Attempt to Control the Invasive Red Alga *Acanthophora spicifera* (Rhodophyta: Ceramiales) in a Hawaiian Fishpond: An Assessment of Removal Techniques and Management Options[1]

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Abstract: *Acanthophora spicifera* (Vahl) Børgesen was unintentionally introduced to Hawai‘i in 1950 and has since become the most common nonindigenous algal species in the main Hawaiian Islands. On the west coast of Hawai‘i Island it has been documented at three sites, including Kaloko Fishpond in Kaloko-Honokōhau National Historical Park. The fishpond has an open connection to the sea, increasing the risk that *A. spicifera* will establish itself on neighboring shallow coral reefs and rocky intertidal habitats. To diminish that risk and to develop an efficient management strategy, a range of approaches was assessed to control this invasive alga in Kaloko Fishpond. Removal techniques were labor intensive and had limited effect. All experiments showed a substantial initial decrease in algal density, but the long-term effect was minimal because of rapid regrowth. The most promising removal method was the use of submerged shelters to raise local densities of herbivorous fishes. Fishes grazed the alga and quickly reduced the biomass. However, the large number of predators and absence of topographical structure will make it challenging to provide sufficient shelters to increase the herbivorous fish population in the entire fishpond. A management strategy to substantially reduce the algal biomass in the fishpond includes a combination of biological control and periodic manual removal of the alga.

Numerous publications have documented dramatic changes in marine ecosystems after invasive species intentionally or unintentionally were moved across geographical or ecological barriers (Carlton 1987, Boudouresque et al. 1995, Trowbridge 1995, Jousson et al. 2000, Curiel et al. 2001, Smith et al. 2002, 2004, Conklin and Smith 2005). In response to the seriousness of invasive species issues, state, federal, and nongovernmental agencies have developed programs or initiatives to determine the impacts of these species on ecosystem structure and to develop strategies to minimize those impacts. Management of invasives by implementing eradication or control programs, although difficult, can be successful, as seen in numerous terrestrial examples of invasive plant species (e.g., Foxcroft and Richardson 2003, Van Wilgen et al. 2004). Development of management options for control of marine invasives is much more challenging (e.g., Conklin and Smith 2005). Possibly the only presumed successful marine example is the short-term "injection" of bleach under a tarped-off area for *Caulerpa taxifolia* in a coastal lagoon of southern California (Woodfield and Merkel 2005).

Hawai‘i is a major recipient of introduced species. A conservative estimate of the number of marine introduced species in Hawai‘i is in the hundreds (Carlton 1987). There are 19 documented species of introduced macroalgae in Hawai‘i, at least five of which have

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become invasive: *Acanthophora spicifera*, *Avrainvillea amaldelpha*, *Gracilaria salicornia*, *Hypnea musciformis*, and *Kappaphycus* spp. (Rodgers and Cox 1999, Eldredge and Carlton 2002, Smith et al. 2002, 2004). To date, *A. spicifera* and *Kappaphycus* spp. are the only taxa that are known to be sexually reproductive on a regular basis in the Hawaiian Islands (J. E. Smith, pers. comm.), thus increasing their dispersal potential. In Kāne'ohe Bay, O'ahu, *Kappaphycus* spp. were introduced on the assumption that they would not spread (Russell 1983). However, surveys conducted in 1996 (Rodgers and Cox 1999), 1999 (Woo 2000), and 2002 (Conklin and Smith 2005) found that the algae had spread as far as 6 km away from the introduction site and were continuing to spread northward in the bay, where they were overgrowing live coral. Once invasive macroalgae have become established, eradication is difficult and costly, and can lead to high economic losses (Cesar and Beukering 2004).

Acanthophora spicifera (Vahl) Børgesen, 1910, a marine red alga, arrived in Pearl Harbor, O'ahu, from Guam on a barge in the 1950s (Russell 1992). Now it is the most common nonindigenous algal species in the state and displaces many native species where it is abundant (Smith et al. 2002). The success of *A. spicifera* in invading benthic habitats is attributed to: (1) its ability to reproduce both sexually and vegetatively (by fragmentation); (2) successful epiphytism; and (3) its adaptability to a wide range of hydrological conditions (Russell 1992). When and how *A. spicifera* first entered Kaloko Fishpond is unknown. Despite its dominance on other islands, on the west coast of Hawai'i Island its presence has been documented at only three sites: Pu'ukoholā Heiau National Historic Site (Ball 1977; L. Basch, unpubl. data, 2005), Pu'uhonua o Hōnaunau National Historical Park (C. Squair, unpubl. data, 2006), and Kaloko-Honokōhau National Historical Park (Marine Research Consultants 2000, Smith et al. 2002). Only in Kaloko Fishpond, located in Kaloko-Honokōhau National Historical Park, has the alga been observed in abundance. The alga might have been present at low levels within the pond for much longer (beginning sometime after the species' wider introduction to the west coast of Hawai'i), but it apparently did not become invasive in Kaloko Fishpond until the late 1990s. The presence of this species was not mentioned in a 1971 evaluation of fishponds (Kikuchi and Belshé 1971), nor in a 1988 marine inventory study (Chai 1991) nor in a 1996 biological and water quality study (Brock and Kam 1997). The first report of *A. spicifera* being abundant throughout the fishpond was made in 2000 (Marine Research Consultants 2000). Currently, it is the dominant macroalgal species in the pond.

In the last three decades, two important alterations have changed the hydrology of the fishpond and might have influenced the susceptibility of the pond to invasion by *A. spicifera*. First, the condition of the fishpond wall separating the pond from the ocean has been continuously changing: It was left to deteriorate from wave and wind action from the 1970s to the late 1990s, at which time rehabilitation efforts began (Bond and Gmirkin 2003). Alterations in the integrity of the wall led to changes in water quality within the pond and the rate of exchange with adjacent ocean waters, and are therefore probably associated with shifts in the pond biota. Second, mangroves that had invaded the pond periphery in the 1980s were removed in the early 1990s (Bond and Gmirkin 2003). Accumulation of detritus in mangrove stands would have changed the bottom sediment and water quality, and likely also affected the pond biota. In addition, upslope development beginning in earnest two decades ago has most likely led to nutrient increases in the groundwater that enters the fishpond.

In the summer of 2003, the first comprehensive study to quantify the distribution and density of *A. spicifera* in Kaloko Fishpond was conducted. A 20–m grid was laid out over the pond and at each grid point the presence and, if present, the abundance (from sparse to concentrated) of *A. spicifera* was scored. At that time, the pond bottom was 48% covered by *A. spicifera* either as drift, embedded in silt or sand, or attached to oysters or rock substratum (National Park Service, unpubl. data). A primary concern for Park resource managers was, and is, that *A. spicifera* might spread to the intertidal zone and coral reefs just seaward of Kaloko Fishpond. Fragments of drift *A. spicifera* have escaped the pond through the sluice channels (M.W., pers. obs.). The current absence of visible *A. spicifera* on the adjacent reef could be because the alga is not able to establish outside the pond, perhaps due to locally high-grazing intensity, or because propagule pressure has so far been insufficient to promote establishment. However, because of the prevailing surface and deep-water currents offshore of Kaloko Fishpond (Storlazzi and Presto 2005), we cannot discount the potential for this alien alga to establish on nearby shallow reefs.

To reduce the risk of *A. spicifera* spreading to adjacent reefs, the following techniques were used from April to December 2006, to determine the feasibility of controlling or eradicating *A. spicifera* in Kaloko Fishpond: manual removal, shading of the benthos, and use of herbivorous fish (biocontrol). Chemical-control methods were not explored in this study because of the associated risks to aquatic organisms and ecosystems within this national park unit. It soon became apparent that *A. spicifera* regrew rapidly after manual removal. Therefore, trials to determine an efficient manual removal technique were also conducted. These included cropping to three different specific thallus lengths (minimum viable thallus length trial), repeatedly removing the same alga (repetitive removal trial), and removing attached algae with their hard substrate and replacing the substrate after a period of drying (substrate removal/ replacement trial). In each case we measured extent and speed of recovery of *A. spicifera* populations for periods of up to 4 months.

MATERIALS AND METHODS

Study Site

Kaloko Fishpond is a 4.5–ha ancient Hawaiian fishpond (Figure 1) located in Kaloko-Honokōhau National Historical Park on the west coast of Hawai'i Island. It is a shallow (maximum depth 3.5 m, mean depth 1.5 m) natural embayment with a human-made dry-stack stone wall partially closing it off from the ocean. Two sluice channels in the wall allow some water circulation between the ocean and pond. The fishpond seawall deteriorated substantially from about 1970 until rehabilitation began in 1998 because of the impact of winter storm swells (Bond and Gmirkin 2003). At the time of the study about 60% of the wall and one sluice channel were rehabilitated. Work on the wall continued throughout the study. Kaloko Fishpond water is stratified due to freshwater springs and seepage from cracks in the basalt bottom. The dominant substrate is silt composed of decomposing organic material varying in depth from a few centimeters on the ocean side of the pond to at least 1 m on the inland side, often with anoxic conditions (Kikuchi and Belshé 1971). Allochthonous sand is predominantly found on the ocean side of the pond. The remaining bottom type is hard substrate such as basalt rock and oyster conglomerates with an associated biota that includes anemones, fireworms, sponges, tunicates, and brittle stars. The benthos is mostly blanketed by an algal mat composed of a rich microflora assemblage (cyanobacteria, diatoms, dinoflagellates) and macroalgae. Preliminary surveys in April 2005 showed that the fishpond bottom was 66% covered by *A. spicifera*, and that sand and oysters were the main algal substrate types. The alga was mostly absent on silt bottoms. Oysters are primarily found in shallow water ($\leq$1 m) and were therefore easy to reach for removal efforts. Oyster islands are present in 14% of the fishpond and are concentrated in the NW corner of Kaloko Fishpond. That area is where we concentrated our removal efforts.

Measurement of Algal Coverage and Periodic Surveys

It was difficult to get a good estimate of algal cover due to the three-dimensional structure of the plants, very low visibility (sometimes as low as 25 cm), and the daily movement of unattached drift algae. A 25 by 25 cm quadrat with nine, 1–cm^2 sampling squares evenly distributed was used to calculate "algal coverage." Presence or absence of *A. spicifera* was

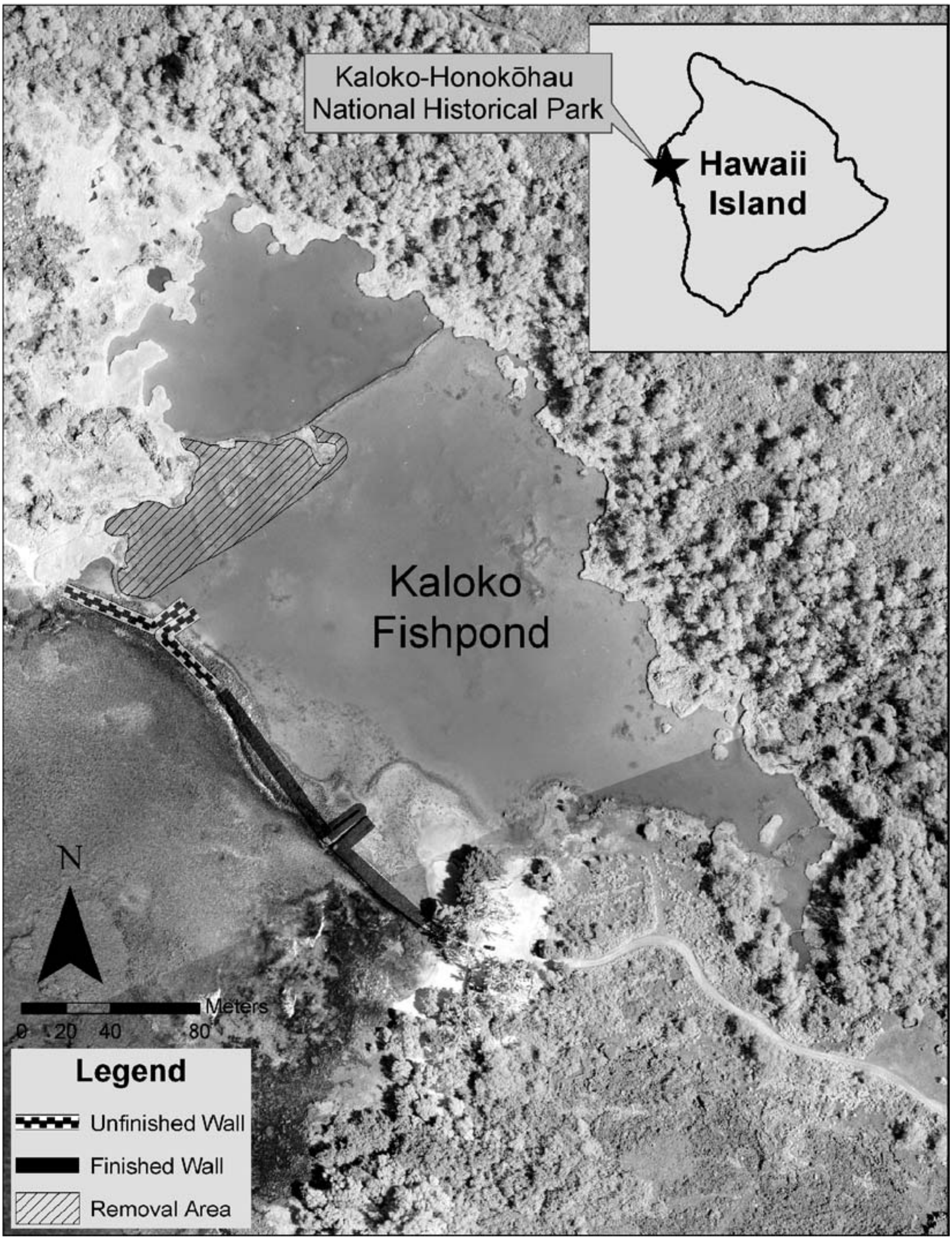

FIGURE 1. Kaloko Fishpond and adjacent reef shelf with modifications of the seawall drawn in for an up-to-date image. The removal area (lined) in the northwest corner is the 2,200 m^2 removal and experimental area of this study. The lighter areas within the removal area are the oyster islands. Kaloko Fishpond is located in Kaloko-Honokōhau National Historical Park just north of Kailua-Kona, on the west coast of Hawai'i Island.

recorded in each sampling square. Percentage of sampled areas with algae present is referred to as "algal coverage" as an indication of algal cover.

Physical hydrology data were collected in May, June, September and October 2005 at 43 stations located throughout the pond. At each location, measurements (accuracy and resolution, respectively, given in parentheses) of salinity ($\pm 1\%$ of reading $\pm$ 1 count; 0.01 PSS [Practical Salinity Scale]), dissolved oxygen (± 0.2 mg/liter; 0.01mg/liter), temperature ($\pm 0.2°C$; 0.01°C), pH (± 0.2 units; 0.01 unit), and depth (± 0.1 m; 0.1 m) were made around noon near the surface (0.2 m depth) and at 1–m intervals down to the bottom using a multiprobe instrument (Hydrolab Quanta). Because of the existing stratification, it was assumed that no changes due to variation in tide heights would occur in the hydrological characteristics of the sampled depth layers.

To better understand the life cycle of *A. spicifera*, the lengths of about 30 plants were measured bimonthly from March to December 2005. A regression analysis was used to examine the decreasing trend of thallus height over time. In addition, thalli were haphazardly collected throughout the fishpond and were examined using stereomicroscopy several times during the study to determine the presence of sexual reproductive structures. Quantitative *A. spicifera* surveys in the adjacent intertidal and reef flat area were conducted by snorkeling and walking around the seawall and intertidal area, and by scuba diving.

Experiments

MANUAL REMOVAL: *Acanthophora spicifera* was manually pulled off the substrate close to attachment points and drift algae collected in an area of approximately 2,200 m^2 varying in depth between 0.3 and 2 m (Figure 1). Total area removed, removal time, and number of persons removing were recorded. The alga was collected in a mesh or burlap bag to allow excess water to seep out and weighed to the nearest 0.25 kg. Removal effort was the time it took for one person to clear 1 m^2 of algae. Removal yield was the number of kilograms of *A. spicifera* biomass removed per 1 m^2. Removal events occurred in June 2005 and August 2005. Before and after the removal events, percentage coverage of *A. spicifera* was estimated weekly for 6 weeks by snorkeling in parallel transects across the removal area encompassing a range of depths (0 to 2 m) and substrate types. Every three fin kicks, a 25 by 25 cm quadrat was haphazardly dropped. Algal presence, depth, and substrate were recorded for each quadrat.

In addition, we conducted three removal trials to assess whether manual removal could be more effective. These three trials were the viable thallus length trial, the repetitive removal trial, and the substrate removal/replacement trial; a brief description of each follows.

(1) Viable thallus length trial: To determine if regrowth of *A. spicifera* is dependent on the height of the remaining thalli after removal, plants were cut at different lengths and regrowth was monitored for 2 months. There were four treatments: no removal (control), cut to 3 cm height, cut to 1 cm height, and "scraped" (0 cm height). For scraped, attachment points were removed with a wire brush until no algal biomass was visible. Each treatment consisted of 35 individual algae attached to oyster conglomerates placed on a plant nursery tray and submerged at 0.5 m depth. We recorded the length of the tallest branch per plant, the number of branches per plant, and the total number of plants. We sampled before treatment, just after, and then at 2-week intervals until no differences in average thallus height between treatments was observed.

(2) Repetitive removal trial: To assess the ability of *A. spicifera* to regrow after multiple removal events, we collected 35 specimens of the alga attached to several oyster conglomerates. The height of the tallest branch per individual plant (clone) was measured. All biomass was then manually removed close to alga attachment points. The oyster conglomerates were placed on a tray and submerged to 0.5 m depth. On a separate tray the same number of attached algae served as a control group. Height of the tallest branch and the

number of branches per plant were recorded at 2-week intervals for both groups. After 1 month, the regrown biomass was removed. This process was repeated for four removals. We used a Spearman rank correlation to measure the strength of the association between the number of times biomass was removed and growth rate. A Mann-Whitney test was used to examine statistical difference in number of branches between the control and treatment group.

(3) Substrate removal/replacement trial: To determine how quickly *A. spicifera* reestablished itself on bare, hard substrate, a 30–m^2 area was cleared of all algae. When algae were attached to hard substrate, which consisted only of oyster conglomerates, the conglomerates were removed and dried on land for 14 days to assure that all algal tissue died. The oyster conglomerates were replaced in the same collection area. New growth was monitored along a 7–m fixed transect line by placing a quadrat every 30 cm and calculating the percentage coverage of returning *A. spicifera* either as drift or attached to oysters. In a control area with similar bottom type (sand and oysters) only drift algae were initially removed and *A. spicifera* coverage was surveyed in the same way.

SHADE EXPERIMENT: A trial shade experiment (1 by 1 m plots) indicated that when sunlight was blocked to 3% ambient light levels (LiCor SA radiation sensor), the average height of thalli decreased to 20% of the initial average height within a month and stayed low, at about 1.8 cm $\pm$ 0.5 SD for 6 weeks. To determine the effect of shading on a larger scale, a frame-supported 5 by 3.5 m tarp (3% ambient light) was placed 30 cm from the bottom, allowing water circulation to the benthic invertebrates but preventing mechanical breakage of the algae. Due to the buildup of silt and algae, the tarp was cleaned every 2 weeks by swimming over it and gently removing the accumulated silt. Percentage algal cover was measured with a 1 by 1 m quadrat for both the control and experimental sites before the tarp was placed. Under the tarp, four trays were placed with 15 clones each and the height of the tallest branch per clone was measured weekly. Four control trays with the same number of algae were placed just north of and adjacent to the shaded area at a similar depth. When the average height of the shaded algae did not appear to change for four consecutive weeks, the tarp was removed and algal cover was recorded. A final measurement of thallus heights and percentage algal cover was conducted at the end of the study period, 2.5 weeks after tarp removal, to measure the regrowth rate.

BIOLOGICAL CONTROL EXPERIMENT: We used a Hawaiian method of providing shelters for fish, known as an *imu*, to increase herbivorous fish populations as a potential means of control. These *imu* were constructed by piling stones in a conical shape with multiple holes big enough to allow sunlight in and deter moray eels from entering but small enough to allow herbivorous fish to seek refuge from predators. Four *imu* (approximately 1 m height and 1 m in diameter) were built between 4 and 12 m from shore. The first fish species to establish themselves were *Abudefduf sordidus* and juvenile *Lutjanus fulvus*. Six weeks later, *Acanthurus triostegus* and various species of Chaetodontidae had colonized the *imu*. When the fish population in the *imu* had similar fish species and numbers for three consecutive weeks, the experiment was initiated. Drift and attached *A. spicifera* were removed between and around the group of *imu*, leaving roughly 25% algal coverage. At each *imu*, 20 algae attached to oyster conglomerates were placed in a tray next to the *imu* at 0.5 to 1 m depth. In addition, four control trays with algae were placed at a site similar in bottom type and depth, 11 m away from the *imu* and 11 m from shore. To monitor grazing, weekly measurements of the height of the tallest branch per alga were recorded. Fish surveys were conducted before each algal survey. Fish in and around the *imu* and at the control site were identified to species, counted, and recorded. A one-way analysis of variance (ANOVA) was performed to determine any differences in fish numbers between *imu*. The change in algal height over time was plotted for the *imu* trays. After initial grazing to approximately 1 cm height

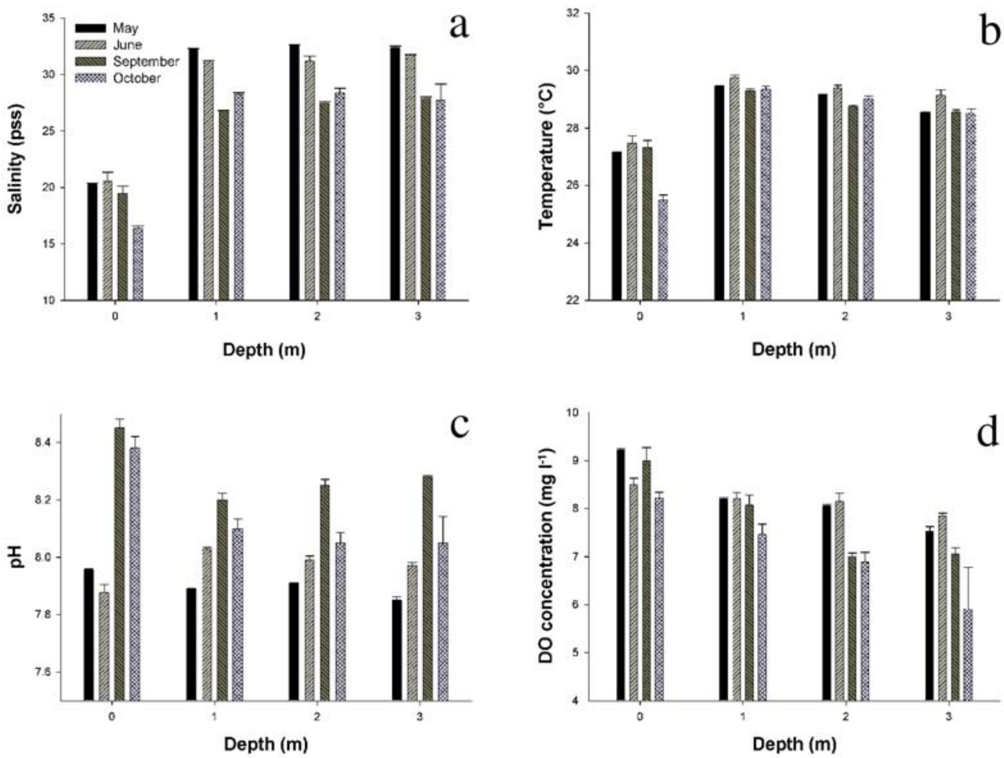

FIGURE 2. Averaged physical parameters of Kaloko Fishpond across a depth profile in 2005. *a*, mean salinity (PSS [Practical Salinity Scale]); *b*, mean temperature (°C); *c*, mean pH; and *d*, mean dissolved oxygen (%). Data are means of 45 sampling stations ± 1 SE. Note that y-axis scales do not start at 0.

(over a 2-week period), a one-way ANOVA was used to determine a change in thallus height with each *imu*. Three weeks into the experiment, the tray at one of the *imu* disappeared, resulting in exclusion of those data from analysis.

RESULTS

Physical Hydrology of Kaloko Fishpond

The fishpond water showed strong stratification, with a cold, brackish top layer (temperature 25°C to 27°C, salinity 16 to 20 PSS) and a warmer and more saline bottom layer (29°C, 27 to 32 PSS) (Figure 2). Coldest surface temperatures (22°C to 25°C) and corresponding lowest salinities (13.9 to 16.6 PSS) were measured near a freshwater discharge area in the southeast section of the pond. Warmest (27.8°C to 29.1°C) and most saline (25.5 to 28.4 PSS) surface waters were encountered close to the seawall. From August onward, the seawall and northern sluice channel were blocked with a sand berm, reducing water circulation. Within a few months, the water in the fishpond became fresher. Average surface salinity ($n = 43$) dropped from 20.3 ± 0.08 PSS in May to 16.4 ± 0.25 PSS in October, and in deeper waters it decreased from 32.4 ± 0.01 PSS to 28.2 ± 0.03 PSS. Over the same time period the surface pH increased from 8.0 ± 0.00 in May to 8.4 ± 0.00 in October and less so in deeper water, and the dissolved oxygen concentration dropped from 9.2 ± 0.04 mg/liter to 8.2 ± 0.01 mg/

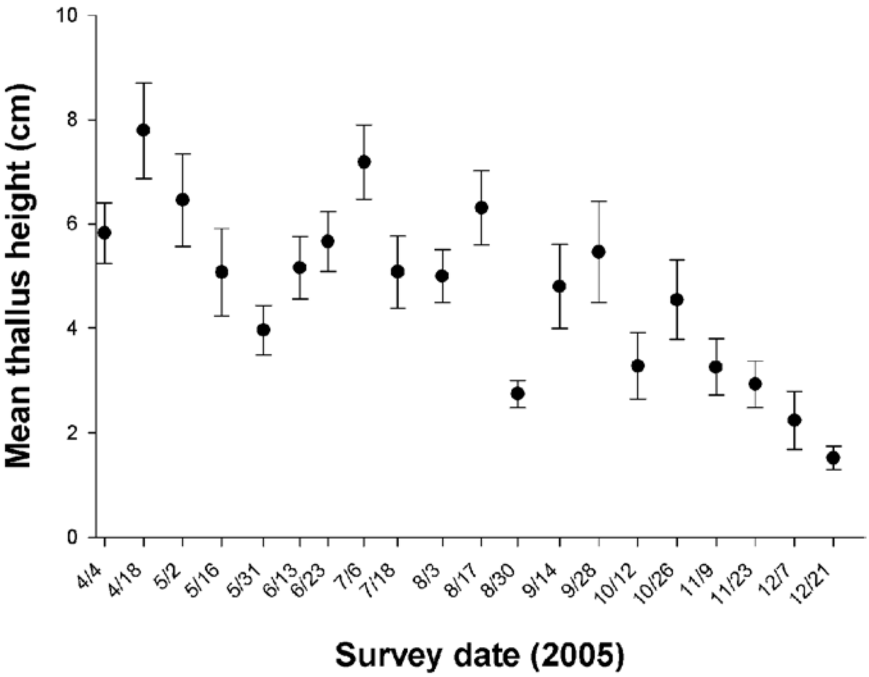

FIGURE 3. Thallus height over time. Data points are mean thallus height ± 1 SE of 30 *Acanthophora spicifera* clones sampled at 2-week intervals from the start of the study in March until the end of the study in December.

liter in surface waters and decreased from 8.1 ± 0.01 mg/liter to 7.1 ± 0.02 mg/liter in deeper waters.

General Observations of A. spicifera

From the results of field observations and experiments, we have a better understanding of the population dynamics of *A. spicifera.* Growth appears to be governed by rate of fragmentation and reattachment of branches (reproduction), which is likely to be influenced by thallus dynamics, and growth of existing clone. Branches grew to 15 cm and then broke off, became drift, and generally became entangled in nearby bushy *A. spicifera* adult clones. These clumps increased in size due to the collection of drift fragments and growth of attached clone, and eventually broke off as well. In the shallow areas (<1 m depth) the bottom type is predominantly oysters, a suitable substrate for *A. spicifera*. In the deeper areas (1–3 m), the bottom type is sand and/or silt, and the alga was found either embedded in the sand or rolling across the bottom in drift clumps. Drift formation from fragmentation led to large quantities of biomass in the shallow areas first, which then became concentrated in downwind areas of the pond on sand or silt bottoms. This could serve as a "fragment bank" with substantial reattachment potential. The average thallus height of 30 thalli showed a decreasing trend over time from March to December ($R^2 = 0.6$, $P < 0.0001$) (Figure 3). The average size of the five tallest thalli, however, was stable around 12.1 cm ± 1.2 SE ($R^2 = 0.05$, $P = 0.4$), and average thallus length of algae throughout the fishpond declined (see results of other experiments). Growth, therefore, appears to show seasonal variation with a peak in summer. In the winter the thalli showed signs of necrosis with possibly minimal attachment points persisting that grow out to new clones in the spring/summer. It could be that no single part of the clone persists

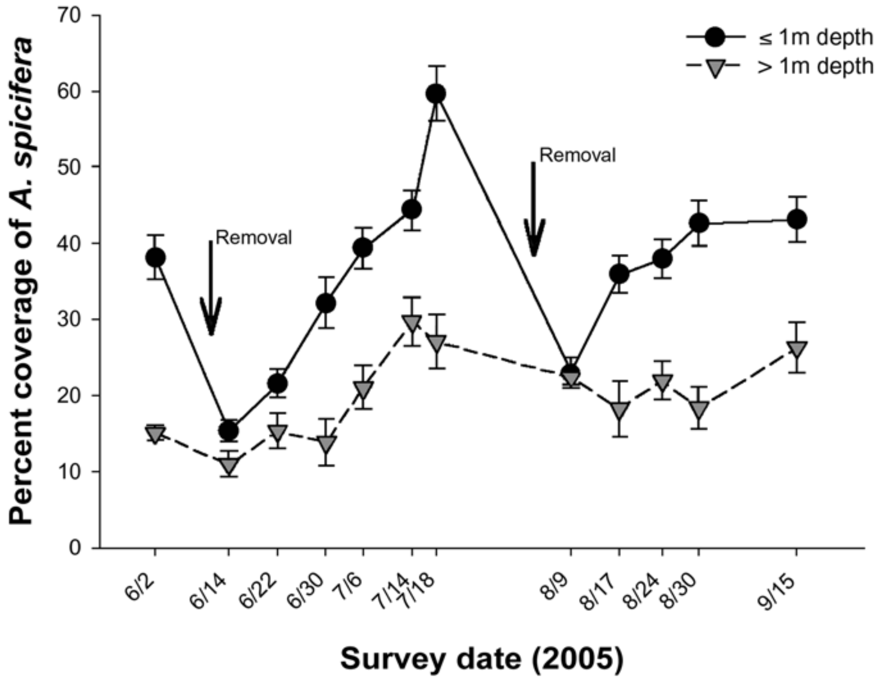

FIGURE 4. Density of *Acanthophora spicifera* after two manual removal events. Data points are mean percentage coverage $\pm$ 1 SE of approximately 300 quadrats dropped along parallel transects in the removal area. The first sampling point represents pre-removal abundance. Arrows indicate onset of removal events. Removal was done manually by pulling off algae close to attachment points and collecting drift algae.

for more than a year, but the individual survives by means of indefinite vegetative development.

Just outside the fishpond, seven intertidal and reef flat surveys were conducted. No established *A. spicifera* was observed. On two occasions, floating fragments were seen outside the fishpond, close to the southern sluice channel. No sexual reproductive structures were seen during the study period.

Manual Removal

Manual removal took less effort in August than in June. In June, initial *A. spicifera* coverage was low (25%) and only some drift algae were present. It took 12.9 min for one person to remove all algae from 1 m^2. In August, there was more drift and higher thallus density. Pre-removal coverage was consequently higher in August (45%), and removal effort was 3.2 min/m^2. Removal yield was about equal in both cases: 0.46 kg/m^2 in June and 0.51 kg/m^2 in August. Weekly density surveys after each removal event showed that *A. spicifera* returned to pre-removal coverage within a month (Figure 4).

(1) Viable thallus length trial: *A. spicifera* was capable of regrowing even after removal with a wire brush. The length of the remaining thalli appeared to have no influence on the initial regrowth rate (Figure 5). When the alga reached a height of around 15 cm, fragments broke off, reducing the average height. Algae from all treatments attained the same average height of 4 cm after 2 months. The number of clones and the number of branches per clone showed no clear difference between the four treatments (data not shown).

(2) Repetitive removal trial: Multiple removals of the same adult plant appeared to limit the rate at which *A. spicifera* regrew, making it a potentially effective removal strat-

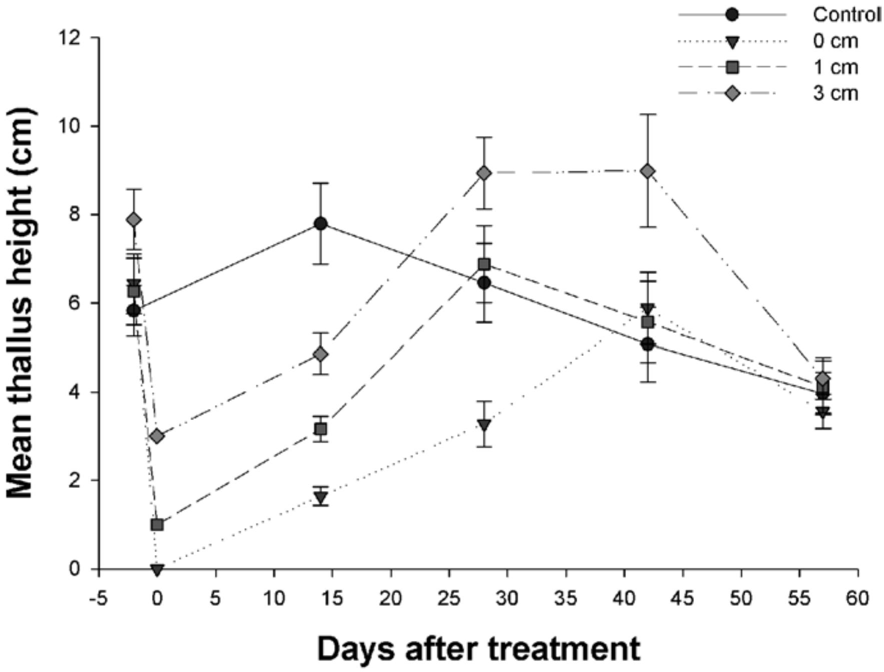

FIGURE 5. Regrowth of *Acanthophora spicifera* after cutting to four initial thallus heights: 0 cm (scraped), 1 cm, 3 cm, control (no removal). First data points represent pretreatment height and are plotted offset for improved visibility. Data are mean heights ± 1 SE of tallest branch per alga, $n = 35$ per treatment. Declines in mean thallus height are due to self-fragmentation.

egy (Figure 6). It also reduced the number of clones over time and reduced the number of branches per clone. The number of repetitive removals was strongly associated with growth rate (Spearman Rank Correlation, $P < 0.0001$, $r = 1.00$, $n = 4$). The number of clones also significantly decreased ($R^2 = 0.59$, $P = .002$), indicating that some of the removed adults did not survive. Repetitively removed algae regrew with significantly fewer branches than the control algae, reducing fragmentation potential (i.e., reproduction) (Mann-Whitney test, W = 133.0, $P = 0.014$, $n = 26$). However, effort was high because all clones needed to be removed as close to the attachment point as possible.

(3) Substrate removal/replacement trial: When attachment points on oyster conglomerates were completely eliminated, it took more than 2 months for *A. spicifera* to reestablish itself on the hard substrate. Even after 9 weeks, percentage coverage was only 7.7% (±2.7 SE), 2.4 times lower than the nearby control site (18.4% ± 2.7 SE). Complete deterrence of adult survival could be effective if no floating fragments can enter the cleared area to prevent new establishment or possibly if the substrate is permanently removed. The initial effort of removing all oysters was, however, very high, and naturally all infaunal species will be destroyed by this method, which makes it a potentially less suitable management strategy.

Shade Experiment

Shading the benthos substantially reduced the height of *A. spicifera*, but after removing the shade cloth algae rapidly regrew. The average thallus height decreased by approximately 1 cm per week after tarpaulin placement and leveled off after 4 weeks at an average of 1.0 cm (±0.1 SE, $n = 4$) compared with an average of 2.4 cm (±0.3 SE, $n = 4$) for the con-

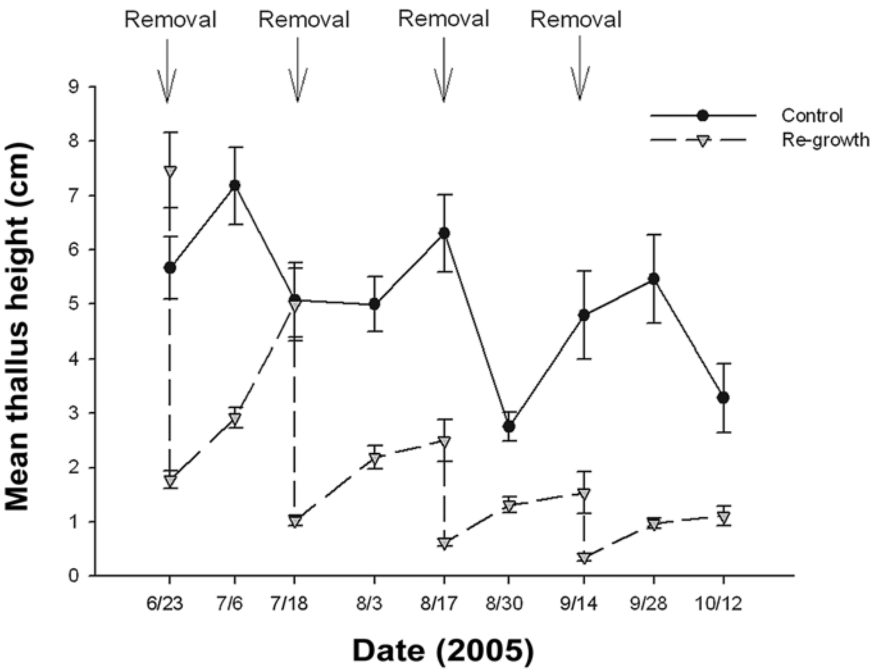

FIGURE 6. Effects of repetitive, manual removal of the same plants on the regrowth of *A. spicifera*. On each removal date, indicated by arrows, data before and directly after removal are shown. Data are average height of tallest branch per alga (± 1 SE) of removed and control algae, $n = 30$ algae.

trol algae (Figure 7). The percentage cover declined from 56.6% (± 5.6 SE) to 1.7% (± 0.8 SE). In addition, when 97% of ambient sunlight was blocked, the algae became shorter and dark in color. Eighteen days after removing the tarpaulin, the algae regrew to an average thallus height of 2.7 cm (± 1.5 SE), and the average percentage cover increased to 6.9% (± 1.0 SE). Light attenuation substantially decreases the thallus density and therefore the fragmentation potential, but the adult clone survived and quickly regrew. Initial effort was medium and thereafter low to maintain.

Biological Control Experiment

The fish population in Kaloko Fishpond was able to substantially lower the abundance of *A. spicifera* around constructed shelters within 2 weeks. The initial mean thallus height of *A. spicifera* across the three *imu* was 4.0 cm (± 0.1 SE, $n = 3$ *imu*) and was reduced to 1.4 cm (± 0.2 SE, $n = 3$) after 2 weeks. After the algae had been cropped, there was a significant difference in the change in thallus height with *imu* location (ANOVA, $F = 4.52$; df $= 18, 2$; $P = .03$) (Figure 8). Fish numbers in the *imu* area (54 m^2 including the four *imu*) varied between 0.5 (*imu* B) and 3.4 (*imu* A) fish per *imu* and included *Abudefduf sordidus* (1.9), *Acanthurus triostegus* (1.5), and Chaetodontidae species (2.4). Species and numbers of fish observed in the *imu* area appeared to be site specific with some movement among different *imu*. Fish numbers differed significantly with *imu* location (ANOVA, $F = 9.86$; df $= 21, 2$; $P = 0.001$). *Acanthophora spicifera* at the control site was grazed upon as well, making it an inappropriate control. The relationship between *imu* location, thallus height, and fish numbers suggests that when herbivores are present, the algae stay in a cropped state. Effort was initially high (building the *imu*) and dropped to a low annual maintenance (restacking twice a year).

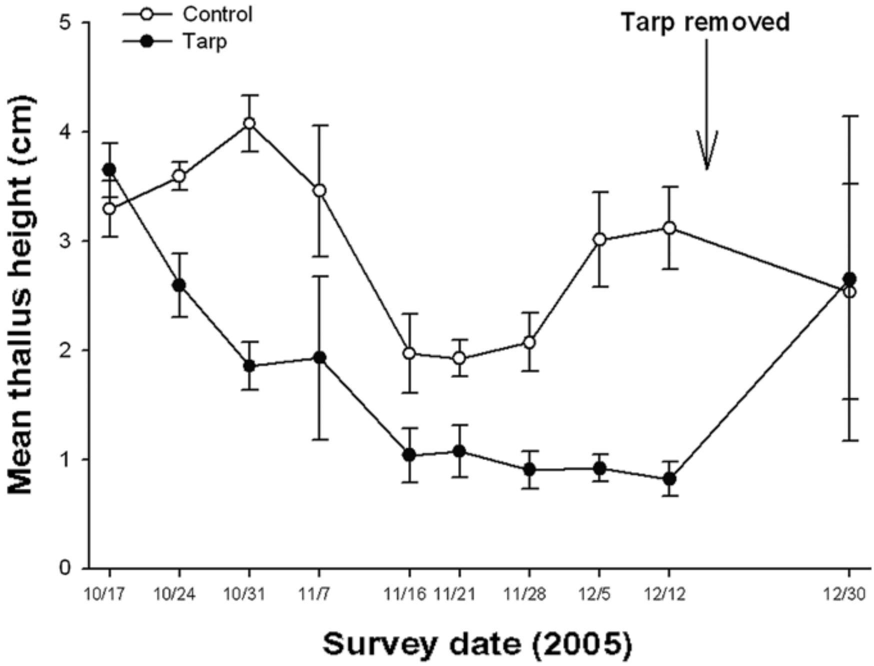

Figure 7. Effect of shading to 3% ambient light on the height of *Acanthophora spicifera*. Data are mean heights $\pm$ 1 SE of tallest branch per alga. Data for first date were collected before shading, arrow indicates removal of shade tarpaulin, and data for last date are the regrowth 18 days later, $n = 4$ trays with 15 algae per tray.

DISCUSSION

Acanthophora spicifera is a very difficult alga to eradicate, but controlling its spread and density may be feasible in Kaloko Fishpond and similar environments. The experiments show that manual removal alone would be extremely labor intensive (1 hr to clear 4.6–18.9 m^2) and also ineffective due to rapid algal regrowth. The alga is abundant on oyster islands that are found in 14% of the 4.5 ha fishpond. This area translates to approximately 330 to 1,350 person-hours to remove all algae in the fishpond. The regrowth rate was approximately 1 cm/week, and plants fragment at heights of around 15 cm, suggesting that removal should occur every 3 months to prevent drift formation and thus recolonization. For this method to be effective, it would require one to three full-time workers constantly removing algae throughout the fishpond, returning to the same area every 3 months. This said, the repetitive removal trial showed a negative relationship between growth rate and number of removals, indicating less effort might be necessary with subsequent removal events, assuming that these can be maintained indefinitely over time. Concentrating removal efforts at different phases of the life cycle (e.g., growth, fragmentation) has proven to be effective for *Caulerpa taxiflora* in terms of reducing adult survival and decreasing the rate of growth (Ruesink and Collado-Vides 2006). However, it appeared that complete eradication has a chance only in the early stage of invasion if all material can be removed to prevent new establishment. For *A. spicifera*, clone removal before the summer and sweeping up fragments and drift after the summer might be more effective and should be explored further. This strategy could make manual removal more feasible in the fishpond by reducing the amount of removal effort neces-

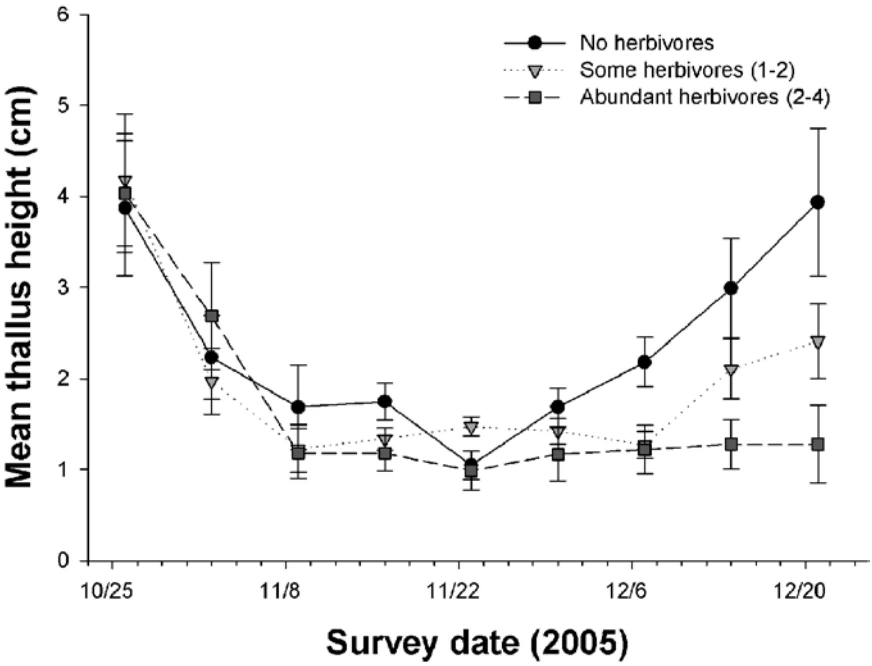

FIGURE 8. Mean thallus height of *Acanthophora spicifera* for each *imu* (stone shelter for herbivores). Data are mean heights ± 1 SE of tallest branch per alga, $n = 3$ trays with 20 algae per tray. Controls not included.

sary. Although high in effort, if combined with rotational shading to reduce initial algal biomass and with the removal of oysters to prevent reattachment, this strategy could lead to a substantial decrease in algal growth. If removal of the primary substrate of *A. spicifera* can be done successfully, it could lead to eradication of this invasive species from the fishpond. However, as a short-term strategy, removal of all oysters is unrealistic.

Algal abundance is influenced by both nutrient availability and herbivory. The combination of high nutrient concentration and low herbivory, as in Kaloko Fishpond, promotes greater increases in algal abundance than an increase in nutrients alone (Burkepile and Hay 2006). Herbivory, therefore, appears to play an important role in preventing tropical macroalgal growth. *Acanthophora spicifera* is a palatable and highly preferred food for herbivorous fishes in Hawai'i (Stimson et al. 2001) and has been found in the mouths of green sea turtles (Russell and Balazs 1994). When refuge was provided in the fishpond, herbivorous fishes appeared to effectively reduce *A. spicifera* biomass. Fishes were able to crop down the long thalli of the alga within 2 weeks and have the potential to keep them in a cropped state. Increasing the herbivore populations sufficiently in the fishpond is, however, a challenge because of the high number of fish predators and the shortage of natural refuges. Relatively few herbivorous fish were seen at the *imu* shelters, and further experiments are necessary to assess fish numbers and the number of shelters that would be necessary to keep *A. spicifera* in a cropped state throughout the fishpond. Some macroalgae species survive digestion by reef fishes (Paya and Santelices 1989). Research is necessary to examine the viability of *A. spicifera* after digestion, because there is a possibility that increased cropping within the pond could be a vector for spread of algae outside the fishpond with the migration of fishes or sea turtles.

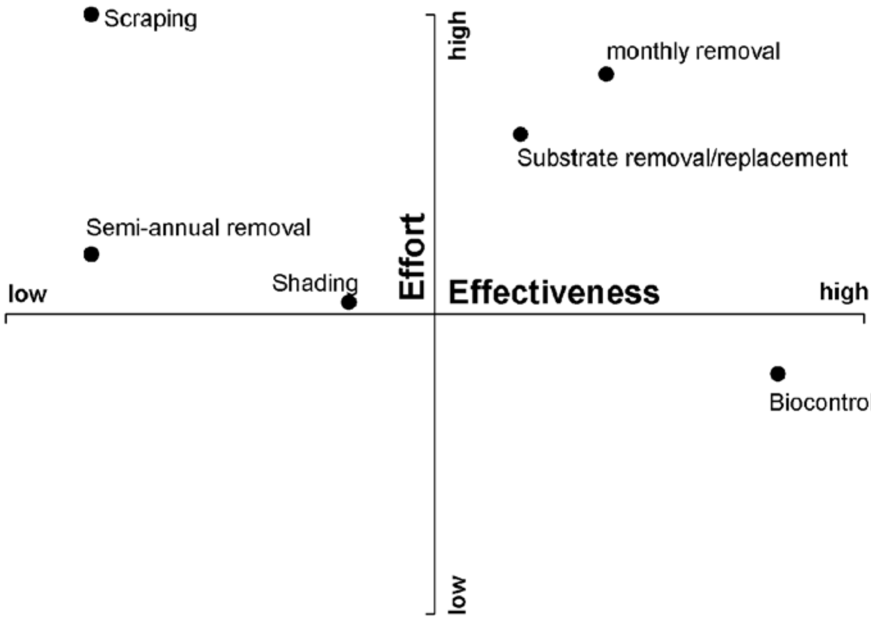

FIGURE 9. Conceptual schematic of *A. spicifera* control efficiency. Efficiency is a function of effectiveness and effort required for various removal techniques. Values are long-term average estimates. Most efficient techniques are those located in the lower right quarter, least efficient in the upper left quarter. "Scraping" refers to the results of the viable thallus length trial, "monthly removal" refers to the results of the repetitive removal trial, and "Semi-annual removal" refers to the results of the manual removal technique.

Chemical treatment by injecting bleach under a large tarp was effective in reducing *Caulerpa taxiflora* (Woodfield and Merkel 2005). Studies with other macroalgae (Smith et al. 2004; J. E. Smith and E. J. Conklin, unpubl. data) have shown mixed results regarding algal resistance to temperature, salinity, and chemical treatments. However, these damaging methods are currently not an option in the national park without comprehensive studies of associated impacts on other aquatic resources.

Efficiency of removal techniques depends on the effectiveness of removal (i.e., is the alga eradicated or, at the least, maintained in a sustained cropped state) and the effort necessary to complete removal. Rates of regrowth varied among the different removal techniques used. Rapid recolonization is probably due to the ability of *A. spicifera* to regrow from even small amounts of residual tissue and the high rate of reproduction. Of the three eradication experiments and the three manual removal trials conducted, five had a low efficiency: *A. spicifera* grew back rapidly or a high number of person-hours was required to complete removal. Only biocontrol through herbivory has the potential for controlling the overall biomass with a reasonable amount of effort. By ranking effectiveness and effort from low to high based on the fieldwork required and the results of the experiments, the efficiency of each method was assessed to help resource managers make decisions on removal strategies (Figure 9). Once removed or controlled it is important that resource managers continue to monitor the persistence of the restored pond biota because recovery of macroalgal assemblages after the removal of an invasive species can be slow (Piazzi and Ceccherelli 2006).

Reducing the distribution and control of the *A. spicifera* in the fishpond could be feasible, albeit initially labor intensive, with repetitive manual removal to decrease the standing crop and drift removal to reduce the "seed" bank. To keep the alga in a controlled state and substantially reduce fragment production, multiple artificial structures (e.g., *imu*) should be placed and periodically maintained to boost herbivore populations. Without the increased grazing pressure that would accompany such structures, it is unlikely that the restored pond biota would persist long after manual removal of *A. spicifera*.

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