ABSTRACT. The establishment of action thresholds is becoming critical in mosquito control management to implement effective proactive control measures using limited available resources. As a part of a large-scale study to identify different mosquito control action thresholds used in different geographical regions, we conducted an initial survey to identify mosquito control programs that claim to have set action thresholds and to investigate their associated program characteristics. We identified 68% (USA), 60% (mainland Australia), 78% (Asia), 35% (Africa), and 50% (US military units) of the responding programs, which perform mosquito control, have set mosquito control action thresholds. More than 50% of the programs that have not set mosquito control action thresholds already collect basic surveillance information as do the programs with thresholds. Further investigations with the selected mosquito control programs from this initial survey will help develop guidelines on establishing action thresholds by identifying different types of actual action thresholds used by programs in different geographical settings and other related information.

KEY WORDS Action thresholds, best management practices, geographic distribution, mosquito control, surveillance

INTRODUCTION

Mosquitoes are present in virtually every region worldwide, causing considerable public nuisance and serving as vectors of disease-causing organisms. Mosquito control interventions and implementation methods vary widely between countries and between regional programs within the same country. The concept of integrated mosquito management (IMM) is central to the goal of mosquito control in the USA (AMCA 2017) as well as in many other countries. As a principle of IMM, preemptive rather than reactive mosquito control measures are recommended and have been shown to be effective in suppressing mosquito populations (WHO 2012). Without appropriate knowledge and analytical tools, knowing when best to implement control measures is challenging (Peterson and Higley 2002). Hence, understanding and establishing evidence-based thresholds for action to reduce both nuisance and vector mosquitoes is becoming critical.

An action threshold for mosquito control is a point at which mosquito populations or environmental conditions indicate that mosquito control action must be taken (EPA 2021). For example, more than 25 total mosquitoes per trap-night indicates the need to initiate adulticiding in Florida (State of Florida 2010), and a landing rate of more than 50 mosquitoes/min informs to initiate adulticiding in Harris County, TX (W. Qualls, personal information). Effective nuisance and vector control rely on being able to predict patterns of mosquito biology and behavior, as well as disease distribution, over time. These patterns, identified through surveillance systems, are used by mosquito control programs at a local scale in establishing action thresholds. Identification of key surveillance parameters and the use of years of surveillance data are necessary to establish standardized and effective action thresholds. However, those thresholds may be heavily influenced by economic and political factors. Consequently, mosquito control programs that serve geographically similar regions with overlapping vector species may impose vastly different action thresholds. At the same time, possible discrepancies in action thresholds developed for the same species could have arisen due to geographical variations. Once established, the thresholds for action will help mosquito control programs implement timely control measures to maintain mosquito populations (adult and/or immature) at levels below which unacceptable nuisance and disease transmission would not occur. The use of action thresholds with comprehensive surveillance will ensure that resources are allocated to areas with priority requirements. In addition, to be imperatively helpful in timely and spatially effective mosquito control, the use of action thresholds will help manage the development of insecticide resistance and program logistics by reducing the number of unwarranted adulticide missions.

With climatic changes conducive for increasing and spreading of mosquito populations and the emergence and reemergence of vector-borne diseases in recent years, effective methods for timely control are required to protect US military units deployed in different operational environments across the globe. The Armed Forces Pest Management Board (AFPMB) recommends policy, provides guidance, and coordinates the exchange of information on all...
matters related to pest management through the Department of Defense (DoD). However, DoD entomologists and pest managers do not always have an opportunity to develop appropriate action thresholds in operational regions outside the USA. The Anastasia Mosquito Control District (AMCD), St. Augustine, FL, is researching the development of action thresholds for mosquitos in different geographical regions.

This preliminary questionnaire survey (survey hereafter) was conducted to identify mosquito control programs in different geographical regions that claim to have set action thresholds to initiate their control operations and associated program characteristics. The survey did not intend to identify actual action thresholds used by different mosquito control programs, which was instead planned for a follow-up interview with programs identified in the current survey.

**METHODOLOGY**

A preliminary survey of 17 questions (Supplemental Data 1) was developed on the Qualtrics online platform (www.Qualtrics.com). The questions inquired about program demographics, surveillance (mosquito, environmental, disease), and mosquito control efforts. Some of the questions had a single answer while others had multiple answers. Some questions had either a yes or no answer. A pretest of the survey was carried out with 10 mosquito control programs in the USA to identify any possible errors and to obtain constructive comments that would help improve the survey. The finalized survey was distributed online using numerous strategies to maximize the number of responses; the survey web-link was distributed to mosquito control programs in the North American region through the addresses found from the websites of the American Mosquito Control Association (AMCA), the Florida Mosquito Control Association, the California Mosquito Control Association, and the National Pesticide Information Center. Assistance with reaching out to additional mosquito control programs was gained through the project managers of the Centers of Excellence in Vector-borne Diseases of the Centers for Disease Control and Prevention, and the personal contacts of the AMCD study team. An advertisement with the survey link was published in the AMCA Bi-weekly news. The US military units were contacted through the AFPMB and the advertisement posted on AFPMB’s Facebook page with the survey link. The survey was sent out starting in mid-February 2021 and responses were received until mid-May 2021. All the response data were exported from Qualtrics to an Excel spreadsheet (Microsoft, Albuquerque, NM) for analysis.

A total of 266 responses were received from different countries/continents, and 42 of them were removed from further consideration due to being completely blanks, duplicates, no information provided on the program identity, and not performing either mosquito control or surveillance. Thus, 224 responses were selected for initial data summarization (subtitle 1 in Results). Programs that perform only surveillance (n = 21) were used only in the initial data summarization to provide a general overview of the responded programs. Those responses were removed from subsequent data summarization as they do not conduct mosquito control. Responses given for each answer of each question by different programs were summarized as percent responses.

**RESULTS**

The initial selection of 224 responses were received from mosquito control programs of 18 countries: the USA (n = 152), mainland Australia (Australia hereafter; n = 11), 2 countries in Asia (n = 15), 13 countries in Africa (n = 39), 1 country in Europe (n = 1), and 6 US military units (n = 6) (Fig. 1). The single survey response received from Europe was excluded from subsequent data summarization.

Responses received from the USA were from 29 states (Fig. 2) and 1 US territory (the US Virgin Islands).

### 1. Performance of mosquito control and surveillance

In the USA, 97.4% (148/152) of responded programs perform mosquito control while 95% (144/152) perform surveillance (either mosquito, disease, and/or environmental surveillance). Most of those programs (92% [140/152]) perform both mosquito control and surveillance. A few programs in the USA perform only surveillance (3% [4/152]) or only mosquito control (5% [8/152]). Ninety-one percent (10/11) of responded programs in Australia perform both mosquito control and surveillance while only 1 program performs surveillance only. Sixty percent (9/15) of the responded programs in Asia perform both mosquito control and surveillance while 40% (6/15) perform only surveillance. In Africa, 72% (28/39) of the responded programs perform mosquito control and surveillance while 26% (10/39) perform only surveillance and 1 program performs only control. All the responded programs of US military units perform mosquito control while only 67% (4/6) of those programs perform surveillance.

The total number of responded programs that perform mosquito control is 202 (148 in the USA, 10 in Australia, 9 in Asia, 29 in Africa, and 6 US military units). The majority of those programs conduct routine mosquito control (78% [116/148] in the USA, 80% [8/10] in Australia, 78% [7/9] in Asia, 72% [21/29] in Africa). In contrast, 83% (5/6) of US military unit programs conduct intermittent mosquito control only (i.e., only during natural disasters or public health crises).
2. Use of mosquito control action thresholds

Programs that perform mosquito control and have set either different action thresholds for different species or one threshold for all target species were defined as programs “with thresholds” and the rest (with state/military guidelines, other methods, no action thresholds, and no relevant information...
provided) were defined as programs “without thresholds.” State/military guidelines were included in the “without threshold” category as they are assumed to be more generalized for specific programs. In the USA, 68% (101/148) of the programs are with thresholds. Of them, 67% (68/101) are with different action thresholds for different species, while 33% (33/101) are with one threshold for all target species. Of the 32% (47/148) programs without thresholds in the USA, 45% (21/47) use state/military guidelines, 34% (16/47) use other methods to initiate their mosquito control operations, and 21% (10/47) have no thresholds or did not provide relevant information (Table 1 and see Fig. 3 for the geographical

Table 1. Use of mosquito control action thresholds by the mosquito control programs of different countries/continents and US military units.1

| Use of action thresholds | USA, % | Mainland Australia, % | Asia, % | Africa, % | US military units, % |
|--------------------------|--------|-----------------------|--------|-----------|---------------------|
| With action thresholds   |        |                       |        |           |                     |
| Total                    | 68.2 (n₁ = 148) | 60 (n₁ = 10) | 77.8 (n₁ = 9) | 34.5 (n₁ = 29) | 50 (n₁ = 6) |
| Different thresholds     | 67.3 (n₂ = 101) | 66.7 (n₂ = 6) | 85.7 (n₂ = 7) | 90 (n₂ = 10) | 66.7 (n₂ = 3) |
| One threshold            | 32.7 (n₂ = 101) | 33.3 (n₂ = 6) | 14.3 (n₂ = 7) | 10 (n₂ = 10) | 33.3 (n₂ = 3) |
| Without action thresholds|        |                       |        |           |                     |
| Total                    | 31.8 (n₁ = 148) | 40 (n₁ = 10) | 22.2 (n₁ = 9) | 65.5 (n₁ = 29) | 50 (n₁ = 6) |
| Guidelines               | 44.7 (n₂ = 47) | 0 (n₂ = 4) | 50 (n₂ = 2) | 31.6 (n₂ = 19) | 33.3 (n₂ = 3) |
| Other methods            | 34.04 (n₂ = 47) | 75 (n₂ = 4) | 50 (n₂ = 2) | 47.4 (n₂ = 19) | 66.7 (n₂ = 3) |
| No thresholds            | 19.1 (n₂ = 47) | 25 (n₂ = 4) | 0 (n₂ = 2) | 15.8 (n₂ = 19) | 0 (n₂ = 3) |
| No information           | 2.1 (n₂ = 47) | 0 (n₂ = 4) | 0 (n₂ = 2) | 5.2 (n₂ = 19) | 0 (n₂ = 3) |

1 n₁, number of responded programs that perform mosquito control; n₂, total number of programs with/without thresholds.

Fig. 3. Distribution map of mosquito control programs that were included in the analyses for the USA and US military units (only one located in North America) showing the type of action thresholds used—the dots indicate the primary address of the program headquarters (approximate location) and do not necessarily indicate the extent of real-time program location or operational coverage. States with at least one included program are colored purple while states with no survey responses are blank. The US Virgin Islands was categorized as part of the USA for analyses. (<Null> = no information provided.) The shapefile dataset of the US states was retrieved from the United States Census Bureau (2020).
distribution of programs with and without thresholds. In Australia, 60% (6/10) of the programs are with thresholds, while in Asia 78% (7/9) are with thresholds. Different thresholds for different species is the most common category in Australia (67% [4/6] and Asia (86% [6/7]). Seventy-five percent (3/4) of the total programs without thresholds in Australia use other methods, while 25% (1/4) have no set thresholds in their control programs. In Asia, 50% (1/2) of the programs without thresholds use state/military guidelines and 50% (1/2) use other methods. Only 35% (10/29) of the African programs are with thresholds and 90% (9/10) of them have different thresholds for different species. Most of the programs without thresholds in Africa use other methods (47% [9/19]), followed by state/military guidelines (32% [6/19]), while 21% (4/19) have no set thresholds or not provided relevant information. Fifty percent (3/6) of the US military unit programs are with thresholds and 67% (2/3) of them have different action thresholds for different species while 33% (1/3) have one threshold for all target species. Of the 50% (3/6) programs without thresholds in the US military units, 67% (2/3) use other methods while 33% (1/3) use state/military guidelines (Table 1).

3. Level of function and funding sources of mosquito control programs

In the USA, the highest proportion of programs with and without thresholds functions at the county level (61% [62/101] and 45% [21/47], respectively), followed by the local/city levels (23.8% [24/101] and 36% [17/47], respectively). In Australia, the largest proportion of programs with thresholds functions at the local/city level (50% [3/6]) followed by the state level (33% [2/6]), while all of the programs without thresholds (4/4) function at the local/city level. The largest proportion of programs with thresholds in Asia functions at the local/city level (71% [5/7]), while the 2 programs without thresholds function at the state and county levels. In Africa, the highest proportion of programs with thresholds functions at the state level (40% [4/10]), while those without thresholds function the most at county and “other” levels (32% [6/19] for both).

Most of the programs with thresholds in the USA are funded as independent taxing districts [43% (43/101) and county/city levied funds [40% (40/101)], while the majority of programs without thresholds are funded by county/city levied funds [55% (26/47)]. Programs with thresholds in Australia and Asia are mainly funded by county/city levied funds [67% (4/6] and 86% [6/7], respectively) while those without thresholds are funded by county/city levied funds (50% [2/4] and 50% [1/2], respectively) as well as through other sources (50% [2/4] and 50% [1/2], respectively). African programs, both with and without thresholds, are funded mainly by other sources (60% [6/10] and 79% [15/19], respectively).

4. Surveillance categories performed by mosquito control programs

Mosquito surveillance is the most common category of surveillance in programs with and without thresholds in the USA (97% [98/101] and 89% [42/47], respectively). All programs with thresholds (6/6) in Australia perform all 3 categories of surveillance. All programs without thresholds (4/4) in Australia perform mosquito and environmental surveillance while only 50% (2/4) perform disease surveillance. In Asia, all programs with (7/7) and without (2/2) thresholds perform all 3 categories of surveillance. All the African programs with thresholds (10/10) perform mosquito surveillance while 90% (9/10) and 80% (8/10) programs perform disease and environmental surveillance, respectively. Mosquito surveillance is the most common category (95% [18/19]) in African programs without thresholds followed by disease (84% [16/19]) and environmental (74% [14/19]) surveillance. All the programs with thresholds (3/3) in US military units perform mosquito surveillance followed by disease surveillance while only 1 out of the 3 programs without thresholds performs surveillance (Fig. 4).

5. Mosquito surveillance

5.1. Surveillance frequency: The majority of the programs with thresholds in the USA (86% [84/98]) perform mosquito surveillance at least once a week. In Australia, 50% (3/6) of the programs with thresholds perform surveillance at least once a week while 33% (2/6) perform once every 2 wk. In Asia, 43% (3/7) of the programs with thresholds perform surveillance at least once a week, while for 43% (3/7) of programs the frequency is once every 2 wk. The most common surveillance frequency of programs with thresholds in Africa is once a month (40% [4/10]) followed by “other” category of frequency (30% [3/10]). Three programs of US military units with thresholds have 3 different surveillance frequencies. In the USA, 74% (31/42) of programs without thresholds perform weekly surveillance. None of the programs without thresholds in Australia perform weekly surveillance, while 1 of the 2 Asian programs without thresholds perform weekly surveillance. Surveillance frequency of most of the programs without thresholds in Africa is 56% (10/18) and the single program in US military units falls into the “other” category (Fig. 5).

5.2. Life stage categories of mosquito surveillance: Adult mosquito surveillance is performed by all programs, both with or without thresholds, in all countries/continents and US military units. Most of the programs perform larval surveillance as well (93% [112/121] of programs with and 89% [59/66] without thresholds in all countries/continents). In the USA, 93% (91/98) and 88% (37/42) of programs with and without thresholds, respectively, perform larval surveillance. All the programs with and
without thresholds (6/6 and 4/4, respectively) in Australia perform larval surveillance. In Africa and Asia, 90% (9/10) and 86% (6/7) of programs with thresholds, respectively, and 89% (16/18) and 100% (2/2) of programs without thresholds perform larval surveillance. Only 1 of the 3 US military units with thresholds and the single unit without thresholds perform larval surveillance. The number of programs that perform egg surveillance is comparatively low in all countries/continents. In the USA 50% (49/98) and 38% (16/42) of programs with and without thresholds, respectively, perform egg surveillance. Egg surveillance is performed by 50% (3/6) of Australian programs with thresholds but by none of the programs without thresholds. Fifty-seven percent of programs (4/7) with thresholds and 1 of the 2 programs without thresholds in Asia perform egg surveillance. In Africa, egg surveillance is performed by only 40% (4/10) of programs with thresholds and 28% (5/18) of programs without thresholds. Two of the 3 US military units with thresholds and the single unit without thresholds perform egg surveillance as well.

5.3. Use of different adult mosquito sampling methods and techniques: Focus/hot spot sampling is the most common method used for adult sampling by the programs with and without thresholds in the USA (72% [71/98] and 67% [28/42], respectively). Australian programs with thresholds use both focus/hot spots (50% [3/6]) and sentinel/fixed sampling (50% [3/6]) as their most common sampling methods, while 100% of programs without thresholds use focus/hot spot sampling. Programs with thresholds in Asia use sentinel/fixed sampling the most (57% [4/7]) followed by focus/hot spot sampling (43% [3/7]). The most common sampling method used by the programs with and without thresholds in Africa is sentinel/fixed sampling (70% [7/10] and 67% [12/18], respectively). The 3 US military unit programs with thresholds use 3 different methods, while the single program without thresholds uses all 3 listed methods.

Chemical or animal baited traps are the most common sampling technique used in adult mosquito surveillance by programs with and without thresholds in the USA (68% [67/98] and 60% [25/42], respectively). Baited traps are used by 50% (3/6) of programs with thresholds in Australia while 50% (3/6) of programs use landing rates. The programs without thresholds in Australia have not provided information on the use of different adult sampling techniques. Baited traps are the most common technique (43% [3/7]) in Asian programs with thresholds while the 2 programs without thresholds...
use both baited traps and landing rates. In Africa, the majority of programs with thresholds use baited traps (70% [7/10]) while those without thresholds use landing rates (44% [8/18]). All 3 programs with thresholds in US military units use baited traps and 2 programs use landing rates, while the single program without thresholds uses only baited traps. Some programs in all regions and US military units have not given information on the sampling methods and/or techniques.

5.4. Use of different trap types and target mosquito types: BG sentinel traps (Biogents AG, Regensburg, Germany) (76% [74/98]) and gravid traps (76% [74/98]) are the most common trap types used by mosquito control programs with thresholds in the USA and most of the programs without thresholds use gravid traps (69% [29/42]). The most common trap type in all other countries/continents is the light trap (in Australia 67% [4/6] and 75% [3/4], in Asia 100% [7/7] and 100% [2/2], in Africa 80% [8/10] and 88% [15/18], for programs with and without thresholds, respectively). All 3 US military unit programs with thresholds use BG traps, while those without threshold use all 3 trap types interchangeably. Some programs in all countries/continents and US military units use other trap types such as encephalitis virus surveillance traps, CO₂ traps without light, and resting boxes. See Table 2 for their target mosquito types. The group labeled as “other” in Table 2 includes vectors of malaria, filaria, Japanese encephalitis virus, Ross River virus, etc.

5.5. Sampling techniques used in mosquito larval and egg surveillance: Dipping is the most used technique in the larval mosquito surveillance by programs in all countries/continents (USA 97% [88/91] and 78% [29/37]; Australia 100% [6/6] and 100% [4/4]; Asia 67% [4/6] and 100% [2/2], and Africa 89% [8/9] and 75% [12/16], respectively, for programs with and without thresholds). Only 1 US military program with thresholds and only 1 program without thresholds perform larval surveillance, and both programs use the dipping technique. Ovitrapting is the main egg surveillance technique of programs with thresholds in all countries/continents and US military units except in Australia. More than 95% of programs with thresholds that perform egg surveillance in all countries/continents and US military units, except Australia, use ovi-traps. Ovitrap surveillance is common in programs without thresholds in the USA (76.5%), Africa (75%), and 1 US military unit program uses ovi-traps as well.

5.6. Use of customer complaints/service requests in mosquito surveillance: The majority of mosquito control programs with and without thresholds in the
USA use customer complaints/service requests for both adult (93% [91/98] and 86% [36/42] of programs with and without thresholds, respectively) and larval (87% [79/91] and 78% [29/42] of programs with and without thresholds, respectively) mosquito surveillance. All the programs with (6/6) and without (4/4) thresholds in Australia use customer complaints/service requests for adult surveillance while 67% (4/6) programs with thresholds use them for larval surveillance. The use of complaints/service requests by programs in Asia and Africa is low. One of the 7 programs with thresholds in Asia uses them for adult surveillance, while 1 of the 6 programs uses them for larval surveillance. None of the programs without thresholds in Asia use customer complaints/service requests either for adult or larval surveillance. Thirty percent (3/10) of programs with thresholds in Africa use customer complaints/service requests for adult surveillance, while 56% (5/9) use them for larval surveillance. None of the programs without thresholds use them for adult surveillance, while only 13% (2/16) use them for larval surveillance. Two of the 3 US military unit programs with thresholds and the single program without thresholds use customer complaints/service requests only in adult surveillance.

6. Environmental surveillance

The majority of mosquito control programs that perform environmental surveillance in all countries/continents and US military units use at least 2 environmental parameters. Rainfall and temperature are the most commonly used parameters in the programs with (78% [61/78] for both) and without (78% [21/27] for both) thresholds in the USA, while wind speed follows in rank (64% [50/78] and 56% [15/27], respectively). All the programs with (6/6) and without (3/3) thresholds in Australia use rainfall and temperature. The most common environmental variables used by programs with thresholds in Asia is relative humidity (RH) (86% [6/7]) followed by temperature and wind speed at the same rank (71% [5/7 for both]). All programs (7/7) without thresholds in Asia use temperature while 86% (6/7) use RH. Rainfall and wind speed follow at the same rank with (57% [4/7] for both). The majority of programs with thresholds in Africa use rainfall, temperature, and RH (86% [7/8] for all) in their surveillance. Most of the African programs without thresholds use RH (48% [10/21], followed by temperature (43% [9/21]) and rainfall (38% [8/21]). Tidal information is the least used environmental variable in all countries/continents except Australia. In Australia, all programs (6/6) with thresholds and 67% (2/3) of programs without thresholds use tidal information in environmental surveillance. Only 1 of the US military unit programs with thresholds (1/3) performs environmental surveillance and it uses only RH, while the single US military unit program that performs environmental surveillance and without thresholds uses 4 different environmental parameters.

7. Disease surveillance

Mosquito pooling for arboviruses (87% [78/90] and 76% [31/41] with and without thresholds, respectively) and number of human cases (84% [76/90] and 76% [31/41] with and without thresholds, respectively) are the most used disease surveillance parameters, while sentinel chickens (20% [18/90] and 20% [8/41] with and without thresholds, respectively) is the least used by programs in the USA. The number of human cases is the most common parameter used by the programs with (83% [5/6]) and without (100% [3/3]) thresholds in Australia. Asian programs use the number of human cases (86%
[6/7] and 80% [4/5] with and without thresholds, respectively) and mosquito pooling for arboviruses (71% [5/7] and 60% [3/5] with and without thresholds, respectively). The most common parameter used by African programs is the number of human cases (78% [7/9] and 85% [17/20]) with and without thresholds, respectively. All the US military unit programs with and without thresholds that perform disease surveillance use mosquito pooling for arboviruses and the number of human cases.

Most of the USA, Australian, Asian, African, and US military unit programs, with thresholds, perform in-house or outsourced pathogen testing in their disease surveillance system (96% [86/90], 83% [5/6], 100% [7/7], 89% [8/9], and 100% [2/2], respectively). The majority of programs without thresholds in the USA, Africa, and US military units perform pathogen testing (71% [29/41], 65% [13/20], and 100% [2/2], respectively). However, the performance of pathogen testing by programs without thresholds in Australia and Asia is comparatively low (33% [1/3] and 33% [2/6], respectively).

The majority of programs, both with or without thresholds, in all countries/continents share data or cooperate with local health departments regarding human and/or animal cases of any mosquito-borne diseases or positive mosquito pools (USA 99% [89/90] and 100% [41/41], Australia 100% [6/6] and 100% [3/3], Asia 100% [7/7] and 67% [4/6], Africa 78% [7/9] and 95% [19/20], respectively, for programs with and without thresholds). Only 2 US military units without thresholds perform disease surveillance. Those 2 programs and the single program without thresholds share surveillance data or cooperate with local departments.

8. Summary of the surveillance characteristics of programs with and without thresholds

A total of 202 responses of mosquito control programs from 2 countries (USA and mainland Australia), different countries from 2 continents (Asia and Africa), and US military units deployed in different regions of the world were selected for the characterization of their surveillance systems. Of them, 63% of (127/202) the programs are identified as programs with thresholds while 37% (75/202) programs are without thresholds. The majority of programs with (98% [124/127]) and without (89% [67/75]) thresholds perform mosquito surveillance, followed by disease surveillance (90% [114/127] and 79% [59/75] with and without thresholds, respectively) and environmental surveillance (78% [99/127] and 67% [50/75] with and without thresholds, respectively). Mosquito surveillance frequency is at once a week in 76% (94/124) of programs and at least once in every 2 wk in 84% (104/124) of programs with thresholds. The frequency is spaced out to more than once a week in 51% (34/67) of programs without thresholds and only 54% (36/67) of programs without thresholds perform mosquito surveillance at least once every 2 wk. Adult mosquito surveillance is performed by all programs with and without thresholds, while larval surveillance is performed by 91% (113/124) of programs with thresholds and 90% (60/67) of programs without thresholds. Focus/hot spot and sentinel/fixed sampling is used most by programs with (67% [83/124] and 57% [71/124], respectively) and without (47% [31/66] and 53% [35/66], respectively) thresholds. Sixty-seven percent (83/124) of programs with thresholds and 52% (34/66) of programs without thresholds use baited traps in their surveillance systems. Eighty-three percent (103/124) of programs with thresholds and 61% (41/67) of programs without thresholds use customer complaints/service requests for adult surveillance, while 79% (89/113) of programs with thresholds and 58% (35/60) of programs without thresholds use it for larval surveillance. Temperature and rainfall are the most used environmental parameters by programs with (80% [80/100] and 77% [77/100], respectively) and without (69% [41/59] and 63% [37/59], respectively) thresholds. The majority of programs with and without thresholds use the number of human cases (84% [95/113] and 80% [56/70], respectively) followed by mosquito pooling for arboviruses (82% [93/113] and 56% [39/70], respectively). Ninety-six percent (108/113) of programs that perform disease surveillance and with thresholds and 66% (46/70) of programs without thresholds perform in-house or outsourced pathogen testing. Ninety-eight percent (111/113) of programs with thresholds and 91% (64/70) of programs without thresholds share data or cooperate with local departments of health regarding human and/or animal cases of any mosquito-borne diseases or positive mosquito pools (Table 3).

DISCUSSION

Based on ecological variances and other logistical inconsistencies, different mosquito control programs in different countries, as well as in the same country, would use different surveillance systems and control tools. Thus, there would be different action thresholds, which may vary in type or magnitude, for the control of the same groups of genera or species. For example, dengue outbreaks occurred in Singapore when the national overall house index of *Aedes aegypti* L. was <1% (Unknown Author 1993) while dengue outbreaks never occurred in Fortaleza, Brazil, when the house index was <1% (Pontes et al. 2000). Identification of the mosquito control programs with action thresholds in different geographical settings and scrutinizing their surveillance systems would give guidance on how best to use the surveillance information in effective as well as proactive mosquito control programs. As a part of a large-scale study, this preliminary survey targeted to identify the programs that use any mosquito control action threshold/s and to look into associated surveillance information.
The survey identified that 60–78% of mosquito control programs that perform either routine or intermittent mosquito control, in all surveyed countries/continents except Africa (68% in the USA, 60% in mainland Australia, 78% in Asia, and 35% in Africa), use action thresholds. Fifty percent of the responded US military unit programs that perform mosquito control use action thresholds as well. The comparative low proportion of programs having set action thresholds (35%) and discrepancies in the surveillance systems in African programs could be due to the fact that most of the responded programs are mandated by research grants and/or independent agencies.

The development of reliable action thresholds is a complex process of comprehensive surveillance over a number of years (Bowman et al. 2016, Nasci and Mutebi 2019) which requires a good source of funding. Some researchers have demonstrated that local-scale action thresholds at smaller geographical levels would be more reliable (Sanchez et al. 2006, Nasci and Mutebi 2019) while Bowman et al. (2016) emphasized the importance of the use of action thresholds at broad spatial units. We identified that most of the responded mosquito control programs (with or without thresholds), except those in Africa, function at county or local city levels and are funded as independent taxing districts (mostly in the USA) or through county/city levied funds. Program logistics and thus the performance of surveillance systems may be affected by the availability of funds.

Surveillance information is the backbone for any successful mosquito control program. Surveillance systems for mosquito control may include mosquito surveillance alongside with disease and/or environmental surveillance. Frequency of surveillance is critical in developing reliable action thresholds that will give minimum false alarms. Surveillance frequency based on the duration of the mosquito life cycle would give more reliable information compared with spaced out surveillance. Spaced out surveillance frequency identified in many programs without thresholds should be addressed in developing guidelines. Performance of adult and larval/egg surveillance will produce information for action thresholds for both adult and larval control. Selection of the most appropriate sampling technique/s to best address the requirement and the most appropriate sampling method for the target mosquito species and life stage (adults/larvae) is vital in any mosquito surveillance system. The use of customer complaints/service requests would be an important indirect surveillance indicator to be used in the development of action thresholds, particularly for nuisance mosquito control. In addition to the information on mosquito abundance, mosquito-based surveillance systems also produce important indirect information on disease surveillance in the form of vector infection rate. Indirect disease surveillance produces information earlier than direct surveillance, which relies on the number of human cases of a particular disease. For example, Liu et al. (2009) found that a dead bird sighting in the last 30 days and a West Nile virus–positive bird in the last 30 days were significantly associated with increased risk of human infection. Aryaprema and Xue (2019) demonstrated that Ae. aegypti Breteau Index over 2.45 in the Colombo District, Sri Lanka, will increase the number of dengue cases in the following months. Environmental variables such as rainfall, temperature, and RH affect mosquito abundance (Dickerson 2007, Couret et al. 2014) as well as disease transmission dynamics (Yi et al. 2003, Pham et al. 2011, Xiang et al. 2017). Information gathered through well-planned surveillance systems, including mosquito surveillance along with disease and/or environmental surveillance, would derive reliable action thresholds for mosquito control. Further investigations of those surveillance systems of programs with thresholds will allow us to see how best that surveillance information could be used to develop action thresholds for mosquito control.

Surveillance systems including all the important variables addressed in this survey allow us to gather an array of data sufficient for the development of evidenced-based action thresholds to control mosquito abundance. Survey findings indicate that most of the responded mosquito control programs in all
countries/continents and US military units have already set mosquito control thresholds generated from information gathered through well-planned surveillance systems. Most of the programs that do not have set action thresholds still have good surveillance systems with similar characteristics as the programs that do have thresholds. It indicates that those programs without thresholds already have the capacity to develop their own action thresholds. This baseline information will be used to select programs for the future follow-up survey to identify actual mosquito control action thresholds used by different programs and to develop guidelines for establishing and using evidenced-based thresholds to initiate mosquito control at the right time.

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