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EVALUATION OF THE NEW MODULAR BIOGENTS BG-PRO MOSQUITO TRAP IN COMPARISON TO CDC, EVS, BG-SENTINEL, AND BG-MOSQUITAIRE TRAPS

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ABSTRACT. Mosquito surveillance is an essential component of mosquito control and mosquito traps are a universally employed tool to monitor adult populations. The objective of this paper was to evaluate the new modular Biogents BG-Pro mosquito trap (BGP) and compare its performance to 4 widely used traps for adult mosquitoes: the BG-Sentinel (BGS), the BG Mosquitaire (BGM), the CDC miniature light trap (CDC), and the encephalitis vector survey trap (EVS). One semi-field and 9 field Latin square trials were performed in 7 countries. Results showed that the collection performance of the BGP was equivalent to or exceeded that of the BGS, BGM, CDC, and EVS traps in head-to-head comparisons. The BGP uses 35% less power than the CDC and 75% less than the BGS and BGM. This lower power consumption allows it to run at 5 V for 2 days using a small lightweight 10,000-mAh rechargeable power bank. The BG-Pro is an excellent alternative for the surveillance of mosquito species that are usually monitored with BG-Sentinel, CDC, or EVS traps.

KEY WORDS BG-Pro, BG-Sentinel, CDC light trap, EVS trap, mosquito surveillance

INTRODUCTION

Mosquito-borne diseases such as malaria, dengue, Japanese encephalitis, yellow fever, Zika, and West Nile fever infect hundreds of millions of people annually, resulting in over 440,000 fatalities (World Health Organization [WHO] 2017). As vaccines or specific treatments are only available for some of these diseases, mosquito control is crucial to reducing infection rates. Mosquito surveillance is vital to control programs as it informs staff of vector mosquito distributions and potentially infection rates, as well as the efficacy of control measures. Furthermore, daily and seasonal activity fluctuations can be assessed to provide critical information for proper timing of control measures.

Mosquito traps are important tools used by public health personnel and researchers worldwide for the surveillance of vector and nuisance mosquito populations. The most widely used traps for adult mosquitoes are the Centers for Disease Control and Prevention (CDC) miniature light trap (Sudia and Chamberlain 1962), the encephalitis vector survey (EVS) trap (Rohe and Fall 1979), and the Biogents BG-Sentinel (BGS) trap (Kröckel et al. 2006). The BG-Mosquitaire (BGM) is a hardened version of the BG Sentinel that is powered by household electrical current and sold to end consumers as a trap for tiger mosquitoes (Degener et al. 2019). The BG Sentinel 1 (BGS 1) was introduced in 2004 and a modified and improved version, the BGS 2 (BGS), became available in 2014. Previous field studies have shown that there is no difference in the catch rates of the 2 BGS versions (Arimoto et al. 2015, Akaratovic et al. 2017, Unlu and Baker 2018). The BG-Sentinel is considered the "gold standard" trap for *Aedes aegypti* (L.) and *Ae. albopictus* (Skuse) surveillance (Williams et al. 2007, Meeraus et al. 2008, Farajollahi et al. 2009, Staunton et al. 2019), and the EVS and CDC light traps are usually employed for general monitoring of a wide range of mosquito species (McNelly 1989, van den Hurk et al. 2012).

There are a range of attractants used in combination with the various mosquito traps to increase trap sensitivity and effectiveness. The addition of carbon dioxide as a supplemental attractant can greatly increase both the number and species spectrum of collected mosquitoes (Newhouse et al. 1966, Carestia and Horner 1968). The CDC and EVS traps are most commonly supplemented with CO_2, as light alone is a poor and nonspecific attractant, which can increase undesired bycatch and result in potential damage to captured mosquito specimens. The artificial human skin scent lures, BG-Lure (BGL) or BG-Sweetscent (BGSw), are recommended for use with the BGS and BGM to increase trap attractiveness for host-seeking

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anthropophilic mosquito species, for example, *Ae. aegypti*, *Ae. albopictus*, and *Culex quinquefasciatus* (Say) (Degener et al. 2019). The main operational advantage of the EVS and CDC trap is that they run on 6-volt (V) batteries, whereas the BGS and BGM require 12 V or grid power. This means that for use in remote areas, where grid power cannot be accessed, it is necessary to carry along a heavy 12-V battery to operate the BGS or BGM. Compared to the CDC and EVS, the BGS is bulkier, but can be placed in a variety of locations, as it does not require a tree branch or other support for hanging. The BGM was not designed for mobile field use, but rather for monitoring in fixed locations. A major difference between the BGS and the BGM in relation to the other 2 trap types is the airflow mechanism. EVS and CDC traps use a downdraft mechanism where the ventilator located at the top of the trap draws air, CO_2, and mosquitoes downward into the trap. The air and CO_2 then exit the device on the opposite end while mosquitoes are retained. In contrast, the BGS and BGM use a bidirectional airflow where the ventilator creates a downward airflow through the suction funnel in the center of the trap. The airflow changes its direction inside of the trap body and is released through the top surface surrounding the suction funnel. Consequently, when CO_2 or attractant lures are used, they are drawn through the trap and released in a plume around the suction funnel, drawing mosquitoes into the trap.

Biogents has recently developed a new modular mosquito trap called BG-Pro (BGP). The trap can be configured to hang, similar to the CDC and EVS, or sit on the ground like BGS. The trap uses a high-efficiency fan that runs on 5 or 6 V and can be powered by a small lightweight power bank. The present study reports on a series of Latin square experiments that were performed in 7 different countries to evaluate the effectiveness of the BGP in comparison with the BGS, BGM, EVS, and CDC traps.

MATERIALS AND METHODS

Description of the BG-Pro trap

The modular Biogents BG-Pro (Fig. 1) is a cone-shaped fabric trap with white sides and a blue-colored base. The trap uses the same black collection funnel as the BGS and BGM. A bidirectional airflow similar to the BGS is generated by a 3-blade fan that runs on 5 or 6 V. A power supply is available to run the trap from grid power. The trap design enables the use of a fan with a lower power requirement (0.85 W), resulting in longer run times with no appreciable differences in fan speed when using 5 or 6 V. The BGP can be powered for 2 days with a 10,000-mAh rechargeable power bank weighing only 180 g compared to an average of 1.8 kg for commonly used 6-V sealed lead acid batteries of equal performance. With a footprint 75% smaller than a normal 6-V battery, the power bank is also much easier to transport. The trap comes with a number of accessories (UV-LED light strip with intensity peak at 375 nm, rain cover, and internal tripod) that allow the user to hang the trap, similar to the CDC and EVS traps, or place it on the ground like a BGS (Fig. 1a–1c). The trap is collapsible and fits into an 18 × 19 × 19–cm insulated carry bag. Similar to the BGS and BGM, the BGP can be operated with the catch bag located above the fan, where collected specimens are not subject to possible damage from passing through the fan (as in CDC or EVS traps). The insulated carrier bag of the BGP can be used for supplying the trap with CO_2 from dry ice or yeast fermentation. The bag includes a separate compartment where a power bank can be stowed during operation (Fig. 1c).

Trials

To evaluate the new BGP mosquito trap comprehensively, 10 experiments were performed in 7 different countries located on 5 continents during 2018 and 2019. Study sites were selected based on the presence of specific target mosquito species. The selection of which traps to use at a specific site and how to configure them was based on optimizing collection rates of the target species. Consequently, different trap comparisons could be evaluated under varying environmental conditions, and for different target species. An overview of the experiments is provided in Table 1. All experiments followed Latin square designs, with traps being rotated after 24 h, except for the experiments in Mozambique, where traps were rotated after 48 h, and Australia, where traps were rotated after 1 h.

When olfactory lures, BG-Lure (BGL) or BG-Sweetscent (BGSw), were added to the BGP they were placed inside the trap body. When the BGS was operated with a BGL, the lure was placed in the hole provided in the white lid of the trap, and when it was operated with a BGSw, the lure was placed inside the trap body. When the BGS 1 was operated with BGL, the lure was placed inside the trap body.

Semi-field trial in Australia: The BGP (6 V, without rain cover, light, or lure and hanging with its funnel at the same height as the BGS) was compared to a BGS trap (standing on the ground, without lures). Ten replicates of a 2 × 2 Latin square trial were conducted in the James Cook University Mosquito Research Facility Semi-Field System (Ritchie et al. 2011) in Cairns, Australia in April and May 2019. The F_0 generation of *Wohlbachia* (wMel strain) infected *Ae. aegypti*, collected from Cairns using ovitraps, were used for the experiments. Mosquitoes were maintained with densities of about 300 specimens per cage in 30 × 30–cm bug dorms in a room with constant temperature at 28°C and 70% relative humidity adhering to established protocols (Hoffmann et al. 2011, Ritchie et al. 2015). At 0800 h each day, 800 *Ae. aegypti* (mixed sex, 3–4 days postemergence, about 500 females and 300 males)

Fig. 1. (A) BG-Sentinel configuration shown with power bank; (B) CDC configuration with power bank inserted in carrying bag used for supplying the trap with CO_2 from dry ice or yeast fermentation; (C) EVS configuration; (D) exploded view showing all parts of the inner cylinder: collection funnel with lid and attached catch bag, upper part, lower part, ventilator, and tripod; (E) assembled inner cylinder minus tripod; (F) the parts of the inner cylinder can be collapsed to fit in the insulated carrying bag (bag dimension: 18 × 19 × 19 cm).

were released into the flight cage (465 m^3). At 0900 h, both traps, separated by 5 m, were switched on and operated for 60 min. After each test, catch bags were removed, mosquitoes were identified to sex, and trap positions were exchanged. This process was repeated up to 8 times during the same day.

Field trial in Brazil: The BGP (6 V, standing on the ground with internal tripod, BGSw) was compared to a BGS (standing on the ground, 12-V battery, BGSw). The study was conducted inside a horse stable (20 × 40 m) of the Veterinary Hospital of the Federal University of Minas Gerais, located in Belo Horizonte city (Minas Gerais State), where *Ae. aegypti* breeding sites are available throughout the year. The traps were at a distance of 15 m apart and they were checked every 24 h. The position of the traps was changed daily to avoid position effect. Nine replicates of the experiment were performed from November 2018 to February 2019.

Field trial in Tahiti: The following 4 traps were compared in this experiment: 1) BGP (6 V, without lure); 2) BGP (6 V, with BGL); 3) BGS 1 (12 V, without lure), and 4) BGS 1 (12 V, with BGL). To prevent sample damage from ants, all traps were hung at a height of ~20 cm and cords greased to prevent access of ants. Two 4 × 4 Latin square trials, each of which was replicated 4 times for 24 h each, were performed on 2 transects between June and August 2019 (n = 32). The experiment was performed on densely vegetated terrain at the Institute Louis Malardé, Medical Entomology Laboratory, Tahiti, French Polynesia, where both *Ae. aegypti* and *Ae. polynesiensis* (Marks) were present. The traps were installed in shady locations, with a minimum distance of 10 m between the traps.

Field trial in France: A BGP trap (standing on the ground with integral tripod, 5 V power supplied by a 10,000-mAh power bank, with BGSw) was compared to a BGM (on the ground, grid powered, with BGSw) in a backyard garden in Antibes, Côte d'Azur, southern France, where *Ae. albopictus* was the predominantly collected mosquito species. Traps were separated by a distance of 15 m and collections were for 24 h. Nine replicates of a 2 × 2 Latin square trial were performed ($n = 36$).

Field trials in the USA—experiment USA 1: Three traps were compared in this experiment: a BGP (6 V, standing with integral tripod), a BGS (standing), and CDC (light off, hanging at ground level). All traps were set at ground level, with their openings at 46 cm

Table 1. Overview of the 10 Latin square trials that were performed to evaluate the BG-Pro trap.

Experiment	Location	N	Traps[1]	Trap configuration: Standing	Hung	Height	Light	Power source	Rainshield	Attractant	Target mosquito species
AUS	Australia	20	BGP		×	Ground level		6 V			*Ae. aegypti*
	Cairns		BGS	×		On ground		12 V			
BRA	Brazil, Belo	27	BGP	×		Ground level		6 V		BGSw	*Ae. aegypti*
	Horizonte		BGS	×		Ground level		12 V		BGSw	*Cx. quinquefasciatus*
TAH	Tahiti	32	BGP		×	20 cm		6 V		BGL	*Ae. polynesiensis*
			BGP		×	20 cm		6 V			*Ae. aegypti*
			BGS 1		×	20 cm		12 V		BGL	
			BGS 1		×	20 cm		12 V			
FR	France	36	BGP	×		On ground		5 V		BGSw	*Ae. albopictus*
	Antibes		BGM	×		On ground		12 V		BGSw	*Cx. pipiens*
USA 1	USA	9	BGP	×		On ground		6 V	×	CO_2 (cylinder) + BGL	*Ae. albopictus*
	Suffolk, VA		BGS	×		On ground		12 V	×	CO_2 (cylinder) + BGL	
			CDC		×	Ground level		6 V	×	CO_2 (cylinder) + BGL	
USA 2	USA	16	CDC		×	152 cm		6 V	×	CO_2 (cylinder)	*Cs. melanura*
	Suffolk, VA		CDC		×	152 cm	×	6 V	×	CO_2 (cylinder)	*Cx. erraticus*
			BGP		×	152 cm		6 V	×	CO_2 (cylinder)	*Cx. pipiens*
			BGP		×	152 cm	×	6 V	×	CO_2 (cylinder)	
GER 1	Germany	44	BGP	×		Ground level		6 V		CO_2 (cylinder)	*Ae. vexans*
	Regensburg		BGS	×		Ground level		12 V		CO_2 (cylinder)	*Cx. pipiens*
GER 2	Germany	12	BGP		×	20 cm		6 V	×	CO_2 (1.5 kg dry ice)	*Ae. vexans*
	Regensburg		EVS		×	20 cm		6 V	×	CO_2 (1.5 kg dry ice)	*Cx. pipiens*
GER 3	Germany	26	BGP		×	20 cm		5 V	×	CO_2 (1.5 kg dry ice)	*Ae. vexans*
	Regensburg		EVS		×	20 cm		6 V	×	CO_2 (1.5 kg dry ice)	*Cx. pipiens*
MOZ	Mozambique	12	BGP		×	20 cm		6 V		BGSw	*Culex* spp.
			BGP		×	20 cm inverted		6 V		BGSw	*Anopheles* spp.
			BGS	×		On ground		12 V		BGSw	

[1] BGP: BG-Pro, BGS: BG-Sentinel 2, BGS 1: BG-Sentinel 1, BGM: BG Mosquitaire, CDC: CDC miniature light trap, EVS: encephalitis vector survey trap, BGSw: BG-Sweetscent, BGL: BG-Lure.

above ground, baited with CO_2 gas (200 ml/min) and BGL, and were run for 24 h. Traps were protected from rain with a 52-cm-diameter plastic lid attached to wooden stakes which was affixed 29 cm above each trap. Three replicates of a 3 × 3 Latin square trial ($n = 9$) were conducted in a 3,500-m^2 wooded lot within an urban area of downtown Suffolk, Virginia, USA. The area is bordered by residential housing on 3 sides and a large commercial property on the 4th side. Many of the bordering properties harbor an assortment of litter, tires, and other materials that are likely larval habitats for *Ae. albopictus*. Mixed hardwoods line the outer edge of the site along with ivy (*Hedera helix* L.) and other low vegetation, and the center space is open field. Traps were placed 20 m apart in a triangular arrangement in shady positions within the vegetation.

Experiment USA 2: In this trial, the following 4 traps were compared: BGP in CDC mode (with rain cover, UV-LED light strip), BGP (with rain cover, no light strip), CDC trap (with incandescent light), and CDC trap (light off). All traps were set hanging at 152 cm above the ground, with CO_2 gas (200 ml/min), and without the use of additional lures. Four replicates of a 4 × 4 Latin square trial ($n = 16$) were conducted about 1.5 km southwest of the location of experiment USA 1. This site was a slightly larger wooded area (approx. 6,000 m^2) in a suburban neighborhood on the edge of downtown Suffolk, VA. The site is densely populated with mixed hardwoods and underlying ivy; a ravine about 10 m deep runs through the middle and functions as a stormwater drainage ditch, holding water regularly. The location was chosen because of the high abundance of *Culiseta melanura* (Coquillett). Traps were placed with 20 m spacing in shady locations within the vegetation and run for 24 h.

Field trials in Germany: Three different 2 × 2 Latin square field experiments were performed in backyards of a residential neighborhood in Regensburg, Bavaria, Germany during July and August 2019. The neighborhood is located close to the Regen River and is comprised mainly of single-family houses and small apartment buildings, all of which are surrounded by gardens. Trap locations were shady and close to vegetation. At the time of the experiments, floodwater and house mosquitoes (*Ae. vexans* Meigen and *Cx. pipiens* L.) were abundant in this area.

Experiment GER 1: During this trial, the BGP (6 V, standing on the ground with tripod, CO_2 at a flow rate of 200 ml/min from a gas cylinder) was compared to a BGS (grid power, standing on the ground, CO_2 at a flow rate of 200 ml/min from a gas cylinder). The collection period was 15 h (1700–0800 h) with a minimum spacing of 12 m between traps. This trial comprised 22 replicates of a 2 × 2 Latin square trial ($n = 44$).

Experiment GER 2: The BGP (6 V, hanging 20 cm above the ground, CO_2 from 1.5 kg dry ice, rain cover installed 20 cm above the trap opening, no light strip) was compared to an EVS trap (hanging 20 cm above the ground, CO_2 from 1.5 kg dry ice, rain cover installed 20 cm above the trap opening, light off). Suction inlets of the traps were placed at equal heights of approximately 65 cm above ground level. The experiment comprised 12 replicates of a 2 × 2 Latin square trial ($n = 24$). Each trapping period was 15 h (1700–0800 h) with a minimum spacing of 12 m between traps.

Experiment GER 3: The BGP and EVS trap were used as described in experiment GER 2, but this time the BGP was powered with 5 V from a 10,000-mAh power bank). This 2 × 2 Latin square experiment was replicated 13 times ($n = 26$). Each trapping period was 15 h (1700–0800 h) with a minimum spacing of 12 m between traps.

Field trial in Mozambique: The following 3 traps were compared in this experiment: 1) BGS (standing with BGSw); 2) BGP (hanging at 20 cm, with BGSw); 3) BGP (hanging inverted, at approximately 50 cm, with BGSw). The BGP was tested in the inverted position, as previous studies have shown, that *Anopheles* catch rates increase when the BGS is hung upside down (Gama et al. 2013, Batista et al. 2018). Four replicates of a 3 × 3 Latin square trial ($n = 12$) were conducted in a housing area for volunteers of the nongovernmental organization Kululeku in Vilanculo, Mozambique, between July 30 and August 23, 2019. Traps were separated by a minimum of 10 m and all collections were for 48 h. In this trial, mosquitoes were only identified to genus because of the lack of necessary equipment.

Data analysis

All analyses were performed using Rstudio version 1.1.453 (Rstudio Team 2016), based on R version 3.3.2 (R Development Core Team 2015). Data from all experiments were analyzed with generalized linear mixed models (GLMMs) using the packages 'lme4' (Bates et al. 2015) and 'MASS' (Venables and Ripley 2002). The fixed main effect was the variable *trap,* which included all trap configurations evaluated for each experiment. The factor *position* was added as a secondary fixed effect to account for location influences. For the Tahiti data set, where 8 positions were used, the factor *position* was added as random effect. The random factor *date* was chosen *a priori,* to account for temporal influences on all field experiments. In the semi-field study in Australia, where the tests were conducted for 3 days, *Repetition* was included as a random factor instead of *date*. The dependent count variable was either the number of female or male mosquitoes of each target species that were collected. Poisson models were first fitted and when these were overdispersed, they were replaced with negative binomial models with log-link functions. Adequacy of models was assessed through evaluation of overdispersion using the RVAideMemoire Package

Table 2. Number of observations (N), sum, mean ± standard deviation of collected mosquitoes in 1 semi-field trial (Australia), and 2 field trials (Brazil and Tahiti).

Location	N	Trap[1]	*Aedes aegypti* Female	*Aedes aegypti* Male	*Ae. polynesiensis* Female	*Ae. polynesiensis* Male	*Culex quinquefasciatus* Female	*Culex quinquefasciatus* Male
Australia	20	BGP	239 (11.9 ± 9.1)	576 (28.8 ± 20.3)	—	—	—	—
		BGS	103 (5.2 ± 4.9)	349 (17.4 ± 14.3)	—	—	—	—
Brazil	27	BGP + BGSw	460 (17.0 ± 15.2)	278 (10.3 ± 12.7)	—	—	42 (1.6 ± 2.2)	29 (1.1 ± 1.8)
		BGS + BGSw	99 (3.7 ± 5.7)	37 (1.4 ± 3.3)	—	—	6 (0.22 ± 0.4)	2 (0.07 ± 0.4)
Tahiti	32	BGP	44 (1.4 ± 2.0)	44 (1.4 ± 3.4)	28 (0.9 ± 1.1)	29 (0.9 ± 1.9)	17 (0.5 ± 1.0)	47 (1.5 ± 1.8)
		BGP + BGL	23 (0.7 ± 0.9)	29 (0.9 ± 1.3)	85 (2.7 ± 4.3)	32 (1.0 ± 2.1)	25 (0.8 ± 1.8)	40 (1.3 ± 2.0)
		BGS 1	45 (1.4 ± 3.2)	66 (2.1 ± 4.5)	50 (1.6 ± 1.7)	20 (0.6 ± 0.9)	8 (0.3 ± 0.6)	3 (0.1 ± 0.3)
		BGS 1 + BGL	47 (1.4 ± 2.0)	39 (1.2 ± 2.6)	97 (3.0 ± 3.7)	44 (1.4 ± 2.1)	3 (0.1 ± 0.3)	8 (0.3 ± 0.9)

[1] BGP: BG-Pro, BGS: BG-Sentinel 2, BGS 1: BG-Sentinel 1, BGSw: BG-Sweetscent, BGL: BG-Lure.

(Hervé 2020), and diagnostic residual plots. Tukey multiple comparisons of means of the GLMMs with more than 2 trap types was performed using the emmeans package (Lenth 2018).

RESULTS

Semi-field trial in Australia

In the semi-field test, mean catches of female *Ae. aegypti* collected in the BGP and BGS were 11.9 ± 9.1 and 5.2 ± 4.9, respectively, per each 60-min interval (Table 2, Fig. 2A). Catches were on average 2.4 times (95% confidence interval [CI] = 1.8–3.3) higher in the BGP trap after correcting for trap position and repeated sampling ($P < 0.0001$; Table S1). The BGP trapped 28.8 ± 20.3 male *Ae. aegypti*, and the BGS collected 17.4 ± 14.3 per each 60-min interval (Table 2, Fig. 2A). Catch rates of male *Ae. aegypti* were on average 1.7 times (95% CI = 1.2–2.3) higher in the BGP (GLMM; $P = 0.0013$). Some variation in trap collections that could not be controlled were expected, for example, the gradual depletion of the released mosquito population over time due to trapping out and variations in activity due to changing microenvironmental conditions (clouds passing over, wind gusts, etc.). Variation due to normal daily activity patterns (crepuscular activity) was controlled for by both traps being run simultaneously and traps being randomly rotated between locations for each trial.

Field trial in Brazil

In Brazil, only 2 species, *Ae. aegypti* and *Cx. quinquefasciatus*, were collected. The BGP caught significantly ($P < 0.0001$) more *Ae. aegypti* per 24-h period than the BGS 2. The mean number of female *Ae. aegypti* in the BGP and BGS 2 was 17.0 ± 15.2 and 3.7 ± 5.7, respectively. The BGP collected on average 10.3 ± 12.7 male *Ae. aegypti*, and the BGS 2 collected 1.4 ± 3.3 (Table 2, Fig. 2A). According to the GLMM models that corrected for position and repeated measures, the BGP collected on average 5.5 times (95% CI = 3.3–9.3) more female *Ae. aegypti* ($P < 0.0001$) and 7.5 times (95% CI = 5.3–10.9) more male *Ae. aegypti* than the BGS 2 ($P < 0.0001$; Table S1). *Culex quinquefasciatus* were collected in much lower numbers than *Ae. aegypti*, with a mean of 1.6 ± 2.2 females in the BGP and 0.2 ± 0.4 in the BGS 2 (Table 2, Fig. 3B).

Field trial in Tahiti

In this trial, *Ae. polynesiensis* (260 female, 125 male), and *Ae. aegypti* (159 female and 178 male) were the most abundant mosquito species captured. *Culex quinquefasciatus* was also commonly collected, with a total of 53 female and 98 male specimens captured (Table 2). Furthermore, 79 females and 1 male *Wyeomyia mitchelii* Theobald were trapped, most of them by the BGP (42 females and 1 male),

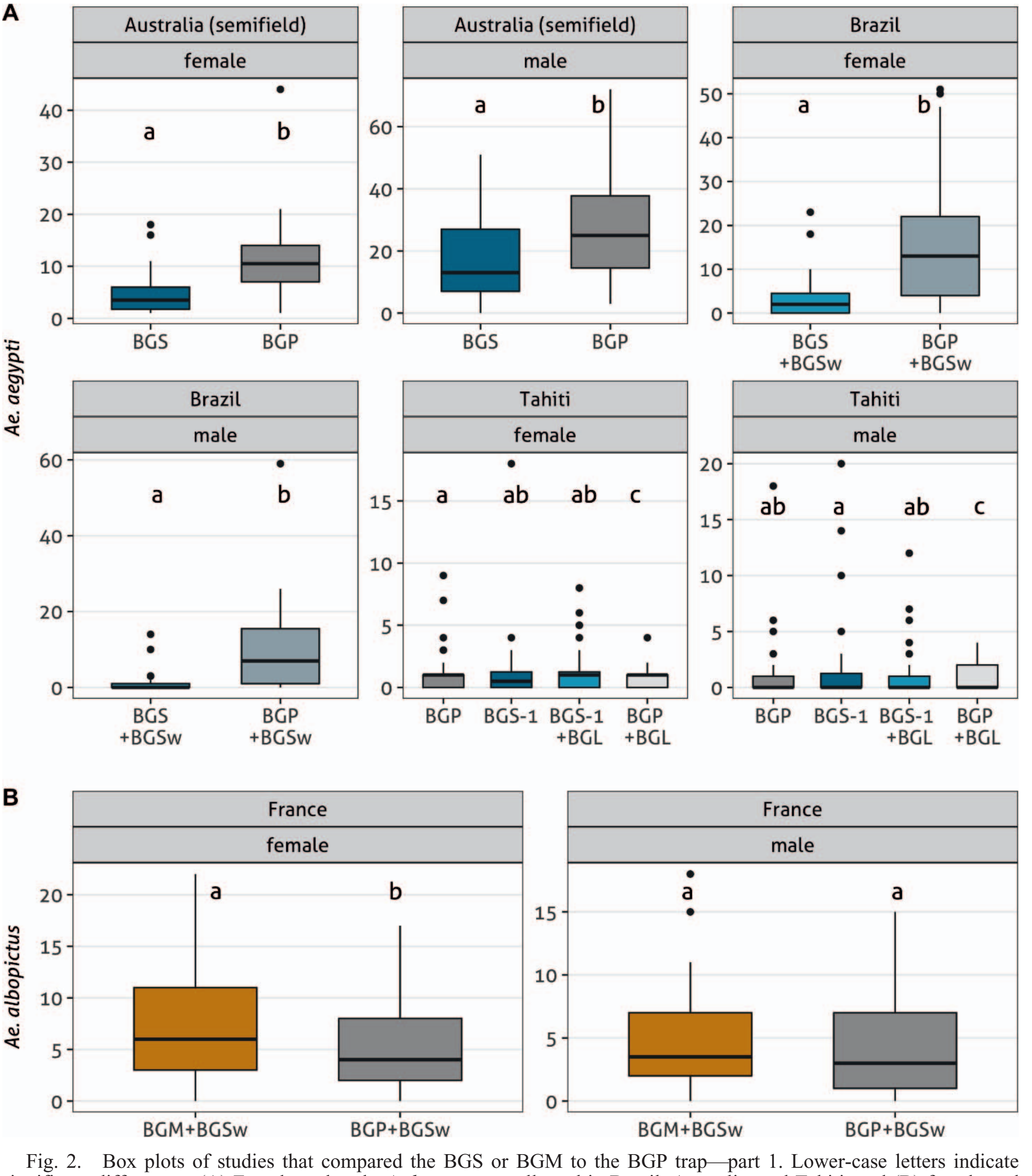

Fig. 2. Box plots of studies that compared the BGS or BGM to the BGP trap—part 1. Lower-case letters indicate significant differences. (A) Female and male *Aedes aegypti* collected in Brazil, Australia, and Tahiti; and (B) female and male *Ae. albopictus* collected in France. BGS: BG-Sentinel 2, BGS 1: BG-Sentinel 1, BGP: BG-Pro, BGM: BG-Mosquitaire, BGSw: BG-Sweetscent, BGL: BG-Lure.

followed by the BGP with BGL (32 females). *Culex atriceps* (Edwards) (1 female, 6 males) and *Toxorhynchites amboinensis* (Doleschall) (1 female, 1 male) were collected. Formal statistical analysis is presented only for the 2 *Aedes* species.

Mean catch rates of female *Ae. polynesiensis* were higher in the 2 traps operated with BGL: When using the BGL, the BGS 1 and the BGP collected 3.0 ± 3.7 and 2.7 ± 4.3 female *Ae. polynesiensis* per day, respectively (Table 2, Fig. 3A). Without lure, the BGS 1 and the BGP collected 1.6 ± 1.7 and 0.9 ± 1.1 female *Ae. polynesiensis*, respectively (Table 2). The BGS with BGL collected 1.7 times (95% CI = 1.6–6.5, $P = 0.014$) more than the BGS without BGL,

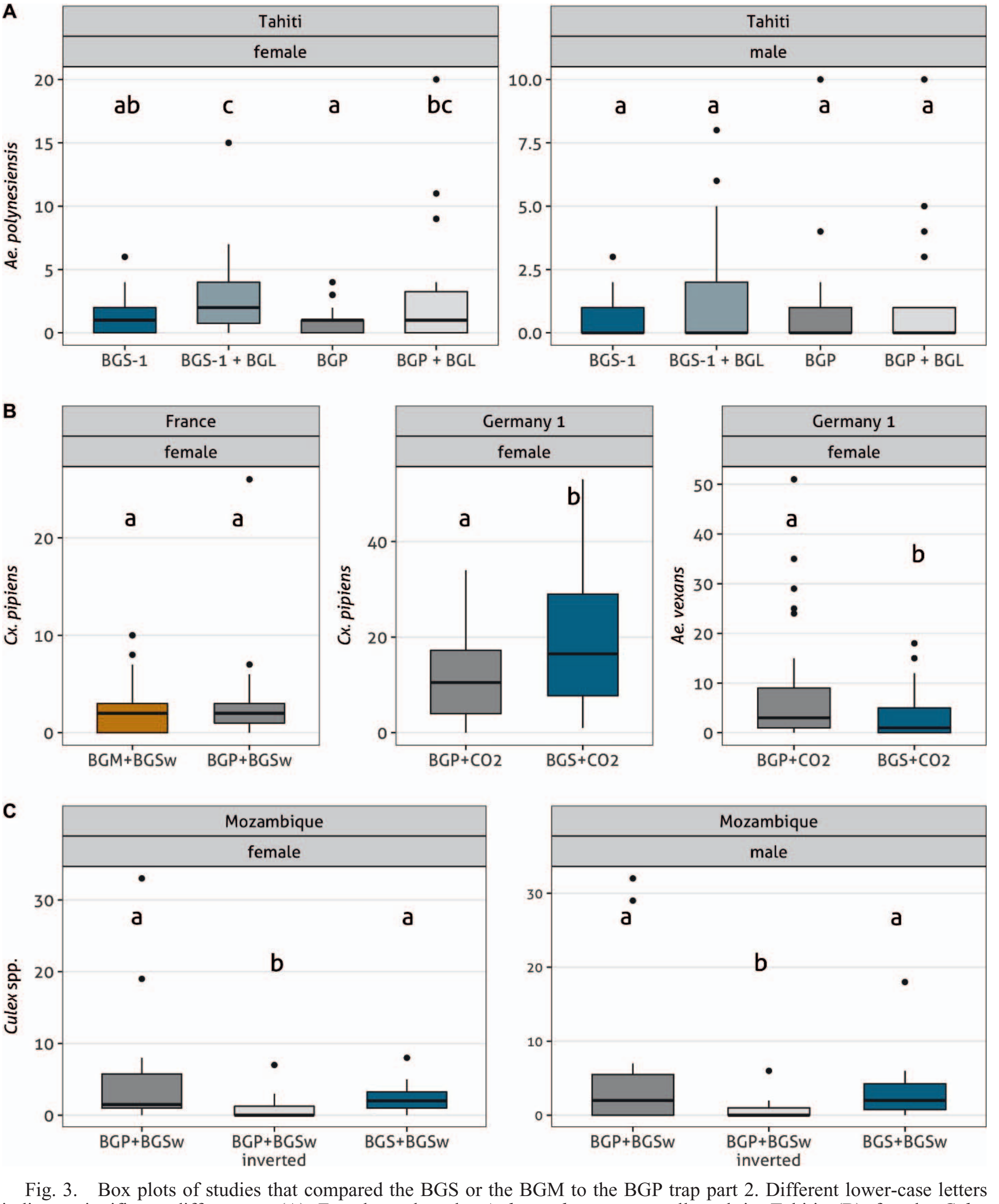

Fig. 3. Box plots of studies that compared the BGS or the BGM to the BGP trap part 2. Different lower-case letters indicate significant differences. (A) Female and male *Aedes polynesiensis* collected in Tahiti; (B) female *Culex quinquefasciatus* collected in Brazil, female *Cx. pipiens* collected in France and Germany (experiment GER1), and female *Ae. vexans* collected in Germany; and (C) female and male *Culex* spp., collected in Mozambique. BGS: BG-Sentinel 2, BGS 1: BG-Sentinel 1, BGP: BG-Pro, BGM: BG-Mosquitaire, BGSw: BG-Sweetscent, BGL: BG-Lure.

and 3.2 times (95% CI = 1.8–5.6, $P < 0.0001$) more than the BGP without BGL. The BGP with BGL collected 2.7 times (95% CI = 1.5–4.8, $P = 0.004$; Table S2).

For male *Ae. polynesiensis*, catch rates were slightly higher in traps that were operated with BGL. The BGS 1 and the BGP with BGL collected 1.4 ± 2.1 and 1.0 ± 2.1 male *Ae. polynesiensis* per day, respectively, and the BGS 1 and the BGP without lure collected 0.6 ± 0.9 and 0.9 ± 1.9 male *Ae. polynesiensis* (Table 2, Fig. 3A). None of the pairwise differences between the traps were significant (Table S2).

Mean female *Ae. aegypti* catch rates in the BGP, BGS 1, and the BGS 1 with BGL were 47 ± 1.4 ± 2.0 specimens per trap per day, and the BGP with lure collected 0.7 ± 0.9 (Table 2, Fig. 2A). The effect difference was highest between the BGP without lure and the BGP with BGL (the former collected on average 1.9 times [95% CI = 1.0–3.7] more female *Ae. aegypti* than the latter, $P = 0.045$). All the other trap comparisons did not differ significantly (Table S2).

For male *Ae. aegypti*, the 2 traps without BGL were more effective than their counterparts that were operated with BGL: the BGS 1 collected on average 2.1 ± 4.5, and the BGS 1 with BGL collected 1.2 ± 2.6 male *Ae. aegypti* per 24 h. The BGP collected on average 1.4 ± 3.4, and the BGP with BGL collected 0.9 ± 1.3 male *Ae. aegypti* per 24 h (Table 2, Fig. 2A). The BGS 1 without lure collected on average 1.9 times (95% CI = 1.03–3.5) more than the BGP with BGL ($P = 0.034$). All the other traps did not differ significantly (Table S2).

Field trial in France

In this trial, *Ae. albopictus* was the predominantly collected mosquito species, with a total of 449 females and 325 males. The second most common species was *Cx. pipiens* L., with 194 females and 69 males. Additionally, small numbers of *Culiseta* spp. were collected.

The BGM, with a mean catch rate of 7.0 ± 5.0 *Ae. albopictus* females per day, slightly outperformed the BGP that collected a mean of 5.5 ± 4.3 per day (Fig. 2B). According to the GLMM, the BGM collected on average 1.3 times (95% CI = 1.1–1.6) more female *Ae. albopictus* than the BGP ($P < 0.01$; Table S1). Catch rates of male *Ae. albopictus* did not differ significantly (Fig. 2B), with an average 4.6 ± 4.1 specimens per day in the BGM, and 4.4 ± 4.1 in the BGP ($P = 0.3$). Similarly, catch rates of *Cx. pipiens* were not significantly different with a mean number of 2.9 ± 4.3 *Cx. pipiens* females per day in the BGP and 2.5 ± 2.8 per day in the BGM ($P = 0.52$; Fig. 3B, Table S1).

Field trials in the USA

Experiment USA 1: Of the total of 791 collected female Culicidae, 738 were *Ae. albopictus*. The second most abundant species collected was *Cs. melanura* with 23 specimens followed by *Cx. salinarius* Coquillett with 12 specimens. Catch rates of the latter 2 species were too low for formal statistical analyses, but both species were collected in higher numbers in the BGP and BGS 2 traps (Table 2). Eleven other mosquito species were collected with a total number of 1–3 specimens.

The BGP, the BGS 2, and the CDC traps collected mean numbers of 34.0 ± 12.1, 35.7 ± 12.3, and 12.3 ± 8.1 female *Ae. albopictus* per trapping period, respectively (Table 3, Fig. 4A). The BGP collected on average 2.9 times (95% CI = 2.1–4.0) more female *Ae. albopictus* than the CDC trap ($P < 0.0001$), and the BGS collected on average 3 times (95% CI = 2.2–4.2) more than the CDC trap, ($P < 0.0001$; Table S2). There was no significant difference between the female *Ae. albopictus* catch rates of the BGP and the BGS 2 ($P = 0.89$).

For male *Ae. albopictus*, the BGP, the BGS and the CDC trap collected mean numbers of 33.9 ± 9.1, 37.0 ± 15.8, and 3.1 ± 2.7 specimens per trapping period, respectively (Table 3, Fig. 4A). The BGP collected on average 10.8 times (95% CI = 6.1–19.1) more male *Ae. albopictus* than the CDC trap ($P < 0.0001$), and the BGS collected on average 11.7 times (95% CI = 6.6–20.7) more than the CDC trap ($P < 0.0001$). There were no significant differences between male *Ae. albopictus* catch rates of the BGP and the BGS ($P = 0.87$; Table S2).

Per trapping period, the BGS collected up to 5 mosquito species, followed by the BGP that collected up to 4, and the CDC trap collected a maximum of 2 mosquito species in 24 h.

Experiment USA 2: *Culiseta melanura* was by far the most abundant species, comprising 7,628 out of the total of 8,226 collected females. Other species that were collected in considerable numbers were *Cx. erraticus* (Dyar & Knab) (208 females), *Ae. albopictus* (129 females), and *Cx. pipiens* (125 females; Table 3). Seventeen other species were collected sporadically. All 4 traps collected a minimum of 2 and a maximum of 7 different mosquito species per trapping period.

With a mean catch rate of 264.1 ± 304, *Cs. melanura* females were collected more frequently by the BGP with UV-LED light strip, followed by the BGP without light (119.2 ± 189.7; Table 3, Fig. 4B). The BGP with light collected on average 2 times (95% CI = 1.04–3.8) more *Cs. melanura* females, than the BGP without light ($P = 0.035$; Table S2). The catch rates of the CDC traps were considerably lower (51.6 ± 60.3 with light, and 47.3 ± 91.0 without light; Table 3) and did not differ statistically between each other ($P = 0.98$). The BGP with light collected on average 5 times (95% CI = 2.6–9.6) more female *Cs. melanura*, than the CDC with light ($P < 0.0001$), and 5.6 times (95% CI = 2.8–10.9) more than the CDC without light ($P < 0.0001$). The BGP without light collected significantly more *Cs. melanura* than both CDC trap configurations: on average 2.5 times (95% CI = 1.3–4.9) more than the CDC with light ($P = 0.0015$), and 2.8 times (95% CI = 1.4–5.5) more than the CDC without light ($P = 0.0005$; Table S2).

Culex erraticus (Dyar & Knab) was collected in significantly higher numbers by the BGP with UV-

Table 3. Number of observations (*N*), sum, mean ± standard deviation of collected mosquitoes in 6 field trials performed in Germany, USA, and France.

Experiment	*N*	Trap[1]	*Aedes albopictus* Female	*Aedes albopictus* Male	*Culex pipiens* Female	*Ae. vexans* Female	*Cx. erraticus* Female	*Culiseta melanura* Female
GER 1	44	BGP + CO_2	–	–	505 (11.5 ± 8.4)	331 (7.5 ± 10.5)	–	–
		BGS + CO_2	–	–	845 (19.2 ± 13.5)	144 (3.3 ± 4.4)	–	–
GER 2	12	BGP + CO_2	–	–	154 (12.8 ± 12.8)	143 (11.9 ± 7.8)	–	–
		EVS + CO_2	–	–	19 (1.6 ± 2.02)	163 (13.6 ± 14.9)	–	–
GER 3	26	BGP (5 V) + CO_2	–	–	129 (5.0 ± 3.5)	95 (3.7 ± 5.0)	–	–
		EVS + CO_2	–	–	48 (1.9 ± 1.6)	90 (3.5 ± 4.6)	–	–
USA 1	9	BGS + BGL + CO_2	321 (35.7 ± 12.3)	333 (37.0 ± 15.8)	0	–	0	9 (1 ± 1.1)
		CDC + BGL + CO_2	111 (12.3 ± 8.1)	28 (3.1 ± 2.7)	0	–	0	1 (0.1 ± 0.3)
		BGP + BGL + CO_2	306 (34.0 ± 12.1)	305 (33.9 ± 9.1)	1 (0.1 ± 0.3)	–	2 (0.07 ± 0.3)	13 (1.4 ± 1.0)
USA 2	16	CDC + CO_2+ light	19 (1.2 ± 1.1)	1 (0.06 ± 0.3)	10 (0.6 ± 1.0)	–	32 (2.0 ± 1.4)	825 (51.6 ± 60.3)
		CDC + CO_2	63 (3.9 ± 4.3)	1 (0.06 ± 0.3)	20 (1.3 ± 0.9)	–	22 (1.4 ± 1.2)	757 (47.3 ± 91.0)
		BGP + CO_2+ light	0	0	48 (3.0 ± 3.0)	–	119 (7.4 ± 4.2)	4,226 (264.1 ± 304.0)
		BGP + CO_2	47 (2.9 ± 4.8)	6 (0.4 ± 0.7)	47 (2.9 ± 1.4)	–	35 (2.2 ± 2.0)	1,820 (119.2 ± 189.7)
FR	36	BGM + BGSw	251 (7.0 ± 5.0)	166 (4.61 ± 4.1)	91 (2.5 ± 2.8)	–	–	–
		BGP + BGSw	198 (5.5 ± 4.3)	159 (4.4 ± 4.1)	103 (2.9 ± 4.3)	–	–	–

[1] BGP: BG-Pro, BGS: BG-Sentinel 2, BGS 1: BG-Sentinel 1, BGM: BG Mosquitaire, CDC: CDC miniature light trap, EVS: encephalitis vector survey trap, BGSw: BG-Sweetscent, BGL: BG-Lure.

LED light strip (7.4 ± 4.2 per trapping period) compared to the other 3 traps. The mean *Cx. erraticus* catch rates of the BGP without light, the CDC with light and the CDC without light were 2.2 ± 2.0, 2.0 ± 1.4, and 1.4 ± 1.2, respectively (Table 3, Fig. 4C). The BGP with light collected on average 3.4 times (95% CI = 2.1–5.6) more than the BGP without light ($P < 0.0001$), 5.4 times (95% CI = 3.0–9.7) more than the CDC ($P < 0.0001$), and 3.7 times (95% CI = 2.2–6.2) more than the CDC + light ($P < 0.0001$). There was no statistical difference between the 2 CDC traps ($P = 0.54$), or between the BGP without light and the CDC with or without light ($P < 0.3$; Table S2).

Both BGP traps collected significantly more *Cx. pipiens* than the CDC traps (Table 3, Fig. 4D). The BGP with or without light collected on average 2.4 times (95% CI = 1.2–4.7) more female *Cx. pipiens* than the CDC without light ($P < 0.01$), and 4.7 times (95% CI = 1.9–11.5) more than the CDC with light ($P < 0.0001$). With a mean number of 3.0 ± 3.0 and 2.9 ± 1.4 *Cx. pipiens* females in the BGP with light and the BGP without light, respectively, there was no difference between these 2 traps (P =1.0). Mean catch rates of the 2 CDC traps (1.3 ± 0.9 without light, 0.6 ± 1.0 with light) also did not differ statistically ($P = 0.27$; Table S2).

In experiment USA 2, *Ae. albopictus* was most successfully trapped by the CDC trap without light (3.9 ± 4.3 females per trapping period), followed by the BGP without light (2.9 ± 4.8), and the CDC with light (1.2 ± 1.1). The BGP with light did not catch any *Ae. albopictus* (Table 3). No formal statistical analysis is presented on these data, as GLMM models, including zero-inflated models, resulted in inappropriate diagnostic plots.

Field trials in Germany

Aedes vexans Meigen and *Cx. pipiens* females were the predominant mosquito species at all locations. Five other species were collected in low numbers and the collection rates of males were very low.

Experiment GER 1: With a mean catch rate of 7.5 ± 10.5 and 3.3 ± 4.4 female *Ae. vexans* per 24 h in the BGP and the BGS, respectively (Table 3, Fig. 3B), the BGP collected 2.2 times (95 % CI = 1.8–2.8) more *Ae. vexans* than the BGS ($P < 0.0001$; Table S1).

House mosquitoes, on the other hand, were better collected by the BGS: The BGS collected a mean of 19.2 ± 13.5, and the BGP 11.5 ± 8.4 female *Cx. pipiens* (Table 3, Fig. 3B). According to the GLMM, the BGS collected 1.7 times (95% CI = 1.4–2.0) more female *Cx. pipiens* than the BGP ($P < 0.0001$; Table S1).

Experiment GER 2: With a mean of 11.9 ± 7.8 and 13.6 ± 14.9 female *Ae. vexans* in the BGP and the EVS trap, respectively (Table 3), the catch rates between the 2 trap types did not differ significantly

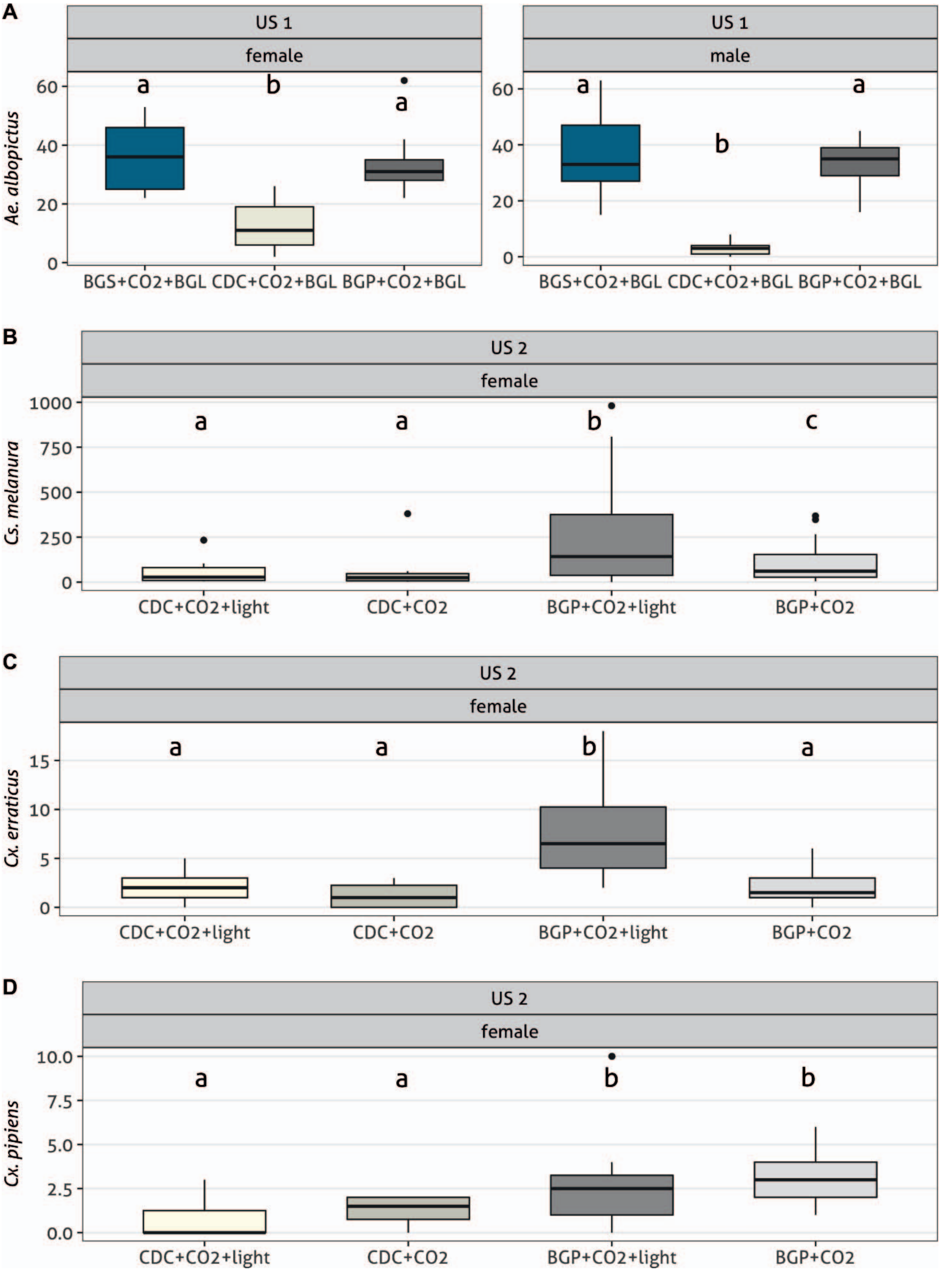

Fig. 4. Box plots of a study comparing a BGS and a CDC trap to a BGP trap (USA 1). (A) Female and male *Aedes albopictus* (USA 1). In a second study, USA 2, a CDC trap was compared to the BGP. (B) Female *Culiseta melanura* collected (USA 2), (C) female *Cx. erraticus* collected (USA 2), and (D) female *Cx. pipiens* collected (USA 2). Different lower-case letters indicate significant differences. BGS: BG-Sentinel 2, CDC: CDC miniature light trap, BGP: BG-Pro, BGL: BG-Lure.

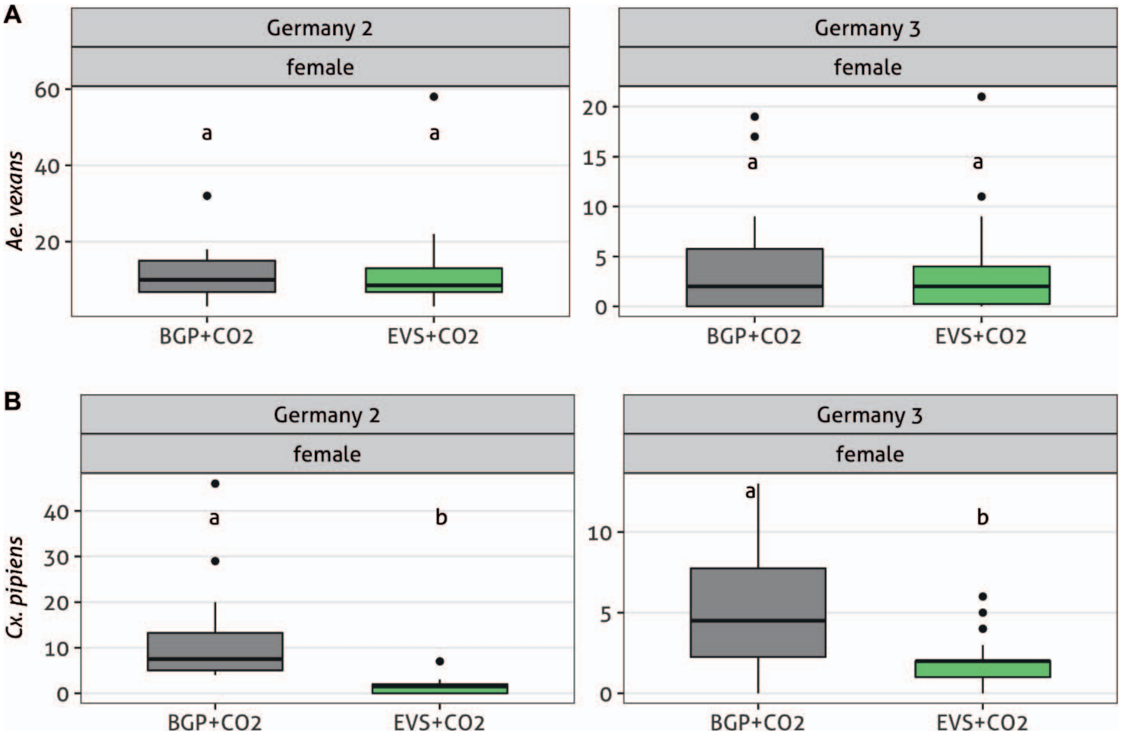

Fig. 5. Box plots of studies that compared the EVS trap to the BGP. Different lower-case letters indicate significant differences. (A) Female and male *Aedes vexans* collected in Germany (experiments GER 1 and GER 2); (B) female *Culex pipiens* collected in Germany (experiments GER 2 and GER 3). BGP: BG-Pro, EVS: EVS trap.

according to the GLMM model ($P = 0.22$; Fig. 5A, Table S1).

The BGP collected a mean of 12.8 ± 12.8, and the EVS trap 1.6 ± 2.0 female *Cx. pipiens* (Table 3). This species was collected on average 8 times (95% CI = 5.1–13.4) more in the BGP than in the EVS trap ($P < 0.0001$; Fig. 5B, Table S1).

Experiment GER 3: The BGP (5 V) collected a mean of 3.7 ± 5.0, and the EVS 3.5 ± 4.6 female *Ae. vexans* (Table 3, Fig. 3B). As in the previous experiment, there was no significant difference between the female *Ae. vexans* catch rates of the 2 traps ($P = 0.41$; Fig. 5A).

The BGP collected a mean of 5.0 ± 3.5, and the EVS trap 1.9 ± 1.6 female *Cx. pipiens* (Table 3, Fig. 4B). This species was collected on average 2.7 times (95% CI = 1.9–3.8) more in the BGP than in the EVS trap ($P < 0.0001$; Fig. 5B, Table S1).

Field trial in Mozambique

In this trial, mosquitoes were only identified to genus because of a lack of proper laboratory equipment. The most abundant genus was *Culex*, with 118 females and 134 males, followed by *Anopheles* with 20 females and 25 males (Table 4). Mosquitoes of the genus *Aedes* and *Mansonia* were occasionally collected. Mean catch rates of female *Culex* were higher in the BGP (6.2 ± 10.0 per 48 h) than in the BGS (2.5 ± 2.2 per 48 h; Table 4); however, their catch rates did not differ significantly according to the GLMM that corrected for repeated sampling and position effects ($P = 0.7$; Fig. 3C). The BGP and the BGS collected significantly higher numbers of female *Culex* than the BGP in the inverted configuration. The BGP collected on average 5 times (95% CI = 2.4–10.9) more than the BGP inverted ($P < 0.0001$), and the BGS collected on average 4 times (95% CI = 1.7–9.6) more *Culex* females than the inverted BGP ($P < 0.001$; Fig. 3C, Table S2).

The result for male *Culex* was similar. The BGP was the most successful trap, with on average 6.8 ± 11.4 specimens per 48 h, whereas the BGS collected an average of 3.6 ± 4.9 male mosquitoes of the genus *Culex* (Table 4). The difference between the 2 traps was, however, not statistically significant according to the GLMM ($P = 0.96$; Fig. 3C). The BGP collected on average 6.3 times (95% CI = 1.6–24.3) more than its inverted counterpart ($P = 0.004$), and the BGS collected on average 7.2 times (95% CI = 1.7–29.9) more than the BGP in the inverted configuration ($P = 0.003$; Table S2).

As the catch rates of *Anopheles* males and females were very low (Table 4), the effect of trap type on catch rates was not evaluated.

Table 4. Number of observations (*N*), sum, mean ± standard deviation of collected mosquitoes in the field trial in Mozambique.

		Aedes spp.		*Culex* spp.		*Anopheles* spp.	
N	Trap[1]	Female	Male	Female	Male	Female	Male
12	BGP + BGSw	1 (0.08 ± 0.3)	2 (0.2 ± 0.4)	74 (6.2 ± 10.0)	81 (6.8 ± 11.4)	14 (1.2 ± 1.8)	16 (1.3 ± 1.6)
	BGP (inverted) + BGSw	1 (0.08 ± 0.3)	0	14 (1.2 ± 2.1)	10 (0.8 ± 1.8)	1 (0.08 ± 0.3)	0
	BGS + BGSw	6 (0.5 ± 1.0)	0	30 (2.5 ± 2.2)	43 (3.6 ± 4.9)	5 (0.4 ± 1.0)	9 (0.8 ± 1.5)

[1] BGP: BG Pro, BGS: BG-Sentinel 2, BGSw: BG-Sweetscent

DISCUSSION

In this study, we evaluated the new modular Biogents BG-Pro trap and compared it to 4 different adult mosquito traps (BG-Sentinel, BG-Mosquitaire, CDC trap, and EVS trap). Trap comparisons were carried out in 7 countries on 4 continents against relevant local vector mosquito species. We demonstrated that across the targeted species, the BGP performed equally to, or significantly better than, the 4 other traps in the study. Species of interest in this study were in 3 genera: *Aedes* (*Ae. aegypti*, *Ae. albopictus*, *Ae. polynesiensis*, and *Ae. vexans*), *Culex* (*Cx. pipiens*, *Cx. quinquefasciatus*, and *Cx. erraticus*), and *Culiseta* (*Cs. melanura*).

Aedes aegypti

Two experiments were conducted to compare the BGP to the current gold standard BGS which is highly recommended for *Ae. aegypti* surveillance (CDC 2018). In both experiments the BGP had significantly higher collection rates for *Ae. aegypti* than the BGS. In semi-field trials in Australia, the BGP collected 2.4 times and 1.7 times more female and male *Ae. aegypti* than the BGS trap, and in Brazil the BGP collected 5.5 times more female and 7.5 times more male *Ae. aegypti* than the BGS.

In Tahiti, where the catch rates of *Ae. aegypti* were much lower than in Brazil or Australia, the BGP was compared to the original BGS 1. In this study, catch rates of female and male *Ae. aegypti* for the BGS 1 with and without BGL did not differ statistically from those of the BGP trap with and without BGL. Based on data collected to date, it appears that in locations with high *Ae. aegypti* densities, the BGP significantly outperforms the BGS in collecting both males and females, while at lower densities the traps yield similar results. Overall, the BGP was shown to be equal or better in collecting *Ae. aegypti* than the gold standard BGS, making the BGP an attractive alternative for *Ae. aegypti* and dengue surveillance programs.

Aedes polynesiensis

The BGP was compared to the BGS 1 in Tahiti for effectiveness in collecting *Ae. polynesiensis*. When run without attractants, there were no significant differences between the 2 traps. Adding BGL significantly increased the catch rates for both traps, but again, there were no significant differences. Hapairai et al. (2013) also observed a similar increase in *Ae. polynesiensis* catch rates with the BGS 1 when using the BGL. Generally, BGL and BGSw increase catch rates for *Ae. aegypti*, *Ae. albopictus*, *Ae. polynesiensis*, and *Cx. pipiens/quinquefasciatus*, but have little impact on other species (Degener et al. 2019, Wilke et al. 2019).

Aedes albopictus

The BG Sentinel has long been the most frequently used trap for *Ae. albopictus* surveillance (Unlu and Farajollahi 2014, Li et al. 2016, Gibson-Corrado et al. 2017). In Suffolk, VA, the BGP was compared to the BGS in an area where trap catches of female *Ae. albopictus* exceeded 30 females per day. In this study, there were no significant differences in the catch rates of females and males between the 2 traps. At another location in Suffolk, the BGP was compared to the CDC. Generally, CDC light traps in their standard configuration (with light and hung between 150 and 160 cm) are not recommended for *Ae. albopictus* surveillance (CDC 2018); however, their performance can be improved by setting the traps at a lower height without the light (European Centre for Disease Prevention and Control 2018, West Virginia Department of Health and Human Services 2018). In this experiment, the BGP was installed in BGS mode at ground level, and a CDC trap without light was also hung at ground level (all traps were baited with CO_2 and BGL). Not unexpectedly, the CDC trap was significantly outperformed by the BGP for both female and male *Ae. albopictus*. Other studies have yielded similar results comparing the CDC with the BGS (Drago et al. 2012, Li et al. 2016).

In southern France, where the BGM is sold in retail stores to reduce *Ae. albopictus* populations, the BGP was evaluated against the BGM in a typical residential backyard garden. In this test, the BGM slightly outperformed the BGP for female but not for male *Ae. albopictus*.

Results from these 3 experiments indicate that for *Ae. albopictus*, the BGP significantly exceeds the performance of the CDC and provides similar catch rates to the BGS and BGM, making it a good choice for surveillance of this species.

Aedes vexans

Aedes vexans and other floodwater mosquitoes are an annual problem in many areas of Germany. In Regensburg, Germany, we compared the EVS to the BGP in 2 experiments in residential gardens. Catch rates for female *Ae. vexans* were not significantly different between the traps. The main difference between the BGP used in EVS style and a conventional EVS trap is the light source and the air flow mechanism. *Aedes vexans* may be attracted primarily by the amount of CO_2 released, as the updraft generation in the BGP did not increase attractiveness. In a third study, the BGP was compared to the BGS with both traps at ground level and using CO_2 as an attractant. The BGP significantly outperformed the BGS collecting over twice as many *Ae. vexans* females. There was no advantage in using a BG Sentinel style trap for *Ae. vexans* collections. Similar findings were found in a previous study comparing the BGS 1, CDC, and EVS traps in Europe (Lühken et al. 2014).

Culex pipiens, Cx. erraticus, and *Cx. quinquefasciatus*

Culex pipiens was a target in 3 studies in Germany. In GER 1, The BGS collected significantly more *Cx. pipiens* when compared to the BGS. In experiments GER 2 and GER 3, the EVS trap was compared to the BGP. In both studies, the BGP significantly outperformed the EVS for female *Cx. pipiens*. The only difference between the 2 experimental setups was that in GER 2, the BGP was operated with a 6-V battery, whereas in experiment GER 3, a 5-V power bank was used. Although overall catch rates were lower during experiment GER 3 (this trial was performed in late July and August when the overall mosquito abundance was lower) the relative differences in collection rates between the 2 trap types were similar in both studies. As no light was used in experiments GER 2 and GER 3, and the same attractant was used for both traps (CO_2 from dry ice); it is again most likely that higher *Cx. pipiens* catch rates are because of the bidirectional airflow. These results mirrored the comparison between the CDC and the BGP in USA 2. In this study, the BGP significantly outperformed the CDC for female *Cx. pipiens*.

Culex erraticus was also a target in USA 2. In this study the BGP with UV LED light strip collected significantly more *Cx. erraticus* than the BGP without light and the CDC traps both with and without light. There was no statistical difference between the 2 CDC traps or between the BGP without light and the CDC with or without light. The high attraction of *Cx. erraticus* to the UV light was unexpected and should be further investigated in areas where this species is a problem.

In Brazil, the BGP collected significantly more female *Cx. quinquefasciatus* than the BGS. *Culex* spp. catch rates did not significantly differ between the BGS and the BGP in Mozambique or France. Overall, the BGP proved to be very effective in collecting *Culex* species.

Culiseta melanura

Culiseta melanura, a major vector of eastern equine encephalitis, was the target of an evaluation of the CDC trap and the BGP in USA 2. In this experiment, CDC traps (with and without light) and BGP traps in CDC style configuration (with and without light and with a rain shield) were hung at a height of 160 cm. Carbon dioxide was used as a supplementary attractant. Both BGP traps (with and without light) significantly outperformed the CDC traps in collecting *Cs. melanura. Culiseta melanura* females were collected most often in the BGP trap with the UV LED strip: 2 times more than the BGP without light and 5 times more than the CDC with and without light. Although the BGP with UV LED collected significantly higher numbers than all the other traps, it also had the largest amount of undesirable bycatch. The main differences between a BGP used in "CDC style," and a CDC miniature light trap are the light source (UV-LED light strip for the BGP, and incandescent light bulb for the CDC), and the trap airflow mechanisms, as explained in the Introduction. The collection data for *Cs. melanura* show that with and without light, the BGP collected significantly more specimens than the CDC with light. Thus, the increased performance of the BGP cannot only be attributed to the light source alone. It is likely that the bidirectional airflow plays an important role in the superior performance of the BGP trap used in CDC style. Significantly higher catches of *Cs. melanura* with the UV LED light was an interesting finding that could be exploited in areas with eastern equine encephalitis surveillance programs targeting this species. Additional studies are needed to determine if the LED light strip can also enhance the collection of certain anopheline species that are attracted to UV light around 365 nm (Wilton 1975, Sexton et al. 1986, Rubio Palis et al. 1996, Kim et al. 2016, Mwanga et al. 2019).

Collection of male mosquitoes

The increasing effort to seek nonchemical pesticide control measures for mosquitoes has led to the application of sterile insect techniques (SIT) with mass release of males sterilized by irradiation, infected with *Wolbachia* or modified genetically (O'Connor et al. 2012, Carvalho et al. 2015, Bellini et al. 2021). An efficient monitoring of male mosquitoes is crucial for SIT projects to assess survival, dispersal, longevity, and the ratio of SIT to wild males (Alphey 2002, Carvalho et al. 2015, Bouyer et al. 2020, Staunton et al. 2020). Currently, the BG Sentinel is often used for monitoring populations of male *Aedes* mosquitoes (Bouyer et al. 2020; Staunton et al. 2020, 2021). In our studies, the BGP was found to be significantly more effective than the BGS for collecting male *Ae. aegypti* and male *Cx. quinquefasciatus*. For male *Ae. albopictus* the BGP was equally effective as the BGS trap or the BGM trap and significantly better than the CDC trap. Therefore, the BGP trap might be considered as a less costly, more convenient, and effective alternative for monitoring male mosquitoes in such programs.

Attractants

The selection of attractants used in these studies was based largely on findings from previous studies and local availability. *Aedes aegypti* was the main target species for the BG-Sentinel trap and the BG-Lure when they were first introduced in the year 2006. This combination of visually attractive trap (BGS) and a lactic-acid–based attractant (BGL) proved to be highly sensitive for this species, even without the use of carbon dioxide (Kröckel et al. 2006, Williams et al. 2006). In the following years, the BGS/BGL combination proved to be equally effective in the collection of the Asian tiger mosquito, *Ae. albopictus*, and has since become a commonly used method for the collection of adults of both species (CDC 2018). The BGS was also shown to be an excellent tool to catch a third species from the subgenus *Stegomyia*, the Polynesian tiger mosquito, *Ae. polynesiensis* (Hapairai et al. 2013). Yet another important species that has been shown to be captured well by the BGS/BGL combination is the southern house mosquito, *Cx. quinquefasciatus* (Wilke et al. 2019).

The only trial in our study comparing traps alone to traps with BGL was the one performed in Tahiti. Although the difference between treatments was insignificant for *Ae. aegypti*, there was a significantly increased catch rate for *Ae. polynesiensis* when either BGP or BGS 1 was used in combination with the BGL. *Culex quinquefasciatus* was also captured in low numbers, and although no differences could be observed between traps with or without attractant, the BGP performed better than the BGS. This was mirrored by the results for *Cx. quinquefasciatus* in Brazil.

Carbon dioxide is recognized as a strong mosquito attractant (Gillies 1980). To increase collections of most mosquito species other than those listed above, the addition of carbon dioxide as a supplementary attractant is recommended (Lühken et al. 2014, Wilke et al. 2019). The combination of CO_2 and BGL was shown by Roiz et al. (2016) to be the most effective combination for trapping *Ae. albopictus*. Therefore, we decided to use carbon dioxide alone or in combination with the BGL or BGSw in environments with additional species, like *Cx. pipiens*, *Ae. vexans*, *Cx. erraticus*, or *Cs. melanura*, as well as *Ae. albopictus*. Carbon dioxide can be added from sublimating dry ice (as in trials GER 2 and 3), from CO_2 cylinders (GER 1, USA 1 and 2), or from a fermenting sugar solution and yeast (Saitoh et al. 2004, Smallegange et al. 2010).

Technical aspects of the trap

In comparison to the BGS trap, the BGP offers several advantages: it is cheaper, weighs less, has a smaller packing volume and is more energy efficient. Perhaps the biggest advantage is the ability to run the trap on 5-V rechargeable power banks. A 5-V 10,000-mAh power bank weighs 180 g compared to an average 4.4 kg for a 12-V Ah sealed lead acid battery. For individuals doing field work, the weight reduction associated with using power banks to operate the BGP is a significant benefit. The BG-Pro can be deployed in a range of configurations to meet various operational requirements. Flexibility to run on 5 or 6 V, hang the trap or place it on the ground, use with or without light, CO_2 or a rain shield, make it more versatile than a BG-Sentinel. The suction flow of the BGP trap decreases only slightly (less than 10%) if the fan runs on 5 V compared to 6 V, and this had no effect on the collection of mosquitoes in preliminary laboratory tests with *Ae. aegypti* (M. Geier, personal communication). The collection performance of the BGP trap with 5 V and 6 V were also very similar compared to EVS traps in the field tests with *Cx. pipiens* and *Ae. vexans*, indicating that the trap can be used with both voltage ratings.

Comparison of the CDC, EVS, and BGP traps shows that all 3 traps are similarly priced, run on 6 V, operate in a hanging position, and can be run with or without light. The main advantages of the BGP are its lower power consumption, which also allows operation on 5 V with a small power bank, and the flexibility of using the trap in multiple configurations. One drawback to the power bank is its higher initial cost, but this is offset by the fact that it can be recharged with any USB connection, whereas the sealed lead acid batteries used by the CDC and EVS traps require purchase of a special charging station.

The strength of the present study is that it includes 10 experiments conducted across a wide geographic area and includes several important vector mosquito species. This data set provides a very comprehensive comparison between the BGP and BGS in locations where *Ae. aegypti*, *Ae. albopictus*, and *Ae. polynesiensis* were the most important vector species. Collection performance of BGP in France was not significantly different from the BGM where the BGM is a popular trap with homeowners in residential areas with high *Ae. albopictus* populations.

Future studies should expand on comparisons between the BGP, EVS, and CDC traps to evaluate their relative efficacy for surveillance in a wider variety of habitats and with a wider variety of species, especially anopheline vectors of malaria (Batista et al. 2017).

We conclude that the new BG-Pro trap is an effective alternative to adult mosquito traps commonly used for the surveillance of diverse vector mosquito species in different settings. Currently, mosquito control districts often use different trap types to monitor different mosquito species. The need for multiple trap types increases equipment costs and involves logistical challenges, as different traps use different power sources, cables, catch bags, and CO_2 sources. With the BGP, different surveillance tasks can be performed using the same tool set with the expectation to achieve similar or better performance than is provided by the BGS, CDC, and EVS traps.

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