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ALBOMAURICE: A predictive model for mapping *Aedes albopictus* mosquito populations in Mauritius

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ABSTRACT

The ALBOMAURICE software runs a mosquito population dynamics model to predict the temporal and spatial abundance of *Aedes albopictus*, the dengue disease vector in Mauritius. For each vector surveillance zone, it solves a system of ordinary differential equations describing different stages of the mosquito life cycle. ALBOMAURICE uses daily rainfall and temperature input data to produce abundance maps used operationally by health services for targeting areas where to apply vector surveillance and control measures. Model simulations were validated against entomological data acquired weekly during a year at nine locations. Different control options can also be simulated and their effects compared.

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Legal Code License	CC BY NC SA
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If available Link to developer documentation/manual	Tran Annelise, Lo Seen Chong Danny, Degenne Pascal. 2019. Use of ALBOMAURICE: predictive mapping tool of *Aedes albopictus* in Mauritius - User guide and training guideline document ALBOMAURICE V1 - QGIS V3.2. Sainte-Clotilde, Reunion Island: CIRAD, 30 p. http://agritrop.cirad.fr/594724/
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ALBOMAURICE software metadata

Current software version	1.0
Permanent link to executables of this version	Data persistent ID: *doi:10.18167/DVN1/FL7QML*
Legal Software License	CC BY NC SA
Computing platforms/Operating Systems	Windows
Installation requirements & dependencies	Windows 7 or later version
If available, link to user manual - if formally published include a reference to the publication in the reference list	Tran Annelise, Lo Seen Chong Danny, Degenne Pascal. 2019. Use of ALBOMAURICE: predictive mapping tool of *Aedes albopictus* in Mauritius - User guide and training guideline document ALBOMAURICE V1 - QGIS V3.2. Sainte-Clotilde, Reunion Island: CIRAD, 30 p. http://agritrop.cirad.fr/594724/
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1. Motivation and significance

Ranked among the 100 most invasive species in the world [1], the mosquito *Aedes albopictus*, in laboratory setting, could successfully transmit most of the viruses for which it has been experimentally tested [2]. Moreover, in field condition, 26 viruses including those causing Eastern equine encephalitis, La Crosse, Japanese encephalitis, Venezuelan equine encephalitis, Chikungunya, Dengue and Zika, have been isolated from wild-caught *Ae. albopictus* specimens [2–4].

In Mauritius, a small island (1865 km^2, 1,265,000 inhabitants) located in the Indian Ocean, 890 km East of Madagascar (Fig. 1), *Ae. albopictus* was responsible for epidemics of Chikungunya (2005–2006) and Dengue (2009, 2014, 2015, 2019 and 2020) [5–7]. Mauritius has a mild tropical maritime climate with two seasons - a warm humid summer (November to April) and a cool dry winter (June to September). Mean temperature and mean annual rainfall are respectively 24.7 °C and 1344 mm during summer and 20.4 °C and 666 mm during winter [8]. The island consists of a high central plateau (approximately 600 m above sea level) that slopes downward to the coast. The coastal climate is hot and the atmosphere is either dry on the leeward side (West) or intensely humid on the windward side (East). The higher central plateau is relatively cooler and more humid, receiving an average annual rainfall of 3000–3600 mm [9]. This climate is favourable to maintain *Ae. albopictus* populations throughout the year.

To date, no specific treatment exists for diseases caused by arboviruses transmitted by *Ae. albopictus* and the World Health Organization (WHO) recommends the dengue vaccination only in countries with a high burden of disease [10]. Thus, in the absence of endemicity of mosquito-borne diseases on the island of Mauritius, the control of *Ae. albopictus* remains a major tool to prevent infections from the pathogens it may transmit [1]. Moreover, the control of this species is a high priority for the Mauritian Government since tourism is one of the pillars of its economy. Mosquito control measures currently undertaken by the national health authorities include larviciding and spraying of adulticides at and around the residence of imported and suspected case of Dengue or Chikungunya [11–13]. Furthermore, mosquito surveillance is carried out on a routine basis across the island and results submitted to the Health Inspectorate for control interventions where needed. Control interventions in regions with high mosquito incidence, consists of yard inspection by Health Inspectors and larviciding of breeding sites which cannot be overturned by Insecticide Operators [12]. However, due to the ecological plasticity of *Ae. albopictus*, control of the species remains a major challenge to the country. Thus, the need was also felt to develop a model that could predict the distribution and population dynamics of the species across the island. Data generated from such a model could assist vector surveillance and vector control departments in better planning and prioritizing their interventions so that pro-active measures can be undertaken in a timely and optimal manner.

Modelling approaches are powerful tools for identifying and prioritizing where and when surveillance and control should be targeted [14–17]. Mechanistic modelling approaches have been successfully used to predict the temporal and spatial dynamics of *Ae. albopictus* in temperate and tropical areas [18–21]. However, to be used by public health authorities and vector control services, there is a need for the development of operational tools, with easy-to-use interfaces, from such models. Recently, 'ALBORUN', a population dynamics model of *Ae. albopictus*, was developed for Reunion Island [19], located approximately 175 km away from Mauritius Island. Based on daily rainfall and temperatures, the model accurately predicts the spatio-temporal abundance of the species at local scale.

The software ALBOMAURICE [22] presented in this article was developed by adapting 'ALBORUN' to the local conditions and needs of the Mauritian Ministry of Health and Wellness. ALBOMAURICE was also validated by comparing predicted larval densities with entomological data from mosquito traps set up in the vicinity of nine national weather stations.

2. Software description

2.1. Model description

The model of *Ae. albopictus* population dynamics is based on a system of ordinary differential equations (ODE) and represents all steps of the mosquito life cycle, considering aquatic juvenile and aerial adult stages. In addition, adult mosquito females are subdivided in compartments regarding their behaviour (host-seeking, resting, ovipositing). Daily precipitation and temperature are the main drivers of mosquito population dynamics. Indeed, temperatures affect the development of aquatic stages, egg maturation, and the mortality rates of larvae, pupae and adults [23]; rainfall has an impact on the availability of breeding sites in the environment and on the mortality rates of aquatic stages by flushing the breeding habitats [18,24]. Full description of the model (ODE details, parameters and functions) is provided in [19].

In the ALBOMAURICE tool, the model inputs are (i) operational zones used by the vector control service (polygon geometry, shapefile format), characterized by their standard fixed and variable environment carrying capacities, two values that describe the availability and characteristics of the breeding sites in the zone (see [19] for details), (ii) the location of weather stations (point geometry, shapefile format), and (iii) the corresponding daily rainfall and temperature (text file, csv format). The size of the operational zones defines the spatial resolution of the model, and can be either small (a city block, a neighbourhood), or large (in the example of Fig. 1, they are 303 parcels with a minimum, median and maximum sizes of 9 ha, 363 ha, and 7788 ha, respectively).

As outputs, ALBOMAURICE predicts the abundances of *Ae. albopictus* mosquitoes per stage at a time frequency which can be defined by the user, and for each operational zone (shapefile or KML formats).

2.2. Software architecture

ALBOMAURICE is composed of two main software components (Fig. 2): (i) the model of *Ae. albopictus* population dynamics, which is written using the Ocelet modelling language [25] and (ii) the user interface which is written using the Java programming language. The compiled and executable software is entirely in Java though because Ocelet is a domain specific language that is translated into java sources automatically.

A series of input parameters is declared (in Ocelet) by the population dynamics model. The generated code after these declarations allow any Java program to instantiate the model, send parameters values, run a simulation and obtain some feedback from the running process. From the Ocelet Modelling Platform, the model is in fact exported as a java archive (jar) file to become a standalone java class that can be controlled by a user interface.

The user interface component is developed using the JavaFx library (https://openjfx.io). Most of the graphics layout of the interface is described in XML files (fxml format). And a series of Java classes contain the control code of the interface widgets. The user interface main class creates an instance of the jar-packed model. It collects settings from the user, turn these settings into the series of input parameters stored in a key–value table, and that table is sent to the model to run a simulation.

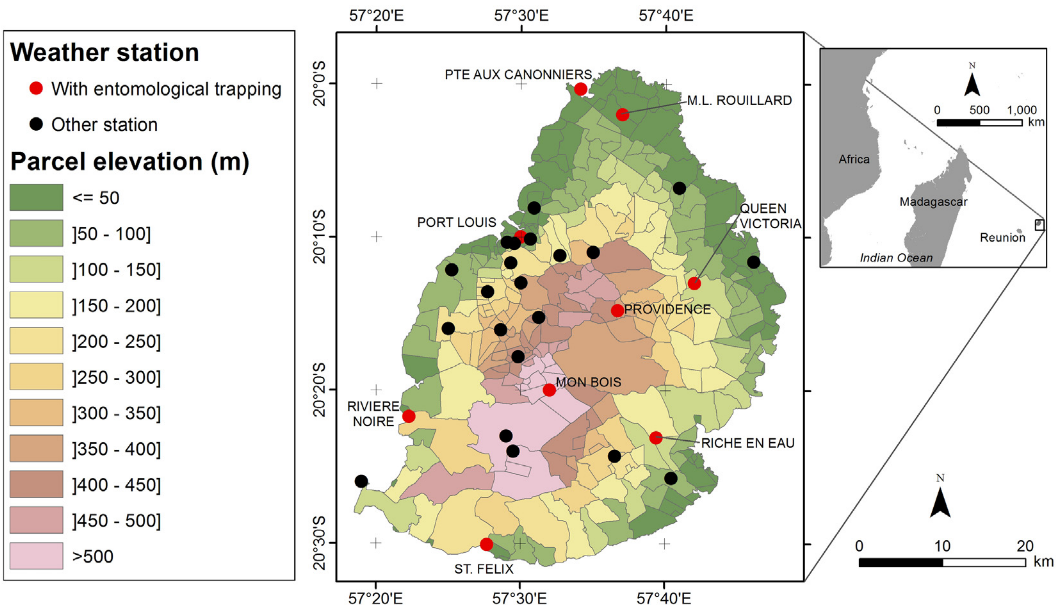

Fig. 1. Location of Mauritius, Indian Ocean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

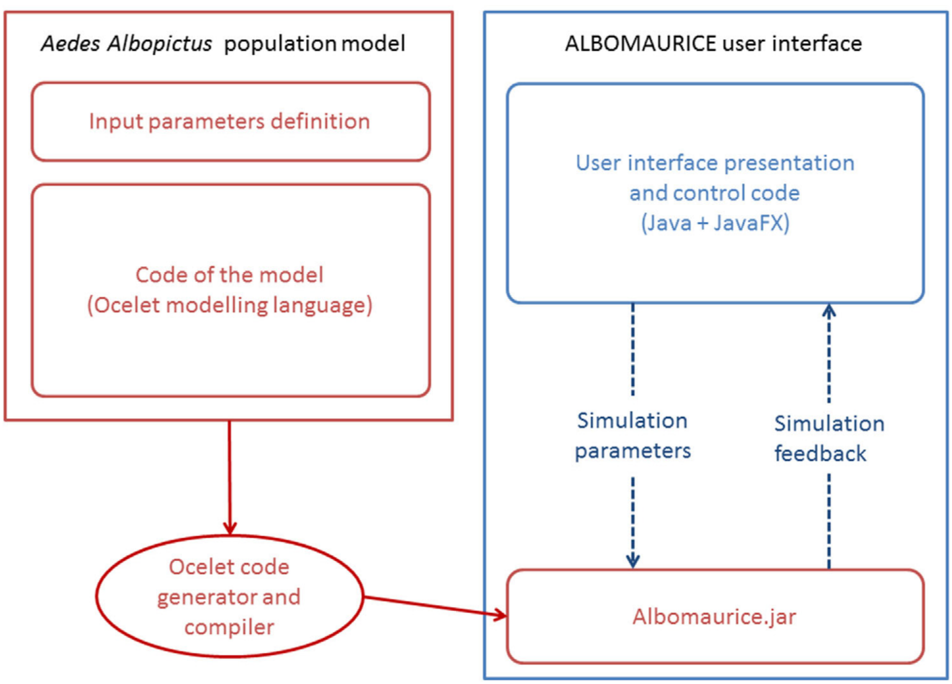

Fig. 2. Diagram of the software general architecture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Software functionalities

Using the ALBOMAURICE interface, the user can (i) define different settings regarding the simulation, inputs and outputs, and vector control options; (ii) run a simulation.

Simulation settings. On ALBOMAURICE main configuration menu (Fig. 3a), the user can define the start and end simulation dates, and if new weather data are used. The options "Save state file" and "Use previous state file" allow saving intermediate state values of a simulation and re-use them to run ulterior simulations faster.

Input settings. In the Input settings menu are defined the work directory, the weather data file, the parcels files and the weather stations file (Fig. 3b).

Output settings. The Output settings menu allows the user to choose the output directory and the output formats for the results of the simulation (Fig. 3c): shapefile or KML format, saving single date (the last date of the simulation), or multi-dates results. In this last case, the output frequency can be modified.

Vector control options. ALBOMAURICE allows simulating the population dynamics of *Ae. albopictus* mosquitoes under different

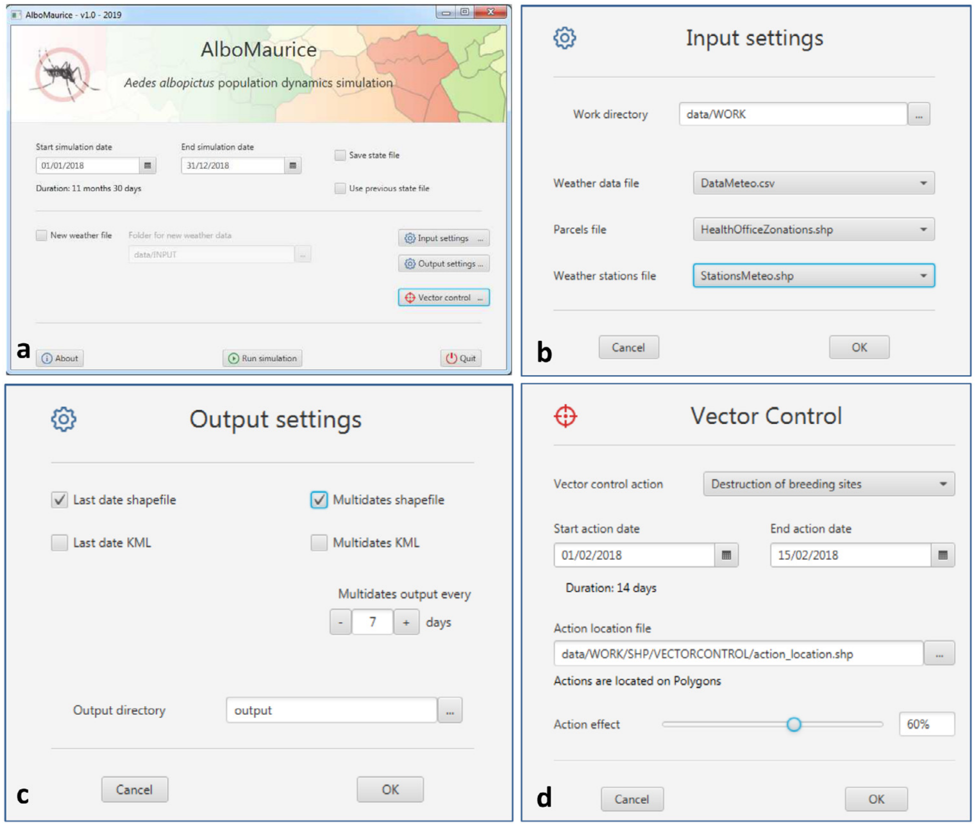

Fig. 3. ALBOMAURICE interface. (a) Main configuration menu; (b) Input settings menu; (c) Output settings menu; (d) Vector control menu. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scenarios of vector control: (i) no action, (ii) destruction of breeding sites, (iii) larviciding, and (iv) fumigation. The options of each scenario are defined in the Vector Control menu (Fig. 3d): type of action, start and end dates of the action, location where vector control takes place (as shapefile format), effect of the action (as percentage). Depending on the action, this percentage is applied to reduce the environment carrying capacities (destruction of breeding sites), to increase the larvae mortality (larviciding) or the mosquito adult mortality (fumigation). The options of each scenario have to be chosen by the user considering operational constraints (*e.g.* the percentage of households visited) and technical characteristics of the insecticides used and their impact on *Aedes* mosquito mortalities (*e.g.* from results of experimental studies such as [26]).

Running a simulation. Simulations are launched from the main page (Fig. 3a). A progress status bar and message window allow following the progress of the simulation. A text file summarizing all users' choices is created.

3. Illustrative examples

Three examples are briefly presented to illustrate some uses of ALBOMAURICE: (i) mapping *Ae. albopictus* densities in Mauritius; (ii) comparison of predicted *Ae. albopictus* abundances and field entomological data and (iii) assessing the impact of vector control actions on the temporal dynamics of *Ae. albopictus*. For these three examples we used weather data provided by the Mauritius Meteorological Services (MMS): the daily temperature (minimum and maximum) and rainfall records from January 2017 to February 2020 at 30 weather stations (Fig. 1).

3.1. Mapping *Ae. albopictus* densities

Mauritius is divided into 303 parcels corresponding to the Health Office zones where vector surveillance takes places (Fig. 1). Each parcel is characterized by its elevation and environment carrying capacities. In this illustrative example, the environment carrying capacities were roughly estimated for each parcel from its surface covered with urban areas extracted from a land cover map [27], assuming that *Ae. albopictus* breeding sites are mainly human-made containers located in urban areas, with a greater number of breeding sites in discontinuous urban areas (500 breeding sites per ha) than in continuous urban areas (300), and a mean number of 10 larvae per breeding site. For more realistic estimations of the environment carrying capacities, field observations are required [18].

During the simulation, at each time step, for each cell weather data are read from the closest weather station (Fig. 1), and mosquito population is estimated by solving the ODE system. As output, a shapefile of 303 polygons corresponding to the input Health Office zonation is created for the last date of the simulation chosen by the user. Its attribute table include the predicted number of *Ae. albopictus* eggs, larvae, pupae, total female adults and host-seeking female adults. This information can be used in a Geographic Information System (e.g. QGIS, Fig. 4). KML files can be also produced for visualization in Google Earth.

3.2. Validation of ALBOMAURICE outputs

In February 2019, a set of 6 larval traps were positioned within a radius of 100 m around nine national weather stations (Fig. 1). Traps consisted of an empty 1-litre black plastic container that could naturally be filled by rainfall. Over a span of one year, the traps were serviced on a weekly basis. This consisted in counting

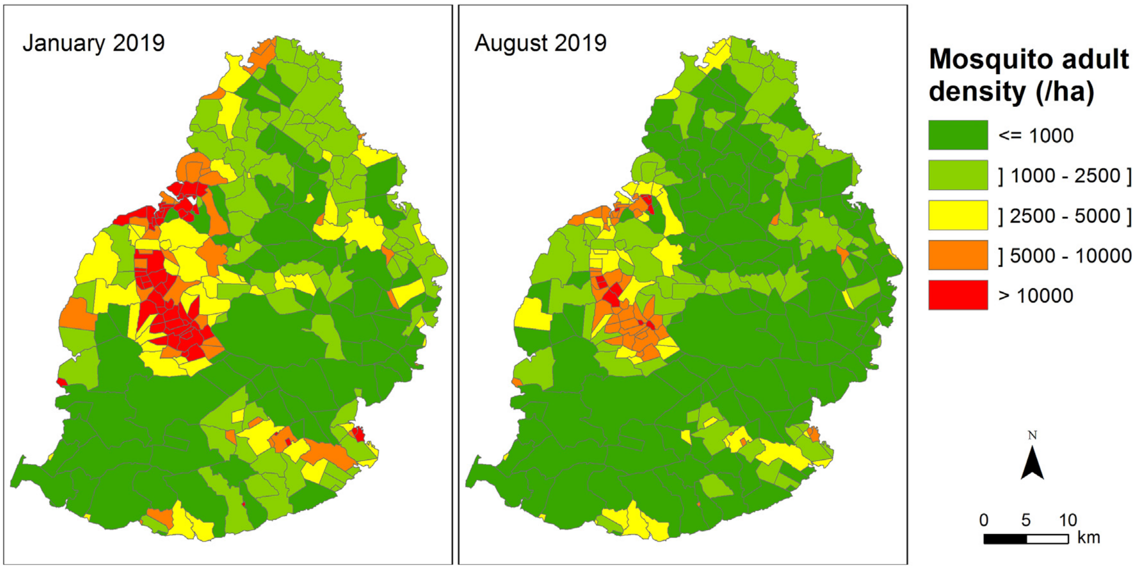

Fig. 4. Illustrative example: mapping *Ae. albopictus* densities in Mauritius at two different periods: January (austral summer, left panel) and August (austral winter, right panel). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and removing the number of larvae and pupae from each trap while maintaining the rainwater that had collected in the latter. ALBOMAURICE was run with as input parcels 100 m-buffer zones around the nine weather stations, from 1st February 2019 to 31 January 2020. As output, a multi-date shapefile with a daily frequency was generated. The number of trapped mosquitoes over time was compared to ALBOMAURICE's predictions for larvae using Spearman's correlation coefficient. The predictions were consistent with the observed *Ae. albopictus* larvae abundance in the nine collections sites, with significant correlation coefficients ranging from 0.3 (Riche en Eau) to 0.68 (Port Louis) (Fig. 5).

3.3. Simulation of vector control actions

ALBOMAURICE can be used to analyse different vector control actions. In this example, three simulations were run for the same period (1st January–30 June 2019) and the same area (Port Louis), but with different vector control options: (i) no action; (ii) destruction of breeding sites (start and end dates: 1st and 8th February); (iii) fumigation of adult mosquitoes (start and end dates: 1st and 2nd February). The output multi-date files, created with a daily frequency, were used to create graphs illustrating the expected impact of the different actions, and the time the mosquito population dynamics returns to the natural dynamics (without control) (Fig. 6).

4. Impact

4.1. Operational use

The main objective of our work was to develop a predictive mapping tool of *Ae. albopictus* mosquito populations that can be easily used by public health stakeholders for targeting their surveillance and control actions. Several models have been developed to predict mosquito population dynamics (e.g. [9,14–18]), but few of them lead to the development of operational tools [19,28]. ALBOMAURICE aimed at filling the needs of the Mauritian Ministry of Health and Wellness by adapting an existing mosquito population model to the geographic context of this tropical island. It was successfully transferred to agents of the Vector Biology and Control Division and other departments involved in mosquito surveillance and control activities. Of note, the users have to be familiar to Geographic Information Systems and mapping softwares to exploit and interpret the outputs of ALBOMAURICE. In the future, such tool could be also deployed in similar tropical environments such as Madagascar and the other islands in the Western Indian Ocean. In temperate areas, similar tool could be used, provided that the population dynamics model of *Ae. albopictus* is modified to take into account diapause processes during winter (e.g. [18]).

4.2. Future research

As ALBOMAURICE predicts *Ae. albopictus* densities from weather variables, it could be used for studying the impact of climatic conditions on mosquito population dynamics, either using the current conditions or the future projections of temperature and precipitations as predicted by the different scenarios of climate changes [29]. Such studies would help characterizing the vulnerability of tropical islands such as Mauritius to vector-borne diseases in the future. ALBOMAURICE could also contribute to study the impact of vector control strategies. Indeed, it can predict variations in mosquito abundance for a large range of typical control strategies (date of control, frequency, control efforts), that cannot all be tested in the field [14]. Finally, future developments of ALBOMAURICE could consist in coupling the mosquito population dynamics to epidemiological model of disease transmission. Such approach (e.g. [30,31]) would allow mapping the basic reproduction number (i.e. the expected number of people that would become infected from the introduction of a single infected host in a fully susceptible population) of the main diseases transmitted by *Aedes* mosquitoes, such as Dengue, Zika, or Chikungunya.

5. Conclusions

The ALBOMAURICE software contributes to address the pressing need for operational solutions to control the spread of mosquito-borne diseases, including Dengue Fever, into new areas where mosquitoes can thrive due to environmental changes. It encapsulates scientific knowledge of the *Ae. albopictus* mosquito lifecycle with vector control requirements in a given geographical environment (here Mauritius Island) to predict mosquito abundance in space and time. These predictions come in the form of

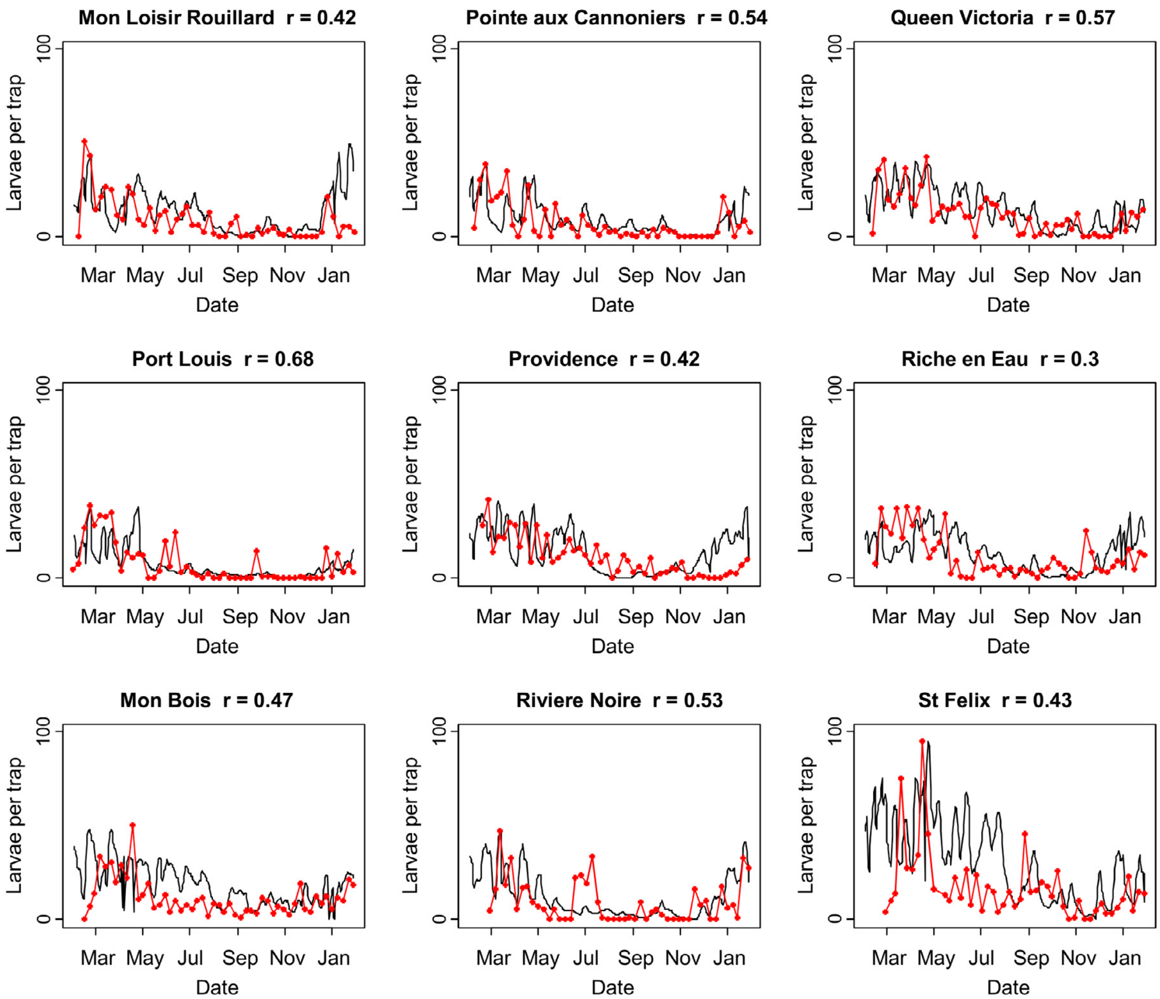

Fig. 5. Illustrative example: comparison of ALBOMAURICE outputs (in black) with entomological data collected in the field (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

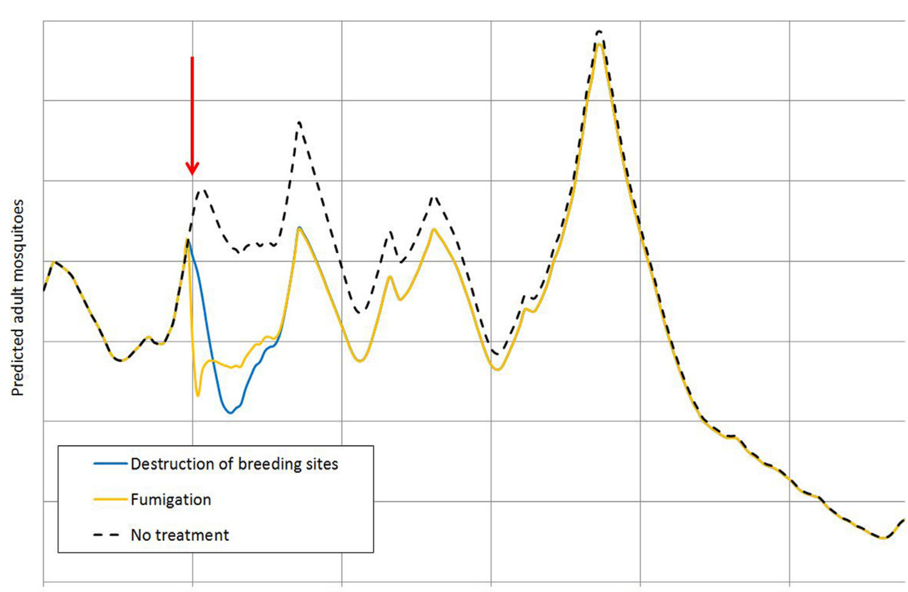

Fig. 6. Illustrative example: simulating impacts of vector control actions on the mosquito population dynamics (the red arrow indicates the starting date of vector control action). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maps and indicators that health services can use operationally for identifying priorities and optimizing field intervention efforts. An interesting feature of ALBOMAURICE software is that the impact of various control measures can be estimated beforehand. Scenarios of different control strategies can be simulated and compared prior to decision-making. ALBOMAURICE is open-source and can be adapted for use in other islands in the region or in anticipation of the vector adaptation to climate change. It can also be tailored for testing and assisting future control methods such as the promising Sterile Insect Technique (SIT).

Declaration of competing interest

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.

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