MODIS Environmental Data to Assess Chikungunya, Dengue, and Zika Diseases Through *Aedes (Stegomia) aegypti* Oviposition Activity Estimation

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***Abstract*—*Aedes aegypti* is the main vector for Chikungunya, Dengue, and Zika viruses in Latin America and it represents a main threat for our region. Taking into account this situation, several efforts have been done to use remote sensing to support public health decision making. Moderate resolution imaging spectroradiometer (MODIS) sensor provides moderate-resolution remote sensing products; therefore, we explore the application of MODIS products to vector-borne disease problems in Argentina. We develop temporal forecasting models of *Ae. aegypti* oviposition, and we include its validation and its application to the 2016 Dengue outbreak. Temporal series (10/2005 to 09/2007) from MODIS products of normalized difference vegetation index and diurnal land surface temperature were built. Two linear regression models were developed: model 1 which uses environmental variables with time lag and model 2 uses environmental variables without time lags. Model 2 was the best model (AIC = 112) with high correlation ($r = 0.88$, $p < 0.05$) between observed and predicted data. We can suggest that MODIS products could be a good tool for estimating both *Ae. aegypti* oviposition activity and risks for *Ae. aegypti*-borne diseases. That statement is also supported by model results for 2016 when a dengue outbreak that started unusually earlier this season. If such activity could be forecast by a model based on remote sensing data, then a potential outbreak could be predicted.**

***Index Terms*—Diseases, environmental factors, epidemiology, forecasting, image processing, image sensors.**

I. Introduction

The earth observing system (EOS) from the National Aeronautics and Space Administration (NASA) is funded by the NASA Earth Science Enterprise program. The moderate resolution imaging spectroradiometer (MODIS) is one of the remote sensing instruments onboard Terra, the first NASA EOS satellite [1]. MODIS provides substantial improvements in spatial resolution, number of spectral channels, choices of bandwidths, radiometric calibration, and an enhanced set of preprocessed and freely available products [2]. Having 36 spectral bands and 12-bit radiometric resolution in the visible, near, mid, and far infrared bands, MODIS has the highest number of spectral bands of any global-coverage moderate-resolution imager. MODIS products could be used for regional and global applications and are grouped in product suites in accordance with NASAs Science strategy: a vegetation product suite, a surface radiation product suite, and a land cover product suite [1]. Remote sensing environmental variables as the normalized difference vegetation index (NDVI) and land surface temperature (LST) have been relevant to epidemiology and public health studies because environmental conditions strongly affect both the distribution and abundance of vectors [3]–[6] and the transmission of viruses [7], [8]. Temperature, humidity, and precipitation have proven to significantly influence mosquito development, survival, and oviposition activity [9]–[11]. Therefore, environmental conditions could be characterized by remote sensing measurements, and using remote sensing environmental variables, vectors and diseases outbreak could be estimated and evaluated [12]–[14]. In particular, both NDVI and LST, which derivate from MODIS, have been used in several vector-borne disease studies as examples of epidemiological application of remote sensing data [15]–[19].

Aedes aegypti is the main vector for Chikungunya, Dengue, and Zika viruses in Latin America. *Aedes aegypti* is a day-biter and peridomestic mosquito that breeds preferably in household containers. Setting ovitraps serves as a method to provide useful data on spatial and temporal distributions of *Ae. aegypti* and other container-inhabiting mosquito species, allowing a better knowledge of the vector activity [20].

In the last ten years, progress has been made on the study of mosquitoes in Argentina, fostered by interdisciplinary work and by the aim to produce predictive risk models based on monitoring the environmental conditions, using both remote sensing and meteorological data that influence mosquitoes spatiotemporal distribution [12], [13], [16], [21], [22]. In previous studies, we have built statistical models to forecast larval indices (House and Breteau indices) using both, environmental data obtained from satellite images and meteorological variables at Oran city, Salta, Argentina [23], [24]. Mathematical models of *Ae. aegypti* oviposition activity allowed us to determine the most effective timing for vector control measures, considering its intrinsic rate of vector population growth [25]. A study of spatial patterns of high *Ae. aegypti* oviposition activity has also been developed for Oran, which enabled us to present a predictive map showing areas of maximum probability of *Ae. aegypti* oviposition activity

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(a) (b)

Fig. 1. Argentina and San Ramóm de la Nueva Orán City. (A) Location of the study area, San Ramón de la Nueva Orán in northwestern Argentina. (B) Location of the 90 sampling sites used in the study. Figure used from doi:10.1371/journal.pone.0054167.g001 Estallo *et al.* 2013.

and also high transmission risk areas [17]. It is important to consider that the unique method for controlling or preventing dengue virus transmission is to combat its vector [26], [27] and, in this context, forecasting models based on remote sensed data would allow prediction of increment and decrement in the *Ae. aegypti* oviposition activity and that could be used to assess disease's menace.

In this paper, we explore the application of MODIS products to assess Chikungunya, Dengue, and Zika, through *Ae. aegypti* oviposition activity estimations in San Ramón de la Nueva Oran City, northwestern Argentina. We have developed temporal forecasting models of *Ae. aegypti* oviposition, including its validation and its implementation applied to the 2016 Dengue outbreak in our country.

II. Materials and Methods

A. Study Site

The current study was done in San Ramón de la Nueva Oran City (see Fig. 1), hereafter Oran City, located in the northwestern area of Argentina (23°08′S, 64°20′W, and elevation 337 m) with a total population of 76 070 inhabitants [28]. Despite its dry season, Oran City has subtropical climate with 1000 mm annual accumulated rainfall and 78% mean annual humidity. It has a mean annual temperature of 21 °C, with hot summers of 45 °C maximum and 11.5 °C minimum. Winters are temperate, with one or two frosts in July, having 38 °C as maximum temperature and –3 °C as minimum temperature. The city is surrounded by native forest along with agriculture fields, mainly sugarcane, grains, citrus, horticulture, and tropical fruits [29].

B. Aedes aegypti Data Acquisition

Oviposition activity was monitored using 90 ovitraps placed at 90 random selected houses in the urban area of Oran City. *Aedes aegypti* population size was weekly estimated by the sum of egg-catches of the 90 sampled houses of the city. Sampling was done during two consecutive years (October 2005 to September 2007). Ovitraps were placed outside in a shaded site at ground level in the backyard of each house following the WHO guidelines [30]. Ovitraps consist on 350 mL plastic cups containing 250 mL of hay infusion. The hay infusion was prepared one week before and it provides an effective attractant to gravid *Ae. aegypti* female mosquitoes [30], [31]. Ovitraps were weekly replaced and eggs were counted on laboratory. From several ovitraps, eggs were randomly selected and kept moist for 2 to 3 days, then eggs were hatched to third or fourth instars and examined to corroborate that belonged to *Ae. aegypti*. No other species but *Ae. aegypti* was recorded. These ovitraps provided useful data regarding temporal variation of vector population density [31].

C. MODIS Remote Sensing Products for Model Development and Validation

Satellite-derived vegetation indices, LST, middle infrared radiation and land cover estimates were used to characterize suitable environmental conditions for mosquito development [32]. NDVI was used in this study because it provides an indirect proxy of humidity and precipitation [12], [33], [34]. Also, we used LST, because it gives an approximation of the environmental temperature [12], [33], [35]. The advanced MODIS specifications allows that these variables can now be obtained at finer spatial resolutions than before and, through the MODIS processing procedure, are available atmospherically corrected, georegistered, composited and at no cost to the user. The MODIS products are distributed, along with other NASA EOS products from the Distributed Active Archive Center, using a World Wide Web interface developed by ESDIS in a tiled hdf format.

Temporal series of environmental remote sensed MODIS NDVI products (MOD13Q1) and MODIS LST products (MOD11A2) were obtained from EOS Data Gateway from October 2005 to October 2007. The MOD13Q1 product is a 16-day composite having a 250 m pixel size built by choosing observations with minimal cloud cover, low solar zenith angle, and near-nadir views in that period, in which the NDVI dataset included 45 images. The MODIS 1 km diurnal LST product MOD11A2 is produced in eight-day maximum values composite of diurnal LST images. The LST dataset included 93 images. The scene corresponding to the h12v11 tile encompasses the study area. These scenes were reprojected from sinusoidal to Latitude/Longitude Geographic Projection System using "Modis Reprojection Tool" [36]. From each scene, two spatial subset containing the city study area (where ovitraps were placed) and the forest surrounding the city were generated, following the same procedure reported by Estallo *et al.* [33] using Landsat images. For NDVI scenes, ENVI software [37] was used to extract two areas of 15×19 pixels (pixel size $= 250$ m), one for the city and other one for the forest. For LST scenes, there were extracted equivalent and coregistered areas of 4×5 pixels (pixel size $= 1$ km). Then, statistics were performed in order to obtain the mean and standard deviation for each NDVI and LST subsets of the temporal series. Because NDVI is a 16-day product and LST is an eight-day product, we interpolated linearly to obtain a data series with a seven-day frequency (to match with the temporal step of the egg sampling dataset).

TABLE I
PEARSON CORRELATION BETWEEN *Ae. aegypti* EGGS NUMBER AND THE MODIS ENVIRONMENTAL VARIABLES WITH AND WITHOUT TIME LAGS DURING THE SAMPLING YEARS (2005–2007)

Variables	Correlation without time Lags ($p < 0.05$)	Best correlations time lags (L)	Correlation with time lags ($p < 0.05$)
Mean city LST	–	15 weeks (L_{15})	$r = 0.54$
Mean forest LST	0.26 ($p < 0.05$)	11 weeks (L_{11})	$r = 0.61$
Mean city NDVI	0.76 ($p < 0.05$)	1 week (L_1) and 21 weeks (L_{21})	$r = 0.71$ $r = –0.70$
Mean forest NDVI	0.61 ($p < 0.05$)	1 week (L_1) and 21 weeks (L_{21})	$r = 0.61$ $r = –0.68$

D. Using the Model for Present Data

To simulate the current situation with the developed model, we used present environmental data from MODIS products. We built two new temporal series from NDVI and LST (h12v11 tile). For NDVI data, 35 MOD13Q1 products from July 28th 2014 to January 17th, 2016 and, for LST data, 69 MOD11A2 products from August 5th 2014 to 25th January 2016 were downloaded, reprojected and the spatial subset was analyzed in the same way that previously for the 2004/2007 series.

E. Data Analysis

1) MODIS Model Developed: The selection of the statistical approach was supported by previous experience on modeling with environment remotely sensed derived variables [12], [33], [38], [39]. According to this, linear regression modeling was used to develop basically two models (with and without lag times over the independent environmental variables). For both models developed, data from the 90 ovitraps were used as a dependent variable. The first year dataset (October 2005–2006) was used to build the model, whereas the second year dataset (October 2006–2007) was used to validate the best selected model. Because *Ae. aegypti* development is mainly affected by weather conditions [40]–[42], we strove to add realism to the models by considering environmental variables with lag time. Model 1 used lag times for satellite environmental variable (1–24 weeks), whereas model 2 used the satellite environmental variables without lag time (i.e., lag = 0). To select the best lag time for each variable, simple linear correlation between the eggs number and each environmental variable (1–24 weeks) was performed. The variables with the lag time that maximize the aforementioned correlation were selected as variables to develop the model 1 (see Table I).

Due to the nature of the response variable, eggs number (N) was transformed to logarithm "ln($N1$)" to normalized residuals. Also, environmental variables were standardized and the developed models were compared using the Akaike Information Criteria (AIC) [42] to determine the optimal model in terms of both, fit goodness and number of parameters. The model with the smallest AIC was selected as being the best.

The second year dataset was used to validate the model, then Pearson correlations were done between the observed eggs number during that period (October 2006–2007) and the prediction given by the model developed. Modeling was performed using R3.1.0 software [44].

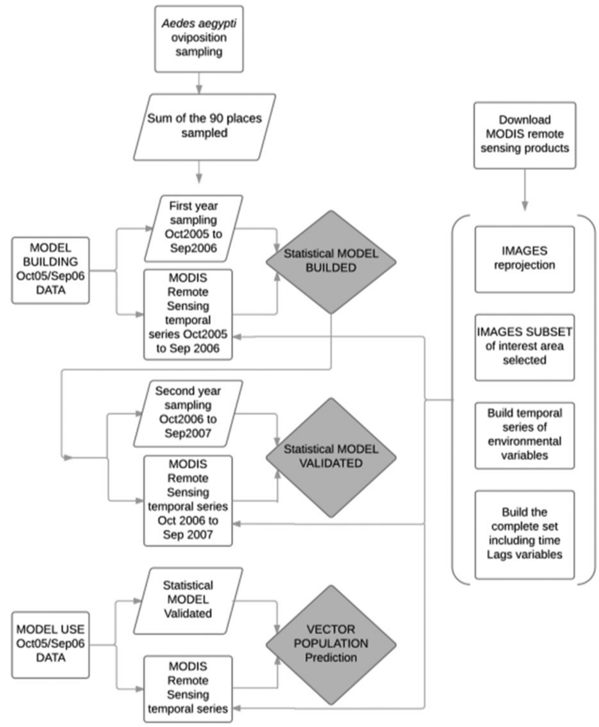

Fig. 2. Procedure for model building, validation and used through mosquitoes ovipotition sampling data and MODIS environmental variables.

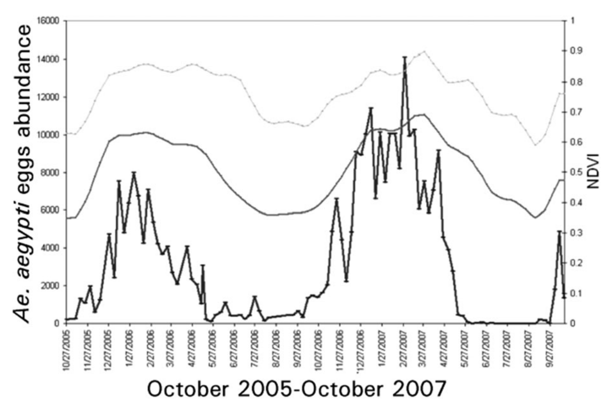

Fig. 3. NDVI and eggs collected patterns from October 2005 to October 2007 in the study area, San Ramón de la Nueva Orán in northwestern Argentina.

Taking into account the dengue outbreak in progress in Argentina at the time of writing this paper, we ran the model feed with current environmental MODIS data products (2015–2016) using the previously described methodology (see Fig. 2).

III. RESULTS

During the two year sampling period 321 141 eggs were collected using ovitraps, 109 253 during the first year and 211 888 during the second year. In Fig. 3, the NDVI showed a similar pattern for the city and its surrounding forest, and it showed coincident increments of both, NDVI and eggs collected patterns. Abundance peaks were detected during January, February and March, and then they decreased gradually because of minimum temperatures during winter months [11]. We found a high correlation between the mean NDVI from the city and the number

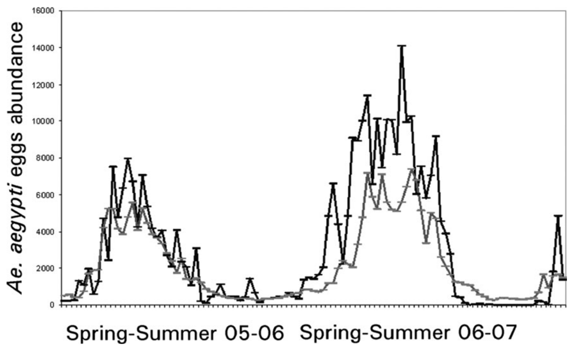

Fig. 4. Observed number of *Ae. aegypti* eggs (black line) and forecasted number using developed model 2.

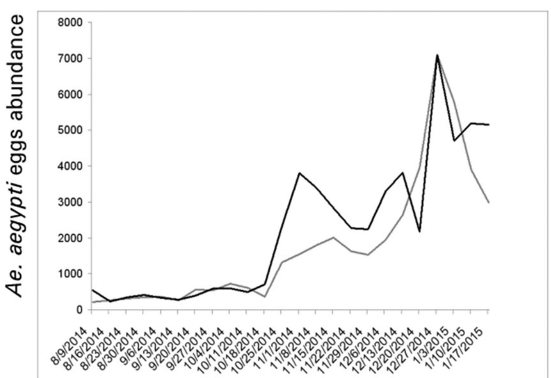

Fig. 5. *Aedes aegypti* fluctuation estimated through the simulation of model 2 with present MODIS environmental data for the season 2014–2015 (gray line) and 2015–2016 season (black line).

of collected eggs (see Table I) while for LST, there is a lag regarding NDVI (see Fig. 3).

Both developed models have a good fitness with observed field data. Model 1 includes lagged variables with adjusted $R^2 = 0.62$ ($F = 28.15;\ p < 0.05$) and model 2 without lag time (or lag $= 0$) with adjusted $R^2 = 0.69$ ($F = 37.26;\ p < 0.05$). According to AIC, model 2 (AIC $=$ 111.93) was the best one (model 1, AIC $=$ 121.63). Validating model 2, the correlation between observed data and predicted data was 0.88 ($p < 0.05$) (see Fig. 4).

Model 1 (with lag time):

$$\begin{aligned}\ln(H) = {}& 6.83 + 0.56\ \ mNDVI_{\text{city}}(L_{21}) - 1.04 \\ & mNDVI_{\text{forest}}(L_{21}) + 0.39\ \ mLST_{\text{forest}}(L_{11}) \quad (1)\end{aligned}$$

where L_{XX} means that the variable must be evaluated with a lag time of *XX* weeks.

Model 2 (without lag time):

$$\begin{aligned}\ln(H) = {}& 7.17 + 0.94\ \ mNDVI_{\text{city}} - 0.66\ \ mLST_{\text{city}} \\ & + 1.04\ \ mLST_{\text{forest}}. \qquad (2)\end{aligned}$$

Finally, we run the model with present (2014–2016) environmental data, to simulate the eggs fluctuation, therefore the oviposition activity of the mosquito vector *Ae. aegypti*. The results of that simulation are shown in Fig. 5. It is observed that for the present 2015–2016 season, *Ae. aegypti* activity started two months before it started for the previous 2014–2015 season. Also, it could be seen for the present year. These features are in agreement with the real outbreak evolution where Dengue cases notification started early this year.

IV. Discussion and Conclusion

We used MODIS products to test the effectiveness of forecasting *Ae. aegypti* oviposition activity in San Ramón de la Nueva Oran City, northwestern Argentina. Then, two oviposition forecasting models were developed and it was found that model 2 (without lag time) was the better model. According with Tatem *et al.* [2], MODIS sensors represent important advances in remote sensing providing exceptional data for public health and epidemiology studies. MODIS sensors are considered adequate because of the temporal, spatial, and spectral resolutions [2], [45]. Both models developed in this paper showed that MODIS environmental variables (NDVI and LST) are good predictors because both environmental variables are present in the two models providing acceptable fitting and validation results. Recently, consist with our results, other studies have used MODIS products where LST is one of the most important variables to determine distribution patterns and major abundance of *An. pseudopunctipennis* and *An. argyritarsis* within malarious areas of northwestern Argentina [16]. The models developed in this study showed similar goodness of fit and number of parameters as others models developed for forecasting mosquitoes larval indices based on images with a higher spatial resolution as Landsat images [33]. In contrast, here we propose to estimate the vector activity via the oviposition activity, this based on the fact that both oviposition and disease transmission are carried out by female mosquitoes [46]. According to our results and as shown in Fig. 3, NDVI increases at the same time that eggs number increases during the sampling years, showing both the same kind of fluctuation. From this, we can understand that NDVI increment could be due to precipitation in the near past followed by an increment in the vector activity which is verified by the oviposition activity increments. Estallo *et al.* [33] developed predictive models to forecast larval indices in Oran City where they found that variations in larval indices were corresponding to precipitation four weeks before (time lag four months).

The use of MODIS products for modeling is a good tool that could be useful on estimating *Ae. aegypti* oviposition activity and therefore the meaning of mosquitoes as a menace for diseases like Chikungunya, Dengue, and Zika helping this with vector management. The main advantage of a model based on MODIS product, in contrast with models based on higher resolution images as Landsat [33], is the possibility to envisage an operational forecast program at national level [47]. In fact, we need more than 200 Landsat scenes to cover the whole Argentinean territory; in addition, they must be calibrated and atmospherically corrected in order to obtain a temporal series with frequency lower than 16 days taking into account the cloud clover. Clearly, that scheme would not produce an operational framework. This was suggested from the simulation model with updated data where it could be seen that an early oviposition increment was predicted by the model. Nowadays, in Argentina, we are suffering a Dengue outbreak that started earlier this year, in total agreement with the oviposition estimates of our model fitted with MODIS environmental data. If the vector fluctuation starts earlier and that could be predicted by a model, then a potential outbreak could be predicted before it happen. Indirectly, if there is a high vector activity and virus circulation, a high number of cases could be expected.

A large number of MODIS products are available for free download and they could be useful for model applications as decision-support tools to help public health authorities manage *Ae. aegypti* derived risk. In this sense, we aim next to simulate oviposition for other localities of the north area of Argentina such as Tartagal and Salvador Mazza cities.

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