# The Distribution of Central Pacific Seabirds: Relationships with Productivity, Distance from Land, and Island Nutrient Systems

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**Abstract:**

Seabirds are a major top marine predator and in large numbers, can play a large role in nutrient cycling between land and sea. Understanding the relationship between seabird distribution across the ocean and factors such as productivity and distance from land can help us to understand the area of this nutrient flow, and to predict where seabirds may influence marine systems. This project strove to understand the effect of productivity on population size and distance traveled from land in two central Pacific seabird communities. One hundred and eighty-two 10-minute observations, recording the number and type of seabirds seen, were carried out on a cruise track between 19 degrees north and 2 degrees north. This cruise track passed from the Hawaiian Islands to the Line Islands. Forty-eight sea surface water samples were also analyzed for chlorophyll-a concentration. Results show that the Line Islands are surrounded by much more productive waters than the Hawaiian Islands, and as such support a much larger and more diverse seabird community. In addition, the Line Islands seabirds travel less far from land, on average, to forage. This suggests that there is a relationship between productivity and foraging distance. The Line Islands supported a seabird community dominated by terns and boobies, whereas the Hawaiian Islands community was dominated by shearwaters and petrels, a group with much lower cost of traveling. These results suggest that the more productive Line Islands system is receiving more nutrients from seabirds, but from a much smaller ocean area than the Hawaiian Islands.

## Introduction:

Birds are endothermic organisms, and therefore have an inherently high energetic cost of living. In tropical waters, foraging seabirds have to meet their energetic demands in oligotrophic waters, where areas of high productivity are patchy and ephemeral. By looking at some of the factors that may influence and limit tropical seabirds during foraging, this project strives to understand their pelagic distribution in the central Pacific Ocean. The factors that will be examined include the availability of prey (productivity) and the distance from land that seabirds have to travel to get this prey.

Many seabirds feed primarily on flying fish and Ommastrephid squid (Le Corre 1997, Harrison et al. 1983, Schreiber et al. 2005, Au 1986). The two most important factors influencing how far a seabird must fly to feed are the availability and accessibility of this prey. In this case, availability and accessibility are two very different things. Prey is available if it exists in a certain location, such as in productive waters. "Productive" waters are those that contain a high concentration of chlorophyll, which is a proxy for primary productivity, or phytoplankton biomass. The phytoplankton feed small zooplankton which feed larger zooplankton which in turn feed the flying fish and squid that seabirds eat. More productive waters may support greater densities of prey, so seabirds may be more efficient at feeding there and productive waters may support higher densities of seabirds. However, these prey items are only available if they are near the surface, because pelagic seabirds cannot dive deep as a result of their wing structure, which supports efficient long-distance flying but not deep diving (Burger et al. 1980, Haney and Stone 1988, Weimerskirch et al. 2005). Those seabirds capable of traveling far out to sea only have access to the top few meters of the sea surface (Le Corre 1997, Au and Pitman 1986). Seabirds, like boobies and frigatebirds, are often found feeding in association with underwater predators, such as tuna, dolphins, and occasionally whales. The feeding behavior of these marine predators scares fish and squid to the surface, where seabirds can access them (Harrison 1990, Weimerskirch et al. 2003).

We predict that prey (flying fish and squid) are going to be *available* in areas of high productivity, because that is where *their* prey is concentrated. We also predict, then, that the highest concentrations of seabirds will exist in areas of relatively high productivity. Indeed, studies have shown that seabirds congregate at areas of high productivity (Weimerskirch et al. 2005).

Spear et al. (2001) reported that the foraging distribution of piscivorous seabirds is influenced entirely by feeding tuna. Harrison (1990) supports this idea, saying that "tuna birds [those seabirds associated with tuna] rarely feed in the absence of tuna and may depend on them for survival." If seabirds do in fact rely on marine predators in order to access their prey, this has enormous implications for the future of marine ecosystems, on a grand scale. Top predator populations worldwide, including tuna, are plummeting as a result of severe over-fishing (among other things) (B. Block, personal communication). If seabirds rely on tuna to feed, then diminishing underwater marine predator populations could also mean a severe decline in piscivorous seabird populations. Because most tropical seabirds reproduce "opportunistically," or only when their foraging efficiency is high enough to support a body other than their own (Simmons 1967), a decline in marine predators could mean a decline in seabird fecundity and recruitment. Indeed, the Birds of North America species account for Red-footed Boobies notes that booby populations around the world are diminishing, as are those of most other tropical seabirds (Schreiber et al. 2005). This study hopes to investigate the extent of the relationship between seabirds and feeding marine predators.

We have discussed the important factors affecting a seabird's choices when foraging on the open ocean. Given this information, we predict to find seabirds foraging preferentially in productive waters, wherever they may occur across the ocean, and most often in concert with underwater predators. There is just one crucial factor left to consider: distance from land. Many seabirds, including boobies, do not spend the night at sea. They rely on land for sleeping and breeding. The foraging range of such central-place foragers is limited by the distance they can travel out to sea and back during a typical 12-hour foraging period (Harrison 1990, Weimerskirch et al. 2005). The farther out to sea the bird has to fly to forage, the more expensive it is to forage there. As a result, the range of such central-place foragers should be restricted to a circle with the island as its center. The second aim of this study is to find out just how large this foraging circle is for birds based in Hawaii and on the Line Islands. Birds living in more productive areas should not fly as far to feed, because they should be able to find sufficient food closer to shore. Hyrenbach et al. (2006) demonstrated that the distribution of some seabirds (terns and shearwaters) was more strongly associated with distance from land than ocean productivity. Due to the energetic constraints, it is obvious that distance from land probably plays a significant role in determining where central-place foragers can go to feed.

Seabirds are a major marine top predator, and in large numbers can have a substantial effect on the pelagic ecosystems where they feed. Understanding what factors effect their distribution can help us to predict where they will be found, and to better understand and manage the ocean. Because seabirds forage and obtain their energy from the ocean, but roost, sleep, and nest on land, they are also an important nutrient and energy link between land and sea. Seabirds extract energy from the sea and then deposit nutrients on land, in the form of guano, their own dead bodies, or scavenged eggs. Because of this link, it is important to consider seabirds when studying the nutrient and energy cycles of islands. This study aims to determine how far out to sea seabirds forage, which can help to determine the true area of such island nutrient cycles.

There have been very few ship-based studies of seabirds in tropical waters (Weimerskirch et al. 2005). This study hopes to begin to fill this gap by setting sail with a few questions in mind: How are seabird groups distributed across the Central Pacific Ocean with respect to distance from land, productivity, and association with marine predators? How does the radius of the foraging circle from an island change with productivity? We hope to answer these questions via daily observations during a south-bound cruise from Hawaii (18 degrees north latitude) to the Line Islands (2 to 5 degrees north latitude) between May 10 and May 31, 2007. We expect to find the most seabirds close to land and/or in productive waters, due to the energetic constraint of traveling far out to sea. We expect that birds will forage as close to land as they can.

## **Methods**:

### Bird Observations:

Ten minute bird observations were conducted each hour on the hour from 0700 to 1900 during the sea portion of our cruise (May 10 through May 31). One hundred and eighty-three observations were used in the analysis for this study. The bird observation periods consisted of two people standing on opposite sides of the quarterdeck and recording each bird they saw on their side of the ship. We recorded the number and type of birds (categories: shearwaters, petrels, boobies, frigatebirds, terns, other) and noted if there were associates visible (flying fish or feeding tuna/dolphins). For each hourly observation, we also recorded GPS location. The GPS unit is accurate to 10 meters.

### **Measures of Productivity**:

Chlorophyll-a concentration is a proxy for the amount of phytoplankton in the water, which is a proxy for productivity. We measured the chlorophyll concentration (micrograms/liter) of forty-eight surface water stations. We took surface water samples four times daily at 0700, 1000, 1300, 1600. At each station, two hundred and fifty milliliters of water was filtered through a 0.45 filter and frozen until group processing took place. Once a collection of filters had built up, we cooked each filter in 7 milliliters of acetone for 12 hours and then ran the sample through an AU10 benchtop fluorometer in order to determine the chlorophyll-a concentration. Fluorometers shine UV light at the sample, which excites the chlorophyll-a. The fluorometer then measures the amount of light released as the chlorophyll-a becomes de-excited.

**Distance from Land:**

Distance from land was calculated by choosing the latitude and longitude for one point on each of the islands we passed (Hawaii, Palmyra, Washington, Fanning, and Christmas). An Excel equation then calculated the distance between each island and the GPS location of every observation site. I took the shortest distance to land for each site and used this distance as the "distance from land" for analysis.

## **Results**:

**Hawaii vs. the Line Islands:**

I cut the data set into two groups: those observations closer to Hawaii and those closer to the Line Islands. Most of the analysis was done on the two groups separately, although some analysis was done on the data set as a whole.

**Bird Numbers:**

Bird observations were made from the Robert C. Seamans from May 11 to May 31st, 2007 while sailing from Hawaii (19 degrees north latitude) to the Line Islands (2 to 5 degrees north latitude). We observed five groups of birds on our cruise track: 1) shearwaters and petrels, 2) terns, 3) boobies, 4) frigatebirds and 5) tropicbirds. Table 1 displays the number of observation periods in which we saw each group, the average number seen when they were observed, the total number seen during all observations, and the farthest each group was observed from land. We saw a total of 6,488 birds. Shearwaters and petrels were seen in the largest percentage of observations (83/182 or 45.6%) and tropicbirds in the smallest percentage of observations (6/182 or 3.6%). Terns were seen in the largest groups (average 88 birds) and tropicbirds in the smallest groups (average 3 birds, but usually seen alone). Terns were the most populous group at 5,157 and tropicbirds the least at 19. Shearwaters and petrels were seen farthest from land (847 kilometers) and frigate birds the least far (64 kilometers). The farthest distance from land that we traveled during the cruise was 847.85 kilometers. Shearwaters and petrels were seen here. We saw an average of 0.11 birds per minute in the Hawaiian system and 6.24 birds per minute in the Line Islands system.

**Associates:**

We recorded associates (schools of feeding tuna/dolphins and flying fish) when they were observed during an observation period. Tuna/dolphin schools were seen during 38 of the 182 observation periods (20%). Flying fish were noted during 39 out of 72 observation periods (54%) (Table 2). Due to the large number of observers involved in this project, and the decision late in the project to note flying fish, it is not justified to analyze where these associations were observed, only that they did occur.

**Time of Day:**

There was no relationship between time of day and the total number of birds seen (Figure 1, $P = 0.89$). Likewise, there was no significant relationship between time of day and number of shearwaters/petrels, boobies, or terns seen ($P > 0.05$ for all).

**Chlorophyll-a Concentration:**

There was a distinct difference in chlorophyll-a concentrations between the Hawaii dataset and the Line Islands data set (Figure 2). Chlorophyll-a concentrations in the Hawaii dataset were clustered around 0.070 micrograms/liter, while the concentrations in the Line Islands were clustered around 0.175 micrograms/liter for all distances from land. Birds seen closer to Hawaii were seen in less productive waters (chlorophyll-a concentrations less than 0.10 micrograms/liter) while birds seen closer to the Line Islands were seen in more productive waters (between 0.10 and 0.30 micrograms/liter) (Figure 3). There were also more total birds seen closer to the Line Islands (6.24/min versus 0.11/min in Hawaii).

**Distance from Land:**

The total number of birds dropped off exponentially with distance from land (Figure 4, $P = 0.0000$). Separate analyses of each major bird group (boobies, terns and shearwaters/petrels) showed similar significant relationships ($P = 0.000$ for all). Tern numbers dropped off the quickest as we moved away from land, followed by boobies and then shearwaters. When the distance from land was analyzed separately for Hawaii versus the Line Islands, all of the bird groups' numbers dropped off much quicker from the Line Islands than Hawaii (Figure 5). Once again, shearwaters were more evenly spread across the distances than the other bird groups. Figure 6 shows that the average distance from land was farther for all bird groups from Hawaii than the Line Islands. Table 3 displays the total number of birds seen from each group for Hawaii and the Line Islands, the farthest distance from land each group was seen, and the average distance from land each group was seen. All bird groups were seen farther from Hawaii than the Line Islands. More birds were seen in the Line Islands (6,425) than Hawaii (65).

**Community Composition:**

Figure 6 displays the community composition in the Hawaii group and the Line Islands group. The Line Islands seabird community was dominated by terns and boobies while shearwaters and petrels played a larger role in the Hawaii community. The Line Islands community supported larger numbers of all groups and also one more group than Hawaii.

## **Discussion**:

The aim of this study was to characterize the distribution of central Pacific seabirds in order to learn where they are hanging out in the pelagic habitat and how community composition differs from place to place. In addition, we strove to understand the role that certain variables play in determining this distribution. These variables were: distance from land, productivity, and associations with marine predators. We hypothesized that overall bird numbers would decrease with distance from land, because the distance a bird can travel out to sea to feed will be limited by time and energetic constraints, especially for bird groups such as boobies which are central-place foragers and return to land each night to sleep. We also hypothesized that birds would be more abundant in more productive waters, where prey such as squid and flying fish would presumably be more abundant and feeding therefore more efficient. In addition, marine predators such as tuna and dolphins are more likely to feed in more productive areas, and seabirds display an association with feeding marine predators, which drive prey to the surface where it becomes available for shallow diving seabirds. We predicted that the relationship between productivity and distance from land would force birds living in less productive waters to travel farther out to sea to find enough food.

**Association with Marine Predators**:

Before continuing in the discussion, a brief moment will be taken to discuss our data on the association between seabirds and marine predators. Due to the nature of the marine predator observations (one can be sure of a 'present' observation, but cannot be sure that predators are not present just because they are not seen), it was not feasible to do statistical analysis on this section of the data. We observed seabirds feeding in association with marine predators 38 out of 181 observations, or 21% of the time. We observed seabirds feeding in association with flying fish (one of their main prey items) in 39 out of 72 observations, or 54% of the time. Given the difficulty of sighting underwater marine predators, especially at distance, it is likely that seabird aggregations are associated with marine predators on a larger scale than our data shows, but no further conclusions can be made from the present study. The high proportion of observations in which flying fish were sighted supports the idea that flying fish are a main prey source fro seabirds, but no other conclusion can be drawn from this data.

**Productivity:**

Unraveling the relationships between bird numbers, distance from land, and community composition as they relate to productivity were tackled by comparing the Hawaiian Island system with the Line Island system.  Chlorophyll-a concentration is used here as a proxy for productivity because it is an indication of the number of phytoplankton in the water, which form the base of the food chain.  The water in the Line Islands system had more than double the concentration of chlorophyll-a than the Hawaiian Islands system.  We therefore look at the Line Islands system as a highly productive environment, while the Hawaiian Islands system is an oligotrophic system. Since distance from land did not affect chlorophyll-a concentrations in either system, it was possible to investigate how seabird distance from land varies between the productive and oligotrophic systems.

Two major important observations emerged from this investigation.  First, we found that Line Islands birds foraged in more productive waters than Hawaiian birds. This is to be expected, since this is the water type available to the birds in each system. More interestingly, however, is the observation that the total bird population observed in the Line Island system was much greater (62 times) than that in the Line Islands.  These results support the hypothesis that more birds feed in more productive waters.  Since the analysis is on such a large scale, it may be more descriptive to say that productive waters support a higher population of seabirds.

**Distance from Land:**

The distance from land a bird has to travel to feed determines how much energy it must expend in order to gain energy through foraging.  It is therefore a potentially extremely strong influence on pelagic seabird distribution.

Before analyzing the distance from land data, it was necessary to look at the relationship between time of day and bird numbers.  Because many seabirds, including boobies, are thought to be central place foragers that return to a “home island” each night, it was expected that the time of day would effect our observations.  Early and late in the day, birds might not be seen as far out to sea as they actually forage because they may be commuting at these times.  However, time of day did not have an effect on bird numbers.  This, combined with the boobies seen up to 701 kilometers from shore, calls into question prior papers which claim that adult boobies never spend the night at sea (Harrington 1977, Weimerskirch et al. 2005, Shreiber et al. 2005, Weimerskirch et al. 2005).  The ship itself is likely to influence bird behavior because they see it as a “life raft” where they can land to rest overnight, instead of flying all the way back to land.  However, not many birds overnighted on the ship.  It is possible, therefore, that boobies actually do spend greater than 12 hour periods foraging in the ocean.  What they do at night remains a question.

Since time of day did not influence bird numbers, we could analyze distance from land without taking into account time of day.  Distance from land proved to be a key component in determining seabird densities for all groups studied, which follows our predictions and the results of Hyrenbach et al. (2006).  Numbers dropped off exponentially as we traveled farther away from land.  Tern numbers dropped off the quickest, followed by boobies and then shearwaters/petrels.  This trend follows our predictions, as shearwaters/petrels have a lower cost of flight than the other bird groups, and are the most pelagic of the three groups.

This trend was repeated in the Hawaiian Islands and Line Islands data sets. Analysis of these datasets separately uncovered an interesting difference, however. For all bird groups, the Line Islands had many more of each bird group close to land and the numbers dropped off much quicker than in Hawaii. Hawaii started with lower numbers near land and birds were observed farther out to sea than they were in the Line Islands, for all groups. This discrepancy has several possible explanations, and also important implications. It is possible that the more productive waters of the Line Islands not only support a larger overall seabird population, but also allow the birds to find adequate food sources closer to land, so they do not have to travel as far out to sea to forage. The high productivity, therefore, could explain both the higher overall numbers and the steeper drop in numbers with distance from land. The oligotrophic Hawaiian system, on the other hand, displays fewer overall birds, and these birds were found farther out to sea in all groups. The average distance from land was farther in the Hawaiian system for boobies, terns, and shearwaters/petrels. This could be a result of less productive waters requiring birds to travel farther out to sea in order to find sufficient food. Such waters would also support a smaller total population.

The distance from land that a seabird travels to forage is an indication of the sea area that is being gleaned for nutrients. These nutrients are then deposited on land via excrement. It is therefore important to understand how far seabirds travel to feed when trying to understand the nutrient system of an island such as the Hawaiian Islands or the Line Islands. This study indicates that while the Line Islands support a much larger community of seabirds, the total area of sea from which nutrients are coming is much smaller than that of the Hawaiian Islands. In addition, tern numbers drop off the quickest (average distance 16 kilometers), and terns were by far the most populous group in the Line Islands. They made up 80% of the Line Island seabird community. Boobies were the next group to drop off, with an average distance of 22 kilometers, and they were the second most populous group at 13%. This indicates that the majority of nutrients is probably coming from very near shore in the Line Islands. In the Hawaiian Islands, shearwaters and petrels made up the majority of the seabird community (65%), and their average distance from land was 241 kilometers. This indicates that the Hawaiian Island nutrient system is spread thinly over a much larger area, although not as many nutrients are being added because there are not as many birds.

**Community Composition:**

Not only were there many more birds in the Line Islands community, the community composition between Hawaii and the Line Islands also differed significantly. The Hawaiian community was dominated by shearwaters and petrels (65%) and then terns (18%) and boobies (12%). The Line Islands were dominated by terns (80%) and then boobies (13%) and shearwaters (5%). The Line Islands community was also richer, with five seabird groups present instead of the four present in the Hawaiian Islands. This difference in community composition is supported by Ballance et al. (1997), who compared bird group numbers with sea surface chlorophyll. They showed that shearwaters and petrels (with lowest cost of flight) feed in less productive waters than boobies and terns (with higher cost of flight). They argue that community composition of feeding areas is shaped by two factors: competition and energetic constraint. Birds with higher cost of flight, such as terns and boobies, are restricted to feeding in highly productive areas, whereas birds with lower cost of flight, such as shearwaters and petrels, can avoid competition by feeding in less productive waters. This may be what we are seeing with the difference in community composition between oligotrophic Hawaii and the productive Line Islands.

## Conclusion:

The differences in total bird numbers, distance traveled from land, and community composition between the Line Islands and Hawaii may be the result of several factors. First, the difference in productivity could drive the difference in total bird numbers (with higher populations supported by more productive waters) and community composition (with the farther-traveling shearwaters and petrels supported in Hawaii while the shorter-distance seabirds like boobies and terns thrive in the Line Islands). Human development and influence may also play a role in the differences identified here. The Hawaiian Islands are highly developed and have a long history of human habitation, whereas the Line Islands are much less developed and support a much smaller population. Development often destroys bird breeding grounds, and such development could prevent seabirds from breeding in areas they otherwise might, lowering populations. With human traffic also comes introduced organisms, and many seabird and egg predators have been introduced to the Hawaiian Islands. Island-nesting seabirds are often particularly susceptible to introduced predators because they evolved in a predator-free environment and are relatively unwary and easily caught. They also often nest on the ground, which makes their eggs easily accessible for consumption. Finally, heavy fishing around the islands can keep marine predator levels low so the birds have fewer associates and it is harder for them to catch prey. The fishing pressure around Hawaii is stronger than that in the Line Islands. The combination of oligotrophic waters, human development, and introduced predators in Hawaii could have worked together to shape the current observed seabird community. Shearwaters and petrels are also extremely pelagic seabirds, completing some of the longest migrations on earth (Shaffer et al. 2006). This means that the shearwaters and petrels we saw in the observations were not necessarily associated with the closest landmass; they could be passing through on a feeding trip or migration. For this reason, the Hawaiian seabird community could be even more depleted than this data set shows.

Because the sooty terns made up such a large proportion of the Line Islands community, it would be interesting to complete observations along the same track during a time when the sooty terns were not breeding (as they were during this study). Such a study could look at how the distance traveled from land changes for terns between breeding and non-breeding season, and how this influences the pelagic area of the Line Islands nutrient system.

# Figures

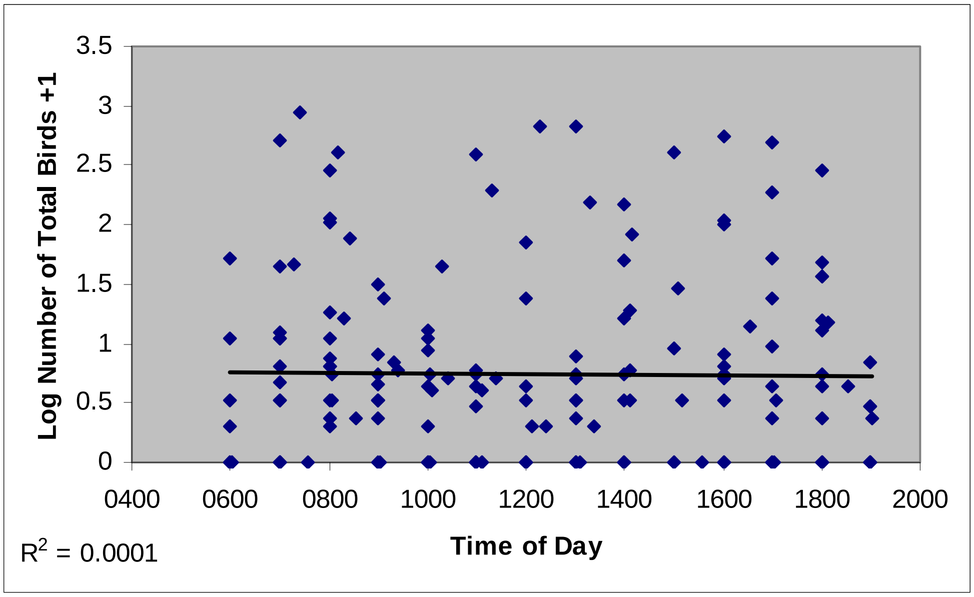


Figure 1. The log number of total birds (+1) as it changes with time of day. P > 0.05.

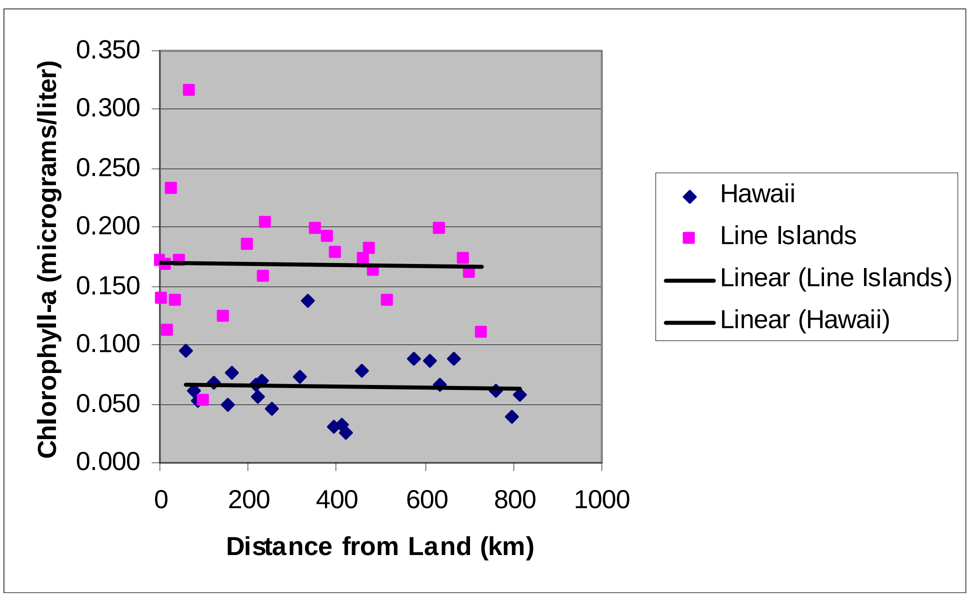


Figure 2. Chlorophyll-a concentrations in the waters off Hawaii and the Line Islands.

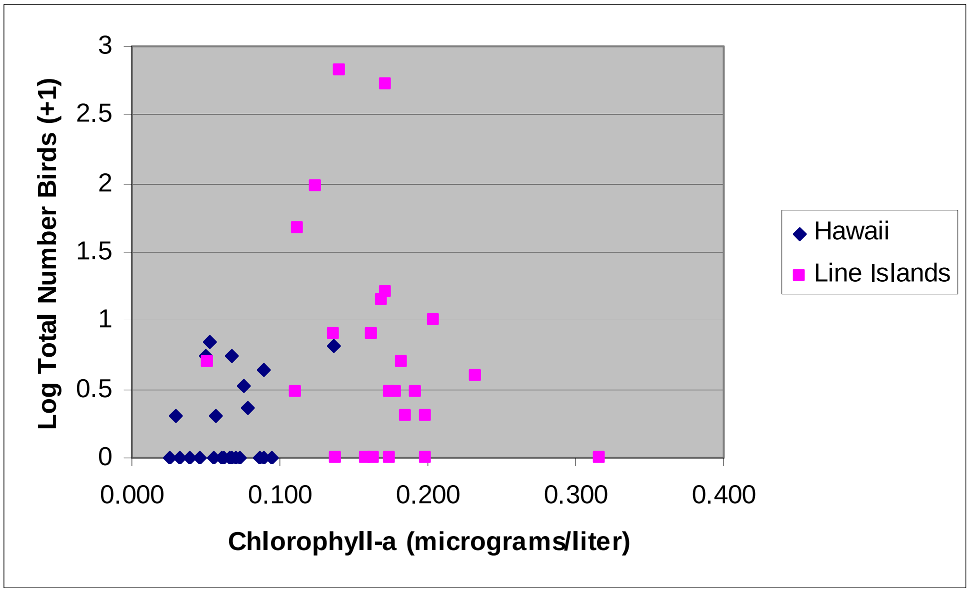


Figure 3. The log total number of birds (+1) as effected by chlorophyll-a concentrations in Hawaii and the Line Islands.

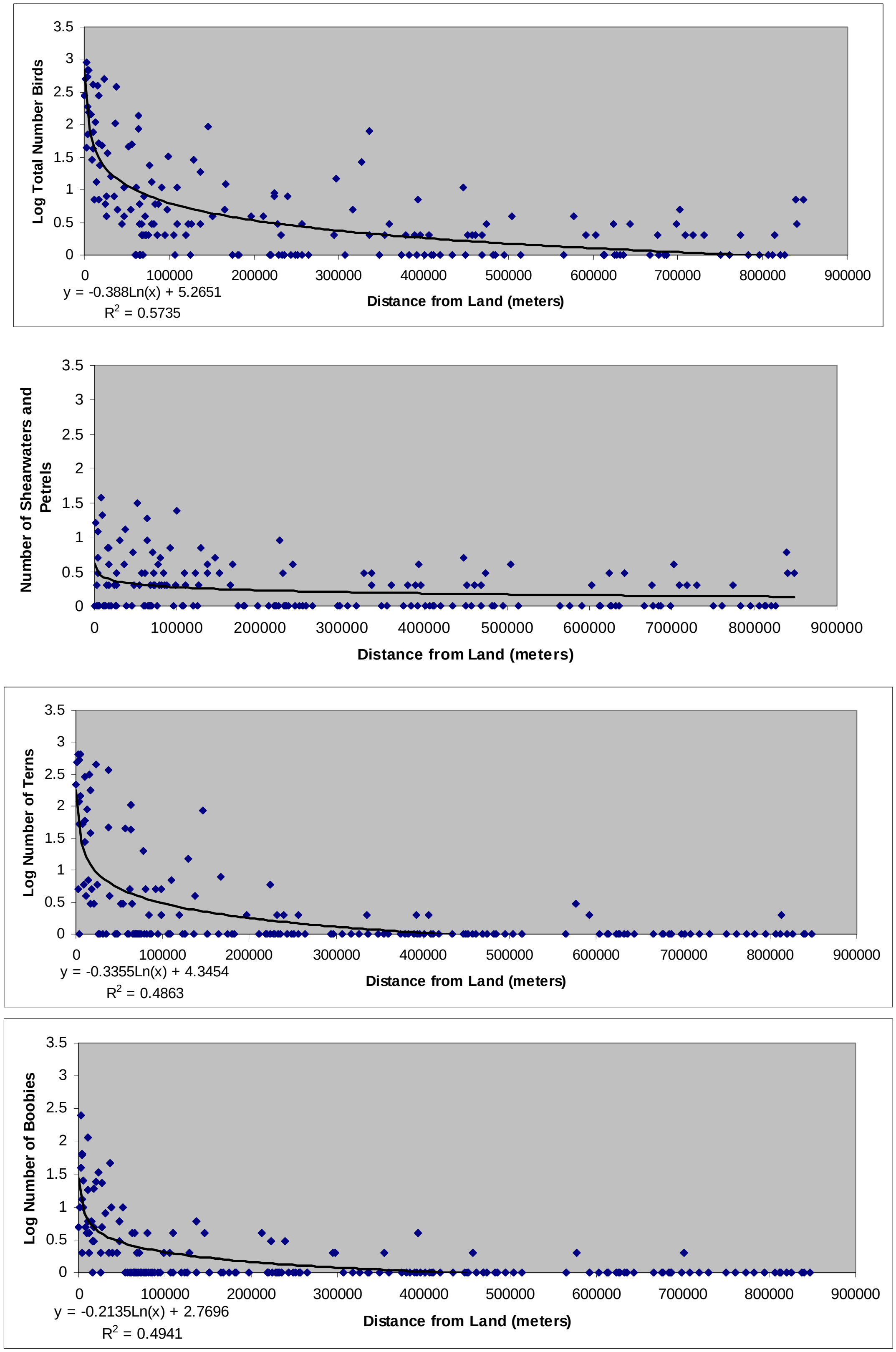


Figure 4. The log number of birds (total, shearwaters and petrels, terns, and boobies) as effected by distance from land.

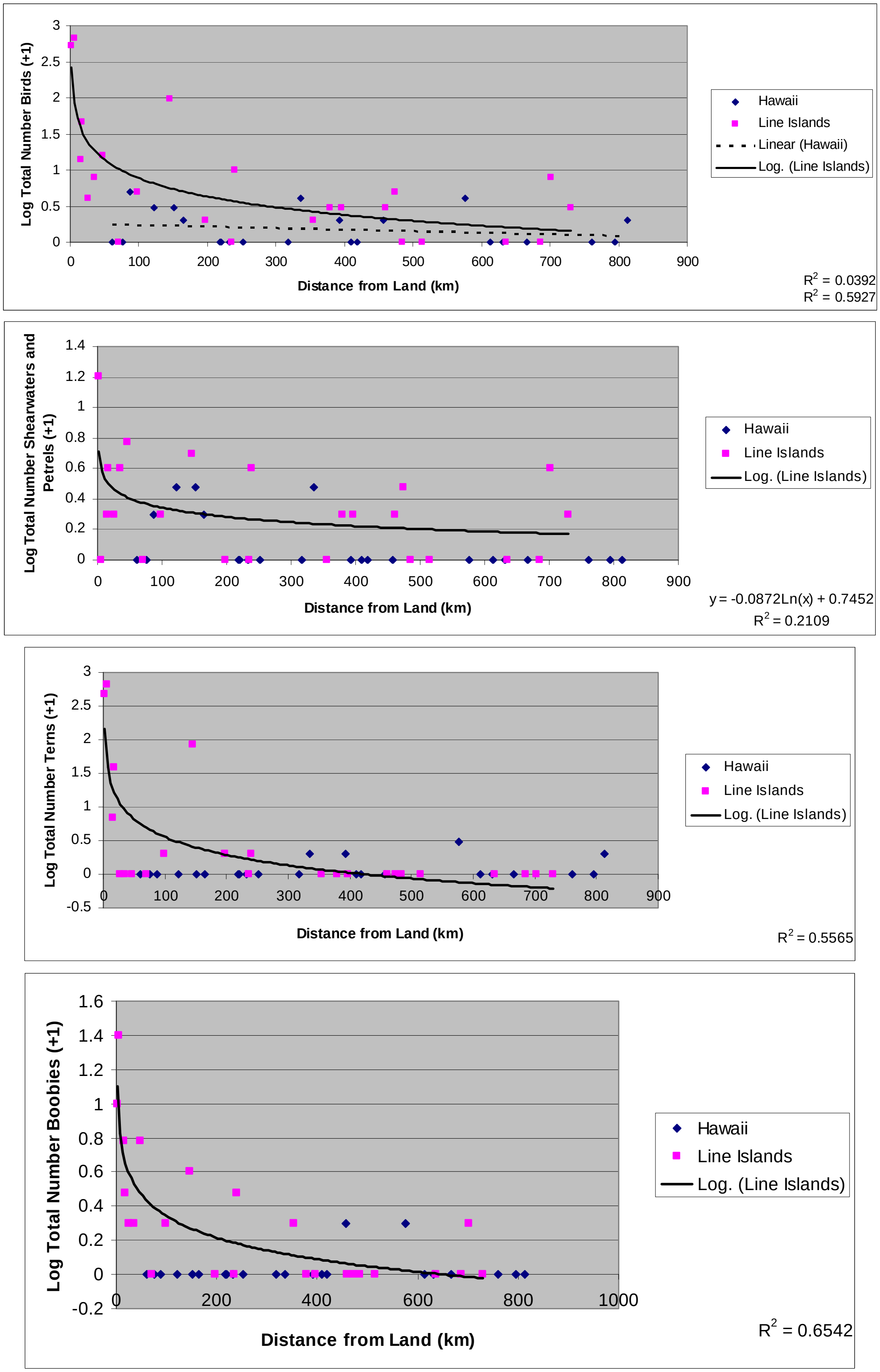


Figure 5. The log number of birds (total, shearwaters and petrels, terns, boobies) as effected by distance from land in Hawaii and the Line Islands.

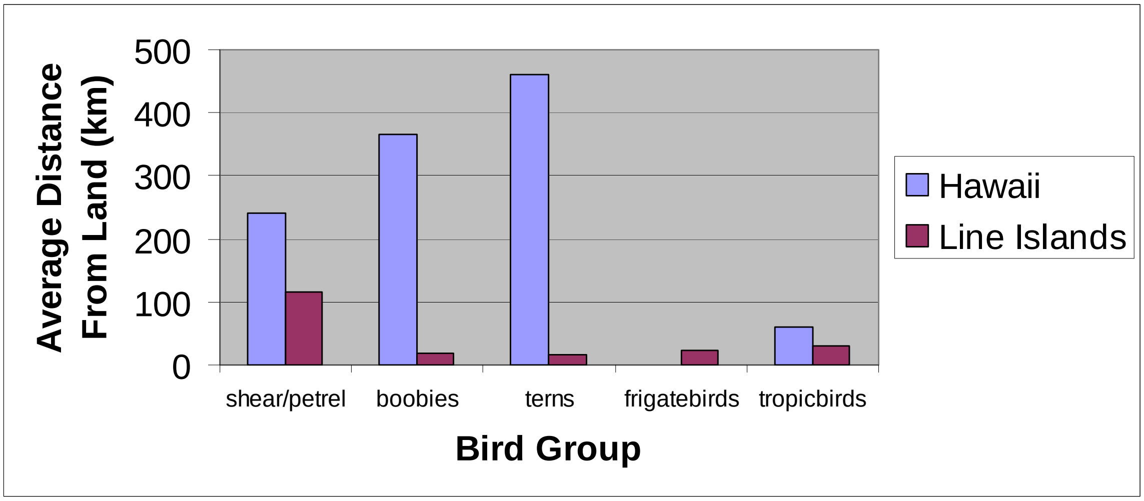


Figure 6. Average distance from land for all bird groups for Hawaii and the Line Islands.

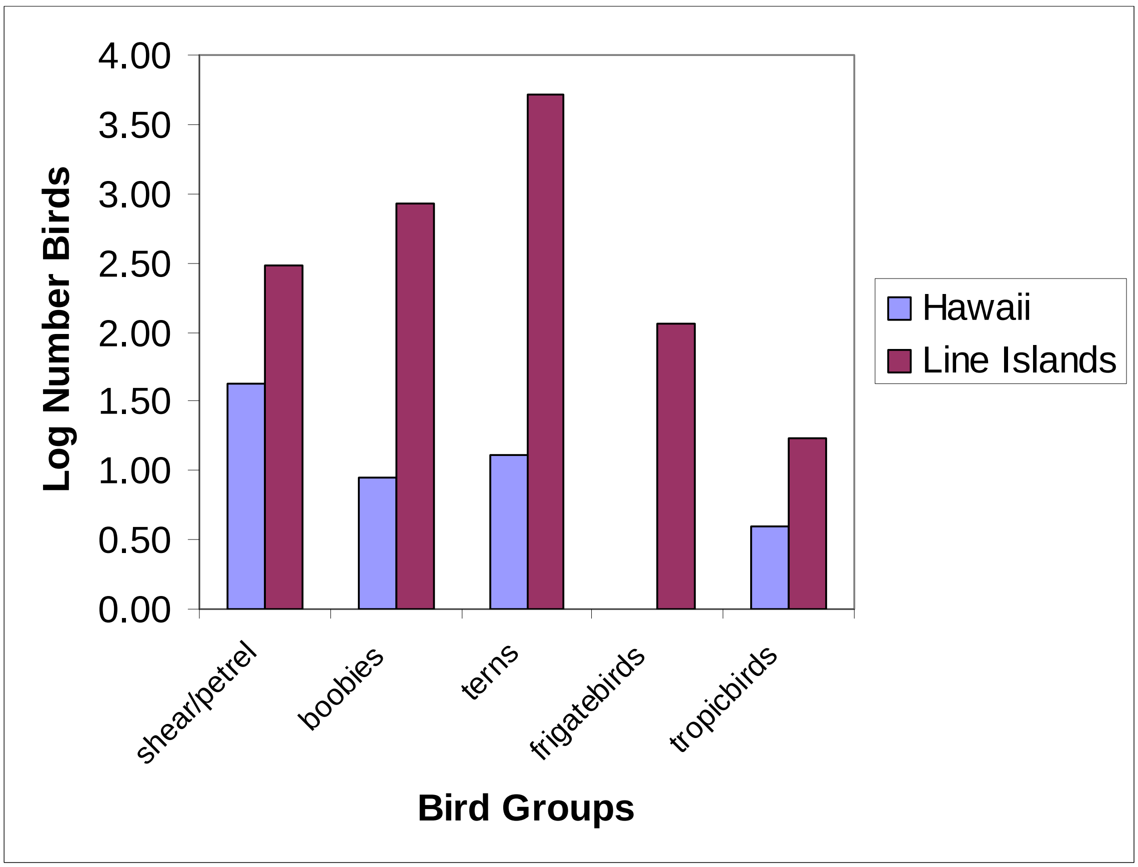


Figure 7. Community composition of the seabird communities around Hawaii and the Line Islands.

# Tables

| Bird Group | Observations | Average # | Total # | Farthest Distance from land |
|---|---|---|---|---|
| Total | 122 | 62.26 | 6488 | 848 |
| Shear/Pet | 83 | 4.16 | 341 | 848 |
| Terns | 58 | 88.92 | 5157 | 64 |
| Boobies | 59 | 14.53 | 857 | 146 |
| Frigate | 12 | 9.5 | 114 | 591 |
| Tropicbirds | 6 | 3.17 | 19 | 702 |

Table 1. An overview of the birds seen in the 182 10-minute observations.

| Associate | # Observations Seen | Percent Observations Seen |
|---|---|---|
| Tuna/Dolphins | 38/181 | 20% |
| Flying Fish | 39/72 | 54% |

Table 2. Summary of associate observations.

**HAWAII**

| Bird Group | Total | Proportion | Farthest Distance from Land | Average Distance From Land |
|---|---|---|---|---|
| shear/petrel | 42 | 0.65 | 841 | 241 |
| boobies | 8 | 0.12 | 577 | 366 |
| terns | 12 | 0.18 | 813 | 460 |
| frigatebirds | 0 | 0.00 | n/a | n/a |
| tropicbirds | 3 | 0.05 | 87 | 61 |
| total | 65 | | | |

**LINE ISLANDS**

| bird group | total | proportion | Farthest distance from land | Average distance from land |
|---|---|---|---|---|
| shear/petrel | 301 | 0.05 | 847 | 115 |
| boobies | 849 | 0.13 | 701(365) | 18 |
| terns | 5145 | 0.80 | 256 | 16 |
| frigatebirds | 114 | 0.02 | 64 | 22 |
| tropicbirds | 16 | 0.00 | 145 | 31 |
| total | 6425 | | | |

Table 3. The total number of birds seen, community composition, farthest distance from land, and average distance from land for each bird group in Hawaii and the Line Islands.

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