Analytical models integrated with satellite images for optimized pest management

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Abstract The global field protection (GFP) was developed to protect and optimize pest management resources integrating satellite images for precise field demarcation with physical models of controlled release devices of pesticides to protect large fields. The GFP was implemented using a graphical user interface to aid the end-user to select location and define an arbitrary perimeter for protection. The system provides coordinates of drop points for the controlled release devices which can be delivered using drone technology, e.g. unmanned air vehicles. In this work, we present the first proof of concept of this technology. A vast number of pest management applications can benefit from this work, including prevention against vector-borne diseases as well as protection of large agriculture fields.

Keywords Pest management · Satellite images · UAV · Drones · Controlled release devices · Vector-borne diseases

Introduction

The objective of this research work was to develop a unique system integration for delivery and dispersion of functional micro-dispensers (FMDs) as controlled release devices of insecticides using satellite images and basic drone technology. This unique integration will

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provide an effective preventive pest management control of areas that are at risk of pathogen vectors, e.g. mosquitoes carrying malaria, while minimizing environmental impact.

Recent advances in pest management have allowed a more precise delivery of pesticides based on satellite technology that provide topographical and environmental conditions (Bratney et al. 2005; Herring 2001; Chenghai et al. 2013).

Resources can therefore be allocated and optimized in order to address large areas of interest. These unique approaches have, for example, opened up a number of opportunities in precision agriculture. Farmers today rely on advanced satellite images in order to optimize dispersion of pesticides and fertilizers over areas of interest as a function of climate conditions. Recent attention on pest management has been dedicated to developing models to optimize dispersion of pesticides against pathogen vectors, such as mosquitoes (Perkins et al. 2013; Schleier and Peterson 2014; Alonso et al. 2011; Smith et al. 2014). The challenge in developing models for dispersion of pesticides against pathogen vectors is that targeted concentrations of pesticides to repel or knock down a vector in air need to be sustained over a period of time. Physical properties of pesticides, e.g. volatility, are affected by environmental conditions, e.g. temperature and humidity. Therefore, the goal is to optimize the allocation of resources for more efficient coverage of affected areas without unnecessarily increasing dispersion intensity and pesticide concentration in air, which can lead to a blanket approach that may cause a negative environmental impact. Recent developments in drone technology have allowed technology transfer from military to civilian use (Zhang and Kovacs 2012; Primicerio et al. 2012). This translational path has allowed transformative novel applications, for which a number of drone technologies, e.g. unmanned air vehicles (UAVs) such as self-navigation, auto-pilot and advanced camera technologies, have now been commoditized. Examples of these technologies include drones for capturing images of large agriculture fields and drones for dispersion of pesticides. Convergence of satellite and drone technologies will open up a new field of applications for pest management control. In this research work, an integrated system was developed consolidating satellite images with dispersion models of controlled release devices to perform computation of drops given targeted concentrations of pesticides for an arbitrary area of interest. The system integrator was developed as a graphic user interface (GUI) named global field protection (GFP). The challenge was to find a user's location, allow the user to define a coverage area of protection and have GFP provide the drop points. The entire GUI is a standalone package compiled from C++ translated from Matlab built-in compiler (Mathworks, Inc.).

We present a novel approach in delivery and dispersion of pesticides against pathogen vectors that could be implemented using drone technology. The key novelties include: (1) adaptation of satellite images to obtain precise location and demarcation of targeted areas

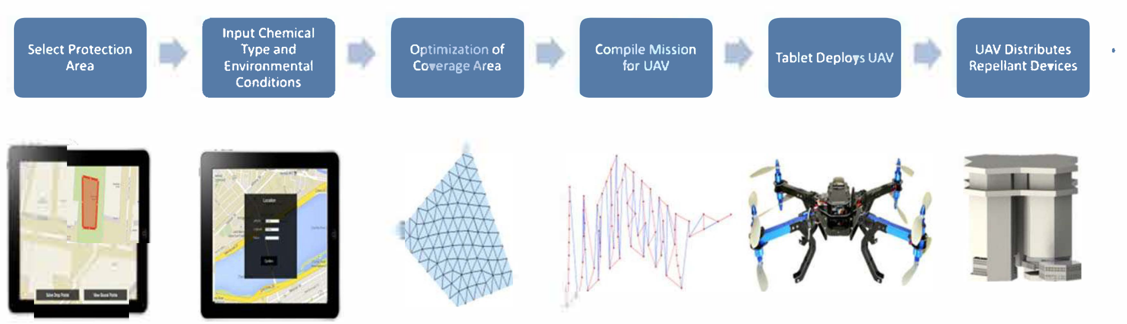

Fig. 1 Flow diagram showing steps in global field protector (GFP)

for protection; (2) integration of a physical model to define area of coverage for a controlled release device to perform chemical release, for which a controlled release device protects a cell according to temperature conditions and chemical properties (dispersion); (3) discretization of the area of interest according to optimal single cell dimensions; (4) calculation of coordinates of drop points where devices need to be released; (5)optimization of drone flight path to drop off devices. Figure 1 shows a flow diagram of the process herein described. Figure 2 shows a schematic diagram of a sample system implementation. Please refer to the video to see a proposed system in operation. Please click video link here to show a demo of the system (https://www.dropbox.com/s/qct94u7uq34lqub/ISN%20Demo%20Video%20Draft%202.0.mp4?oref=e%26n=19293994).

Materials and methods

Controlled release devices for insecticide dispersion

FMDs are a new family of controlled release devices designed to perform delivery of pesticides over a targeted period of time, as shown in Fig. 3. FMDs have been designed as polymeric devices that include arrays of reservoirs with active ingredients (Elman 2013). FMDs may include a combination of pesticides, repellents or attractants, depending on the vector application. FMDs may also include an exothermic reaction to increase the internal temperature of the reservoir and further increase evaporation rate of the chemicals.

The primary advantages of FMDs are: controlled release is performed over a defined period of time, e.g. hours, days and even weeks (1); reduction of insecticide toxicity as

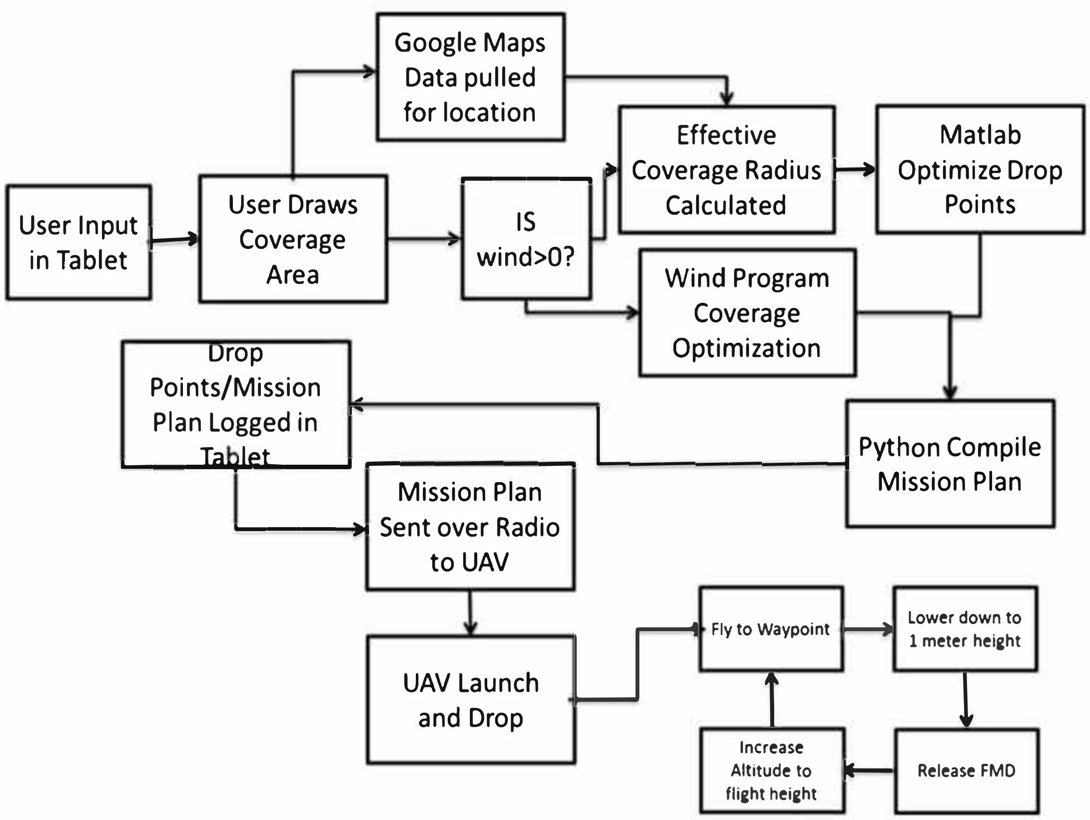

Fig. 2 Schematic diagram of system integrator

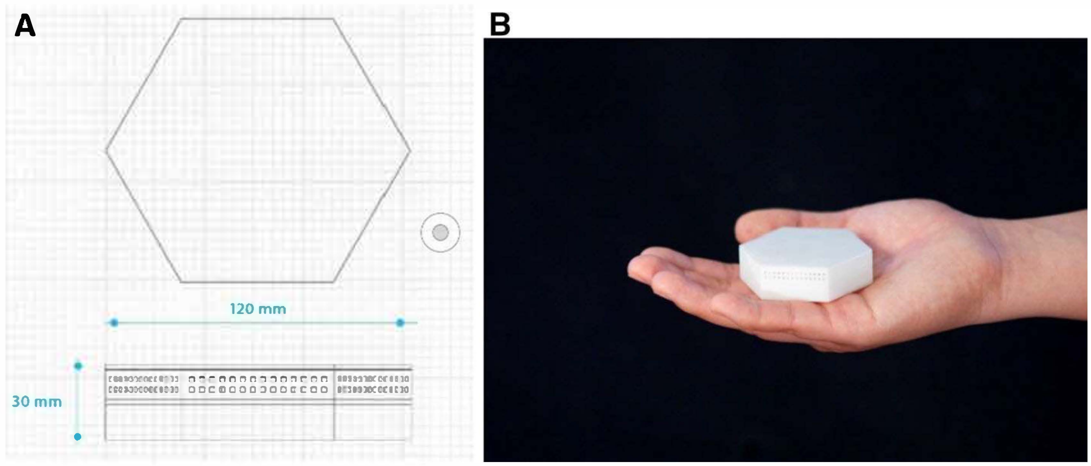

Fig. 3 Preliminary design of a field-use FMD. **a** Example of a large payload FMD (d = 120 mm). **b** Example of a small payload FMD (d = 60 mm)

dosages are reduced as release of chemicals is performed slowly over time (2); use of biodegradable polymers, such as polylactic acid (PLA) and poly (lactic-co-glycolic acid) (PLGA) (3), allowing soil bioabsorption over time without creating any environmental hazard. FMDs have been designed to include a number of active ingredients, including metofluthrin, transfluthrin and imidacloprid. For the purpose of calculating the concentration gradient as a function of space and time, the FMD can be modeled as a point source. The concentration as function of space (r) and time (t) can be defined as follows (Jenkins 2008):

$$C(r,t) = \frac{\dot{M}}{2\pi Dr} erfc\left(\frac{-r}{2\sqrt{Dt}}\right) \tag{1}$$

where $\dot{M}$ is the evaporation rate of an FMD, D is the diffusivity, which can be calculated using Fueller et al. approximation (Fuller et al. 1966).

Satellite images, mapping and cell tessellation

A GUI was developed integrating the GFP. Two major components were developed: the mapping tool and the drop point calculator. The GUI was developed to allow a user to visually define an area of interest based on satellite images. The user is requested to follow a sequence of steps in order to obtain the optimized drop points for the FMDs. The first step requires selecting a pesticide of interest characterized by a given evaporation rate assuming certain environmental conditions, such as temperature and humidity. The second step requires the user to select a geographical area of interest. This step is performed by communicating with Google Maps in order to obtain a tile of an arbitrary area of interest defined by the user. This step is performed using a Google Maps API, by pulling URLs to request the images, thus the user must have Internet access. The code was written with interrupters and handlers which update the query based off of the axes values. Whenever the bounds of the current query are changed using the zoom option, a new query is called to update to the proper setting. This is built off of some robust code written and submitted by Zohar Bar-Yehuda to the MathWoks FileExchange.

The tiles were imported and displayed as satellite images with their own Geodetic coordinates, which are then converted to Cartesian coordinates. The third step requires the user to select an area of protection by graphically defining an enclosed arbitrary perimeter superimposed on the imported Google Maps Tile.

Each FMD was modeled as a point source as described in Eq. 1. The radius of protection for each FMD is therefore calculated for a given characteristic evaporation rate and targeted concentration as a function of time. Figure 4 shows an example of a plot to calculate protection radius as a function of time. For example, a default time of protection of 10 days would result in a radius of protection of approximately 2.2 m for Metofluthrin and 2.9 m for Transfluthrin. The radius of protection, R, is therefore modeled as a hemispherical plum. Figure 5 shows a schematic diagram that depicts calculation of the effective protection radius, R_{eff}, required for arraying devices using mesh generation tools. R_{eff} is defined as the projection of the radius of protection to the field plane at a given vertical distance, D_v, of the spherical plum. The effective protective distance between devices, $H = 2R_{eff}$, is defined as the characteristic element size of the mesh.

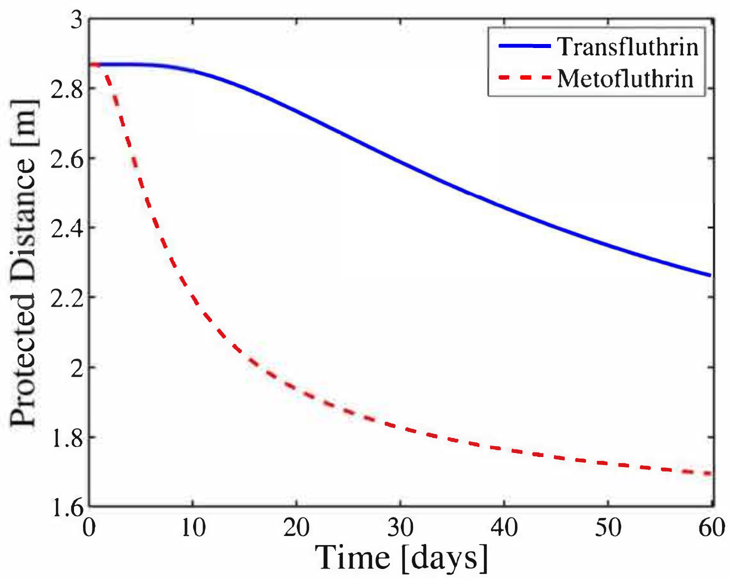

Fig. 4 Protection distance and time dependence using analytical solutions for diffusion for a target concentration

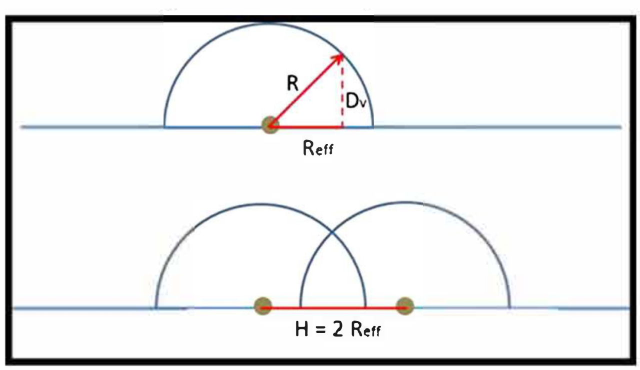

Fig. 5 Schematic diagram showing the protection radius, R, the effective protection radius, R_{eff}, required for arraying devices using mesh generation tools. R_{eff} is defined as the projection of the radius of protection to the field plane at a given vertical distance, D_v, of the spherical plum. The effective protective distance between devices, $H = 2R_{eff}$, is defined as the characteristic element size of the mesh

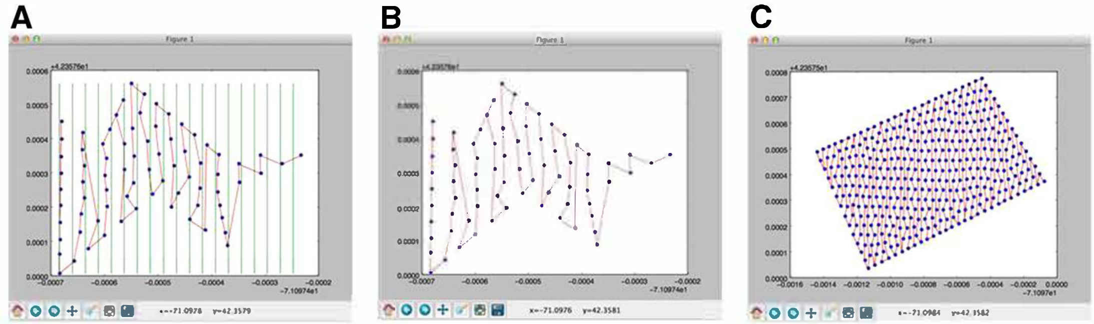

Fig. 6 **a** The figure shows a sample coverage area with the defined dividing lines. This method allows to Drone to take a straight path and step over or loop around for another pass. This methodology is inspired by traditional farming methods and reflects the applications this project may hold in agriculture. **b** The same path shown without the dividing lines for clarity. **c** A significantly larger path shown to reflect that areas of arbitrary size are able to be rasterized effectively

Drone flight optimization

After calculating the FMD drop locations, a code was written to have the server create segmented mission plans for the autonomous quadcopter UAVs, i.e. the waypoints are broken into ranges of 10–30 points where a single drone would deliver the FMDs without interfering with the path of another UAV (Fig. 6). Mission plans were performed, compiled and sent to the Web Application as well. More specifically, each mission plan per drone can be described as follows:

1. The drone is launched.
2. A waypoint sends the drone to a safe flying altitude, here we have selected 10 m, above the launch area.
3. A new waypoint is located at the GPS coordinates of the 1st drop point for the FMD array, at 10 m height.
4. Another waypoint sends the drone down to the same GPS latitude and longitude, but at 2 m above the ground.
5. A servo action is commanded on the drone to drop an FMD at the location.
6. A waypoint sends the drone straight up to 10 m height again at the latitude long of the FMD point.
7. The next waypoint is at flying altitude and at the 2nd drop point.
8. The process repeats for 10–30 FMD units.
9. The drone flies back to launch location at 10 m.
10. Automated landing takes the drone back to home base to be replenished with FMDs and battery charge.

The missions were designed as a flight path optimization and segmentation of the FMD array such that in the future multiple UAVs may also be deployed. Initially, for each mission a single drone was programmed for deployment. The array of FMD drop points were sorted in such a way to “rasterize” the area. Areas are divided into subgroups, widths of longitudinal boundaries set at a distance apart equal to $\frac{2R}{\sqrt{3}}$ where R is the radius of coverage of the area. This calculation was used to match calculated values for optimized coverage by Delaunay Triangulation. Each area was then sorted by latitude and proximity to the previous waypoint to give a straighter path for the drone. Thus, as one drone can only complete an $N = 30$ FMD mission, per flight, the raster path is divided into N/30 sections, where each drone can be commanded to complete their prescribed $N = 30$ delivery, return to be

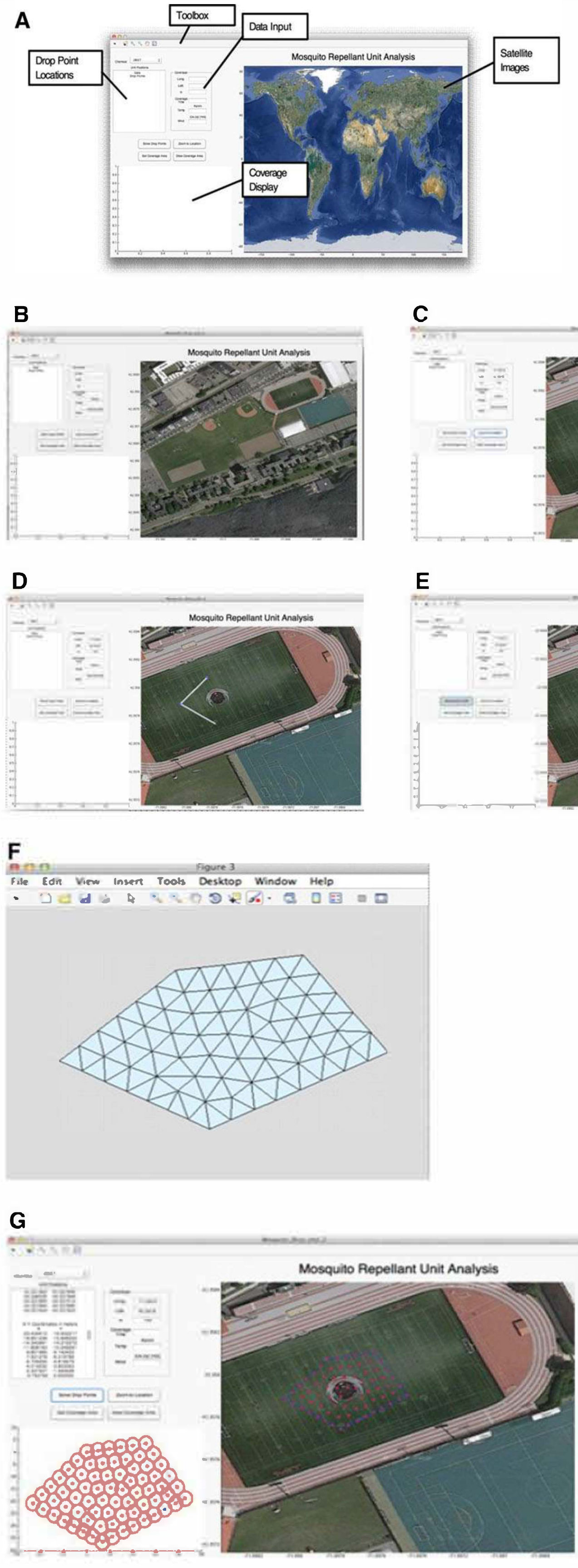

Fig. 7 Software platform: global field protection (GFP). **a** Graphical interface. **b, c** Satellite locations for area of interest. **d, e** Definition of polygon. **f** Cell tessellation. **g** Output coordinates for location of FMDs

'refueled' with more FMDs and proceed to the next set of 30 deployments. This method can therefore be scaled to multi-drone deployment. This method was chosen for its purpose of being robust to arbitrary size and shape of the coverage area given. Sorting algorithms can effectively be considered short polynomial time, and the division system occurs in single operation, making this algorithmically computationally inexpensive and fast.

Results and discussion

As an illustrative example, an irregular quadrilateral 2600 m^2 domain was defined by user using GUI shown in Fig. 7. In this example, a mesh for an arbitrary protected area of interest is generated using FMDs ($t = 3$ days, $D_v = 1.62$ m, $H = 5$ m). A mesh generator, distMesh (Persson and Strang 2014; Persson 2004), was used to create the mesh with the Delaunay triangulation algorithm using H as an input. Each node location on the generated mesh represents a drop point for an FMD. The GUI displays the location of each FMD drop point superimposed on the imported Google Maps tile. The GFP then converts the Cartesian coordinates for each drop point to Geodetic coordinates for the delivery of FMDs using drones. The GFP allows entering latitude and longitude either by graphical interface using a mouse cursor to draw over a map as part of the Toolbox, or by manually entering the coordinates to define the perimeter of interest. Arbitrary polygons can be drawn to define the area by just dragging and dropping vertices using the GUI. Once the polygon is defined, then the coverage area is set for optimization. Each base station can then be placed at each coordinate to get optimized coverage that for a given target concentration for as long as the time input calls for, at the given average temperature. Future versions will also take into account wind speed, as well as other environmental conditions such as humidity at the site.

Conclusions

In this work, we presented a novel system integrator for delivery and dispersion of pesticides. The system integrator was named GFP. A GUI, was implemented to aid the end user to protect large areas from pathogen vectors using controlled release devices. The system integrates a simple physical model for dispersion of pesticides, and integrates satellite images for precise representation of targeted areas. A mesh tessellation is performed to provide the user with the drop points where controlled release devices need to be located. In addition, GUI provides coordinates for a drone to deliver the devices. The results of this work could be applied to a wide variety of applications that require protection against pathogen vectors. We believe that the ramifications of this research work will open up a number of opportunities for future protection and prevention of vector-borne diseases, as well as protection of crops.

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Compliance with ethical standards

Conflict of interest The authors declare that they have not conflict of interest.

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