Occurrence and Distribution of Mosquitoes (Diptera: Culicidae) of Public Health Importance on the Island of Oahu

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Abstract. The Vector Control Branch of the Hawaii State Department of Health has accumulated a large volume of written inspection data on pests of public health for the island of Oahu. By far, the greatest amount of arthropod pest information available is on mosquitoes. The objectives of this study were to conduct a survey of the occurrence of mosquito complaints on Oahu over a 10-year period, determine the distribution of complaints over time, graphically compare mosquito occurrence within and between district/areas, and correlate mosquito occurrence and distribution with season. Mosquito data were drawn from inspection reports from 1990 to 1999, population information was obtained from Hawaii Census and State of Hawaii Data Books, 125 district/area geographic locations were defined, and mosquito occurrence and distribution were adjusted for population and mapped using ArcView GIS 3.2. Most of the mosquito activity was found within the central, south and east urban districts. Drier areas from Kalihi Kai to Portlock had the highest number of complaints, and the levels of mosquito activity were highest during the winter, spring and summer. The primary mosquito species recorded was *Aedes albopictus* (Skuse), the Asian tiger mosquito, and the main breeding sources were various containers, plus bromeliad plants. *Aedes albopictus* populations are being maintained in urban districts by human activities. As a result, dengue transmission is possible in the drier, urban areas of Oahu. These results indicate that educational programs should be carried out in late fall and early spring, and that residential mosquito surveys may be concentrated in a limited number of district/areas.

Key words: Mosquitoes, *Aedes albopictus*, public health, vector control, Oahu, GIS

Introduction

Rodent Control and Mosquito Control programs were established in the Territory of Hawaii in the early 1900s. The primary vector-borne diseases at that time were bubonic plague, dengue fever and yellow fever. Shortly before Hawaii became a state, Hayes (1958) reported that vector-borne diseases of humans were well under control. Murine typhus remained a significant problem, but plague had been eradicated from Oahu and restricted to limited enzootic foci on two major islands (Maui and the Big Island of Hawaii). The Vector Control Branch (VCB) of the Hawaii State Department of Health (HDOH) was created in 1970 with the merging of the Rodent Control and Mosquito Control programs. The VCB is a statewide inspection, education, regulatory, prevention and control program. It, along with other HDOH agencies, routinely monitors for plague, dengue fever, murine typhus, leptospirosis and West Nile virus (WNV). The primary vector-borne disease concerns today are dengue fever, murine typhus, leptospirosis and WNV. As part of their regular duties, Vector Control Inspectors deal with other arthropods of public health importance in addition to insect disease vectors and vertebrate pests. As a result, a large volume of mainly hand-written inspection data on pests of public health importance has been accumulated for the island of Oahu.

A 10-year period was chosen to obtain sufficient data to draw reasonable conclusions. However, in order to effectively manage such a large volume of information, it was decided that only arthropod specific pest problems would be included at this time. Thus, the final study objectives were to conduct a survey of the occurrence of public health arthropod pest and nuisance problems on Oahu over a 10-year period, obtain a general list of arthropod related problems and determine their distribution over time, graphically compare pest occurrence within and between district/areas, correlate pest occurrence and distribution with season, and identify target pests and regions for more efficient application of prevention, control and education programs. Geographic analyses of derived data was carried out using ESRI© ArcView GIS 3.2. We report here the results obtained for mosquitoes, the most frequently reported public health pests.

Mosquitoes in Hawaii. There are six biting species of mosquitoes in the state of Hawaii, all of which are non-native and were introduced accidentally through human activities. These include two night-biting species, *Culex quinquefasciatus* Say, the southern house mosquito, and *Aedes vexans nocturnus* (Theobald), the floodwater mosquito; and four day-biting species, *Ae. aegypti* (Linnaeus), the yellow fever mosquito, *Ae. albopictus* (Skuse), the dengue or Asian tiger mosquito, *Wyeomyia mitchellii* (Theobald), the bromeliad mosquito, and a new introduction, *Ae. (Finlaya) japonicus japonicus* (Theobald). *Culex quinquefasciatus* was introduced to Hawaii in 1826 from Mexico in water barrels aboard the ship Wellington when it landed at the port of Lahaina, Maui (Van Dine 1904, Usinger 1944, Hess 1957, Hardy 1960, Ikeda 1982), and *Ae. vexans nocturnus* was discovered on the island of Oahu in 1962 by Joyce and Nakagawa (1963) (Ikeda 1982). *Aedes aegypti* was widespread in Hawaii when Perkins (1913) started his collection for Fauna Hawaiiensis in 1892 (Usinger 1944, Hess 1957, Hardy 1960, Ikeda 1982), and *Ae. albopictus* arrived shortly thereafter, probably around 1895, since it was very abundant by 1902. *Wyeomyia mitchellii* was recovered by D. Shroyer in July 1981 while collecting in the Tantalus-Makiki area of Oahu (Shroyer 1981, Ikeda 1982), and *Ae. (Finlaya) japonicus japonicus* was collected from a mosquito light trap in Laupahoehoe on the island of Hawaii by Linda Burnham Larish in November 2003 (Larish and Savage 2005). Four of these six mosquito species, *C. quinquefasciatus*, *Ae. vexans nocturnus*, *Ae. albopictus* and *W. mitchellii*, occur on the island of Oahu today.

Culex quinquefasciatus is a known vector of human and canine filariasis (Hardy 1960, Goff 1980, Ikeda 1982, Chin 2000), has transmitted avian malaria (*Plasmodium relictum*) between introduced and native bird populations (van Riper III et al. 1986), and research confirms that it will be the primary vector for West Nile virus (WNV) if the disease should be introduced into Hawaii (Sardelis et al. 2001, Goddard et al. 2002). Human filariasis (*Wuchereria bancrofti*) has not been a problem in Hawaii, but canine filariasis or the dog heartworm (*Dirofilaria immitis*) is transmitted primarily by *C. quinquefasciatus* and is of major veterinary importance (Hardy 1960, Gubler 1966). *Aedes vexans nocturnus* is a vector for dog heartworm (Joyce and Nakagawa 1963, Goff 1980), and may be a competent, though low risk vector for WNV like its sibling species *Ae. vexans* (Meigen) (Goddard et al. 2002, Kilpatrick et al. 2002). *Aedes albopictus* is an important vector of dengue fever and has been implicated in a recent dengue outbreak on Maui that peaked in September 2001 (Effler et al. 2005). It is also a vector for dog heartworm (Hardy 1960, Goff 1980, Ikeda 1982), is listed by Boyd (1949) as a minor vector of avian malaria (Goff 1980), and is a very competent and important bridge vector for WNV (Sardelis et al. 2002). Despite being a painful biter, *W. mitchellii* is not known to vector any human diseases (Frank 1990) and was not found to be carrying any arboviruses by Nayar et al. (2001).

As a reminder of the increased frequency of pest introductions into Hawaii, one of the authors (MKHL) recovered an *Anopheles sp.*, subsequently identified as *An. punctipennis* (Say) (Furumizo et al. 2005, Larish and Savage 2005), from a Sand Island mosquito light trap in December 2003. Fortunately, extensive surveillance indicated this human malaria and WNV vector was not established on Oahu.

This is one of a series of six related papers submitted for publication in the *Proceedings of the Hawaiian Entomological Society.*

Materials and Methods

Study area. Oahu is the third largest of the Hawaiian Islands and the most populous island in the State of Hawaii (Macdonald et al. 1983). It is 71 km (44 mi) long and 48 km (30 mi) wide with a total land area of 1,600 km^2 (608 $mile^2$), there are 366 km (227 mi) of shoreline with many bathing beaches, and Pearl Harbor's well sheltered lochs indent the island's southern coast. Oahu is home to ~900,000 people (approximately 75% of the resident population of the state). Honolulu, the state capital and the economic center of Hawaii, is on the island's highly urbanized southern coast. Development has expanded into the rural country side, and extensive growth has recently occurred in the central and Ewa Plains areas of the island. Large pineapple and sugarcane plantations that once covered the rural areas of Oahu are giving or have given way to residential development or diversified agriculture. Dairy, pig and chicken farming located primarily along the dry leeward coast has been declining over the past decade due to residential encroachment and socioeconomic pressures. Pearl Harbor continues to accommodate military and a large volume of commercial shipping, and the Honolulu International Airport is a busy commercial hub for the Asia-Pacific region.

As with Hawaii in general, Oahu's climate is characterized by a two-season year, mild and fairly uniform temperature conditions, striking marked geographic differences in rainfall, and a general dominance of trade-wind flow (National Climatic Data Center 2006). The cooler, winter season runs from October through April when widespread rainstorms are common, and the warmer, summer season runs from May through September during a period when there is an overwhelming dominance of trade winds.

Study methods. A comprehensive arthropod pest data set was extracted from Hawaii State Department of Health Vector Control Branch inspection reports from 1990 to 1999, with supporting data being drawn from Vector Control logbooks for the inspection reports. Population data were obtained from Hawaii Census 1990 and 2000 and The State of Hawaii Data Books for 1990 through 2004.

Vector Control inspection reports from 1990 to 1999 were reviewed and compiled into general pest categories using the reported problem on the original complaint that stimulated the inspection. This approach avoids the problem of introducing increasing complexity into the GIS analysis through the use of specific findings (species identified) from multiple inspectors and the fact that a negative finding by an inspector does not necessarily mean the reported pest was not present prior to an inspection. It also preserves an aspect of the data that can be useful in an educational program, i.e., the public perception that a particular pest is a problem. Since inspections have been known to be ongoing or otherwise kept open for a year or more, using an earlier rather than a more recent time period for the study ensures that the data set is as complete and accurate as possible. Out of a total of 17,695 inspection reports over the 10-year study period, there were 8,154 (46.1%) arthropod related inspections. Twenty-four inspections were eliminated due to discrepancies in their site addresses leaving 8,130 inspections. All together, a total of 8,936 individual pest problems were found from which 27 pest categories were obtained, plus a miscellaneous category for very minor or anomalous reports (Table 1).

District/area geographic locations were established using community structure, geographic features and inspection report designations. Distinctions among communities were

Table 1. Pest categories by reported problem on the original complaint. The top 10 categories have been bolded.

Pest category	**Pest complaints**	
	%	**No.**
Ants	**6.4**	**572**
Aphids	0.0	1
Bedbugs	0.5	47
Bees	**8.3**	**740**
Beetles	0.2	21
Centipedes	**3.0**	**268**
Cockroaches	**6.1**	**546**
Crickets	0.0	1
Earwigs	0.0	2
Fleas	**9.2**	**820**
Flies	**15.0**	**1338**
Gnats	0.7	61
Lice	0.8	69
Mealybugs	0.0	1
Midges	0.1	6
Millipedes	0.2	19
Mites	**6.8**	**607**
Mosquitoes	**30.4**	**2718**
Moths	0.1	9
Psyllids	0.0	2
Scorpions	0.5	45
Silverfish	0.1	6
Spiders	0.9	84
Termites	0.4	33
Ticks	**2.1**	**186**
Wasps	**1.2**	**106**
Whiteflies	0.1	8
Miscellaneous: insects, bugs, something biting, worms	6.9	620
Total	**100.0**	**8936**

based upon subdivision outlines and major streets, types of land use, bodies of water such as large streams and lakes, mountains and valleys, and city and community boundaries. The total area of the established geographic locations did not cover the entire island as there are large tracts of vacant land, and individual district/areas vary in physical and population size. As a result, the data needed to be standardized for population differences. Population data drawn from Hawaii Census 1990 and 2000 and State of Hawaii Data Books were often grouped differently with respect to Honolulu county subdivisions and designated places, so census tracts and tract blocks were used in their entirety when appropriate, or subdivided along the same divisions created between established communities as necessary. Since census data and state population estimates were available only for 1990, 1995 and 2000, the population for the intervening years was estimated using a straight-line curve. One hundred twenty-five district/area geographic locations were defined (Table 2).

The raw pest occurrence data were standardized for each district/area by dividing by the estimated population and multiplying the decimal number generated by 10,000 ($n \div p \times 10{,}000$). The results were rounded up to the nearest whole number. Industrial parks, heavy commercial areas and very small communities produced standardized pest occurrence well into the 100s and 1000s, and required that district/areas with populations of less than 500 be excluded from occurrence analysis. The resulting transformed pest occurrence data were then mapped on a traditional four-season basis (winter, January to February plus December; spring, March to May; summer, June to August; and fall, September to November) rather than with two-seasons so that a better picture of activity during the year could be obtained. ArcView GIS 3.2 was used to create 40 maps for each of 10 major pest categories (Figure 1) along with four additional maps each showing cumulative seasonal activity. Three of the major pest categories did not contain enough data to make annual, seasonal mapping very useful. See Leong (2008) for the complete set of GIS maps.

The occurrence data are presented in six mapped groups or levels of activity, 1–3 (very light; white), 4–8 (light; yellow), 9–15 (moderate; orange), 16–24 (heavy; red), 25–35 (very heavy; pink) and Pop.<500 (excluded; violet) (Figure 1). Pest occurrence was graphically compared within and between district/areas, and pest occurrence and distribution were correlated with season. Finally, pest occurrence and distribution were evaluated using inspection data, including species identifications.

Results

Mosquito activity during the winter of 1990 was scattered along the north shore and south, lower east, central and west Oahu. There were noticeable concentrations of activity in the central area of Halawa Valley and from Kapahulu to Aina Haina along the south coast. In winter 1991, mosquito activity was concentrated in lower central, south and lower east Oahu from Halawa, around Makapuu to Mahinui-Kokokahi. There were seven moderate peaks (9–15 complaints) from Halawa Valley to Portlock, including Kalihi Kai, Kakaako, Makiki Heights-Round Top, Kahala and Aina Haina; and heavy (16–24 complaints) spikes in mosquito activity occurred in Waialae Iki and Hawaiiloa Ridge. Overall mosquito activity doubled as compared to the preceding fall. Mosquito activity in winter 1992 was concentrated in the south between Saint Louis Heights and Kuliouou with a moderate peak occurring in Kalani Valley. Winter 1993 mosquito activity was much reduced from that in 1992 and well scattered across the island. One moderate peak occurred in Hawaiiloa Ridge. A sharp drop in mosquito activity occurred in the winter of 1994. Activity was found along the central, south and east areas of Oahu from Waipahu to Kaaawa. The winter of 1995 saw mosquito activity occurring around south, east and north Oahu in Aina Haina, Niu Valley, Mahinui/Kokokahi and Waialee-Waimea. There was one moderate peak in Mokuleia and a very heavy spike (25–35 complaints) in mosquito activity in Wailupe. Mosquito activity in winter 1996 was concentrated in south and east Oahu. There was a moderate peak in activity in Punaluu and a heavy spike in Portlock. The mosquito activity in winter 1997 was fairly spread out over the island with activity peaking moderately in Niu Valley and mosquito activity spiking very heavily in Kalihi Kai. Moderate peaks in activity also occurred in West Loch Estates in central Oahu and in the vicinity of Kahe Point in the west, and there was a heavy spike in mosquito activity in Yacht Club Knolls on the east side of the island. Nearly all of the mosquito activity in winter 1998 was in south, east and central Oahu with a heavy spike in activity on Mariners Ridge in south Oahu. Finally, mosquito

Table 2. Examples of district/area geographic locations established for the island of Oahu together with their community populations.

District/area	Census 1990	Est. pop. 1991	Est. pop. 1992	Est. pop. 1993	Est. pop. 1994	Census 1995	Est. pop. 1996	Est. pop. 1997	Est. pop. 1998	Est. pop. 1999	Census 2000
Airport	22	23	23	23	23	23	23	23	24	24	24
Kalihi Kai	2253	2153	2053	1953	1854	1754	1665	1576	1487	1398	1309
Sand Island	408	385	361	338	315	291	270	248	227	205	184
Downtown	8301	8474	8646	8818	8991	9163	9384	9605	9826	10047	10269
Nuuanu/Dowsett Highlands	10693	10650	10607	10564	10521	10478	10494	10510	10526	10542	10558
Kakaako	1147	1443	1739	2034	2330	2626	2932	3239	3545	3852	4159
Punchbowl/Pauoa/Pacific Hts.	19007	18989	18970	18952	18933	18915	19002	19089	19176	19263	19350
Ala Moana	10986	11127	11268	11409	11550	11691	11895	12099	12303	12507	12711
Makiki/Punahou	21112	21016	20921	20825	20730	20634	20655	20675	20695	20716	20736
Makiki Hts./Tantalus/Round Top	4487	4415	4343	4271	4199	4127	4079	4031	3982	3934	3886
Waikiki/Kapiolani Pk.	20190	20122	20053	19984	19916	19847	19890	19933	19975	20018	20061
McCully/Moiliili	28551	28263	27976	27688	27400	27112	26979	26845	26712	26578	26445
Kapahulu/Diamond Head	13370	13226	13082	12938	12795	12651	12579	12507	12436	12364	12293
Manoa/Woodlawn	18500	18489	18478	18468	18457	18446	18538	18630	18722	18814	18906
Saint Louis Heights	5431	5344	5257	5169	5082	4995	4937	4878	4820	4762	4704
Kaimuki/Waialae	14093	13976	13859	13742	13625	13508	13468	13428	13387	13347	13307
Palolo/Palolo Valley	12838	12814	12790	12767	12743	12719	12766	12814	12861	12908	12955
Wilhelmina Rise/Maunalani Hts.	6468	6472	6476	6480	6484	6488	6529	6569	6609	6649	6689
Kahala	7742	7705	7667	7630	7592	7555	7560	7565	7571	7576	7581
Waialae Nui	1645	1635	1625	1615	1605	1595	1595	1594	1593	1592	1591
Kalani Valley	781	775	770	764	758	753	751	750	749	747	746
Waialae Iki	3169	3205	3241	3277	3313	3349	3403	3457	3511	3565	3619
Wailupe	604	602	600	598	596	593	595	596	597	599	600
Aina Haina	4071	4092	4113	4134	4155	4176	4220	4264	4308	4352	4396
Hawaiiloa Ridge	850	868	885	903	920	937	960	982	1005	1027	1050
Niu Valley	2413	2410	2407	2405	2402	2399	2410	2421	2432	2442	2453

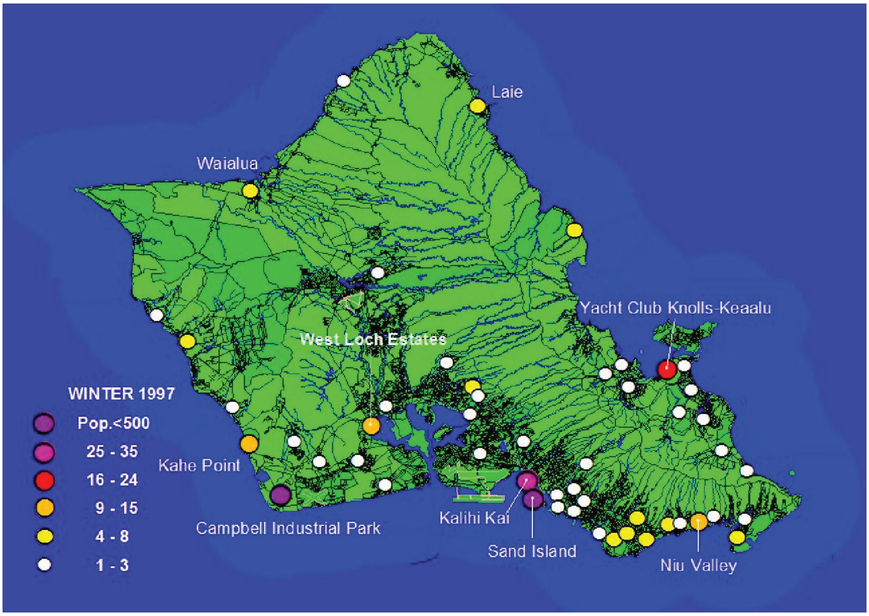

Figure 1. Example of a map including all levels of pest activity.

activity increased sharply in the winter of 1999 with activity mainly occurring in the south, east and central district/areas. The activity was most intense along east Oahu where moderate peaks were found in Yacht Club Knolls, Waiahole-Waikane and Kaaawa. In addition, an area of unusual inactivity between Kahala and Hawaii Kai in south Oahu was noted.

Spring 1990 mosquito activity remained scattered in general like that in the winter, but there was increased activity along the south districts from Kalihi Kai to Hawaii Kai. Moderate peaks were found in Kalihi Kai and Aina Haina, and a heavy spike occurred in Kakaako. Mosquito activity was reduced in spring 1991 with moderate peaks occurring in Yacht Club Knolls-Keaalu on the east shore and Pupukea in the north, and a very heavy spike in mosquito activity in Kalani Valley on the south coast. In spring 1992, mosquito activity increased across north, south, west and lower east Oahu. Activity was concentrated in the south between Kapahulu-Diamond Head and Niu Valley with a moderate peak occurring in Kalani Valley and a very heavy spike showing up in Wailupe. Mosquito activity decreased in spring 1993 with activity being concentrated in south Oahu between Kalihi Kai and Aina Haina. Overall spring 1994 mosquito activity was three times that of in the winter with new and increased activity occurring mainly in the west, central and south Oahu district/areas. In the south, there were moderate peaks in Kalihi Kai, Kakaako and Aina Haina together with a heavy spike in activity in Portlock. Mosquito activity also increased in spring 1995, especially in south and east Oahu. Activity peaked moderately in Kahala and Hawaiiloa Ridge in the south and Waiahole-Waikane in the east, and spiked heavily in Wailupe. Spring 1996 mosquito activity was comparable overall to that in winter 1996 with occurrence decreasing in east Oahu, and increasing in central and west Oahu. Activity peaked moderately in Fort Shafter and spiked heavily in Wailupe in the south, and moderate peaks in mosquito activity occurred in Waianae Valley and the Kahe Point area in the west.

There was an increase in mosquito activity in south and west Oahu in spring 1997, and a decrease in activity on the east coast. Most of the activity occurred in the south, east and central district/areas with activity peaking moderately in Kahala and Portlock on the south shore. Mosquito activity in spring 1998 was much reduced and was reported across south, lower east and central Oahu. Lastly, spring 1999 showed decreased mosquito activity in east and central Oahu, and an increase in intensity on the north shore with the occurrence of a moderate peak in Waialee-Waimea and a heavy spike in Kawela.

There was a slight decrease in overall mosquito activity in summer 1990 from that in the spring with mild increases in north and lower east Oahu. Moderate peaks occurred on the south coast in Kakaako and Kahala, and Portlock had a heavy spike in activity. There was a mild increase in the number of district/areas affected in summer 1991, but this was accompanied by a reduction in the level of individual site activity. Mosquito activity peaked moderately in Kakaako and Portlock as well as in Mokuleia on the north shore. A heavy spike occurred in Wailupe in south Oahu. The number of district/areas reporting mosquito activity decreased in the summer of 1992 from in the spring. South and lower east Oahu were most affected, yet three south shore areas peaked moderately, Kahala, Kalani Valley and Hawaiiloa Ridge, and a very heavy spike occurred in Wailupe. Summer 1993 mosquito activity increased to above that of spring and winter with the affected district/areas being fairly well scattered island wide. Activity peaked moderately in east Oahu in Yacht Club Knolls-Keaalu and Waiahole-Waikane, and on the north shore in Mokuleia. Summer 1994 showed reduced mosquito activity in the south, east, central and west Oahu district/areas and a mild increase on the north shore with a moderate peak in Mokuleia. Summer 1995 mosquito activity showed a decrease in south and east Oahu by close to half from that in the spring. Activity peaked moderately in Mokuleia and a heavy spike in mosquito activity occurred in Portlock on the south shore. Overall mosquito activity in summer 1996 was unchanged with occurrence decreasing in south Oahu, and increasing in north and central Oahu. Mosquito activity peaked heavily in Wailupe in the south and a very heavy spike occurred in Mokuleia in the north. A large decrease in mosquito activity occurred in summer 1997 in the north, south and west district/areas. There was a moderate peak in the south in Portlock along with heavy spikes in mosquito activity in Hawaiiloa Ridge and Niu Valley, and heavy activity was also found in the east in Yacht Club Knolls-Keaalu. Except for a decrease in activity in central Oahu, the summer of 1998 saw a general increase in mosquito activity from that in the spring. The main areas of activity were Downtown to Portlock in the south and Kailua to Ahuimanu in the east. Mosquito activity declined on the north shore as well as in the east and central district/areas of Oahu in summer 1999. There was a small rise in activity on the west coast, and overall activity was concentrated in south Oahu from Kalihi Valley to Niu Valley.

In the fall of 1990, mosquito activity further decreased from that in the summer with a moderate peak in activity occurring only in Kapolei. Activity was mainly in the south Oahu district/areas. During the fall of 1991, the number of district/areas affected remained about the same as in the summer while the level of individual site mosquito activity decreased. A moderate peak in mosquito activity occurred in Kakaako. There was a light increase in mosquito activity in fall 1992 with reported activity moving up into central Oahu and central east Oahu. Activity peaked moderately in West Loch Fairways, Kahala, Waialae Nui and Waiahole-Waikane, and spiked very heavily in Kalani Valley. In addition, a heavy spike occurred in Mokuleia. Fall 1993 saw an increase in the number of district/areas reporting mosquito activity. There was an overall decrease in mosquito activity in the fall of 1994 across the island. However, a clear increase in activity occurred on the north shore with heavy spikes in Kawela and Mokuleia. A light increase in mosquito activity also occurred in Lanikai and Olomana-Pohakupu in lower east Oahu. There was increased mosquito activity in fall 1995 with much of the increase occurring in south Oahu, especially from Kahala to Queen's Gate-Kalama Valley. Moderate peaks in activity were found in Kahala, Mariners Ridge, Portlock and Punaluu, and a heavy spike occurred in Wailupe. In fall 1996, mosquito activity increased in south, east and west Oahu while it decreased in north and central Oahu. Moderate peaks in activity occurred in Mokuleia in the north and Kahe Point in the west, and mosquito activity spiked heavily in Wailupe in the south. A further decrease in mosquito activity from in the summer occurred in the fall of 1997 in the south, east and central district/areas. In fall 1998, there was a decrease in mosquito activity in the south and east district/areas that resulted in an overall level of occurrence about half that of in the summer. The problem sites were scattered with a moderate peak appearing in Kakaako in south Oahu. There was a mild decrease in overall mosquito activity in fall 1999 and occurrence was more distributed over the island. Activity was mainly in the south and central district/areas.

Most of the mosquito activity was found within the central, south and east urban districts of the island of Oahu (Figure 2A–D). Drier areas from Kalihi Kai to Portlock showed the highest number of complaints, and the levels of mosquito activity were highest during the winter, spring and summer. There were a relatively low number of mosquito problems around the ports of entry. However, the major ports of entry, Honolulu International Airport, Sand Island and Campbell Industrial Park, could not be evaluated by adjusting for population due to their low residential population.

Discussion

The primary mosquito species recorded was *Aedes albopictus* (~81.3%; n = 2,163), the Asian tiger mosquito (Table 3). Isolated *Wyeomyia mitchellii* (~7.1%), bromeliad mosquito, and few *Culex quinquefasciatus* (~11.6%), southern house mosquito, cases were recorded. Species occurrence increased slightly to ~89.5%, ~7.8% and ~12.8% respectively when the number of sites (n = 1,965) was taken into consideration since multiple species have been found together on the same site. The main breeding sources found were various containers (~41.2%; n = 631) such as plant pots, buckets and tires plus bromeliad plants (Bromeliaceae; ~34.4%) (Table 4). Gardening activities, irrigation, poor drainage, toys holding water, and man-made ponds and pools all contributed to mosquito breeding. Although it may appear there was a significant socioeconomic component to the high occurrence of mosquito activity from Kahala to Portlock, the cases actually involved residents with a broad range of ethnic and social backgrounds. Economic status was a more important consideration since it allowed for extensive landscaping and gardening which often included the planting of bromeliads and regular watering, and the presence of swimming pools and man-made ponds. Although the major ports of entry and other industrial district/areas had a relatively low number of mosquito complaints, infestations were generally heavy when they occurred. The main breeding sources in these areas were car and truck tires, buckets and various other storage containers, and construction materials such as large sections of plumbing.

It was previously thought that there would be a higher occurrence of mosquito activity around the east, north and west areas of Oahu due to known *C. quinquefasciatus* breeding sites and within district/areas bordering forested lands due to standing populations of *Ae. albopictus*, also known as the forest-day mosquito. However, instead, this survey has determined that *Ae. albopictus* populations were being maintained in urban districts by human activities. As a result, dengue transmission is possible in the drier, urban areas of Oahu. This is especially significant since dengue cases in the past (Usinger 1944) had occurred in nearly inverse proportion to the incidence of mosquito breeding and could be correlated with the density of the human population rather than with mosquito density (note: a 1948

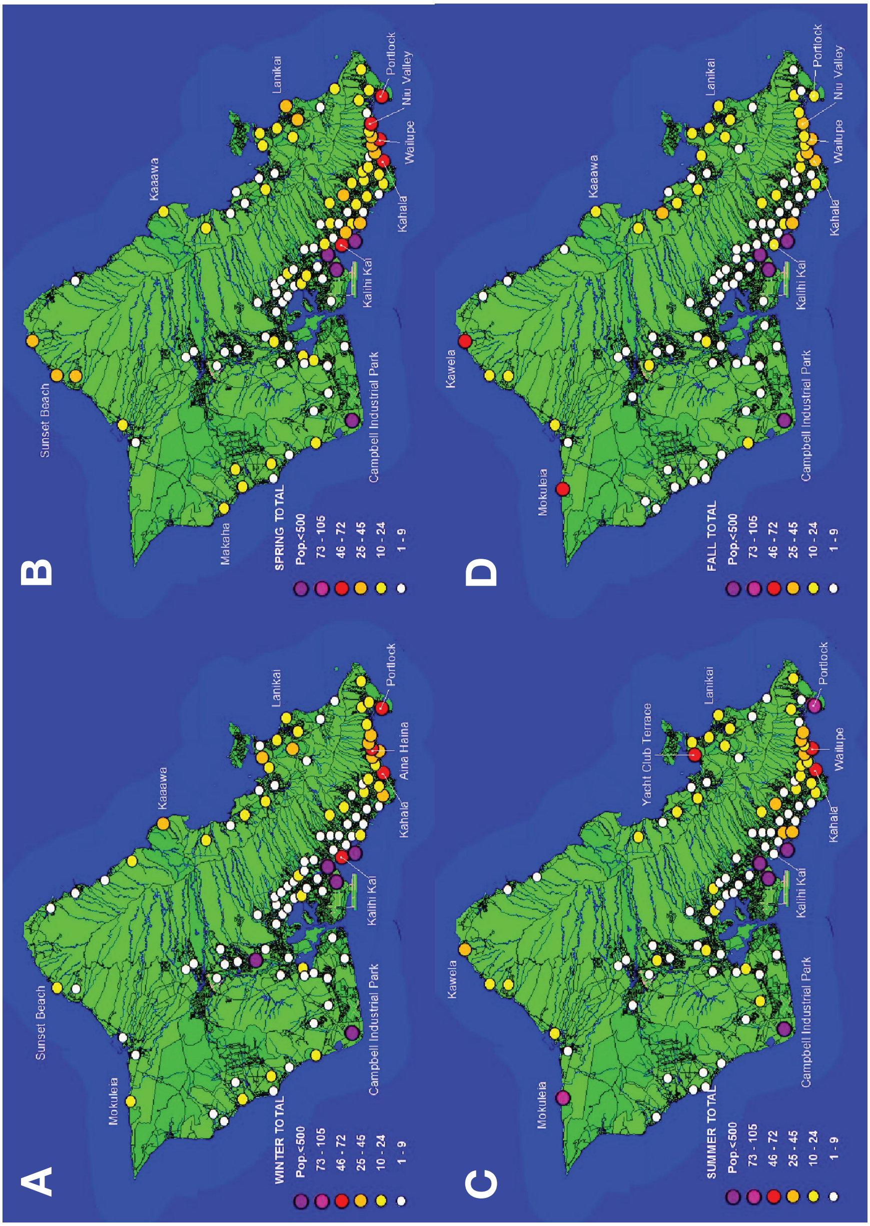

Figure 2. Mosquitoes, seasonal totals (1990–1999) for winter (A), spring (B), summer (C) and fall (D).

Table 3. Mosquito species occurrence as determined by a sampling of 2,536 mosquito-related inspection reports.

Species	%	Mean	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total
Aedes albopictus	81.3	175.8	204	193	228	108	120	194	225	246	88	152	**1758**
Culex quinquefasciatus	11.6	25.1	20	28	34	19	24	28	45	16	12	25	**251**
Wyeomyia mitchellii	7.1	15.4	7	8	9	3	6	12	38	42	10	19	**154**
Total	**100.0**	**216.3**	**231**	**229**	**271**	**130**	**150**	**234**	**308**	**304**	**110**	**196**	**2163**

Table 4. Mosquito breeding sources as determined by a sampling of 1,459 mosquito-related inspection reports.

Breeding sources	%	Mean	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total
Ape/spider lilies	2.1	2.2	N/A*	N/A	N/A	N/A	4	2	1	3	3	0	**13**
Bromeliads	34.4	36.2	N/A	N/A	N/A	N/A	26	44	52	51	13	31	**217**
Containers/tires	41.2	43.3	N/A	N/A	N/A	N/A	6	29	15	66	46	98	**260**
Ground pools/ditches	4.8	5.0	N/A	N/A	N/A	N/A	4	1	3	5	7	10	**30**
Pools/ponds/sumps	17.6	18.5	N/A	N/A	N/A	N/A	4	16	9	25	24	33	**111**
Total	**100.0**	**105.2**	**N/A**	**N/A**	**N/A**	**N/A**	**44**	**92**	**80**	**150**	**93**	**172**	**631**

*Data not available.

mosquito survey finding reported by Bonnet (1949) that *Ae. aegypti*, an excellent dengue vector, was found strictly on the seaward side of a line drawn along Beretania Street may be a contributing factor for this observation). There was limited information for assessing the occurrence and distribution of night biting mosquitoes across the island. Inspection reports, therefore, need to be supplemented with mosquito light trap data to better determine *C. quinquefasciatus* and *Ae. vexans nocturnus* activity.

As in this study, Usinger (1944) also indicated that mosquito activity was usually low during the fall months since they form the ending of the dry season and anticipated an increase in mosquito breeding with the coming of winter rains. The results indicate that community or island-wide educational programs should be carried out in late fall and early spring to prepare the public for and reinforce awareness during Hawaii's mosquito season, and that residential mosquito surveys may be concentrated in a limited number of district/areas according to mosquito complaints received. Educational activities are currently conducted in response to dengue cases identified locally and West Nile virus (WNV) threats from the continental U.S.A., or on a limited basis during inspections. A WNV prevention and mosquito control effort carried out in September 2004, WNV Mosquito Survey and Larviciding for Ports of Entry on Oahu, confirmed the practicality of using small-target area surveys. In a survey that encompassed all areas within 2 miles of Honolulu Harbor and Kalaeloa Barbers Point Harbor, only 17 of 1,051 (1.6%) of the sites inspected contained mosquito activity and much of the major breeding areas were already known. As pointed out earlier, relatively few mosquito complaints were received for industrial parks and heavy commercial areas overall, but particular mosquito problems were often found to be severe. Taking the workforce, visitor and transient resident populations into consideration, this is a very important implication for the spread of a vector-borne disease or introduction of a new mosquito vector, especially in the industrial parks and harbor areas.

Geographic analysis can help to target areas and times of the year for more efficient application of mosquito prevention, control and education programs by continuously tracking mosquito activity using Vector Control inspection reports. Improvements in methodology include incorporating mosquito gravid trap (currently employed only in the ports of entry) and light trap data to achieve a better picture of night-biting mosquito activity, and using the actual number of complaints within a district/area and the severity of the mosquito infestation found together with data adjusted for population to more accurately determine the need for targeted survey, abatement and education efforts. For example, geographic analysis of transformed mosquito occurrence may flag a potential problem district/area for increased scrutiny, but additional action would be taken only if at least three complaints were received, the level of infestation was heavy and/or the mosquito problem was found to occur over an extensive area. The same deciding factors may be applied directly for the excluded district/areas with resident populations of less than 500.

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