Using Underwater Sound to Measure
Biodiversity and Productivity in the Line Islands

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Abstract

In order to create a more complete description of coral reef habitats for use in conservation, this study aims to develop acoustic indices for biodiversity and productivity. Qualitative analysis, sound pressure levels, biological sound signal detection, and spectral variability in recorded underwater sound combine to give detail on coral reefs in Washington Island, Kiritimati Island, and Palmyra Atoll. Qualitative analysis and sound pressure level correlate strongly with biomass and biodiversity in the island reefs, and sound pressure and spectral variabilities give insight into the type and number of marine animals in each habitat. These measurements show evidence of a fishing gradient along the Pacific Line Islands and help create an aesthetic definition of coral reef health and biodiversity.

Introduction

Biodiversity measurements are of great value to conservationists. With species indices, genetic variability tests, and habitat variability assessments, conservationists can identify areas of ecological importance that should be protected. Erosion of biodiversity increases at an alarming rate, and scientists struggle to find ways of demonstrating the need for conservation (Pearce). One method for changing governmental and popular perceptions about natural resources has been through stressing the economic value of conservation. This technique must be coupled with a more aesthetic approach to raising awareness of biodiversity. Museums, educational outreach programs, and recreational parks help connect people to nature, but scientific research uses a definition of biodiversity that does not account for the emotional aspect of ecology.

An aesthetic definition of biodiversity should encompass all the sensory input from the environment, but my expertise as a sound engineer focuses my project on the acoustic component of aesthetics. Acoustic diversity has been hypothesized to correlate to traditional definitions of biodiversity in many ways. The soundscape, or acoustic signature of a habitat, can be divided into two elements: keynotes, or background sounds, and sound signals, or foreground sounds intended to attract attention (Wrightson, 2000). In a marine ecosystem, keynotes could include seismic activity, tidal action, and wave events. A definition of acoustic biodiversity would use keynotes to determine habitat variability. Sound signals would be a measure of speciosity; the niche hypothesis of animal vocalization suggests that sounds from each type of animal occupy specific sound frequencies at specific times (Krause, 1987). A recent literature review of marine sound production indicates that size, sex, and specie can be determined from fish sound characteristics (Amorim, 2005). Oceanic sonic niches might indicate a temporal and spectral acoustic variability in areas that are diverse.

Little scientific work has been done on bioacoustic diversity, especially in the ocean. Although sound communication in many specific marine animals is well-documented, acoustic diversity as a whole is relatively unknown. Biological underwater noises often exhibit fewer differences than terrestrial noises (Amorim, 2005), making diversity harder to examine. However, direct acoustic monitoring (rather than sonar techniques) has been used to estimate fish populations (Lobel, 1992) and quantify river disturbance (Joo et al., 2005). In the Joo et al. study, acoustic intensity measurements found significant spectral differences in disturbed and undisturbed sites.

The aim of this project is to define reliable indices for acoustic biodiversity in the ocean and test it using a gradient of human interaction along habitats. In this study, acoustic biodiversity is defined as the variability of spectral and sound pressure levels over time. In particular, spectral variability is the number of 20-Hz frequency bands significantly above oceanic keynotes and corresponds to the speciosity measurement in biodiversity. Sound pressure variability is comprised of two measurements: the abundance of sound signals, which corresponds to population estimation, and intensity averages, which correspond to habitat variability. Combined with qualitative analyses, these data could provide an acoustic description of coral reefs near the Pacific Line Islands and can be correlated with biomass and biodiversity levels collected in concurrent Line Island studies (Rego et al., 2007 and Vichit-Vadakan et al., 2007). Since biodiversity and biomass are good indicators of habitat health (Leigh, 1965), the accuracy of this acoustic approach in assessing coral reef environment health can be determined.

The application of aesthetic, musical analysis techniques on recorded underwater sound could produce an index of acoustic biodiversity on which measurements increase along the Line Islands from Washington Island to Kiritimati Island to the Palmyra Atoll. The fishing gradient along these islands mentioned studied Stevenson et al. supports this hypothesis: Washington Island, with an estimated population of 2100, has a very small reef area, while Kiritimati Island has a population of 8,000 but a much larger fishing region. Palmyra, a nature reserve privately owned for the last 100 years, has the least fishing pressure of the islands. The total biomass levels of reef animals increase as the fishing gradient decreases (Rego et al., 2007 and Vichit-Vadakan et al., 2007). Rego et al. also show an increase in Shannon-Wiener biodiversity, although they only studied apex predators, which we could see as an increase in some of our spectral and sound pressure variability indices in the soundscapes of the different reef habitats.

Materials and Methods

We chose sample sites similar to the backreef areas studied by Stevenson et al. and Rego et al. Due to time constraints, we had different numbers of recording sites at each island: six at Kiritimati, four at Washington, and three at Palmyra (Figure 1).

Equipment Used:

- HTI-96-MIN hydrophone with pre-amp
- MAudio Microtrack 24/96 Professional 2-Channel Mobile Digital Recorder
- Audacity, Praat, and Java Eclipse software for data analysis

We first conducted proof-of-concept analyses on music to set the parameters of our data analysis software. Two songs were picked, one with the high spectral and loudness variability of 80s synthesizer pop, and one with the low variability of acoustic and slide guitars. Once we calibrated the sensitivity to the scale of musical variability, the synthesizer pop song showed more acoustic diversity than the guitar song in all of our indices.

Sample collection started at Kiritimati Island and continued to Washington and Palmyra. At each sample site, we recorded three to five minutes at a 44.1 kHz sampling rate. We could not replicate recordings at the sites during different times of the day, because our time was limited. Because reef sounds generally increase from low levels in the day to high levels in the evening and at night (McCauley et al., 2000), the time of day variability added an extra independence in our data that we could not account for through replication. Although point transects are less efficient than line transects in sampling numbers of individuals in coral reefs (Bortone et al., 1989), we chose the point recording method so the hydrophone would not be dragged through the water and pick up turbulent noise. We placed the hydrophone at one meter depths at each site and measured depth with a transect tape. In addition to collecting audio data, we estimated sea state conditions using the Beaufort Scale of Wind Force (Wenz, 1962) to aid in the differentiation of keynotes and sound signals.

Sample processing started with inverse filtering to reduce the response bias of the specific hydrophone and recorder used. Using Audacity (audacity.sourceforge.net), we reduced each recording’s low frequency levels in accordance with the HTI-96-MIN specifications given by the manufacturer (High Tech, Inc.). Further filtering was not needed due to the flat frequency response of the MAudio Microtrack (M-Audio). Because our hydrophone was very sensitive, periods of time with strong currents created clipping, so we edited these parts from the audio. The remainder of the sample processing was completed in Praat (www.fon.hum.uva.nl/praat). We measured intensity level, or loudness, for each recording. We then created spectrograms to identify frequency changes over time. All spectral processing used 20-Hz frequency bins as a compromise between data storage size, processing time, and spectral resolution. We also converted the sound files from waveform audio format, .wav, into bitwise representations for easy analysis in Java. Finally, we constructed oceanographic noise level filters based on each observed sea state condition using standard ocean ambient noise formulae (Wenz, 1962) (Figure 2).

Because perception of acoustic aesthetic is influenced almost entirely by music, we modeled our acoustic biodiversity measuring tools after established musical analysis techniques: qualitative analysis, total intensity comparison between islands, comparison of the number of biological sound signals, and measures of spectral variation from background noise.

Qualitatively, we listened to each recording and noted what biological sounds we heard. We classified the different types of calls with a general description, such as groan, chirp, or pop, and calculated calls per minute for each site to account for the variability in length of recording. Although it was sometimes difficult to distinguish water turbidity, noise from snorkelers or nearby ships, and wildlife sound, I have heard many different underwater sounds prior to this study, such as snapping shrimp and various fish calls on the internet, and know what to listen for. We then used the Pearson product-moment correlation coefficient to compare number of calls to the sum of fish biomass levels measured by Rego et al., and Vichit-Vadakan et al., and apex predator fish biodiversities measured by Rego et al.

We measured intensity decibels and calculated a moving average intensity for each island. By using a moving average, we could account for having varying times of recording; we used midway between afternoon and sunset as the base time for the moving average. These averages were then normalized with the ocean noise filters so variability in sea surface conditions would not affect our results. We then used correlation to compare intensities to fish biomass and biodiversity levels.

We measured biological sound signals using note-onset detection. In musical analysis, note onsets occur when a note is played in a song, and a musical note equates to a biological sound signal in acoustic diversity. So, a program that counts the number of piano notes played in a song would be similar to a program that counts how many wildlife calls occur in a marine habitat. We used Eclipse (www.eclipse.org) to program note onset detection using a thresholding technique described in Bello et al, 1998. The tool monitors the sound level of the recording, and when the intensity rises significantly above the average, the number of biological sound signals is incremented. We ran this tool over each recording to find number of signals per minute, calculated a moving average for the number of biological sound signals for each island, and used correlation to compare with fish biomass and biodiversity levels.

We measured spectral variation using spectrograms and baseline ocean noise calculations. A complex method of spectral variation measurement is outlined in Berenzweig et al., 2004 using probability distributions, but we chose a simpler method in order to acquire the experience of making our own. Our program counts the number of

20-Hz frequency bands that, at some point in the audio stream, rise significantly above the average for that frequency. For example, suppose ocean noise at 420 Hz given by Wenz is 70 dB. In the spectrogram of a site's recording, we monitor the intensity of 420 Hz over time, and if is ever far above 70 dB, we assume this frequency is a niche occupied by some specie of animal. We associate a large number of frequency bands above their ambient noise levels with a high diversity of sound production, and this accompanies a high speciosity. We calculated frequency distribution for each recording's spectrogram, averaged the number of frequencies found, and used correlation to compare with fish biomass and biodiversity levels. Because we would not expect speciosity to increase as sunset approached, we assumed a moving average was not necessary.

Results

Qualitative analysis demonstrated an abundance of biological sound calls in all of the recordings. Sounds such as pops, grunts, purrs, crunches, and chirps were heard as distinct sound events; the event clarity is shown with a spectrogram in Figure 3. We noted similarity between the types of calls made on the different island reefs, although Washington had many more pops than Kiritimati and Palmyra, and Palmyra had very few. Palmyra exhibited loud crunching and cracking noises heard only faintly on the other islands. Figure 4 illustrates the number of calls per minute from each recording, excluding the crunches and pops, which were much more frequent than any other type of sound signal; we see an increase in number of calls as afternoon turns to sunset. We also see an increase in number of calls from Washington to Kiritimati to Palmyra.

Sound pressure levels were very different among the islands, as shown in Figure 5. Similar to the qualitative analysis, sound intensity increased as the day progressed at each island. In contrast to the number of calls, sound intensity increased from Kiritimati to Washington to Palmyra. We avoided depth as a confounding factor of loudness; we saw no significant trend in each island between loudness and depth (Figure 6).

Biological sound signals detected are shown in Figure 7. The number of signals is much higher at each island in automatic detection than qualitative analysis. Also, Washington has considerably more signals than Kiritimati and Palmyra, which have similar numbers of signals. Contrary to our prediction, the number of signals does not increase as time of day progresses.

Frequency distribution, as predicted, does not increase as time of day progresses, as illustrated in Figure 8. Distribution is reverse along the islands to expected speciosity; Washington has the widest range of frequencies, then Kiritimati, and then Palmyra with the smallest number of frequency bands detected.

Correlation values with fish biomass and apex predator fish biodiversity varied among the different acoustic productivity indices. Table 1 shows the correlations and also the ANOVA p-values between the islands for each acoustic index.

Discussion

In our qualitative analysis, we might interpret the rise in number of calls over time as confirmation of earlier research in the McCauley et al., study and as validation of our results. Because we saw this rise in sound pressure level as well, our results become doubly convincing. The lack of trends over time in our frequency index is encouraging as well, because even though fish sound activity increases towards sunset, most fish are active during the day as well (Amorim, 2005).

However, in our sound signal detection index, we see no trend over time, which seems to contradict these other results. One possible explanation might be that our algorithm counts keynotes such as water turbidity. Kiritimati, though, was much calmer during recording than Palmyra, yet shows a higher number of sound signals, so this explanation is unlikely. Another explanation is that the notes are entirely dominated by snapping shrimp calls. Although we made no visual confirmation of specific animals, I have seen snapping shrimp up close prior to this study and have stressed them until they made their characteristic popping noise. The sounds heard at Washington and Kiritimati sound very similar to this noise, and the high number of sound signals at Washington supports this explanation. Rego et al., have noted a lack of benthic predators at Washington and Kiritimati, whose absence could allow for a rise in the snapping shrimp population, and therefore the number of shrimp calls. From this, we would expect Kiritimati to have more signals than Palmyra, but they have similar numbers. Perhaps Palmyra makes up for this discrepancy through other types of calls, such as the high number of crackling and crunching noises discussed in our qualitative results. We assume these are parrotfish feeding sounds, although this was not confirmed visually.

Our frequency distribution results are interestingly opposite of our expected acoustic diversity values along the fishing gradient in the islands. Although Figure 8 could suggest that the different types of fish calls were truly varied at Washington and less varied at Kiritimati and Palmyra, this is improbable, because apex predator biodiversity increases along the islands in the opposite order (Rego et al, 2007). Although this is only a small component of the total diversity, we might assume that apex predator biodiversity drives acoustic diversity due to their large size. The sounds produced in the swim bladders of fishes (Amorim, 2005) we expect to be louder for fishes with large bladders. Some other factor must be driving our frequency distributions; we hypothesize that snapping shrimp causing the high numbers of significantly varying frequency bands at Washington and Palmyra. We had to set our sensitivity very low when determining whether a certain band was significantly varied from the noise floor level, otherwise Washington exhibited frequency variation off the scale; with high sensitivity, Washington showed variation at all frequency bands. By lowering sensitivity, our algorithm mostly detected popping and crunching noise frequencies, because these were the loudest. We heard crunching as low frequency, and since crunching was prevalent in Palmyra and popping was not, these specific sound types could account for the low frequency variability in Palmyra. Popping sounds occurred at high densities at Washington, and we believe this was accompanied by varying types of popping as well. This could correlate to a rich diversity of snapping shrimp species, and the intermediate level of frequency variation at Palmyra could correlate to only one or two snapping shrimp species. Given this hypothesis, the high negative correlation between frequency variation among the islands and biomass and biodiversity (Table 1) indicates that as reefs become healthier, snapping shrimp are less prevalent. The same correlation in sound signals detected supports this conclusion as well.

Qualitative analysis and sound pressure levels were correlated with biomass and biodiversity as trends (Table 1). Qualitative analysis showed an increase along the Line Island fishing gradient, although sound pressure level analysis did not. Therefore, we conclude that qualitative analysis is our best acoustic index to gauge reef health, and sound pressure level analysis might be a satisfactory acoustic index. Sound signal detection and frequency distribution measurement, when combined with background knowledge of the sounds of an area, could provide insight into the variation and numbers of animals in a reef. Future studies could imitate our methods and conduct similar reef recordings and analysis that validate acoustic indices as measurements of reef health. Snapping shrimp filters, created from spectrograms of known shrimp calls, would be invaluable in eliminating popping noise. Other improvements could be a double hydrophone array that eliminates ocean noise, better reproducibility through time of day and site replication, and a wider variety of reef islands studied, such as Kingman Reef and Fanning Island.

Conclusion

A reliable aesthetic definition of biodiversity created from musical analysis techniques could be a major asset to scientists and conservationists defending threatened ocean habitats. Public knowledge that areas are measurably, aesthetically diverse might influence support away from ecologically harmful activities such as poaching, the aquarium trade, and unsustainable fishing. Sound is a large part of the aesthetic experience, and this definition of acoustic diversity can serve as a model to develop a complete sensory biodiversity and productivity index. In addition, the technique used to survey acoustic diversity has many advantages over traditional survey techniques; it is non-invasive, there is no bias at night, and automated monitoring could be quick and continuous. However, an aesthetic definition of biodiversity could never supplant the less qualitative scientific definition, but it would help bridge the gap between esoteric information and practical knowledge. Practically, my study showed that Kiritimati Island, Washington Island, and Palmyra Atoll each have a characteristic acoustic soundscape that is aesthetically pleasing; each sounds beautiful enough to warrant conservation.

Figures

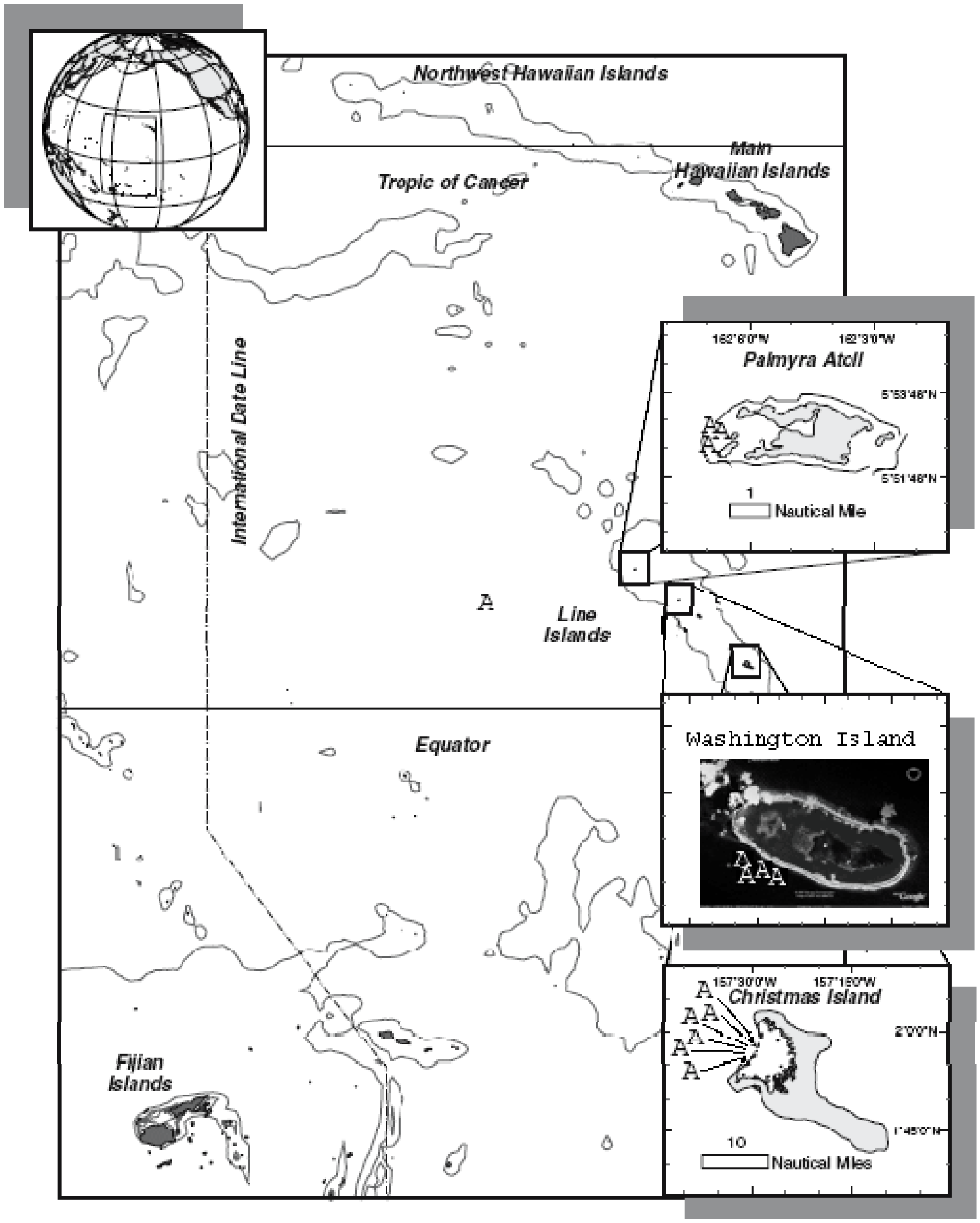

Figure 1: Locations of study sites in the Line Islands
Backreef recording locations on each island marked with A's: six at Kiritimati, four at Washington, and three at Palmyra. Although this study uses Stevenson et al.,and Rego et al.,as benchmarks and therefore emulates its data sites as closely as possible, data storage and analysis time limitations forced the site count down. Sites shown to have a high amount of background noise from wave action were eliminated.

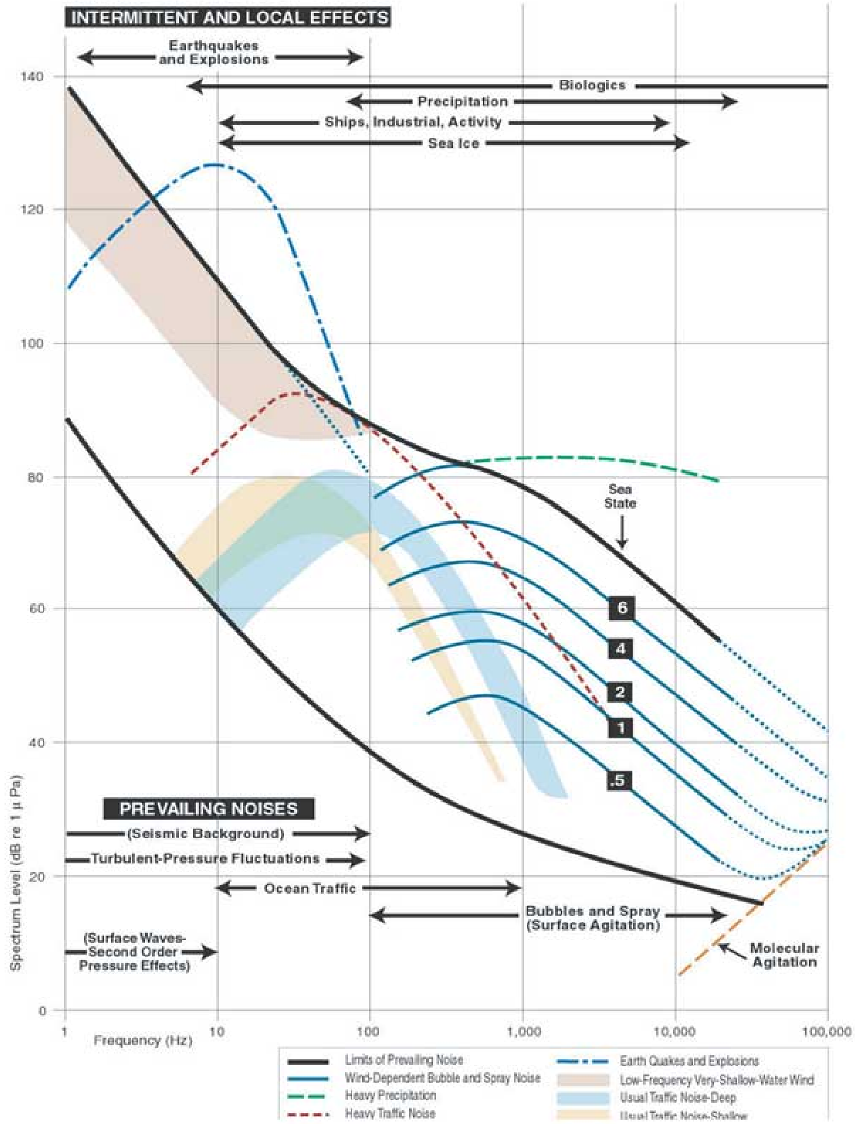

Figure 2: Ambient Ocean Noise at Different Frequencies (Wenz 1962)

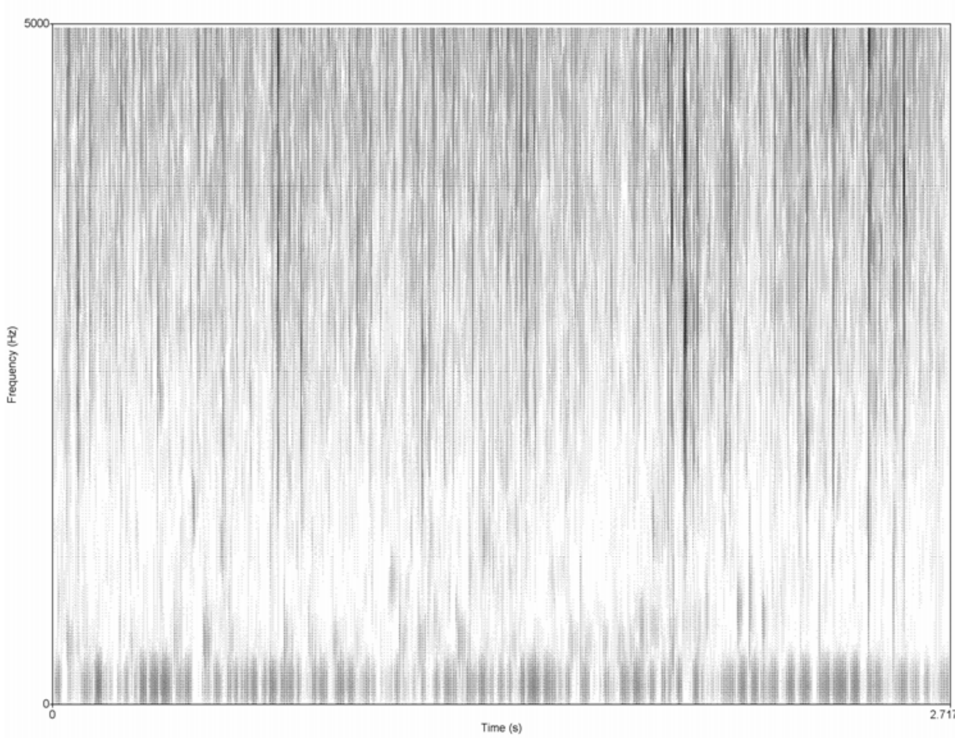

Figure 3: Spectrogram Showing Fish Call
In this spectrogram, the heavy black vertical lines are clicks in a fish groan.

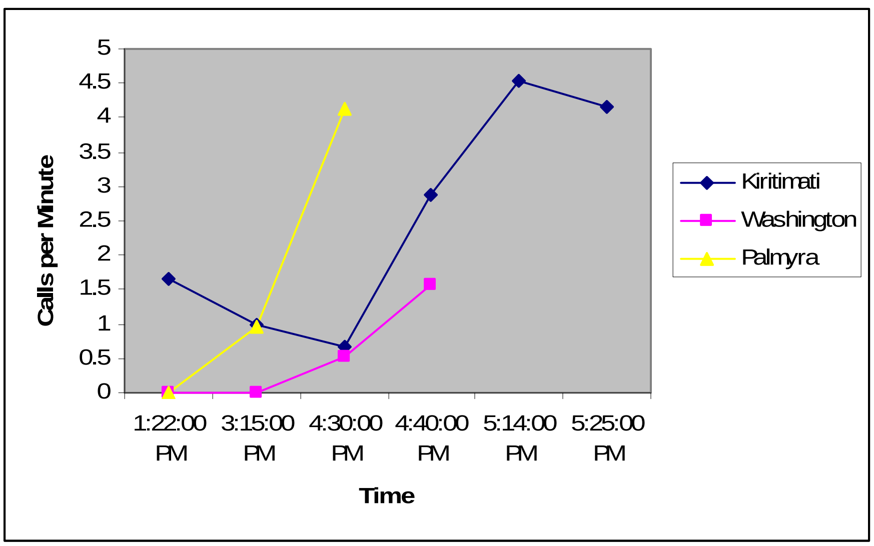

Figure 4: Number of Calls per Minute versus Time, counted qualitatively

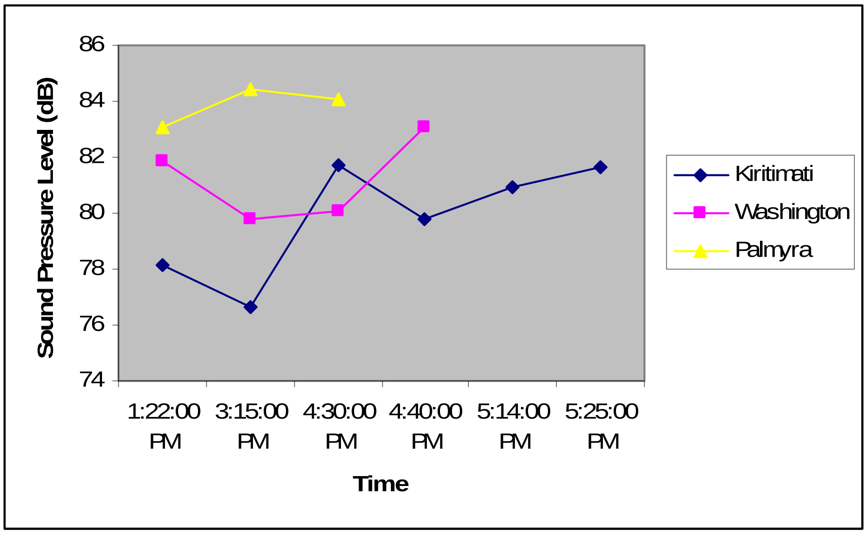

Figure 5: Sound Intensity Levels versus Time

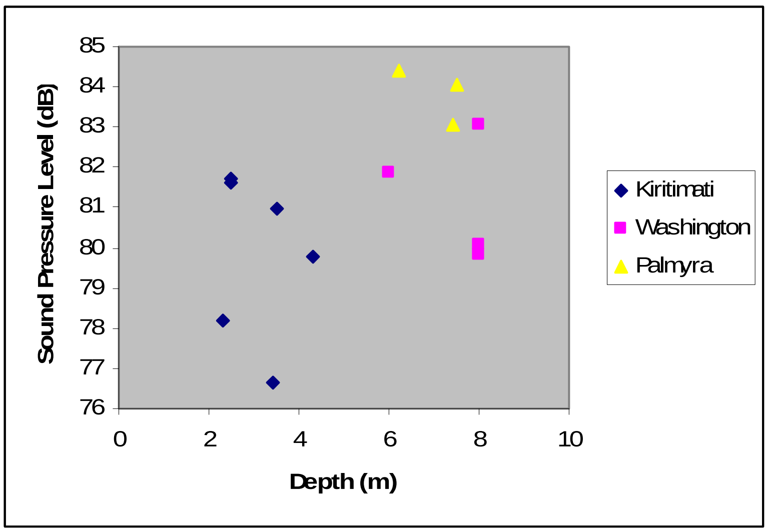

Figure 6: Sound Intensity Levels versus Depth

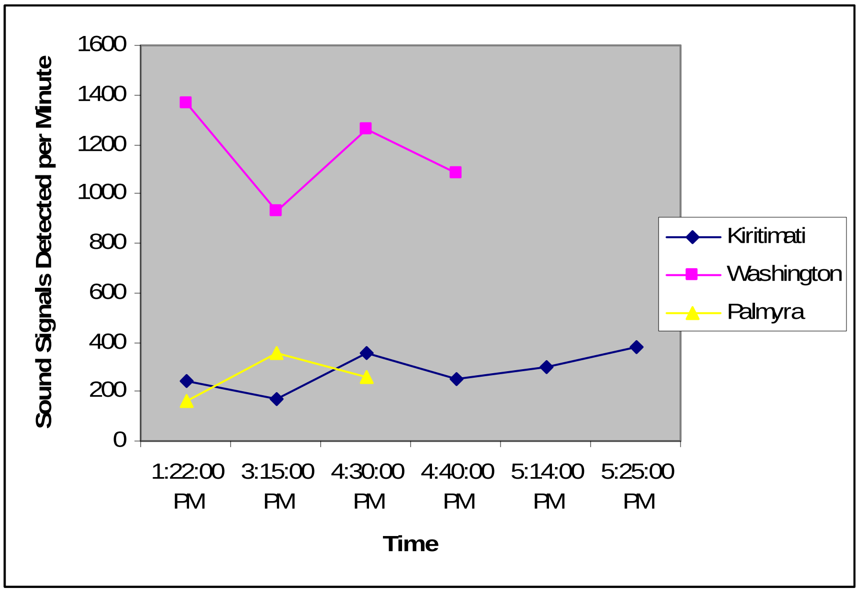

Figure 7: Number of Biological Events Detected versus Time

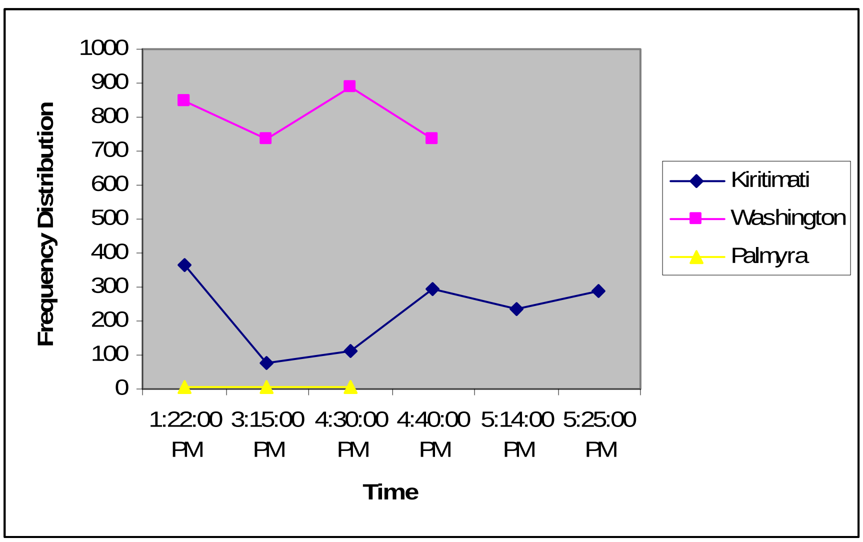

Figure 8: Number of Frequency Bands Above the Noise Floor versus Time

Tables

Acoustic Index	Qualitative Analysis $p = .13$	Sound Pressure Level $p = .03$	Number of Sound Signals $p < .01$	Frequency Distribution $p < .01$
Biomass	.92	.89	-.53	-.76
Biodiversity	.99	.74	-.73	-.90

Table 1: Correlation Coefficients Between Fish Biomass and Acoustic Diversity Indices

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