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Short Communication

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The Use of Automated Traps to Assess the Efficacy of Insecticide Barrier Treatments Against Abundant Mosquitoes in Remote Environments

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Abstract

Commercially available 'smart' trap technology has not yet been widely used to evaluate interventions against mosquitoes despite potential benefits. These benefits include the ability to capture data continuously at fine temporal scales without the human resources usually required for conventional trap deployment. Here, we used a commercially available smart trap (BG-Counter, Biogents) to assess the efficacy of an insecticide barrier treatment (BiFlex AquaMax) in reducing mosquito nuisance in a logistically challenging coastal environment in Queensland, Australia. Adoption of smart trap technology permitted us to conduct a uniquely detailed assessment of barrier treatments, ultimately allowing us to demonstrate significant reductions in mosquito collections from treated properties over all temporal scales. On average, daily mosquito collections from treated properties were reduced by 74.6% for the duration of the post-treatment period (56 d). This observation was supported by similar reductions (73.3%) in mosquito collections across all hours of the day. It was further found that underlying mosquito population dynamics were comparable across all study sites as evidenced by the high congruence in daily collection patterns among traps (Pearson $r = 0.64$). Despite limitations related to trap costs and replication, the results demonstrate that smart traps offer new precision tools for the assessment of barrier treatments and other mosquito control interventions.

Key words: barrier treatment, mosquito control, smart trap, nuisance

A constant challenge for mosquito management in urban and sub-urban settings in coastal landscapes is the encroachment of residential areas on highly productive saltmarsh mosquito habitat (Johnson et al. 2020a). Even effective larviciding programs in these environments may permit a small percentage of larvae to survive and emerge as adults. When larval densities are high, the resulting 'blooms' of dispersing adults can cause a great biting nuisance. In Southeast Queensland (SEQ), Australia, conventional adulticiding using ultra-low volume aerosols is not popular with local government or householders and, in any case, provides only short-lived impacts on mosquito abundance (Bonds 2012). Pest management authorities are therefore considering alternative interventions, including those available through commercial service providers that homeowners may pursue to reduce the number of mosquitoes on their own properties.

Barrier treatments, where vegetation interposed between mosquito breeding sites and human residential and/or recreational areas is treated with a long-lasting insecticide, is a common mosquito control tool and one increasingly offered by commercial service providers. Barrier treatments have a long history in mosquito control programs and are increasingly being used to control invasive urban *Aedes* (Meigen) (Diptera: Culicidae) species (Muzari et al. 2017, Stoops et al. 2019). However, there is a lack of contemporary data on the technique's effectiveness against highly pestiferous saltmarsh and flood-water mosquitoes, some of which are also disease vectors. The lack of data makes the endorsement of barrier treatments by mosquito control units and public health agencies difficult. Endorsement is further complicated by issues of data variability and poor data resolution that make interpretation of efficacy challenging (Stoops et al. 2019). Such problems arise from an over-reliance on discrete sampling techniques such as infrequent trap-based surveillance (Cilek 2008, Richards et al. 2017, Unlu et al. 2018), short-term (often <15 min) human landing counts (Anderson et al. 1991, Marini et al. 2015), or a combination of both (Trout et al. 2007, Hurst et al. 2014). This results in poor continuity in data collection and considerable intra- and intertrap variation. Improved sampling resolution (i.e., shorter times between individual observations) would greatly improve the assessment of efficacy trials, especially where traditional surveillance techniques are challenged by the logistics and costs of evaluation.

Usefully, great advances have recently been made in the development of 'smart' traps that can remotely detect and identify flying insects of economic and social importance (Batista et al. 2011, Chen et al. 2014, Potamitis and Rigakis 2015). Smart traps typically employ one or more sensors to automate traps and increase efficiency. In some cases, the traps collect and remotely transmit the resulting information offering real-time vector surveillance (Day et al. 2020). Most current designs incorporate optical sensors; usually infrared-based light arrays, which detect small variations in the light captured by phototransistors as the insect enters the trap (Batista et al. 2011, Potamitis and Rigakis 2015). These variations can then be used to differentiate flying insects like mosquitoes from nontarget organisms. Smart trap technology has begun to be adopted by mosquito control and surveillance agencies (Lucas et al. 2019), allowing operators to quantify fine-scale population dynamics and aspects of host-seeking activity within the most logistically challenging environments (Johnson et al. 2020a,b). Thus, adoption of smart trap technology has the potential to greatly enhance the assessment of mosquito control interventions by increasing data resolution and continuity while reducing logistical constraints.

Here, we present data from the first use of a commercially available smart trap to assess an insecticide barrier treatment applied in a logistically challenging coastal environment. We then discuss the benefits and limitations of the available technology in overcoming problems common to studies reliant on discrete sampling techniques.

Materials and Methods

Study Site

The study was performed on Russell Island (153°25′S, 27°40′E), an inhabited island (population 2836, ABS 2018) located in the Moreton Bay Marine Park in SEQ, Australia (Fig. 1). The island has an area of 1,493 ha, of which ca. 98 and 99 ha are classified as productive saltmarsh and freshwater mosquito habitat, respectively. Neighboring uninhabited islands provide large swaths of additional saltmarsh mosquito habitat (ca. 360 ha). Consequently, mosquito nuisance on the island is often high despite the existence of a well-managed larviciding program operated by local government (Jeffery et al. 2002). The mosquito community on the island is dominated by the saltmarsh mosquitoes *Aedes vigilax* (Skuse) (Diptera: Culicidae) and *Culex sitiens* (Theobald) (Diptera: Culicidae) and the freshwater mosquitoes *Coquillettidia linealis* (Skuse) (Diptera: Culicidae), *Culex annulirostris* (Skuse) (Diptera: Culicidae), and *Verrallina funerea* (Theobald) (Diptera: Culicidae) (Jeffery et al. 2002). Each species is a known or suspected vector of Ross River virus and/or Barmah Forest virus, and all are known to blood-feed on humans (Harley et al. 2001, Kay et al. 2007, Jansen et al. 2009).

Property Selection and Barrier Treatments

Six properties, two control and four treatment properties, were selected for this study. Properties were chosen based on the following criteria: single dwelling property, easily accessible backyard, and the presence of perimeter vegetation consisting of small- to medium-sized trees and shrubs. Adjoining properties were not selected to remove potential confounding effects. Treatment properties were treated with a bifenthrin-based (BiFlex AquaMax, 100 g [a.i.]/liter) residual barrier spray. Applications were made by a Redland City Council-licensed pest control operator using a backpack sprayer (STIHL PTY. LTD., Victoria, Australia). All perimeter fencing and vegetation (i.e., both front and backyards) were treated, excluding flowering or budding vegetation. Application rates were as per the label directions. Spray volume and time of treatment was recorded for each property. Block sizes ranged from 549 to 1,638 m^2, and the amount of finished spray applied ranged from 27 to 82 l (ca. 5 liters/100 m^2).

Mosquito Population Monitoring

Daily mosquito abundance and host-seeking activity were recorded on each property using CO_2-baited BG-Counter (Biogents AG, Regensburg, Germany) trap stations. General trap deployment and operation followed methods outlined by Johnson et al. (2020a). During that study, the mean agreement rate between manual and automated mosquito counts was 85.12% (95% confidence interval [CI]: 77.36–92.89%), indicating that the BG-Counter can reliably and accurately differentiate captured mosquitoes from nontarget insects. The traps (BG-Sentinel 2; Biogents AG) and counters were operated continuously with data reports transmitted to a web-based database at 15-min intervals. The trap 'dashboard' and data were accessed remotely at Redland City Council and QIMR Berghofer staff for monitoring and analysis. CO_2 was released at a rate of 200 ml/min, and traps were serviced once per fortnight. Mosquito numbers across all traps were monitored for 25 d prior to the application of the barrier treatment and for 56 d post-treatment.

Data Analysis

Differences in daily mosquito collections and hourly biting activity, and some recorded environmental variables were analyzed using two-way repeated-measures ANOVA on log-transformed (log+1) count data. Separate analyses were performed on data collected before and after the application of the barrier treatment. Percent reduction in mosquito captures post-treatment was calculated using Mulla's formula (Mulla et al. 1971).

Results

In total, 97,978 mosquitoes as identified by the BG-Counters were captured over the course of the study. The daily (per 24 h) site average was 205.8 (95% CI 180.8–230.8). Subsampling and morphological identification of collections demonstrated that the mosquito community was dominated by the saltmarsh species *Ae. vigilax* and *Cx. sitiens* and the freshwater species *Cq. linealis*, *Cx. annulirostris*, and *Ve. funerea*. We were unable to accurately determine the relative dominance of each species due to the degradation of specimens during the 2-wk service interval.

Daily mosquito captures during the pretreatment interval were higher in treatment properties (mean = 489.3; 95% CI: 405–573.5) than in the controls (mean = 364.2; 95% CI: 276.4–452), although these differences were not significant ($F_{21, 84}$ = 0.62, P = 0.89; Fig. 2A). Following the application of the barrier treatment, daily mosquito captures in treatment properties (mean = 47.8; 95% CI: 40.4–55.4) were significantly ($F_{55,}$

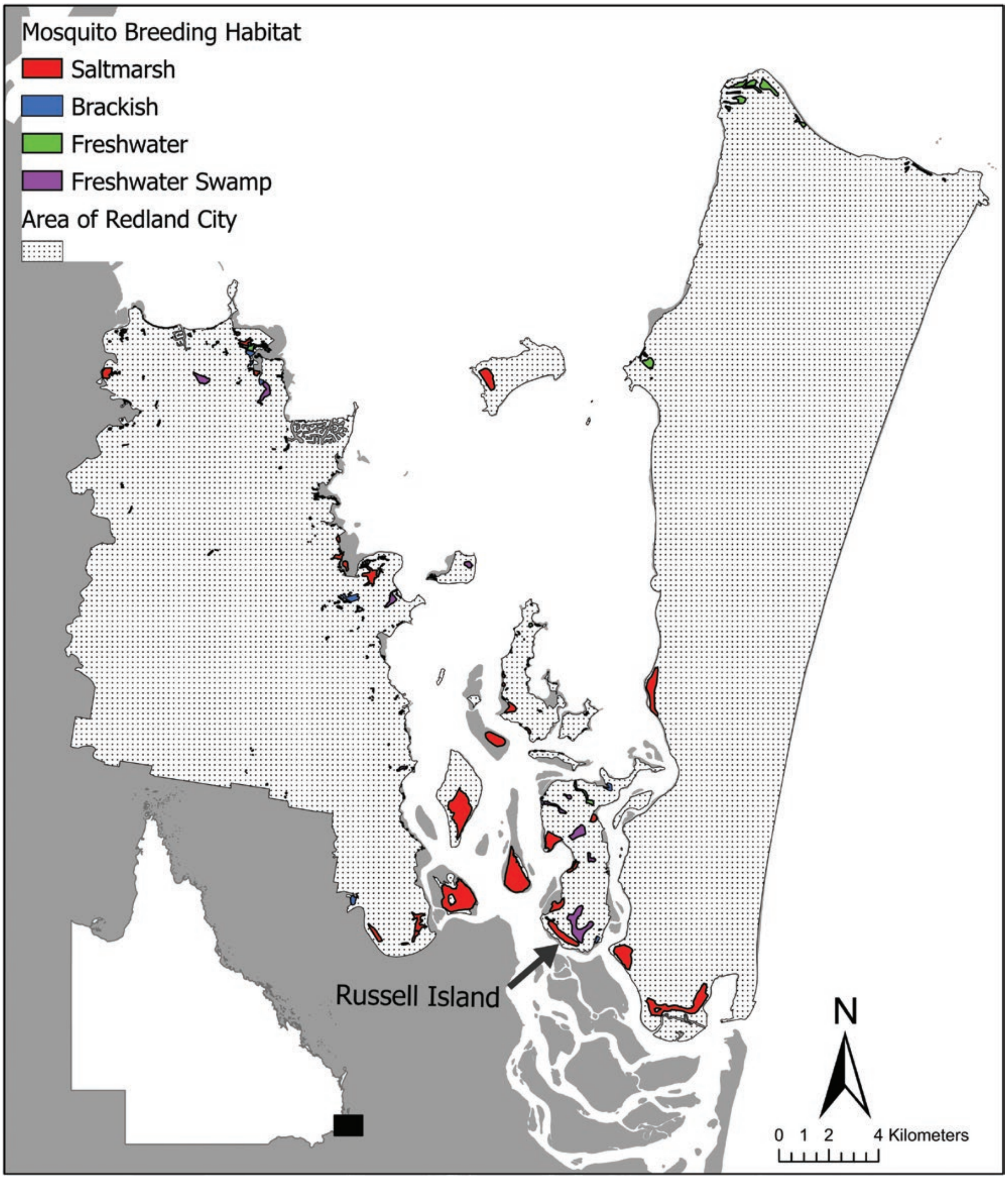

Fig. 1. The location of Russell Island in Redland Bay, QLD, Australia. Known saltmarsh and freshwater mosquito breeding habitat in and around Russell Island is shown. The dotted area represents the extent of Redland City, QLD, Australia.

$_{220}$ = 1.47, P = 0.02; Fig. 2B and C) lower than those of the controls (mean = 180.9; 95% CI: 146.3–215.5). These decreases corresponded to a 74.6% (95% CI: 71.8–77.5; Fig. 2D) reduction during the post-treatment interval. A high congruence in daily mosquito collections was observed among all traps (Fig. 3), suggesting that underlying population dynamics were similar across the study area. The mean Pearson correlation coefficient (r) among all traps was 0.64 (95% CI: 0.53–0.75) and 0.80 (95% CI: 0.72–0.87) among treatment traps. All correlations were significant with P-values < 0.003 (two-tailed).

During the pretreatment interval, hourly biting activity was similar between the properties assigned to control or treatment groups ($F_{23, 623}$ = 1.03, P = 0.42), with activity being slightly greater in treatment properties (mean = 20.1; 95% CI: 14.2–26.2) than in the controls (mean = 17.3; 95% CI: 12.5–22.1; Fig. 4A). After treatment, biting activity on treatment properties (mean = 1.7; 95% CI: 0.8–2.6) was reduced significantly ($F_{23, 1320}$ = 11.53, P < 0.001) during crepuscular peaks in biting activity relative to control properties (mean = 6.0; 95% CI: 3.5–8.4; Fig. 4B).

No significant differences in daily mean temperatures (22.6°C; 95% CI: 21.9–23.2°C vs 23.7°C; 95% CI: 23.1–24.2°C) or % relative humidity (61.1%; 95% CI: 59.5–62.7 vs 65.4%; 95% CI: 63.8–67.1%) was observed (Fig. 4C and D). Notable heavy rainfall events occurred during the pretreatment surveillance interval with rainfalls totaling 445.4 mm. These did not correspond to large increases in mosquito captures in control properties relative to the preceding period (Fig. 2C). Mosquito captures on treatment properties did appear to respond positively to several moderate rainfall events that occurred

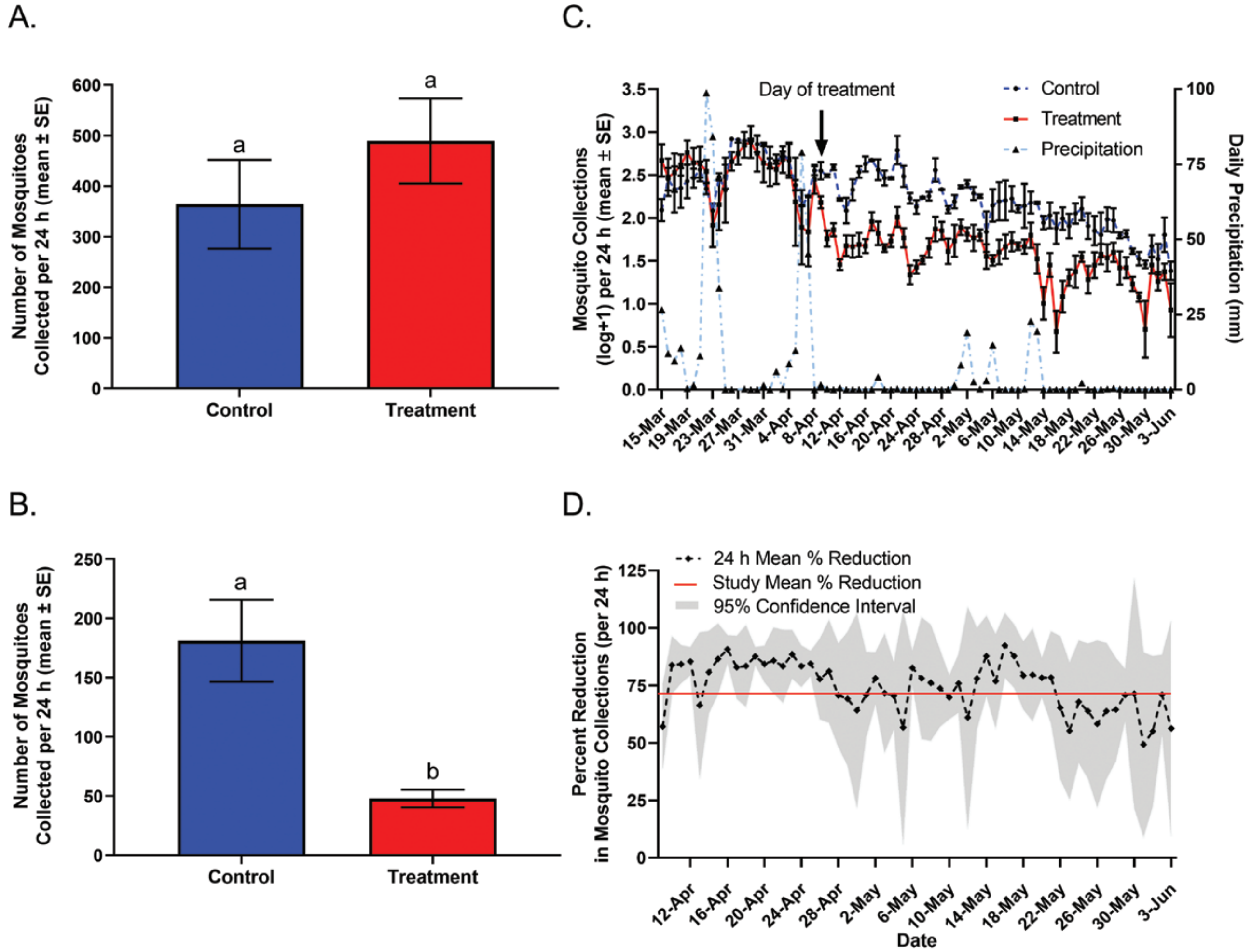

Fig. 2. The mean (±SE) number of mosquitoes collected per 24 h from treatment and control properties before (A) and after (B) the application of the barrier treatment (BiFlex AquaMax, 100 g [a.i.]/liter). (C) Daily mosquito captures (mean ± SE) on treatment and control properties and daily precipitation totals (mm) for the study area for the duration of the study. (D) The percent reduction of mosquito populations on treatment properties relative to the controls following the application of the barrier treatment as determined by Mulla's formula (Mulla et al. 1971). The study mean is represented by the solid line. Points that do not share the same letter denote statistical significance ($P < 0.05$).

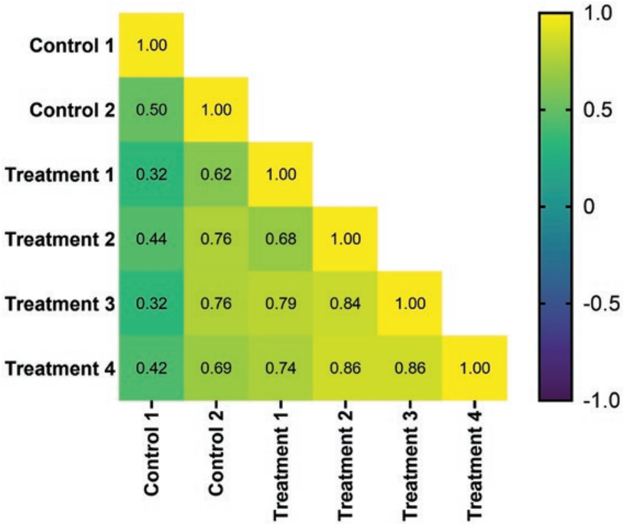

Fig. 3. Correlation matrix (Pearson correlation coefficients, *r*) of daily mosquito collections (log+1 transformed) for all traps.

in close succession during the post-treatment period (1–13 May; total of 101.4 mm); however, captures on treatment properties remained consistently lower than those on control properties during this time.

Discussion

The present study demonstrates that insecticide barrier treatments effectively reduce mosquito nuisance in high-abundance coastal environments. Although previous studies have reported similar trends, statistical evidence of efficacy was often obstructed by high intra- and interobservational variation (Stoops et al. 2019). Adoption of emerging smart trap technology allowed us to monitor mosquito captures continuously and without interruption for the duration of the study. This reduced observational bias and variation and allowed us to provide a uniquely detailed assessment of the intervention and a decisive endorsement of the capacity of barrier treatments to reduce mosquito nuisance in high-abundance environments.

The study had limitations. The high cost of each BG-Counter (ca. $3,050 AUD/unit) limited the number of individual properties that we could monitor and therefore limited experimental replication. A lack

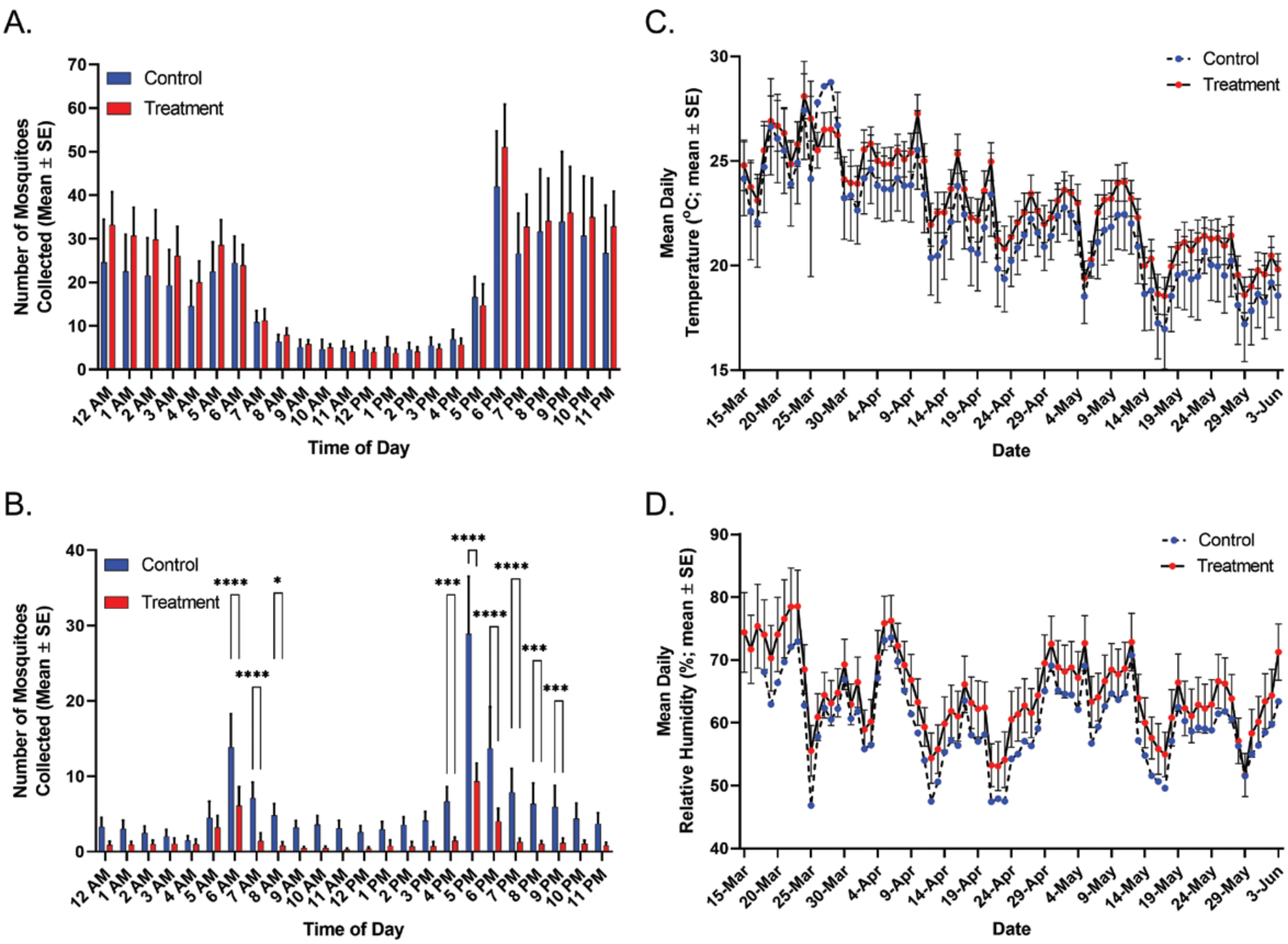

Fig. 4. The number of mosquitoes collected per hour (mean ± SE) from treatment and control properties (A) before and (B) after the application of the barrier treatment (BiFlex AquaMax, 100 g [a.i.]/liter). (C) The mean (mean ± SE) daily temperature and (D) relative humidity (%) recorded on treatment and control properties during the study. One asterisk (*) indicates *P*-value smaller than 0.05 (>0.001). Three asterisks (***) indicate $P < 0.001$, and four asterisks (****) indicate a $P < 0.0001$. Nonsignificant ($P > 0.05$) comparisons are not shown.

of intra- and interstudy replication has long plagued assessments of barrier treatments (Stoops et al. 2019) and entomological field studies in general (Chaves 2010, Wittman and Aukema 2020). However, the high number of observations per replicate (mean = 7,207 data points; 96 per day) achievable with smart traps may alleviate some concerns regarding the veracity of the data. Ideally, the maturation and adoption of commercially available technology will reduce future per unit costs and allow for more robust trial design.

The study was further hindered by a lack of species-specific data. Although species-specific data are often desired, a mosquito captured at ground level (especially for the species present) can largely be assumed to present a biting risk to residents. Perhaps more importantly, total mosquito captures is a common statistical unit of these types of studies, even when speciated collections exist (Amoo et al. 2008, Cilek 2008, Fulcher et al. 2015).

Lastly, concerns over nontarget impacts should not be overlooked. Future trials might attempt to reduce nontarget impacts by focusing on individual mosquito–plant associations (i.e., identification of primary nectar and harborage sources) and seasonal peaks in abundance. Future advances in the automatic identification of flying insects are sure to assist these efforts by providing real-time, species-specific data when feasible (Genoud et al. 2020, Kim et al. 2021, Kirkeby et al. 2021).

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