JUST PASSING THROUGH? THE EFFECTS OF A BOAT CHANNEL ON THE CORAL REEF COMMUNITY IN MO'OREA, FRENCH POLYNESIA

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Abstract. The increasing amount of development occurring worldwide has had a considerable effect on coral reefs. Often, the reef is directly altered by such disturbances. This study addressed the effects of an artificially-deepened boat channel in the lagoon of Mo'orea, French Polynesia in terms of water quality, substrate cover, coral health and diversity, and fish abundance. Turbidity measurements taken both before and after boat and personal watercraft (PWC) passage demonstrated a significant increase caused by boat activity. 10 transects conducted throughout the channel showed that substrate cover changed with increasing distance from the channel: live coral cover increased while sand cover decreased further from the channel. Coral diversity also increased with distance from the channel; most notably, there was a significant increase of *Pocillopora*, a coral genus sensitive to sedimentation. The coral community at the edge of the channel, on the other hand, was dominated by massive *Porites,* a genus and growth form known to tolerate sedimentation and other disturbances. The habitat alteration caused by the boat channel also altered the fish assemblage, with different species demonstrating changes in abundance that reflect the change in habitat. These community-wide changes provide strong evidence that the use of the boat channel is affecting the environment around it. Given the susceptibility of coral reefs to anthropogenic disturbances, these results provide a small representation of the potential threat posed to coral reefs worldwide by boating and shipping activity.

Key words: boat channel; anthropogenic effects; turbidity; coral health; Porites; Pocillopora; *fish assemblage; Mo'orea, French Polynesia*

INTRODUCTION

Anthropogenic effects on coral reef ecosystems have been widely documented. Although the extent of these impacts depends on both a temporal and spatial scale (Karlson and Hurd 1992), human-related disturbances have significantly affected coral reefs through processes ranging from global warming (Glynn 1991, Hoegh-Guldberg 1999, Hoegh-Guldberg et al. 2007, Sammarco and Strychar 2009) to localized processes such as construction and development (Rogers 1990, Jordan et al. 2010). Coral reefs have been shown to recover from both natural and anthropogenic disturbances (reviewed in Pearson 1981, Garfield 2001), but the community structure is often significantly changed as a result (Berumen and Pratchett 2006, Green et al. 2008, Adjeroud et al. 2009). As the coral reef provides the framework for the rest of the ecosystem, a change in coral composition affects the community as a whole, including entire fish assemblages (Bell and Galzin 1984, Sano 2000, Feary 2007, Graham 2007). Therefore, studying the community-wide effects of disturbance is an important part of assessing disturbance.

As part of a naturally dynamic ecosystem, coral communities exhibit a range of characteristics shaped by the varying degrees of light, depth, turbidity, and other abiotic factors present (Huston 1985). For instance, the same species will exhibit different growth forms depending on the environment (Veron 1986. Sanders and Baron-Szabo 2004); branching, massive, columnar, laminar, and encrusting forms all represent adaptations to differing environmental parameters (Chappel 1980). In addition to these intraspecific changes, interspecific competition among corals can change with the environment, leading to a change in dominant coral species (Huston 1985, Veron 1986, Green et al. 2008).

Anthropogenic disturbances often change the intensity of the physical factors shaping this coral community makeup. Increased sedimentation, for instance, is a common consequence of development (Rogers 1990) and has been shown in numerous studies (Huston 1985, Rogers 1990, Riegl 1995, Hirst 2002, Philip and Fabricus 2003, Crabbe and

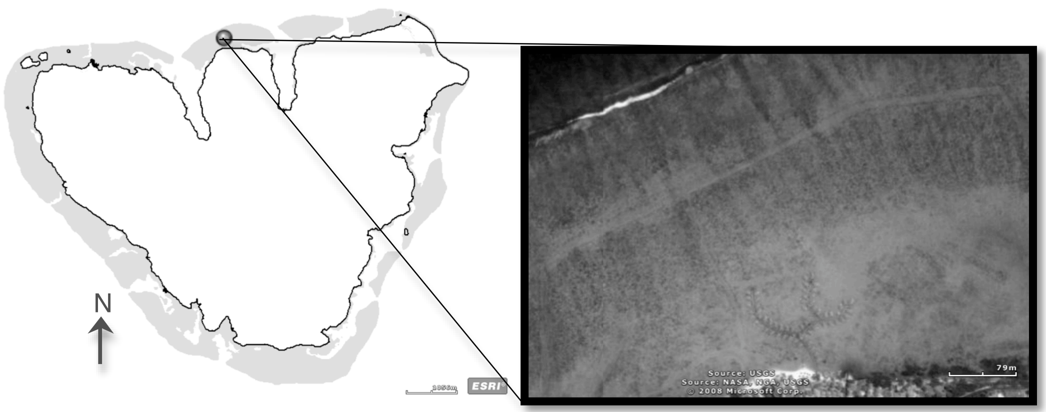

FIG 1. Location of the study site on the island of Mo'orea, with an aerial view of the boat channel in the lagoon. (Images ®ESRI, source: USGS, NASA, NGA)

Smith 2005, Macintyre et al. 2007, Ebeid et al. 2009) to affect coral communities. Thus, while corals have adapted to a spectrum of environmental parameters, the unnatural change in abiotic factors that results from development has the potential to affect the entire community.

The dynamic nature of coral reefs enables the study of localized anthropogenic effects; community changes that arise from manmade disturbances would be reflected in phenomena such as the survival of certain growth forms or a change in dominant coral species in the area of disturbance. This study focused on the coral reef community in an area that has undergone the construction and subsequent use of a boat channel. Boating in freshwater has been shown to affect both water quality (Garrad and Hey 1987) and the biological community (Asplund and Cook 1997, Bulte et al. 2010, Statzner and Beche 2010). In the marine environment, boating has been shown to affect vertebrates (Richardson et al. 1995, Codarin et al. 2009) but its effects on coral reefs are infrequently studied, although they have been shown to be highly localized (Kaly and Jones 1994).

Addressing this localized effect and the importance of documenting disturbance effects on coral reefs (Adjeroud et al. 2002), this study assessed how the artificial boat channel has affected a coral reef ecosystem on the north coast of the island of Mo'orea.

Located in the Society Islands in French Polynesia, Mo'orea (Fig. 1) is a high volcanic island surrounded by a barrier reef. The lagoon enclosed by this barrier reef ranges from 500-1500 m in width, with twelve passes connecting it to the ocean (Galzin and Pointier 1985). In several locations, however, artificial channels have been cleared or deepened to facilitate small boat and personal watercraft (PWC), or Jet Ski, transport through the lagoon. Many of these cut through coral reef ecosystems, dividing the reef to allow boats and PWC to pass through the lagoon.

To monitor the effects of this development, the study consisted of two parts: sedimentation measurement and reef ecosystem assessment. The former was based on hypothesis that:

1. The use of PWC and small motorboats has increased the amount of turbidity and sedimentation in the area of the reef closest to the boat channel.

The latter assessed the coral reef community by measuring changes in substrate cover, coral growth form and species, and fish abundance. This was based on the following hypotheses:

2. The construction and subsequent use of the channel has altered the substrate cover with (a) an increase in sand, rubble, and dead coral cover and (b) a decrease in live coral cover close to the channel.
3. The coral community closest to the boat channel exhibits (a) higher abundance of stable, sediment-tolerant genera such as *Porites* and lower abundance of more fragile genera such as *Pocillopora* and *Acropora* and (b) higher abundance of sturdier coral growth forms such as columnar and massive and lower abundance of more fragile branching forms.
4. This unnatural change in substrate and reef structure has altered the fish assemblage; the fish populations will differ between the open water column in the channel, the coral at the edge of the

channel, and the coral reef further from the effects of the channel.

METHODS

Study site

The study site (Fig. 1) consisted of the artificial boat channel at Vaipahu, located on the northern coast of Mo'orea between Cook's Bay and 'Opunohu Bay. The 2.5m-deep boat channel has been artificially deepened (Galzin and Pointier, 1985) to facilitate the passage of boats and PWC between the two bays. The study area ran parallel to shore and was approximately 1km in length.

Background on coral genera

Coral genera included in the study are *Porites*, *Montipora*, *Pocillopora*, and *Acropora*. Changes in percent cover between these genera were compared based on the fact that their relative tolerances to disturbance differ. *Porites* is capable of surviving in disturbed environments (Riegl and Purkis 2008) and is sediment-tolerant (Sanders and Baron-Szabo 2004). Massive *Porites* species have even been described as "weedy" due to an increased ability to proliferate in disturbed environments (Green et al. 2008). *Acropora* is more sensitive to turbulence (Somerfield et al. 2008) and other disturbances (Macintyre et al. 2007, Riegl and Purkis 2008). Members of *Pocillopora* are also more susceptible to sedimentation than *Porites* (Demartini et al. 2010). Although *Montipora* is sediment-tolerant (Sanders and Baron-Szabo 2004), ithas been shown to be more sensitive to disturbance than *Porites* as well (Graham 2007).

Sedimentation & turbidity measurement

The weekly sediment load on the reef was measured by placing 8 sediment traps 5m apart along a 35m transect. The sediment traps were made of PVC pipes cemented to plastic flowerpots. The pipes had a 5:1 height to diameter ratio, as recommended for sediment traps (Hargrave and Burns 1979). Samples from the traps were collected by covering the PVC pipe and transporting it to the surface before emptying its contents into another container. The traps were put back in place and emptied on a weekly basis for 3 weeks. Sediment from the samples was then dried, weighed, and compared along distances.

To measure the amount of turbidity caused by boating activity, water samples were taken both directly before and 1 minute after boat passage. Turbidity was quantified with a HF Scientific DRT-15CE portable turbidimeter.

Coral community assessment

The coral community was studied by comparing substrate cover and community composition with increasing distance from the boat channel. Transects were conducted by placing two parallel 30m transect tapes 2m away from each other, starting at the boat channel and running perpendicular to and towards shore. Sampling was done in a series of 10 2mx2m quadrats within the transects, starting at 0m from the boat channel. Each quadrat was 1m away from the previous. The following data were taken:

- distance from the boat channel
- percent substrate cover: live coral, dead coral, macroalgae, coral rubble, or sand
- coral growth form and genus-level identification
- percent algae cover on coral

The 10 transects were haphazardly placed throughout the length of the channel.

Fish assemblage

Fish community and abundance were studied along 5 30m transects, also haphazardly placed perpendicular to shore along the length of the channel. Data on species abundance were taken in 5m intervals within each transect. 5 minutes were spent directly above the transect tape at 5m, 10m, 15m, 20m, 25m, and 30m, facing the boat channel. All fish seen in the field of view while looking straight ahead, from the current distance to 5m before it, were included in the count for each 5-minute interval.

Data analysis

Differences between the paired turbidity samples taken before and after boat passage were analyzed using a student's t-test. Trends in substrate cover, coral diversity, and fish abundance were analyzed using regressional analysis. Shannon diversity indices were calculated to test for changes in coral diversity with distance from the channel. Each coral growth form and genus was treated as an individual unit in the index calculations.

RESULTS

Sedimentation & turbidity measurement

The 9 paired water samples (Table 1) taken before and after boat passage reflected a significant (p=0.00037) increase in turbidity after boat or PWC passage.

	1	2	3	4	5	6	7	8	9
a	0.2	0.4	0.3	0.6	0.7	0.4	0.6	0.3	0.4
b	0.5	0.8	0.4	0.7	1.0	0.5	0.7	0.7	0.7
						p-value= 0.00037			

TABLE 1. Turbidity values in NTU (*a*) before and (*b*) after boat passage.

The sediment trap samples for week 2 were the only quantifiable samples, as several of the traps in weeks 1 and 3 had either tipped over or moved from their assigned distances. The samples for week two showed no notable difference in sediment amount.

Coral community assessment

Substrate cover transects reflected clear patterns for live coral and sand cover (Fig. 2). Percent cover of sand (Fig. 2a) decreased with increasing distance from the boat channel. Conversely, live coral (Fig. 2b) increased in percent cover starting after quadrat 6 (15m from the channel). Percent cover of dead coral, coral rubble, and macroalgae showed no significant pattern with distance from the channel.

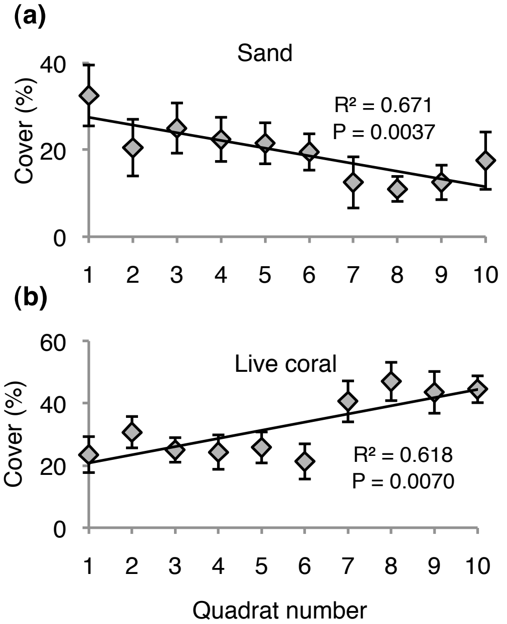

FIG. 2 Average percent cover from 10 substrate cover transects. Quadrat number refers to the 2x2m quadrat within the transect and increases with distance. Sand **(a)** significantly decreased (P=0.0037) with distance, while live coral **(b)** significantly increased (P=0.0070).

Coral genus abundance changed with increasing distance from the boat channel. *Porites* was found throughout the transects with no clear change in percent cover. However, the dominance of massive *Porites* – represented by the percent of live coral cover made up by massive *Porites* – decreased with distance (Fig. 3a). Percent cover of *Pocillopora* increased (Fig. 3b) further from the boat channel. Although *Acropora* was not present in any of the transects, it was observed in the area. *Montipora* was present but showed no clear pattern. Members of Faviidae also appeared in the transects but only after quadrat 6.

Growth forms among corals did not show a clear pattern with increasing distance from

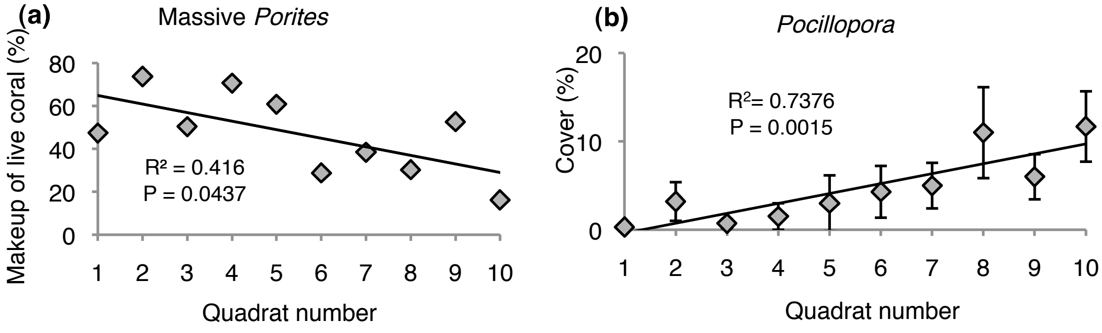

FIG. 3. Changes in coral diversity with increasing distance from the channel, as shown by **(a)** the decrease in dominance of massive *Porites* (calculated as percent live coral made up of massive *Porites*) and **(b)** the increase in *Pocillopora* cover. Both trends were significant (p= 0.0437 and 0.0015, respectively)

the channel. *Pocillopora* with laminar growth form was found in small numbers throughout the transects, with no significant trend related to distance from the channel. *Porites* of all three growth forms – branching, massive, and columnar – had a strong presence throughout the transects with no clear pattern.

Shannon indices (Fig. 4) significantly increased with distance from the channel. Each coral growth form and genus was treated as a separate unit.

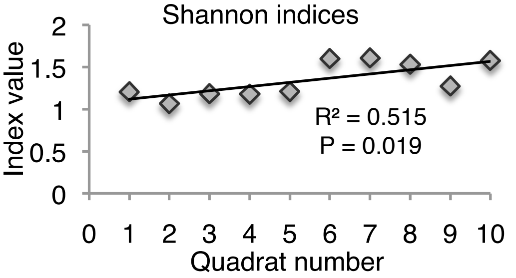

FIG. 4. Diversity of coral species and growth forms represented by Shannon indices significantly (p = 0.019) increased with distance.

Fish assemblage

Several species of fish exhibited changes in abundance (Fig. 5). Members of family Pomacentridae showed strong patterns related to distance from the boat channel. *Dascyllus trimaculatus* was only present at the first two quadrats. *Abudefduf sexfasciatus* was greatest in abundance closest to the boat channel, while *Chromis viridis* and *Stegastes nigricans* were highest further from the channel.

Odonus niger was present only at the first quadrat at the edge of the channel. *Thalassoma hardwicke* weakly increased with distance from the channel.

DISCUSSION

Sedimentation & turbidity measurement

Boating activity increases turbidity in the water, as predicted in hypothesis 1. Although the sediment traps showed no results, this is more likely an issue of equipment than an actual reflection of the sediment load on the reef. Resuspension of sediment in the traps proved difficult to prevent and the presence of fishermen, kayakers, and natural water currents were likely the cause of tipping or moving the traps. Nevertheless, the increased turbidity after boat passage proves that boating activity transports a notable amount of sediment and particles through the water column. This may be the main contributing factor to the disturbance caused by the use of the boat channel.

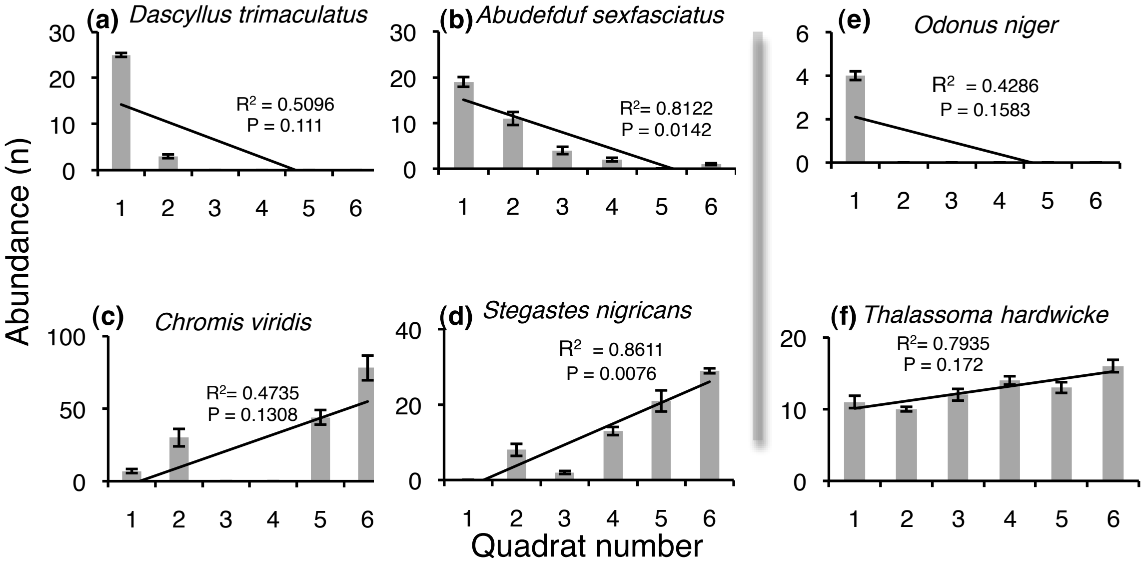

FIG. 5. Abundance of fish species with increasing distance (represented by increasing quadrat number: Quadrat 1 = 0-5m, 2 = 5-10m, 3 = 10-15m, 4 = 15-20m, 5 = 20-25m, 6 = 25-30m from the channel). Pomacentrids **(a-d)** showed contrasting patterns: **(a)** *D. trimaculatus* was present only at the edge and **(b)** *A. sexfasciatus* significantly (P = 0.0142) decreased in abundance, while **(c)** *C. viridis* and **(d)** *S. nigricans* (P = 0.0076) increased. Other notable trends were **(e)** disappearance of *O. niger* and **(f)** increase in *T. hardwicke.*

Coral community assessment

The change in substrate cover, coral diversity, and fish abundance that occurs with increasing distance from the boat channel provides strong evidence that the use of the channel is affecting the biological community. Hypothesis 2 of the reef ecosystem assessment was proven correct by the increase in sand and decrease in live coral cover that occurred closer to the channel. The increased percent cover of sand reflects the habitat alteration that has taken place. It may also be contributed to by the transport of sediment by boats; from personal observation, the particles stirred up by boat passage seemed to originate in the middle of the channel and drift over the reef at the edge of the channel. Given the sensitivity of corals to sedimentation (Huston 1985, Rogers 1990, Riegl 1995, Hirst 2002, Philip and Fabricus 2003, Crabbe and Smith 2005, Macintyre et al. 2007, Ebeid et al. 2009), this very likely plays a role in the decreased amount of live coral cover close to the channel. A possible explanation for the sharp increase in live coral (Fig. 1) that occurs at quadrat 7, at 18m-20m from the channel, is that this particular distance represents the extent of the boat channel's effects; the decreased cover of live coral before this distance is likely due to boat activity.

The coral diversity results support hypothesis 3(a) that there is a decreased presence of sediment-sensitive genera close to the channel. Although *Acropora* was not present in any of the transects, from personal observation it seemed to be healthiest and most abundant far from the channel; there was isolated *Acropora* seen at the channel but it had high algal cover, a sign of poor health (Done 1992). The clear increase of *Pocillopora,* a sediment-sensitive genus (Demartini et al. 2010), away from the channel strongly suggests that the use of the boat channel is negatively affecting *Pocillopora*.

The dominance of massive *Porites* at the channel also provides an indication of disturbance (Riegl and Purkis 2008, Adjeroud et al. 2009). I noticed a strong presence of small individual massive *Porites* close to the channel, a sign that the genus is proliferating despite disturbance by boats and PWC. A study of recruitment in the area is needed to assess which coral species are able to recruit near the channel, but this poses a potential threat to the preservation of biodiversity in the area. The boat channel already affects adult coral diversity – reflected by the increased Shannon index further from the channel – so any threat to coral recruitment posed by its use would have detrimental effects on the future coral community.

There was no clear change in coral growth form, proving hypothesis 3(b) incorrect. The change in genus composition was much more notable. This suggests that survival at the channel is determined by genus-level traits such as sediment removal responses and not by interspecies traits such as growth form.

Fish assemblage

The change in substrate cover and coral makeup seems to have a direct effect on the abundance of several fish species, proving the fourth hypothesis correct. Changes within the damselfish family, Pomacentridae, corresponded directly with the habitat preference of the species. *Dascyllus trimaculatus* and *Abudefduf sexfasciatus* are pelagic feeders (Frederich et al. 2009) and were observed feeding on the particles stirred up at the edge of the channel. The increased presence of the two species (Fig. 5) close to the channel is explained by this behavior. *Chromis viridis* is associated with live coral (Feary 2007); its increased abundance corresponds with the increased live coral cover away from the channel. *Stegastes nigricans* is a farming damselfish that establishes territories within coral (Jones et al. 2006), so its increased presence further from the channel also correlates with the increase in coral cover.

Several other fishes showed changes in abundance due to habitat change. *Thalasomma hardwicke* increased in abundance further from the channel. Shima et al. (2008) determined that *Pocillopora* presence increases juvenile *T. hardwicke* survival, so it is likely that *Pocillopora* – and its increase away from the channel – influences the presence of *T. hardwicke* at the site. *Odonus niger* is a triggerfish that was only present in the channel and at the edge of the reef. The data does not reflect its actual abundance in the area, as the transect started at the reef and did not include the channel itself, which had a high abundance of *O. niger*. However, this provided perhaps the most dramatic example of change in fish abundance due to habitat alteration caused by the channel; *O. niger* clearly preferred the open water in the channel to the shallower coral reef.

Conclusion

The increased turbidity, altered fish abundance, and decrease in live coral cover and diversity that occur at the boat channel provide strong evidence that the use of the channel at Vaipahu is affecting the community. The effects are community-wide; they range from abiotic factors such as turbidity to species distribution within fish assemblages.

Although these changes occur in a relatively small area – all transects were 30m long – the fact that there are indeed quantifiable changes along increasing distance from the channel shows that boating is having a direct effect on the coral reef community. The boat channel at Vaipahu is a small channel, which only small motorboats and PWC use to pass between Cook's Bay and 'Opunohu Bay. It represents a mere fraction of the potential threats posed to the diversity of reefs worldwide by boating and shipping activity. With the ever-increasing amount of transportation and development taking place around the world, it is imperative to monitor anthropogenic effects on the environment. As demonstrated by the boat channel in Mo'orea, the biodiversity of our coral reefs depends on it.

ACKNOWLEDGMENTS

I thank Professors George Roderick, Jere Lipps, Brent Mishler, Vincent Resh, and Patrick Kirch for their guidance and support. I also thank Justin Lawrence, Sonja Schwartz, and Erin Meyer for their commitment of both time and energy. *Mauru'uru roa* to Hinano Murphy, Emilio Teupootahiti, and the Gump Station staff. Special thanks to my courageous kayaking buddies: Sabina Lau, Quynh-Nhu Mai, Lauren Williams, Mark Phuong, and Annika Gacnik. And a sincere thank you to my family – especially my parents – for their unconditional encouragement and support.

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