EFFECTIVENESS OF COMMUNITY-MANAGED “REST AREAS” IN RESTORING A POPULATION OF BROADCAST-SPAWNING MARINE INVERTEBRATES

A Thesis

by

BRENDA SUE BENNETT

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This thesis meets the standards for scope and quality of
Texas A&M University-Corpus Christi and is hereby approved.

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August 2018

ABSTRACT

Due primarily to overharvesting, marine fisheries have been declining for decades and achieving sustainable fisheries has proved challenging. Top-down, enforcement-centric fisheries management has been largely ineffective, particularly for small-scale and coral reef-associated fisheries. Community-based management (CBM), where stakeholders are empowered to take active management roles is one alternative. While there are several examples of successful CBM accomplished in collaboration with a government, there are few studies of CBM that is conducted independently of the government and without legal enforcement. Here, we test the effectiveness of CBM without enforcement in two independent Hawaiian communities. Both community groups chose to target a multispecies assemblage of intertidal, broadcast-spawning patellogastropods (*Cellana* spp., ʻopihi) which comprise a crashed fishery that has not recovered despite four decades of top-down management (minimum size limit). To reverse the decline in ʻopihi abundance, both community groups established "Rest Areas" where fishers were asked to avoid harvesting ʻopihi. Both communities encouraged voluntary compliance through positive outreach and education, and there was no enforcement, legal or otherwise. Abundance surveys were conducted for one species (*C. exarata*) 2-4 times per year, weather permitting, for three years both within and up to ~1000 m beyond both Rest Areas' borders using a protocol informed by both traditional Hawaiian and Western scientific knowledge entailing participation by all stakeholders. Significant increases in abundance both within and down-current, but not up-current, from both Rest Areas indicate that the CBM resulted in compliance, decreased mortality of reproductively-mature ʻopihi in Rest Areas, increased self-recruitment and larval subsidy to open areas. There were indications that environmental factors also affected ʻopihi abundance and modulated the effectiveness of the Rest Areas. Overall, this study indicates that substantial compliance can be engendered by CBM

without enforcement, and that fisheries management should explicitly employ actions that engender compliance independently of enforcement.

DEDICATION

I would like to dedicate this thesis in honor of Dad, Arthur L. Warren Jr. who instilled in me the values of dedication, hard work, and the love for animals and nature and my brother, Lane Richards, who was the kindest, sweetest person I ever knew and who taught me that generosity and kindness were strengths to be desired and admired; I love and miss you both so very much. To my Mom, Doe Statham Warren Johnson, who told us to dream big and encouraged me to pursue my dreams. My sister, Kathy Warren Sims Schafer, who stands by me, has my back, and can make me laugh with every slip off the curb; I love you for everything you have done for me. My oldest brother, Marion Hightower, who supports me by making sure our Mother is taken care of which allowed me to concentrate on my studies; I cannot thank you enough for that peace of mind; I love you for taking such good care of our Mother. My other brother, Gary Warren, who is my hero for putting his life on the line defending our country for over 20 years in the United States Army Special Forces; I love you for your bravery, everything you have done for our country, and our family. Melanie Bennett, who was supportive and was my role model for returning to college after surviving raising two teenage boys. My kids, Randall Bennett, Ryan Bennett, Shannon Bennett, and Averie Thompson, who are the loves of my life, my inspiration and who have supported me with encouragement and sarcasm throughout my college career. My furry, four-legged children, Vance Warren Torres Dawg, Quay Lo Dawg, Wolfgang Amadeus Mozart Dawg, and Pickles Kat for supporting me by staying awake night after night studying with me and being my study partners these past few years. Lastly, my best friend and husband, Sam Torres, who has supported me emotionally, financially (let's face it, grad students work hard and are not paid well). Also, for accepting the fact that not all butter containers in the fridge, were in fact NOT butter, but some science homework or project; like algae or sedimentation and smelled very unpleasant. I cannot thank Sam enough for being patient with me while I worked on my homework, research, or thesis for the last seven years instead of watching movies and hanging out with him; You have my heart, I could not and would not want to do this without you, I love you.

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Introduction

Managing and restoring declining commercial, recreational, and sustenance fisheries is one of the great challenges faced by society. Food security, the fishing economy, and maintenance of ecosystem services provided by marine ecosystems all rely upon sustainable fisheries and ocean health (Halpern et al. 2015). Due to unsustainable harvesting, changes in climate, and habitat alteration and loss, the world's fisheries are in decline (Heymans et al. 2014; Montero-Serra et al. 2015; Pauly et al. 1998). The most critical aspect of maintaining a sustainable fishery is ensuring that the exploited populations reproduce (Lavazza et al. 2015; Ricker 1954). If the birth rate is not high enough to replace the existing adults and offset the elevated rate of mortality caused by fishing, then a population will decline, and the fishery will not be sustainable (Adams 1980; Kindsvater et al. 2016). Too often, the long-term goal of sustainability is outweighed by social and economic pressures for immediate gain, reproductive adults are over-harvested, fished populations decline, and social pressure to harvest ratchets upwards in a positive feedback loop.

Providing a universal management approach for declining fisheries can be challenging. In an effort to achieve sustainability, the global fisheries management enterprise has largely adopted either top-down management (TDM) where management planning, decisions, and actions are taken by government entities (McCay & Jones 2011); co-management where user participation is institutionalized in governmental management (Linke & Bruckmeier 2015; Nielsen & Vedsmand 1999); or community-based management (CBM) where resource users self-organize from the bottom-up and participate in management process (Johannes 2002). It was originally believed that the social dynamics surrounding common property resources, such as fisheries, were so complex that simple TDM was required to be successful (see Cox et al. 2010), and in large commercial fisheries with adequate funds for enforcement, TDM can be successful (Pew Trusts 2016). However, TDM has been largely unsuccessful (Botsford et al. 1997), and there has been a world-wide movement towards co-management (Gaymer et al. 2014) and community-based management (CBM). Co-management and CBM aim to build social capital and trust between governmental managers and other stakeholders and ease social pressure for unsustainable harvest (Garcia Lozano 2014).

A common characteristic of most management strategies is the goal of engendering compliance. A variety of factors can affect compliance, such as financial gain, perceived probability of enforcement and financial loss, the nature of regulations, social pressure, self-interest, sense of duty/obligation, habit, and the behavior of others (Sutinen & Kuperan 1999). Compliance should be targeted by both enforcement of regulations (financial gain/loss) and education, which can address many of the factors affecting compliance (Fig. 1). The definitive nature of enforceable regulations can lead to them becoming mandatory, especially in governmental management agencies, and sometimes at the expense of unenforceable guidelines that may, nonetheless, generate compliance through social pressure, self-interest, or sense of duty/obligation. For example, many management agencies require, either explicitly or implicitly, that fishery regulations be enforceable. In contexts where there are not sufficient funds for enforcement, using the perceived loss to elicit compliance is less likely to be successful (Görg et al. 2016). In many artisanal fisheries or relatively low-value recreational and commercial fisheries where enforcement funding is insufficient, the establishment of unenforceable guidelines that engender compliance can increase the probability of sustainably managing the fishery.

One case that exemplifies the weaknesses of enforcement-based TDM is the Paraty, Brazil artisanal fishery (Lopes et al. 2013). Marine Protected Areas (MPA) was established by the Brazilian government in 1990 as remediation for a nearby nuclear power plant, but local fishers were not consulted, and there was no enforcement or education about the MPA for 18 years. In

2008, when enforcement abruptly began, fishermen were unaware of the existence of the MPA, and thus, could not have complied with the regulations. The sudden onset of enforcement strained relationships between management and resource users and bred distrust. While compliance increased with enforcement, conflicts between resource users and managers were common (Lopes et al. 2013). Beginning in 2009, there were efforts to employ adaptive co-management, but as of 2016 an agreement had yet to be reached (Nakachi 2016; Seixas et al. 2017). As of 2018, there does not appear to be an official co-management agreement in place. It is likely that more effective communication and engagement of stakeholders could lead to more effective management of Paraty's marine resources.

Similarly, the Motu Motiro Hiva Marine Reserve was established in 2010 on Rapa Nui by the Chilean government without consulting resource users, and compliance was low (Gaymer et al. 2014). The Rapa Nui people are connected physically and culturally to their marine resources, are very knowledgeable, and did not respond positively to TDM. The government started a new co-management initiative engaging the Rapa Nui communities to establish the Hanga Roa Bay Marine Reserve. This initiative was so successful; the Chilean government collaborated with Rapa Nui communities to establish the Rahui Marine Protected Area, one of the largest MPAs in the world in 2017 (~720,000 km^2) that was designed to respect the Easter Islander's ancestral use and subsistence fishing practices. Demonstrating the effectiveness of good-faith efforts to involve resource users in management planning, 73% of islanders favored the establishment of the MPA which was much larger than the original Motu Motiro Hiva Marine Reserve Similar success stories have been observed in many locations where CBM is employed, particularly in the locally-managed marine areas of Oceania (Johannes 2002), Madagascar (Mayol 2013), Kenya (Kawaka et al. 2017), Fiji (Gillett et al. 2014), and Solomon Islands (Kereseka 2014).

While most managed areas begin with government action, resource users can also self-organize and take management actions. In Verata, Fiji, the Ucunivanua community worked with the University of the South Pacific to establish areas closed to the harvest of cockles (*Anadara* spp.) in 1997 (Johannes 2002; Tawake et al. 2001). What is noteworthy about this action and the assessment of its effectiveness is that it was conducted by the community without any prompting or assistance from the Fijian government. After two years of self-monitoring, the cockle abundance increased both inside and downstream (cockles have planktonic larvae) from the closed area (Johannes 2002), demonstrating that resource users complied without legal enforcement. These efforts have led to the adoption of resource co-management between the local communities and the government. Communities and resource users that are also stewards are more likely to take pride in the management process and comply with the rules they have agreed to implement through social dynamics, education, and outreach programs (Senyk 2012). Indeed, decentralized management of mangrove fisheries in Ecuador, where fishers were given stewardship rights, has led to a heightened sense of empowerment and increased the catch of cockles (*Anadara* spp., Beitl 2017).

In Hawaiʻi, there too has been a growing movement to embrace traditional, place-based resource management practices by local communities (Friedlander et al. 2000; Poepoe et al. 2006). As in Verata, Fiji, these CBM actions are being taken, without government assistance, by communities that depend upon their resources for subsistence. For example, the Hui Mālama O Moʻomomi (2013) has been successfully managing its resources for decades and has approached the government with a detailed and thorough resource co-management proposal based upon proven traditional practices that has been in negotiation for over 23 years (see also Ayers & Kittinger 2014; Hui Malama o Moʻomomi 1995; Poepoe et al. 1995). This highlights one of the challenges of resource co-management: time is required to successfully negotiate agreements. As of 2018, only two Hawaiian communities have negotiated co-management agreements (Hāʻena and Miloliʻi Community-Based Subsistence Fishing Areas) with the state government. Of these, only Hāʻena has active regulations. Without legal stewardship status, communities that choose to manage their resources do so without the benefit of enforcement and depend upon compliance engendered by other means. With only very few examples of the effectiveness of CBM without the benefit of co-management with government agencies and the associated enforcement of regulations, more study is necessary to assess its effectiveness.

Targeted Population for Management and Restoration: ʻOpihi

Here, we report on the effectiveness of CBM employed by two Hawaiian communities on the island of Maui that targeted intertidal Hawaiian limpets (*Cellana* spp., Patellogastropoda, Nacellidae), locally known as ʻopihi. ʻOpihi are culturally-important (Mau & Jha 2017; Titcomb 1978) and are among Hawaii's most expensive seafood products (NOAA Commercial Fisheries Statistics). The ʻopihi populations have diminished, as evidenced by the decline in commercial harvest from 67.4 metric tons in 1900 (Cobb 1905) to 6.4 metric tons in the 1970s (Kay et al. 1982, Fig. 2). In response to these declines, the State of Hawaiʻi imposed a minimum harvestable size limit of 1.25" (3.1 cm) in shell length in 1978. There have been no indications, however, of recovery after 40 years of enforcing this regulation (see NOAA Commercial Fisheries Statistics, Fig. 2). ʻOpihi are fecund broadcast-spawners with females synchronously releasing hundreds of thousands of eggs, each, approximately every six months in the week after the new moon (Corpuz et al. 1982). The pelagic larval duration is from 2 to 18 days (Bird 2006; Corpuz et al. 1982). Recruits less than one-1-2 months-old typically have shells that are < 1 cm long (Bird 2006; Kay et al. 1982). *Cellana exarata*, the species of ‘opihi studied here, is reproductively mature (i.e., the majority of the population can be sexed) at 2 cm shell length (6-7 months, Kay & Magruder 1977), and individuals greater than 3.1 cm long are legal to harvest (Bird 2006; Kay et al. 2005).

Community-Based Management Action: ‘Opihi Rest Areas

The management action taken by both Maui communities was to set aside a section of shoreline where it was requested that people not harvest ‘opihi - termed a Rest Area. Each community arrived at this decision through their respective boards of directors and with consultation from their expert fishers, Texas A&M University–Corpus Christi (TAMUCC) and The Nature Conservancy’s Maui Marine Program (TNC). The decision to manage the Rest Areas was influenced by resource monitoring activities conducted between 2008 and 2013. Both communities with assistance from TNC, TAMUCC, the United States National Park Service (NPS) and the Hawai‘i Institute of Marine Biology, conducted annual intertidal resource monitoring surveys and found that the abundance of *C. exarata* was declining in both locations (Bird, pers. comm.). During this same time period, Papahānaumokuākea Marine National Monument (PMNM) sponsored an annual intertidal resource monitoring cruise that was manned by the aforementioned groups, as well as students, educators, resource stewards and cultural practitioners from other Hawaiian communities, the Kaho‘olawe Island Reserve Commission, Nā Maka o Papahānaumokuākea, Conservation International, the University of Hawai‘i at Hilo, and Scripps Oceanographic Institute. Papahānaumokuākea is the largest MPA in the world where no commercial or recreational resource exploitation is allowed. These combined experiences of both measuring the decline of local abundance and directly observing the abundance of ‘opihi in the remote and protected PMNM were primary factors that influenced the Maui communities to take action. The suggestion was first made by expert fishers and cultural practitioners who noted the ‘opihi are fast-growing and highly-fecund – “if you leave ‘opihi alone, they will come back and make more ‘opihi.” The communities considered a variety of management strategies and selected the MPA approach (which is a traditional Hawaiian practice to manage marine resources), hypothesizing that it would be the most biologically effective and socially acceptable. It was also noted that ‘opihi in the Rest Areas could potentially seed other shorelines due to their pelagic larval stage. The location and size of these ‘Opihi Rest Areas (as labeled by the communities) was determined by consultation with kupuna (elders), feedback from TAMUCC and TNC, and ratified by the board of each community group. Both Rest Areas were positioned along the most accessible shoreline in each location, so that they could be easily monitored, and community members could easily see the results. Each Rest Area was managed directly by each community group, but there was no legal recognition or enforcement authority beyond their rights as the knowledgable and respected people in the community and traditional caretakers of the ‘aina (land), kai (ocean), and i‘a (marine life).

Compliance with the Rest Areas was voluntary, which required education and outreach efforts to notify the greater Maui community of their existence and the rules. This outreach and education were accomplished through social media, “coconut wireless” (word-of-mouth), signage, directly approaching fishermen on the shoreline, distribution of flyers and refrigerator magnets, hosting educational field trips for the local schools, manning booths at festivals, and hosting monitoring events where volunteers help census the ‘opihi. The Nature Conservancy’s Maui Marine Program directly assisted the community organizations with the development and implementation of their management plans, communication, and outreach, while the NPS aided in posting signage and educating fishermen.

In this thesis, we test for effects of the two Maui Rest Areas on the abundance of ‘opihi both within the Rest Areas and in adjacent open areas. In so doing, we also test the effectiveness of CBM without government co-management and enforcement.

Methods

Survey Locations and Approach

The two Rest Areas were established in 2014 and each was composed of a contiguous section of intertidal shoreline inhabited by ‘opihi. To anonymize their exact locations in this report, as required by a data-sharing agreement between TAMUCC and the communities, we refer to the land divisions with a Rest Area as Region 1 and Region 2 from here forward. In Region 1, the entire Rest Area was surveyed. In Region 2, the Rest Area was too large to survey as one site, so it was divided into eight sub-sites. Within each region, additional survey sites were delineated approximately 100 m and 1000 m from the Rest Area boundaries to assess whether ‘opihi in the Rest Areas provided larval subsidies to open areas (Fig. 3). Some of the open area survey sites were also sub-divided due to differences in habitat. Survey sites ranged from 67- 225 m of coastline, with the exception of the Region 2 Rest Area (1,734 m). This resulted in a total of 21 survey sites (nine of which were within Rest Areas) that were surveyed bi-annually in 2014-2015 and quarterly in 2016-2017, as weather and conditions permitted. Deviations between the targeted and actual placement and sizes of these survey sites adjacent to the Rest Areas are due to accessibility and the presence of at least 40 m of viable habitat.

The survey protocol was developed by the two communities, TNC, and TAMUCC using both traditional Hawaiian and Western scientific principles. The surveys were conducted with the communities and volunteer participation, enabling stakeholders to participate in the monitoring process. On each day of surveying, an initial 30-minute orientation session was held to educate new volunteers about the Rest Areas and the survey methodology. New surveyors were paired with an experienced surveyor until they felt comfortable enumerating transects without assistance. While many "citizen science" efforts involve exhaustive training with a high emphasis on precision, we found that this was not conducive to volunteer participation (especially repeat participation). Consequently, we employed high amounts of replication by censusing hundreds of meters of coastline to ensure that a signal could be detected despite inevitable errors committed by volunteer surveyors.

At each survey site, the shoreline was divided into ~2 m wide transects, oriented perpendicular to the shoreline, that were delineated with the traditional Hawaiian biometric measurements of anana (arm-span, Fig. 4), ha'ilima (elbow to fingertip), and pi'a (hand) (Gon 2014). To reduce the variance in transect widths, the same person delineated the transects and calibrated their biometrics with a tape measure. Lateral transect boundaries were marked on the rock with a lumber crayon, a GPS waypoint was taken in the center of each transect, and the waypoint number was written in the transect using a lumber crayon. The transects spanned the entire elevation/depth range of *C. exarata*. The transect lengths varied because bathymetry/topography, wave run-up and splashing explain a substantial proportion of the variation in the size and extent of the high-shore habitat of *C. exarata* (Bird et al. 2013). We chose to account for the variation in transect length by testing for changes in abundance within each site, and we did not explicitly measure transect length. Each site in each region had fixed start and end points marked by natural features, and thus, the same amount of shoreline was surveyed within each site at each time point. The length of each site was measured using the polygon tool in Google

Earth. The mean transect width was calculated by dividing site length (transects run perpendicular to shoreline) by the number of transects for a given site and time.

Each transect was surveyed by 1-2 people, and several transects were surveyed simultaneously. Each surveyor was equipped with at least two tally counters and a ruler modified with explicit size classes to record the numbers of *C. exarata* in each of three size classes: sublegal recruits (<1 cm shell length), sublegal juveniles, adolescents, and early-stage adults (1-3 cm shell length), and legally-harvestable adults (>3 cm shell length, Fig. 5). The counts were reported to data recorders equipped with either Rite in the Rain waterproof datasheet or the ‘Opihi Mapper Android® application (Bird unpublished). Additional data recorded included the GPS waypoint identifiers of each transect, dates, times, island, region names, site name, surveyor names, and any other relevant notes.

Testing the effects of CBM on ‘Opihi density in and outside of Rest Areas

The establishment of the Rest Areas was expected to decrease the mortality rate for legal adult ‘opihi (>3 cm shell length), which would increase the birth rate, and thus lead to an increase in the abundance of all size classes of ‘opihi within the Rest Areas. In open areas adjacent to the Rest Areas, sublegal ‘opihi were expected to increase in abundance due to larval subsidies from the Rest Areas, but legal-sized ‘opihi were not expected to increase due to continued harvesting. The glm.nb command in the R package nlme (Pinheiro et al. 2018; R Core Team 2013) was used to conduct a negative binomial regression analysis to test for an increasing trend in the abundance of ‘opihi with time for each combination of survey site and size class (21 sites * 3 size classes = 63 regression analyses). The model tested was as follows:

$$abundance \sim survey\ time + offset(log(mean\ transect\ width)).$$

The *abundance* was the number of ‘opihi of a given size class in a transect; the *survey time* was the number of years since the establishment of the Rest Area for a given region; and the *offset* was included to account for the effect of different transect widths among survey times on the observed abundances within a sampling site. Including the offset in the model effectively results in the observed variable (*abundance*) being modeled as a density. The primary estimate produced by the negative binomial regression is a population growth rate – the mean change in the natural log of abundance per meter of shoreline per year. To make the growth rate estimates easier to interpret, they were converted to the change in the number of ‘opihi per meter over the three years of surveying (# m^{-1} t^{-1}) in the text and figures. If we reported these more easily-interpretable population growth rate estimates as units per meter per year, there would be a different estimate for each year of the project, which given the large number of regressions, would become unwieldy. Negative estimates indicate population decline and positive estimates indicate growth.

Results

Survey effort

The sites were surveyed at multiple times each year, weather permitting, from September 2014 to November 2017, by a total of 227 volunteers from Maui, governmental and non-governmental organizations, and students. Table 1 shows the number of surveys conducted at each site location for Region 1 and 2, by month and year, as well as the total number of surveys per year for each region.

Effects of harvest exclusion on C. exarata in Rest Areas

The results were mixed for changes in abundance of legal adults in the Rest Areas, with a decline in Region 1 (Fig. 6a, Table 2) but increases in five of the eight Rest Area survey sites in Region 2 (Fig. 7a, Table 2). Three of the Rest Area 2 sites exhibited a significant increase in abundance ($p<0.05$), with the growth rate estimates of 3.1 – 5.5 m^{-1} t^{-1}. Two sites exhibited a weaker indication of increased abundance ($0.05<p<0.1$, 2.2 - 3.5 m^{-1} t^{-1}). The remaining three sites in Rest Area 2 exhibited no trend in abundance ($p>0.1$). The opposite trend was detected in the Rest Area of Region 1, where there was a significant decline in the abundance of legally harvestable ‘opihi ($p<0.05$, -4.1 m^{-1} t^{-1}). The abundance of legal adults did initially increase but declined precipitously in 2016 when high surf generated by a hurricane disturbed the Rest Area in Region 1.

Among the strongest of signals in the data set are the increases in the abundance of sublegal ‘opihi (1-3 cm) in the Rest Areas of both Region 1 and 2 (Fig. 6b & 7b, Table 2). In Region 1, abundance increased by 8.8 m^{-1} t^{-1} ($p<0.05$). In Region 2, the four sites on the down-current side of the Rest Area exhibited significant increases in abundance ($p<0.05$, 5.7 – 12.2 m^{-1} t^{-1}). The remaining four sites on the up-current side of the Rest Area exhibited no trends in abundance ($p>0.1$).

It was expected that if the CBM was effective, then there would be an increase in sublegal recruits in the Rest Areas, however, the results were inconsistent for Regions 1 and 2 (Fig. 6c & 7c, Table 2). Population growth rate estimates for recruits were characterized by much greater variance than the other size classes, which is not unexpected given the synchronized spawning and rapid growth of *C. exarata* combined with the vagaries of currents, dispersal patterns, and post-recruitment mortality. Nonetheless, there was an increase in the abundance of recruits ($p<0.05$, 3.5 m^{-1} t^{-1}) in the Rest Area of Region 1. One site in the Rest Area of Region 2 (F2), which also exhibited increases larger sub-legal and legally-harvestable ‘opihi, exhibited an increase in the abundance of recruits ($p<0.05$, 1.1 m^{-1} t^{-1}) (Table 2). Three sites in Region 2, however, exhibited significant declines in abundance ($p<0.05$, -6.1 - -9.8 m^{-1} t^{-1}), and the remaining four sites exhibited no trend ($p>0.1$).

Effects of Rest Areas on adjacent, harvested populations

If the Rest Areas were effective in sheltering breeding ‘opihi, from harvest, then an increase in the abundance of sublegal ‘opihi would be expected in adjacent open areas due to the larval subsidy. Indeed, only 1/14 (7.1%) of the combinations of site and size class exhibited an indication of a decline in the abundance of sublegal ‘opihi in open areas located down-current from the Rest Areas. In contrast, 9/16 (64%) of combinations exhibited increases in abundance (Fig. 6 & 7, Table 2). The modest decline in recruits occurred at the 1000S-C site in Region 2 ($0.05<p<0.1$, -1.6 m^{-1} t^{-1}, Fig 7c). Significant ($p<0.05$) increases in recruits occurred in both Regions 1 [100S (3.0 m^{-1} t^{-1})] and 2 [100S (6.1 m^{-1} t^{-1})]. The was also an indication of increased recruit abundance in Region 2 [$0.05<p<0.1$, 1000S-B (0.3 m^{-1} t^{-1})]. Significant ($p<0.05$) increases in larger sublegal ‘opihi (1-3 cm) occurred in both Regions 1 [100S (21.7 m^{-1} t^{-1}), 1000S-B 7.9 m^{-1} t^{-1})] and 2 [1000S-A (1.9 m^{-1} t^{-1}), 1000S-B (1.7 m^{-1} t^{-1})]. In Region 1, the increase in the abundance of larger sublegal ‘opihi at the 100S site was greater than within the Rest Area. The was also an indication of increased sublegal abundance in Region 1 [$0.05<p<0.1$, 1000S-A (4.6 m^{-1} t^{-1})]. The remaining sites in both Region 1 and 2 exhibited no trend ($p>0.1$) in the abundance of recruits.

Up-current from the Rest Areas, there were no indications of sublegal abundance increases in the open areas that were surveyed (Fig. 6 & 7, Table 2). There was a significant decrease in the abundance of 1-3 cm sublegal ‘opihi at the 100N site in Region 2, which coincided with a landslide that covered the ‘opihi habitat ($p<0.05$, $-28.8\ m^{-1}\ t^{-1}$). This landslide covered approximately 1/3 of the coastline, and thus ‘opihi habitat. The remaining sites up-current from the Rest Areas in Regions 1 and 2 either exhibited no indication of a change in abundance ($p>0.1$).

As expected, there was either no change or a decline in the abundance of legally-harvestable adult ‘opihi in the open areas (Fig. 6a & Fig. 7a, Table 2). In Region 1, there were declines in the abundance of legal ‘opihi both up- and down-current from the Rest Areas at the 1000N ($p<0.05$, estimate = $-3.2\ m^{-1}\ t^{-1}$) and 1000S-A sites ($0.05<p<0.1$, estimate = $-2.9\ m^{-1}\ t^{-1}$). In Region 2, there was a significant decline in the abundance of legal ‘opihi at the 1000N site ($p<0.05$, $-5.2\ m^{-1}\ t^{-1}$) which was up-current of the Rest Area. The remaining open areas were characterized by no change in abundance ($p>0.1$).

Discussion

Effects of harvest exclusion on C. exarata in Rest Areas

The changes in ‘opihi abundance both in the Rest Areas and open areas indicate that voluntary reduction in harvesting pressure elicited by CBM was effective. In Region 2, the abundance of legally-harvestable ‘opihi increased within, but not outside of, the Rest Area. The abundance of sublegal ‘opihi (1-3 cm) increased within the Rest Areas of both Regions 1 and 2. The abundance of recruits increased in the Rest Area of Region 1 and at one site in the Rest Area of Region 2. These patterns are consistent with expectations based on a decrease in mortality and an increase in recruitment. While the increases in abundance were not as extreme at the Fijian blood cockles (Johannes 2002), these results do indicate that management actions taken by resource users can be effective in garnering compliance, even without enforcement.

The effect of the Rest Areas on abundance was, however, not ubiquitous, and other factors were also affecting the variation in ‘opihi abundance. The Rest Area in Region 1, which is mostly boulders, was disproportionately affected by swells from Hurricane Celia in July 2016 (Brown & Jacobson 2016) relative to most other survey sites. The whole beach was turned over and the decline in legal ‘opihi was noticeable without surveying. There was also at least one observed case of non-compliance in 2016, where ‘opihi were harvested within the Rest Area. When viewed in conjunction with the increase in sublegal ‘opihi within the Rest Area of Region 1, however, the measured decrease in legal ‘opihi does not mean that the Rest Area was ineffective. Increases in the abundance sublegal ‘opihi indicate that recruitment was positively affected despite the overall decrease in legally-harvestable adults. It is probable that the increased abundance of reproductively-mature ‘opihi ranging from 2-3 cm and the increase in the number of legal ‘opihi from 2014-2016 was responsible for the increased abundance of sublegal ‘opihi.

The recruitment signal in the Region 2 Rest Area was largely inconsistent with a positive effect of the Rest Area, but it is likely that the recruitment signal was not completely reliable because observations of abundance were not frequent enough to track the changes in abundance of recruits with the spawning cycle of ‘opihi. ‘Opihi, like all broadcast-spawners, must synchronize the release of gametes to ensure reproductive success (Corpuz et al. 1982). *Cellana exarata* is known to spawn in the first quarter of the lunar calendar (Corpuz et al. 1982; Tom 2011), and biannual synchronization is evident in spawning peaks near the solstices (Kay et al. 1982). ‘Opihi also grow quickly, with a time frame between fertilization and growing to >1 cm under two months (Corpuz et al. 1982). The window of time between a recruit being visible and growing to >1 cm is even narrower. For these reasons, the abundance of recruits was changing more rapidly than we could effectively capture with 2-4 surveys per year. As a result, the recruit data were unlikely to reflect the true signal (i.e. aliased, Deeming 1975).

There was variability in the changes in abundance of sublegal (1-3 cm) and legal ‘opihi over the three-year survey period in the Rest Area of Region 2. We propose that this was likely due to boulders rolling and crushing ‘opihi (Rest Area E which exhibited decreases in abundance), non-compliance for the legally-harvestable ‘opihi (Rest Area D2 & H which exhibited no change in abundance) and larval transport patterns for the sublegal (1-3 cm) ‘opihi. There appears to be a pattern where sublegal ‘opihi abundance increased in the down-current end of the Rest Area of Region 2 (Rest Area F1, F2, G, and H), but abundance was not affected in the up-current end (A, B, D2, and E). On its own, this might be an equivocal pattern, but there are consistent indications of net down-current effects of the Rest Areas on ‘opihi abundance in both Regions (see discussion below). We propose that the Rest Area has resulted in increased numbers of larvae being produced by the increased population of reproductively-mature ‘opihi at the northern end of the Rest Area, which is then transported down-current to the other sites in the Rest Area.

Effects of Rest Areas on harvested populations

There were additional indications that the Rest Areas affected sublegal ‘opihi abundances down-current in both Regions 1 and 2, but not up-current. The best explanation for the pattern where sublegal ‘opihi abundance in open areas only increased down-current from the Rest Areas is that increased reproductive output from the Rest Areas resulted in more larvae being transported down-current to harvestable areas. For both Regions, the abundances of sublegal ‘opihi increased at either the 100S, 1000S, or both sites. The increase in sublegal (1-3 cm) ‘opihi abundance at the 100S site in Region 1, was even greater than the increases observed within either of the Rest Areas, which correlates with observed hydrographic patterns. The Region 1 Rest Area is in a shallow embayment. Powerful ocean swells wash into the embayment at the up-current edge of the site, sweep down along the shore, and wash out over the 100S site, which marks the end of the embayment. Current lines and slicks can form off the 100S site and have been observed to extend to the 1000S sites across a second embayment, where sublegal ʻopihi abundance also increased.

For Region 2, the 1000S A and B sites which are down-current from the Rest Area, exhibited increases in sublegal (1-3 cm) ʻopihi, but no effect was detected at the 1000S-C or 100S sites which were both nearer to the Rest Area, suggesting that other factors are influencing abundance. Both 100S and 1000S-C are located in small bays that cut severely into the land and which may act to decrease migration from outside sources (Hoyer et al. 2015). Another coastal feature that may have reduced recruits to 100S in Region 2 is a basalt monolith that juts ~110m into the ocean, perpendicular to the prevailing coastline and current, at the southern edge of the Rest Area. Slicks and current lines, where larvae can become entrained (Shanks & Wright 1987), form off the monolith, across the mouth of the embayment where 100S resides, suggesting that larvae are additionally being diverted away from 100S.

Technical Recommendations for the Delineation of ʻOpihi Rest Areas

There are some lessons to be learned here for those who seek to implement a Rest Area or some other form of CBM. First, the size of a Rest Area matters, however even a small Rest Area of 90 m had desirable effects. A larger Rest Area, like that in Region 2, is also more likely to harbor great habitat, and are more likely to affect harvestable areas that are farther away. Greater than 20% of available habitat could be used as a guide when determining the size (O'Leary et al. 2016).

Second, the location of the Rest Area will affect the results (Caselle et al. 2015). Near-shore current patterns played a prominent role in the effects of the Maui Rest Areas. In the case of ʻopihi, the placement of a Rest Area on a primarily boulder shore where projectiles and rolling stones increase the mortality rate may limit the effectiveness of the Rest Area. Habitat quality is variable, and Rest Areas should be delineated such that they can both protect a large population of breeders while also providing the subsidy to other high-quality habitats.

Third, maintaining a Rest Area is a lot of work and requires dedication. Gill et al. (2017) report that staff and budget capacity are strong predictors of MPA success. This project was well-funded by grants from the NOAA Coral Reef Conservation Program – TNC Partnership and NOAAʻs Saltonstall-Kennedy Program. Countless hours were dedicated to education and outreach, and approximately 2-4 weeks per Rest Area per year were dedicated to surveying.

Fourth, implementation of the Maui ʻOpihi Rest Areas was critically-dependent upon building a trusting relationship among several entities over the course of years. This effort began with the formation of a partnership between community, non-governmental organizations, governmental organizations, and academia in 2008. The partnership coalesced while developing a common ʻopihi monitoring protocol and implementing it archipelago-wide. The Maui ʻOpihi Rest Areas were born from this partnership and provided an example for both successful community-based management and collaboration between organizations with different skills, missions, and mandates.

Fifth, Marine resource management is primarily focused on ecosystem-based management and the Rest Areas could easily be adapted to include all species. While the focus of the management effort reported here was primarily on ʻopihi, the communities that implemented the Rest Areas have more broad and comprehensive management plans that span both terrestrial and marine resources, and the Rest Areas are one property in their portfolio. If Rest Areas are expanded to include other species and be true MPA, they may need to be somewhat larger to better protect fishes and other species with larger cruising ranges (Edgar et al. 2014; Pittman et al. 2014).

CBM and the future of marine resource management in Hawai'i

The State of Hawaiʻi seeks to manage 30% of its coastal marine resources by 2030, and CBM could make up the majority of that 30%. For that to occur, the rate at which co-management agreements are generated will need to increase substantially (effectively in the last 25 years, Ayers & Kittinger 2014). One concession that could accelerate the process is for the government to ease their application top-down principals engrained in the established management structure. Evaluating the effects of rules, regulations, and guidelines on *compliance*, rather than enforceability, will yield the most effective results and will make the establishment of co-management agreements easier by adding much needed flexibility.

The distribution of the marine managed areas around Hawaiʻi will also be important (see Beltran et al. 2017). There are two locations on Maui where harvesting of ʻopihi is prohibited by law, the ʻĀhihi-Kīnaʻu Natural Area Reserve at the southern end of Maui and the Honolua-Mokulēʻia Marine Life Conservation District at the northern end. Each is likely to provide substantial larval subsidy to the surrounding harvested areas, but both of these locations are separated by 10's of km from each other and the Rest Areas studied here and have little hope of meaningfully increasing larval subsidy to all of Maui's ʻopihi habitats. A good beginning target for Maui, and other Hawaiian Islands to reach the goal of 30% by 2030 would be for at least one community-based marine-managed area to be delineated in each moku (major land division, typically within an island). A secondary target can be to delineate community-based marine-managed areas in multiple ahupua‘a (land subdivision, watershed) in each moku. The goal would be to create a synergistic effect among the managed areas, and as the distance between areas decreases synergy becomes more likely (Fovargue et al. 2018).

These if community-based subsistence fishing areas were implemented in a large proportion of ahupua‘a, more similar to the traditional Hawaiian management system, it could have a major positive impact on Hawaii's marine resources. While the Maui Rest Areas were successful in affecting population growth rates within and down-current from the Rest Areas, there was no overt indication of synergy between the Rest Areas despite being only 3.5 km apart. Here, the 90 m Rest Area in Region 1 did not affect abundance at the 1000N survey site in Region 2, ~2.5 km down-current. More and better data on connectivity of marine species is required to reliably predict and calculate the optimal size and spacing of management units (Fovargue et al. 2018).

Demonstration of compliance without government enforcement

In Hawai‘i, and in many locations world-wide, enforcement and penalties are viewed as the primary mechanism used to achieve compliance with fisheries regulations (Hauck 2008; Randall 2004). However, the top-down fisheries and conservation management approach that relies upon enforcement can generate a lack of confidence in regulations, unintended non-compliance by fishermen (Lee & Rahimi Midani 2015), and management failure, especially in tropical fisheries (McClanahan et al. 2014). Indeed, the style of management can affect public perceptions of trust and cooperation with governments (Kamiyama et al. 2018). Despite healthy skepticism (Jentoft 2000), co-management of fisheries and CBM offer two alternative paths to pure top-down management that have been successful (Campos-Silva & Peres 2016; Defeo et al.

2014). This experiment was designed to test the effectiveness of resource stewardship by the primary resource users without government aid, which was first demonstrated in Fiji (Johannes 2002) and Moloka‘i, Hawai‘i (Friedlander et al. 2000). As in these other efforts, the Maui community groups sought voluntary compliance from fishers and used the monitoring effort as an educational tool to further engender compliance and strengthen the sense of ownership and empowerment. The success of the Rest Areas is a stark contrast to the 40 years of top-down ‘opihi management, where there has been no indication that the size limit on the Hawaiian ‘opihi fishery has been effective. The Maui ‘Opihi Rest Areas lend additional support to the premise that other resource user groups can self-organize to effectively manage resources in areas where government process and procedures are too slow. These grass-roots efforts, fueled by the dedication of community organizations, can help to rehabilitate resources and serve to inform later co-management agreements and assessment efforts.

Conclusion

Sustainable exploitation of marine resources is one of the greatest challenges faced by human society. It is important for the stakeholders in both fisheries and conservation to find common ground and work together towards this common goal (Hilborn 2016). In areas where top-down management is ineffective, community-based and co-management efforts hold great promise. The positive results reported here demonstrate that with a long-term community-based outreach campaign, voluntary management actions can promote sustainability. When combined with legal enforcement, the CBM management model could be extremely effective.

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Figures

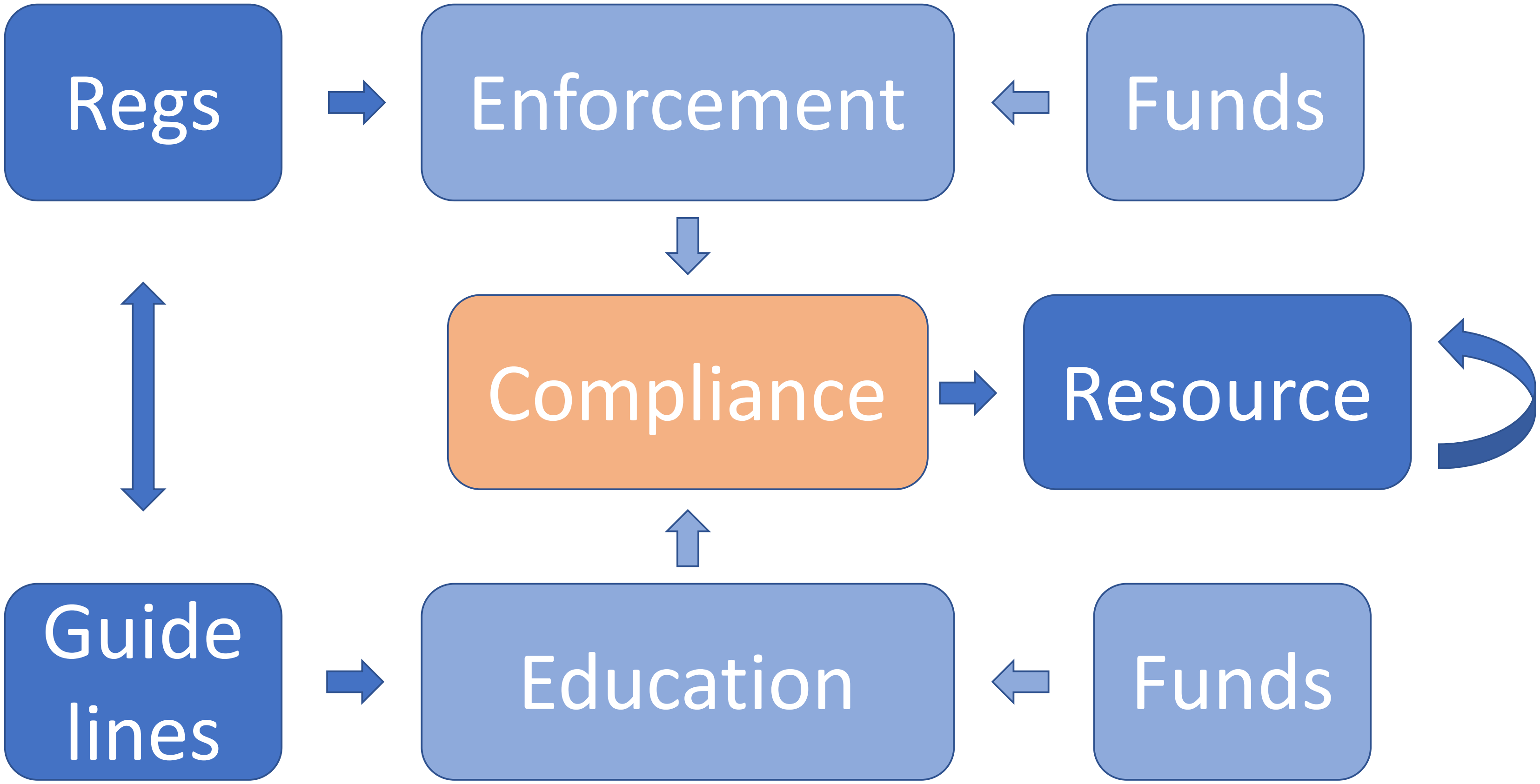


Figure 1. Flow chart showing how compliance may be achieved to promote sustainable resources.

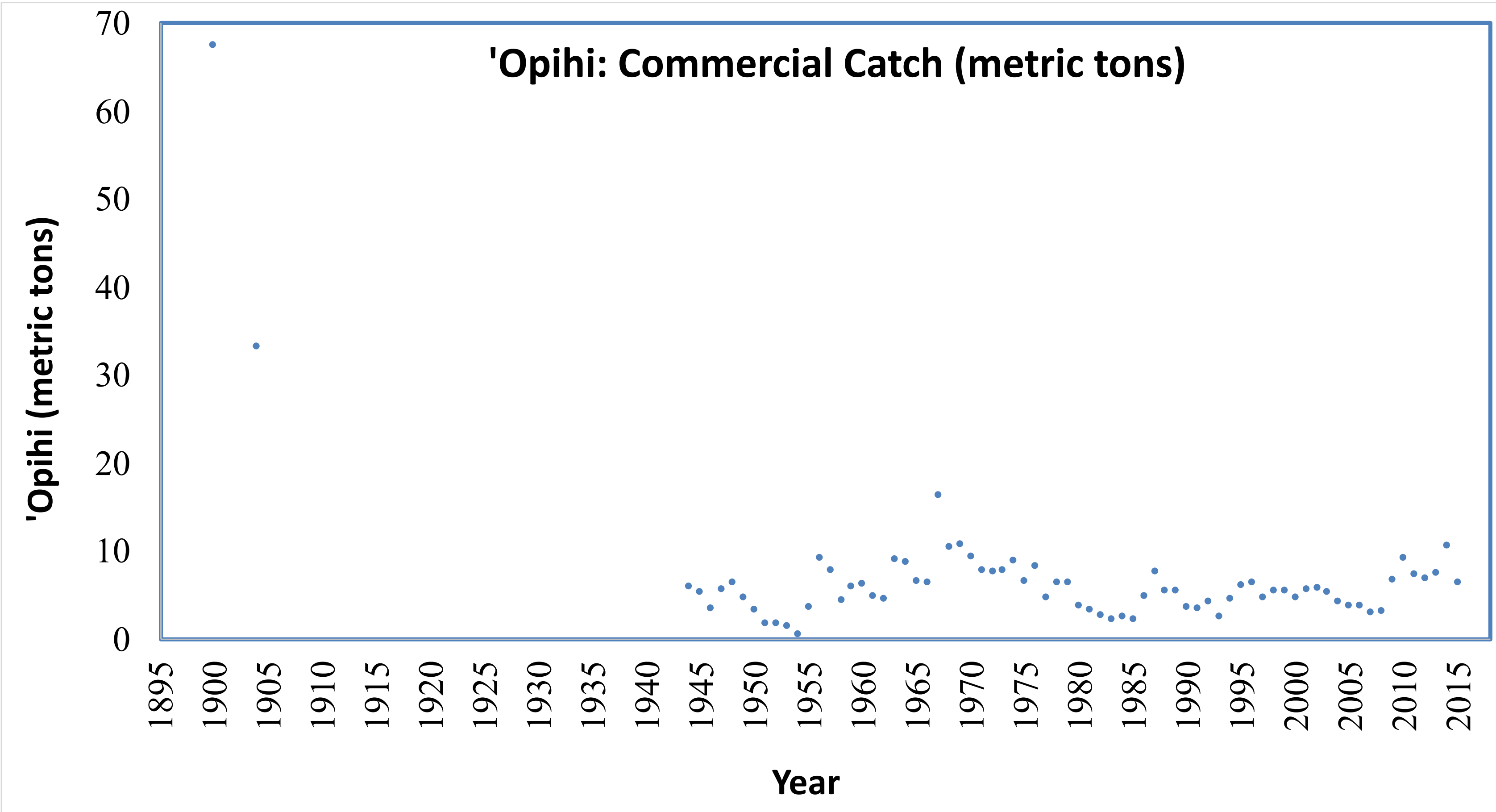
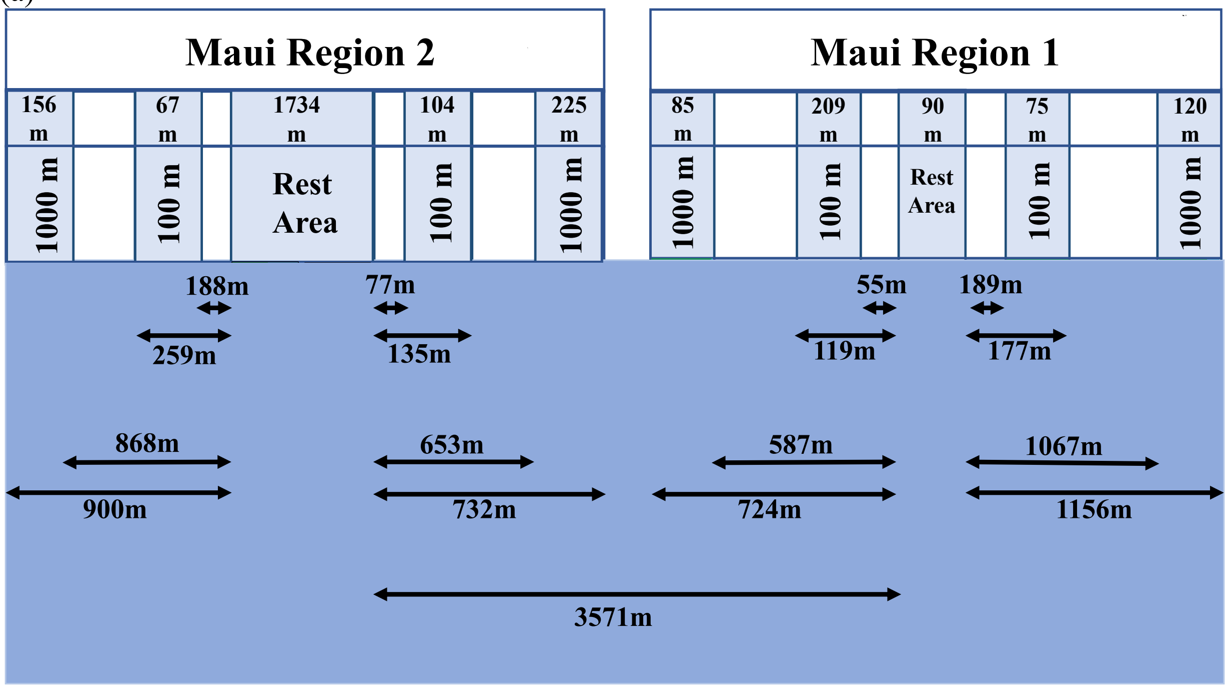
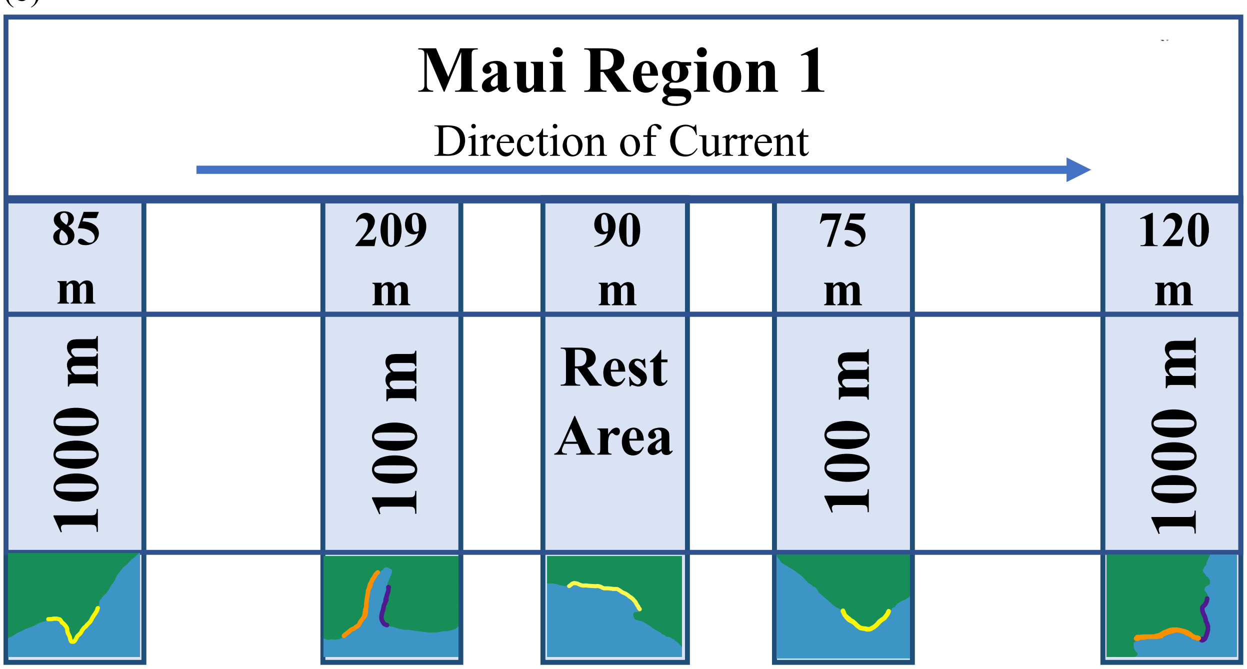


Figure 2. Estimated annual harvest (tons) of *Cellana exarata* over time throughout the Hawaiian Islands. Data were aggregated from (Corpuz et al. 1982; DAR 2016; Kay & Brilliande 1973).

(a)


Maui Region 2
156 m
67 m
1734 m
104 m
225 m
1000 m
100 m
Rest Area
100 m
1000 m
Maui Region 1
85 m
209 m
90 m
75 m
120 m
1000 m
100 m
Rest Area
100 m
1000 m
188m
77m
55m
189m
259m
135m
119m
177m
868m
653m
587m
1067m
900m
732m
724m
1156m
3571m

(b)


Maui Region 1
Direction of Current
85 m
209 m
90 m
75 m
120 m
1000 m
100 m
Rest Area
100 m
1000 m

(c)

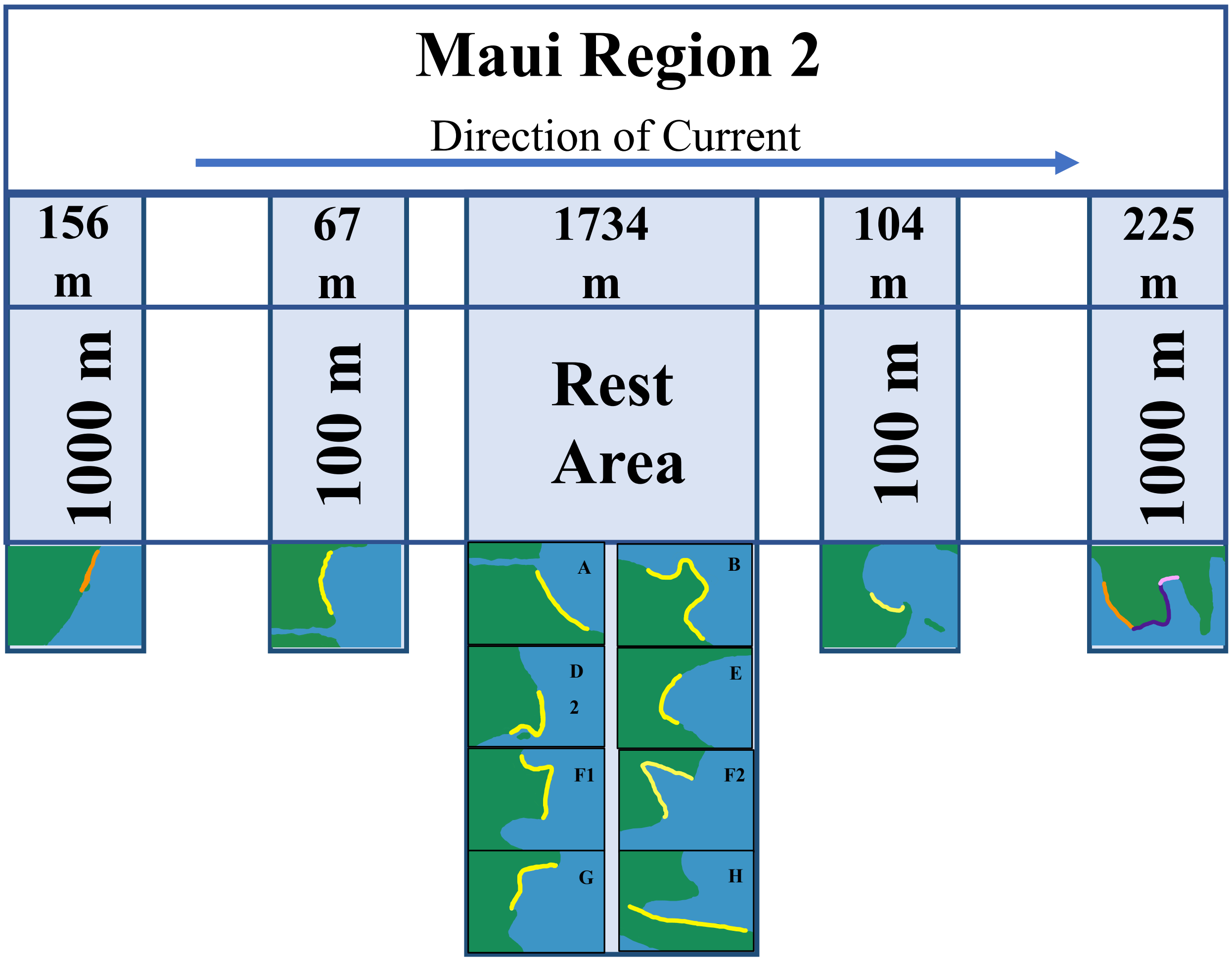
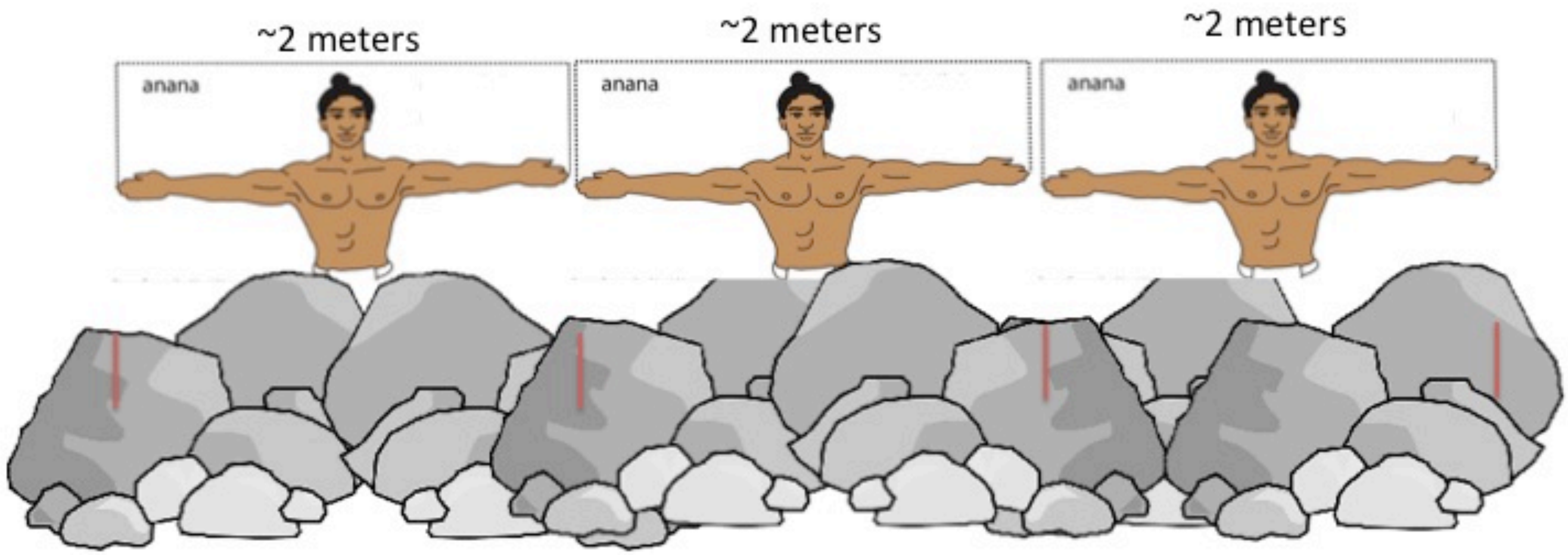


Figure 3. (a) The spatial arrangement (not to scale) of survey locations at Maui Region 1 and Maui Region 2 along the coast of Maui Island, Hawai‘i. Arrows in the blue area indicate the shortest and longest direct distance (m) larvae could travel between the Rest Areas and survey sites positioned north (left) to south (right). Note that the survey sites outside of the Rest Areas are named with respect to their approximate distances from the Rest Areas (i.e., 100m and 1000m). Figures b (Maui Region 1) and c (Maui Region 2) show basic geographic coastline maps for sites (green indicates land, blue indicates ocean, and yellow indicates regular survey area, orange indicates survey area A, purple indicates survey area B, and pink indicates survey area C).



Transect 1 Transect 2 Transect 3

Figure 4. The traditional Hawaiian measurement, anana or wingspan, (Gon 2014) which is used to divide survey sites into manageable units for counting *Cellana exarata*. Note that the goal is to count the total number of *C. exarata* in each size class (protected recruits <1 cm shell length, protected adolescents 1-3 cm shell length, and legally harvestable adults > 3cm shell length) at each survey site, so the exact size of the transects within a site is inconsequential to the analysis.

Figure 5. The three *Cellana exarata* size classes that are counted during surveys.

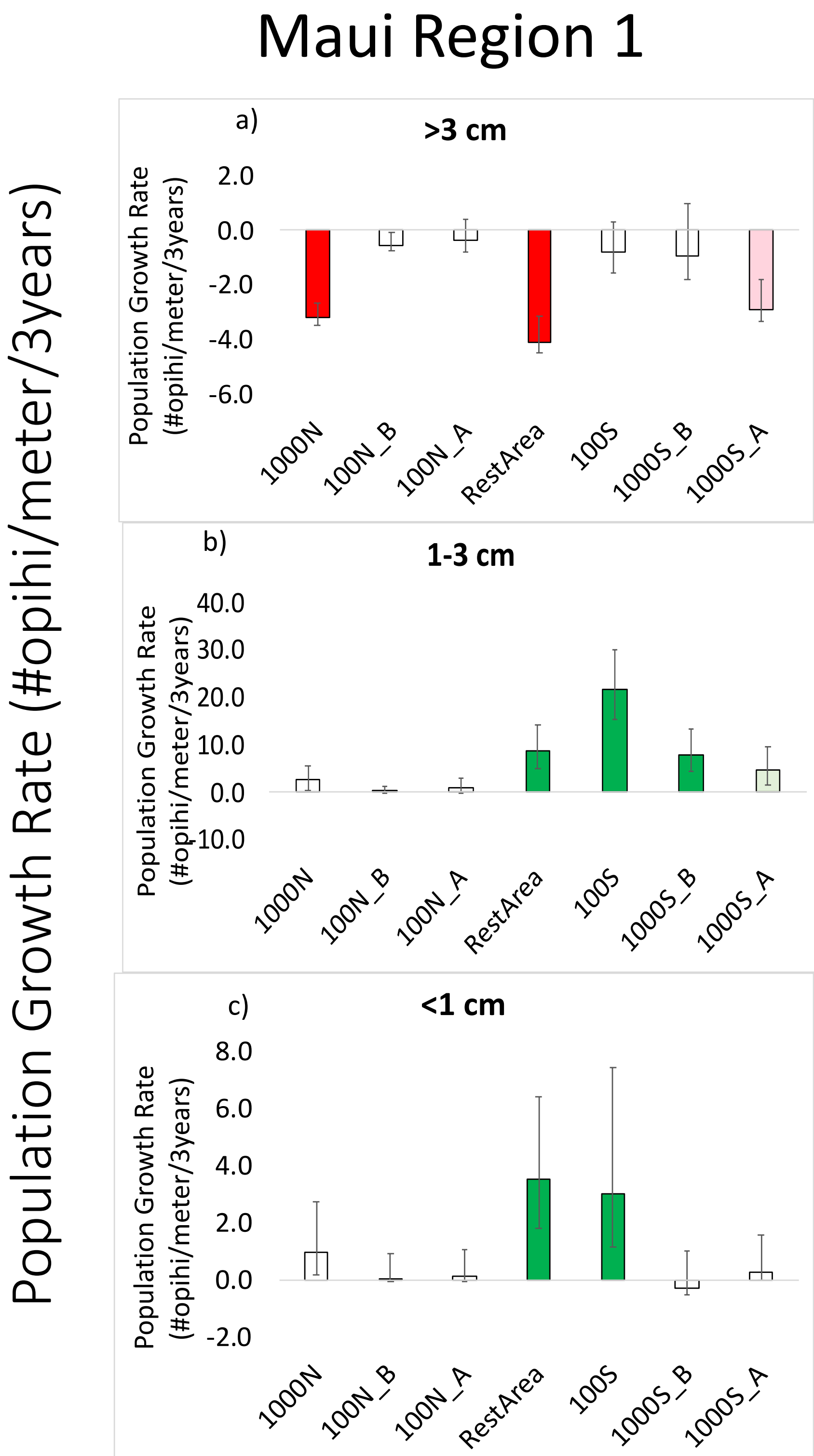


Figure 6. Negative binomial regression analysis of change in abundance over 3 years); a) harvestable adult (> 3cm shell length) b) sublegal (1-3 cm shell length), and c) juvenile (<1 cm shell length), *Cellana exarata* for Region 2 between the establishment of the rest area in September 2014 and September 2017. Bars shaded green indicate a significant ($p<0.05$) increase in abundance per day, red indicates a significant decrease ($p<0.05$), light green and pink indicate weak support for a change in abundance ($p<0.1$), and empty bars indicate no support ($p>0.1$) for a change in abundance.

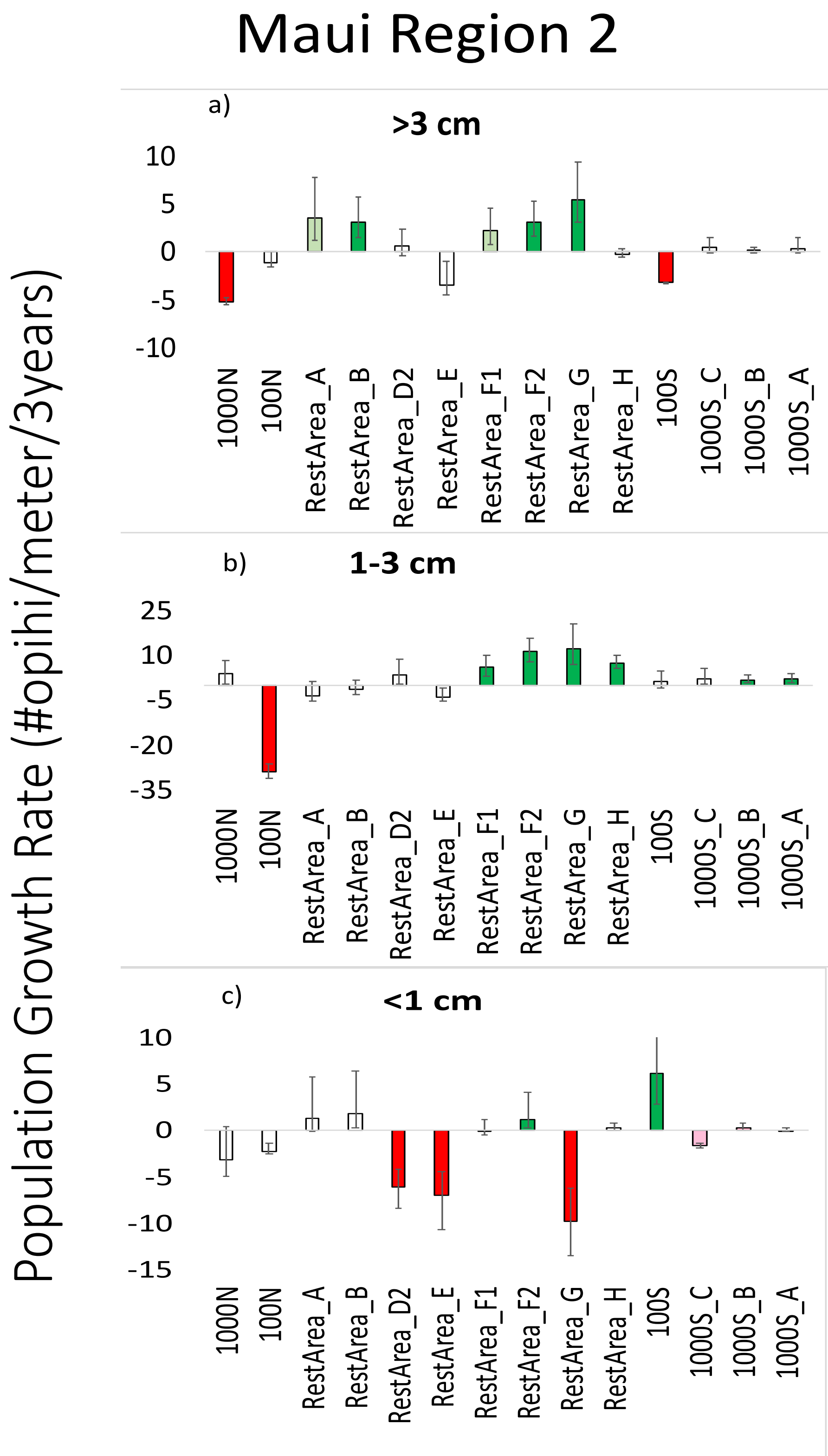


Figure 7. Negative binomial regression analysis of change in abundance over 3 years); a) harvestable adult (> 3cm shell length) b) sublegal (1-3 cm shell length), and c) juvenile (<1 cm shell length), *Cellana exarata* for Region 1 between the establishment of the rest area in September 2014 and September 2017. Bars shaded green indicate a significant (p<0.05) increase in abundance per day, red indicates a significant decrease (p<0.05), light green and pink indicate weak support for a change in abundance (p<0.1), and empty bars indicate no support (p>0.1) for a change in abundance.

Tables

Table 1. Survey counts of *Cellana exarata* for Maui Regions 1 and 2, listed by location, listed north (first) to south (last), month (weather permitting) and summed by year, from the establishment of the Rest Areas to the November 2017 survey.

Region	Location	2014 Sept	2015 Jan	2015 Mar	2015 Aug	2015 Oct	2016 Jan	2016 Feb	2016 Apr	2016 Jun	2016 Jul	2016 Nov	2017 Feb	2017 May	2017 Sep	2017 Nov
Maui Region 1	1000N	20	32		33		27		24			24	27	26	24	
	100N B	12	27		29		27		29			29	26	24	30	
	100N A	15	36		26		34		33			30	31	31	34	
	RestArea	34	37		44		43		42			39	39	38	68	
	100S	17	40		36		47		36			41	38	36	63	
	1000S B	12	20				28		22			22	20	21		
	1000S A	9	31				26		26			28	28	26	50	
Maui Region 2	1000N	72		71		69			74				71	72		110
	100N	45		38		41	39		40			36	35	37	37	
	RestArea A	14		24		26		25	25			23	23	28	25	
	RestArea B			28			39		43	38		42	39	40	40	
	RestArea D2	24					33		37	45		37	40	40	31	
	RestArea E	23					24		26	25		22	24	25	21	
	RestArea F1	32		26			30		31	33		28	32	33	34	
	RestArea F2	32		39			12		35	34		33	33	36	38	
	RestArea G	29							34	33		28	31	37	32	
	RestArea H	84		88		81		85	84	82		86	93	97	95	
	100S	47		63		51		55	53	55		51	54	54	55	
	1000S C	26		28		28		25	26		25		27	28	29	
	1000S B	57		42		64		53	40		61		56	61	60	
	1000S A	43		38		32		36	25		34	41	34	38	42	

Transects per Year by Region

	2014	2015	2016	2017
Maui Region 1	119	391	0	680
Maui Region 2	528	877	1921	1867

Table 2. Negative binomial regression analysis estimates (Population Growth Rate~ln(count/meter/year), standard errors (SE), standard score (Z value), and probability values (Pr(>|z|)) for *Cellana exarata* Maui Region 1 and Region 2 locations by reproduction size recruits (<1cm shell length), adolescents (1-3cm shell length), and harvestable adults (>3cm shell length); red number with asterisks indicates significant p-values.

		(<1cm shell length)				(1-3cm shell length)				(>3cm shell length)			
Region	**Location**	**Est.**	**SE**	**Z value**	**Pr(>|z|)**	**Est.**	**SE**	**Z value**	**Pr(>|z|)**	**Est.**	**SE**	**Z value**	**Pr(>|z|)**
East Maui 1	1000N	2.2E-01	1.4E-01	1.53	1.3E-01	6.7E-02	5.4E-02	1.25	2.1E-01	-1.8E-01	6.2E-02	-2.97	**3.0E-03** *
	100N_B	6.1E-02	3.6E-01	0.17	8.7E-01	2.6E-02	8.8E-02	0.30	7.6E-01	-1.1E-01	9.5E-02	-1.13	2.6E-01
	100N_A	1.1E-01	2.2E-01	0.49	6.3E-01	5.7E-02	8.6E-02	0.66	5.1E-01	-4.8E-02	8.5E-02	-0.57	5.7E-01
	RestArea	3.3E-01	9.0E-02	3.63	**2.8E-04** *	1.3E-01	4.5E-02	2.89	**3.8E-03** *	-1.8E-01	7.4E-02	-2.42	**1.6E-02** *
	100S	5.8E-01	1.6E-01	3.64	**2.8E-04** *	4.8E-01	5.4E-02	8.85	**8.8E-19** *	-4.1E-02	5.4E-02	-0.76	4.4E-01
	1000S_B	-7.2E-02	1.9E-01	-0.37	7.1E-01	2.0E-01	6.2E-02	3.19	**1.4E-03** *	-5.9E-02	9.9E-02	-0.59	5.5E-01
	1000S_A	1.8E-01	2.4E-01	0.77	4.4E-01	1.6E-01	8.4E-02	1.94	5.2E-02	-1.5E-01	7.8E-02	-1.88	**6.0E-02** *
East Maui 2	1000N	-8.1E-02	8.8E-02	-0.92	3.6E-01	3.8E-02	3.5E-02	1.06	2.9E-01	-4.6E-01	7.1E-02	-6.52	**7.1E-11** *
	100N	-1.9E-01	1.1E-01	-1.63	1.0E-01	-4.7E-01	7.6E-02	-6.16	**7.4E-10** *	-1.1E-01	1.2E-01	-0.96	3.4E-01
	RestArea_A	1.8E-01	1.9E-01	0.94	3.5E-01	-7.3E-02	9.0E-02	-0.81	4.2E-01	1.8E-01	9.6E-02	1.88	**6.0E-02** *
	RestArea_B	2.3E-01	1.7E-01	1.37	1.7E-01	-3.9E-02	6.9E-02	-0.56	5.8E-01	1.8E-01	7.0E-02	2.60	**9.4E-03** *
	RestArea_D2	-6.8E-01	1.8E-01	-3.79	**1.5E-04** *	7.9E-02	7.6E-02	1.05	2.9E-01	3.4E-02	6.5E-02	0.53	5.9E-01
	RestArea_E	-9.2E-01	2.1E-01	-4.29	**1.8E-05** *	-1.0E-01	7.9E-02	-1.28	2.0E-01	-1.1E-01	8.5E-02	-1.25	2.1E-01
	RestArea_F1	-3.1E-02	1.7E-01	-0.18	8.6E-01	1.4E-01	5.3E-02	2.55	**1.1E-02** *	1.1E-01	6.3E-02	1.69	**9.0E-02** *
	RestArea_F2	4.2E-01	2.1E-01	1.99	**4.7E-02** *	3.0E-01	4.8E-02	6.24	**4.4E-10** *	1.9E-01	6.2E-02	3.00	**2.7E-03** *
	RestArea_G	-5.8E-01	2.3E-01	-2.48	**1.3E-02** *	4.1E-01	8.0E-02	5.15	**2.6E-07** *	3.4E-01	7.8E-02	4.39	**1.1E-05** *
	RestArea_H	1.1E-01	1.1E-01	0.99	3.2E-01	2.6E-01	3.9E-02	6.73	**1.7E-11** *	-2.5E-02	4.9E-02	-0.51	6.1E-01
	100S	3.2E-01	1.0E-01	3.14	**1.7E-03** *	2.7E-02	5.4E-02	0.50	6.1E-01	-2.9E-01	6.0E-02	-4.76	**1.9E-06** *
	1000S_C	-3.4E-01	1.9E-01	-1.78	**7.5E-02** *	8.6E-02	8.0E-02	1.07	2.8E-01	6.7E-02	1.0E-01	0.65	5.1E-01
	1000S_B	2.8E-01	1.6E-01	1.71	**8.7E-02** *	2.2E-01	8.4E-02	2.60	**9.2E-03** *	4.2E-02	1.0E-01	0.42	6.8E-01
	1000S_A	-6.2E-02	1.9E-01	-0.32	7.5E-01	1.9E-01	8.2E-02	2.38	1.7E-02	5.8E-02	9.7E-02	0.60	5.5E-01