areas of the lagoon on the southeast of Ofu Island contain numerous species of coral and much of the substrate is covered by live coral.

Related questions that arise from the study:

- Does the higher N content of *Chlorodesmis* make it a preferred food for herbivores, and therefore less abundant on reefs than the carbonate-rich *Halimeda* and tough-membraned *Dictyosphaeria*? The same question can be asked of the blue-green alga.
- Is there a difference in herbivore (specifically macroalgae-feeding fish species) abundance among the three lagoons? If so, would this predispose some areas to algal blooms under conditions of high nutrient influx?

Conclusions

From this study, Ofu and Olosega lagoons seem to have good water quality, with nitrogen influx of predominantly oceanic/atmospheric origin. At the time of this study, anthropogenic sources of nutrients were not detected in macroalgae in the lagoons. The major factors driving the differences among the three lagoons (live coral cover, macroalgae cover, and number of coral species) remain unproven. Data from this study provide the baseline needed to compare against data from future episodic events, to determine the nitrogen sources fueling algal blooms in the lagoons of Ofu and Olosega.

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