Distribution and abundance of *Lingula reevii,* in Kaneohe Bay, Oahu, Hawaii

Cover Photo:
Unique siphon openings formed by *Lingula reevii* burrows.

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Abstract:

The inarticulated brachiopod, *Lingula reevii,* is listed as a NOAA National Marine Fisheries Service Pacific Islands Region Species of Concern (SOC) due to its sharp population decline in the last few decades. *L. reevii* has been observed in the wild in Kaneohe Bay, Oahu, Hawaii, as well as Japan, and Ambon, Indonesia. In 1969, estimates of the *L. reevii* population within Kaneohe Bay were as high as 500 individuals/m^2 in southern sectors of the Bay. Sewage was diverted from southern Kaneohe Bay in 1978-79 and highest densities of *L. reevii* declined to 100 individuals/ m^2 (Emig 1981). Surveys in Kaneohe Bay in 2004 and 2007 yielded even lower population estimates. In 2004, quantitative surveys of approximately 2,950 m^2 yielded a density of 4 *L. reevii*/m^2. In 2007, surveys of 2,420 m^2 found a maximum density estimate of 0.94 *L. reevii*/m^2. The present study, covering 11,600 m^2, found only 919 total *L. reevii* individuals among 32 sites, with the lowest observed maximum density to date of 0.87 *L. reevii*/m^2. However, moderate numbers of *L. reevii* were found at deeper sites at the Sand Bar in the mid-Bay not previously surveyed. There was a significant inverse correlation between invasive alien algae and abundance of *L. reevii*. The continuing decline in *L. reevii* population may be due to the presence of mats of invasive algae covering suitable habitat and/or inhibiting the brachiopods feeding behavior. The current population appears to be a fraction compared to historical levels of *L. reevii* in Kaneohe Bay and may be in need of concerted recovery efforts. The results of this study provide additional information for future conservation efforts for *L. reevii* in Hawaii.

Introduction:

The inarticulated brachiopod *Lingula reevii*, a NOAA National Marine Fisheries Service (NMFS) Pacific Islands Region Species of Concern (SOC), has declined dramatically over the past few decades (Hunter *et al*. 2008). There is a critical need for monitoring to assess population size and to improve our understanding of possible factors for any further decreases in population numbers for this species. Monitoring data will aid the NMFS Pacific Islands Regional Office (PIRO) in determining whether on-the-ground conservation measures (e.g., continued removal of alien/invasive algae from SOC habitats; test reintroductions of captively propagated individuals; controlled breeding trials) may be effective in protecting these species from further declines in Kaneohe Bay, Oahu, Hawaii.

Lingula reevii is a filter-feeding invertebrate that burrows vertically in soft sediment. It has three recorded occurrences: 1) Kaneohe Bay, Oahu, Hawaii; 2) Ambon, Indonesia (Cals and Emig 1979); and 3) Japan (Emig 1997). Past surveys of Kaneohe Bay populations suggested a distinct decrease in abundance following the diversion of sewage effluent from the southern Bay in 1978/1979 (Worcester 1969; Emig 1978, 1981). In 2004, University of Hawaii-Manoa (UHM) students in a field course conducted visual surveys in areas of historical *L. reevii* abundance as well as in areas appearing to have suitable habitat. Approximately 2,950 m^2 were surveyed and a maximum density of 4 *Lingula*/m^2 was observed, a precipitous decrease from previous maximum estimates of 500 individuals/m^2 (Worcester 1969) and 100 individuals/m^2 (Emig 1981). In 2007, students in this UHM field course, partly funded from NMFS PIRO SOC funds, conducted extensive surveys throughout Kaneohe Bay and found that 1) the *L. reevii* population had further declined to a maximum density of 0.94 individuals/m^2, and 2) a shift had occurred in the population to deeper reefs and sandy habitats. Therefore, additional surveys and mapping were conducted in 2008 to determine if the population decline and apparent habitat shift are continuing. This information is necessary for future conservation efforts.

The decline in abundance of *L. reevii* in Kaneohe Bay is likely due to decreased organic enrichment from the sewage discharge diversion that occurred more than three decades ago, as well as the more recent reduction of suitable habitat by the invasion of mat-forming alien algae species (*Gracilaria salicornia*, *Acanthophora spicifera*, *Kappaphycus/Eucheuma* spp.). Alien algae continue to spread, despite efforts to control their growth on targeted reefs in Kaneohe Bay. Currently the State of Hawaii operates a “Super Sucker”, which is an underwater device that removes the invasive alien algae. It is presently unknown how successful this device is at improving habitat for *L. reevii*. Therefore, continued monitoring of population size, and additional manual removal of impinging alien algal over-growth from the vicinity of remaining *L. reevii* individuals are important protective measures.

The goal of this study was to continue the monitoring of *L. reevii* and to quantify the effect of alien algal over-growth on this SOC. Continued monitoring will ultimately provide insight for better management strategies and to encourage their survival in the wild.

Materials and Methods:

Snorkeling surveys were conducted at 32 sites between July 7th and August 8th, 2008, covering a total of 11,600 m^2. Chosen sites included those studied by Worcester (1969) and Emig (1981), sites surveyed in 2004 and 2007 by UHM students, as well as other areas that appeared from aerial photographs of Kaneohe Bay to have sandy habitat suitable for *L. reevii*. Limited SCUBA surveys were used for the first time to survey deeper habitats (>3 m) in the south and mid-Bay.

Two surveying techniques were employed in this study. Of the 32 sites sampled, 26 were surveyed using quantitative belt transects, and 6 sites were sampled by free swim searches (Figure 1).

The following protocol was established for areas surveyed using belt transects. Once an area was selected, a 20 meter transect was laid perpendicular to shore. Five teams consisting of two students each would take their place every five meters along the transect. A compass heading was selected that either ran parallel to shore (fringing reefs), along the isobath (sandbar), or the longest reef diameter (patch reefs). A 50 m transect was then laid by each team following the specific compass heading at each site. Each team recorded the sediment depth, sediment type, and water depth at the beginning and end points of each transect as well as the weather conditions of the day. GPS coordinates were recorded at all beginning and end points of each transect at each site. As determined by Hunter *et al*. (2008), a waiting time of six minutes was allotted for *L. reevii* to reestablish its identifying siphon holes in the event that any disturbance from laying the transects may have caused animals to retract below the sand surface.

The number of *L. reevii* were counted in a total of 100, 1 m^2 quadrats, 50 on each side of the transect. Estimated percent cover for invasive/alien algae *Gracilaria salicornia*, *Kappaphycus/Echeuma* spp., and *Acanthophora spicifera* was also recorded along with a category for clumped mixtures of *G. salicornia/A. spicifera* ("combo"). Percent of "non-suitable substrate," such as coral heads or rubble was also estimated for each quadrat. A total of 119 transects (2 x 50 m) were conducted using this protocol. The sediment types were recorded as qualitative data and classified as silt, fine, medium, or coarse sands. Due to the subjective nature of this type of data gathering, a single person recorded this information at each site to maintain consistency.

Sites that were not surveyed using transects were surveyed using free swim searches for the presence or absence of *L. reevii*. This technique involved using compasses and a selected heading for the group, as 10 snorkelers swam in parallel across the reef. The swimming distance was not specified, but more area was generally covered than in the transect surveys.

For deeper sites beyond snorkeling range (sandbar slopes and Large Dredged Reef), University of Hawaii scientific divers conducted 2 x 25 m transect surveys using SCUBA along isobaths of 3 and 6 meters.

Results:

Overall *Lingula reevii* densities found in the present study were similar to those found in 2007, with a maximum average density of 0.87 individuals/m^2 in areas of suitable habitat (Table 1, Figures 2 and 3). Presence/absence surveys conducted on six selected reefs resulted in three reefs with one to ten *L. reevii* present in low numbers (<10) and three reefs with no *L. reevii* observed (Table 2). The maximum concentration of *L. reevii* observed among the 26 sites was 10 individuals/m^2 at Reef Platform A.

Significant correlations were found between various habitat characteristics (substratum type and alien algae abundance) and the number of *L. reevii* present (Figures 4 – 12). *L. reevii* abundance was positively correlated with the presence of sand (Figures 7 and 8) and negatively correlated with the presence of various alien algae types (Figures 9-12).

A greater number of *L. reevii* were present on reefs with a fine sediment type (Table 2 and Figure 6). However, two-tailed t-tests showed no significant difference between sediment type and number of *L. reevii*. There were no consistent bay-wide significant correlations between sediment depth and the presence of *L. reevii (*Table 6, Figure 13). Two sites (Reef Platform D and Sand Bar Middle A) were found to have significant correlations between water depth and the presence of *L. reevii* (Table 6, Figure 13).

Discussion:

In the past, surveys for *Lingula reevii* in Kaneohe Bay, Oahu, Hawaii, estimated maximum densities as high as 500 individuals/m^2 (Worcester 1969) and 100 individuals/m^2 (Emig 1981). Students in Biology 403 courses at UHM reported a maximum of only 4 individuals/m^2 in 2004 and 0.94 individuals/m^2 in 2007 (Hunter *et al*. 2008). In the present study, *L. reevii* surveys of Kaneohe Bay documented a current average density of 0.079 individuals/m^2, ranging from 0-0.87 individuals/m^2 for any one site. These estimates are not all directly comparable due to differences in data collection techniques such as quadrats, approximations, transects, free swim counts, along with the number of sites surveyed and total area surveyed. Yet, an overall continued decline of *L. reevii* populations in Kaneohe Bay is still apparent.

The data collection technique used here consisted of visually surveying a total of 26 sites via quantitative transects which amounted to a total area of 11,600 m^2, plus six presence/absence free swim surveys. It should be noted that the *L. reevii* found at these latter six sites were not included in the average density value of 0.079 individuals/m^2. Sites were chosen based on the previously surveyed areas in past studies, in addition to areas that appeared to have suitable habitat. *Lingula reevii* typically live in fine sandy areas, though they are known to occur in a variety of sediment types (Worcester 1969).

The Sand Bar 1 site was one such location that was surveyed in 2004 and 2007 due to its abundance of sandy habitat. Although sandy habitats were abundant north of Sand Bar 1, this marked the northernmost site of data collection in our study for several reasons. First, the historical literature suggested that *L. reevii* were abundant only in the southern sector (Worcester 1969), although our data indicated otherwise at sites such as Sand Bar Middle C. Here, there was an abundance of *L. reevii* comparable to that in the southern region of the Bay. Secondly, limited time, resources, and manpower restricted the overall area covered. Therefore, priority was given to those locations that had been surveyed in past studies, allowing for an up to date record of *L. reevii* abundance in these areas. Finally, although the northernmost part of the Bay had sandy habitats, surveying was avoided due to health and safety warnings of bacterial contamination, which closed the beaches and their surrounding waters (Leone 2006). Therefore, potentially suitable habitats in northern Kaneohe Bay were not surveyed but could be valuable for future studies to investigate.

Given that sandy habitats largely determined the abundances of *L. reevii* at different locations, we recorded the sediment type, sediment depth, and water depth at each of our sites in order to characterize the environmental conditions. The sediment type results indicated that the majority of *L. reevii* were found in fine sand. However, a two-tailed t-test with unequal variances showed there was not a significant difference when compared to the number of *L. reevii* found in the sediment types. It is important to note that *L. reevii* abundances were not distributed equally over the various sites. Thus, although a high percentage of *L. reevii* may have been found at sites with fine sediment, the majority of these were concentrated in only two of the sites (Reef Platform A and Large Dredged Reef). Due to this difference in population densities, statistical analyses resulted in no significant differences between sediment types. Further sampling may conclude a significant correlation between sediment type and the number of *L. reevii*. The variance found in this study was in accordance with Worcester's 1969 observation that the sediments in which *L. reevii* are found in Kaneohe Bay are varied.

The results for sediment and water depth also exemplified the variation in habitat suitable for *L. reevii*. The sediment depth did not have a significant effect on the number of *L. reevii* found. However, the relationship between the two varied. Some of the sites had a positive correlation and some had a negative correlation, meaning *L. reevii* abundance both increased and decreased with increasing sediment depth.

Water depth was even more variable than sediment depth with only two survey sites showing significant correlations with *L. reevii* abundance: Reef Platform D and Sand Bar Middle A. Reef Platform D showed a negative correlation while Sand Bar Middle A showed a positive correlation with water depth. All other sites were found to be not significant with seven being negatively correlated and nine of them positively correlated.

To further characterize the sites, data were recorded on the type and percent cover of alien algae vs. sand and the percent cover of non-suitable substrates (NSS). Instead of examining each of the 26 sites individually, we organized the alien algae percent cover from the total area surveyed into categories of percent cover (such as 51+%, 26-50%, 11-25%, etc.) and related it to the total number of *L. reevii* found. In this way any slight inconsistencies in data collection due to the approximate nature of percent cover were reduced. It also ameliorated any inconsistencies that may have resulted from minor variations in data reporting among the ten individual surveyors.

The abundance of *Gracilaria salicornia, Acanthophora spicifiera,* and *Kappaphycus* spp. had a significant negative relationship to the number of *L. reevii* found**.** Furthermore, there was a significant positive correlation between percent cover of sand to number of *L. reevii* present. These findings indicate that the rapid spread of alien algae over Kaneohe Bay (Rogers and Cox 1999; Conklin and Smith 2005) may be encroaching on *L. reevii* habitat and that it could be responsible for the decrease in average density over the past several years.

There are several possible explanations for this trend. First, the alien algae taking over the preferred habitats and blocking water flow over the three siphonal openings could ultimately cause the decrease in average *L. reevii* density. This would, in turn, prevent the *L. reevii* from effectively feeding on the plankton in the water column. Secondly, just as when humans swim over or touch the sediment near a *L. reevii* burrow, alien algae mats may continually “startle” the *L. reevii* back under the sand. Finally, *L. reevii* fertilize externally with their gametes being broadcast into the water column (Hyman 1959). If there are mats of alien algae covering *L. reevii*, then the release of their gametes could be repressed and inhibit the fertilization process.

It should be noted that although these alien algae species seemed to interfere with *L. reevii*’s habitat, not all marine plants did. At the Sand Bar sites we documented abundances of the native Hawaiian seagrass, *Halophila hawaiiensis,* with patchy distributions in areas of notable abundances of *L. reevii.* We observed *L. reevii* burrows in the thick of these native plant meadows. Snorkelers as well as divers noted these trends at depths from 0.5-8 m.

SCUBA was used in the 2008 surveys as a new tool to survey certain sites in addition to snorkeling. SCUBA allowed us to survey sandy areas that are at deeper depths (e.g., Small Dredge Reef, Large Dredge Reef, Reef 15, Sand Bar 1, and Sand Bar Middle A). We found *L. reevii* at depths to (but not beyond) 8 m, which gives future studies incentive to investigate other areas where there may be sandy slopes or deeper sand patches. Documenting these suitable habitats in deeper depths adds to the known habitat range of *L. reevii* throughout Kaneohe Bay.

Conclusions:

That approximately 40 years ago, *Lingula reevii* was present in the hundreds per square meter in Kaneohe Bay, compared to less than one per square meter at present, suggests that there need to be steps taken to conserve and monitor this species of concern. *L. reevii* still occurs throughout the south and mid-Bay, and may be increasing its habitat range on the deeper slopes of the Sand Bar, but potential overgrowth by alien algae throughout most of its range in the Bay remains a current threat.

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Table 1 – Historical comparisons of *Lingula reevii* densities studied in Kaneohe Bay, Oahu, Hawaii.

Number of Sites	Author	Year	Max Avg Density / m^2		Total Area*
2	Worchester	1969	500		N/A
N/A	Emig	1981	100		N/A
20	UHM	2004	4		2,950 m^2
17	UHM	2007	0.94		2,420 m^2
26	UHM	2008	0.87		11,600 m^2

*Computed differently in each study

Table 2 – Presence/absence surveys conducted on select reefs around Kaneohe Bay. “Presence” indicates the recording of 1-10 individuals for the entire site.

Reef	***L. reevii***
Patch Reef 8	Absent
Patch Reef 14	Absent
Sandbar 2	Absent
Coconut 12	Present
Coconut 13	Present
Reef Platform H	Present

Table 3 – Number of *L. reevii* and dominant sediment type at each survey site. Area surveyed was 500 m^2 for each site except for Small and Large Dredge Reef (100 m^2) and Sandbar Middle B (100 m^2).

Reef	***L. reevii (#)***	**Conditions**	**Reef**	***L. reevii (#)***	**Conditions**
Reef Platform A	435	Fine Sand	Goby Bay	1	Fine Sand
Reef Platform B	31	Silt	Patch Reef 3	2	Medium
Reef Platform C	83	Silt	Patch Reef 5	1	Fine Sand
Reef Platform D	18	Fine Sand	Patch Reef 25	0	Medium
Reef Platform E	15	Fine Sand	Patch Reef 4	3	Fine Sand
Reef Platform F	19	Fine Sand	Patch Reef 7	0	Fine Sand
Reef Platform I (North)	0	Coarse Sand	Patch Reef 15	18	Medium Sand
Reef Platform I (South)	0	Silt	Sandbar 1	5	Medium Sand
Reef Platform J	2	Silt	Sandbar Middle A	75	Fine Sand
Reef Platform K	1	Coarse Sand	Sandbar Middle B	27	Medium Sand
Reef Platform L (North)	2	Coarse Sand	Sandbar Middle C	11	Coarse Sand
Reef Platform L (South)	0	Fine Sand	Small Dredge Reef	4	Fine Sand
Reef Platform M	1	Silt	Large Dredge Reef	165	Fine Sand
			Total *L. reevii*:	919	
			Avg density over all transects:	0.079 *L. reevii*/m^2	

Table 4 – Total *L. reevii* in the presence of differing amounts of alien algae across various reef transects around Kaneohe Bay.

***G. salicornia* (%)**	***L. reevii* (#)**	***A. spicifera* (%)**	***L. reevii* (#)**	***A. spicifera/G. salicornia* mixture (%)**	***L. reevii* (#)**
51 +	0	51 +	0	51 +	9
26 - 50	1	26 - 50	2	26 - 50	25
11 - 25	4	11 - 25	7	11 - 25	46
1 - 10	26	1 - 10	21	1 - 10	38
0	888	0	889	0	801

Table 5 – Total *L. reevii* in the presence of differing amounts of alien algae and sand across various reef transects around Kaneohe Bay

Sand (%)	***L. reevii* (#)**	***Kappaphycus spp.* (%)**	***L. reevii* (#)**
51 +	896	51 +	0
26 - 50	17	26 - 50	0
11 - 25	5	11 - 25	0
1 - 10	1	1 - 10	1
0	0	0	918

Table 6 - Correlations between abundance of *L. reevii* with sediment depth and water depth.

Reef	Correlation Coefficient (Sediment Depth)	Correlation Coefficient (Water Depth)
Reef Platform A	-0.867257187	-0.44813572
Reef Platform B	-0.731308579	0.922612906
Reef Platform C	-0.092251551	0.485661864
Reef Platform D	-0.582954104	-0.88130326
Reef Platform E	0.753279751	-0.82971598
Reef Platform F	-0.754171693	0.133630621
Reef Platform J	-1.98762E-17	-0.40347887
Reef Platform K	-0.332105582	0.133630621
Reef Platform M	0.375	-0.75666881
Reef Platform L (N)	-0.702189968	-0.06784934
Goby Bay	0.250801027	-0.33253109
Patch Reef 3	-0.47304679	-0.52910672
Patch Reef 4	-0.28396507	0.224166643
Patch Reef 5	-0.696022273	0.058874481
Sandbar 1	0.135085807	0.449004914
Sandbar Middle A	0.451375535	0.99949052
Sandbar Middle B	-0.837062414	0.638316332
Sandbar Middle C	-0.238474939	-0.52216262

Figure 1. Sites in Kaneohe Bay at which numbers of *Lingula reevii* were estimated from 100 m^2 quadrats per transect. A total 11,600 m^2 of reef area were surveyed at 26 sites. Patch reef numbers are from Roy (1970).

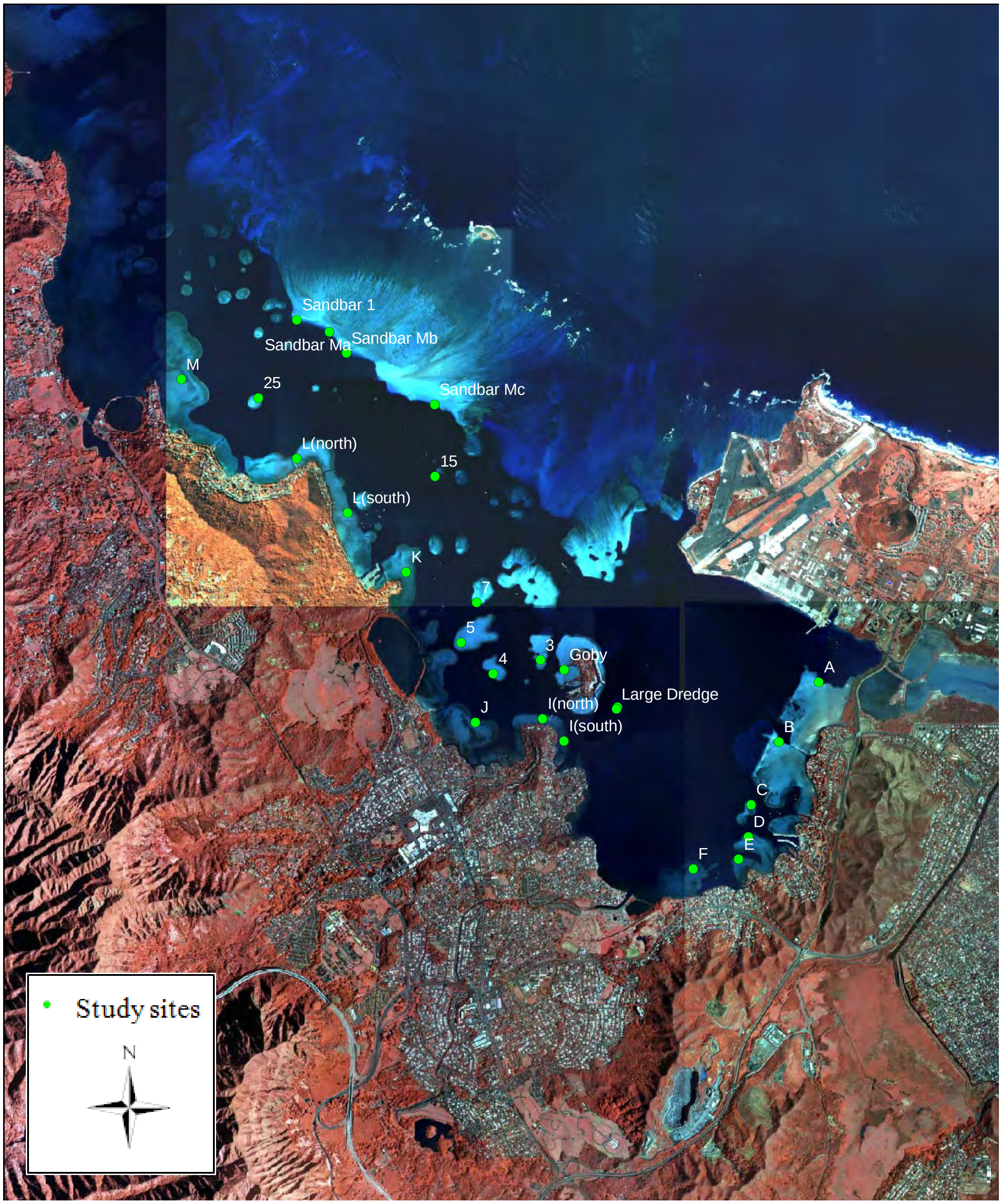

Figure 2: Total *Lingula reevii* found at 22 sites surveyed in 2008; each represents the total found in five, 2 m x 50 m transects (500 m^2). The counts for Small Dredge Reef, Large Dredge Reef, Sandbar Middle B and Reef Platform 15 were not included since either fewer than five transects and/or shorter than 50 meters were surveyed.

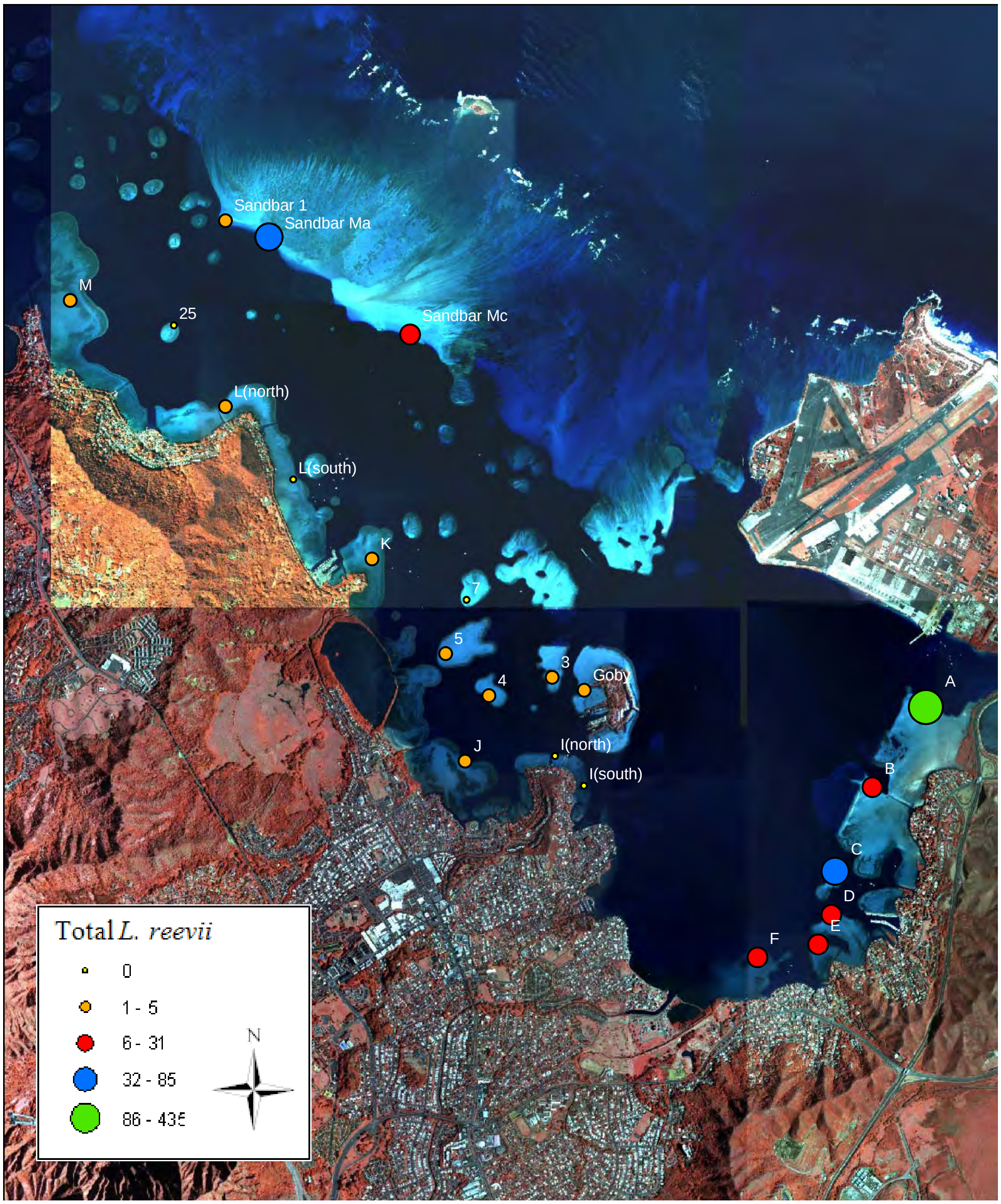

Figure 3: Average *Lingula reevii* per m^2 at 26 sites surveyed in 2008.

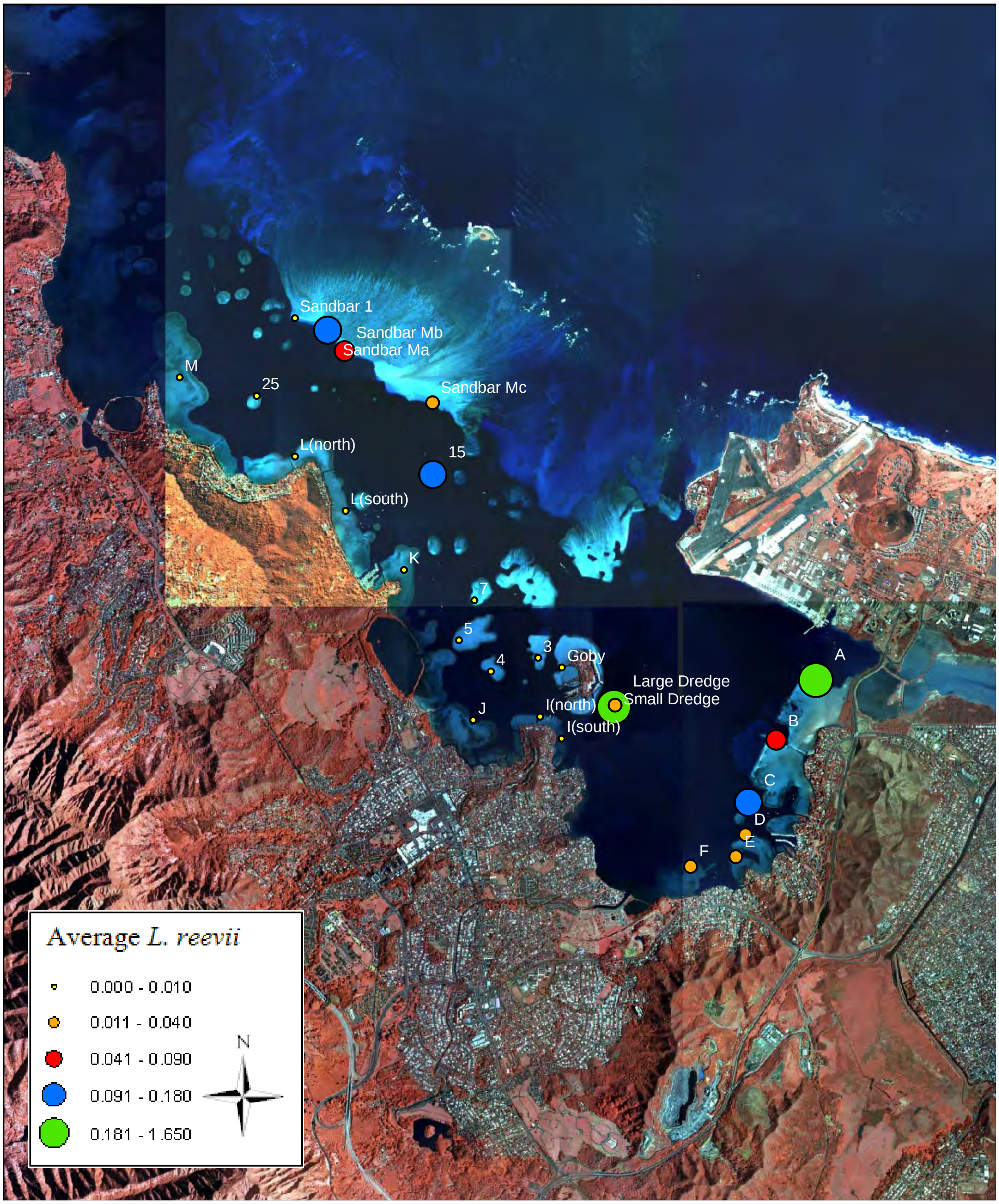

Figure 4: Percent cover of the benthic community at the 26 survey sites, including alien algae (*Kappaphycus spp.*, *Gracilaria salicornia*, *Acanthophora spicifera*, and *G. salicornia*/*A. spicifera mats)*, non-suitable substrate (coral, rubble, and non-invasive algae), and suitable substrate (sand).

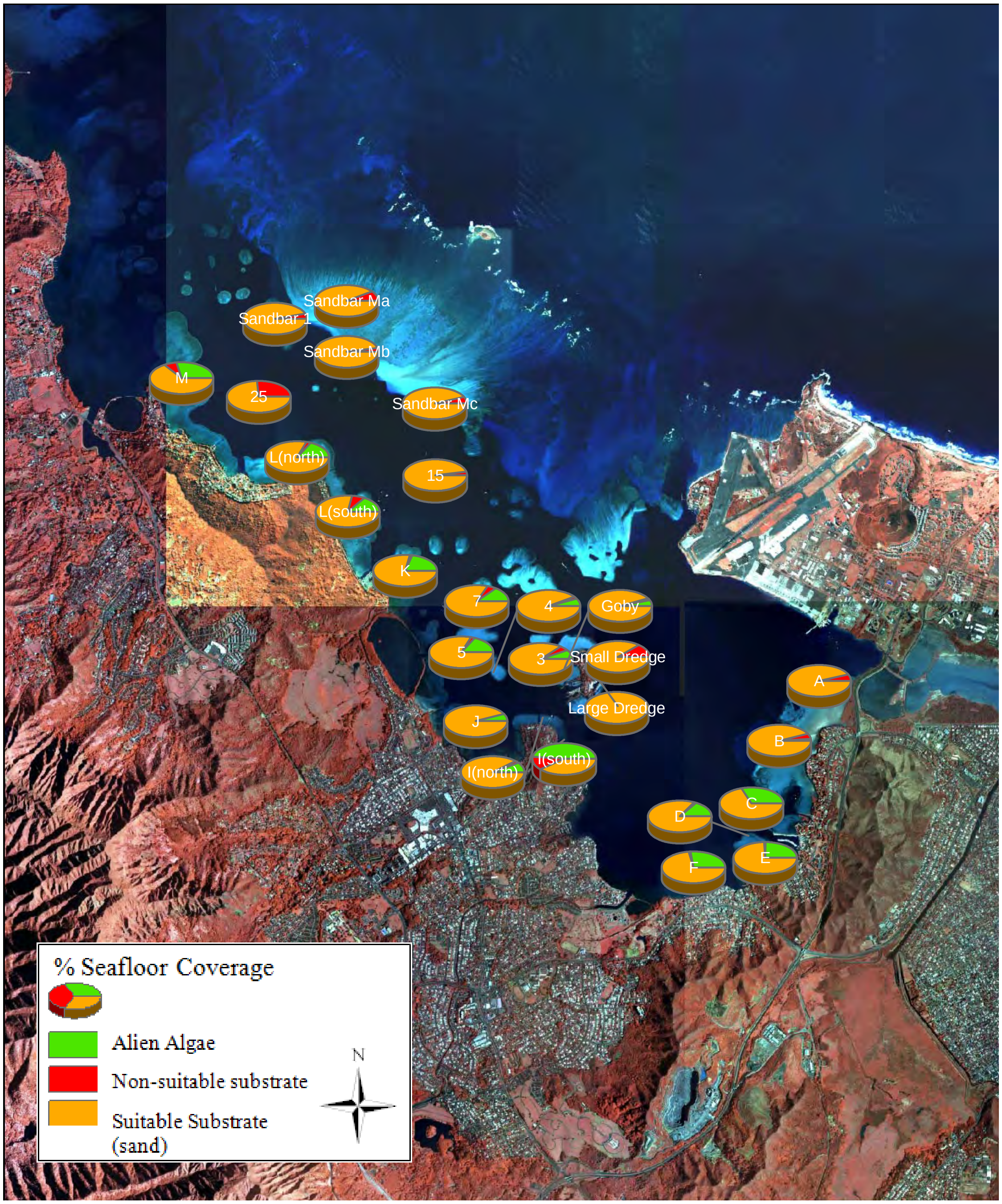

Figure 5: Percent cover of the alien algae (*Kappaphycus spp.*, *Gracilaria salicornia*, *Acanthophora spicifera*, and *G. salicornia*/*A. spicifera mats)* surveyed at *Lingula reevii* sites. Note that Sandbar 1, Sandbar Middle A, Sandbar Middle C, Small Dredge Reef, and Large Dredge Reef had no alien algae present.

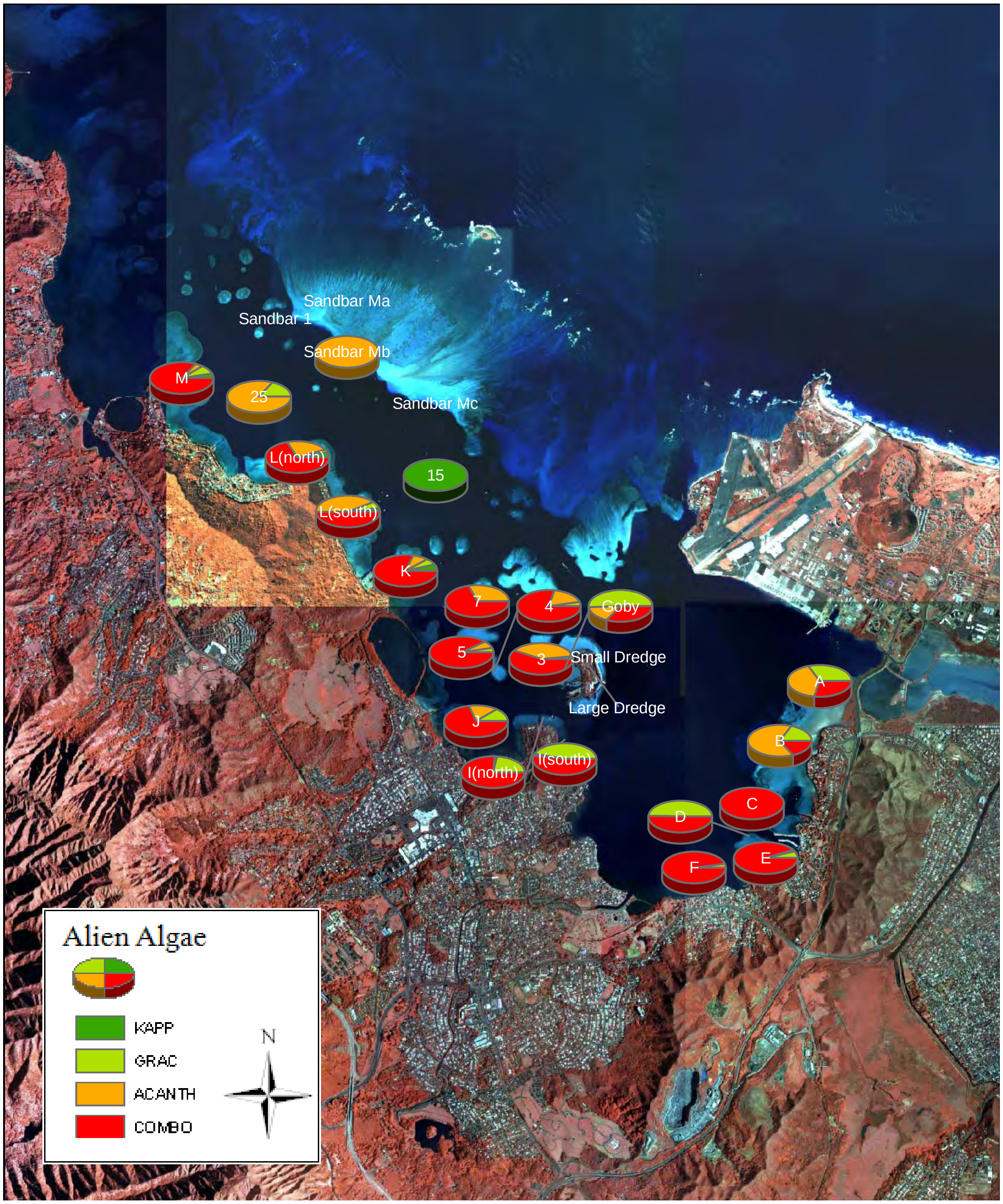

Figure 6. Number of *L. reevii* found in various sediment types at 26 sites in Kaneohe Bay.

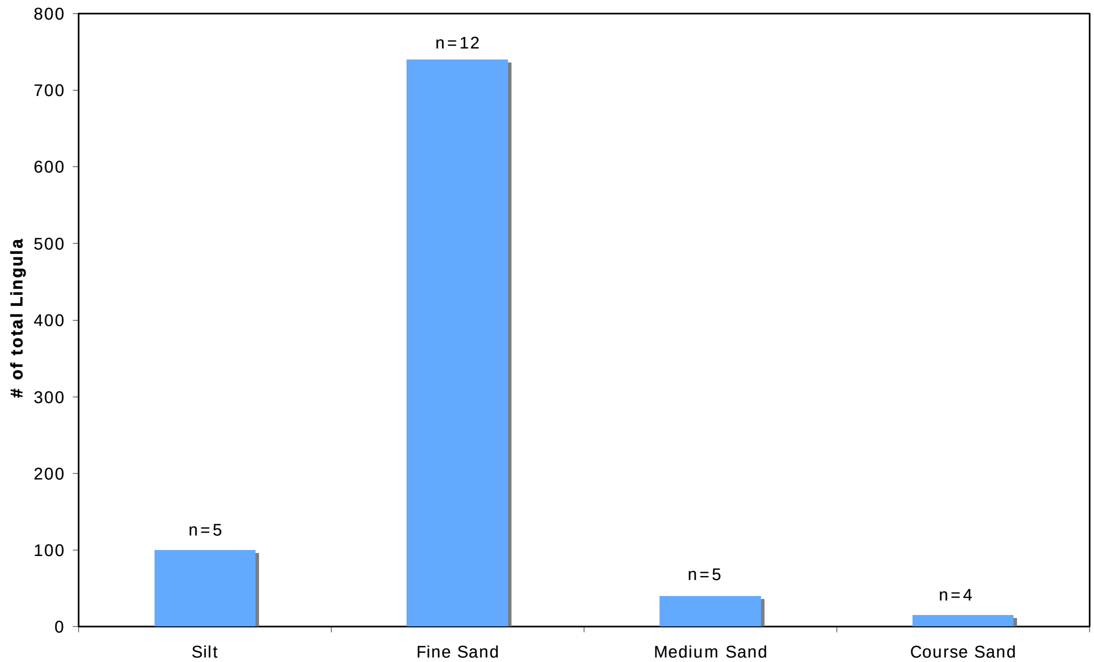

Figure 7. Relationship between percent cover of sand and abundance of *L. reevii* at 26 survey sites.

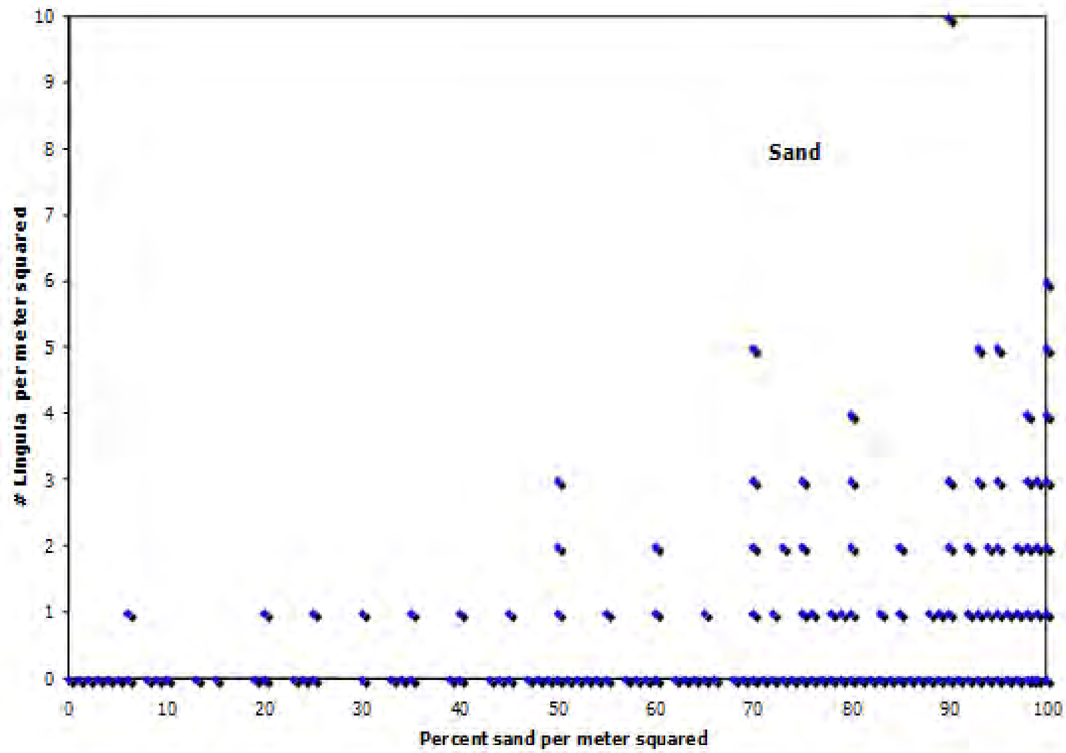

Figure 8. Relationship between percent cover of non-suitable substratum (coral, course rubble) and abundance of *L. reevii* at 26 survey sites.

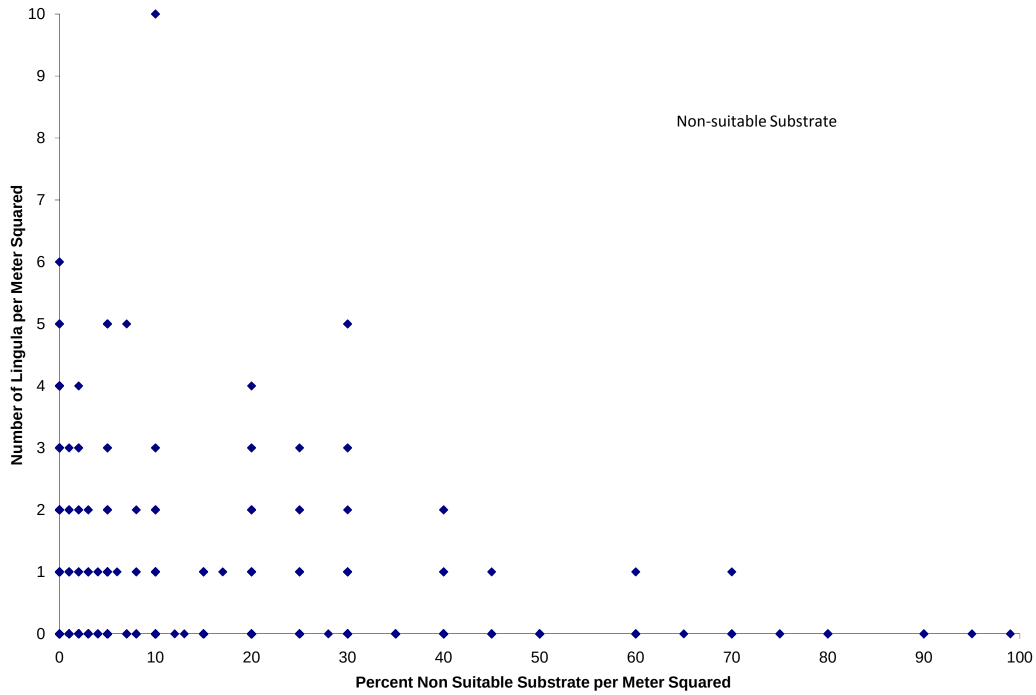

Figure 9. Relationship between percent cover of *Gracilaria salicornia* and abundance of *L. reevii* at 26 survey sites.

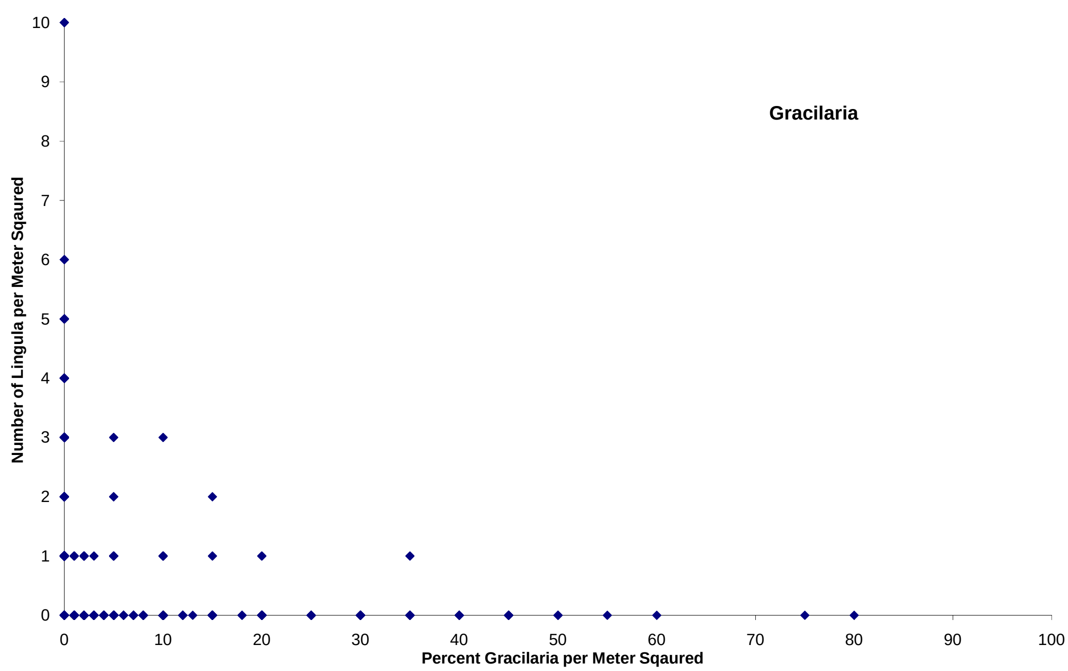

Figure 10. Relationship between percent cover of *Kappaphycus spp.* and abundance of *L. reevii* at 26 survey sites.

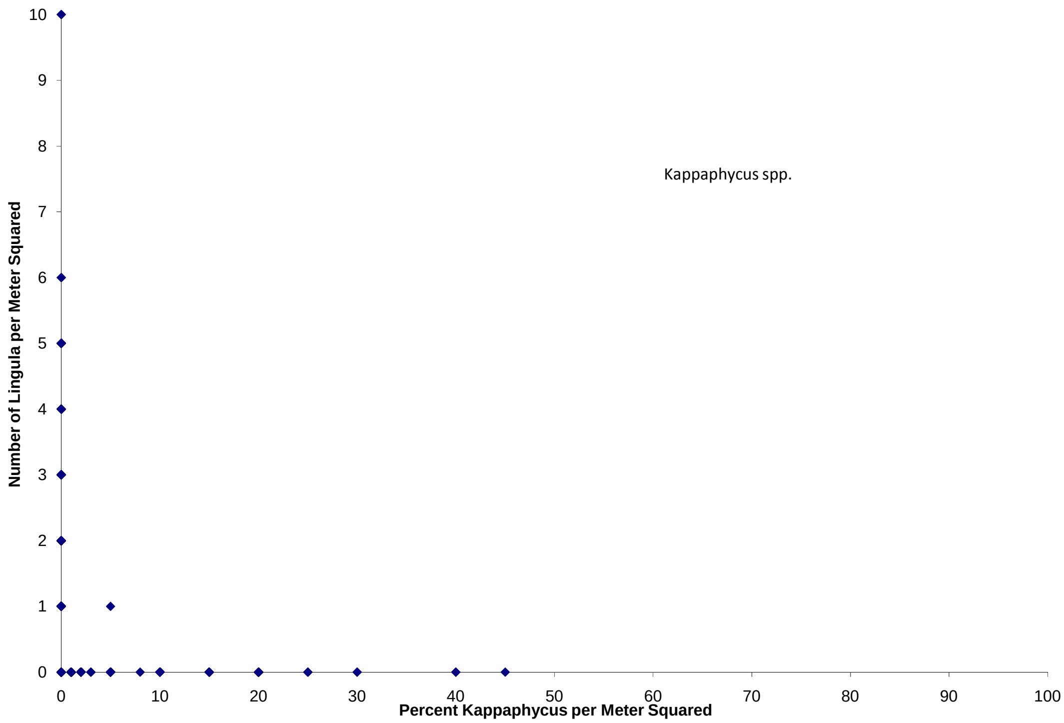

Figure 11. Relationship between percent cover of *Acanthophora spicifera* and abundance of *L. reevii* at 26 survey sites.

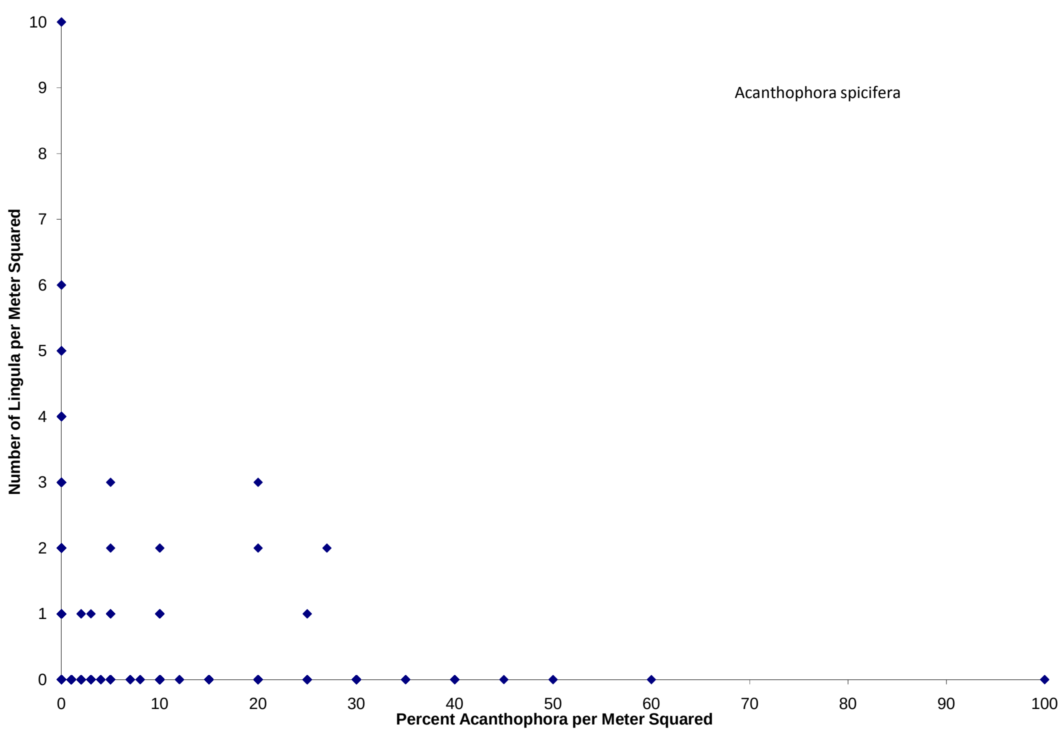

Figure 12. Relationship between percent cover of total alien algae and abundance of *L. reevii* at 26 survey sites.

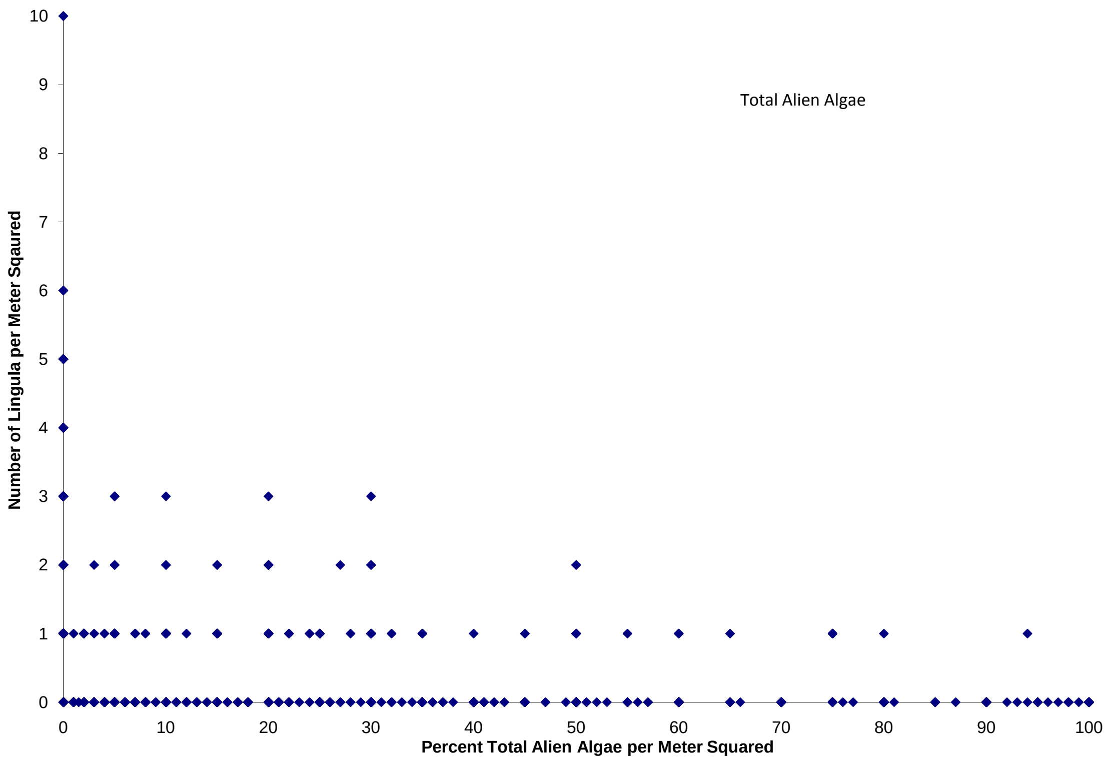

Figure 13. Comparison of average water and sediment depth to the number of *L. reevii* at selected reef sites around Kaneohe Bay, Oahu HI.