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SHORT COMMUNICATION

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Evaluation of a mass trapping strategy to prevent mosquito nuisance in campsites of southern France

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Abstract

Mosquito traps, historically used for surveillance and research, have gained prominence as a tool for mosquito control, amidst concern over the environmental impact and increased resistance to insecticide-based methods. In this study, we tested the effectiveness of a mass trapping barrier design with two types of traps, Mosquito Magnet (MM) traps and BG-Protector (BGP) traps. This experiment was conducted in three coastal camping areas in southern France between summer and autumn 2022, where the presence of floodwater mosquito species with anthropophilic preferences like *Aedes caspius* represents a year-long nuisance. MM traps were set around the campsite as a barrier to interfere with mosquitoes from entering the campsites, whereas BGP traps were set within the campsites, with the aim of diverting mosquitoes away from humans at peak activity hours. Over 210,000 mosquitoes of 11 species from 4 genera were collected by both trap types across treatment campsites, with no significant differences in mosquito community samplings between BGP and MM traps. Barrier traps effectively targeted *Ae. caspius*, reducing total mosquito abundance in two of the three study sites by 34% and 55%. This study provides valuable insights into the efficacy and feasibility of using mass trapping barriers as a complementary control strategy for mosquito species in wetlands.

KEYWORDS
mass-trapping, mosquitoes, vector control, wetlands

INTRODUCTION

Mosquitoes are notorious vectors of diseases and represent a continuous nuisance to human populations worldwide through their biting behaviour. Traditional mosquito control methods rely on the application of insecticides, which can target both adult and larval states, but have raised widespread concerns regarding their environmental impact on non-target species and even on ecosystem health (Brühl et al., 2020). Furthermore, as their effectiveness is becoming increasingly limited by the surge of insecticide resistance, there is a growing interest in alternative control strategies.

Mosquito traps have long served as valuable tools in mosquito surveillance, strengthening the research and monitoring of mosquito population dynamics and community composition. Over the past decade, there has been increasing interest in evaluating the potential of trapping strategies for vector control, as reflected by the continuous development and enhancement of trapping devices, as well as a growing number of studies that evaluate trap-based interventions to reduce mosquito populations (Barrera, 2022).

A recent review by Jaffal et al. (2023) assessed the evidence for the efficacy of mosquito traps in reducing the abundance of two invasive species, *Aedes aegypti* and *Aedes albopictus*. Although this review was species-specific, they concluded that there is clear support of trapping as an effective method to reduce the density of these species, albeit in combination with classical vector control methods. Traps have also been tested on other arbovirus vectors like *Aedes vexans* or nuisance mosquitoes like *Aedes caspius*, with results indicating moderate- to high-density reductions in comparison with control areas (reported as 30% and 70% reductions in Jackson et al., 2012 and Poulin et al., 2017, respectively).

Traps are a versatile tool to incorporate into mosquito control strategies, with trap designs that target specific life stages (e.g., gravid female traps seeking to lay their eggs) or that are more attractive to certain mosquito species (e.g., container-seeking species like *Ae. aegypti*). Host-seeking female traps are of particular interest because they target a demographically relevant fraction of the population: by reducing the number of biting females, they directly impact mosquito–human interaction, potentially reducing the risk of disease transmission and mosquito-related nuisance. These traps attract mosquitoes by releasing visual and olfactory attractants that mimic the human host.

Mosquito traps can be deployed strategically in areas where environmental and health concerns limit the use of insecticide-based control methods (Brühl et al., 2020) or in areas prone to mosquito nuisance, such as recreational areas. The idea of deploying traps to reduce mosquito–human contact and nuisance was tested with success in nature trails in a study by Kline (2007), highlighting the potential of setting up traps around an area to act as barriers.

In this study, we assessed the efficacy of a trap set-up to reduce nuisance mosquito abundance at three campsites in southern France, by comparing mosquito abundance in treated and control sites within the same region. Floodwater mosquitoes like *Ae. caspius* are abundant in this region, causing significant and year-long nuisance that can deter outdoor activities (Carrieri et al., 2008). We assessed a trap set-up consisting of two different types of host-seeking traps: Mosquito Magnet® (MM) traps set around the edges of the campsite in continuous operation to form a barrier to stop mosquitoes from entering the campsite, and BG-Protector® (BGP) traps, distributed within the campsite to divert mosquitoes away from humans at peak mosquito-activity hours. This study provides valuable insights into the efficacy and feasibility of using mass trapping as a strategy to balance mosquito control and environmental safety in recreational areas.

METHODS

Study area

The trapping strategy was deployed in campsites located within wetlands along the Mediterranean coast in southern France (see Figure 1a). The study region has a Mediterranean climate, which is characterised by warm and dry summers, with mild wet winters. The vegetation is composed of riverine forests, reed marshes and wet meadows. The landscape is heavily influenced by the presence of saltwater and cycles of evaporation and artificial flooding linked to human activities (agriculture, fishing), composing a mosaic of natural and agricultural activities. Anthropophilic floodwater mosquitoes like *Ae. caspius* and *Aedes detritus* are the main nuisance species in the area. These mosquitoes emerge upon the inundation of their breeding areas, often in large numbers (Veronesi et al., 2012). The EID Mediterranée, in charge of mosquito control in the French Mediterranean region, routinely implements Bti-based larviciding strategies throughout the region to control mosquito emergence. These operations target larval developmental habitats in wetlands and marshes, and were implemented due to heightened concern for the impact of mosquitoes on quality of life and tourism in the region: only in the coastal cities of Occitanie and Provence-Alpes-Côte d'Azur (PACA), visits were estimated at 51 and 85.9 million overnight stays, respectively (Le Gentil et al., 2023).

Trap deployment

Three replicates of treatment were implemented at three separate campsites: Camping Les Aresquiers, Camping Les Bois Flottés and Camping International (see Figure 1a for more details). For each treated campsite, there were one or two negative control sites within a range of 0.75–4 km of each treated campsite, as measured by the measuring distance tool in Google maps (Table S1). At each treatment site, MM traps were placed on the outskirts of campsites and near mosquito breeding areas. These traps operated continuously and autonomously, equipped with a battery and a butane bottle of 13 kg capacity designed to emit for 3–4 weeks (Model: Independence or Executive, Woodstream Corporation, USA). These traps release CO_2 from the combustion of butane as a primary stimulus along with heat and water vapour, which are secondary stimuli for attracting mosquitoes, and are designed to attract and capture mosquitoes in large outdoor areas. MM traps were checked weekly to ensure proper functioning. BGP (Biogents, Germany) traps were set within the campsite to act as a second line of defence targeting host-seeking mosquitoes. These traps were equipped with BG-CO_2 Booster Kit and a 6 kg pressurised CO_2 tanks as CO_2 source. A timer was used to diffuse the attractants only during hours of peak mosquito activity, for discontinuous mosquito capture at dusk and dawn. Trapping hours were tuned twice to fit the shift of sunrise and sunset time during the season. Traps were set and activated after the first tidal or artificial flooding event of breeding sites at each treatment campsite and kept running for 2–3 weeks (the estimated lifespan of adult mosquitoes) by field agents of the EID Mediterranée. This trapping scheme was repeated throughout the year from June to November. The number of BGP and MM traps deployed at each campsite and the trapping periods for each site are indicated in Table S2. BGP and MM traps are referred to 'barrier traps' hereafter, to reflect their specific placement around the campsites to serve as a barrier.

Mosquito abundance monitoring

At both treatment and control sites, CDC traps were used to monitor mosquito populations. These traps were baited either with dry ice

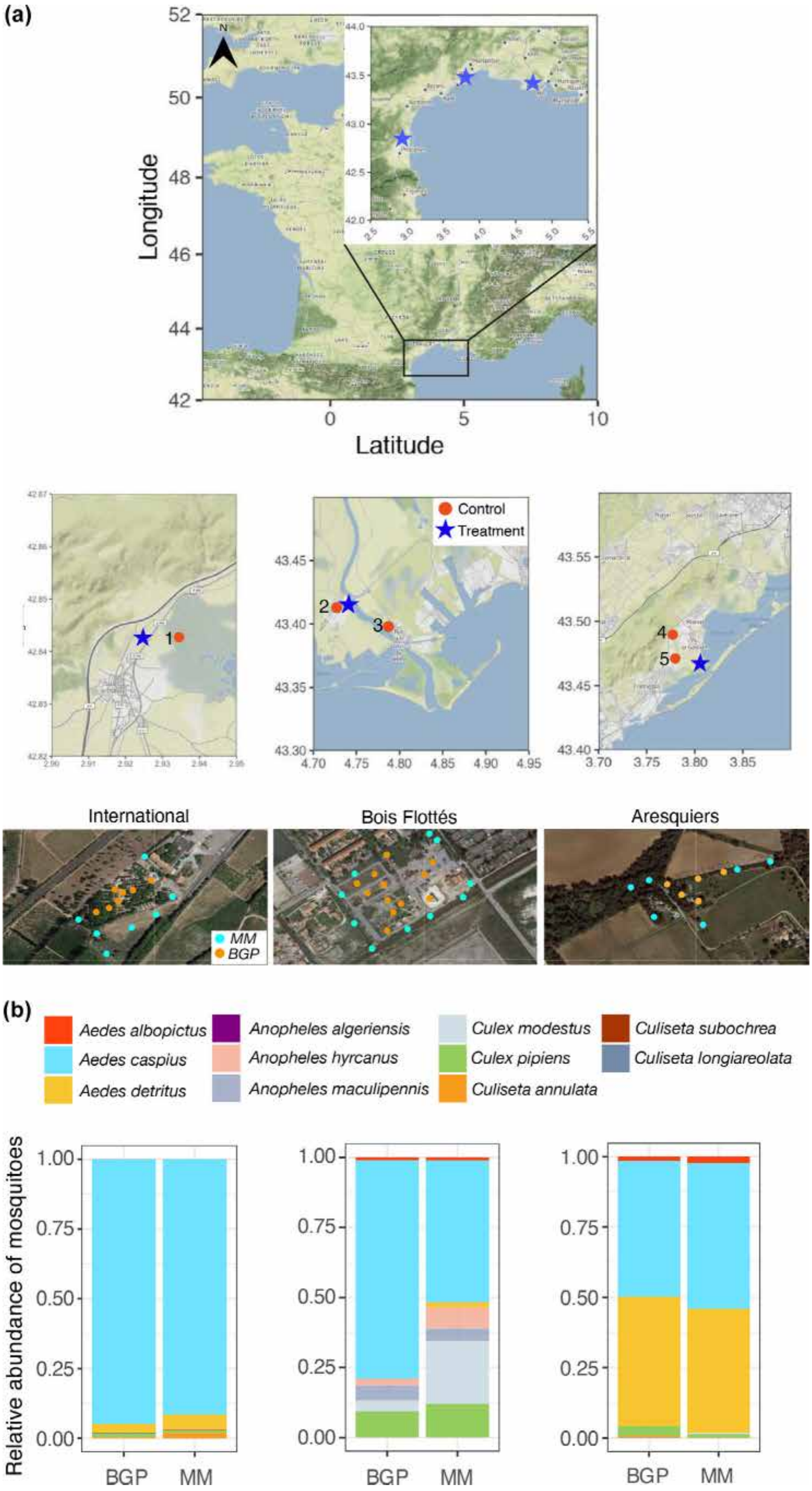

FIGURE 1 Legend on next page.

(1 kg) or CO_2 from pressurised tanks. CDC traps were operated 24 h on a weekly basis. In each site, sampling effort was the same for treated and control localities, but the number of traps and the duration of the experiment (in weeks) differed between sites (see Table S2 for details). Thus, in the Bois Flottés site, we had a total of 13 trap nights per locality (1 CDC trap per locality), whereas in the Aresquiers and International sites (where two CDC traps per locality were deployed), we obtained 30 and 36 trap nights, respectively.

Mosquito collection and identification

Adult mosquitoes were brought back to the laboratory and immediately frozen prior to identification. Mosquitoes were counted and identified per trap by EID Mediterranée entomologists, using identification keys (Becker et al., 2010; Gunay et al., 2022).

Data analysis

Due to differences in sampling efforts, results for each campsite were analysed separately. All statistical analyses were conducted in R statistical software (v.4.3.2) (R Core Team, 2021). We assessed differences in the mosquito assemblages collected by the BGP and the MM barrier traps at each campsite using the Morisita dissimilarity index, estimated with the 'vegdist' function. This is an abundance-based index, in which individuals in the communities to be compared are weighted equally. Because this index weights each species according to its abundance, rare species have little effect on its value (Chao et al., 2006). This index was deemed adequate for our objectives, as we wanted to assess the similarity of mosquito communities in terms of the most abundant species with a persistent presence throughout the sampling period, while accounting for sample size differences between groups. The index was transformed to a measure of similarity by subtracting the result from 1. We further compared the mosquito species composition of barrier traps at each campsite using a permutational multivariate analysis of variance (PERMANOVA), with 9999 permutations based on Morisita-Horn distances. Finally, we assessed the contribution of each mosquito species to the observed differences between trap types using the similarity percentage (SIMPER) method. To remain consistent with previous analyses, Morisita-Horn sample distance matrices calculated in R were imported and used in the SIMPER analyses. Similarity estimates were calculated using the R package 'vegan' (v.2.6-4). Diversity analysis to assess comparability in species composition between sites is included as Supplementary Material. Finally, we tested for differences in mosquito abundances between control campsites and sites where the barrier strategy was deployed, using generalised linear mixed models (GLMMs) with negative binomial error structure. Mosquito abundances, as recorded by CDC traps, was used as a response variable, with treatment level as the fixed effect. After excluding rare species where $n < 5$, we included mosquito species as a random effect to account for species-specific variation in abundances. Trap date was also included as a random effect to account for temporal variation, controlling for temporal pseudo-replication. Models were used to calculate the incidence rate ratios (IRRs), which were used to estimate the efficacy of the intervention as $E = (1 - \text{IRR}) \times 100$ (Vazquez-Prokopec et al., 2017), to describe the percent of reduction of mosquito abundance in treated campsites with respect to control sites.

RESULTS

Similarity analysis

A total of 11 species from 4 genera (*Aedes*, *Anopheles*, *Culex* and *Culiseta*) were collected by barrier traps across treatment campsites, for a total of 212,248 specimens. BGP traps in Les Aresquiers recorded 1211 mosquitoes from 6 species, and MM traps registered 26,368 specimens of 6 species. Of these species, 5 were shared between traps, whereas two species, *Culiseta longiareolata* and *Culex modestus*, were only captured in BGP or MM traps, respectively (Figure 1b). In Bois Flottés, BGP traps registered 6642 specimens of 7 species, all of which were also recorded in MM traps, which registered 55,860 specimens. BGP traps at campsite International collected 12,008 mosquitoes of 6 species, with MM traps reporting 110,159 specimens of 7 species, with the species *Culiseta subochrea* only recorded in this trap type.

Aedes caspius typically dominated mosquito community composition in barrier traps (∼50% of captures or more). In Les Aresquiers, this species comprised 48.1% of all mosquitoes collected in BGP traps, and 67.3% of collections in MM traps (Figure 1b). In Bois Flottés, it represented 77.9% of captures in BGP traps and 50.6% of samples from MM traps. At the International campsite, this species represented over

FIGURE 1 Location of the study sites within France and the relative abundance of mosquitoes collected in barrier traps at each campsite. (a) The top map indicates the location of the three sites where the experiment was conducted. From left to right: Campsite International, campsite Bois Flottés and campsite Aresquiers. The second row of maps shows the location of the control and treatment sites. Control sites are numbered as follows: (1) campsite Grand Sagne, which served as control for campsite International, (2) campsite Caisse d'epargne and (3) campsite Bois François, which were the control sites for campsite Bois Flottés, (4) campsite L'Europe and (5) campsite Le Désert, control sites for campsite Aresquiers. Note that the results from campsite L'Europe were ultimately excluded because of opposition of the campsite administration to the deployment of traps. The third row of maps displays a close-up of the barrier trap configuration at each treatment campsite, with Mosquito Magnet (MM) traps indicated as turquoise dots, and BG-Protector (BGP) as orange dots. (b) Relative abundance of the mosquito species collected by each type of barrier traps throughout the experiment. The position of the graph corresponds to same order as the maps above.

90% of total captures in both traps. The Morisita-Horn index indicated a high similarity in mosquito community profiles between barrier traps at campsites Les Aresquiers and International (0.94 and 0.99, respectively). At campsite Bois Flottés, the similarity was estimated at 0.88. SIMPER analysis of the mosquito community at this campsite showed that *Ae. caspius* and *Cx. modestus* contributed the most to the observed differences (Table S4), although the PERMANOVA indicated no significant difference in the mosquito communities collected by BGP and MM traps at this or any of the campsites (Table S5).

Effect of barriers trap deployment on mosquito abundance

The GLMM analysis suggested that the trapping strategy reduced mosquito abundance in the majority (two of three) of the study sites as compared with their negative control sites (Figure 2, Table S6). In campsite Les Aresquiers, the model estimated a significant 34.5% (CI: 4%–42% $p = 0.028$) reduction in mosquito abundance as compared with its negative control site, Le Desert. In the treated campsite Bois Flottés, the difference was estimated at a 55.5% reduction (CI: 27%–73%, $p = 0.002$) if compared with the negative control site in Bois François, but a reduction of 32.2% was not significant if compared with the other negative control site for Bois Flottés, (Caisse d'Epargne, $p = 0.139$). A reduction of 23% between campsite International and its negative control was not significant ($p = 0.632$).

Malfunctioning of traps was recorded throughout the sampling season, and although barrier trap coverage (functioning traps) was maintained above 75% throughout the experiment in campsites Les Aresquiers and Bois Flottés, at campsite International, issues with trap functioning were more frequent, with 20% of trap nights conducted at less than 75% coverage. However, when we assessed the correlation between trap coverage and mosquito collection, we found no statistically significant effect at an overall level ($r = 0.18$, $p = 0.280$).

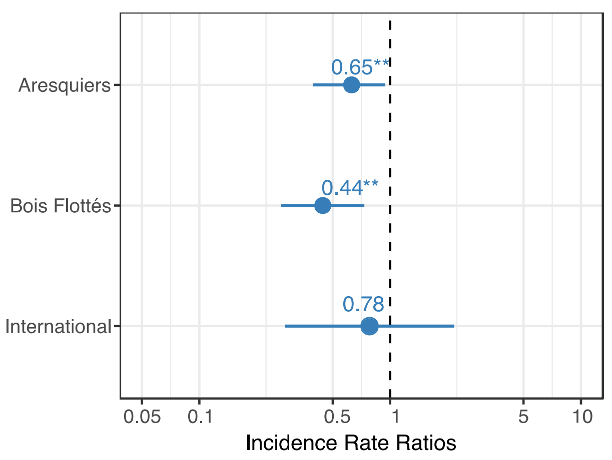

FIGURE 2 Visual representation of the incidence rate ratio (IRR) values for each treated site, as estimated from the model coefficients (see Table S6 for details on the values). An IRR value lower than 1 (dotted vertical line) indicates a reduction in mosquito abundance. Asterisks (**) indicate whether the estimate is statistically significant. IRR values were used to estimate the efficacy of the intervention, as detailed in Methods section.

DISCUSSION

Our results provide support for the use of host-seeking traps as a control tool to reduce the abundance of nuisance mosquitoes. The trap set-up tested in this experiment reduced mosquito populations in two of the three treatment sites in comparison with their negative controls, with the model-estimated reduction ranging from 34% to 55% fewer mosquitoes by the end of the trial. These estimates are in line with other studies using the same traps, for example, an experiment in British Columbia using MM traps found an average decrease of 32% in the average number of adult nuisance mosquitoes collected per day (Jackson et al., 2012). Further assessment to determine whether reduced abundance translates into decreased nuisance perception among camp goers is required, although perceived nuisance levels have been correlated with mosquito captures of *Ae. caspius* using CO_2-baited traps (Carrieri et al., 2008). Overall, these results provide support for the trap set-up as a viable design for reducing the population of nuisance mosquitoes at campsites. However, the specific contribution of the set-up to mosquito reduction cannot be clearly disentangled from the contribution of complementary larviciding methods (Bti-based) in the study areas: while the estimated differences in mosquito abundance of control and treated sites indicate an effect of trap deployment, it is currently unclear whether this is synergistic or independent of the intensity of larviciding activities.

Despite positive results, the intervention did not translate into reduced abundance in all control-treated comparisons. Interestingly, control sites where no differences were detected were located at one or less than 1 kilometre away from the intervened site. This was the case for trapping-site Grande Sagne and trapping-site Caisse d'épargne, which were located ~750 m and ~0.95 km, respectively, from the treated site. Although the choice of sites was affected by comparability and the willingness of campsite owners or visitors to allow barriers trap deployment, the flight distance of the mosquito species present should be carefully considered in experimental design, to minimise the potential contamination of results due to the mosquito spillover from untreated to treated sites, particularly when long-distance species like *Ae. caspius* are reported (Bogojević et al., 2011). Another issue during the experiment that could potentially present itself in similar trials was the malfunctioning of traps. Although these malfunctioning events did not significantly impact mosquito captures at a systematic level according to our results, trap malfunctioning or underperformance can impact the effect of the intervention. Thus, constant monitoring of trap-based control methods is crucial for ensuring robust results. In other trapping studies, a minimum of >80% coverage has been estimated as a 'best guess' based on the success of mass trapping trials (Johnson et al., 2017), although optimal coverage for trapping trials requires further research.

In terms of trapping the target species, *Ae. caspius*, both traps had a similar performance, as indicated by the SIMPER analysis where this species was the most abundant and contributed the most to the observed differences in both traps. This is an important nuisance species in the region, present throughout the year with peak density during the summer month in the region of study (Ponçon et al., 2007). Other important nuisance species captured by the barrier traps included the saltmarsh mosquito, *Ae. detritus* (found in high abundance in campsite Les Aresquiers only) and *Culex pipiens*. Both species have been determined as nuisance species and potential vectors of some pathogens, like West Nile Virus (WNV) (Bellini et al., 2014).

Our results indicated no significant differences in mosquito community profiles between BGP or MM traps at campsites International and Aresquiers and no significant differences in trap performance in terms of the collected species. However, some mosquito species were only detected in either MM or BGP traps, potentially indicating that some species were more attracted to one trap instead of the other. These differences could be partly explained by BGP traps in this experiment targeting specific activity periods, for example, peak activity for *Cx. modestus*, found mainly in MM traps, has been reported in the evening (Veronesi et al., 2012), with geographical and seasonal variation (Guo et al., 2015). We did not detect significant differences between traps despite using distinct lures and differences in trap activity time. However, other studies have found differential performance between trap types, for example, Degener et al. (2021) found MM traps to be more efficient at capturing *Anopheles* mosquitoes, whereas BG-Sentinel traps, equivalent in performance and design to BGP, were associated with higher abundances of *Culex* mosquitoes (Lühken et al., 2014).

An important caveat of this experiment is that, although control and treated sites were deemed comparable using prior field-agent data (EID field agents, personal communication), a more robust assessment would require comparing the baseline levels of mosquitoes between control and treated sites before deployment of the barrier strategy.

Despite these limitations, which are pertinent to discuss for the design of future assessments, our study provides a solid starting point to further assess the strategy and enhance the design of the intervention by considering the lessons learned.

AUTHOR CONTRIBUTIONS

Paulina A. Pontifes: Formal analysis; writing – review and editing; writing – original draft; data curation; visualization. **Jean-Baptiste Ferre:** Conceptualization; investigation; funding acquisition; methodology; data curation; supervision; project administration; writing – review and editing. **Jéremy Lavergne:** Data curation; investigation; writing – review and editing. **Nicolas Sidos:** Funding acquisition; conceptualization; project administration; writing – review and editing; supervision. **David Roiz:** Writing – review and editing; supervision; writing – original draft; validation; formal analysis.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Distances (in km) between control and treatment areas. Le Désert was the negative control site for Les Aresquiers. Bois Flottés had two negative control sites: Caisse d'epargne and Bois François. Grand Sagne was the negative control site for International.

Table S2. Number of traps and length of the trapping sessions with barrier traps for each campsite.

Table S3. Diversity indices values for the mosquito community collected by BGP and MM traps at each campsite.

Table S4. SIMPER (similarity percentage) analysis of which species contributed the most to the observed differences comparing mosquito community composition profiles between BGP and MM traps at each campsite.

Table S5. Results of the PERMANOVA analysis.

Table S6. Model estimates for mosquito abundance at each study site. The IRR is estimated from the model coefficients as the exponent of the slope coefficient when the control level (untreated) is the reference level. *p*-Values of <0.05 are considered significant and highlighted in bold.

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