ANT AND TERMITE DISTRIBUTIONS ON OAHU, HAWAIʻI

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Reina L. Tong

Thesis Committee:

J. Kenneth Grace, Chairperson
Helen Spafford
Paul Krushelnycky

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<u>DEDICATION</u>

This thesis is dedicated to my grandfather, Dr. Wing You Tong.

ABSTRACT

Ants are successful social insects that provide several ecosystem functions and are found in almost every part of the world. Ants can also negatively affect agriculture, the economy, biodiversity, and human and vertebrate health. Hawaiʻi has fifty-seven established species of ants. An island-wide hand-collection survey of ants has not been carried out since 1966-1967. A systematic survey of ants was conducted along roads on Oahu from September to November 2012. Ants were collected by hand during 30-minute searches of 44 sites. Generalized linear models were run for species' presence or absence, using elevation, rainfall, and soil type as possible sources of variation. Species co-occurrence was analyzed with a probabilistic model. The number of ant species in the presence and absence of dominant ant species was compared with analysis of variance. Twenty-four species from five subfamilies were found. *Ochetellus glaber* was found in drier areas ($p < .0109$); *Paratrechina longicornis* was found in lower elevations ($p < .0009$) and in areas with Mollisols ($p < .0059$); and *Tetramorium simillimum* was found in lower elevations ($p < .0215$) and in areas with Mollisols ($p < .0190$). *Pheidole megacephala* had seven negative co-occurrences (*Monomorium floricola, Pseudomyrmex gracilis, Solenopsis geminata, Solenopsis hi01, Tapinoma melanocephalum,* and *Technomyrmex albipes*). *Technomyrmex difficilis* and *Tetramorium simillimum* had a positive co-occurrence. *Pheidole megacephala* was associated with fewer ant species at sites where it occurred, while *P. longicornis and T. difficilis* were associated with higher numbers of ants where they occurred. Once-common ants, *Nylanderia bourbonica* and *Nylanderia vaga* were not found or found at only one site, respectively; while the more recently introduced *O. glaber* and *T. difficilis* seem to be expanding in range. Mapping ant distributions on Oahu may contribute to understanding the factors that determine each species' spread, may reveal species interactions, and may help inform possible management decisions.

Termites (Blattaria) are economically important structural pests. On Oahu, the last published termite alate survey was in 1969-1971, and the last termite distribution survey was from 1998-2000. An updated survey was performed in order to discover any newly-established species, monitor possible expansions of the recent invaders

Coptotermes gestroi, Cryptotermes cynocephalus, Incisitermes minor, and *Zootermopsis angusticollis*; and track distributions of *Coptotermes formosanus, Cryptotermes brevis, Incisitermes immigrans,* and *Neotermes connexus*. A light-trap survey of termite alates was conducted from February 2011-September 2012. Square-root transformed *C. formosanus* captures were subjected to a two-factor analysis of variance with location and month as explanatory variables. A multiple regression indicated environmental factors predicted *C. formosanus* alate capture ($R^2=.29$, $F(4,47)=4.58$, $p < .0025$). Average wind speed ($\beta = -3.68$, $p < .0006$) and average rainfall ($\beta = 2.20$, $p < .0325$) significantly predicted *C. formosanus* alate capture, while average temperature and percent moon illuminated did not. A systematic survey along Oahu roads was conducted from September to November 2012. Of the forty-four sites surveyed, four termite species were found: *I. immigrans* (n = 8), *C. formosanus* (n = 2), *C. cynocephalus* (n = 1) and *Neotermes sp.* (n = 1). *Coptotermes gestroi, C. brevis, I. minor, N. connexus* and *Z. angusticollis* were not found. There was no relationship between *I. immigrans* incidence with elevation and average annual rainfall. Co-occurrence with ant species was examined using a probabilistic model, and positive co-occurrences of *I. immigrans* with *Paratrechina longicornis* and *Solenopsis geminata* were significant ($p < .0422$ and $p < .0140$, respectively), while negative co-occurrence of *I. immigrans* and *Pheidole megacephala* was significant ($p < .0007$). *Coptotermes formosanus* and *C. brevis* termites were found more often from alate surveys, which may be a better method to map subterranean and primarily structure-dwelling termite distributions. Continued termite education along the windward and leeward coasts is recommended due to the presence of *C. formosanus* and *C. gestroi.*

Convenience sampling draws samples from readily available sources and is often the most practical method of surveying animal and plant distribution, but can also be biased. Convenience sampling is often justified due to time, money, personnel and equipment constraints. However, inferences from data obtained from such studies may need to be limited. To explore convenience sampling bias in roadside surveys of ants and termites, a distribution study was conducted on Oahu from September to November 2012. A timed search (one person, 30 minutes) was conducted at each paired site near (less than 15-m) roads and away (more than 15-m) from roads. Ants

and termites were collected and identified to species. There was no significant difference in the species richness of road and away sites. No significant difference between road and away sites was detected with a multi-response permutation procedure. However, the species compositions as measured by Jaccard distance of road and away sites were significantly different at four sites individually. However, Jaccard distances by combined vegetation zone for ants and termites were not significant, and the overall combined road and away Jaccard distance (36.00%) was not significant. Although differences were minimal in the present study, caution is still recommended when conducting distribution surveys based on convenience.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. ANT DISTRIBUTION ON OAHU, HAWAI'I

ABSTRACT

Ants are successful social insects that provide several ecosystem functions and are found in almost every part of the world. Ants can also negatively affect agriculture, the economy, biodiversity, and human and vertebrate health. Hawai'i has fifty-seven established species of ants. An island-wide hand-collection survey of ants has not been carried out since 1966-1967. A systematic survey of ants was conducted along roads on Oahu from September to November 2012. Ants were collected by hand during 30-minute searches of 44 sites. Generalized linear models were run for species' presence or absence, using elevation, rainfall, and soil type as possible sources of variation. Species co-occurrence was analyzed with a probabilistic model. The number of ant species in the presence and absence of dominant ant species was compared with analysis of variance. Twenty-four species from five subfamilies were found. *Ochetellus glaber* was found in drier areas ($p < .0109$); *Paratrechina longicornis* was found in lower elevations ($p < .0009$) and in areas with Mollisols ($p < .0059$); and *Tetramorium simillimum* was found in lower elevations ($p < .0215$) and in areas with Mollisols ($p < .0190$). *Pheidole megacephala* had seven negative co-occurrences (*Monomorium floricola, Pseudomyrmex gracilis, Solenopsis geminata, Solenopsis hi01, Tapinoma melanocephalum,* and *Technomyrmex albipes*). *Technomyrmex difficilis* and *Tetramorium simillimum* had a positive co-occurrence. *Pheidole megacephala* was associated with fewer ant species at sites where it occurred, while *P. longicornis and T. difficilis* were associated with higher numbers of ants where they occurred. Once-common ants, *Nylanderia bourbonica* and *Nylanderia vaga* were not found or found at only one site, respectively; while the more recently introduced *O. glaber* and *T. difficilis* seem to be expanding in range. Mapping ant distributions on Oahu may contribute to understanding the factors that determine each species' spread, may reveal species interactions, and may help inform possible management decisions.

INTRODUCTION

Ants (Hymenoptera: Formicidae) are complex social insects considered by Hölldobler and Wilson to be the "culmination of insect evolution" (1990). Ants thrive in a range of environments (Hölldobler and Wilson, 1990) and are usually ecologically dominant (Moreau, 2008). These diverse social insects provide several ecosystem functions, such as soil turnover, nutrient redistribution, and as prey for a variety of predators including mammals, reptiles, spiders (Holway et al., 2002), and other ants (Hölldobler and Wilson, 1990). Ants also act as seed dispersers, scavengers, predators, and detritivores (Hill, Summerville, and Brown, 2008; Holway et al., 2002). As such influential and ubiquitous insects, ants affect agriculture, the economy, biodiversity, and human and vertebrate health (Chong, and Lee, 2010; Grace and Leong, 2008; Gutrich, VanGelder, and Loope, 2007; Holway et al., 2002; Krushelnycky, 2005; Pantoja et al., 2009; Rust and Su, 2010). Invasive ant species in particular especially have the potential to adversely affect areas to which they are introduced (Holway et al., 2002).

Ants in Hawai'i

Hawai'i is the most isolated island archipelago in the world, 3200 km from any other island and 4000 km from the nearest continent (Howarth, Sohmer, and Duckworth, 1988). Only half the insect orders and about 15% of insect families are represented in Hawai'i's native terrestrial fauna (Howarth et al., 1988).

Wilson and Taylor (1967) considered the ant fauna of Hawai'i to be completely introduced. Regardless of whether or not Hawai'i has never had any native ants, ants are found throughout the islands, with most limited to lower elevations (Krushelnycky, et al., 2005; Reimer, 1994). Hawai'i is now considered home to five of the six most damaging invasive ants, *Anoplolepis gracilipes,* long-legged ant; *Linepithema humile*, Argentine ant; *Pheidole megacephala*, big-headed ant; *Solenopsis geminata*, tropical fire ant; and *Wasmannia auropunctata*, little fire ant (Holway et al., 2002; Krushelnycky et al., 2005). Ten species of ants are considered to be of public health concern on Oahu: *Camponotus variegatus, Linepithema humile, Monomorium pharaonis, Monomorium floricola, Ochetellus glaber, Paratrechina longicornis, Pheidole megacephala, Pseudomyrmex gracilis,*

Solenopsis geminata and *Tapinoma melanocephalum* (Leong and Grace, 2008; Pantoja et al., 2009).

The number of ant species in Hawaiʻi has changed over time. Forel (1899) reported twenty species of ants in Hawaiʻi, three of which were later identified as synonymous with another species, mislabeled, or no longer occurring in Hawaiʻi (Wheeler, 1934). Gulick (1913) prepared a synoptic list and key to twenty-three ants in Hawaiʻi. Wheeler (1934), through examination of museum specimens in addition to his own collection, presented a revised list of thirty-five ant species for Hawaiʻi. Phillips (1934) surveyed ants in pineapple fields. Wilson and Taylor's "Ants of Polynesia" monograph (1967) lists thirty-six species of ants in Hawaiʻi, thirty-four occurring in Oahu. Further, Wilson and Taylor (1967) considered all of Hawaiʻi's ants to be introduced, whereas six species were previously thought to be endemic. Huddleston and Fluker (1968) found forty-two species of ants in Hawaiʻi in an island-wide hand-collection survey. Reimer presented the distribution of thirty-eight ants by ecological communities from historical data (1994). Krushelnycky (2005) reported forty-seven species of ants established in Hawaiʻi based on a review of historical data. Leong and Grace (2008) analyzed Hawaiʻi Department of Health Vector Control Branch inspection reports from 1990-1999 to evaluate pest occurrences on Oahu. Ant complaints occurred mostly in urban environments in southern Oahu as well as drier areas of the island, with the most complaints regarding *Monomorium pharaonis, Camponotus variegatus,* and *Ochetellus glaber* (Leong and Grace, 2008). Plentovich (2010) surveyed Makua and Oahu Implementation Plan Management Units (primarily within the Waianae and Koʻolau mountain ranges) on Oahu from 2004-2009 using bait cards. The Cooperative Agricultural Pest Survey (CAPS) Program of the Hawaiʻi Department of Agriculture used bait cards at high-risk ports of entry around Oahu to detect the red imported fire ant (*Solenopsis invicta*), and has reported twenty species of ants at thirty-eight sites from a 2005 survey (Heu and Suh, 2006). Brigham Young University faculty and students have collected ants on Oahu and several other islands from 1988-1996 using roadside hand-collection techniques, but data from Oahu remain unpublished (J. Auger, personal communication). To date, at least fifty-seven species of ants have become established in Hawaiʻi (Krushelnycky, 2013), and the last island-wide survey of ants on Oahu was conducted in 1966-1967 by Huddleston and Fluker (1968).

The objective of this study is to provide an updated descriptive distribution of ants on Oahu. Huddleston and Fluker's 1968 "Distribution of Ant Species of Hawai'i" is the most recent published hand-collected island-wide survey of ants, making a new survey timely for continued documentation of the ants of Hawai'i. Mapping ant distributions on Oahu may contribute to understanding of the factors that determine each species' spread, may reveal species interactions, and may help inform possible management decisions (Krushelnycky et al., 2005). Information regarding alien ants may be useful to other geographic areas experiencing invasions (Reimer, 1994). Finally, the current survey will also provide reference data for future comparisons.

MATERIALS AND METHODS

A systematic survey of ants was conducted along major roads on Oahu, Hawai'i from September to November 2012.

Study location

Oahu is the third largest and most populous island of Hawai'i, with about 80% of the state's population (Hartley and Chen, 2010). Two major mountain chains span the island: the Ko'olau Range on the eastern coast (~500 – 950 m high by ~72 km long) and the Wai'anae Range on the western coast (~470 – 1200 m by ~56 km long) (Hartley and Chen, 2010). Oahu has two primary physiographic zones, windward and leeward, with higher rainfall on the windward side (Brasher, Wolff, and Luton, 2003). Small variation in solar radiation, buffering of the ocean, and the effect of trade winds contribute to Oahu's mild temperatures (Brasher et al., 2003). Oahu has a colder, wetter season from October to April and a warmer season from May to September (Brasher et al., 2003).

Ripperton and Hosaka (1942) characterized five major vegetation zones primarily to describe areas with similar climate, soils and vegetation types for use in agriculture (Table 1). These factors also influence ant distribution (Huddleston and Fluker, 1968). Vegetative zone is highly influenced by rainfall.

4

Table 1. Vegetation zones of Oahu, Hawai'i as characterized by Ripperton and Hosaka (1942).

Zone	Elevation (m)	Average Annual Rainfall (mm)	Vegetation
A	0 - 600 (usually < 150)	< 500	Xerophytic shrubs (mostly exotic), coastal fringe of trees
B	0 - 900 (average of 600)	500 - 1000	Xerophytic shrubs, trees in higher elevations
C	0 - 1200	1000 - 1500	Open shrubs and grasses in lower elevations, mixed open forest
D	0 - 2000	> 1500	Shrub to open grasslands and closed and open forests
E	> 2000	< 1270	Open forest and shrub, upland forest, to above tree line (Hawai'i and Maui only)

Soil type is also of interest as an explanatory variable for ant distributions. In Portugal, certain soils were suggested to prevent colonization of *Linepithema humile* (Way, Cammell, Paiva and Collingwood, 1997). Ant species composition and abundance differed in serpentine and non-serpentine soils in chaparral ecotypes (Fisher, 1997). Further, leaf-cutting ants were found to have a preference for Oxisols (Schoereder and DaSilva, 2008). Nine soil orders occur on Oahu (Deenik and McClellan, 2007). By acreage, Oxisols are the most common order, followed by Ultisols, Mollisols, and Vertisols (Deenik and McClellan, 2007). Oxisols are infertile, weathered soils in varying elevations and degrees of rainfall; Ultisols are weathered soils in wetter areas; Mollisols are nutrient-rich soils common in grasslands and coastal plains; and Vertisols are clay-rich soils in dry, lowland regions (Deenik and McClellan, 2007).

Mapping of points

A random starting point between 0-1000 m from the beginning of major roads (Farrington Highway, Kalanianaole Highway, Kamehameha Highway, Kaukonahua Road, King Street, Pali Highway, Roosevelt Avenue) was selected. From this starting point, possible collection points were generated at 1-km intervals using "Construct Points" in ArcMap 10.1 (ESRI, 2013). Points were numbered (e.g., PPFARR01 for "Planned Point Farrington Highway 1") and evaluated for suitability in Google Earth (version 7.0.3.8542) street view. Suitable points were areas that were accessible (not on private property) and safe (not on a steep cliff or dangerously close to traffic).

Starting from the random point, every fourth point was selected (4 km intervals). Points considered unsuitable were replaced with the nearest suitable point (1-2 km away from original selection) or discarded entirely if no replacement was accessible. Points that fell within state parks where a permit was denied (Kaena Point) were also discarded.

Collection

Special use application permits were obtained for collecting ants at points that fell within state parks from the Division of State Parks. No permits were necessary for city parks.

A timed search (one person, 30 minutes) for ants occurred at each suitable site. A 15-m tape measure was laid down starting from the edge of the pavement or edge of a barrier (e.g., stone wall or fence) in a perpendicular direction. Collection occurred within the 15-m distance. The area searched varied from 25-450 m^2, depending on the layout of the site and searchable substrates; however, all searches were of the same duration (30 minutes).

Ants were collected by hand with an aspirator, forceps or by covering with a tube. Specimens were stored in 95% ethyl alcohol. To ensure peak ant activity, collection times were restricted to between 8:00 a.m. - 11:00 a.m. and 1:00 p.m. - 4:00 p.m.

Ants were collected from plants (flowers, leaves, trunks, twigs, etc.), the ground (leaf litter, concrete, grass, etc.), objects (walls, telephone poles, trash cans, etc.), and under objects (rocks, logs, trash, etc.) (Nelson, 1993). Fallen branches with evidence of insect damage were opened to extract ants. Separate vials for different substrates were used (e.g., "leaf litter", "plumeria tree", etc.).

Weather data were taken from nearby weather stations using the WeatherBug application (Earth Networks, version 2.0) on an iPhone. Visual observations were also recorded. Soil temperature was taken from a depth of ~15 cm near the generated point, or within the search area where soil was penetrable.

Latitude, longitude, and altitude were taken with a Garmin GPS 76. Coordinates were then re-checked with Google Earth (version 7.0.3.8542) for accuracy. Sites were labeled sequentially to get map codes.

Map layers were downloaded from the State of Hawaiʻi Office of Planning GIS Data site, the U. H. Geography Department, and the United States Department of Agriculture Natural Resources Conservation Service's Geospatial Data Gateway (Coastal Geology Group, 2013; Giambelluca et al., 2013; State of Hawaiʻi, 2013; USDA, 2014). Honolulu County Land Cover data were downloaded from the NOAA Coastal Services Center (2013). Average rainfall (mm), elevation contours (10 m), and soil data were used to create maps and to spatially join data to points. Layers available as raster data were first converted to points and spatially joined with ArcMap 10.1 (ESRI, 2013). Vegetation zones were mapped with ArcMap 10.1 (ESRI, 2013) using Ripperton and Hosaka's map (1942) as an overlay (Figure 1).

Pictures and video were taken of each substrate on which ants were found. Pictures of unknown plants were uploaded to the Hawaiʻi Plant ID Flickr group (http://www.flickr.com/groups/hawaiiplantid/pool).

Identification

Ants were identified to species using the Hawaiʻi Ant Lab's "Key to the Sub Families of Hawaiʻi" (Vanderwoude, 2012), PIA Key (Sarnat, 2008), and Bolton's revision of *Technomyrmex* (2007).

Analysis

The distribution of ants was mapped using ArcMap 10.1 (ESRI, 2013).

For ants occurring at a minimum of 20% (nine) sites, a generalized linear model (binomial, logit link) was performed on the presence or absence of ants at each site with elevation, average annual rainfall, and soil order as explanatory variables using JMP 11.1.1 (SAS Institute, 2013). A generalized linear model (binomial, logit link) was also analyzed for the same subset of ants with vegetation zone as the explanatory variable using JMP 11.1.1 (SAS Institute, 2013) for comparison with Huddleston and Fluker (1968).

Species and site data were put into a matrix for analysis in the 'cooccur' package in R (Griffith, Veech, and Marsh, 2014), a probabilistic model of species co-occurrence, which follows Veech (2013). Observed and expected frequencies of co-occurrence are calculated for each species pair, with expected frequencies "based on the distribution of each species being random and independent of the other species" to

find positive or negative species co-occurrences (Griffith, et al., 2014). Species pairs not expected to co-occur more than once were filtered from results, decreasing the amount of analyzed pairs (Griffith, et al., 2014).

The number of species in the presence and absence of dominant species (Krushelnycky et al., 2005; Wetterer, 2013) occurring at 20% of sites or more (*Paratrechina longicornis, Pheidole megacephala,* and *Technomyrmex difficilis*) was subjected to analysis of variance using JMP 11.1.1 (SAS Institute, 2013) to compare each species' impact on the ant assemblages.

Historical data from Huddleston and Fluker's 1968 survey were mapped by species for comparison with the present survey. Species names were updated according to various sources (Bolton, 1977; Bolton, 1995; Bolton, 1999; Brown, 1975; Heinze, 1999; LaPolla, Brady and Shattuck, 2010; Shattuck, 1992; and Wetterer, 2013).

RESULTS

Forty-four sites were found suitable for collecting ants (Figure 1; Table 2).

Table 2. Site summary of abiotic factors by vegetation zone (Ripperton and Hosaka, 1942).

Vegetation Zone	Number of sites	Elevation (m)		Average Annual Rainfall (mm)	
		Mean ± Std Dev	Range	Mean ± Std Dev	Range
A	11	8 ± 9.97	1 - 35	658 ± 94.31	541 - 784
B	18	12 ± 20.99	1 - 82	876 ± 155.95	615 - 1194
C	13	39 ± 84.17	1 - 234	1370 ± 265.51	934 - 1767
D	2	237 ± 177.80	111 - 362	2198 ± 362.01	1942 - 2454
Total	**44**		**1 - 362**		**541 - 2454**

Twenty-four species of ants from five subfamilies (Dolichoderinae, Formicinae, Myrmicinae, Ponerinae, and Pseudomyrmecinae) were found from the forty-four sites (Table 3). The red imported fire ant, *Solenopsis invicta* (not reported in Hawai'i), the little fire ant, *Wasmannia auropunctata*, and the Argentine ant, *Linepithema humile*, were not observed at any sites in this study. The most frequently-encountered ant was *Pheidole megacephala* (55% of sites), followed by *Ochetellus glaber* (43%), *Technomyrmex difficilis* (27%), and *Plagiolepis alluaudi* (23%).

Table 3. Number of sites (N) and frequency of ant species by subfamily on Oahu, Hawai'i, from Huddleston and Fluker's (H & F) 1968 survey and the present survey.

Subfamily Species	H & F (1968)		Present survey	
	N	Freq (n=65)	N	Freq (n=44)
Cerapachyinae				
Cerapachys biroi (=Hypoponera sinensis; Syscia silvestrii)	14	0.22	-	-
Dolichoderinae				
Linepithema humile (=Iridomyrmex humilis)	8	0.12	-	-
Ochetellus glaber	-	-	19	0.43
Tapinoma melanocephalum	16	0.25	5	0.11
Technomyrmex albipes	-	-	5	0.11
Technomyrmex difficilis	-	-	12	0.27
Technomyrmex pallipes	-	-	2	0.05
Technomyrmex vitiensis (=T. albipes)	3	0.05	2	0.05
Formicinae				
Anoplolepis gracilipes (=Anoplolepis longipes)	17	0.26	1	0.02
Brachymyrmex sp. nr. obscurior	-	-	2	0.05
Camponotus variegatus	8	0.12	3	0.07
Nylanderia bourbonica (=Paratrechina bourbonica)	11	0.17	-	-
Nylanderia vaga (=Paratrechina vaga)	17	0.26	1	0.02
Paratrechina longicornis	9	0.14	9	0.20
Plagiolepis alluaudi	18	0.28	10	0.23
Myrmicinae				
Cardiocondyla emeryi	9	0.14	7	0.16
Cardiocondyla minutior (=C. nuda)	14	0.22	-	-
Cardiocondyla obscurior	-	-	1	0.02
Cardiocondyla venustula (=C. "a")	11	0.17	-	-
Cardiocondyla wroughtonii (=C. wroughtoni)	4	0.06	3	0.07
Monomorium bicolor group	-	-	2	0.05
Monomorium destructor	3	0.05	-	-
Monomorium floricola	15	0.23	5	0.11
Monomorium liliuokalani (=M. minutum)	12	0.18	-	-
Monomorium sechellense (=M. fossulatum)	11	0.17	-	-
Pheidole fervens	1	0.02	-	-
Pheidole megacephala	14	0.22	24	0.55
Solenopsis hi01	-	-	4	0.09
Solenopsis geminata	19	0.29	7	0.16
Solenopsis papuana (=S. "a"; S. "b")	2	0.03	-	-
Strumigenys emmae (=Quadristrumma emmae)	3	0.05	-	-
Strumigenys godeffroyi	3	0.05	-	-

Table 3. (Continued) Number of sites (N) and frequency of ant species by subfamily on Oahu, Hawai'i, from Huddleston and Fluker's (H & F) 1968 survey and the present survey.

Strumigenys lewisi	9	0.14	-	-
Tetramorium bicarinatum (=T. guineense)	16	0.25	-	-
Tetramorium caldarium	-	-	1	0.02
Tetramorium simillimum	30	0.46	9	0.20
Tetramorium tonganum	1	0.02	-	-
Ponerinae				
Hypoponera opaciceps	12	0.18	-	-
Hypoponera punctatissima	4	0.06	-	-
Hypoponera zwaluwenburgi	1	0.02	-	-
Leptogenys falcigera	3	0.05	5	0.11
Pseudomyrmecinae				
Pseudomyrmex gracilis	-	-	4	0.09

Ochetellus glaber was found in drier areas ($p < .0109$) around Oahu (Table 4). *Paratrechina longicornis* was found more often in lower elevations ($p < .0009$) and in areas with the Mollisol soil order ($p < .0059$) (Table 4). *Tetramorium simillimum* was found in lower elevations ($p < .0215$) and in areas with the Mollisol soil order (Table 4). Elevation, rainfall, and soil type were not significant sources of variation for *Pheidole megacephala, Plagiolepis alluaudi,* and *Technomyrmex difficilis* (Table 4).

The presence and absence of *Ochetellus glaber, Paratrechina longicornis, Plagiolepis alluaudi, Technomyrmex difficilis,* and *Tetramorium simillimum* did not differ significantly by vegetation zone. *Pheidole megacephala* was found significantly more in vegetation zone C ($p < .0002$). The presence and absence of *P. longicornis, P. megacephala, P. alluaudi,* and *T. simillimum* from Huddleston and Fluker's (1968) survey did not differ by vegetation zone.

Table 4. Generalized linear model (binomial, logit link) for species occurring at nine sites or more (> 20%).

| Subfamily | Species (n sites) | *p*-value | | | |
		Whole model	Elevation	Rainfall	Soil
Dolichoderinae					
	Ochetellus glaber (19)	0.0293*	0.2188	0.0109*	0.2952
	Technomyrmex difficilis (12)	0.1029			
Formicinae					
	Paratrechina longicornis (9)	0.0063**	0.0009***	0.6212	0.0059**
	Plagiolepis alluaudi (10)	0.1878			
Myrmicinae					
	Pheidole megacephala (24)	0.3411			
	Tetramorium simillimum (9)	0.0375*	0.0215*	0.4584	0.0190*

Out of 300 species combinations, 234 were removed from the analysis because the expected co-occurrence was less than one. Sixty-six species pairs were analyzed, with one positive co-occurrence, nine negative co-occurrences, and fifty-six random pairs (Table 5).

Pheidole megacephala had seven negative co-occurrences. *Monomorium floricola, Pseudomyrmex gracilis, Solenopsis geminata, Solenopsis hi01, Tapinoma melanocephalum,* and *Technomyrmex albipes* did not occur at the same site with *Pheidole megacephala*, the most frequently-encountered ant. *Paratrechina longicornis* occurred at two sites with *P. megacephala*, which is significantly less than expected if the species occurrences were random.

Technomyrmex difficilis and *Tetramorium simillimum* were the only positive species pair, co-occurring at five sites instead of the expected 2.5 (Table 5).

Table 5. Statistically significant species co-occurrences as derived from 'cooccur' package "Probabilistic Species Co-occurrence Analysis in R" (Griffith, et al., 2014). Species pairs expected to have less than one co-occurrence were filtered from analysis. P_c: probability of co-occurrence between species pair; O_c: observed number of sites with both species; E_c: expected number of sites with both species (if independent and random); P_{neg}: probability of negative co-occurrence; P_{pos}: probability of positive co-occurrence.

Species pair (number of sites present in parentheses)	P_c	O_c	E_c	P_{neg}	P_{pos}
Ochetellus glaber (19) *Tapinoma melanocephalum* (5)	0.049	0	2.2	0.0489*	1.0000
Ochetellus glaber (19) *Technomyrmex difficilis* (12)	0.118	2	5.2	0.0308*	0.9957
Pheidole megacephala (24) *Monomorium floricola* (5)	0.062	0	2.7	0.0143*	1.0000
Pheidole megacephala (24) *Paratrechina longicornis* (9)	0.112	2	4.9	0.0347*	0.9955
Pheidole megacephala (24) *Pseudomyrmex gracilis* (4)	0.050	0	2.2	0.0357*	1.0000
Pheidole megacephala (24) *Solenopsis geminata* (7)	0.087	0	3.8	0.0020**	1.0000
Pheidole megacephala (24) *Solenopsis hi01* (4)	0.050	0	2.2	0.0357*	1.0000
Pheidole megacephala (24) *Tapinoma melanocephalum* (5)	0.062	0	2.7	0.0143*	1.0000
Pheidole megacephala (24) *Technomyrmex albipes* (5)	0.062	0	2.7	0.0143*	1.0000
Technomyrmex difficilis (12) *Tetramorium simillimum* (9)	0.056	5	2.5	0.9930	0.0472*

The presence of *Pheidole megacephala* is associated with fewer species of ants per site (2.88 [s.d. = 1.23] with *P. megacephala* and 3.70 [s.d. = 1.46] in the absence of *P. megacephala)* ($p < .0259$) (Table 6). *Paratrechina longicornis* and *Technomyrmex difficilis* were both associated with significantly higher mean numbers of ants per site ($p < .0001$ and $p < .0004$, respectively) (Table 6).

Table 6. Mean number of ant species in the presence and absence of dominant ants on Oahu.

Species	N present	N absent	Present Mean ± Standard Deviation			Absent Mean ± Standard Deviation			*p*-value
Paratrechina longicornis	9	35	4.78a	±	0.97	2.86b	±	1.19	.0001***
Pheidole megacephala	24	20	2.88a	±	1.23	3.70b	±	1.46	.0259*
Technomyrmex difficilis	12	32	4.33a	±	1.07	2.84b	±	1.27	.0004***

As Huddleston and Fluker's survey (1968) used hand-collection techniques and reported coordinates and ecological data, the thirty-two species of ants from sixty-five sites on Oahu are reported here (Table 3) and mapped on ArcGIS Online at http://bit.ly/1rH9gXq. Species Huddleston and Fluker (1968) reported that were not found in the present study are: *Cerapachys biroi, Linepithema humile, Nylanderia bourbonica, Cardiocondyla minutior, Cardiocondyla venustula, Monomorium destructor, Momonorium liliuokalani, Monomorium sechellense, Pheidole fervens, Solenopsis papuana, Strumigenys emmae, Strumigenys godeffroyi, Strumigenys lewisi, Tetramorium bicarinatum, Tetramorium tonganum, Hypoponera opaciceps, Hypoponera punctatissima,* and *Hypoponera zwaluwenburgi.* Species found in the present study not found in the Huddleston and Fluker study are: *Ochetellus glaber, Technomyrmex albipes, Technomyrmex difficilis, Technomyrmex pallipes, Brachymyrmex sp.nr. obscurior, Cardiocondyla obscurior, Monomorium bicolor group, Solenopsis hi01, Tetramorium caldarium,* and *Pseudomyrmex gracilis.* These species have either become established in Hawai'i since Huddleston and Fluker's (1968) survey, or were not recognized as separate species in 1968 (e.g., *Cardiocondyla obscurior, Tetramorium caldarium).*

DISCUSSION

The distributions of twenty-four species of ants were mapped on Oahu, contributing to continued documentation of ants in Hawaiʻi. The bigheaded ant, *Pheidole megacephala*, seems to be the dominant ant of Oahu. Two recent invaders, *Ochetellus glaber* and *Technomyrmex difficilis*, were among the most frequently encountered ants.

Pheidole megacephala seemed to be found more often on the windward side of Oahu, which is consistent with the significant correlation with vegetation zone C. *Pheidole megacephala* was also associated with fewer species of ants where it occurred, possibly because of its aggressive behavior.

Technomyrmex difficilis is rapidly expanding its range outside its native Madagascar (Wetterer, 2013). *Technomyrmex difficilis* is considered by Wetterer (2013) to be a dominant arboreal pest in the West Indies and Florida. However, mean number of ants in the presence of *T. difficilis* is higher than in its absence. Possible reasons include its relatively recent establishment, lack of overlap of resources with other species of ants, and uncertain inter-specific agonistic behaviors.

Ochetellus glaber, the glaber ant, was first noted in 1977 by Beardsley (1980) at Hickam Air Force Base on Oahu. This ant appears to be widely distributed around the island with a preference for drier areas. *Ochetellus glaber* occurred with *Pheidole megacephala* at ten sites and *Solenopsis geminata* at three sites, suggesting it can persist even with strongly competitive species. However, *O. glaber* negatively co-occurred with *Technomyrmex difficilis*, which may be because of the recent invasion histories of both species, different habitat preferences, or possibly some type of competition.

Technomyrmex difficilis and *Tetramorium simillimum* were the only positive species pair, which may be because of similar abiotic environmental preferences. *Technomyrmex difficilis* occurred in elevations of 1-110 m at sites with average annual rainfalls of 541-1492 mm, similar to *T. simillimum*'s elevation range of 1-35 m and average annual rainfall range of 541-1633 mm. Further, both *T. difficilis* and *T. simillimum* did not have a negative co-occurrence with *P. megacephala*, the most common ant. *Pheidole megacephala* and *Solenopsis geminata* were not found together at any site.

14

Two ants were found more often in areas with Mollisol soil (*Paratrechina longicornis* and *Tetramorium simillimum*). However, nearly half of all sites had Mollisol soil, which may reduce the explanatory power of soil type in this study.

The tropical fire ant, *Solenopsis geminata*, was found at seven sites. The red imported fire ant, *S. invicta*, is known to displace *S. geminata* where it occurs (Wetterer, 2011), and the sites where *S. geminata* now occurs should be monitored closely for signs of possible introduction and establishment of *S. invicta.*

Though *Monomorium pharaonis* was first recorded in 1913 (Gulick), both Huddleston and Fluker (1968) and the present study failed to collect this species, possibly due to the ecology of this ant and the collection methodology employed. The Hawai'i Department of Health Vector Control Branch received more complaints about *M. pharaonis* than any other ant species (Leong and Grace, 2008).

Several limitations are inherent in this study. All sites were close to roads, and thus human disturbance and urbanization (Reimer, 1994). Most sites also were near coastlines, and at lower elevations, which limits the representation of ants in differing ecological communities (e.g., montane, cool dry forest, alpine scrub, etc. [Reimer, 1994]). The ants collected may not represent the full assemblages present, as cryptic and nocturnal species may not have been collected. Recent introductions of certain ant species, which have not yet attained their total potential distributions, may skew analyses relating to correlation with other species and with environmental factors.

However, an update to the hand-collection surveys was useful, as nearly twenty species have been added to Hawai'i's ant fauna since the last survey by Huddleston and Fluker (1968). Future studies surveying ants near the present sites may find this data useful for comparison. Surveys sampling a wider range of elevations and soil types are needed though to solidify possible associations with ant distributions.

Ants collected

A list of species found in the present survey is given below.

Anoplolepis gracilipes. The long-legged ant is considered a highly invasive species with negative impacts on natural ecosystems, agriculture and livestock (Chong and Lee, 2010). The long-legged ant was found at only one site in Ulehawa Beach Park in Waianae. Huddleston and Fluker's 1966-67 survey found *A. gracilipes*

at 26% of sites in vegetation zones A and B, spanning from Ko Olina, Kalaeloa, Waipahu, Fort Shafter, Honolulu, and one site in Kaneohe. Kirschenbaum and Grace (2007) found *A. gracilipes* to be dominant at a site on Tantalus one year, but the next year a *Technomyrmex* species was dominant, suggesting *A. gracilipes* may be readily displaced. The lower frequency of the present study's collection of *A. gracilipes* may mean it is being displaced, possibly by *Technomyrmex* ants.

Brachymyrmex sp. nr. obscurior. This small, brown ant is usually not considered a major pest, but can sometimes be a minor urban pest (Klotz et al., 1995). *Brachymyrmex sp. nr. obscurior* was found in Kapolei in a landscaped commercial area and in Hawai'i Kai within Waialae Iki Park. Huddleston and Fluker (1968) noted *B. sp. nr. obscurior* was found in orchid baskets in Honolulu, but did not find any at their survey sites. *Brachymyrmex sp. nr. obscurior* was listed in Krushelnycky's (2005) review of ants in Hawai'i. Collections in the present survey suggest its continued establishment on Oahu.

Camponotus variegatus. This long-established carpenter ant was found in Kapolei, Waialua and the North Shore near Kawela Bay. *Camponotus variegatus* is considered a public health threat, as it is known to bite (Leong and Grace, 2008). The carpenter ant is a frequent household pest (Huddleston and Fluker, 1968). Between 1990-1999, almost 16% of ant pest complaints were about *C. variegatus* (Leong and Grace, 2008). *Camponotus variegatus* is a nocturnal species, which may cause its range to be underestimated. Huddleston and Fluker (1968) found *C. variegatus* in Ko Olina, Kapolei, Waipahu, and Diamond Head.

Cardiocondyla emeryi. *Cardiocondyla emeryi* was found between Waialua and Wahiawa, near Pearl Harbor, Kaneohe, Hawai'i Kai, and in Waianae in Ulehawa Beach Park. *Cardiocondyla emeryi* is one of the six *Cardiocondyla* species that have spread to much of the tropics and subtropics (Heinze et al., 2006). *Cardiocondyla* ants are "ecologically subordinate" and seem to be a minor threat (Heinze et al., 2006). Huddleston and Fluker (1968) found *C. emeryi* in Kapolei, Waipahu, Honolulu, Hawai'i Kai, Kaneohe, and on Poamoho foot trail.

Cardiocondyla obscurior. *Cardiocondyla obscurior* is another species of its genus that has spread throughout much of the tropics (Heinze et al., 2006). *Cardiocondyla obscurior* is polygynous and can spread through budding, but is not considered a major ecological threat because of its ecological subordinate status

(Heinze et al., 2006). A site near the entrance of Malaekahana State Recreation Area had numerous *C. obscurior* foragers. Huddleston and Fluker (1968) did not record *C. obscurior,* because it was not recognized as distinct from *C. wroughtonii* at the time; it was later raised to species level by Seifert (2003). Therefore, some earlier collections of *C. wroughtonii* may actually be *C. obscurior*.

Cardiocondyla wroughtonii. Like the other ants of genus *Cardiocondyla* found in this study, *C. wroughtonii* is a species that has spread throughout the tropics (Heinze et al., 2006). *Cardiocondyla wroughtonii* was found in Kahaluu, near Pearl Harbor, and near Iolani Palace. Huddleston and Fluker (1968) noted that *C. wroughtonii* was found in "higher and wetter" areas than *C. emeryi*. Huddleston and Fluker (1968) found *C. wroughtonii* in Kapolei, Kaneohe, Waimanalo and near Kipapa Stream. As noted, *C. wroughtonii* and *C. obscurior* were not considered separate species in 1968.

Leptogenys falcigera. This African species was one of the first to colonize Hawai'i (Smith, 1879, cited in Kirschenbaum and Grace, 2008). This ant forms small, cryptic colonies, and is able to survive interactions with aggressive ants (Kirschenbaum and Grace, 2008). *Leptogenys falcigera* was found along the north and windward coast, while Huddleston and Fluker (1968) found *L. falcigera* near Kipapa stream, Waimanalo, and Aina Haina. Its cryptic nature may cause its range to be underestimated.

Monomorium bicolor group. This ant was found in Kapolei and in Waianae in Ulehawa Beach Park. Huddleston and Fluker (1968) did not find *M. bicolor group*; however, this species has only been recognized in Hawai'i within the last decade. Inspection of museum specimens is required to assess its date of first record in the state, as earlier collections may have been confused with *M. pharaonis*.

Monomorium floricola. The flower ant is a highly successful tramp ant present throughout the tropics and heated areas of temperate zones (Wetterer, 2010a). This widespread ant is considered a minor home-invading and agricultural pest, but is considered a public health pest as vectors of pathogens (Wetterer, 2010a). *Monomorium floricola* was found on the north shore, Waianae, Kapolei, Aiea, and along the Pali Highway. Huddleston and Fluker (1968) found *M. floricola* at several sites in Ko Olina, Kapolei and Waimanalo, and in Honolulu and Kaneohe.

Nylanderia vaga. Along with *N. bourbonica*, *N. vaga* is a widespread tramp ant common in the tropics (LaPolla, Brady, and Shattuck, 2011). *Nylanderia vaga* was found at one site in Pali lookout. Huddleston and Fluker (1968) found *N. vaga* at 26% of sites (Ko Olina, Kalaeloa, Waimanalo, Waipahu, Wahiawa, and Pupukea), and *N. bourbonica* at about 17% of sites (Makakilo, Kapolei, Diamond Head, Wahiawa, Mt. Ka'ala, and Pupukea).

Ochetellus glaber. The glaber ant was first noted in 1977 by Beardsley (1980) at Hickam Air Force Base on Oahu. The glaber ant is considered a public health pest because of its bite (Leong and Grace, 2008). *Ochetellus glaber* was the second-most frequently encountered ant (43% of sites). Colonies of *O. glaber* ants were observed within tree branches, often also containing *Incisitermes immigrans* termites (see Chapter 2). This ant was found across the island, but less frequently on the wetter windward coast.

Paratrechina longicornis. The longhorn crazy ant is considered the "most widespread of all tramp ants" (Wetterer, 2008). *Paratrechina longicornis* is associated with disturbed areas and can become an agriculture pest as it tends phloem-feeders (Wetterer, 2008). The longhorn crazy ant is considered a public health pest because it is a mechanical vector of pathogens (Pantoja et al., 2009). *Paratrechina longicornis* was found at nine sites spanning from Kahaluu, Kapolei, Waialua, the north shore, and Waianae. Huddleston and Fluker (1968) found *P. longicornis* in Ko Olina, Honolulu, and Waimanalo.

Pheidole megacephala. The African bigheaded ant is a widespread indoor and outdoor pest (Wetterer, 2007). *Pheidole megacephala* is aggressive and has been noted to cause devastating effects on native arthropods (Wetterer, 2007). The African bigheaded ant also tends mealybugs, scales, and aphids, making it an agriculture pest (Wetterer, 2007). This aggressive ant is known to bite and invade homes as well as damage electrical wires and other property (Leong and Grace, 2008; Wetterer, 2007). *Pheidole megacephala* was found in Waianae, Kapolei, Waialua, the North shore, Laie, Hauula, Kaaawa, Kaneohe, Waimanalo, Hawai'i Kai, Honolulu, and Aiea. Huddleston and Fluker (1968) found *P. megacephala* at Ko Olina, Mt. Ka'ala, Kahuku, Waipahu, Honolulu, and Waimanalo. Despite being considered a lowland ant, *P. megacephala* was found at Mt. Ka'ala summit (~1219 m elevation)

(Huddleston and Fluker, 1968) and near Ohikilolo (~880 m elevation) (Plentovich, 2010), in proximity to endangered snail populations.

Plagiolepis alluaudi. The smallest ant in Hawaiʻi (Huddleston and Fluker, 1968) was found in all vegetation zones with no strong preference, while the present study found most instances in vegetation zone B. This tiny ant was found on the North shore, Waimanalo, Waiahole, Hawaiʻi Kai, and Honolulu. *Plagiolepis alluaudi* was found in Ko Olina, Mt. Kaʻala, Waipahu, Kaneohe, Waimanalo, and Honolulu by Huddleston and Fluker (1968).

Pseudomyrmex gracilis. The graceful twig ant was first recorded in 1976 (Wetterer, 2010b). *Pseudomyrmex gracilis* was found in Waianae, Ewa Beach, Waialua, and Kahuku. It is considered a health pest for its painful sting (Leong and Grace, 2008; Wetterer, 2010b).

Solenopsis geminata. The tropical fire ant is one of the six "most dominant invasive ants in Hawaiʻi and around the world" and is known to negatively affect agriculture and natural ecosystems (Krushelnycky et al., 2005). The tropical fire ant is also known to bite and sting, making it a public health threat (Leong and Grace, 2008). *Solenopsis geminata* was found in Waianae, Waialua, the North shore, Kahuku, Kapolei and Honolulu. Huddleston and Fluker (1968) found *S. geminata* in Ko Olina, Barber's Point, Waipahu, Honolulu, and Hawaiʻi Kai.

Solenopsis hi01. *Solenopsis hi01* are small, cryptic ants first collected by students on the island of Hawaiʻi in 2000-2001 (Gruner, Heu and Chun, 2003). *Solenopsis hi01* may be undescribed, but have likely been long established (Gruner et al., 2003). It is considered unlikely to become a pest (Gruner et al., 2003). *Solenopsis hi01* was found in Waianae, Waialua, Aiea, and at Pali Lookout.

Tapinoma melanocephalum. The ghost ant is a widespread pest often invading structures. This ant is known to carry pathogenic microorganisms, including yeasts and fungi, and is often found in hospitals (Pantoja et al., 2009). *Tapinoma melanocephalum* was found in Waianae, Waialua, Pupukea, Kahuku, and Nuuanu. Huddleston and Fluker (1968) found *T. melanocephalum* in Ko Olina, Kapolei, Waipahu, Dole Field, Wahiawa, Kalihi, Waimanalo, and Kaneohe.

Technomyrmex albipes. The white-footed ant is part of a complex of morphologically similar ants that are often misidentified (Wetterer, 2013). The white-footed was found most often in vegetation zone A. *Technomyrmex albipes* was found

in Waianae, Kapolei, Waialua, and Nuuanu. *Technomyrmex albipes* was found together with *T. vitiensis* and *T. difficilis*.

Technomyrmex difficilis. This ant is possibly the most rapidly dispersing member of the morphologically similar white-footed ants (Wetterer, 2013). *Technomyrmex difficilis* was the most common of the *Technomyrmex* species found, occurring at 27% of sites across all vegetation zones, from Waianae, the North shore, Kapolei, Pearl Harbor, Honolulu, Nuuanu, Kaneohe, Waiahole, and Hauula.

Technomyrmex pallipes. *Technomyrmex pallipes* is another member of the white-footed ant complex (Wetterer, 2013). It was found at two sites: Pupukea and Laie.

Technomyrmex vitiensis. *Technomyrmex vitiensis* has long been established in Hawaiʻi, often under the name of *T. albipes* (Wetterer, 2013). *Technomyrmex vitiensis* was found in Waialua and at Pali Lookout. Huddleston and Fluker (1968) found *T. vitiensis* near Waimanalo. It may be better suited for the wetter vegetation zone D than other *Technomyrmex* species.

Tetramorium caldarium. *Tetramorium caldarium* is a widespread species present in the United States, South America, Europe, and Africa (Bolton, 1979). This species may sometimes be misidentified as *T. simillimum* (Bolton, 1979). *Tetramorium caldarium* was found between Waialua and Wahiawa. Huddleston and Fluker (1968) did not record *T. caldarium,* as the species was raised from synonymy by Bolton (1979) after their survey.

Tetramorium simillimum. This widespread tramp ant able to nest in varied sites (Huddleston and Fluker, 1968). *Tetramorium simillimum* was found in Waianae, Kapolei, Waialua, Pearl Harbor, Waiahole, Kualoa, and Hauula. This ant was found in a nest with *Cryptotermes cynocephalus*. *Tetramorium simillimum* was the most frequently found ant in Huddleston and Fluker's 1968 survey, occurring at 46% of sites. *Tetramorium simillimum* was found in all vegetation zones by Huddleston and Fluker (1968), and zones A, B, and C in the present study.

In conclusion, several species of ants remain established in Oahu, even as new species spread throughout the island.
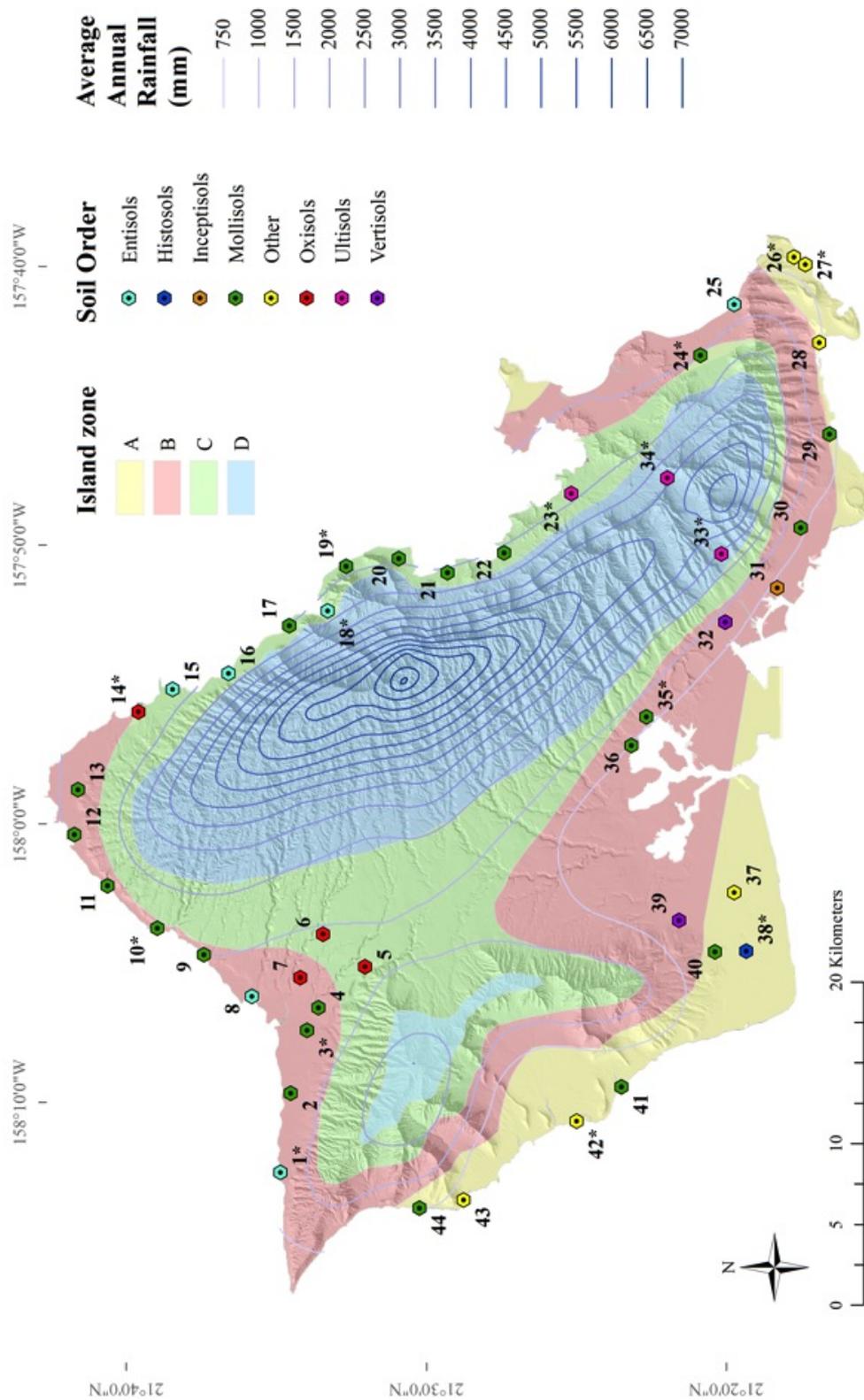
Figure 1. Road survey sites by vegetation zone (Ripperton and Hosaka, 1942), average annual rainfall (Giambelluca et al., 2013), and soil order (USDA, 2014). NAD 1983 4N; WGS 1984.

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CHAPTER 2. TERMITE DISTRIBUTION ON OAHU, HAWAI'I

ABSTRACT

Termites (Blattaria) are economically important structural pests. On Oahu, the last published termite alate survey was in 1969-1971, and the last termite distribution survey was from 1998-2000. An updated survey was performed in order to discover any newly-established species, monitor possible expansions of the recent invaders *Coptotermes gestroi, Cryptotermes cynocephalus, Incisitermes minor,* and *Zootermopsis angusticollis*; and track distributions of *Coptotermes formosanus, Cryptotermes brevis, Incisitermes immigrans,* and *Neotermes connexus*. A light-trap survey of termite alates was conducted from February 2011-September 2012. Square-root transformed *C. formosanus* captures were subjected to a two-factor analysis of variance with location and month as explanatory variables. A multiple regression indicated environmental factors predicted *C. formosanus* alate capture (R^2=.29, $F(4,47)$=4.58, $p < .0025$). Average wind speed (β = -3.68, $p < .0006$) and average rainfall (β = 2.20, $p < .0325$) significantly predicted *C. formosanus* alate capture, while average temperature and percent moon illuminated did not. A systematic survey along Oahu roads was conducted from September to November 2012. Of the forty-four sites surveyed, four termite species were found: *I. immigrans* (n = 8), *C. formosanus* (n = 2), *C. cynocephalus* (n = 1) and *Neotermes sp.* (n = 1). *Coptotermes gestroi, C. brevis, I. minor, N. connexus* and *Z. angusticollis* were not found. There was no relationship between *I. immigrans* incidence with elevation and average annual rainfall. Co-occurrence with ant species was examined using a probabilistic model, and positive co-occurrences of *I. immigrans* with *Paratrechina longicornis* and *Solenopsis geminata* were significant ($p < .0422$ and $p < .0140$, respectively), while negative co-occurrence of *I. immigrans* and *Pheidole megacephala* was significant ($p < .0007$). *Coptotermes formosanus* and *C. brevis* termites were found more often from alate surveys, which may be a better method to map subterranean and primarily structure-dwelling termite distributions. Continued termite education along the windward and leeward coasts is recommended due to the presence of *C. formosanus* and *C. gestroi.*

28

INTRODUCTION

Termites (Blattaria; formerly Isoptera) are social consumers of cellulose and lignocellulose found in dead wood, grass, microepiphytes, leaf litter, and sometimes cultivated fungi (Hartke and Baer, 2011). About 3,000 species of termites have been described, most having a tropical and temperate distribution (Hartke and Baer, 2011) and constitute a large component of terrestrial animal biomass. They are estimated to process between 50-100% of dead plant biomass in the tropics (Hartke and Baer, 2011). In tropical and subtropical areas, termites account for 10% of animal biomass, and for 95% of soil insect biomass (Ghaly and Edwards, 2011). Termite presence and activities create favorable conditions for primary producers, including maintaining soil pH, increasing water retention, mediating decomposition and nutrient cycling, and creating surface areas suitable for microbial colonization (Ghaly and Edwards, 2011; Vasconcellos et al., 2010). They are also an important food source for a variety of animals, such as birds, amphibians, reptiles, and mammals, including humans (DeFoliart, 1999).

However, some species of termites also feed on plant material and lumber used by humans, necessitating expensive repairs, prevention and control efforts (Rust and Su, 2012). Termites may also damage non-cellulosic materials, including electrical and telephone wiring, cables, dams, and farming equipment (Ghaly and Edwards, 2011; Lax and Osbrink, 2003). Worldwide termite control and repair costs are estimated at $40 billion, with 80% of those costs attributed to subterranean termites (Family Rhinotermitidae) (Rust and Su, 2012).

Termites in Hawai'i

Eight species of termites from three families are found in Hawai'i (Table 1). Of the 183 termite pest species in the world, Hawai'i is home to two of the most economically important termite pests, the Formosan subterranean termite, *Coptotermes formosanus* Shiraki, and the Asian subterranean termite, *Coptotermes gestroi* Wasmann, as well as the most damaging drywood termite pest, the West-Indian drywood termite, *Cryptotermes brevis* (Rust and Su, 2012). All of these species are introduced. Of the eight species found in Hawai'i, only one, *Neotermes*

connexus Snyder, the forest tree termite, is not found on the current list of twenty-eight invasive termites worldwide (Evans, Forschler, and Grace, 2013).

Termite control and repair costs residents of Hawaiʻi over $100 million annually (Grace, 2010), which has likely increased since 1990 (J. R. Yates III, personal communication).

Table 1. Termite species of Hawaiʻi by family.

Family	Species	Common name
Termopsidae		
	Zootermopsis angusticollis*	Pacific dampwood termite
Kalotermitidae		
	Neotermes connexus	Forest tree termite
	Incisitermes immigrans	Lowland tree termite
	Incisitermes minor*	Western drywood termite
	Cryptotermes brevis*	West-Indian drywood termite
	Cryptotermes cynocephalus*	Indo-Malaysian drywood termite
Rhinotermitidae		
	Coptotermes formosanus*	Formosan subterranean termite
	Coptotermes gestroi*	Asian subterranean termite

* Structure-destroying pests. Others may occasionally be found in structural lumber.

Originating in China, the Formosan subterranean termite, *Coptotermes formosanus*, was officially recorded on Oahu in 1913, but was likely present in Hawaiʻi at least decades prior (Bess, 1970; Yates III and Tamashiro, 1999; Zimmerman, 1948). The Formosan subterranean termite has since spread to all other major islands (Yates III and Tamashiro, 1999), and is the most costly termite of Hawaiʻi (Woodrow, Grace, and Yates III, 1999).

The Asian subterranean termite, *Coptotermes gestroi* (previously *vastator*) was first found in Hawaiʻi at a single site in Kaimuki, but has since become established on the Ewa side of Oahu (Woodrow, Grace, and Higa, 2001). *C. gestroi* causes severe damage (Grace, 2014; Woodrow et al., 2001).

The West Indian termite, *Cryptotermes brevis*, is a global pest transported by commerce, and has been established in Hawaiʻi before 1884 (Bess, 1970). *C. brevis* is the second most costly termite species in Hawaiʻi (Woodrow et al., 1999). The only known natural (not occurring in human structures) infestation of *C. brevis* outside of

its ancestral home of Peru and Chile (Scheffrahn et al., 2009) is in Nanakuli, Oahu (Scheffrahn et al., 2000).

The Pacific dampwood termite, *Zootermopsis angusticollis* (Hagen), has been found in high elevations on Maui (Grace, 2010). *Z. angusticollis* is originally from the western coast of North America extending from Idaho, Montana and western Nevada (Thorne, Haverty, Page, and Nutting, 1993). *Z. angusticollis* is generally found in dead Douglas-fir and pine trees (Thorne et al., 1993), and in moist structural wood (Thorne and Haverty, 1989).

Neotermes connexus was described in 1923, but was recorded in Hawai'i as early as 1883 (Bess, 1970). It is considered to be a beneficial decomposer, and is found in higher elevations and in forests, as it requires more moisture (Weesner, 1965). *Neotermes connexus* has also been found around Polynesia, including the Society Islands and Marquesas Islands (Light and Zimmerman, 1936), and has likely been present in Hawai'i for centuries (Woodrow et al., 1999).

Incisitermes immigrans Light is also said to have been present in Hawai'i since before 1883 (Bess, 1970), also possibly for centuries (Woodrow et al., 1999). It is distributed around Polynesia as well, including Washington Island, Fanning Island, Jarvis Island, Marquesas Islands, and also spans to the Galapagos Islands and Ecuador (Light and Zimmerman, 1936). *I. immigrans* is also considered beneficial, and rarely infests buildings (Bess, 1970).

Incisitermes minor Hagen, the Western drywood termite, is native to the southwest United States and northwest Mexico (Booth, Lewis, Taylor, Schal, and Vargo, 2008), but has spread sporadically through the U. S. and to Japan (Indrayani, Yoshimura, Yanase, and Imamura, 2006). Infestations have also been reported in China and Canada (Grace, Cutten, Scheffrahn, and Kevan, 1991; Xie, Zhenyu, Gregg, and Dianmo, 2000). *Incisitermes minor* causes severe structural damage and is responsible for most drywood termite damage in the western United States. (Su and Scheffrahn, 1990). In Hawai'i, it has been collected in only three locations on Oahu, but swarms have occurred over several years (J. K. Grace, personal communication).

Cryptotermes cynocephalus Light was first recorded in Hawai'i in 1996 (Scheffrahn et al., 2000). It is known to occur in forests as well as structural lumber (Scheffrahn et al., 2000). *Cryptotermes cynocephalus* is native to Australia, and also

occurs in southeast Asia island nations such as Indonesia and the Philippines (Scheffrahn et al., 2000).

Scheffrahn et al. (2000) surveyed hand-collected termites on Oahu in 1996. Five species of termites: *Coptotermes formosanus, Cryptotermes brevis, Cryptotermes cynocephalus, Incisitermes immigrans,* and *Neotermes connexus*, were found at eighteen coastal sites around Oahu (Scheffrahn et al., 2000). Woodrow et al. (2001) reported twenty-five sites of *Coptotermes formosanus* infestations from a 1988-1989 survey as well as six sites of *Coptotermes gestroi* infestations from 1999-2000. *C. formosanus* was found on the North Shore, the Windward coast, central Oahu, Honolulu, and surrounding Pearl Harbor (Woodrow et al., 2001). *Coptotermes gestroi* was found in a limited range on the leeward coast, near Barber's Point and in Ewa Beach (Woodrow et al., 2001).

Termite swarming

Termite swarming occurs when adult reproductive termites (alates) exit the colony's nest and search for a mate. Termite alates have eyes, thicker exoskeletons, and four wings of about equal size and shape (Yates III and Tamashiro, 1999; Woodrow et al., 1999). Alates are often drawn to sources of light (Yates III and Tamashiro, 1999). Evolutionarily lower termites tend to have small swarms under a wide range of environmental conditions over a long season, while higher termites have larger swarms during specific environmental conditions over a shorter season (Higa and Tamashiro, 1983). The most economically important termite, *Coptotermes formosanus*, exhibits flight patterns of both lower and higher termites (Higa and Tamashiro, 1983).

Oahu alates were last surveyed in 1969-1971 (Higa and Tamashiro, 1983) and 1995 (Grace, unpublished). Higa and Tamashiro (1983) found the general swarming period of *Coptotermes formosanus* to be April through July, with peak capture in May, with small numbers of alates found throughout the year. Microenvironmental factors (wind velocity, light intensity, soil temperature, and vapor pressure deficit) regulating *C. formosanus* flight were surveyed in 1980 by comparing flight and non-flight days during swarming (Leong, Tamashiro, Yates III, and Su, 1983). Wind velocity was the key microenvironmental factor correlated with *C. formosanus* flight,

with the other factors not differing significantly during flight and non-flight days (Leong et al., 1983).

As part of the University of Hawaiʻi's Termite Project's Educate to Eradicate program, partner teachers and students (citizen scientists) participated in alate light-trapping. The Educate to Eradicate program targets schools and adult continuing education to raise termite prevention and treatment knowledge for sustainable area-wide control in Hawaiʻi (Grace et al., 2007; Mason, Aihara-Sasaki, and Grace, 2013).

Termite swarming was monitored to (1), map the occurrence of termite alates across Oahu; (2), track variation in swarming over time; (3), correlate swarming with environmental factors (temperature, precipitation, wind, and moon phase); and (4), to test citizen science, light-trapping partnerships with the University of Hawaiʻi Termite Project. More information on termite swarming phenology may lead to management solutions focusing on preventing or limiting new alate colony foundation (Neoh and Lee, 2009).

A hand-collection survey of termites on Oahu has not been carried out since 1998-2000 (Woodrow et al., 2001). A current survey of termites may reveal newly-established species, and may also aid in targeting locations for implementation of the University of Hawaiʻi's Termite Project's Educate to Eradicate program, which educates students on prevention against the most economically important termites.

MATERIALS AND METHODS

Light-traps were used to collect termite alates on Oahu, Hawaiʻi from February 2011 to September 2012.

A systematic hand-collection survey of termites was conducted on Oahu, Hawaiʻi from September to November 2012.

Swarming survey
Locations

Eight combined locations (Table 2) were monitored by the University of Hawaiʻi Termite Project and citizen scientists. Seven known subterranean termite colonies, (UH Mānoa [4], Kalaeloa [1], Makakilo [1], and Waimanalo [1]), were

monitored by the University of Hawai'i Termite Project from February 2011 to September 2012. Four additional locations initially investigated but excluded and individual light-traps were sometimes removed at different times during the study because of trap interference, construction, or safety concerns.

Table 2. Number of light-traps per combined location on Oahu, Hawai'i. CS: citizen scientists. For citizen scientist-monitored light-traps, only those with specific locations are included in the count.

Combined location	Monitor	Date Range (Month/Year)	Traps per location N (2011)	N (2012)
Aiea	CS	4/2011; 3/2012 – 9/2012	1	1 - 2
Kaiser High School	CS	3/2011 – 5/2011	3	-
Kalaeloa	Lab	2/2011 – 9/2012	3	3 - 6
Makakilo*	Lab	2/2011 – 4/2011	1	-
Mililani High School	CS	3/2012 – 9/2012	-	8
University of Hawai'i at Mānoa	Lab	2/2011 – 9/2012	2 - 4	3
Waimanalo	Lab	2/2011 – 9/2012	4	4
Washington Middle School	CS	3/2011 – 5/2011; 3/2012 – 5/2012	3	2
			17 - 19	21 - 25

Formerly known as Barber's Point Naval Housing

Students from Washington Middle School, Kaiser High School, and Mililani High School monitored traps at school (Washington Middle School) or at home (Kaiser and Mililani High School) during the spring and summer months (March-May or August, 2011-2012). Citizens at a home in Aiea also monitored traps in 2011 and 2012. Citizen scientists using solar light sources were instructed to hang light-traps at least 3 m away from competing sources of light, and to ensure solar lights were exposed to sunlight.

Sites were mapped with Google Earth (version 7.0.3.8542). Students with take-home traps mapped their nearest cross-streets or their home if they had permission from parents. Students who did not provide reliable location information were excluded from distribution maps and statistical analyses.

Light-trap construction

Developed by Makena Mason (personal communication) for the University of Hawai'i Termite Project, plastic funnels were attached with string to light hoods and Hampton Bay solar LED landscape lights that automatically turned on after dark.

Fisherbrand 50 ml centrifuge tube caps were cored and glued to the funnels to allow centrifuge tubes to be twisted off regularly (Figure 4). Some light-traps were hung under existing lights (e.g., porch lights, hallway lighting); these traps did not use a hood or solar light source. Traps exposed to rain used centrifuge tubes with drainage holes. About half an inch to a few inches of water in the centrifuge tubes decreased the amount of beetle and desiccation damage to termite alate bodies.

Checking light-traps

Lab-monitored light-traps were checked bi-weekly for termite alates (weekly during winter months). Citizen scientist-monitored light-traps were checked every school day (Washington Middle School), or every day (Kaiser High School, Mililani High School), or every other day (Miliani High School).

Centrifuge tubes from traps with termite alates were removed and frozen. The date and trap code were recorded on the tube or on a paper inside the tube for later identification.

Alate Identification

Termite alate bodies and wings were counted and stored in 70% ethanol. The number of termites per trap was taken from the larger of either [number of termite bodies] or [number of termite wings divided by four, rounded up to a whole number].

Termite alates were identified using a variety of sources (Bacchus, 1987; Scheffrahn and Su, 2008; Weesner, 1965; Woodrow et al., 1999; Zimmerman, 1948).

Termites that could not be identified (e.g., mold, beetle, or physical damage, etc.) were omitted from analyses. Data from citizen scientists with unclear locations were also omitted from analyses.

Swarming analysis

Termite alate species occurrences were mapped using ArcGIS 10.1 (ESRI 2013). The total number of termite alates per week for all locations was divided by the total number of light-traps out per week and averaged by month, then graphed with average temperature, rainfall, and wind speed (Honolulu International Airport Weather Station: NOAA, 2012).

Statistical analyses focused on *Coptotermes formosanus,* the most

35

economically important termite. Combined locations had different numbers of light-traps; therefore, the total number of *C. formosanus* alates per combined location per week was divided by the number of light-traps per combined location.

To find peak swarming periods during the entire study, *C. formosanus* capture per combined location per week was averaged to find the average *C. formosanus* capture per location per month. Over half of the months had no *C. formosanus* captures and were excluded from the analysis. For the remaining months that had *C. formosanus* alates, average *C. formosanus* alate captures per location per month were transformed ($\sqrt{x} + .5$) and subjected to analysis of variance. Means were separated by Tukey's HSD using JMP 11.1.1 (SAS Institute, 2013) to find peak swarming periods.

To find relationships with environmental factors, *C. formosanus* data were first combined by week and location and square-root transformed. A multiple regression with average wind speed, rainfall, temperature, and percent moon illuminated as explanatory variables was then performed using JMP 11.1.1 (SAS Institute, 2013). The multiple regression was limited to combined locations with *C. formosanus* alates, and only using data from first to last alate capture of the year per location. Weather data were taken from nearby weather stations (NOAA, 2012). Moon phase data were acquired from the Astronomical Applications Department of the U.S. Naval Observatory (2012).

Hand-collection survey

Survey location

Oahu is the third-largest and most populous island of Hawaiʻi, with about 80% of the state's population (Hartley and Chen, 2010). Two major mountain chains span the island: the Koʻolau Range on the eastern coast (~500-950 m high by ~72 km long) and the Waiʻanae Range on the western coast (~470-1200 m by ~56 km long) (Hartley and Chen, 2010). Oahu has two primary physiographic zones, windward (W) and leeward (L), with higher rainfall on the windward side (Brasher, Wolff, and Luton, 2003). Because of small variation in solar radiation, buffering of the ocean, and the effect of trade winds, Oahu has mild temperatures (Brasher et al., 2003). Oahu has a colder, wetter season from October to April and a warmer season from May to September (Brasher et al., 2003).

Ripperton and Hosaka (1942) characterized five major vegetation zones primarily to describe areas with similar climate, soils and vegetation types for use in agriculture in Hawai'i (Table 3). Vegetative zone is highly influenced by rainfall. However, zones sometimes have lower or higher average annual rainfalls than listed because of wind and altitude, which affect evaporation and water retention (Ripperton and Hosaka, 1942).

Table 3. Vegetation zones of Hawai'i as characterized by Ripperton and Hosaka (1942).

Zone	Elevation (m)	Average Annual Rainfall (mm)	Vegetation
A	0 - 600 (usually < 150)	< 500	Xerophytic shrubs (mostly exotic), coastal fringe of trees
B	0 - 900 (average of 600)	500 - 1000	Xerophytic shrubs, trees in higher elevations
C	0 - 1200	1000 - 1500	Open shrubs and grasses in lower elevations, mixed open forest
D	0 - 2000	> 1500	Shrub to open grasslands and closed and open forests
E	> 2000	< 1270	Open forest and shrub, upland forest to above tree line (Hawai'i and Maui only)

Mapping of points

The methodology employed was similar to that used to survey ant distribution on Oahu (see Chapter 1). A random starting point between 0-1000 m from the beginning of major roads (Farrington Highway, Kalanianaole Highway, Kamehameha Highway, Kaukonahua Road, King Street, Pali Highway, or Roosevelt Avenue) was selected. From this starting point, possible collection points were generated at 1-km intervals using "Construct Points" in ArcMap 10.1 (ESRI, 2013). Points were numbered (e.g., PPFARR01 for "Planned Point Farrington Highway 1") and evaluated for suitability in Google Earth (version 7.0.3.8542) street view. Suitable points were areas that were accessible (not on private property) and safe (not on a steep cliff or dangerously close to traffic).

Starting from the random point, every fourth point was selected (4-km intervals). Points considered unsuitable were replaced with the nearest suitable point (1-2 km away from original selection) or discarded entirely if no replacement was

accessible. Points that fell within state parks where a permit was denied (Kaena Point) were also discarded.

Collection

Special use application permits were obtained for collecting termites at points that fell within state parks from the Division of State Parks. No permits were necessary for city parks.

A timed search (one person, 30 minutes) for termites occurred at each suitable site. A 15-m tape measure was laid down starting from the edge of the pavement or edge of a barrier (e.g., stone wall or fence) in a perpendicular direction. Collection occurred within the 15-m distance. The area searched varied from 25-450 m^2, depending on the layout of the site and searchable substrates; however, all searches were of the same duration (30 minutes).

Termites were collected from tree trunks and leaf litter. Fallen branches with evidence of termite damage (e.g., frass, kick-out holes, mud tubes, etc.) were opened to extract living termite soldiers, alates, and workers. Branches that were difficult to open were set aside and extraction took place after the thirty minute search. Termites were collected by hand with an aspirator or forceps. Specimens were stored in 95% ethanol.

Weather data were taken from nearby weather stations using the WeatherBug application (Earth Networks, version 2.0) on an iPhone. Visual observations were also recorded. Soil temperature was taken from a depth of ~15 cm near the generated point, or within the search area where soil was penetrable.

Latitude, longitude, and altitude were taken with a Garmin GPS 76. Coordinates were then re-checked with Google Earth (version 7.0.3.8542) for accuracy. Sites were labeled sequentially to get map codes.

Map layers were downloaded from the State of Hawai'i's Office of Planning GIS Data site, the U. H. Geography Department, and the United States Department of Agriculture Natural Resources Conservation Service's Geospatial Data Gateway (Coastal Geology Group, 2013; Giambelluca et al., 2013; State of Hawai'i, 2013). Honolulu County Land Cover data were downloaded from the NOAA Coastal Services Center (2013). Average rainfall (mm) and elevation contours (10 m) were

used to create maps and spatially join data to points. Layers available as raster data were first converted to points and spatially joined with ArcMap 10.1 (ESRI, 2013).

Vegetation zones were mapped with ArcMap 10.1 (ESRI, 2013) using Ripperton and Hosaka's map (1942) as an overlay (Figure 1).

Pictures and video were taken of each substrate on which termites were found. Pictures of unknown plants were uploaded to the Hawai'i Plant ID Flickr group (http://www.flickr.com/groups/hawaiiplantid/pool).

Identification

Termites were identified based on the soldier or reproductive caste using a variety of sources (Bacchus, 1987; Weesner, 1965; Woodrow, et. al, 1999; Zimmerman, 1948). A mandibular comparison with known species was used for a site where only drywood nymphs were found.

Analysis

Termite occurrences were mapped using ArcMap 10.1 (ESRI, 2013). Abiotic factors (elevation, average annual rainfall, vegetation zone, and physiographic [windward/leeward] zone) from a variety of sources (Giambelluca et al., 2013; Ripperton and Hosaka, 1942; USGS, 2013) were spatially joined to site point data using ArcMap 10.1 (ESRI, 2013).

Termite alate occurrences were compared with hand-collection survey occurrences.

A generalized linear model (binomial, logit link) using JMP 11.1.1 (SAS Institute, 2013) was performed on the presence or absence of *Incisitermes immigrans* with elevation and average annual rainfall, since it was the only species found at more than two sites.

To find patterns of co-occurrence, termite and ant species occurrence data by site were put into a matrix for analysis in the 'cooccur' package in R (Griffith, Veech, and Marsh, 2014), which follows Veech (2013). Species pairs not expected to co-occur more than once were filtered from results, decreasing the amount of analyzed pairs (Griffith et al., 2014).

39

RESULTS

Swarming survey

Termite alates were found every month except November 2011 and February 2012 (Figure 3). *Coptotermes formosanus* alates were captured between April-July 2011 and April-August 2012 from Aiea, Mililani, UH Mānoa, Waimanalo, and Washington Middle School (Figure 3).

In months during which *C. formosanus* alates were captured, a two-factor analysis of variance using combined location and month revealed capture rates differed by month ($F[8,11] = 6.43$, $p < .003$), but not by location ($F[4,15] = 1.16$, $p < .367$). Post-hoc Tukey's HSD showed the peak month of capture to be May 2011 (Table 4).

Table 4. Least squares means of *Coptotermes formosanus* alate capture from a two-factor analysis of variance for five combined locations by month. Levels not connected by the same letter are significantly different.

Month	Mean
2011-05	4.27[a]
2012-07	3.08[ab]
2011-04	2.96[ab]
2012-04	2.07[ab]
2012-06	1.58[b]
2011-07	1.23[b]
2011-06	1.20[b]
2012-05	1.16[b]
2012-08	1.00[b]

The results of the multiple regression indicated that environmental factors predicted *C. formosanus* alate capture ($R^2 = 0.29$, $F[4,47] = 4.58$, $p < .0025$). Average wind speed ($\beta = -3.68$, $p < .0006$) and average rainfall ($\beta = 2.20$, $p < .0325$) significantly predicted *C. formosanus* alate capture, while average temperature and percent moon illuminated did not (Table 5). The Durbin-Watson statistic assessing serial autocorrelation was 1.67 ($p = .0697$). A post-hoc comparison of the same regression of environmental factors to *C. formosanus* alate capture by trap monitor (citizen scientists vs. the termite lab) revealed differences in the Durbin-Watson

statistic: D-W = 2.96 (*p* =.9371) for citizen scientist-monitored traps, indicating no significant serial autocorrelation, and D-W=1.01 (*p* <.0004) for termite lab-monitored traps, indicating significant serial autocorrelation, which violates an assumption of the multiple regression analysis.

Table 5. Multiple regression results for environmental factors with *Coptotermes formosanus* alate capture.

Environmental Factor	β	F Ratio	*p*-value
Mean temperature (Celsius)	1.75	3.06	.2602
Mean wind speed (km/hr)	-3.68	13.53	.0006**
Mean rainfall (mm)	2.20	4.86	.0325*
Mean percent moon illuminated	0.22	0.05	.8234

Asian subterranean termite, *Coptotermes gestroi*, alates were observed in April, June, and July 2011 (n = 14) and in June of 2012 (n = 8). *C. gestroi* was found only in Kalaeloa riding stables (Figure 1).

West-Indian drywood termite, *Cryptotermes brevis*, alates were captured in April through June of 2011 and April through July of 2012. *Cryptotermes brevis* alates were found in Aiea, Kalaeloa, UH Mānoa, and Kaiser High School (Figure 1).

Lowland tree termite, *Incisitermes immigrans*, alates were observed every month except February and November in 2011 and from June through September in 2012. *I. immigrans* alates were found in Kalaeloa, Makakilo, UH Mānoa, and Waimanalo (Figure 1).

Indo-Malaysian drywood termite, *Cryptotermes cynocephalus*, western drywood termite, *Incisitermes minor*, and Pacific dampwood termite, *Zootermopsis angusticollis*, alates were not observed in light-traps. A single desiccated *Neotermes* sp. was found in a Mililani High School student's light-trap, and is assumed to be the forest tree termite, *Neotermes connexus,* although it could not be identified to species.

Hand-collection survey

Four species of termites were found from 44 roadside sites on Oahu, Hawaiʻi (Figure 2). The lowland tree termite, *Incisitermes immigrans*, was most frequently encountered (n = 8), followed by the Formosan subterranean termite, *Coptotermes*

formosanus (n = 2) (Table 6). The Indo-Malaysian drywood termite, *Cryptotermes cynocephalus*, was found at one site (Table 6). A termite likely from the genus *Neotermes* was found at one site (Table 6), and only *Neotermes connexus* is known from Hawai'i. *Coptotermes gestroi, Cryptotermes brevis, Incisitermes minor,* and *Zootermopsis angusticollis* were not found at any road survey site. Abiotic factors by species occurrences are given in Table 7.

  Incisitermes immigrans was not significantly affected by average elevation or average annual rainfall (GLM, $F = 4.61$, $p < .10$).

Table 6. Termite species occurrence (N) by island zone (USGS, 2013) and vegetation zone (Ripperton and Hosaka, 1942). L: Leeward; W: Windward.

Family	Species	N	Frequency (n = 44)	Island zone (N)		Vegetation Zone (N)			
				L	W	A	B	C	D
Kalotermitidae									
	Incisitermes immigrans	8	0.18	5	3	3	4	1	0
	*Cryptotermes cynocephalus**	1	0.02	0	1	0	0	1	0
	Neotermes sp.	1	0.02	0	1	0	0	0	1
Rhinotermitidae									
	*Coptotermes formosanus**	2	0.05	0	2	0	0	2	0
	Total	**12**		**5**	**7**	**3**	**4**	**4**	**1**

* Structure-destroying pest

Table 7. Elevation (m) and average annual rainfall (mm) means ± standard deviations by species occurrences at N sites (total sites = 44).

Family Species	N	Elevation (m)		Avg Annual Rainfall (mm)	
		Mean ± Std Dev	Range	Mean ± Std Dev	Range
Kalotermitidae					
Incisitermes immigrans	8	5 ± 4.24	1 - 12	896 ± 231.19	544 - 1246
*Cryptotermes cynocephalus**	1	1	1	1586	1586 - 1586
Neotermes sp.	1	362	362	2454	2454 - 2454
Rhinotermitidae					
*Coptotermes formosanus**	2	1 ± 0.004	1 - 1	1700 ± 94.97	1633 - 1767
Total	**12**		**1 - 362**		**544 - 2454**

* Structure-destroying pest

  Cryptotermes brevis alates were found at half of all light-trap sites (Figure 1); however, *C. brevis* termites were not found at any road survey location. *Incisitermes immigrans* termites were found near alate light-traps that captured *I. immigrans,*

Coptotermes gestroi, and *C. brevis* (Figure 1). *Incisitermes immigrans* alates were found in four out of ten light-trap locations (Figure 1). The two road survey occurrences of *Coptotermes formosanus* were not found near alate light-trap locations (Figure 1). *Coptotermes formosanus* alates were found in six out of ten light-trap locations (Figure 1). *Coptotermes gestroi* alates were found in one light-trap location (Figure 1).

 Incisitermes immigrans occurred with *Paratrechina longicornis* at four sites, which is more than expected by chance ($p < .04217$, Table 8). *Incisitermes immigrans* occurred with *Solenopsis geminata* at four sites, which is also more than expected by chance ($p < .01399$, Table 8). *Incisitermes immigrans* did not occur at any sites with *Pheidole megacephala*, which is fewer than expected by chance ($p < .00071$, Table 8).

Table 8. Social species co-occurrences as derived from 'cooccur' package "Probabilistic Species Co-occurrence Analysis in R" (Griffith, Veech and Marsh, 2014). Species pairs expected to have less than one co-occurrence were filtered from analysis. P_c: probability of co-occurrence; O_c: observed number of co-occurrences; E_c: expected number of co-occurrences (if independent and random); P_{neg}: probability of negative co-occurrence; P_{pos}: probability of positive co-occurrence.

Species 1 (N)	Species 2 (N)	P_c	O_c	E_c	P_{neg}	P_{pos}
Coptotermes formosanus (2)	*Pheidole megacephala (24)*	.025	2	1.1	1.0000	.2918
Incisitermes immigrans (8)	*Cardiocondyla emeryi (7)*	.029	0	1.3	.2178	1.0000
Incisitermes immigrans (8)	*Ochetellus glaber (19)*	.079	3	3.5	.5190	.7715
Incisitermes immigrans (8)	*Paratrechina longicornis (9)*	.037	4	1.6	.9951	.0422*
Incisitermes immigrans (8)	*Pheidole megacephala* (24)	.099	0	4.4	.0007*	1.0000
Incisitermes immigrans (8)	*Plagiolepis alluaudi (10)*	.041	1	1.8	.4060	.8976
Incisitermes immigrans (8)	*Solenopsis geminata (7)*	.029	4	1.3	.9991	.01340*
Incisitermes immigrans (8)	*Technomyrmex difficilis (12)*	.050	2	2.2	.6247	.7128
Incisitermes immigrans (8)	*Tetramorium simillimum (9)*	.037	1	1.6	.6247	.7128

DISCUSSION

Termite swarming

An earlier termite alate survey on Oahu reported peak *Coptotermes formosanus* swarming during the last two weeks in May (Higa and Tamashiro, 1983); however, no alates were observed during this period in 2011 and only one alate was observed during this period in 2012. This may be because of high average wind speeds at the light-trap locations (8.16-18.60 km/hr and 11.72-24.96 km/hr, respectively).

Formosan subterranean termite swarming correlations with environmental factors are consistent with previous findings on Oahu that found wind velocity to be a key environmental factor regulating swarming (Leong, et. al, 1983). Leong et al. (1983) found termite swarming to start when winds were below 3.7 km/hr. However, Leong et al. (1983) used direct measurements, while the design of the present study used average wind speed per week, as termite alates were collected and combined by week. Despite these differences in methodology, wind velocity remains a predictive environmental factor for *C. formosanus* swarming. When differences in wind speed are accounted for, average rainfall becomes a significant predictor of *C. formosanus* alate capture. *C. formosanus* termites' high susceptibility to desiccation (Yates III and Tamashiro, 1999) may explain the positive relationship of *C. formosanus* capture with rainfall. Bess (1970) noted *C. formosanus* swarmed on "close, humid days, often immediately followed by a shower".

Other factors than those tested in a multiple regression may influence the observed variable, possibly in a manner that correlates the observed variable to its past and future values, known as autocorrelation. Autocorrelation may inflate t-values by decreasing the standard errors between time periods and overestimate the explanatory power of the multiple regressions' factor(s). The Durbin-Watson statistic for autocorrelation was significant for lab-monitored alate capture, possibly due to the study design. Light-traps for lab-monitored locations were hung above known *C. formosanus* colonies, increasing the likelihood of consistent and possibly auto-correlated alate capture. Another possible explanation for autocorrelation is the emergence pattern of *C. formosanus* alates, in which alates emerge slowly over a period of three weeks or longer (Leong et al., 1983). Citizen scientist-monitored traps

had a statistically insignificant Durbin-Watson statistic for autocorrelation; combination with lab data therefore decreased the multiple regression model's likelihood for autocorrelation.

Higa and Tamashiro (1983) found similar peaks in swarming during 1969 and 1970 with large numbers of *C. formosanus* alates swarming from April to July. Similar swarming patterns were not observed in the summers of 2011 and 2012. Average wind speed during swarming was 9.44 km/hr (s.d. = 3.95) in 2011 and 16.81 km/hr (s.d. = 4.89) in 2012, which may contribute to lower numbers of *C. formosanus* alates observed in 2012. Other environmental factors, such as temperature, or intrinsic factors that influence *C. formosanus* flight may also be factors.

Cryptotermes brevis alates were captured primarily by citizen scientists, so the full range of swarming may not have been observed in 2011.

The height of light-traps may also influence the catch. Lab-monitored traps were from 1.5-3 m high, with most about 2 m high. However, this variable was not recorded; further, it is not known at what height students hung traps, though it may be assumed they were within 1-3 m. The "PUB" light-trap from UH Mānoa was hung from a tree with a string-pulley that raised the trap to about 3 m. This trap also had the highest number of alates in a single week (n = 33). However, there was no significant difference between *C. formosanus* captures at different locations.

Not all species of termites that occur in Hawai'i were found in light-traps. Future studies may include: continued alate trapping in current areas, alate trapping in new areas, and trapping near known locations of *Cryptotermes cynocephalus, Neotermes connexus,* and *Zootermopsis angusticollis* to better define find each species' swarming phenologies on Oahu. The Western drywood termite, *Incisitermes minor*, may not be attracted to light-traps, as they swarm during the day. The geographic range of the study was also limited, with no sites on the north or west portions of Oahu, and these areas may be targeted for future alate surveys.

Data from the current study may provide a baseline for studies measuring termite suppression and changes in termite distributions on Oahu. However, studies comparing future swarming data over time should account for wind speed and rainfall, as these were significant predictors of *C. formosanus* alate capture.

Hand-collection survey

The lowland tree termite, *Incisitermes immigrans*, was the most frequently encountered termite, consistent with the findings of Scheffrahn et al. (2000). *I. immigrans* termites were found at around the same areas along the North Shore, Waianae Coast and down to Malaekahana State Park along the Windward Coast, although they were absent from several areas previously identified along the Windward coast (Scheffrahn et al., 2000).

The Indo-Malaysian drywood termite, *Cryptotermes cynocephalus*, was found in fallen logs near a stream between the two sites at which it was first found in 1996: Waiahole Valley Road and Kualoa Regional Park (Scheffrahn et al., 2000). Several nymphs were found, along with alates, indicating a mature colony. *Cryptotermes cynocephalus* termites were not found at any surrounding survey sites, which may mean its dispersal is still somewhat limited. Formosan subterranean termite, *Coptotermes formosanus* workers and soldiers were found crawling freely (not in mud tubes) along the base of a tree in Hauula and in a tree stump in Ahupua'a O Kahana State Park. Scheffrahn et al. (2000) found *C. formosanus* colonies near the same area, but further south, along Kaneohe Bay, as well as Waahila Ridge, Heeia, Kahaluu, and Punaluu. The previous study also found *Neotermes connexus* termites where the current study found *C. formosanus*. This may be because of both species' relatively high moisture requirement. *C. formosanus* distributions may further be delimited with increased light-trapping on the north and west sides of Oahu. It is not clear whether *C. formosanus* is actually decreasing in range or if the current survey's methodology resulted in fewer findings; however, years of termite education, prevention measures (e.g. Basaltic Termite Barrier, Termi-mesh, termite-resistant wood, etc.), bait-systems and other chemical controls may have contributed to smaller populations of *C. formosanus*.

The Western drywood termite, *Incisitermes minor*, was not found at any sites, possibly because it has yet to expand its range, or because it remains in structures that were not examined. *Incisitermes minor* swarms during the day, and may not be attracted to light-traps. Incidental reports may be the best method at present for locating *I. minor* infestations.

The West Indian drywood termite, *Cryptotermes brevis*, was also not found at any sites. This is not unexpected, since this species very rarely occurs in natural

47

settings, although known to be well-established in structures throughout the island. *Cryptotermes brevis* was extremely common in alate light-traps (Figure 1). Alate trapping is therefore recommended to study distributions of *C. brevis*.

Pacific dampwood termite, *Zootermopsis angusticollis*, was not found in this survey. Currently, its known distribution remains limited to Kula, Maui.

Negative co-occurrence of *Incisitermes immigrans* with the ant *Pheidole megacephala* may be the result of overlap in nesting sites preferences. *Ochetellus glaber* and *Technomyrmex difficilis* were also observed at sites with *I. immigrans*. At these sites, both species were often found in the same tree. The higher co-occurrence with *Paratrechina longicornis* and *Solenopsis geminata* may be because of those species similar elevation and rainfall preferences. Lastly, although *Cryptotermes cynocephalus* was only found at one site and was filtered from the co-occurrence analysis, *Tetramorium simillimum* ants were found within the fallen logs containing *C. cynocephlus* termites.

Survey sites in this study were mostly at low elevations near coastlines. Tree branches with evidence of termites were found at multiple locations, but live termites were not always found, especially with regard to subterranean termites. Subterranean termites are cryptic, and light-trap surveys may be more effective in mapping their distribution than hand-sampling. Crowd sourcing, or gathering data from the public on occurrences of termites may also be an option, and pest control reports may also be useful.

At some locations, soldiers and imagoes (alate and dealate reproductives) were not found. At the Pali lookout site (map code 34), two pairs of dealate reproductive termites were found, but positive identification was difficult because of the lack of wings and absence of any soldiers. These dealates were darker, had a smaller pronotum width, a proportionately wider head to pronotum ratio, and larger eyes than voucher *Neotermes connexus* alates. Further surveys in the area may reveal soldiers and more imago samples for positive identification.

Although no novel termite species were identified in these survey efforts, these data provide insight on the swarming period of *Coptotermes gestroi* in Hawaiʻi and the environmental factors inducing swarming, the localized spread of *Cryptotermes cynocephalus*, and the continuing occurrence and co-occurrence of established termite species on Oahu.
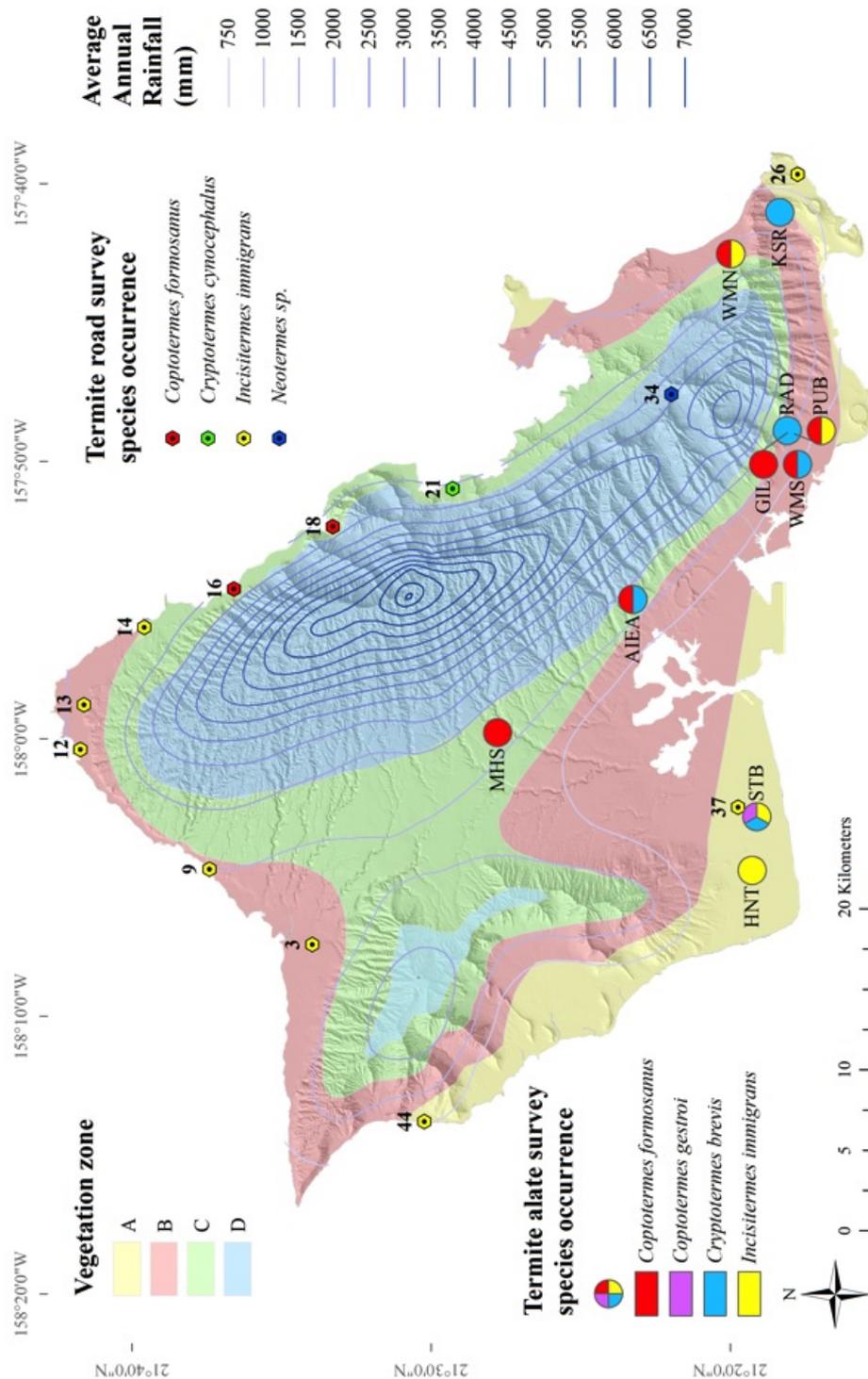
Figure 1. Termite occurrence for survey sites (by map code) and alate survey sites (by trap code) by vegetation zone (Ripperton and Hosaka, 1942) and average annual rainfall (Giambelluca et al., 2013) (NAD 1983 4N, WGS 1984). Light-trap codes: AIEA: Aiea; GIL: Gilmore Hall (UH Mānoa); HNT: Hornet (Makakilo); KSR: Kaiser High School; MHS: Mililani High School; PUB: Publication (UH Mānoa); RAD: Radiator (UH Mānoa); STB: Stables (Kalaeloa); WMN: Waimanalo Research Station (Waimanalo); WMS: Washington Middle School.

49
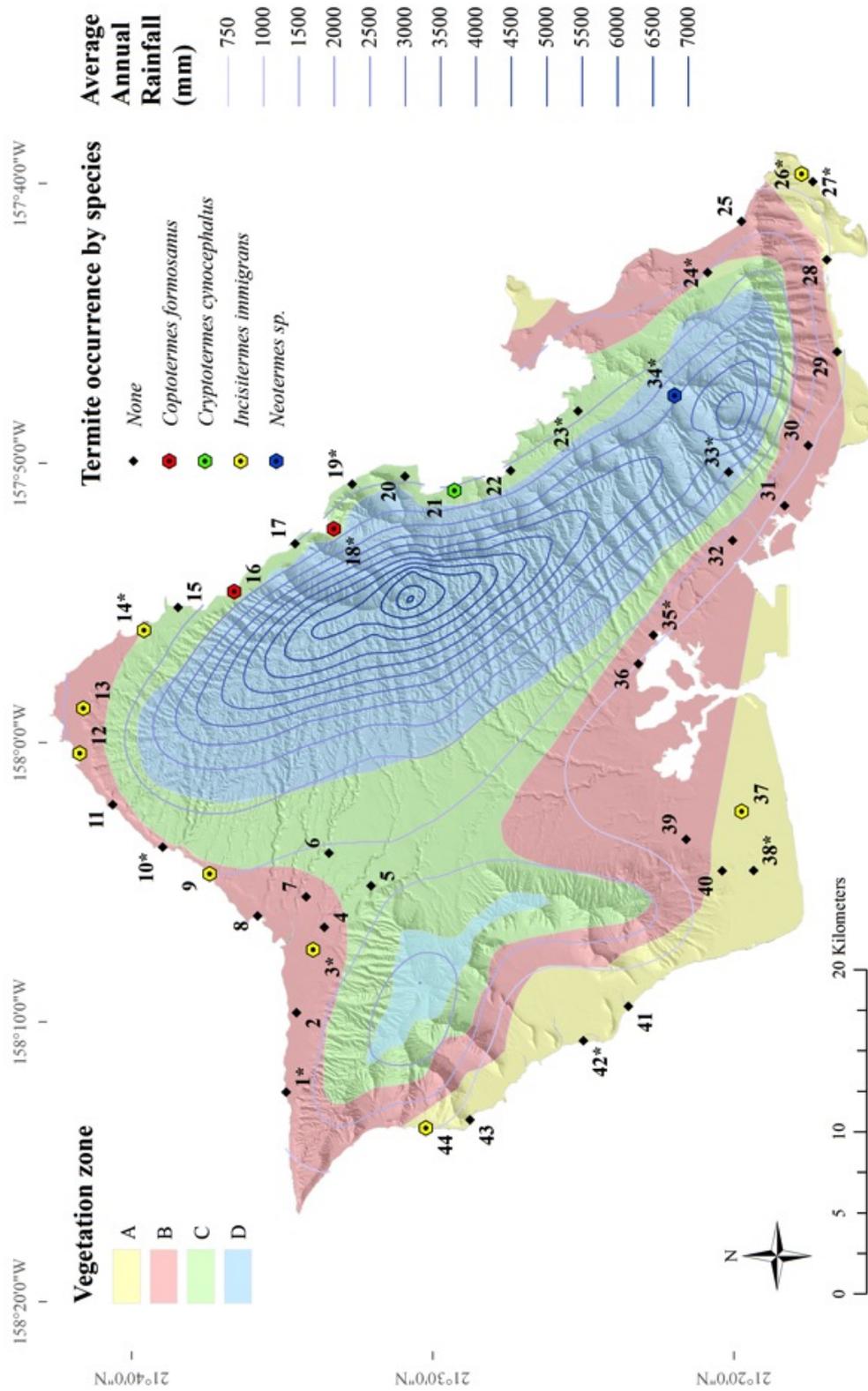
Figure 2. Termite occurrence by vegetation zone (Ripperton and Hosaka, 1942) and average annual rainfall (Giambelluca et al., 2013) (NAD 1983 4N, WGS 1984).
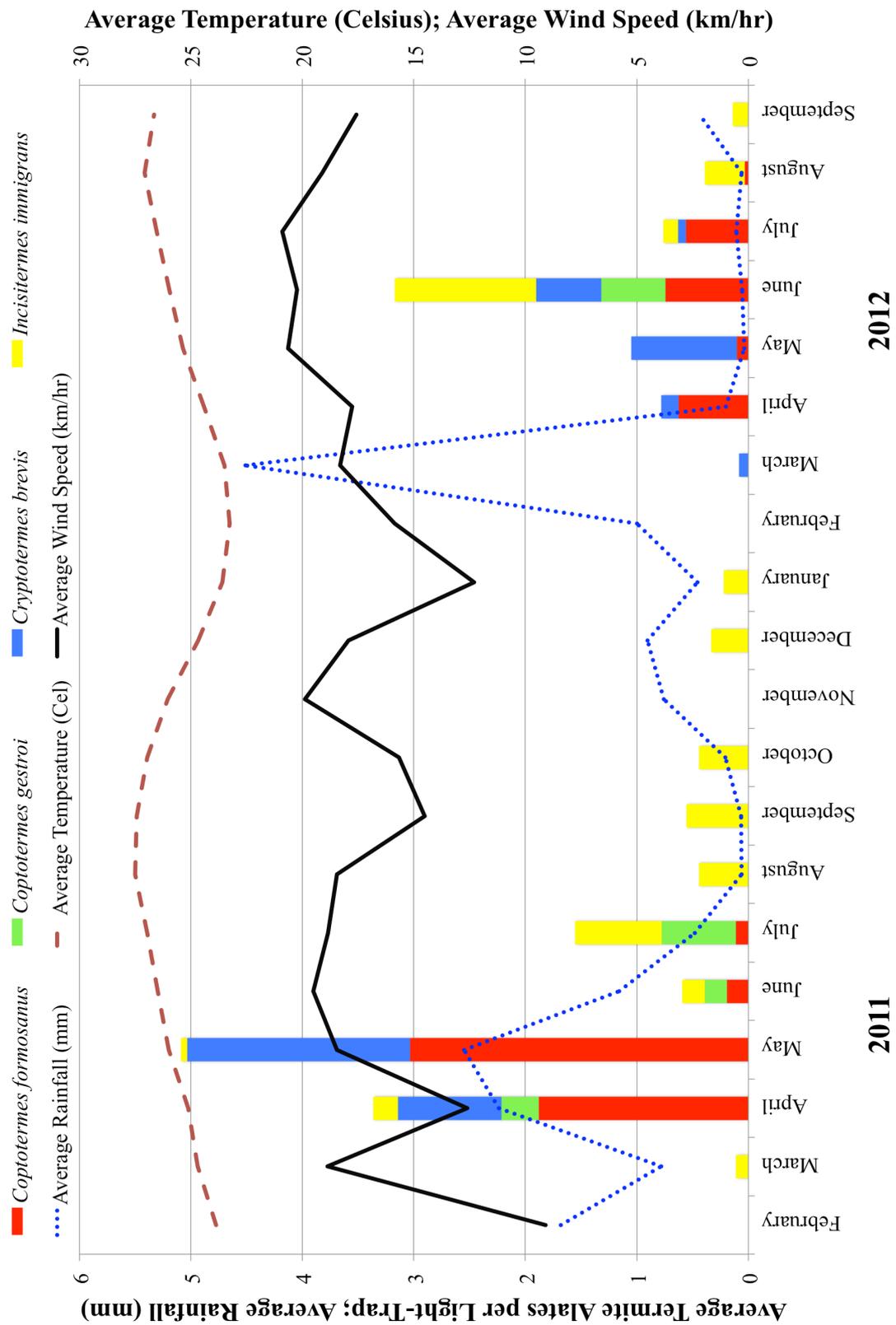
Figure 3. Average termite alate capture from light-traps on Oahu, Hawai'i, from February 2011 – September 2012. Average rainfall (mm), temperature (Celsius), and wind speed (km/hr) from the Honolulu International Airport weather station (NOAA, 2012).

51

Figure 4. Light-trap. From top: solar light source, hood, funnel and removable centrifuge tube.

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CHAPTER 3. CONVENIENCE SAMPLING

ABSTRACT

Convenience sampling draws samples from readily available sources and is often the most practical method of surveying animal and plant distribution, but can also be biased. Convenience sampling is often justified due to time, money, personnel and equipment constraints. However, inferences from data obtained from such studies may need to be limited. To explore convenience sampling bias in roadside surveys of ants and termites, a distribution study was conducted on Oahu from September to November 2012. A timed search (one person, 30 minutes) was conducted at each paired site near (less than 15-m) roads and away (more than 15-m) from roads. Ants and termites were collected and identified to species. There was no significant difference in the species richness of road and away sites. No significant difference between road and away sites was detected with a multi-response permutation procedure. However, the species compositions as measured by Jaccard distance of road and away sites were significantly different at four sites individually. However, Jaccard distances by combined vegetation zone for ants and termites were not significant, and the overall combined road and away Jaccard distance (36.00%) was not significant. Although differences were minimal in the present study, caution is still recommended when conducting distribution surveys based on convenience.

INTRODUCTION

Convenience sampling is "a type of nonprobability sampling that draws samples from that part of the population that is close to hand" (Morrison, 2012). Convenience sampling is often justified by time, money, equipment and personnel constraints (Morrison, 2012).

Convenience sampling is sometimes used when other types of sampling are not feasible due to inaccessibility or a large sampling area (Rodhouse et al., 2010), or where other sampling measures are too costly (Roberts et al., 2006).

Morrison (2012) suggests a "paradigm rut" for habitat studies: "Namely, almost everyone identifies a convenient study area, samples the usual vegetation variables and other environmental parameters, conducts a series of statistical analyses, compares findings to other studies, and then justifies publication by extrapolating findings to some unspecified larger area" (Morrison, 2012). Morrison (2012) suggests this practice may lead to poor management practices and hinders new progress towards understanding wildlife-habitat phenomena.

An example of convenience sampling bias is the use of road surveys used to monitor and estimate Key deer populations (Roberts et al., 2006). Numbers of Key deer were counted weekly along the same 4-km road at sunrise, sunset and nighttime (Roberts et al., 2006). To verify and quantify the amount and direction of bias resulting from the preferred method of road sampling, infrared-triggered camera population estimates were compared to road survey population estimates (Roberts et al., 2006). Infrared-triggered cameras were placed uniformly within suitable deer habitat and hourly photos were pooled to form weekly population estimates (Roberts et al., 2006). Road survey estimates were found to be almost half that of infrared-triggered camera estimates ($p < .0001$); further, a bias towards urban roads was found (Roberts et al., 2006). The authors cite an increased effective sampling area as a typical justification for convenience sampling (Roberts et al., 2006).

Population estimates influence management decisions (Roberts et al., 2006). As convenience sampling may result in poor quality data (Marshall, 1996), the resulting management decisions may be based on invalid inferences (Anderson, 2001). Anderson (2001) asserts that convenience sampling limits the scope of

inferences (e.g., "animal abundance near roads or population density in areas where density is high").

An example of insect convenience sampling in Hawai'i is an ant distribution survey of Kaua'i in which ants were sampled at 3-5 mile intervals along roads (Nelson, 1993). Each sample was taken for minimum of 30-man-minutes in a suitable ant habitat (Nelson, 1993), and sampling points were often completed by several team members (H. Spafford, personal communication), making it likely most samples were taken fairly close to the road.

Sampling site disturbance from proximity to roads may include vehicle and pedestrian traffic, vegetation maintenance (e.g., mowing, landscaping, tree trimming, etc.), and chemical inputs (e.g., fertilizers, herbicides, pollution from vehicles, etc.). Roads may also alter surrounding soil pH, organic material, and favorability to native vegetation (Johnston and Johnston, 2004). Road edges are also more likely to harbor exotic vegetation (Johnston and Johnston, 2004). Species richness is predicted to decrease with increasing disturbance (Niemelä et al., 2002).

The objective of sampling near and away from roads in this study was to determine any bias that may arise from convenience sampling and to determine if proposing sampling further from roads is recommended for a more meaningful survey of ant and termite distributions in Hawai'i. It is assumed that near and away sites are similar in geography, average annual rainfall, elevation, and soil type, and generally only differ in the degree of disturbance.

MATERIALS AND METHODS

A systematic survey of ant and termite distribution was conducted on Oahu, Hawai'i from September to November 2012 (see Chapters 1-2).

Study location

Oahu is the third largest and most populous island of Hawai'i, with about 80% of the state's population (Hartley and Chen, 2010). Two major mountain chains span the island: the Ko'olau Range on the eastern coast (~500-950 m high by ~72 km long)

and the Waiʻanae Range on the western coast (~470-1200 m by ~56 km long) (Hartley and Chen, 2010). Oahu has two primary physiographic zones, windward and leeward, with higher rainfall on the windward side (Brasher, Wolff, and Luton, 2003). Small variation in solar radiation, buffering of the ocean, and the effect of trade winds contribute to Oahu's mild temperatures (Brasher et al., 2003). Oahu has a colder, wetter season from October to April and a warmer season from May to September (Brasher et al., 2003).

Ripperton and Hosaka (1942) characterized five major vegetation zones primarily to describe areas with similar climate, soils and vegetation types for use in agriculture (Table 1). These factors also influence ants (Huddleston and Fluker, 1968), and may influence termites. Vegetative zone is highly influenced by rainfall.

Table 1. Vegetation zones of Oahu, Hawaiʻi as characterized by Ripperton and Hosaka (1942).

Zone	Elevation (m)	Average Annual Rainfall (mm)	Vegetation
A	0 - 600 (usually < 150)	< 500	Xerophytic shrubs (mostly exotic), coastal fringe of trees
B	0 - 900 (average of 600)	500 - 1000	Xerophytic shrubs, trees in higher elevations
C	0 - 1200	1000 - 1500	Open shrubs and grasses in lower elevations, mixed open forest
D	0 - 2000	> 1500	Shrub to open grasslands and closed and open forests
E	> 2000	< 1270	Open forest and shrub, upland forest, to above tree line (Hawaiʻi and Maui only)

Mapping of points

A random starting point between 0-1000 m from the beginning of major roads (Farrington Highway, Kalanianaole Highway, Kamehameha Highway, Kaukonahua Road, King Street, Pali Highway, Roosevelt Avenue) was selected. From this starting point, possible collection points were generated at 1-km intervals using "Construct Points" in ArcMap 10.1 (ESRI, 2013). Points were numbered (e.g., PPFARR01 for "Planned Point Farrington Highway 1") and evaluated for suitability in Google Earth (version 7.0.3.8542) street view. Suitable points were areas that were accessible (not on private property) and safe (not on a steep cliff or dangerously close to traffic).

Starting from the random point, every fourth point was selected (4 km intervals). Points considered unsuitable were replaced with the nearest suitable point (1-2 km away from original selection) or discarded entirely if no replacement was accessible. Points that fell within state parks where a permit was denied (Kaena Point) were also discarded.

Forty-four points were selected for sampling; of these, 15 points were used for the analyses described in this chapter.

Collection

Special use application permits were obtained for collecting termites at points that fell within state parks from the Division of State Parks. No permits were necessary for city parks.

A timed search (one person, 30-minutes) for ants and termites occurred at each suitable site. A 15-m tape measure was laid down starting from the edge of the pavement or edge of a barrier (e.g., stone wall or fence) in a perpendicular direction. Collection for "Road" points were conducted within the 15-m distance. The area searched varied from 25-450 m^2, depending on the layout of the site and searchable substrates; however, all searches were the same length (30-minutes). Collection for "Away" points were conducted beyond the 15-m distance. Beyond the 15-m distance, the area searched varied from 40-750 m^2. Larger areas searched were usually due to large expanses of grass or sand between searchable substrates; however, all away searches were of the same duration.

Fifteen sites were found suitable for both road and away collections.

Ants were collected by hand with an aspirator, forceps or by covering with a tube. Specimens were stored in 95% ethyl alcohol. To avoid periods of low ant activity, collection times were restricted to between 8:00 a.m. - 11:00 a.m. and 1:00 p.m. - 4:00 p.m. Ants were collected from plants (flowers, leaves, trunks, twigs, etc.), the ground (leaf litter, concrete, grass, etc.), objects (walls, telephone poles, trash cans, etc.), and under objects (rocks, logs, trash, etc.) (Nelson, 1993). Fallen branches with evidence of insect damage were opened to extract ants and termites. Separate vials for different substrates were used (e.g., "leaf litter", "plumeria tree", etc.).

Termites were collected from tree trunks and leaf litter. Fallen branches with evidence of termite damage (e.g., frass, kick-out holes, mud tubes, etc.) were opened to extract termite soldiers, alates, and workers. Branches that were difficult to open were set aside and extraction took place after the 30-minute search. Termites were collected by hand with an aspirator or forceps. Specimens were stored in 95% ethyl alcohol.

Weather data were taken from nearby weather stations using the WeatherBug app (Earth Networks, version 2.0) on an iPhone. Visual observations were also recorded. Soil temperature was taken from a depth of ~15-cm near the generated point, or within the search area where soil was penetrable.

Latitude, longitude, and altitude were taken with a Garmin GPS 76. Coordinates were then re-checked with Google Earth (version 7.0.3.8542) for accuracy. Sites were labeled sequentially to get map codes.

Map layers were downloaded from the State of Hawai'i's Office of Planning GIS Data site, the U.H. Geography Department, and the United States Department of Agriculture Natural Resources Conservation Service's Geospatial Data Gateway (Coastal Geology Group, 2013; Giambelluca et al., 2013; State of Hawai'i, 2013; USDA, 2014). Honolulu County Land Cover data were downloaded from the NOAA Coastal Services Center (2013). Average rainfall (mm), elevation contours (10 m), and soil data were used to create maps and spatially join data to points. Layers available as raster data were first converted to points and spatially joined with ArcMap 10.1 (ESRI, 2013).

Vegetation zones were mapped with ArcMap 10.1 (ESRI, 2013) using Ripperton and Hosaka's map (1942) as an overlay (Figure 1).

Pictures and video were taken of each substrate ants were found on. Pictures of unknown plants were uploaded to the Hawai'i Plant ID Flickr group (http://www.flickr.com/groups/hawaiiplantid/pool).

Identification

Ants were identified to species using the Hawai'i Ant Lab's Key to the sub families of Hawai'i (Vanderwoude, 2012), PIA Key (Sarnat, 2008), and Bolton's revision of *Technomyrmex* (2007). Termites were identified based on the soldier or

reproductive caste using a variety of sources (Bacchus, 1987; Weesner, 1965; Woodrow, et. al, 1999; Zimmerman, 1948). A mandibular comparison with known species was used for a site where only drywood nymphs were found.

Analysis

Site data, including longitude/latitude, elevation, average annual rainfall, soil order, vegetation zone, island zone, etc., were averaged by vegetation zone (Table 1). Site data were then combined with species occurrence data (Table 2) and entered into JMP 11.1.1 (SAS Institute, 2013) by rows. Species occurrence data were tabulated.

A paired t-test was performed in JMP 11.1.1 (SAS Institute, 2013) of species richness for road and away sites. A multi-response permutation procedure (MRPP) analyzing road and away sites by vegetation zone and species using natural weighting ($C_1 = n_1/\Sigma n_1$) was done in PC-ORD 5 (McCune and Mefford, 2006).

The Jaccard coefficient, J, (Jaccard, 1912) measures similarity between two sets of presence/absence data, here comparing road and away samples ($J = S/[S + R + A]$ where S = shared road and away species; R = unique road species; A = unique away species).

The Jaccard distance, D, ($D = 1 - J$) was calculated for each pair of road and away samples to compare differences in species composition. The average Jaccard distance for each pair was calculated for each vegetation zone. Jaccard distances for sites combined by vegetation zone were also calculated. The overall Jaccard distance for all road and away sites was also calculated. Real's (1999) table of critical values for Jaccard's index of similarity was used to check for significantly different than random values for Jaccard distances (Urbani, 1979).

RESULTS

Twenty-one species of ants from five subfamilies and four species of termites from four subfamilies (Table 2) were collected from fifteen pairs of road and away sites (Figure 1).

Table 2. Species occurrences of ants and termites in paired road and away sites and Jaccard distances by map code. Jaccard distances in red indicate significance (* = *p* < .05; * = *p* < .001).**

Map Code	Unique Road Species	Species at both Road and Away Sites	Unique Away Species	Jaccard distance
1	*Solenopsis geminata* Technomyrmex difficilis*	*Ochetellus glaber**	*Pheidole megacephala* Plagiolepis alluaudi*	80.00%*
3	*Paratrechina longicornis* Pseudomyrmex gracilis* Tetramorium simillimum*	*Incisitermes immigrans Solenopsis geminata* Tapinoma melanocephalum**	*Cardiocondyla emeryi Ochetellus glaber**	62.50%
10		*Leptogenys falcigera Pheidole megacephala* Plagiolepis alluaudi*	*Cardiocondyla obscurior Ochetellus glaber* Paratrechina longicornis**	50.00%
14	*Pseudomyrmex gracilis**	*Cardiocondyla obscurior Incisitermes immigrans Solenopsis geminata* Tapinoma melanocephalum**	*Monomorium floricola* Technomyrmex albipes Tetramorium simillimum*	50.00%
18	*Coptotermes formosanus*	*Pheidole megacephala**		50.00%
19		*Pheidole megacephala**		0.00%
23	*Cardiocondyla emeryi*	*Pheidole megacephala* Technomyrmex difficilis*	*Plagiolepis alluaudi*	50.00%
24	*Plagiolepis alluaudi*	*Ochetellus glaber* Pheidole megacephala**	*Cardiocondyla emeryi*	50.00%
26		*Incisitermes immigrans Ochetellus glaber**		0.00%
27		*Ochetellus glaber**	*Pheidole megacephala* Plagiolepis alluaudi*	66.67%
33	*Tapinoma melanocephalum* Technomyrmex difficilis*	*Monomorium floricola* Technomyrmex albipes*	*Cardiocondyla obscurior Leptogenys falcigera Pheidole megacephala* Technomyrmex vitiensis*	75.00%*
34	*Nylanderia vaga Solenopsis hi01 Technomyrmex vitiensis*	*Neotermes sp.*		75.00%
35	*Cardiocondyla wroughtonii Monomorium floricola* Ochetellus glaber* Solenopsis hi01*		*Cardiocondyla emeryi Cardiocondyla obscurior Solenopsis geminata* Technomyrmex albipes*	100.00% ***
38	*Monomorium bicolor group Technomyrmex difficilis Tetramorium simillimum*	*Technomyrmex albipes*	*Camponotus variegatus* Coptotermes gestroi*	83.33%*
42		*Pheidole megacephala**	*Ochetellus glaber* Monomorium destructor* Technomyrmex difficilis*	75.00%

* Health pest

65

Abiotic factor averages by vegetation zone are given in Table 3.

Table 3. Mean abiotic factors by vegetation zone (Ripperton and Hosaka, 1942) for paired road and away sites.

Vegetation Zone	Number of sites	Elevation (m)		Average Annual Rainfall (mm)	
		Mean ± Standard Deviation	Range	Mean ± Standard Deviation	Range
A	4	5 ± 6.01	1 - 15	625 ± 77.07	541 - 699
B	4	6 ± 4.39	1 - 12	900 ± 158.44	793 - 1155
C	5	8 ± 11.81	1 - 32	1365 ± 260.97	1008 - 1767
D	2	237 ± 145.69	110 - 364	2198 ± 295.58	1942 - 2454
Total	**15**		**1 - 364**		**541 - 2454**

Species richness did not significantly differ by site type (road vs. away).

Jaccard distances by site showed differences in the species compositions of ants in road and away sites (Table 2). The overall average Jaccard distance by site for ants was 57.02% (s.d. = 33.38%). The lowest average Jaccard distance was in vegetation zone C (31.43%) and the highest average Jaccard distance was in vegetation zone D (87.50%) (Table 4).

Table 4. Average Jaccard distances for ants in road and away sites by vegetation zone (Ripperton and Hosaka, 1942).

Vegetation Zone	Number of sites	Jaccard distance	
		Mean ± Standard Deviation	Range
A	4	55.42% ± 37.35%	0 - 80%
B	4	75.36% ± 20.71%	50 - 100%
C	5	31.43% ± 28.84%	0 - 57%
D	2	87.50% ± 17.68%	75 - 100%
Total	**15**		

Jaccard distances by site for ants and termites combined also differed. The overall average Jaccard distance by site for ants and termites for road and away samples was 57.83% (std. dev. = 27.90%). The lowest average Jaccard distance was still in vegetation zone C (40.00%) and the highest average Jaccard distance was still in vegetation zone D (75.00%) (Table 5).

Table 5. Average Jaccard distances for ants and termites in road and away sites by vegetation zone (Ripperton and Hosaka, 1942).

Vegetation Zone	Number of sites	Mean ± Standard Deviation			Range
				Jaccard distance	
A	4	56.25%	±	38.11%	0 - 83%
B	4	73.13%	±	21.74%	63 - 100%
C	5	40.00%	±	22.36%	0 – 50%
D	2	75.00%	±	0%	75%
Total	**15**				

Using Real's (1999) table of significant values of Jaccard's index of similarity, Jaccard distances by vegetation zone for road and away sites did not differ significantly (Table 6) for ants. Further, the overall combined road and away Jaccard distance (33.33%) was not significant.

Table 6. Combined Jaccard distances for ants in road and away sites by vegetation zone (Ripperton and Hosaka, 1942). (Significance: * = p < .05).

Vegetation zone	Total Species within zone	Jaccard distance
A	9	55.56%
B	16	52.94%
C	12	35.71%
D	10	70.00%*

Jaccard distances by vegetation zone for road and away sites did not significantly for ants and termites. The overall combined road and away Jaccard distance (36.00%) was not significant (Table 7).

Table 7. Combined Jaccard distances for ants ant termites in road and away sites by vegetation zone (Ripperton and Hosaka, 1942). (Significance: * = p < .05).

Vegetation zone	Total Species within zone	Jaccard distance
A	11	54.55%
B	17	56.25%
C	14	33.33%
D	11	63.64%*

The chance-corrected within-group agreement (A) was negative (-0.01), meaning there was more heterogeneity within groups than expected by chance (McCune, Grace, and Urban, 2002). However, the p-value was not significant (p < .89).

DISCUSSION

It was expected that less disturbed areas (away sites) would have more species than disturbed areas (road sites). However, the paired t-test showed no significant difference between species richness of road and away sites. The MRPP also did not show a significant difference between road and away sites. This may be due to the small sample size (n = 15) of road and away sites that would require a large effect size for statistical significance. Thus, further sampling may have revealed differences using this method.

Although differences in species richness of road and away sites were not statistically significant, Jaccard distances revealed some significant differences in species compositions between road and away samples. Four paired samples (map codes 1, 33, 35 and 38) had significant differences in species assemblages between road and away samples. However, combined Jaccard distances for each vegetation zone and the overall Jaccard distance were not significant, suggesting species assemblages near and away from roads are somewhat similar according to this sampling protocol.

Several limitations are inherent in this study. All sites are still relatively close to roads. Most sites also were near coastlines, and at lower elevations. The ants collected may not represent the actual assemblages present, as cryptic and nocturnal species may not have been collected. Recent introductions of ants into areas around the island may skew analyses relating to correlation with other species and with environmental factors. This study also did not collect all the species known to occur on Oahu. Additionally, the species that have established on Oahu may prefer or be suitably adapted to disturbed habitats. Although it was assumed that road and away sites were similar to each other in elevation, rainfall, soil type, and vegetation, some road and away sites may have had different types of vegetation by chance. At site 35, a paved bike path ran between the road and away site and a large expanse of grass was between the start of the away site and a tree and picnic area that was inspected. Similarly, at map code 27, a patch of naupaka (*Scaevola taccada*) was inspected near the road, and an expanse of sand was between the road and away site before suitable ant habitat was found at another patch of naupaka. Despite the variable distance from

road to away sites, all samples were taken within the 30-minute interval and the grass and sand between vegetation patches was inspected.

This sampling protocol, which has an arbitrary distance of 15-m defining road from away sites, may not be the best method to detect differences in species assemblages. Major roads were used in this study to expand the geographic range across the island. Increasing the sample size to include side roads may have improved the comparison. The species collected may also prefer or tolerate disturbance, as well as form large, polygynous colonies.

Vegetation zone C had the lowest average Jaccard distance. This may reflect the dominance of *Pheidole megacephala* in zone C, as *P. megacephala* was found significantly more often in vegetation zone C ($p < .0002$) (see Chapter 1). Several sites had *P. megacephala* in both road and away sites, especially in zone C. Vegetation zone D had the highest average Jaccard distance; however, only two pairs of road and away sites were within vegetation zone D. At site 34, the temperature and wind speed may affect the ant assemblages of the away site. Three species of ants were found closer to the road. The away site was closer to the edge of the mountain, and significant wind and temperature differences may have affected the ant assemblage. Termites were found at both the road and away locations at site 34, which may not be as affected by wind and temperature, as drywood termites live within the wood.

Subterranean termites, *Coptotermes formosanus* and *C. gestroi*, were only found at a few locations. *Coptotermes gestroi* was only found at an away site, while *C. formosanus* termites were found only at road sites. The *C. formosanus* termites found at paired road site (map code 18) were removed from an ironwood tree that had been felled. Thus, the inner portion of the tree had visible termite galleries, which were then opened to reveal termite soldiers. Ironwood trees in the paired away site (map code 18) had evidence of termite damage (e.g., dirt gathered in cracks of trees), but slight digging into the trees did not reveal any termites. However, termites may have been found if the tree was cut down as in the road site. The opposite was true of the road and away site for the location with *C. gestroi* (map code 38): a cut stump was found in the away site, while two intact trees were found in the road site. However,

there did not seem to be evidence of subterranean termites on the two trees within the road site; further, a log barrier in the road site did not contain any *C. gestroi* termites.

The drywood termite *Incisitermes immigrans* was found at several sites around Oahu. In all paired road and away sites where *I. immigrans* occurred (map codes 3, 14 and 26), the termite was found at both road and away sites. Drywood termites nest within the wood they consume, and may be less likely to be affected by road disturbance. Therefore, if a study focused on drywood termites, it may be sufficient to only sample near roads. *Neotermes sp.* (assumed to be *Neotermes connexus*) termites were found at both road and away sites as well.

Since unique species were often encountered further from roads, caution is advised when conducting distribution surveys based on convenience.

Although the overall differences between paired sites were minimal in the present study, unique species were often encountered further from roads, and caution is advised when conducting distribution surveys based on convenience.
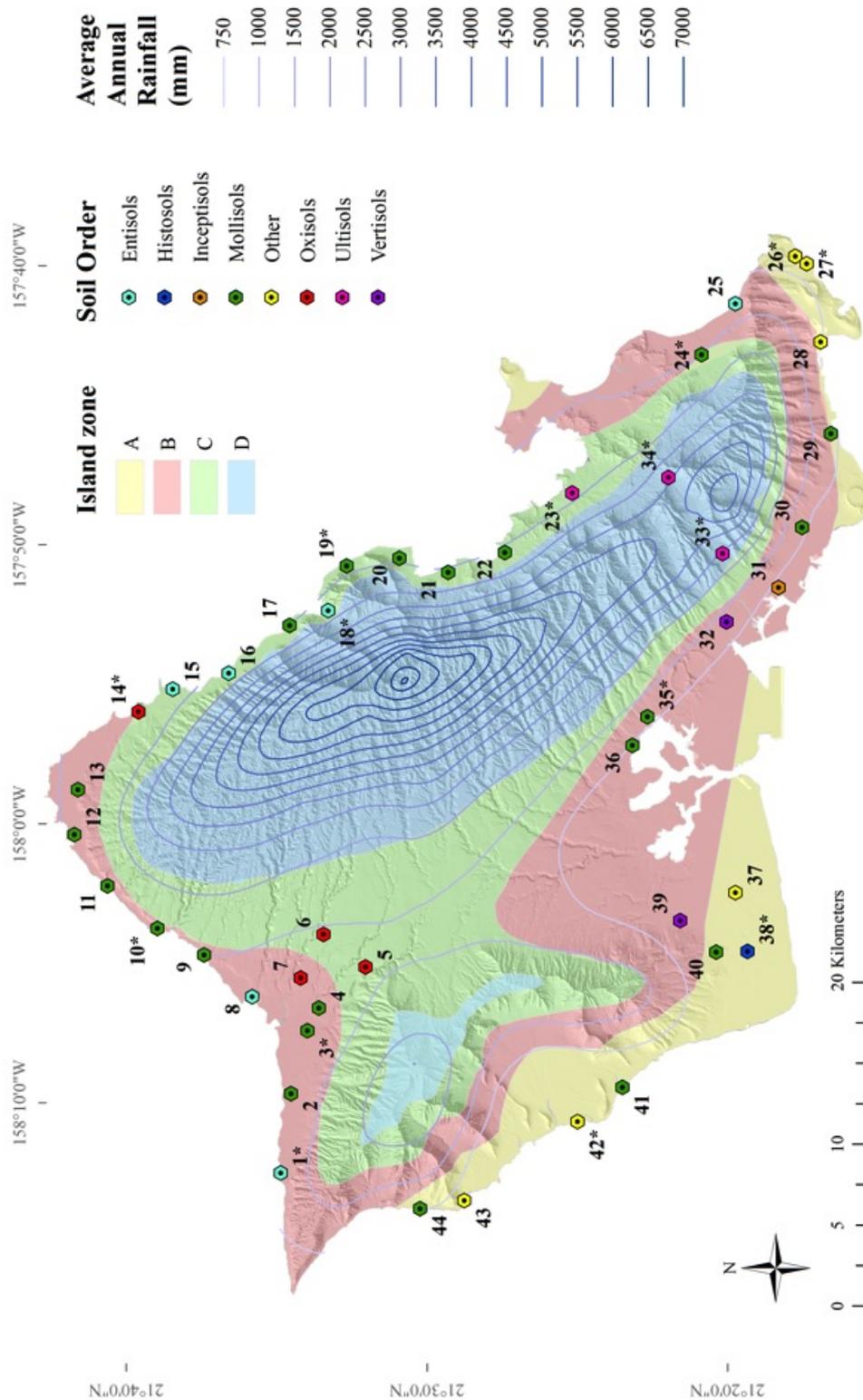
Figure 1. Survey sites on Oahu, Hawai'i, by vegetation zone (Ripperton and Hosaka, 1942), average annual rainfall (mm) (Giambelluca et al., 2013), and soil order (USDA, 2014). Sites with an asterisk * have paired road and away samples. Fifteen paired road and away sites were examined (map codes: 1, 3, 10, 14, 18, 19, 23, 24, 26, 27, 33, 34, 35, 38, and 42).

71

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