

# **Managing NPSA's Coral Reefs in the Face of Global Warming: Research Project Report for Year 1**

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### Abstract

Shallow pools in Ofu Lagoon in the National Park of American Samoa vary in thermal conditions, with temperatures in some pools reaching 35 °C and fluctuating daily by >6 °C. Yet the pools support diverse coral communities, including many species thought to be sensitive to high temperatures such as *Acropora*, *Pocillopora*, and *Millepora* spp. A one year experiment was carried out to evaluate the survival and growth of corals transplanted from cooler to warmer pools and vice versa. Nubbins of *Pocillopora damicornis* and *Porites cylindrica* were obtained from three sites in Ofu Lagoon and one site in Ofu Harbor, dyed with Alizarin red S for measuring growth, and transplanted between the sites. The Ofu Lagoon sites varied in daily maximum temperatures and daily temperature ranges, and Ofu Harbor had more frequent warm temperatures and greater daily ranges than the Ofu Lagoon sites. Water temperatures were monitored hourly at the four sites during the one year period, and other water quality and physical characteristics were studied at the lagoon sites. Regardless of site of origin, both species had the greatest growth in Pool 300, the lagoon pool with the highest daily maximum temperatures and greatest daily temperature ranges of the three lagoon sites. Pool 300 is also the shallowest of the three lagoon sites, thus likely subject to the greatest irradiance. These results do not support the hypothesis that corals found in Ofu Lagoon pools with relatively high temperatures are better acclimatized or adapted to high temperatures than corals in the cooler portions of the lagoon. The hypothesis that corals found in Ofu Lagoon are better acclimatized or adapted to high temperatures than corals outside the lagoon in deeper water has not yet been tested. Extrinsic factors such as water motion, dissolved oxygen, or habitat characteristics may explain the greater survival and growth of coral transplants in Pool 300 than in the other lagoon pools. Water motion is known to increase the ability of corals to withstand high temperatures and irradiance, and flow velocity was higher in Pool 300 than the other two lagoon pools. Hyperoxia, or dissolved oxygen saturation >150%, stimulates the metabolism of zooxanthellae, and hyperoxia was most frequent and highest in Pool 300. Relatively low turbidity during stormy weather was found in Pool 300, which also had the least sandy substrate, possibly limiting sedimentation and abrasion of corals. Extrinsic factors may be an important consideration in establishing Marine Protected Areas to mitigate the effects of global warming on coral communities.

**Cover photo:** The skeleton of a *Porites cylindrica* coral colony one year after being stained and transplanted in Ofu Lagoon. Cleaning and cross-sectioning revealed the pink stain mark, showing that this colony grew upward about 3 cm over the one year period.

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## Introduction

This report describes results from the first year of a three year research project on coral ecology in the National Park of American Samoa (NPSA). The goal of the project is to determine how corals are able to withstand the high temperatures and daily range of 6 °C in Ofu Lagoon. Understanding how corals resist high temperatures can substantially improve the abilities of coral-reef managers to deal with global warming (Done 2001). Resistance of high temperatures may relate to the intrinsic ability of corals to acclimatize or adapt to the stressful conditions (Coles & Brown in press), or to extrinsic factors such as environmental conditions that reduce the severity of the thermal stress (Jokiel in press). If corals are known to be intrinsically resistant, management should focus on preserving and perpetuating those colonies. If extrinsic factors such as strong currents, oxygen levels or topographic complexity are known to impart protection, management should focus on preventing degradation of these conditions (West 2001, West & Salm in press).

### Global Warming and NPSA

Coral reefs are critical components of local and regional economies in the U.S. Reef-related tourism generates an estimates \$8.2 billion in local income and sales for U.S. states and territories (Turgeon & Asch 2001). Commercial reef fisheries add \$94.8 million to local economies in the U.S. The input from recreational fisheries has not been calculated for the U.S. as a whole, but for the state of Florida alone, recreational fishing on coral reefs was estimated at \$500 million per year. Because of the growing scientific and public concerns for coral reefs, President Clinton established a U.S. Coral Reef Task Force in 1998 as a joint project for the U.S. Departments of the Interior and Commerce. The U.S. Congress appropriated \$10 million annually from FY00-02 to the Department of the Interior to enhance its coral reef conservation activities (Turgeon & Asch 2001).

The National Park of American Samoa (NPSA) has jurisdiction over 2,550 acres of coral reefs along 17 miles of coastline within park units on Tutuila, Ofu, and Ta'u Islands in American Samoa (Fig. 1). Shallow coral reef ecosystems such as those within NPSA are among the most diverse ecological communities on earth, often supporting several hundred species of fishes and non-coral invertebrates in a small area (Pauley 1997). NPSA's coral reefs are among the least affected by anthropogenic impacts within the U.S. and its territories, and one of the primary management objectives of the park is to preserve these ecosystems for future generations. However, global warming and increasing local anthropogenic threats are predicted to cause major stress to coral reefs within the next few decades. Global warming will result in increased sea surface temperatures which can be lethal to corals. During the warming event in the south Pacific during 1994, extensive mortalities occurred among branching acroporid and pocilloporid corals throughout American Samoa and especially on a shallow reef on Ofu Island within NPSA (Craig et al. 2001). In 1999 and 2000, American Samoa narrowly missed being affected by a warm water mass that caused severe coral damage in the nearby islands of Fiji and (western) Samoa. In 2002 and 2003, widespread coral bleaching occurred in American Samoa.

Available evidence indicates that reef-building corals will be subjected to steadily increasing temperatures in future decades. Many of these reef coral species are already living near their

thermal limits, thus warming events result in unprecedented mass coral bleaching and mortality, such as occurred in 1998 (Jokiel In press). The Ofu Unit of NPSA provides a unique opportunity for investigating the means by which shallow reef-building corals withstand high temperatures because: (1) Ofu Lagoon supports a community of approximately 100 shallow reef-building coral species; and (2) many of these corals tolerate water temperatures that would normally cause bleaching and mortality of shallow reef-building corals (e.g., periods when temperatures are  $>3$  °C above mean summer maxima, defined as the mean daily maximum temperature for November through May). How are Ofu Lagoon corals able to withstand such high temperatures?

Shallow tropical seas are unstable environments, thus shallow reef-building corals must be able to withstand increases in temperature, irradiance, and other environmental conditions across a range of temporal scales (Brown 1997). This may occur intrinsically by acclimatization (phenotypic plasticity) or adaptation (genotypic selection) of the species or population to the changing conditions (Coles & Brown In press). Corals may also be able to withstand increasing temperatures extrinsically if local conditions, such as strong currents, provide protection (Jokiel et al. 1997). Do Ofu Lagoon corals tolerate high temperatures because; (1) they have acclimatized or adapted (i.e., intrinsic factors), (2) favorable conditions ameliorate the high temperatures (i.e., extrinsic factors), (3) a combination of intrinsic and extrinsic factors, or (4) neither (due to brevity of high temperature periods)? The answers to these questions are needed in order to determine how Ofu Lagoon corals will respond to predicted temperature increases in the 21<sup>st</sup> century, thereby providing critical information for management of NPSA and other coral reef ecosystems (West & Salm In press). Because Ofu Lagoon is subjected to high temperatures and irradiance, is divided into several distinct pools with a range of environmental conditions, supports a diverse community of shallow reef-building corals, and is little affected by human activities, it is ideal for studying the effects of increasing temperatures on shallow reef-building corals.

### Study Area, Observations and Objectives

Field work for this project is being carried out in the Ofu Unit of NPSA (Fig. 1), and will be supplemented by laboratory work in American Samoa and Hawai'i. Observations leading to the project, and its primary objectives, are described below.

Study Area. Ofu Island, located in the Samoan Archipelago (14°S, 170°W), is a small volcanic island (7.5 km<sup>2</sup>) with a well-developed fringing reef that is 80-180 m wide. The study area is Ofu Lagoon, a backreef moat formed by the fringing reef along the island's

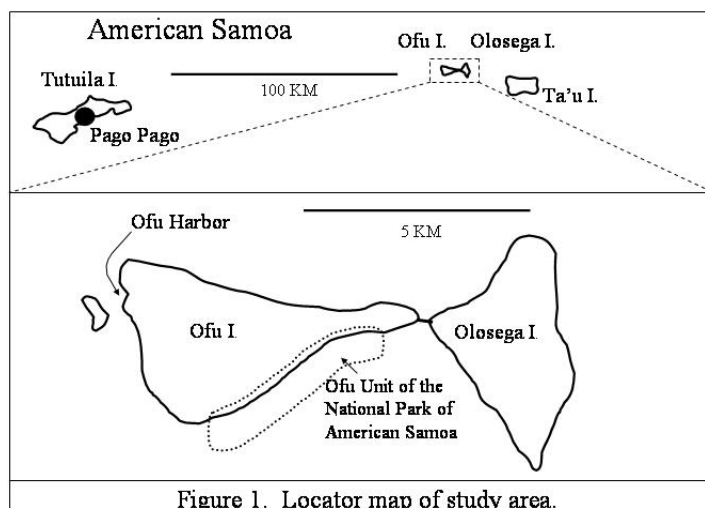


Figure 1. Locator map of study area.

southeastern shoreline. Most of Ofu Lagoon lies within the Ofu Unit of the NPSA (Fig. 1). The lagoon has water depths of 1-2.5 m at low tide when water circulation is minimal because there are no deep channel outlets, but the lagoon is thoroughly mixed during high tides (tidal range  $\approx$ 1 m). No streams enter the area, but freshwater percolates into the lagoon along the shoreline. The lagoon consists of an interconnected network of backreef pools, each with unique environmental conditions (e.g., temperature fluctuations, water flow, salinity, substrate, etc.). As a whole, Ofu Lagoon supports a diverse community of  $\approx$ 100 species of shallow reef-building corals, but each pool within the lagoon has a different coral community (Craig et al. 2001).

Observations and Objectives. Key observations leading to the initiation of this research project include: (1) Ofu Lagoon frequently warms to  $>32$  °C yet supports many coral species known to be sensitive to high temperatures (e.g., *Acropora* spp. and *Pocillopora* spp.); (2) the pools in the lagoon experience substantial diurnal fluctuations in water quality (temperature range of  $> 6$  °C, dissolved oxygen range of 15 to 220 percent saturation, etc.), and (3) distributions of key coral species are discontinuous within the lagoon in a manner not obviously related to habitat characteristics (see “Study site and species selection” section below). The objectives of this project are to: (1) determine the mechanisms that allow Ofu corals to withstand high temperatures; (2) investigate coral distribution patterns in Ofu Lagoon; (3) relate the findings to coral ecology and bleaching; and (4) relate the findings to management of the coral reefs of NPSA and elsewhere.

### Project Design

This research project is based on a series of hypotheses regarding intrinsic and extrinsic factors affecting the capacity of Ofu corals to withstand high temperatures. Each hypothesis is tested with one or more field and/or laboratory experiments. Because only the first of three years of the project has been completed, this report covers only the first phase of the project. The “Hypotheses and Experiments” section below describes the theoretical framework for the project, and the remainder of the report describes the results from the first year. In the section below, a note **in bold** indicates the status of each observation and experiment. This section also describes the study site and species that were selected for the experiments.

Hypotheses and Experiments. Listed below are the four research questions upon which the project design is built. Each question consists of a set of hypotheses and experiments. In some cases the experiments are supplemented by observation. Each question leads to a set of falsifiable hypotheses, and each set of hypotheses will be experimentally tested in the field at the Ofu Lagoon study site or in the laboratory. The intent of each experiment is to produce an outcome that will allow the exclusion of one or more hypotheses in a statistically defensible manner. Each outcome and exclusion should allow for the development of subsequent hypotheses that can again be tested in order to narrow down the number of workable hypotheses. Therefore, each task is intended to link question, hypothesis, experiment, outcome, and exclusion in order to create a logic tree that will provide the most likely answer to each question through the process of strong inference (Platt 1964).

1. Research Question: Do Ofu Lagoon corals withstand high temperatures because of intrinsic factors such as acclimatization or adaptation?
  - 1.1. Hypotheses (designated  $H_{o1}$  (null) and  $H_{a1}$  (alternative)).
    - 1.1.1.  $H_{o1}$ : There is no significant correlation of coral survival and growth with any intrinsic factor (i.e., colonies occurring in the warmest Ofu habitats are not phenotypically or genetically distinct from nearby conspecific colonies).
    - 1.1.2.  $H_{a1-1}$ : Colonies occurring in the warmest Ofu habitats are acclimatized to these thermal conditions, but not genetically distinct from nearby conspecific colonies.
    - 1.1.3.  $H_{a1-2}$ : Colonies occurring in the warmest Ofu habitats are genetically distinct from nearby conspecific colonies.
  - 1.2. Observations (**started 7/02 and ongoing**): Data collection on water temperature and other environmental factors at several Ofu sites (see below for site selection) to quantify environmental differences between study sites.
  - 1.3. Experiments: Three experiments will be used to test  $H_{a1-1}$  and  $H_{a1-2}$ :
    - 1.3.1.  $E_{1-1}$ : Field transplant experiment at Ofu (**started 7/02 and completed 7/03, experimental design may be modified and experiment repeated**): Transplant coral nubbins between the warmest Ofu habitats and cooler sites. Nubbins will be stained, transplanted, and removed after 1-2 years so that growth rates can be measured. Similar growth rates between the transplants at warmer and cooler sites will support  $H_{o1}$  (no intrinsic differences). Dissimilar growth rates will support  $H_{a1-1}$  and  $H_{a1-2}$  (intrinsic differences), provided that temperature is the only environmental difference between the sites. If the results suggest intrinsic factors may be important, distinguish  $H_{a1-1}$  and  $H_{a1-2}$  from one another by  $E_{1-2}$  and  $E_{1-3}$ :
    - 1.3.2.  $E_{1-2}$ : Laboratory transplant experiment (**not started yet**): Collect colonies from the warmest Ofu habitats and from cooler habitats, transplant them to the lab in order to collect larvae. After the larvae are settled on plates, expose the larvae to different high temperature regimes and monitor them for survival. Similar survival of larvae from the two habitats will support  $H_{a1-1}$ . Higher survival of larvae from the warmer habitat than the cooler habitat will support  $H_{a1-2}$ .
    - 1.3.3.  $E_{1-3}$ : Laboratory test (**not started yet**): Conduct molecular tests on tissue samples from the colonies used for experiment  $E_{1-2}$  to determine if there are genetic differences between them.
2. Research Question: Do Ofu Lagoon corals withstand high temperatures because of extrinsic factors such as strong currents or other favorable environmental conditions?
  - 2.1. Hypotheses (designated  $H_{o2}$  (null) and  $H_{a2}$  (alternative)).
    - 2.1.1.  $H_{o2}$ : There is no significant correlation of coral survival and growth with any extrinsic physical factor.
    - 2.1.2.  $H_{a2}$ : The occurrence of colonies in the warmest Ofu habitats are associated with extrinsic physical factors such as strong currents or other favorable environmental conditions.
  - 2.2. Observations (**started 7/02 and ongoing**): Data collection on water movement (total water motion, flow velocity, and flow direction), water quality (temperature, salinity, turbidity, and dissolved oxygen), and habitat characteristics (depth, pool volume, coral

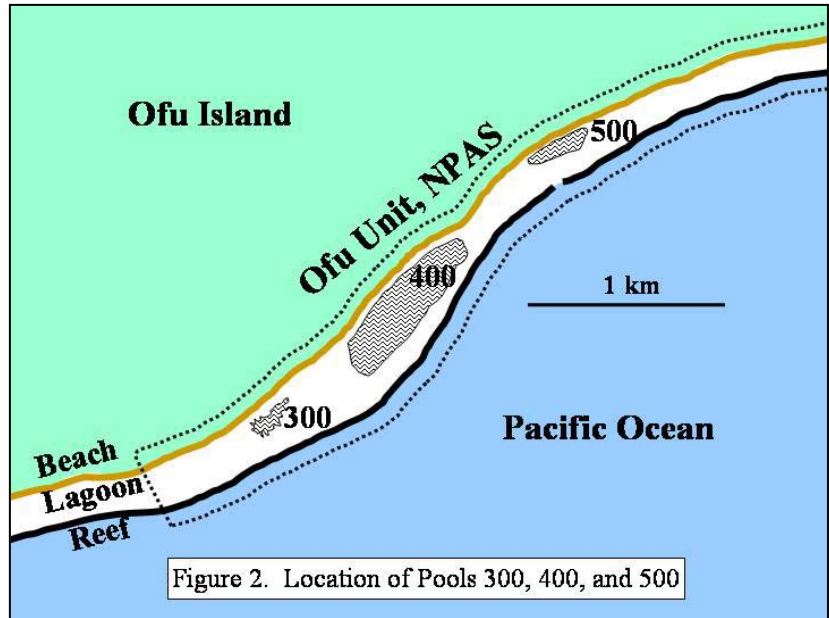
- cover, substrate type, etc.) in Ofu Lagoon (see below for site selection) to quantify differences between study sites.
- 2.3. Experiments: Two experiments will be used to test  $H_{a2}$ :
    - 2.3.1.  $E_{2-1}$ : Field transplant experiment at Ofu (**started 7/02 and completed 7/03**): Coral nubbins were stained and transplanted across a range of depths and temperatures in Ofu Lagoon to determine if extrinsic factors can explain observed differences in coral distributions. E.g., two of the transplant sites appear physically similar yet have substantially different coral distributions (Pools 300 and 500 – see “Study site and species selection” below). Nubbins were stained, transplanted, and removed after 1 year for growth rate measurements. Data on water currents, water quality, and physical characteristics of the transplant sites will be analyzed to determine correlation with growth.
    - 2.3.2.  $E_{2-2}$ : Laboratory transplant experiment (**not started yet**): Nubbins of *P. damicornis* will be stained and transplanted into aquaria to test effects of high temperatures vs. water motion and other extrinsic factors (e.g., salinity, dissolved oxygen, turbidity) on survival and growth. The experiment will be designed to also test the relationship of colony size to survival and growth under different temperature and water movement conditions.
  3. Research Question: Do Ofu Lagoon corals withstand high temperatures because of both intrinsic and extrinsic factors?
    - 3.1. Hypotheses (designated  $H_{o3}$  (null) and  $H_{a3}$  (alternative)).
      - 3.1.1.  $H_{o3}$ : There is no significant correlation of coral survival and growth with any interaction of intrinsic and extrinsic factors.
      - 3.1.2.  $H_{a3}$ : Ofu Lagoon corals withstand high temperatures because of the interaction of intrinsic and extrinsic factors.
    - 3.2. Experiments: Separate experiments will not be necessary to test  $H_{a3}$ ; rather, the results from Experiments  $E_{1-1}$ ,  $E_{1-2}$ ,  $E_{1-3}$ ,  $E_{2-1}$ , and  $E_{2-2}$  will be used to test  $H_{a3}$ . If these experiments support the alternative hypotheses for Research Questions #1 and #2 above, then  $H_{a3}$  will be supported as well.
  4. Research Question: Do Ofu Lagoon corals withstand high temperatures because of the limited duration of high temperature events (i.e., neither intrinsic or extrinsic factors)?
    - 4.1. Hypotheses (designated  $H_{o4}$  (null) and  $H_{a4}$  (alternative)).
      - 4.1.1.  $H_{o4}$ : There is no significant correlation of coral survival and growth with duration of high temperature events in Ofu Lagoon.
      - 4.1.2.  $H_{a4}$ : Ofu Lagoon corals withstand high temperatures because of the limited duration of high temperature events.
    - 4.2. Experiments: One experiment will be used to test  $H_{a4}$ :
      - 4.2.1.  $E_{4-1}$ : Laboratory transplant experiment (**not started yet**): Nubbins of *P. damicornis* will be stained and transplanted into aquaria to test effects of duration of high temperatures on survival and growth.



Study site and species selection. The pools of Ofu Lagoon support a diverse community of  $\approx 100$  species of reef corals, with the deeper pools ( $\approx 2$  m at low tide) supporting more species than the shallower pools ( $\approx 1$  m at low tide) (Craig et al. 2001). The pools of Ofu Lagoon vary in physical conditions, water quality, and coral communities, thus providing useful study sites for comparative experiments.

Within Ofu Lagoon, three study sites (Pools 300, 400, and 500; Fig. 2) were selected based on depth, water temperature, and coral species diversity and distribution. Pool 300 is  $\approx 1$  m deep, was known to be warmer than at least most of the other pools in Ofu Lagoon, and supports about 50 coral species. The deepest section of Pool 400 is  $\approx 2$  m deep, was known to be cooler than Pool 300, and supports approximately 100 coral species (Craig et al. 2001).

Like Pool 300, Pool 500 is  $\approx 1$  m deep, and was thought to be about the same temperature as Pool 300, but Pool 500 supports fewer coral species than Pool 300. For Year 1, an additional site was used at Ofu Harbor (Fig. 1) because it was thought to provide a different temperature environment than Ofu Lagoon.



The reef corals *Porites cylindrica* and *Pocillopora damicornis* (Fig. 3) were selected for the transplant experiments of this study because they: (1) are common in Ofu Lagoon; (2) have discontinuous distributions: Pools 300 and 400 support abundant colonies of both species, but

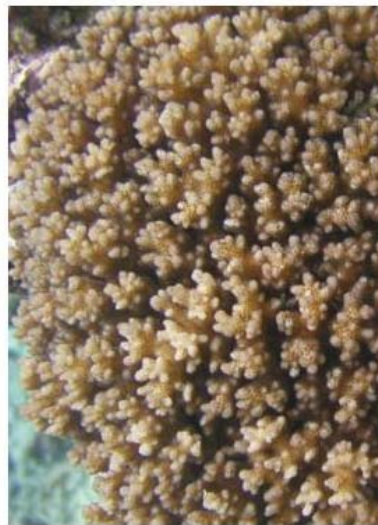


Figure 3. *Porites cylindrica* (left) and *Pocillopora damicornis* (right)

neither are found in Pool 500, despite similar depth and water quality; (3) are known to stain well with alizarin bone stain used in coral growth experiments; and (4) their branching morphologies make them relatively easy to transplant. An additional advantage of these two species for this experiment is that their branching morphologies make them more likely to bleach due to high temperatures than massive or encrusting coral species (Loya et al. 2001).

## Methods For Year 1

During Year 1 of the project, data were collected on water quality, water movement, and habitat characteristics of the Ofu Lagoon study sites, and coral transplant experiments E<sub>1-1</sub> and E<sub>2-1</sub> (see “Hypotheses and Experiments” section above for descriptions) were completed. Data were analyzed using Analysis of Variance (SAS and Minitab), pair-wise comparisons were performed with Tukey post-hoc adjustments, and significance was tested at a level of 0.05.

### Water Quality

Water temperature, salinity, turbidity, conductivity, pH, and dissolved oxygen were measured at the three Ofu Lagoon sites during the one year study period. Water temperatures were measured every 30 minutes over the entire one year period from July 2002 to June 2003 at the three Ofu Lagoon study sites (Fig. 2) and Ofu Harbor (Fig. 1) with Stowaway Tidbit automated loggers made by Onset Co. (Fig. 4). More precise locations of the four tidbits are shown in the aerial photos at the end of Appendix A. The battery-operated loggers are completely sealed, less than 4 cm in diameter, and manufactured for reading water temperatures from -20 °C to +50 °C. Temperature data are downloaded from the loggers optically using a base station attached to a computer. Each group of four loggers was tested before deployment against a calibrated thermometer certified by the National Institute of Standards and Technology (NIST), deployed for six months, then retrieved and tested again against the calibrated thermometer. Loggers that were more than 0.5 °C out of calibration were replaced. Loggers were wrapped in duct tape for protection, and placed near, but not on, the substrate in shaded areas so they were not directly exposed to the sun.



Figure 4. Tidbit temperature logger.



Figure 5. Sonde 6600

Salinity, turbidity, conductivity, pH, and dissolved oxygen were simultaneously measured every 30 minutes over 13 days (7/10-23/02) in the cool season, and 10 days (1/8-17/03) in the warm season at the three Ofu Lagoon study sites (Fig. 2) with three Sonde 6600 water quality automated data loggers made by YSI Inc. (Fig. 5).

The battery-operated loggers are about 10 cm in diameter and 40 cm in length. Turbidity, conductivity, and dissolved oxygen (DO) were calibrated on each Sonde before deployment, and DO was checked after retrieval because of the sensitivity of the probe.

### Water Movement

Water movement was evaluated by quantifying total water motion at each of the three Ofu Lagoon study sites. In addition, flow velocity was quantified and flow direction was described for several points in the tidal cycle at each study site.

Total water motion was measured using the clod-card technique, whereby a plaster of Paris block (“clod”) is glued to a plastic sheet (“card”; Fig. 6) and attached to the substrate for at least 24 hours to provide an index of water motion experienced by benthic organisms over the full tidal cycle (Doty 1971). Because dissolution rates of the plaster of Paris are proportional to water current velocity, this technique provides a simple, valid measurement of total water motion on coral reefs (Jokiel & Morrissey 1993). Clod-cards were constructed using commercial plaster of Paris to form clods in ice cube trays with rounded bottoms. The clods were filed to size and glued to numbered plastic sheets such that the total weight of the clod-card before weight was approximately 40 g. The clod-cards were dried under a fan at room temperature for several weeks, then weighed to the nearest 0.01 g. Clod-cards were deployed by attaching them with plastic cable-ties to areas on the substrate of similar depth (20-30 cm at mean low tide) and topography (flat and unobstructed substrate for at least 5 m radius) at each study site. A total of four sets of clod-cards were set out, consisting of a clod-card at each of the three lagoon sites over the same 24-48 hour period. Clod-cards were retrieved, dried for at least two weeks under a fan at room temperature, then reweighed with the same scale.



Figure 6. Clod-card

Flow velocity and direction were studied at the three Ofu Lagoon sites using objects that float on the surface and move with the surface current (drogues) (Hughes 2002). Oranges are commonly used as low-cost drogues because they are safe for the environment, easy to see, and usually float low in the water. Oranges are usually not available on Ofu Island, so coconuts were used instead, as they meet the same criteria. Heavy, unhusked coconuts were used as they sit low in the water and are less influenced by wind. At each of the three lagoon sites, a 100 m x 50 m grid centered

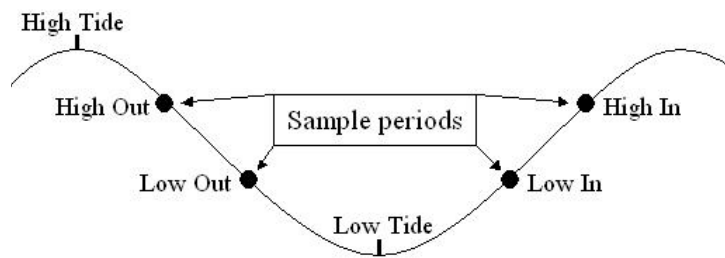


Figure 7. Sample periods for drogue study.

on the tidbit temperature logger locations was set up, using 15 floats spaced 25 m from one another. Sets of four drogues were released from the perimeter of the grid, and their progress through the grid mapped and timed. At least four sets (each consisting of four drogues) were released during each of the following sample periods: (1) High Out (starting two hours after high tide); (2) Low Out (starting two hours before low tide); (3) Low In (starting two hours after low tide); and (4) High In (starting two hours before high tide; Fig. 7). All drogue releases were with the same four coconuts, and all were completed from July 4 to July 12, 2003, during low wind and low swell conditions.

Maximum flow velocity during each of the four sample periods per site was calculated based on the four shortest times drogues covered 25 m near the center of the grid. These four times were used to give mean maximum velocity in cm per second for each sample period at each site. Flow direction during each of the four sample periods at each site was determined by compiling all drogue direction lines that were obtained per sample period onto a single map of the sample site,

which were then superimposed on aerial photos. Thus the drogue study provided four maps of flow direction (one for each sample period) for each study site.

### Habitat Characteristics

The three pools where the sample sites are located in Ofu Lagoon vary considerably in habitat characteristics such as depth, volume, substrate, coral cover, and proximity to the only break (or “ava”) in Ofu reef (Fig. 8). A habitat survey was carried out in January 2003 to quantify and compare physical characteristics of the three pools.

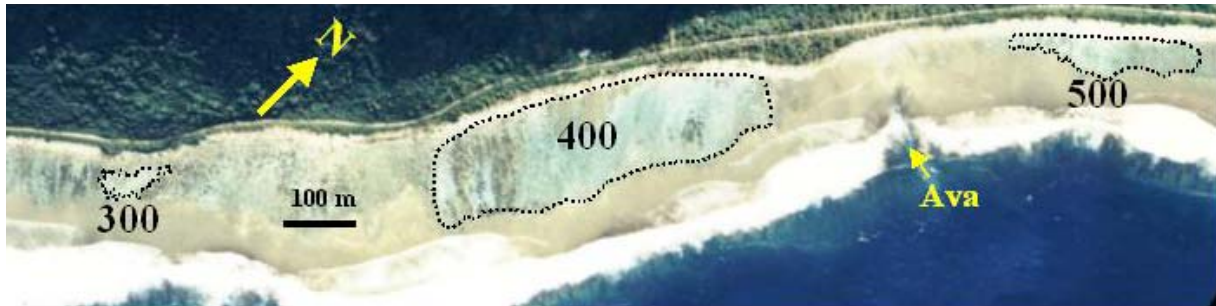


Figure 8. Aerial photo of the three pools in Ofu Lagoon.

Average pool depth for each of the three pools (Fig. 8) at mean low tide was measured by taking several depth measurements along three or four transects (depending on pool size) crossing each pool perpendicularly from the beach. A tidal correction was applied to each measurement to provide a mean low tide sample depth, then the average pool depth was calculated. Total pool volume was calculated with Global Lab Image 2 software (version 2.50) using pool outlines on aerial photos, together with mean pool depth.

Substrate type and rugosity (i.e., substrate topography or spatial heterogeneity) were surveyed by: (1) Laying out a 400 m<sup>2</sup> grid (20 m x 20 m) centered on the tidbit temperature logger locations in each pool (see aerial photos at end of Appendix A); (2) numbering the squares within the grid from 1 to 400; (3) randomly selecting 30 numbers from 1 to 400 for substrate surveys; and (4) surveying each of the 30 selected squares. Each 1 m<sup>2</sup> was surveyed using a quadrat frame with 20 cm x 20 cm gridlines (0.04 m<sup>2</sup>, or 4% of 1 m<sup>2</sup>, Fig. 9) to provide estimates to the nearest 1% of 1 m<sup>2</sup> of the following types of substrate cover: Live coral (by growth form, and in the case of branching corals, by genus), live non-calcareous algae (by type), crustose coralline algae, dead standing coral, reef pavement, rubble, and sand. Notes were made when a type of cover not falling into these categories was encountered.



Figure 9. Habitat quadrat (1 m<sup>2</sup>) with 20 x 20 cm (0.04 m<sup>2</sup>) gridlines.



Figure 10. High rugosity in Pool 400.

Rugosity was also measured during this habitat survey in each of the 30 sampled 1 m<sup>2</sup> quadrat areas using a chain marked in 10 cm increments laid across the quadrat (i.e., the rugosity measurement is the length of chain required to cross the 1 m<sup>2</sup> quadrat when it is carefully placed to match the contours of the substrate). Because of the large coral heads in the pools, a second person or a weight belt was sometimes needed to hold the quadrat in position while the substrate estimates and rugosity measurements were taken (Fig. 10).

During the above habitat survey, some biological data in addition to living cover were collected on each of the 1 m<sup>2</sup> quadrats, such as occurrence of damselfish territories, and the number and diameters of the two coral species used in this study, *Pocillopora damicornis* and *Porites cylindrica*. A survey of fish species and key invertebrate species in the three pools (and elsewhere in American Samoa) was recently completed (Green 2002), and thus was not repeated for this study.

### Coral Transplants

A series of six transplant experiments (three apiece using *P. damicornis* and *P. cylindrica*) lasting one year each were completed in Ofu Lagoon and Ofu Harbor (Fig. 11). For each of the six experiments, groups of 30 coral nubbins were gathered from a source area, stained, and moved to the transplant areas, where 20 nubbins were transplanted (experimental transplants), then the remaining 10 controls were brought back and transplanted at the source area (control transplants). All transplants were placed within a 10 m radius of the of the tidbit temperature

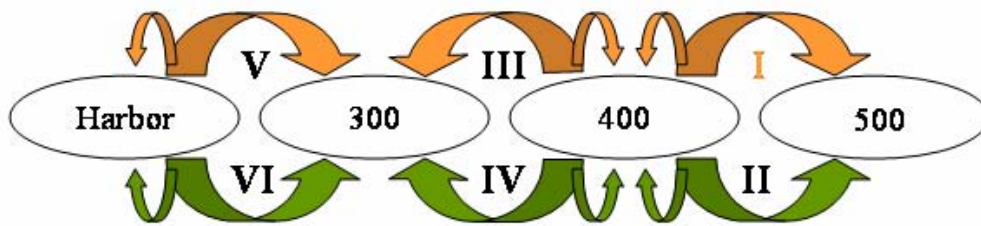


Figure 11. Transplant experiment design, showing source areas and transplant areas for the six experiments of *P. damicornis* (I, III, & V) and *P. cylindrica* (II, IV, & VI) .

loggers located in the three Ofu Lagoon study sites (see aerial photos at end of Appendix A for locations) and Ofu Harbor (Fig. 1) in July 2002, and removed after one year in July 2003. The transplants were sliced to reveal the stain mark, and growth of each transplant was measured to the nearest 0.1 mm. The methods used for the coral transplant experiments are described in detail in Appendix A. The purpose of the six experiments was to compare survival and growth rates of the two species in four different temperature environments (i.e., the three lagoon sites and harbor) in order to test Hypotheses H<sub>a1-1</sub>, H<sub>a1-2</sub>, and H<sub>a2</sub> (see “Hypotheses and Experiments” above).

## Results From Year 1

Results from Year 1 are provided below on water quality, water movement, habitat characteristics, and coral transplant experiments. Additional details on some of the results are found in Appendices B-D.

### Water Quality

Water Temperature. Mean summer (Nov-May) water temperatures at the three sites in Ofu Lagoon were about 30 °C, but maximum and minimum temperatures were more extreme in Pool 300 than in the other two pools (Table 1). Maximum daily temperatures occurred from November through March, with several temperatures of >33 °C recorded in Pool 300, including a maximum of 35.5 °C in February. Maximum daily temperatures in Pools 400 and 500 reached their highest in March (33.5 and 33.6 °C, respectively) during the coincidence of calm, clear weather with midday low tide, at which time Pool 300 reached 34.2 °C (Fig. 12). Temperatures fluctuated widely on a daily basis, especially in Pool 300, where a maximum daily range of 6.3 °C was recorded in February (Fig. 12), and >4 °C on 18 other days throughout the one year period. However, mean daily temperatures did not exceed 31 °C at any time during the one year period at the three lagoon study sites (Table 1). Daily maxima were higher, daily minima were lower, and ranges were greater in Pool 300 than the other two pools ( $p < 0.001$  for each pair-wise test), but daily means did not differ among the three pools ( $p = 0.124$ ).

During the summer (Nov-May), temperatures  $\geq 31$  °C occurred more frequently in Pool 300 than the other two pools, especially at  $\geq 32$  °C (Fig. 13, top), and the duration of temperatures  $\geq 32$  °C and  $\geq 33$  °C was greater ( $p = 0.036$  and  $0.029$ , respectively). Temperatures  $\geq 34$  °C and  $\geq 35$  °C only occurred in Pool 300 (Fig. 13, bottom). Daily fluctuations of  $\geq 2$  °C occurred more frequently in Pool 300 than in Pools 400 and 500 (Fig. 14). Pool 300 is shallower and volumetrically much smaller than the other two pools (Table 2), thus temperatures are higher and fluctuations are greater, particularly when calm, clear weather coincides with low tides.

Table 1. Temperature summaries for the 3 Ofu Lagoon study sites for 7/02-6/03.

Site	Season	Daily temperatures (°C)				Annual/seasonal temperatures (°C)			
		Max	Min	Range	Mean	Max	Min	Range	Mean
300	Nov-May	29.2-35.5	27.1-29.8	0.4-6.3	28.4-30.9	35.5	27.1	8.4	29.8
	Annual	27.4-35.5	25.8-29.8	0.2-6.3	27.0-30.9	35.5	25.8	9.7	29.1
400	Nov-May	29.4-33.5	27.6-30.5	0.2-3.8	28.2-31.0	33.5	27.6	5.9	30.0
	Annual	27.4-33.5	26.7-20.5	0.2-3.8	27.2-31.0	33.5	26.7	6.8	29.2
500	Nov-May	29.3-33.6	27.6-30.1	0.2-4.4	28.5-30.6	33.6	27.6	6.0	29.9
	Annual	27.5-33.6	26.9-30.1	0.2-4.4	27.1-30.6	33.6	26.9	6.7	29.1

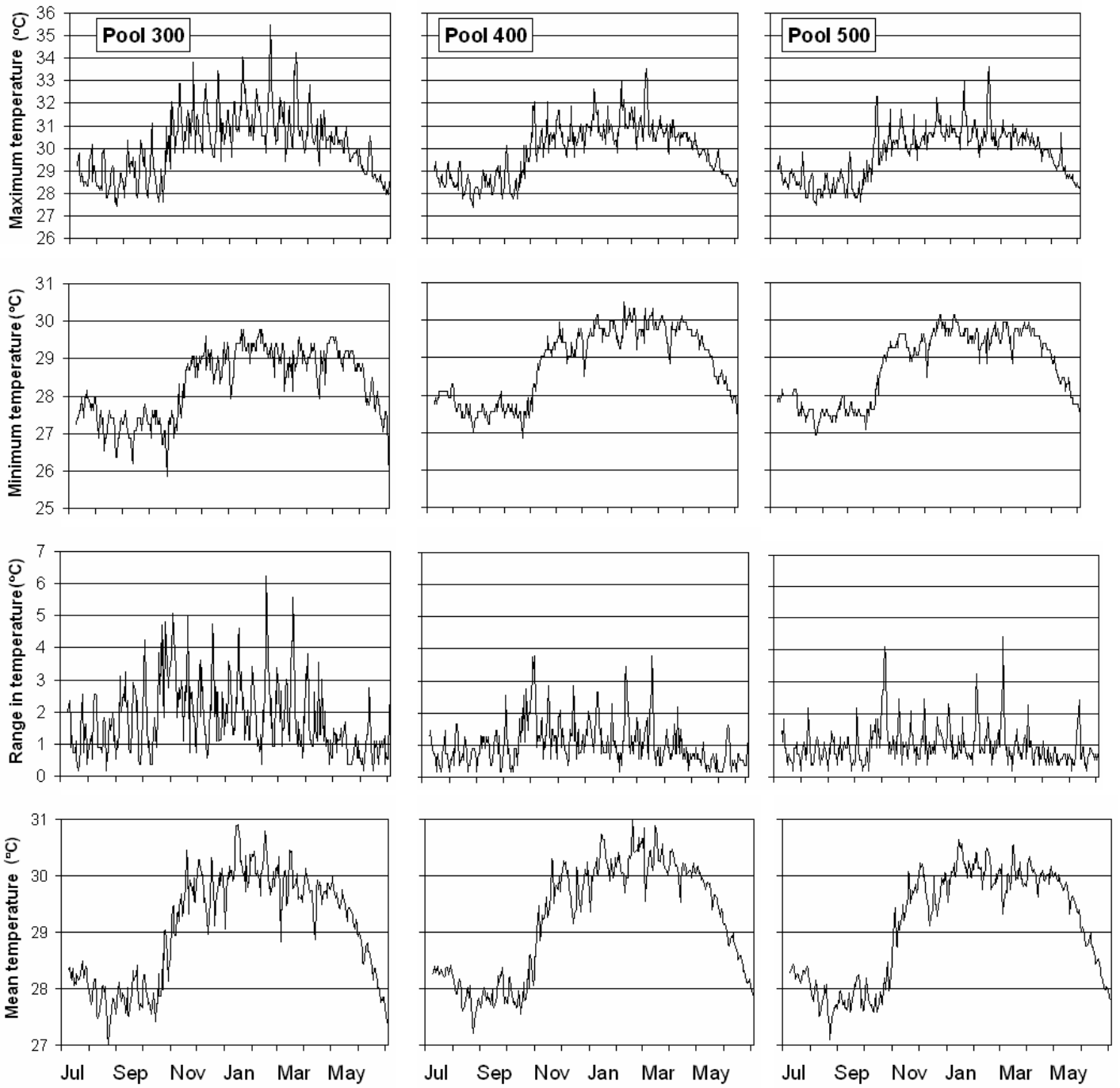


Figure 12. Daily temperature maxima, minima, ranges, and means for the 3 pools in Ofu Lagoon for the 1 year period from July 2002 through June 2003.

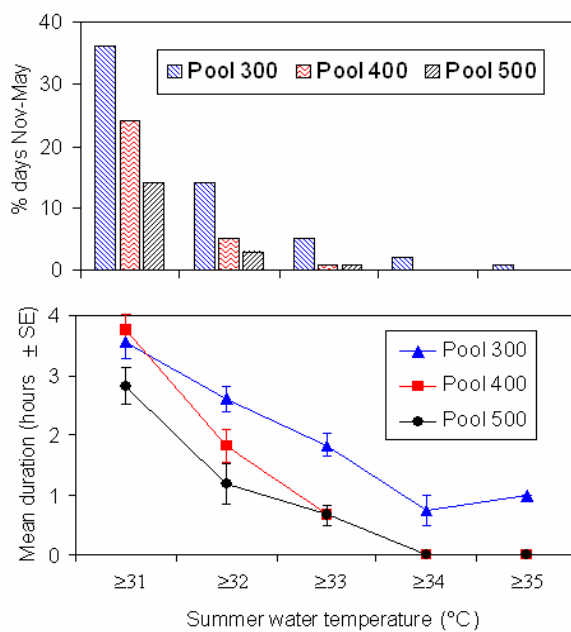


Figure 13. Frequency (top) and mean duration (bottom) of hot water events from 11/02 through 5/03 in the 3 pools.

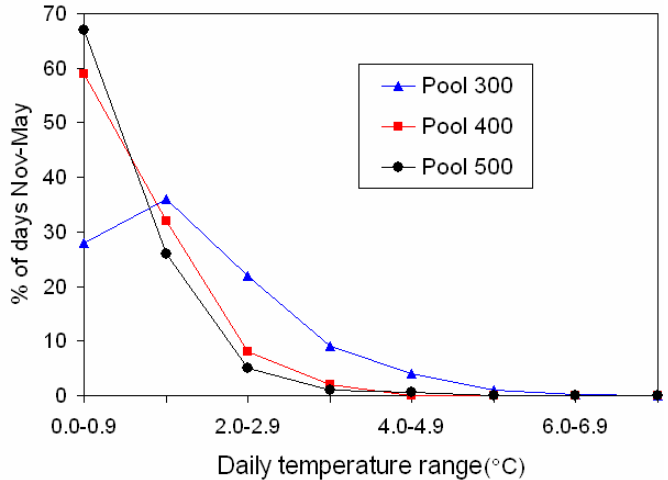


Figure 14. Daily range of temperatures from 11/02 through 5/03 in the 3 lagoon pools.

Dissolved oxygen, salinity, and turbidity. Dissolved oxygen (DO) ranged from 23 to 212% saturation in the three Ofu Lagoon study sites during the 23 days of Sonde deployment (7/10-23/02 and 1/8-17/03). The maximum and minimum were both recorded in Pool 300, with a maximum daily fluctuation of 184%. Daily fluctuations of >100% occurred in all three pools during calm, clear weather, with the fluctuations greatest in Pool 300, intermediate in Pool 400, and least in Pool 500. Daily fluctuations, as well as differences between the pools, were much less during cloudy, windy weather. Clear, calm weather provides high irradiance, resulting in high photosynthetic oxygen production during the daytime. The lack of wind allows DO to build up during the daytime and to drop at night due to minimal mixing of lagoon waters with open ocean waters that remain near 100% saturation. During cloudy, windy weather, irradiance is lower and mixing is higher, moderating DO. Diurnal fluctuations were relatively great in both DO and temperature in Pool 300 compared to Pool 500, in spite of similar depth, suggesting water circulation is greater in the latter. When mixing was low because of calm weather, DO dropped to low levels twice diurnally in Pools 300 and 400 in response to low tides coinciding with low irradiance from the late afternoon until the morning. Graphs of DO data are provided in Appendix B (Fig. B-1 to B-4).

Salinity remained near 36 parts per thousand (ppt) in the three pools during the 23 day sample period except after periods of heavy rainfall when salinity dropped one ppt or more in Pools 300 and 400. No streams enter the part of Ofu Lagoon where the study sites are located, but rivulets of fresh water flow out of layers of sedimentary rock on the adjacent beach, especially after heavy rainfall. Salinity did not decrease in any of the three pools more than 0.5 ppt except during calm, rainy periods when fresh water was flowing into the lagoon, and wind-generated mixing with ocean waters was minimal. Salinity briefly decreased below 34 ppt twice in Pool 300 and once in Pool 400 during such periods. Maximum and minimum salinities recorded were 36.6 ppt in Pool 500 and 33.5 in Pool 300. During periods of stormy weather, salinity was



relatively stable in spite of high rainfall, presumably due to high mixing in all three pools. As with temperature and DO, fluctuations in salinity were higher in Pool 300 than in Pool 500. Pool 300 was the only pool that showed a pronounced effect of tides on salinity, with a consistent drop of  $\approx 0.25$  ppt after low tide, provided that mixing was low (i.e., calm weather). Because of the relatively small volume of Pool 300 (see Table 2 below), groundwater flow and/or rainfall affect salinity in this pool more than the other two pools. Graphs of salinity data are provided in Appendix B (Figures B-5 and B-6).

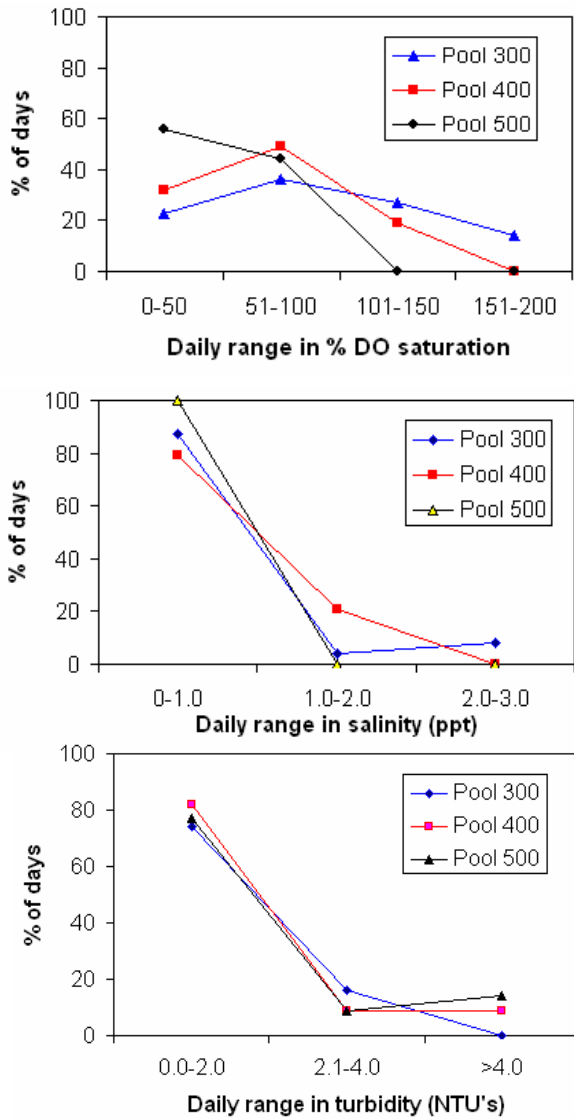


Figure 15. Daily fluctuations in dissolved oxygen, salinity, and turbidity over 23 days.

Turbidity was measured with the Sonde data loggers during the 23 day sample period at the three sites in nephelometric units (NTU's; turbidity in a glass of water becomes noticeably cloudy at about 5 NTU's). The Sondes were each anchored approximately 30 cm above the substrate inside cavities eroded in coral heads. Turbidity generally remained  $< 2$  NTU's throughout the sample period except during stormy weather July 19-22, 2002. Maximum and minimum turbidities recorded were 11.5 NTU's in Pool 500 and zero in all three pools. During calm weather, turbidity was similar between the three sites. However, during the four day stormy period, turbidity was higher in Pool 500 than in Pools 300 and 400 ( $p < 0.001$ ). On the stormiest day, July 21, mean turbidity was 2.44 NTU's in Pool 500, and 1.12 and 0.85 NTU's in Pools 300 and 400. Graphs of turbidity data are provided in Appendix B (Figures B-7 to B-9).

While DO fluctuated widely on a daily basis, salinity and turbidity fluctuated irregularly, primarily in response to weather conditions (Fig. 15). Pool 300 had the greatest fluctuations in salinity, presumably because of its small volume and proximity to groundwater sources. Pool 500 had the greatest fluctuations in turbidity, possibly due to its greater proportion of fine substrate (sand and silt) than the other two pools. Pool size and substrate are discussed below in Habitat Characteristics. Salinity and turbidity are most affected during major storm events, thus the minimal sampling done so far during such conditions is probably inadequate to compare these characteristics of the three pools.

## Water Movement

Total water motion results for the three pools, as measured by dissolution rates of clod-cards, are shown in Figure 16. Dissolution rates were very similar in the three pools ( $p = 0.69$ ), suggesting that total water motion is similar. These results were contradicted by the results from the drogue study, which suggested that flow velocity is greater in Pool 300 than the other two pools.

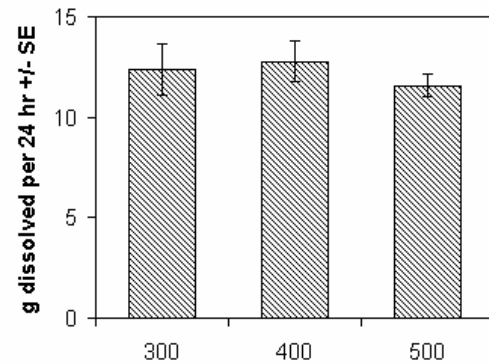


Figure 16. Total water motion in the 3 pools.

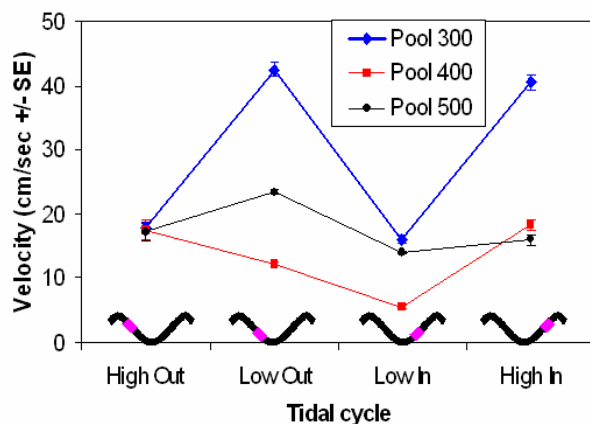


Figure 17. Mean maximum flow velocity at four points in the tidal cycle in the 3 lagoon pools

Flow velocity results for the three pools are shown in Figure 17 as mean maximum surface velocity in each pool at four points in the tidal cycle. At three of the four points, flow velocity was greater in Pool 300 than the other two pools ( $p < 0.001$ ).

Water flow direction results for each of the three pools at the four points in the tidal cycle are plotted on aerial photos in Appendix C. Flow direction was towards the ava in all pools at all points in the tidal cycle. Flow was rather uniform in Pool 500, consistently going directly towards the ava regardless of

incoming or outgoing tide (Fig. C-3). This may be due to closer proximity to the ava (Fig. 8) and less substrate topography (rugosity, Fig. 18) in Pool 500 than the other two pools, resulting in more direct flow towards the ava. Flow direction was less uniform in Pools 300 and 400 than in Pool 500, both spatially and temporally (Fig. C-1 and C-2). Spatially, the velocity of drogues in Pools 300 and 400 was often affected by substrate topography, moving relatively quickly over the extensive shallows found in these pools (but not in Pool 500). Temporally, flow direction also varied from point to point in the tidal cycle in Pools 300 and 400, although the overall direction was always towards the ava (Fig. C-4)

## Habitat Characteristics

Mean depth, total area, and total volume vary greatly for the three pools, as shown in Table 2 below. Although the section of Pool 400 used for this study is  $\approx 2$  m in depth, mean depth for the entire pool is  $\approx 1.5$  m, only slightly deeper than Pool 500, while mean depth for Pool 300 is 1.25 m. Pool 400 is  $\approx 20$ x the volume of Pool 300 and 5x the volume of Pool 500.

	Pool 300	Pool 400	Pool 500
Mean depth (m)	1.25	1.49	1.43
Area (m <sup>2</sup> )	874	14,899	2,938
Volume (m <sup>3</sup> )	1,093	22,200	4,201

Results of the habitat survey are summarized as live coral cover, nonliving substrate type, total cover, and rugosity in the three pools (Fig. 18). Live coral cover was higher in Pool 400 than in Pool 500 ( $p < 0.001$ ), but there were no differences between Pools 300 and 500 ( $p = 0.058$ ) or Pools 300 and 400 ( $p = 0.26$ ). There were no differences in live non-calcareous (soft) algae cover or crustose coralline algae cover between any of the pools ( $p > 0.20$  for each pairwise comparison). Branching corals (*Acropora*, *Millepora*, and *Pocillopora* spp.) made up 10% and 6% of the live coral cover in Pools 300 and 400, respectively, but only one branching coral colony (of *Pocillopora meandrina*) was found in Pool 500 during the habitat survey.

Nonliving substrate type was classified as reef pavement, rubble, or sand. Reef pavement was the dominant substrate in Pool 300, making up nearly 60% of the total sampled area (Fig. 18). The relatively deep, flat areas of Pool 300 are almost entirely reef pavement. Sand and rubble were the primary substrates in Pools 400 and 500, but no differences were found between the two pools in sand ( $p = 0.18$ ) or rubble (0.19) area. However, combined sand and rubble was higher in Pools 500 than in Pool 400 ( $p < 0.01$ ). No differences in rugosity were found between the three pools ( $p > 0.08$  for each pairwise comparison).

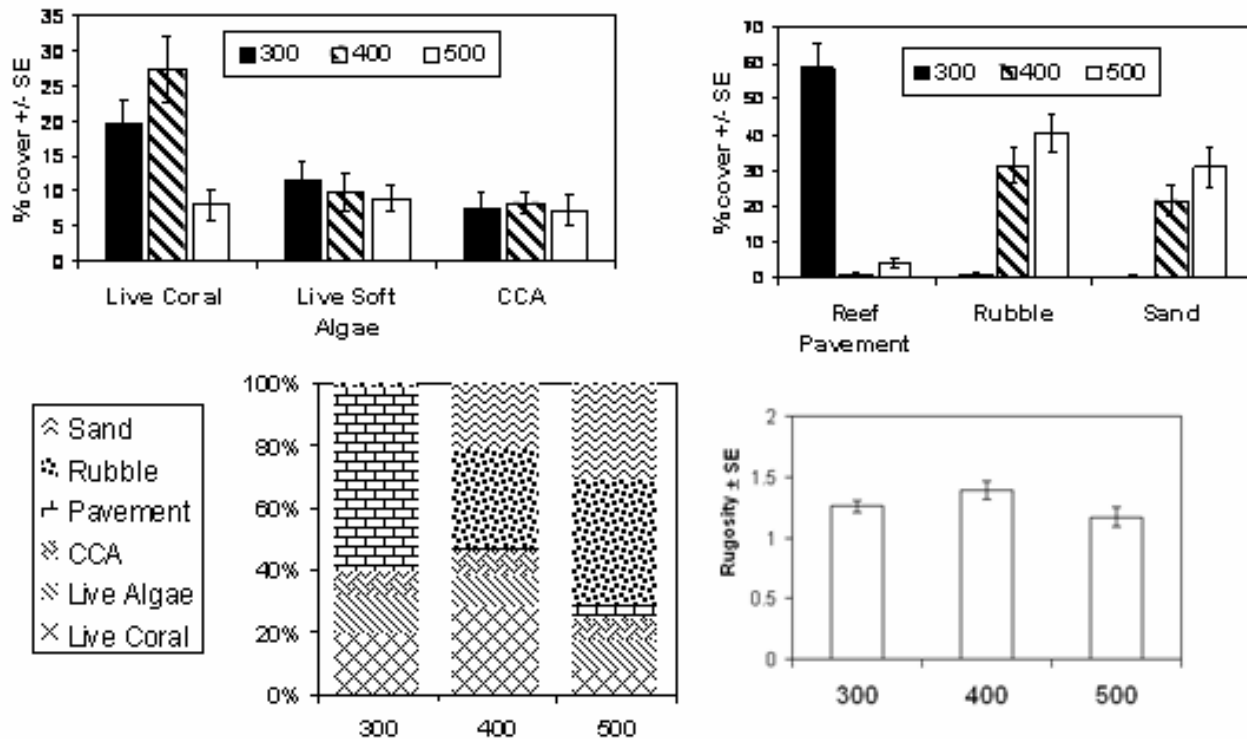


Figure 18. Live cover, nonliving cover, total cover, and rugosity in the 3 pools.

## Coral Transplants

Transplant experimental design is shown in Figure 11. Methods for determining survival and growth of the transplants are described in the Methods section above and in Appendix A. Survival and growth of the transplants over the one year study period are discussed below.

Survival. A total of 180 transplants were placed for the six experiments combined (90 each of *Pocillopora damicornis* and *Porites cylindrica*). During the one year period, 11 of the 180 transplants (6%) failed to stick to the epoxy and disappeared. Of the remaining 169 transplants, 103 (61%) survived for the one year period, but survival of experimental and control transplants combined was more than twice as high for *P. cylindrica* (87%) as for *P. damicornis* (34%).

Survival results for experimental and control transplants are shown below for *P. damicornis* in Table 3, and *P. cylindrica* in Table 4. Experimental transplants were taken from the source area and transplanted to the transplant area, whereas control transplants were taken from the source area to the transplant area, then back to the source area, where they were transplanted. As shown in Figure 11, two of the study sites (Pool 400 and Ofu Harbor) were used as source areas (i.e., for control transplants only), and the other two study sites (Pool 300 and Pool 500) were used as transplant areas (i.e., for experimental transplants only).

Table 3. Survival results for *P. damicornis* transplants in source areas (i.e., control transplants) and in transplant areas (i.e., experimental transplants).

Experiment	Source Area	# surviving/ # total control transplants in source area	Transplant Area	# surviving/ # total experimental transplants in transplant area
I	Pool 400	1/8 <sup>2</sup> (13%)	Pool 500	0/18 <sup>2</sup> (0%)
III	Pool 400	2/10 (20%)	Pool 300	5/18 <sup>2</sup> (28%)
V	Harbor	7/10 (70%)	Pool 300	13/19 <sup>2</sup> (68%)

Table 4. Survival results for *P. cylindrica* transplants in source areas (i.e., control transplants) and in transplant areas (i.e., experimental transplants).

Experiment	Source Area	# surviving/ # total control transplants in source area	Transplant Area	# surviving/ # total experimental transplants in transplant area
II	Pool 400	8/10 (80%)	Pool 500	19/20 (95%)
IV	Pool 400	9/10 (90%)	Pool 300	17/20 (85%)
VI	Harbor	7/9 <sup>2</sup> (78%)	Pool 300	15/17 <sup>2</sup> (88%)

<sup>2</sup> Although a total of 20 experimental transplants and 10 control transplants were done for each experiment, some transplants disappeared during the course of the experiment, thus survival is based on the proportion of the remaining transplants.

Survival of experimental vs. control transplants varied by 2-13% for the three *P. damicornis* experiments (13% vs. 0%, 20% vs. 28%, and 70% vs. 68%; Table 3 and Fig. 19), and by 5-15% for the three *P. cylindrica* experiments (80% vs. 95%, 90% vs. 85%, and 78% vs. 88%; Table 4 and Fig. 20). In three of the experiments (one *P. damicornis* and two *P. cylindrica*), control transplants survived at higher rates, and in the other three, experimental transplants survived at higher rates (Fig. 19 & 20). Survival of transplants between sites varied by 70% for *P. damicornis* (i.e., from 0% in Pool 500 to 70% in Ofu Harbor), and by 17% for *P. cylindrica* (i.e., from 78% in Ofu Harbor to 95% in Pool 500; Tables 3 & 4, and Fig. 21). The greater variability in transplant survival between sites than between experimentals vs. controls for both species suggests that observed survival between sites is due to actual site differences rather than the process of transplanting.

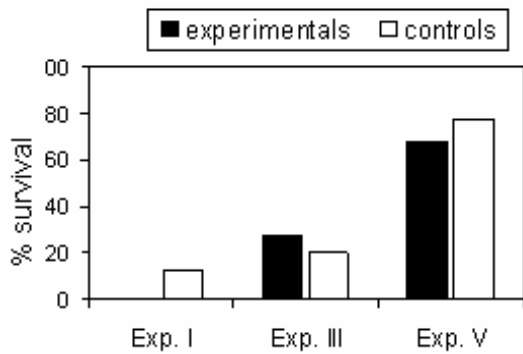


Figure 19. Survival of *P. damicornis* experimental vs. control transplants (no experimental transplants survived Experiment I).

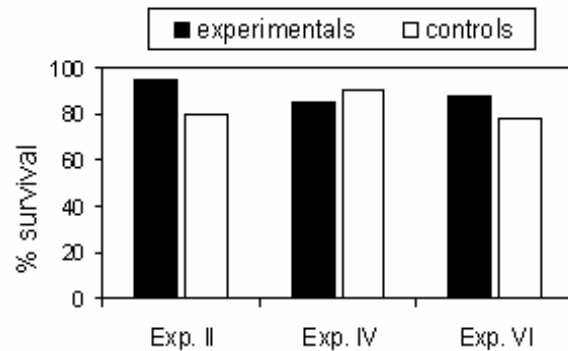


Figure 20. Survival of *P. cylindrica* experimental vs. control transplants.

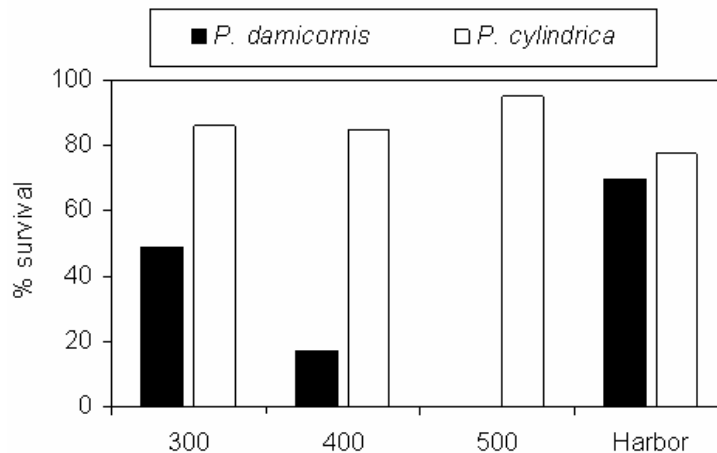


Figure 21. Survival of *P. damicornis* and *P. cylindrica* experimental and control transplants at the four sites.

**Growth.** Annual growth of experimental vs. control transplants is shown in Figure 22 (only five experiments were comparable because Experiment I had no surviving experimental transplants). Experimental vs. control growth rates were different ( $p < 0.001$ ) in the four experiments that could be statistically compared (no experimental transplants survived in Experiment I, and only two control transplants survived in Experiment III). In two experiments (both of *P. cylindrica*), growth rates were higher for controls than for experimental transplants, and the opposite held true for the other three experiments (two of *P. damicornis* and one of *P. cylindrica*). Annual growth of transplants originating in Pool 400 and transplanted to the three lagoon sites (Pools 300, 400 and 500) are shown in Figure 23. Because no *P. damicornis* survived in Pool 500, and only two *P. damicornis* controls survived in Pool 400, no statistical comparison could be done for the growth of this species in the three pools. Growth rates of *P. cylindrica* were greater in Pool 300 than in Pool 400 ( $p < 0.001$ ), and greater in Pool 400 than in Pool 500 ( $p < 0.001$ ).

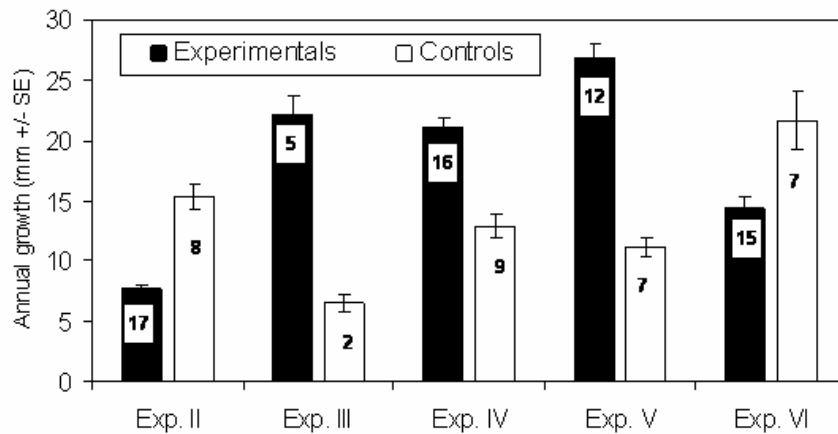


Figure 22. Growth of experimental vs. control transplants (sample sizes shown on bars).

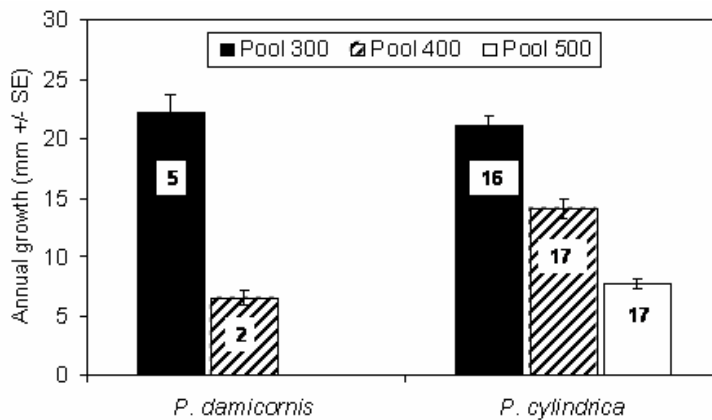


Figure 23. Growth of transplants from Pool 400 in the 3 lagoon pools (results for Pools 300 and 500 are from experimental transplants, and results for Pool 400 are from control transplants; sample sizes shown on bars).

Ofu Harbor was chosen as a fourth temperature logging and coral transplant site because its thermal environment is different than any of the Ofu Lagoon sites (Table 5). The harbor had even greater mean daily maxima (but Pool 300 recorded the highest temperature of the year at 35.5 °C), lower mean daily minima, and greater daily ranges than Pool 300 ( $p < 0.001$  for each comparison). However, the daily means did not differ among Ofu Harbor and the three lagoon sites ( $p = 0.119$ ). The Tidbit temperature logger was placed in inner Ofu Harbor, an area of high temperatures and low coral diversity. Although *P. damicornis* and *P. cylindrica* were both used for transplant experiments using the harbor as a source area (i.e., Experiments V and VI; Fig. 11), only *P. damicornis* results are reported below because *P. cylindrica* could not be found in inner Ofu Harbor (*P. cylindrica* colonies were found in outer Ofu harbor, and these were used as source colonies for Experiment VI). *P. damicornis* nubbins were transplanted from inner Ofu Harbor and from Pool 400 into Pool 300 to compare survival and growth over a one year period. Survival after one year in Pool 300 was more than twice as high for transplants from the inner harbor (78%) than for transplants from Pool 400 (28%). The annual growth rate was greater for transplants from the harbor than for transplants from Pool 400 ( $p = 0.036$ ; Fig. 24).

Table 5. Temperatures in the 3 lagoon pools and Ofu Harbor, 7/02-6/03.

Site	Annual Temperatures (°C)			
	Max	Min	Range	Mean
Harbor	35.0	24.5	10.5	29.1
300	35.5	25.8	9.7	29.1
400	33.5	26.7	6.6	29.2
500	33.6	26.9	6.7	29.1

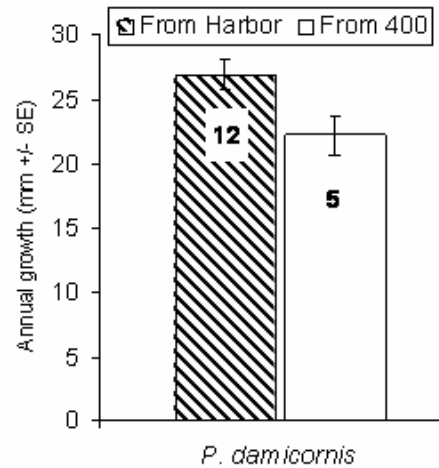


Figure 24. Growth of *P. damicornis* transplants in Pool 300 from Pool 400 and Ofu Harbor (sample sizes on bars).

## Discussion

Data collection on water quality, physical characteristics, and coral growth in the three Ofu Lagoon study sites over the one year study period showed greater growth at the site with the highest water temperatures. *Pocillopora damicornis* and *Porites cylindrica* had significantly higher growth rates in Pool 300 than the other two lagoon sites (Pools 400 and 500). Pool 300 was the Ofu Lagoon site with the highest daily maximum temperatures and greatest daily range in temperatures. In addition, survival of *P. damicornis* was much higher in Pool 300 than the other two lagoon sites. Also, irradiance is likely higher in Pool 300 than the other two pools, based on its shallower depth and similar water clarity. High temperatures and high irradiance are two of the most important factors that increase coral stress (Jokiel In press), thus the higher survival and growth in Pool 300 suggests the presence of intrinsic or extrinsic factors not found at the other two lagoon sites. The effect of the process of transplanting itself, as well as the water temperatures in Ofu Lagoon, are first addressed to provide context for discussing the transplant experiment results.

The process of coral staining and transplanting (described in Appendix A) may reduce survival and growth, thus affecting results of transplant experiments. Variation in survival of experimental vs. control transplants was 2-13% for *P. damicornis* and 5-15% for *P. cylindrica*, and variation in survival by site was 70% for *P. damicornis*, and 17% for *P. cylindrica*. That is, variation between experimental and control groups was less than variation between sites for *P. damicornis* (11% vs. 70%) and *P. cylindrica* (10% vs. 17%), suggesting that observed differences in survival by site are not caused by the process of transplanting. The differences in growth rates of experimental vs. control transplants for the four experiments with adequate sample sizes of surviving transplants ( $p < 0.001$  for all four comparisons; Fig. 22) also support differences between sites, as opposed to an effect of transplanting.

How warm are Ofu Lagoon water temperatures in terms of coral temperature tolerances? The likelihood of coral bleaching is a function of how high temperatures are above the mean summer maximum for the site, the duration of these high temperatures, and the percentage of total surface irradiance (Jokiel In press). For the warmest site in Ofu Lagoon, Pool 300, the mean summer maximum temperature was 30.7 °C in 1999-2001 (i.e., the mean daily maximum temperature for November through May during the three year period). From November through May during this study, temperatures >1°C, >2 °C, >3 °C, and >4 °C above the mean summer maximum temperature of 30.7 °C were recorded 35 times, 12 times, four times, and one time, respectively. The maximum duration of these high temperature events was 5.5 hours, and the mean duration was approximately 3 hours (Fig. 13). Pool 300 is ≈1 m in depth and turbidity is very low, thus irradiance is high, so there is potential for synergistic effects of ultraviolet radiation. The other study sites in Ofu Lagoon, Pool 400 and Pool 500, are slightly deeper and have relatively moderate temperatures (Fig. 12).

Intrinsic Factors: Do Ofu Lagoon corals withstand high temperatures because of intrinsic factors such as acclimatization or adaptation? Acclimatization refers to phenotypic plasticity of an organism that allows it to increase tolerance to stresses in the natural environment. Such phenotypic responses are usually reversible and limited by the organism's genotype, which



determines the boundaries beyond which acclimatization cannot occur. Adaptation refers to genotypic selection brought about by the elimination of less tolerant individuals, leaving the more tolerant individuals in the gene pool (Brown 1997, Coles & Brown In press).

Acclimatization to high temperatures has been shown to occur seasonally for *P. damicornis* (Berkelmans & Willis 1999), and to be induced by exposure to high irradiance in *Goniastrea aspera* (Brown et al. 2002). Coral bleaching patterns in some locations with long-term records of temperatures and bleaching suggest that coral populations have adapted to localized temperature conditions (Cook et al. 1990, Vargas-Angel et al. 2001).

The field experiments conducted to date are intended to search for signs of acclimatization or adaptation in order to determine if laboratory experiments should be pursued. Results of temperature monitoring showed that the three lagoon sites and Ofu Harbor all have similar mean annual temperatures. Within the lagoon sites, Pool 300 had higher daily maxima, lower daily minima, and greater daily ranges than Pools 400 and 500. The harbor had even higher daily maxima, lower daily minima, and greater daily ranges than Pool 300. Thus, assuming higher daily maxima and greater daily ranges are more stressful to corals, the harbor is the most stressful environment, and Pool 300 has the most similar environment to the harbor. If harbor corals are better acclimatized or adapted to thermal stress than Ofu Lagoon corals, then transplants from the harbor would be expected to survive better and grow faster in Pool 300 than transplants from Pool 400. Only *P. damicornis* was transplanted from the inner harbor to Pool 300 because *P. cylindrica* does not occur in the inner harbor. Results suggesting *P. damicornis* colonies from the inner harbor are acclimatized or adapted to the thermal environment found there include: (1) Greater survival of transplants in Pool 300 from the harbor (78%) than transplants from Pool 400 (28%); and (2) greater growth rate of transplants in Pool 300 from the harbor than transplants from Pool 400 ( $p = 0.036$ ; Fig. 24).

However, the control transplants for *P. damicornis* from Pool 400 and from inner Ofu Harbor grew less than the experimental transplants in Pool 300 (Experiments III and V, Fig. 20). Likewise, the control transplants of *P. cylindrica* from Pool 400 grew less than the experimental transplants in Pool 300 (Experiment IV, Fig. 22). Thus, experimental transplants of both species from a cooler site (Pool 400) and a warmer site (inner Ofu Harbor) grew more in Pool 300 than control transplants in the original environments. The transplants in Pool 300 were shallower than those in the other two lagoon sites and the harbor, thus irradiance was likely highest in Pool 300. These results suggest that extrinsic factors, such as water motion, salinity, dissolved oxygen, or turbidity may be affecting the survival and growth of the transplants. Extrinsic factors may also explain the absence of many relatively sensitive coral species (e.g., *Acropora*, *Millepora*, and *Pocillopora* spp.) from Pool 500, and the lower survival and growth of both species of transplants in Pool 500 than the other two lagoon sites (Figures 19-22).

Extrinsic factors: Do Ofu Lagoon corals withstand high temperatures because of extrinsic factors such as strong currents or other favorable environmental conditions? Extrinsic physical factors can increase the ability of corals to withstand the conditions that typically lead to bleaching (i.e., high temperatures, high irradiance). Water movement is positively correlated with coral survival during warming events (Loya et al. 2001, Bena & Van Woelk In press), possibly because increased passive diffusion helps eliminate toxins (Nakamura & Van Woelk 2001), and because water currents increase the density of microsporine-like amino acids which

protect corals from irradiance (Jokiel et al. 1997). Reduction of irradiance by turbidity (Phongsuwan 1998), low sun aspect (Brown et al. 2002), or cloud cover (Mumby et al. 2001) can reduce bleaching and mortality during thermal stress. Increases in salinity up to about 40 ppt can mitigate the effects of high temperatures, at least for short periods (Coles & Jokiel 1978, Porter et al. 1999). Habitat diversity may be important for providing microhabitat with features such as shading or high water motion that ameliorate the effects of thermal stress (Coles & Brown In press). Hyperoxia (>150% dissolved oxygen saturation) stimulates the metabolism of zooxanthellae (Gardella & Edmunds 1999), and thus could play a role in the ability of corals to withstand high temperatures and high irradiance.

Coral transplants may have survived better (*P. damicornis*) and grown more (*P. damicornis* and *P. cylindrica*) in Pool 300 than the other two lagoon pools due to favorable extrinsic factors. Water movement results showed higher flow velocity in Pool 300 than the other two lagoon pools (Fig. 17), but no differences in total water motion (Fig. 16). Sample sizes were small for both the velocity and motion experiments, and the studies were only conducted during calm weather, so more thorough water movement studies are required to determine if there are differences between the pools. Hyperoxia occurred more often and at higher levels in Pool 300 than the other two pools (Fig. 15 and Appendix B), possibly enhancing survival and growth of coral transplants (Gardella & Edmunds 1999). Sand scouring can damage coral tissue (Hubbard 1997) and Pool 300 has less sandy substrate than the other two pools, thus abrasion or scour of corals by sand may reduce survival and growth in Pools 400 or 500, but this was not tested. Salinity was lower in Pool 300 than the other two pools during rainy weather, but lower salinity increases stress on corals and reduces survival and growth (Moberg et al. 1997).

Other factors may also ameliorate or exacerbate coral bleaching and mortality, such as coral colony size, fish predation, coral disease, and damselfish territoriality. Small coral colonies (<5 cm diameter) survive warming events at a higher rate than larger conspecific colonies (Loya et al. 2001, Bena & Van Woesik In press), possibly due to more efficient passive diffusion of heat from the smaller colonies (Nakamura & Van Woesik 2001). The greater survival and growth of transplants in Pool 300 does not appear to be related to colony size because transplants of each species were all approximately the same size (see Appendix D for examples). Although the fish communities of the three lagoon pools are very similar (Green 2002), observations suggested fish predation occurred more heavily on transplants of *P. damicornis* in Pools 400 and 500 than in Pool 300. However, virtually no fish predation was observed on transplants of *P. cylindrica* in any of the pools, yet both coral species grew more in Pool 300 than the other two pools. Fish predation does not appear to have affected the outcome of the transplant experiments, unless the two coral species grew more in Pool 300 for different reasons. Observations made during the habitat survey for this study, as well as the results of a coral health study (Work & Rameyer 2002), did not find different levels of disease between the three pools. Coral survival and growth following bleaching events can be higher within territories of *Stegastes* spp. (Suefuji & van Woesik 2001). Bleaching of sensitive species such as *Millepora* and *Acropora* spp. was observed in Ofu Lagoon following high water temperatures in January through March 2003, thus transplants placed within *Stegastes* territories may have survived and grown better than transplants outside territories. However, all transplants used in this study were placed in areas that appeared to be outside of *Stegastes* territories, at least at the time of transplanting.

Conclusions. The mean daily temperatures of the three pools were nearly identical during the summer (Nov-May), as well as over the entire one year period (Table 1), thus thermal differences between Pool 300 and the other lagoon pools are limited to higher maximum daily temperatures, lower minimum daily temperatures, and greater daily temperature ranges (Fig. 12). These thermal differences may be inadequate to result in greater acclimatization or adaptation of corals in Pool 300 than the other lagoon pools, and the transplant results support the null hypothesis that there are no intrinsic differences, although laboratory experiments are necessary to substantiate this. Such experiments should also test for differences in temperature acclimatization and adaptation between corals from Pool 300 and conspecific colonies from nearby open ocean habitats that experience cooler, more stable temperatures, because these two sample groups experience greater thermal differences in their environments than colonies limited to the lagoon.

Duration of exposure to both temperature and irradiance is a major factor controlling bleaching (Winter et al. 2001, Jokiel In press). Duration thresholds for bleaching are measured in “degree heating weeks” (DHWs), defined as one week of water temperature  $>1$  °C above mean summer maximum temperature. DHWs only accumulate when the temperature remains  $>1$  °C above mean summer maximum temperature (Jokiel In press). That is, while the temperature in Pool 300 rose to  $>1$  °C above mean summer maximum temperature (30.7 °C) approximately 40 times during the one year study, the maximum duration was 5.5 hours and the average was 2.5 hours. Such diurnal fluctuations result in very small DHW accumulations because the DHW count returns to zero every day; e.g., Pool 300 accumulated only 0.03 DHW (5.5 hours) during the one year study period. The very short duration of stressful conditions reduces the likelihood of bleaching and mortality, thus corals can thrive in short-lived temperatures several degrees above mean summer maxima (Brown 1997, Coles 1997).

The most stressful conditions in terms of coral bleaching in Ofu Lagoon occur when calm, clear weather during the summer (Nov-May) coincides with spring low tides at midday, producing high temperatures and high irradiance. In the absence of wind, water movement is minimal because the very low tides result in physical separation of the lagoon pools from the open ocean by the exposed reef crest, preventing mixing until the tide comes in. Among the three lagoon pools, temperatures, and presumably irradiance, are highest in Pool 300 because its shallow depth and small water volume allow it to heat up quickly, and to be most exposed to solar radiation, thus Pool 300 has the most frequent and longest duration hot water events of the three lagoon pools (Fig. 13). However, the duration of these hot water events is only a few hours at the most, reducing the impact of the high temperatures and high irradiance.

The short duration of stressful conditions in Pool 300 does not explain why the coral transplants survived and grew better there than the other two lagoon pools, because high temperatures and high irradiance were of less magnitude and shorter duration in these pools than in Pool 300. Results to date support the hypothesis that extrinsic differences between the lagoon pools such as water motion and dissolved oxygen are more likely explanations for the observed differences in transplant survival and growth than intrinsic differences between the coral colonies found in the pools. While water movement is minimal during the most stressful periods, overall water movement appears to be greater in Pool 300 than the other two pools. Hyperoxia is more frequent and to higher levels in Pool 300 than the other two pools. The lack of water movement

during the coincidence of calm, clear weather with midday spring low tides increases hyperoxia because the dissolved oxygen produced by photosynthesis builds up in the unmixed water. Thus the periods of greatest hyperoxia coincide with the highest temperatures and highest irradiance, possibly ameliorating their effects on corals, and thereby contributing to the greater survival and growth of the coral transplants in Pool 300. Extrinsic factors may act synergistically with one another to affect survival and growth of corals.

The results of this study may provide clues regarding the observed distributions of coral species in Ofu Lagoon, such as the near absence of *P. damicornis*, *P. cylindrica*, and other branching species from Pool 500. Higher turbidity was recorded in this pool during stormy weather than in the other two lagoon pools. Pool 500 also had more sand and rubble than the other two pools. The only accumulation of large rocks on Ofu beach is found near Pool 500, as is the only break in the reef. These observations suggest that wave energy may be greater in Pool 500 than the other lagoon sites during storms, which may result in fewer branching coral colonies. Flow direction may affect distribution of corals in Pool 500 because prevailing current, regardless of tides, is towards the ava (Appendix C), thus the larvae of *P. cylindrica* and other corals may be unable to recruit to Pool 500 because source colonies are downstream. However, abundant colonies of *P. damicornis*, which is also absent from Pool 500, occur on the reef crest adjacent to Pool 500.

In conclusion, coral transplants survived better (*P. damicornis*) and grew more (*P. damicornis* and *P. cylindrica*) in Pool 300, the site with the highest temperatures and highest irradiance of the three lagoon pools. The effects of such stressful conditions on the transplants may have been ameliorated by extrinsic factors such as water motion or substrate characteristics, acting alone or synergistically with one another. These and other extrinsic factors are thought to reduce temperature stress on corals (West 2001). The coral communities found in areas featuring such extrinsic factors may be the most likely to survive the increasing temperatures predicted to result from global warming. Therefore, identifying areas where beneficial extrinsic factors are prominent, and incorporating them into MPAs, can help mitigate the effects of global warming on coral reef ecosystems (Done 2001, West & Salm In press).

### **Future Direction For Years 2-4**

The results from Year 1 provide information needed for designing experiments that more comprehensively investigate intrinsic and extrinsic factors enabling Ofu Lagoon corals to withstand high temperatures. The following field and laboratory experiments should be pursued in Years 2-4 to test the hypotheses outlined in the Project Design section of this report. In addition, data collection on water quality and physical characteristics of the three Ofu Lagoon study sites should continue in order to provide data for this project, as well as for long-term reef ecosystem monitoring.

Intrinsic Factors: While Year 1 results suggest that Pool 300 corals may not be better acclimatized or adapted to high temperatures than corals in the relatively cool Pool 400 and 500, this may be due to the rather slight thermal differences between the pools. Water temperatures outside the lagoon on the forereef are cooler and less variable than any of the lagoon pools, especially Pool 300. Conspecific coral colonies (preferably *P. damicornis*, if colonies can be found at all sites) from the forereef, Pool 300, and possibly Hawai'i are recommended for the following laboratory experiments:

1. To test for acclimatization and adaptation, transplant conspecific colonies from Pool 300, the Ofu forereef, and Hawai'i into aquaria set to thermal conditions similar to Pool 300, and compare survival and growth. Greater survival and growth by Pool 300 corals will support the hypothesis that these corals are acclimatized or adapted to the thermal conditions of Pool 300.
2. Stimulate spawning of the coral colonies collected from Pool 300, the Ofu forereef, and Hawai'i, grow out the larvae in identical moderate thermal conditions, and expose the three groups to thermal conditions similar to Pool 300, then monitor survival and growth. If Pool 300 corals are genetically distinct (i.e., adapted to the high temperatures), then offspring of Pool 300 corals should survive and grow better than offspring from Ofu forereef and Hawaiian corals.
3. Further distinguish between acclimatization and adaptation using molecular methods to compare corals from Pool 300, the Ofu forereef, and Hawai'i.

Extrinsic Factors: Year 1 results suggest that extrinsic factors may be important for enabling Ofu Lagoon corals to withstand high temperatures. Additional experiments will supplement data collected during Year 1, and may provide more evidence for explanations of the coral transplant experiment results. The following field and laboratory experiments are recommended to collect data on extrinsic factors in Ofu Lagoon, and to test the effects of certain extrinsic factors on the survival and growth of corals subjected to high temperatures and high irradiance:

1. Conduct a flow study of the Ofu Lagoon sites, using clod-cards, drogues, and other methods if appropriate, throughout the tidal cycle and across a range of weather conditions, to characterize flow velocity, flow direction, and total water motion.
2. Monitor DO (% saturation) in the three pools with the Sonde water quality data loggers, especially during hot, windless periods coinciding with spring low tides when temperatures and irradiance are highest in the pools.

3. Collect data on sand abrasion in the three pools, especially during stormy weather when turbidity and abrasion are highest. In the laboratory, test the effect of sand abrasion on juvenile coral colonies of several species.
4. Conduct laboratory experiments to test the effect of hyperoxia (DO >150%) on coral survival and growth under stressful conditions of high temperatures and high irradiance.
5. Conduct laboratory experiments to test if coral colonies <5 cm in diameter survive stressful conditions better than large colonies because of small size (i.e., age does not matter as long as colony is small) or young age (i.e., small fragments of older colonies do not survive as well as equally sized young colonies, so age does matter).

Temperature Duration: Year 1 results suggest that corals can survive temperatures above their tolerance thresholds provided that the duration is short. The ability to withstand brief high temperatures is likely affected by other factors such as irradiance, water motion, dissolved oxygen, turbidity, and other factors, thus the following laboratory experiment is recommended:

1. Monitor survival, growth, and zooxanthellae photosynthetic activity (using Pulse Amplitude Modulated Fluorometry, or PAM) of corals in aquaria exposed to brief periods (i.e., a few hours) of high temperatures under different environmental regimes such as high irradiance vs. low irradiance, high flow vs. low flow, high DO vs. low DO, and high turbidity vs. low turbidity.
2. Monitor survival, growth, and zooxanthellae photosynthetic activity of corals in aquaria exposed to high temperatures lasting a few days to a few weeks or longer under the same conditions as #1 above.

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## Appendix A: Methods for Coral Transplant Experiments

The methods used for the coral transplant experiments are described in more detail below, and locations are shown on aerial photos. “Nubbin” refers to branches or small colonies of coral that were used as the transplants. “Experimental transplants” refers to nubbins that were taken from the source area and transplanted in an experimental area at a different site. “Control transplants” refers to nubbins that were taken from the source area to an experimental area, then brought back and transplanted in the original source area. The methods consist of the following ten steps:

- 1) Select source colonies from which to obtain nubbins for transplanting: Nubbins were carefully selected from colonies in the source area with the following considerations in mind: (a) Correctly identifying the coral species can be challenging – e.g., the photo of Step 1 shows a *Pocillopora damicornis* colony on the left, and a *P. danae* colony on the right from Ofu Lagoon. Distinguishing similar species required some practice with an expert (C.

Birkeland) as well as frequently consulting a recent guidebook (Veron 2000); (2) the area from which colonies were selected for obtaining nubbins was small (< 20 m radius from location of the tidbit temperature loggers, see aerial photos below) to reduce the likelihood of habitat variability in the source area; (3) between 3 and 27 source colonies were used to obtain the 30 nubbins used for each experiment in an effort to represent the genetic variability found at the source area; (4) the shape and size of the nubbins is important – e.g., bushy, branched nubbins of *P.*



Step 1. Select source colonies from which to obtain nubbins.

*damicornis* were used to reduce vulnerability to predators, and all transplants (both species) were < 10 cm in diameter or height to facilitate attaching them to the substrate. The collecting, staining, and transplanting of each group of 30 nubbins was usually done in two batches of 15 (10 experimental transplants and 5 control transplants) by one or two people.

- 2) Put nubbins in bags of stain: After all the nubbins to be transplanted that day were collected from the source area and brought to a central location in the water, each nubbin was placed in a plastic bag filled with seawater and containing a solution of alizarin Red S dye. Alizarin is a non-toxic bone stain commonly used in coral experiments because when live corals are placed inside a plastic bag of seawater with a solution of alizarin, and allowed to photosynthesize for a few hours, a layer of stain is



Step 2. Put nubbins in bags of stain.

incorporated into the skeleton that can be later used for determining growth rates (Barnes 1970). Plastic zip-lock bags (1 gallon) were prepared by placing about  $\approx 1/16$  teaspoon of stain powder in one corner held in place with a rubber band, and brought out to the source area. Only one nubbin was placed inside each bag to prevent them from knocking against one another.

- 3) Allow nubbins to photosynthesize in stainbags. After the nubbins (usually 15 in each daily batch) were placed in their individual stainbags, each bag was attached with large binder clips (i.e., the kind used to clip 50 or 100 sheets of paper together) to the gridlines of one or



Step 3. Allow nubbins to photosynthesize in stainbags.

two 50 cm x 50 cm quadrat frames normally used for estimated coral cover. This was done to keep stainbags from being washed away by the current, and to prevent entanglement that would have been caused by using string or twine. The quadrats and stainbags were held on the substrate with weight belts, and left out in the lagoon for 5-6 hours in the middle of the day, usually from approximately 9 a.m. to 3 p.m.

- 4) Prepare transplant site. While the nubbins were photosynthesizing in their stainbags, the experimental and control transplant sites were prepared. The most important part of this step is to appropriately select the locations where each transplant will be placed. Each location should be representative of the study site in terms of where corals would most likely settle and grow naturally. Thus the transplant locations should not be in shaded areas (not enough sun), on loose substrate (not stable), too shallow (too much UV), or too close to other living coral colonies (risk of being overgrown). After the location for each nubbin was selected, the substrate was prepared by scrubbing with a wire brush to remove loose material. It was helpful to select highly indented surfaces so that the epoxy could be pushed into the holes or cracks and thereby hold better.



Step 4. Prepare transplant site.

- 5) Prepare the epoxy. A marine epoxy, Sea Goin' Poxy Putty (Permalite Plastics Corp.), was used to attach the nubbins to the substrate (Birkeland 1976). The epoxy comes in two parts that must be mixed before use, after which it remains workable for approximately 30 minutes



Step 5. Prepare the epoxy.

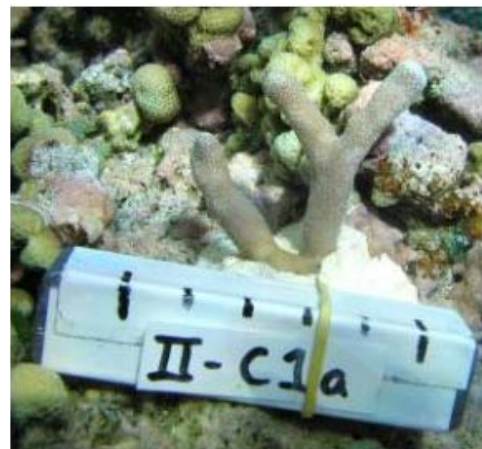
enough epoxy to place 10 nubbins was mixed on the beach. Each nubbin required an amount of epoxy approximately equal to the size of a golf ball.



Step 6. Place the transplants.

epoxy hardened, it became easier to get the nubbins to stay in place. The control transplants were placed back at the source area with the same process, and all nubbins were checked the following day. On several occasions, a nubbin had not stuck, so it was reglued and rechecked until it stayed in place.

- 7) Document the transplants. After the nubbins were in place, each individual was photographed to provide a before-and-after record of growth. A numbering system was devised to identify each of the 180 nubbins (90 *P. damicornis* and 90 *P. cylindrica*) in the six experiments, each of which consisted of 30 nubbins, including 20 experimental transplants and 10 control transplants. The nubbins were meticulously mapped by experiment so each of the 180 transplants could be individually relocated and identified.



Step 7. Document the transplants.

before hardening. A newer version of the epoxy, Poxy Quick, made by the same company, was tried but with poor results because it remains workable for only 5-10 minutes before hardening, and does not adhere as well to the substrate. After the nubbins had been in their stainbags in the lagoon for 5-6 hours, they were retrieved and taken to the site where the experimental transplants were to be placed. Nubbins were transported in 5 gallon buckets while still in their stainbags, which were often noticeably warmer than the lagoon water because of lack of circulation inside the bags.

When everything was ready at the transplant site,

- 8) Remove the transplants. The 180 nubbins were checked after six months to determine how many had become detached, and of those that remained, what proportion had survived. After one year, the remaining nubbins were again checked for survival, and photographed to provide one year before-and-after documentation. The nubbins were then removed, carefully noting the number of each.



Step 8. Remove the transplants.



Step 9. Prepare the transplants for measuring.

- 9) Prepare the transplants for measurement. After the nubbins were removed from the water, the tissue was removed from the skeletons to facilitate cutting or filing them to expose the stain marks. This was done by simply hosing the tissue off with a garden hose and nozzle. The tissue of *P. damicornis* is easily removed in this manner, but that of *P. cylindrica* does not come off as easily because the polyps are deeply embedded in the skeleton. However, it is not necessary to remove all the tissue before cutting or filing.

- 10) Measure growth. Growth was determined by measuring the amount of skeleton added during the one year period since the nubbins were transplanted. *P. damicornis* has a much harder skeleton than *P. cylindrica*, and a more complex growth form, thus requiring more time and effort to measure. Growth of each *P. damicornis* nubbin was determined by: (1) Breaking the transplant into pieces to reveal each branch, and if necessary, sawing the branches (with a hacksaw or Rotozip power jigsaw) longitudinally to reveal the stainmarks; (2) selecting the five branches that had grown the most and measuring each to the nearest 0.1 mm with dial calipers; and (3) taking the average of these five measurements to obtain the growth estimate. Growth of each *P. cylindrica* nubbin was determined by selecting the tallest upward growing branch, sawing (with a hacksaw) or filing it longitudinally to reveal the stainmark, and measuring both the length and girth of growth added since the stainmark to the nearest 0.1 mm to obtain the growth estimate. Stainmarks on *P. damicornis* and *P. cylindrica* are shown below.



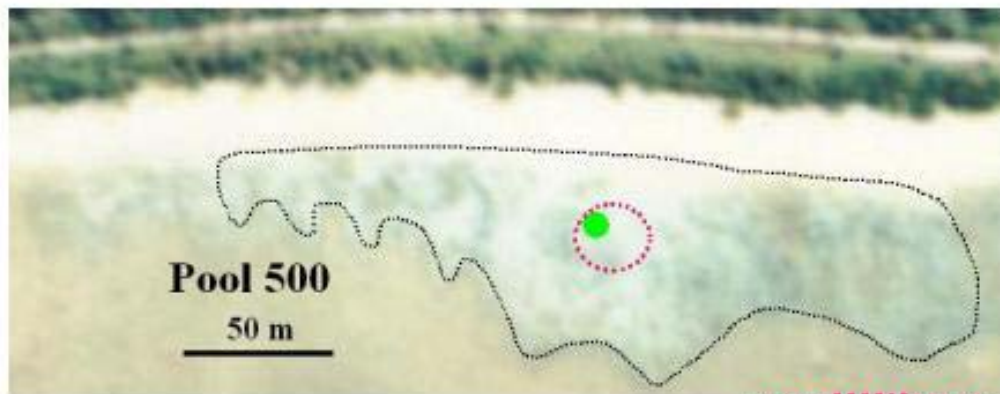
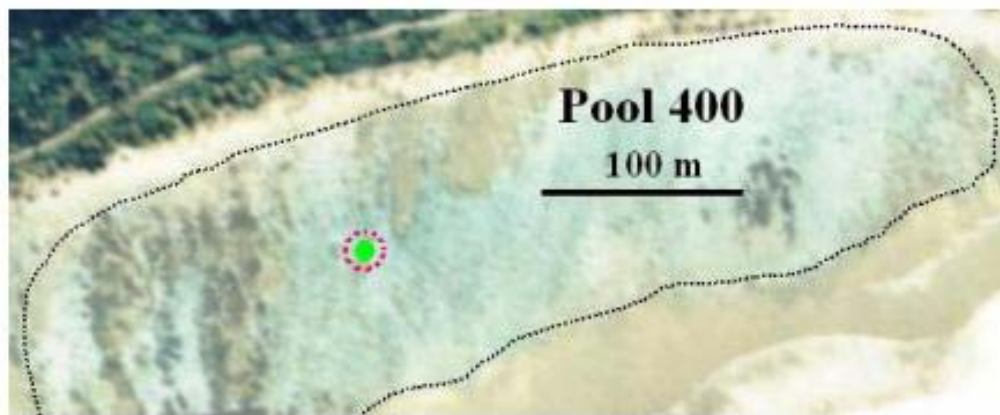
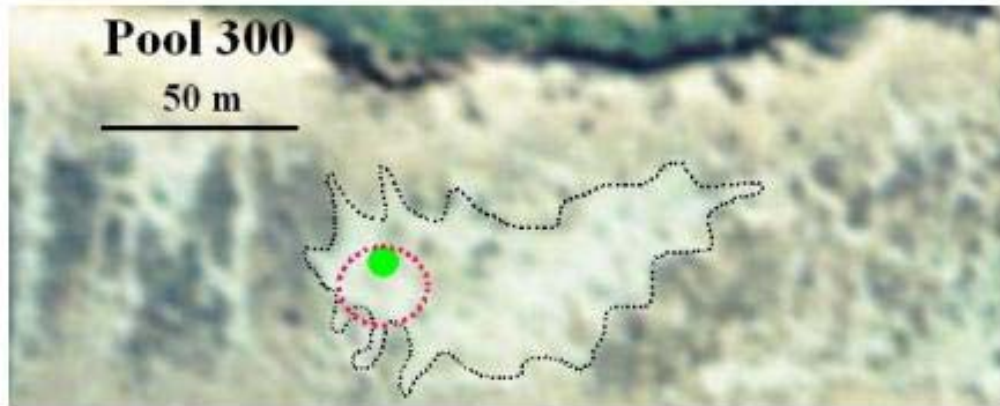
Step 10. Measure growth.



Growth stains on *P. cylindrica*.



Growth stains on *P. damicornis*.



Locations of Tidbit temperature loggers (●) and coral transplant areas

### Appendix B. Water Quality Graphs from Sondes

Graphs of data collected with the Sonde loggers on dissolved oxygen, salinity, and turbidity in the three lagoon pools are provided below. Data for the graphs are included in Appendix E (on CD, not included in the hard copy of this report).

#### Dissolved oxygen.

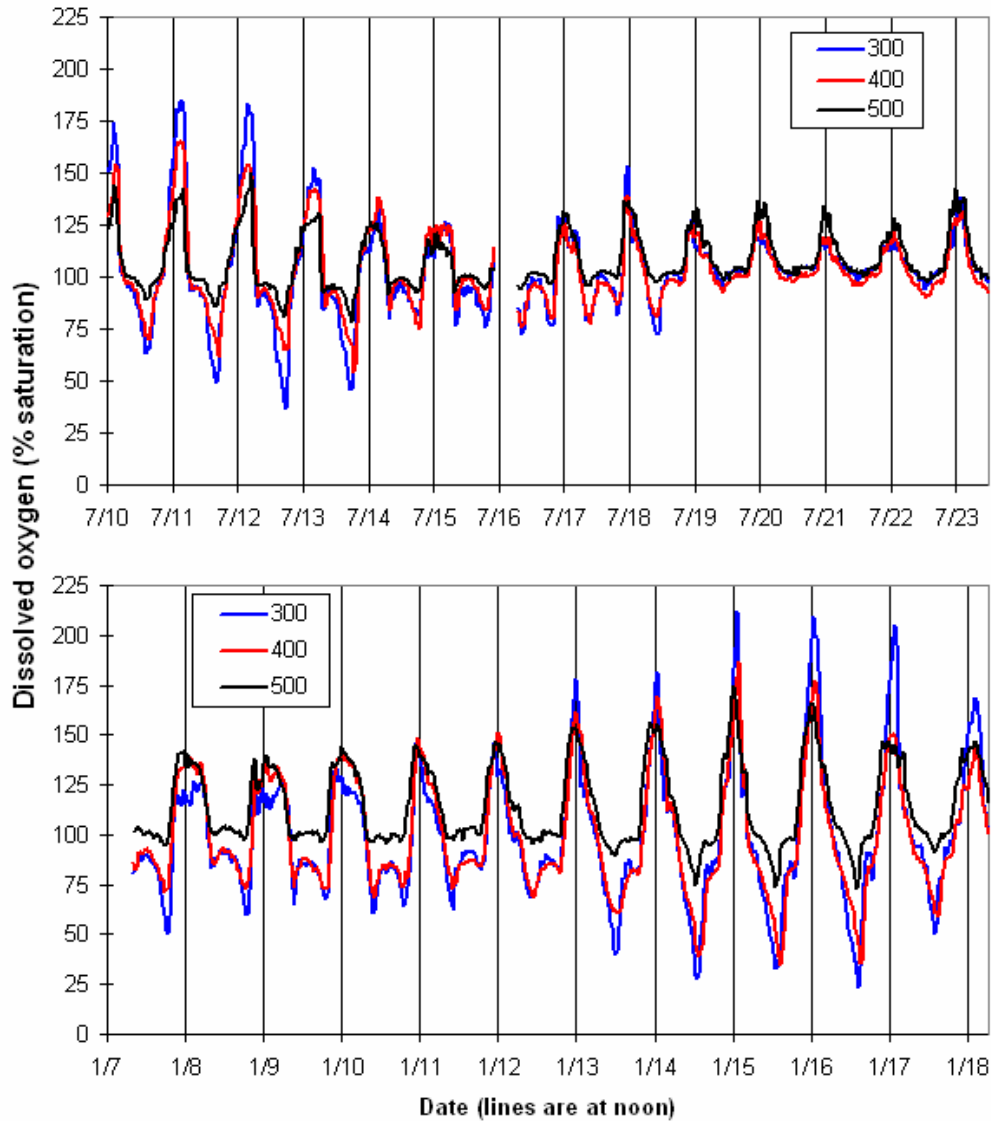


Figure B-1. Dissolved oxygen in the 3 pools, July 2002 and January 2003 (data loggers removed for 8 hours on 7/16/02 to check calibration).

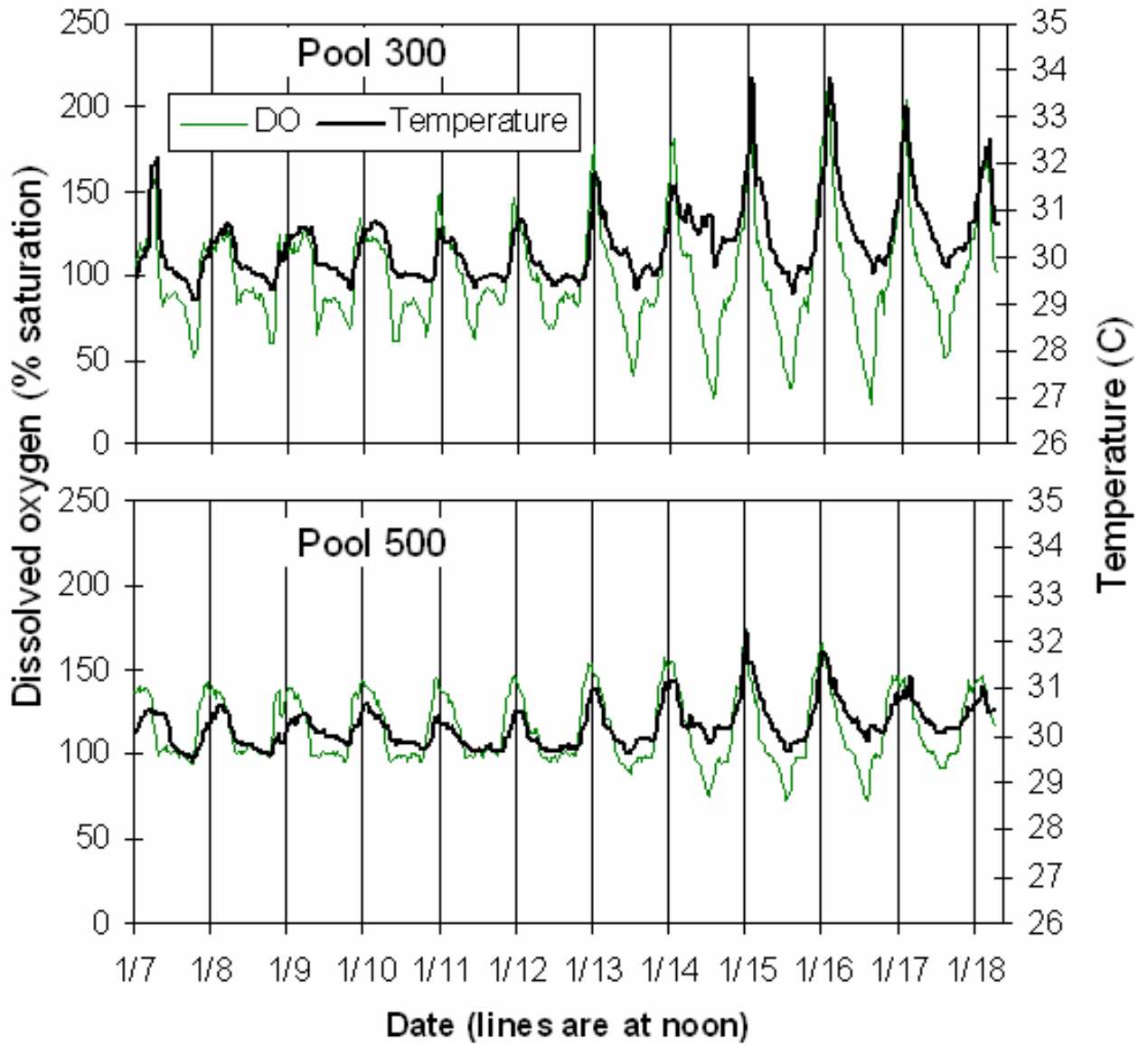


Figure B-2. DO vs. temperature in Pools 300 and 500.



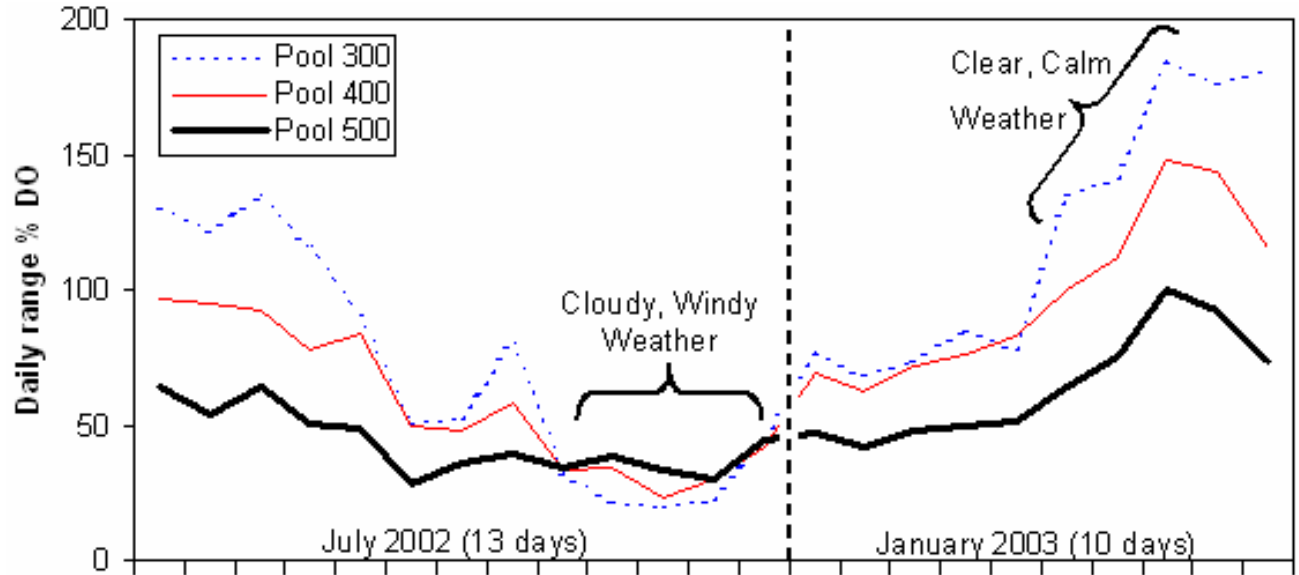


Figure B-3. Daily range in % dissolved oxygen over 23 days, showing effect of cloudy, windy weather and clear, calm weather.

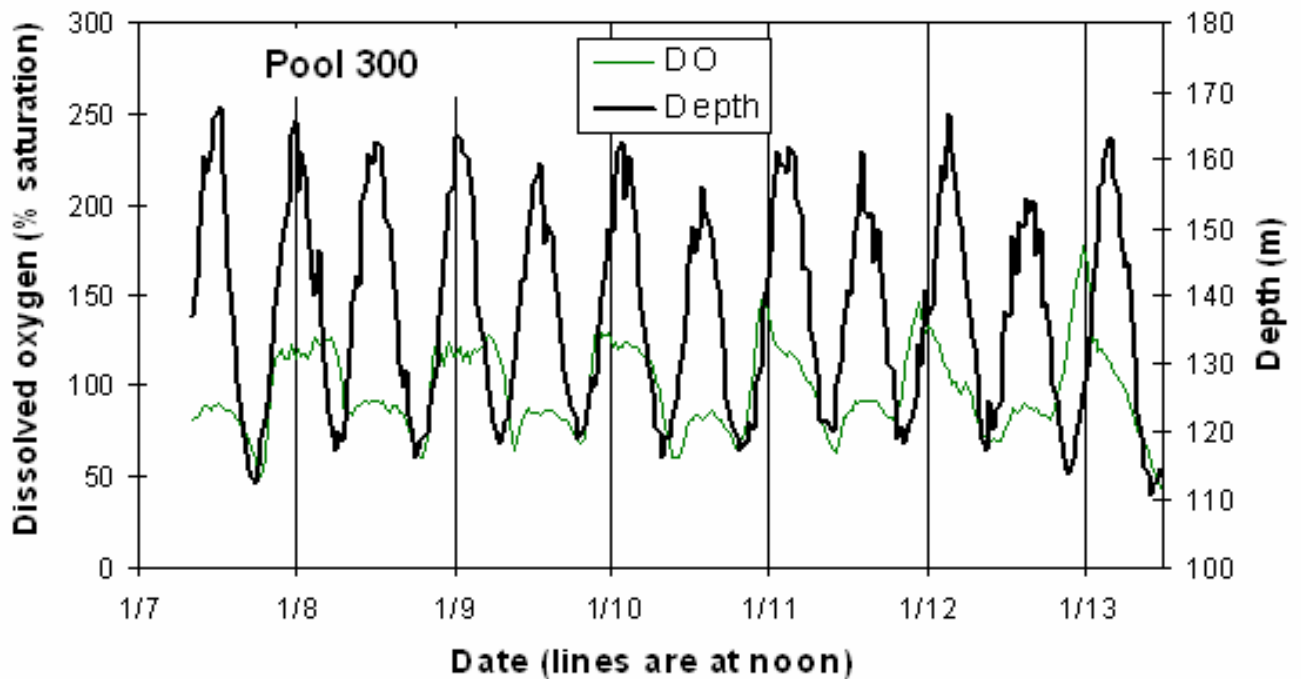


Figure B-4. Tidal effect on dissolved oxygen during calm weather.

Salinity.

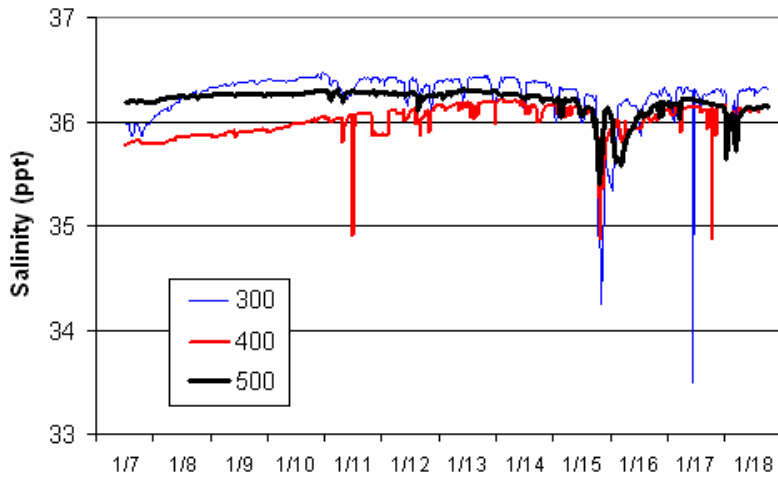
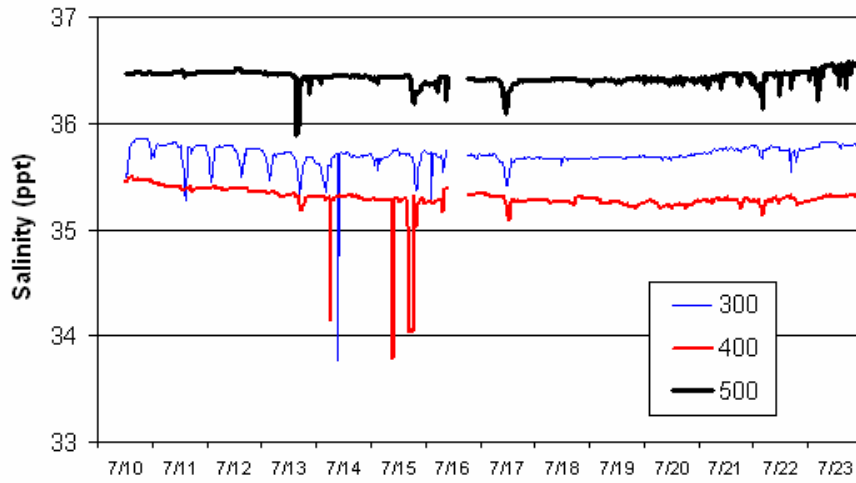


Figure B-5. Salinity in the 3 pools, July 2002 and January 2003 (data loggers removed for 8 hours on 7/16/02 to check calibration).

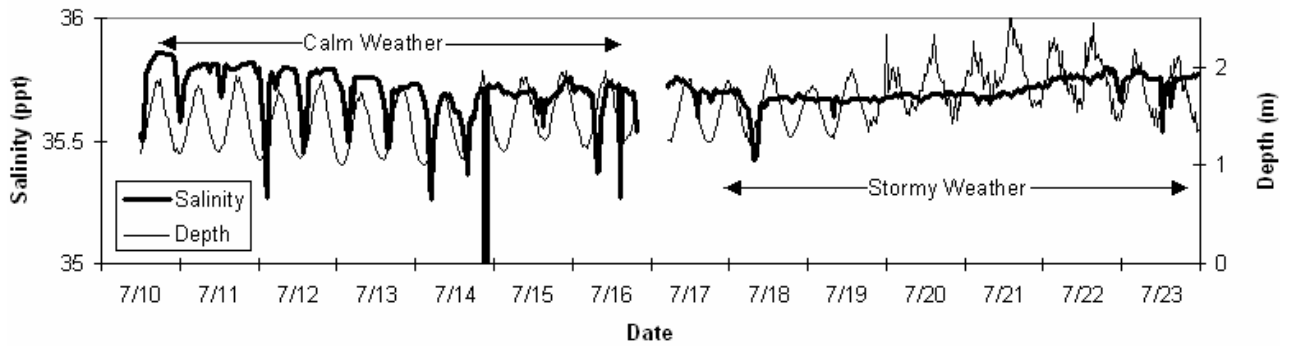


Figure B-6. Salinity vs. depth in Pool 300 during calm and stormy weather.

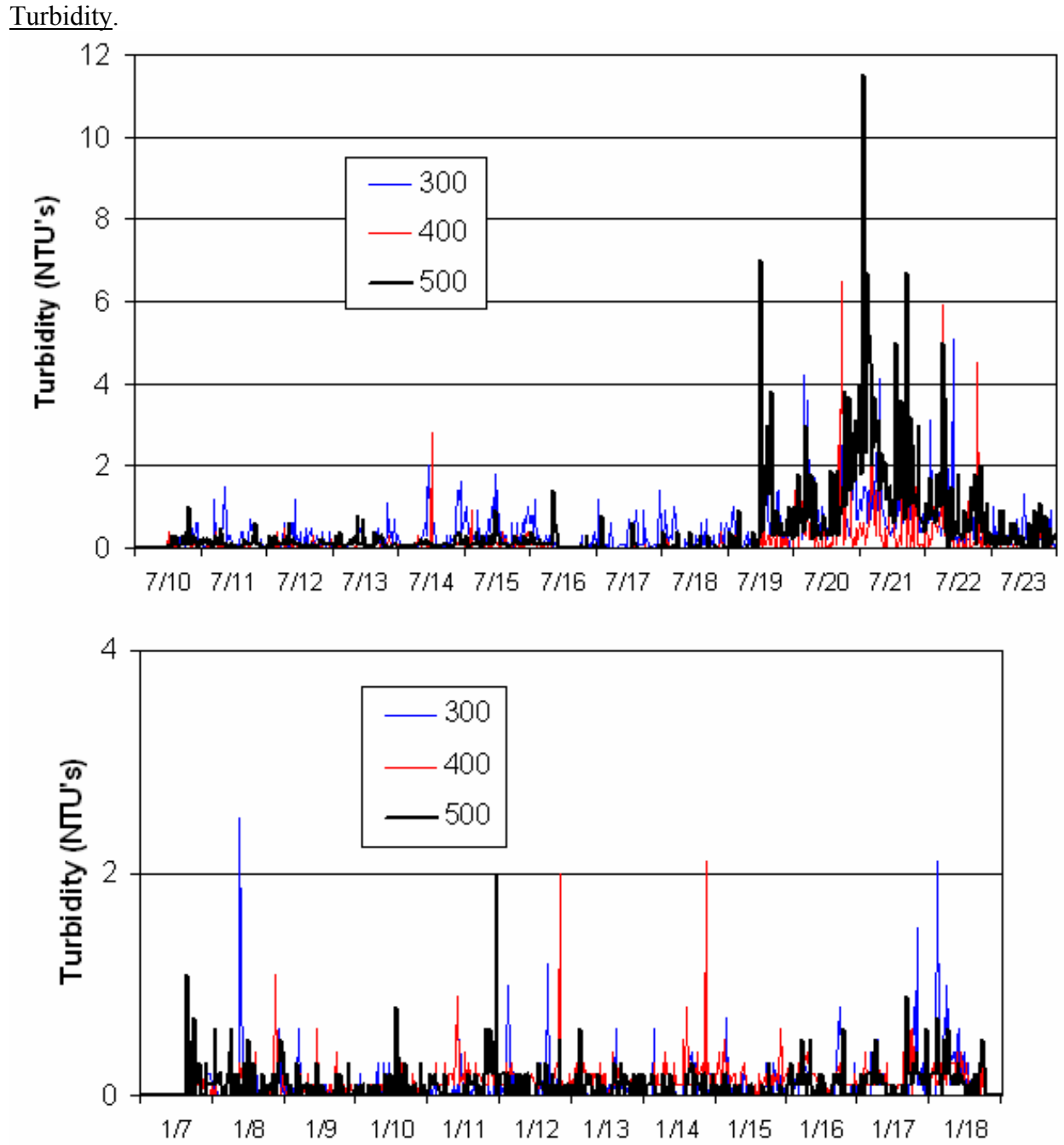


Figure B-7. Turbidity in the 3 pools, July 2002 and January 2003 (data loggers removed for 8 hours on 7/16/02 to check calibration).

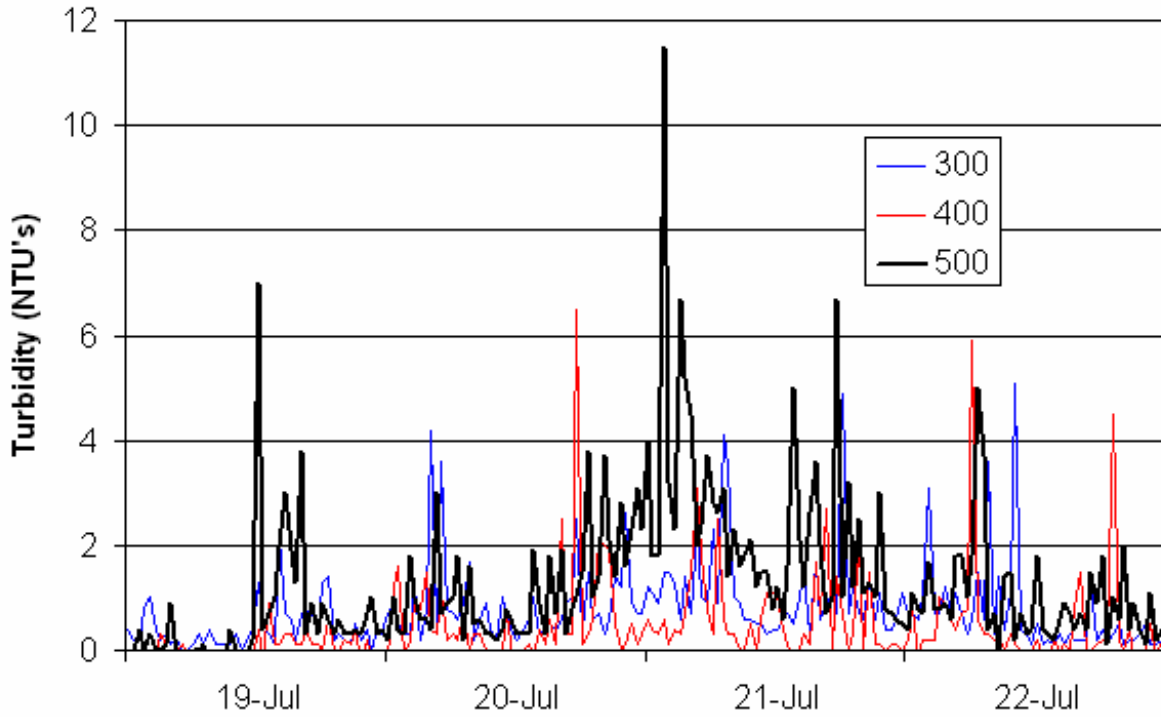


Figure B-8. Turbidity in the 3 pools during stormy period July 19-22, 2002

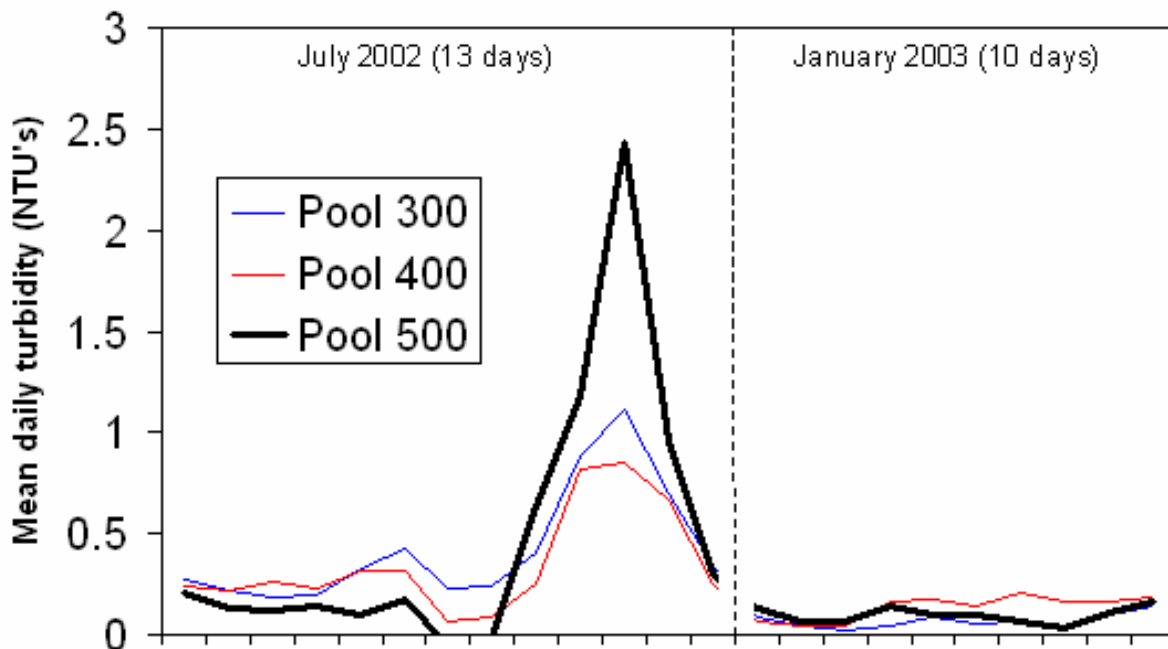


Figure B-9. Mean daily turbidity in the 3 pools over 23 days, showing increase in mean turbidity during stormy weather.

### Appendix C: Water Flow Direction Diagrams

Results from the drogue study of water flow direction in Ofu Lagoon are shown below as diagrams on aerial photos for Pools 300, 400, and 500. A diagram showing these results is also plotted on an aerial photo of the Ofu Unit of NPSA to show larger-scale flow patterns.

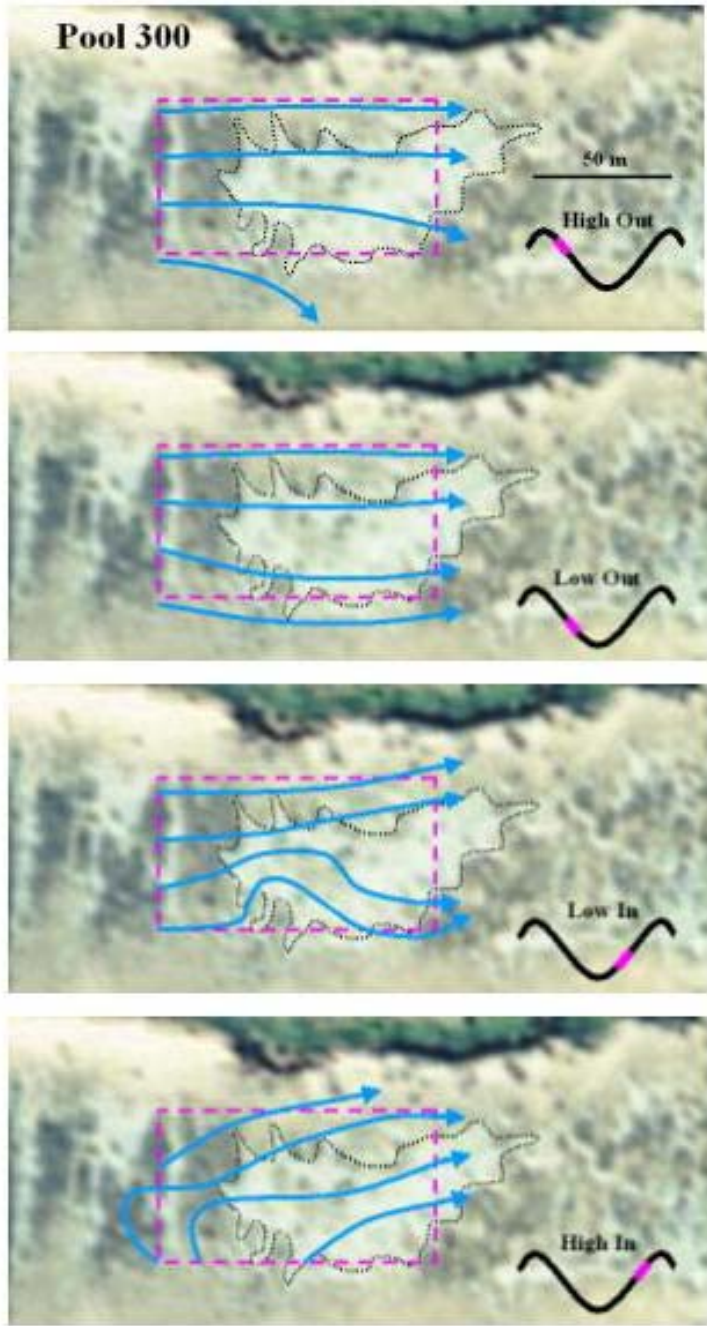


Figure C-1. Surface water current direction (←→) in Pool 300 at four points in the tidal cycle as shown by drogues in a 100 m x 50 m grid.

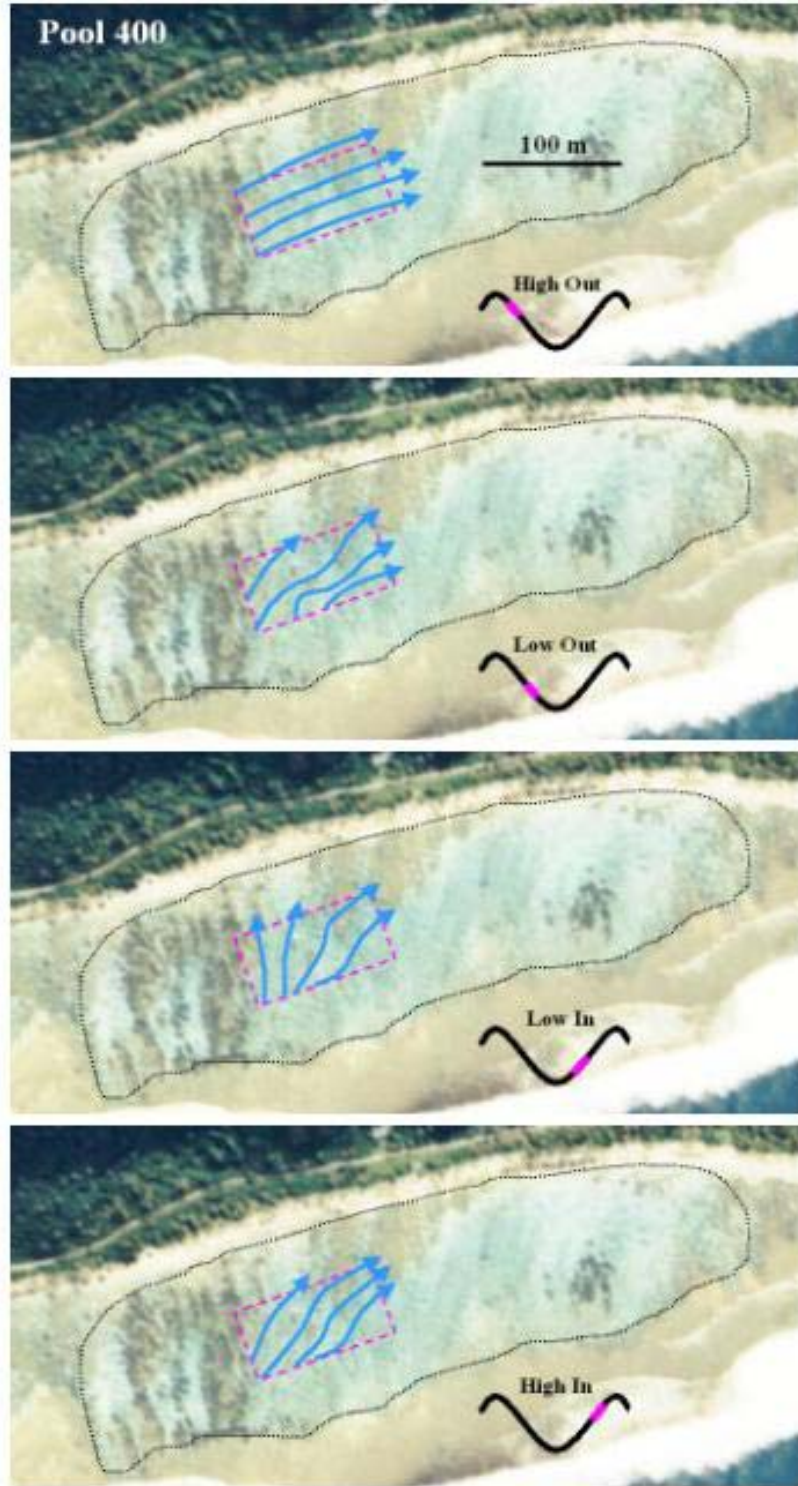


Figure C-2. Surface water current direction (←) in Pool 400 at four points in the tidal cycle as shown by drogues in a 100 m x 50 m grid.

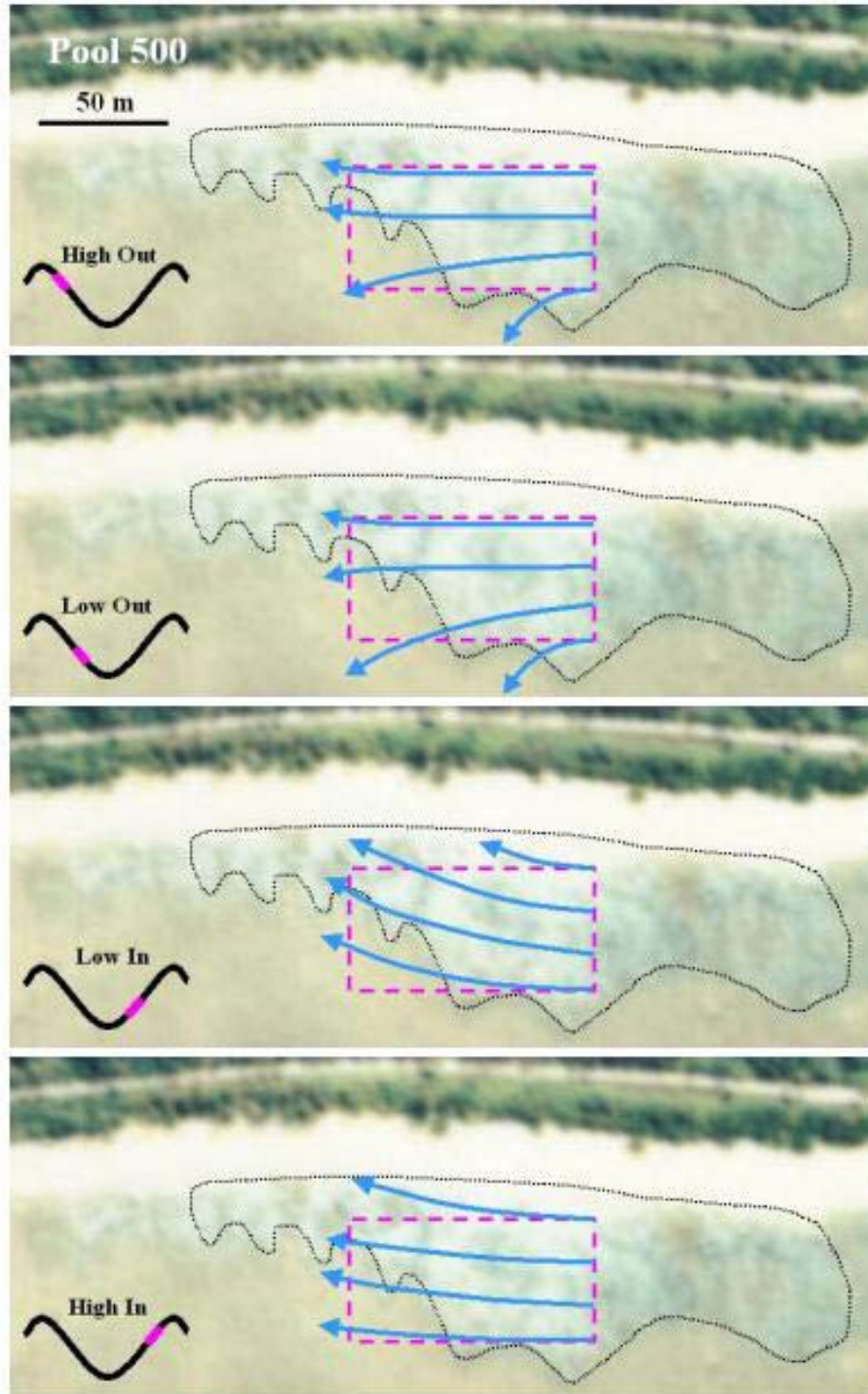


Figure C-3. Surface water current direction (←→) in Pool 500 at four points in the tidal cycle as shown by drogues in a 100 m x 50 m grid.

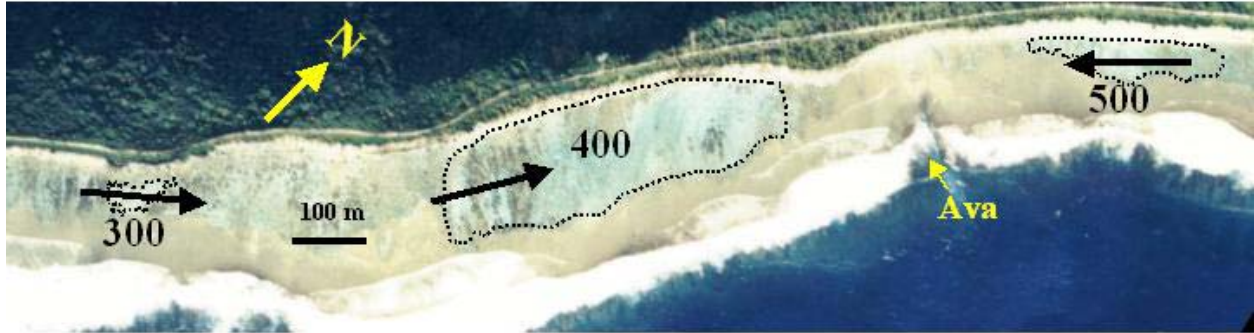


Figure C-4. General water flow patterns in Ofu Lagoon, as suggested by the drogue study.



### Appendix D: Before-and-after Transplant Photos

Photos are shown below of coral transplants at the beginning (July 2002) and end (July 2003) of the 1 year transplant experiment. For *Porites cylindrica*, three transplants from Pool 300, two from Pool 400, and one from Pool 500 are shown. For *Pocillopora damicornis*, four transplants from Pool 300 are shown (few *P. damicornis* survived in Pool 400, and none in Pool 500).



Figure D-1. *P. cylindrica* transplant in Pool 300 July 2002 (left) and July 2003 (right).



Figure D-2. *P. cylindrica* transplant in Pool 300 July 2002 (left) and July 2003 (right).

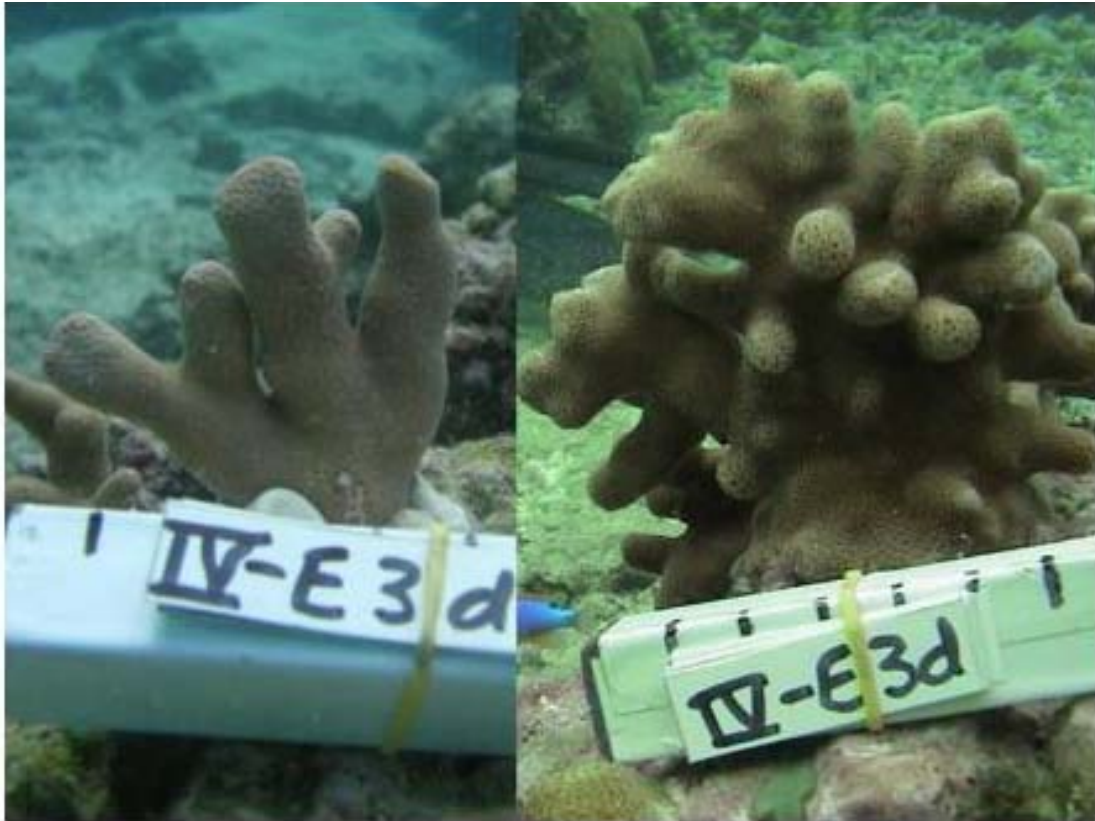


Figure D-3. *P. cylindrica* transplant in Pool 300 July 2002 (left) and July 2003 (right).



Figure D-4. *P. cylindrica* transplant in Pool 400 July 2002 (left) and July 2003 (right).



Figure D-5. *P. cylindrica* transplant in Pool 400 July 2002 (left) and July 2003 (right).

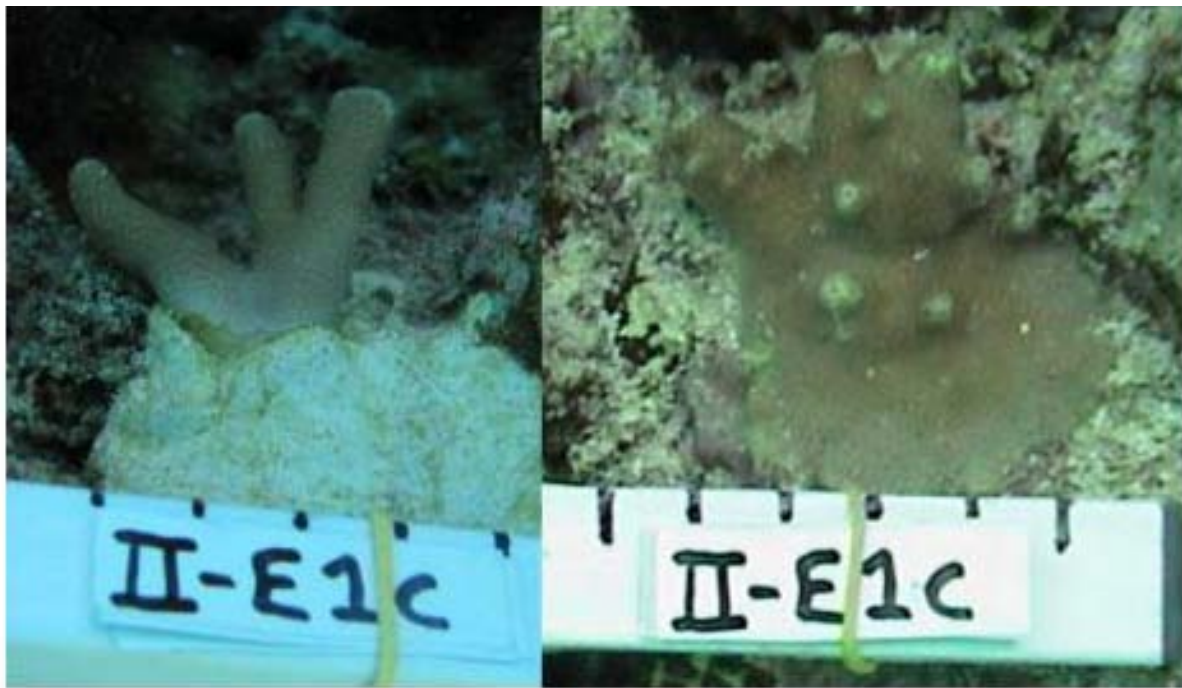


Figure D-6. *P. cylindrica* transplant in Pool 500 July 2002 (left) and July 2003 (right).

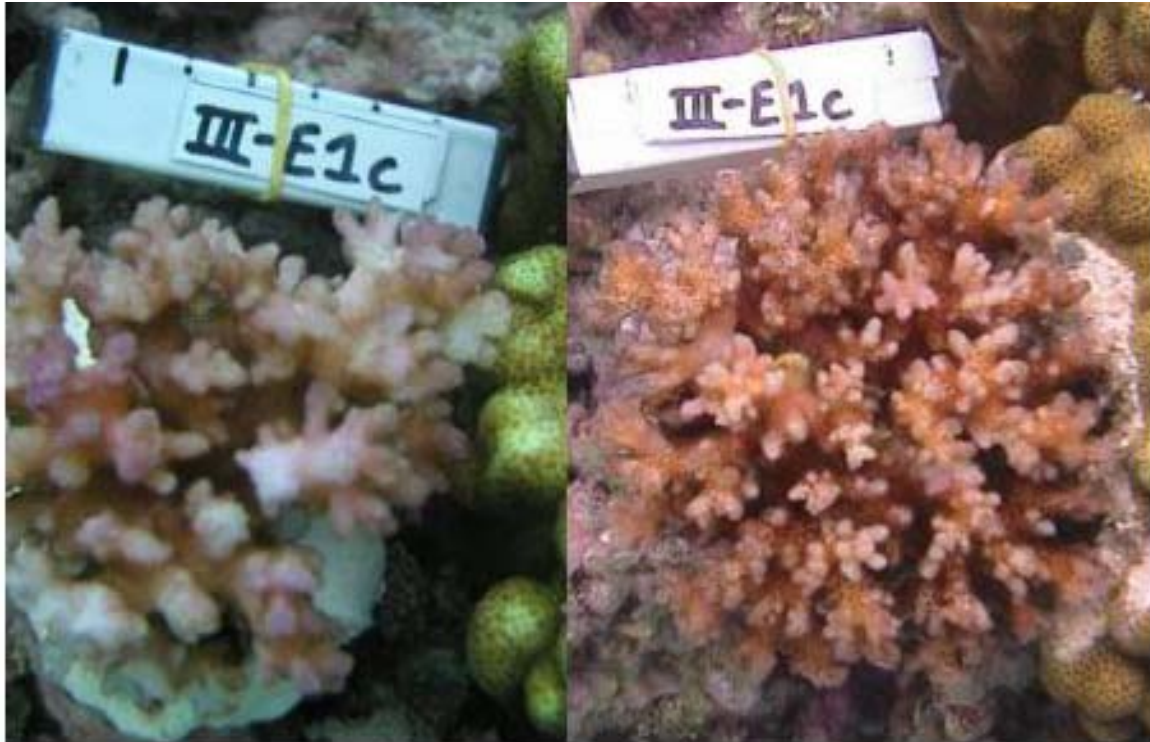


Figure D-7. *P. damicornis* transplant in Pool 300 July 2002 (left) and July 2003 (right).

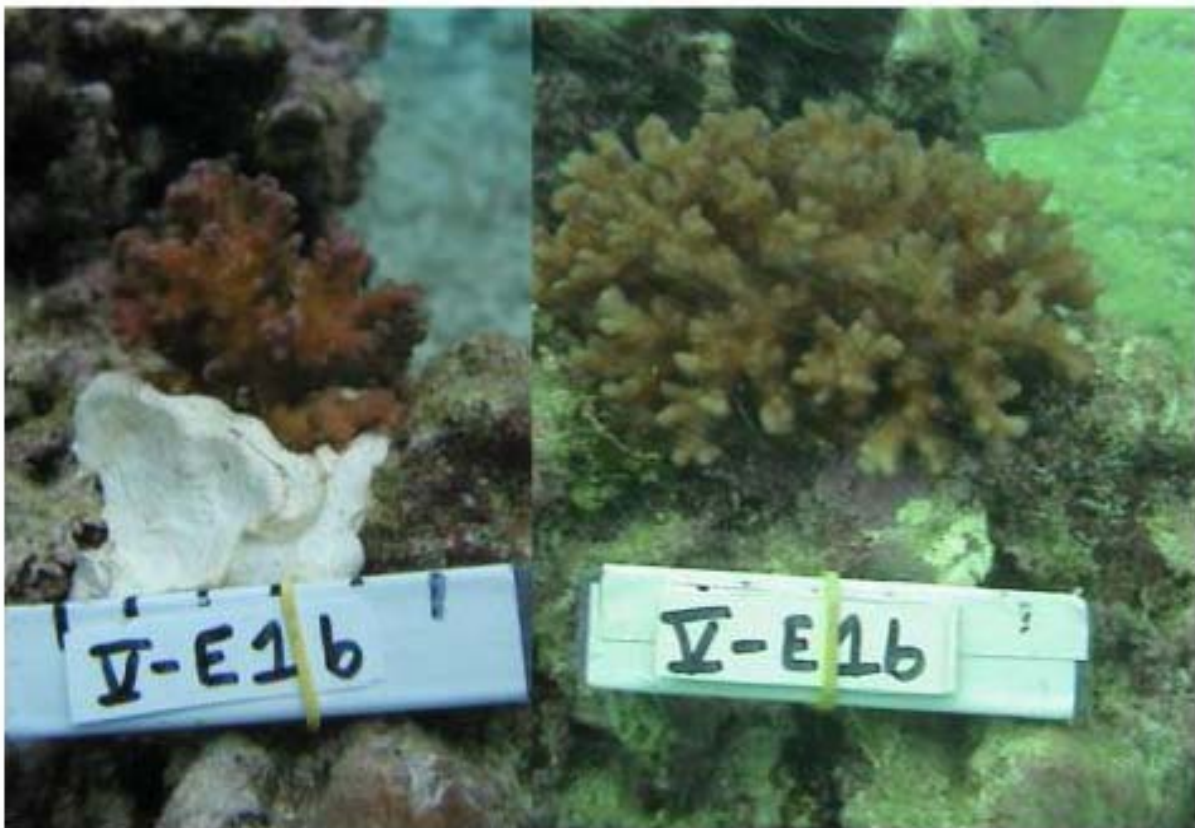


Figure D-8. *P. damicornis* transplant in Pool 300 July 2002 (left) and July 2003 (right).

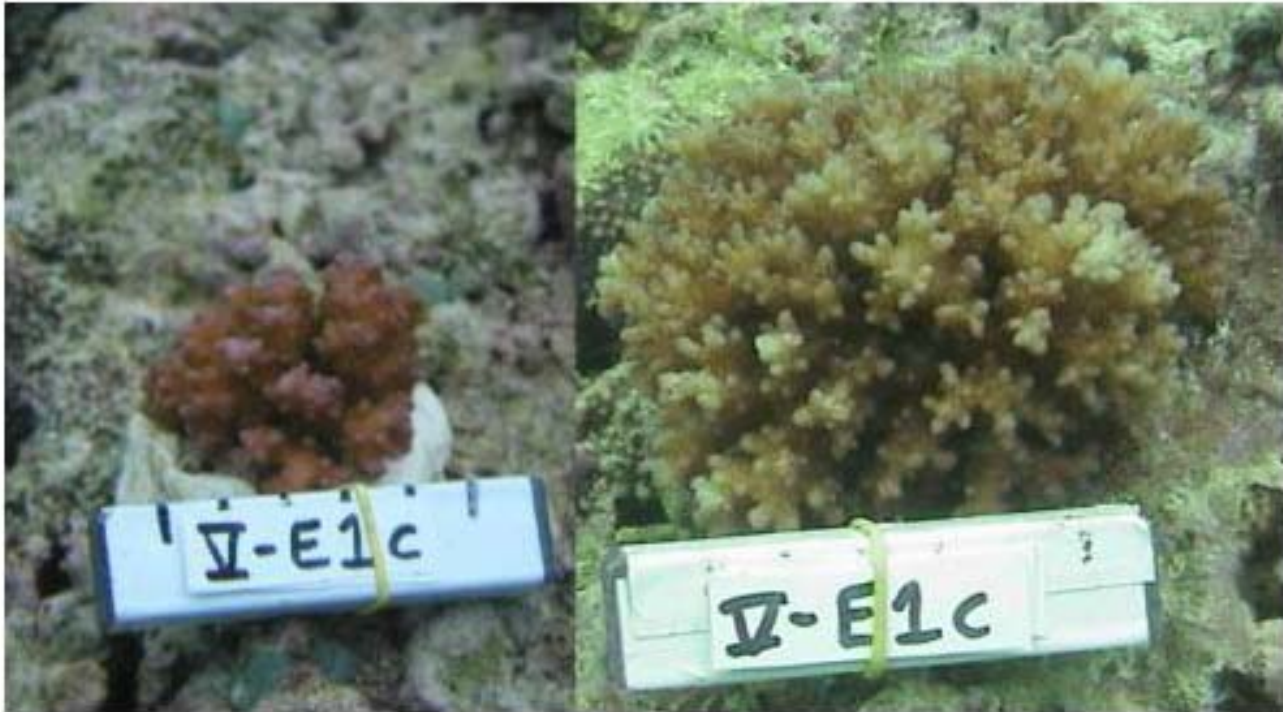


Figure D-9. *P. damicornis* transplant in Pool 300 July 2002 (left) and July 2003 (right).



Figure D-10. *P. damicomis* transplant in Pool 300 July 2002 (left) and July 2003 (right).

**Appendix E: Data for Tables and Graphs in Report (on CD, not in this document)**

Appendix E is not included with the hard copy of this report because it consists primarily of data spreadsheets. A CD with this report, including Appendix E, is on file at the National Park of American Samoa office in Pago Pago (e-mail [NPSA\\_Administration@nps.gov](mailto:NPSA_Administration@nps.gov) or phone 011-684-633-7082), and at the Hawai'i Cooperative Fishery Research Unit office in the Zoology Department at the University of Hawai'i at Manoa (see cover page for contact information). Appendix E includes the data files for tables and graphs in this report, including the graphs in Appendix B.