Satellite-derived NDVI, LST, and climatic factors driving the distribution and abundance of *Anopheles* mosquitoes in a former malarious area in northwest Argentina

María Julia Dantur Juri[1,2]✉, Elizabet Estallo[3], Walter Almirón[3], Mirta Santana[4], Paolo Sartor[3], Mario Lamfri[5], and Mario Zaidenberg[6]

[1]*Instituto Superior de Entomología "Dr. Abraham Willink", Facultad de Ciencias Naturales e Instituto Miguel Lillo, Universidad Nacional de Tucumán, Miguel Lillo 205, CP 4000 Tucumán, Argentina, juliadantur@yahoo.com.ar*
[2]*IAMRA, Universidad Nacional de Chilecito, 9 de Julio 22, CP 5360 Chilecito, La Rioja, Argentina*
[3]*Instituto de Investigaciones Biológicas y Tecnológicas (IIBYT)-CONICET and Universidad Nacional de Córdoba. Centro de Investigaciones Entomológicas de Córdoba (CIEC), Facultad de Ciencias Exactas, Físicas y Naturales. Universidad Nacional de Córdoba, Av. Vélez Sarsfield 1611, CP 5016, Córdoba, Argentina*
[4]*Cátedra de Bioestadística, Facultad de Medicina, Universidad Nacional de Tucumán, Lamadrid 875, CP 4000 Tucumán, Argentina*
[5]*Instituto de Altos Estudios Espaciales Mario Gulich, Centro Espacial Teófilo Tabanera, CP 5187 Córdoba, Argentina*
[6]*Coordinación Nacional de Control de Vectores, Ministerio de Salud de la Nación, Güemes 125, CP 4400 Salta, Argentina*

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ABSTRACT: Distribution and abundance of disease vectors are directly related to climatic conditions and environmental changes. Remote sensing data have been used for monitoring environmental conditions influencing spatial patterns of vector-borne diseases. The aim of this study was to analyze the effect of the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS), and climatic factors (temperature, humidity, wind velocity, and accumulated rainfall) on the distribution and abundance of *Anopheles* species in northwestern Argentina using Poisson regression analyses. Samples were collected from December, 2001 to December, 2005 at three localities, Aguas Blancas, El Oculto and San Ramón de la Nueva Orán. We collected 11,206 adult *Anopheles* species, with the major abundance observed at El Oculto (59.11%), followed by Aguas Blancas (22.10%) and San Ramón de la Nueva Orán (18.79%). *Anopheles pseudopunctipennis* was the most abundant species at El Oculto, *Anopheles argyritarsis* predominated in Aguas Blancas, and *Anopheles strodei* in San Ramón de la Nueva Orán. Samples were collected throughout the sampling period, with the highest peaks during the spring seasons. LST and mean temperature appear to be the most important variables determining the distribution patterns and major abundance of *An. pseudopunctipennis* and *An. argyritarsis* within malarious areas. ***Journal of Vector Ecology* 40 (1): 36-45. 2014.**

Keyword Index: Normalized difference vegetation index, land surface temperature, climatic factors, *Anopheles pseudopunctipennis*, malaria.

INTRODUCTION

Malaria control programs have attempted to reduce the incidence and prevalence of infection and disease by focusing on the vectors to reduce their longevity, density, human contact, and the intensity of local malaria transmission at a community level. Changes in environmental conditions are strongly linked to the distribution, transmission, intensity, and seasonality of malaria cases (Craig et al. 1999, Lourenço et al. 2011). Land use changes (Lindblade et al. 2000, Patz et al. 2004, Munga et al. 2009), including deforestation, agriculture, logging and firewood collection, road construction, mining, and urbanization critically alter features of the environment, including the microclimate, water levels, and soil and vegetation coverage, which can affect the ecology of mosquitoes (Yasuoka and Levins 2007).

Several studies have used Geographical Information System (GIS) and satellite images to investigate environmental changes in relation to malaria epidemiology in countries around the world, including those in South America. Delgado et al. (2004) found that the occurrence of malaria foci can result from environmental modifications by the appearance of new bodies of water or by the generation of new infrastructures for tourism. Solano and Zambrano (2008) reported correlations between environmental and ecological variables obtained from satellite images (temperature and NDVI) and the number of malaria cases in Loreto (Peru) that explain the existence of malaria cases.

In relation to the mosquito vectors, Beck et al. (1994) reported that swamps and natural pastures were land cover types that had significant effects on *Anopheles albimanus* abundance in Chiapas (México). Roberts et al. (1996) used similar images to identify different types of land cover and to predict the spatial distribution of *An. pseudopunctipennis* in Belize. The authors drew up risk maps and showed that *An. pseudopunctipennis* was present in 50% of the localities, with associated high probabilities of malaria transmission. In Argentina, Curto et al. (2003) observed that the geographical distributions of *An. pseudopunctipennis* and the malaria occurrence were reduced in the northwest of the country, suggesting that changes in the environment were an underlying factor leading to this distribution.

It is known that factors such as accumulated rainfall, temperature, and humidity determine malaria transmission because they affect the development and survival of both the mosquitoes and the parasites that they harbor (Rodríguez et al. 2008).

Patz et al. (2000), López Vélez and Molina Moreno (2005), and Sáez Sáez et al. (2007), reported that a rise in temperature produced faster eclosion, thus shortening the larval period and increasing the anopheline population. In addition, as temperatures increase, the gonotrophic cycle of female mosquitoes becomes shorter, which increases the frequency of blood intake and, therefore, bite rate (Patz et al. 2000, Sáez Sáez et al. 2007). A rise in accumulated rainfall was shown to result in an increase in the number and quality of breeding sites, and the increased density of vegetation was also shown to provide suitable habitat for the immature mosquitoes (López Vélez and Molina Moreno 2005). However, above a certain rainfall level, suitable anopheline breeding sites can be exposed to flooding, so the population is likely to decrease in such cases (Dantur Juri et al. 2003).

Relative humidity also has an important role in generating conditions that are favorable to adult mosquitoes (Rodríguez et al. 2008). Dantur Juri et al. (2005, 2010a,b) showed that in the southern area of subtropical mountainous rainforests in northwestern Argentina, the relative humidity during autumn is the major determinant of the abundance of *An. argyritarsis, Anopheles strodei, An. pseudopunctipennis,* and *Anopheles evansae*. Since Argentina is included in the malaria pre-elimination phase, it is important to interrupt local mosquito-borne malaria transmission and to eliminate the incidence of malaria. Therefore, the aim of this study was to determine the influences of NDVI, LST, and climatic variables on the distribution and abundance of *Anopheles* malaria mosquitoes in the scope of malaria transmission research. Hopefully, in subsequent studies, these findings will contribute to the development of models capable of predicting future malaria scenarios in the malarious area of northwestern Argentina.

MATERIALS AND METHODS

Study area

The study area was situated in the northern subtropical mountainous rainforest called Yungas, which stretches to the border with Bolivia in Salta Province of northwestern Argentina. The present study was performed in the Piedmont rainforest altitudinal floor of the Yungas habitat, where the typical vegetation is known as the rainforest of 'palo blanco' (*Calycophyllum multiflorum* Griseb. (Castelo)) and 'palo amarillo' (*Phyllostylon rhamnoides* (Poiss.) Taubert). The soil characteristics and the gentle slopes of this area make it suitable for agriculture and have resulted in the transformation of large areas for extensive cultivation. Farming of sugar cane, bananas, citrus (grapefruit, orange, lemon, and tangerine), horticulture (tomato, corn, squashes, and aubergine), tropical fruits (banana, avocado, and mango), tobacco, and soybeans, was alternated with subtropical mountainous rainforest trees. However, in past decades, the natural vegetation was increasingly cleared to make way for additional cultivated land (Brown 1995, Prado 1995).

Monitoring of adult mosquito populations was carried out at three localities situated at the piedmont rainforest, Aguas Blancas (22°43'8" S; 64°22'26" W; 405 m), El Oculto (23°06'57" S; 64°30'4" W; 508 m), and San Ramón de la Nueva Orán (23°08'49" S; 64°20'06" W; 362 m) (Figure 1).

Different land uses were observed at each sampling site. Aguas

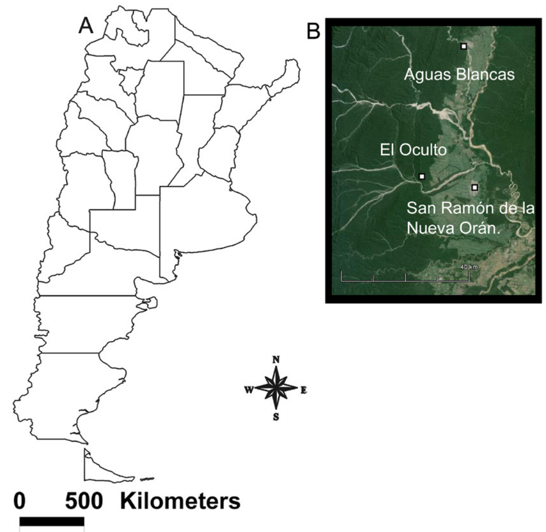

Figure 1. Geographical location of the study area in Salta Province, northwestern Argentina.

Blancas exhibited little patches of domestic agriculture, principally of corn and bananas, within the large area of the subtropical rainforest. The mountainous rainforest dominates El Oculto, although small plots of corn, sweet potatoes, cassava, avocados, mangos, and bananas are also present. At San Ramón de la Nueva Orán and its surroundings, the agricultural land increased during the past years, and the area of the native rainforest decreased. A growth in urbanization was also observed, with land formerly belonging to patches of the Piedmont rainforest, different cultivations of sugarcane plots, and citrus plants.

The area has a subtropical climate with a dry season (June–November) with an average monthly precipitation of <50 mm (Brown et al. 2001). The total rainfall is significantly affected by the surrounding topography. The mean precipitation interval is 700–1000 mm annually. Temperature varies both throughout the year and during the day, and it is possible to differentiate three seasons: one warm and dry, which corresponds to spring (September–December), one warm and rainy, which corresponds to summer (January–April), and one that is cold and humid, which corresponds to autumn and winter (May–August) (Brown 1995).

Specimen collection

Anopheles mosquitoes were collected in Aguas Blancas, El Oculto, and San Ramón de la Nueva Orán. Two consecutive days per month, from December, 2001 to November, 2005, four CDC light traps supplemented with carbon dioxide were run for 8 h (16:00–24:00) from early dusk until midnight) at each site. Sample collections could not be performed much later than midnight because of technical difficulties that affected field work (i.e., robbery) (Dantur Juri et al. 2010a).

Mosquitoes were sacrificed with dry ice and transported to the laboratory for identification using keys by Faran (1980) and Wilkerson and Strickman (1990). Voucher specimens were deposited in the Instituto-Fundación Miguel Lillo Collection, Argentina (IMLA).

Environmental data sets

Land Surface Temperature (LST) is an important climate variable, related to surface energy balance and the integrated thermal state of the atmosphere within the planetary boundary layer. It is widely used in a variety of fields, including evapotranspiration, climate change, hydrological cycle, vegetation monitoring, urban climate, and environmental studies (Hansen et al. 2010, Li et al. 2013). The NDVI, as a measure of the photosynthetic activity of plants, was used as a proxy for suitable conditions of mosquito development, as it refers to spatial and temporal dynamics of different vegetation types that are present naturally around the areas where immature stages of the vector are found (Lourenço et al. 2011).

To develop a model for estimating the effects of environmental variables on the abundance of *Anopheles* mosquitoes, LST and NDVI MODIS products from EOS data Gateway (National Aeronautics and Space Administration) were obtained. For the study sites of Aguas Blancas, El Oculto, and San Ramón de la Nueva Orán, 47, 48, and 35 data sets, respectively, of NDVI product with a 250-m spatial resolution (MOD13Q1), and the same quantity of LST diurnal product data sets with a 1-km spatial resolution (MOD11A2) were obtained from December, 2001 to December, 2005. MODIS products were provided in 'gridded data' format, which has a sinusoidal projection (SIN, Level V004); therefore, they required pre-processing before they could be used. To change the SIN to a geographical projection (latitude/longitude), a MODIS Reprojection Tool (National Aeronautics and Space Administration) was used. Once the reprojection was obtained, it was possible to produce subsets of NDVI and LST data that related to the study areas. Around each one of the three study localities in the northern area of the rainforest (Aguas Blancas, El Oculto, and San Ramón de la Nueva Orán), 13 X 13 pixels for the NDVI product data set, and 3 X 3 pixels for LST product data set, were used to extract the corresponding values and then the mean and standard deviations of NDVI and LST were calculated. NDVI product data recorded every 16 days were linearly interpolated to obtain a data series with an eight-day frequency (to match that of the LST data sets). The subsets and the posterior extraction of environmental data were performed using ENVI 4.2 software (Research Systems Inc., Boulder Co., U.S.A.), which processes satellite images. This work was performed at the Instituto de Altos Estudios Espaciales Mario Gulich, Comisión Nacional de Actividades Espaciales (CONAE). Two weather stations, Aguas Blancas (22°43′ S, 64°22′ W) and San Ramón de la Nueva Orán (23°07′ S, 64°19′ W), were used to record maximum and minimum mean temperature, maximum and minimum mean humidity and accumulated rainfall. These data were collected between 2001 and 2005.

Statistical analyses

Fluctuations in relation to NDVI, LST, and climate variables for anopheline mosquitoes have been analyzed using multilevel Poisson regression (Dantur Juri et al. 2010a); that is, these data have been analyzed using a hierarchical model for count data (HLM6) that uses the restricted penalized quasi likelihood (PQL) method of estimation. This analysis is used for longitudinal studies in which the outcome variable is measured several times for the same individual. Consequently, observations are not independent (Twisk 2004). In this study, NDVI, LST, and climatic data were used to model the effects of these variables on anopheline abundance over the four-year sampling period.

Two levels were considered: level-1, where the unit was the month, and level-2, where the unit was the year. The level-1 predictor was centered on the annual mean, with the following level-1 linear structural model:

$$\mathrm{Log}\,(\mu_{ij}) = B_0 + B_1{*}(X_{ij1} - \overline{X}_{ij1}) + B_2{*}(X_{ij2} - \overline{X}_{ij2}) + \ldots = B_0 + \sum_{q=1}^{Q} B_q\,(X_{ijq} - \overline{X}_{ijq})$$

where μ_{ij} is the event rate per time period, X_{ijq} is a level-1 predictor (LST, NDVI, and climate variables), B_0 is the intercept, B_q is the level-1 slope for the independent predictor variable X_{ijq}, and Q is the number of level-1 predictor variables.

The level-2 model takes the following form:

$$B_0 = \alpha + u_0$$
$$B_q = \beta_q + u_q \text{ with } q = 1,\ldots,Q$$

where α and β_q are fixed effects and u_0 and u_q are random effects, which indicate the variability of the coefficients B_q across level-2.

In this case, the best-fit model, which uses the reliability estimate, was achieved using only the random intercept. Thus, the model corresponding to level-2 was:

$$B_0 = \alpha + u_0$$
$$B_q = \beta_q \text{ with } q = 1, \ldots Q$$

Regardless of the values of the climatic variables, the first level-2 equation indicates that the mosquito incidence rate changes according to the year. The second level-2 equation indicates that the relationship between mosquito incidence rate and climatic variables does not change based on the year.

The Incidence Rate Ratio (*IRR*) of each variable on the mosquito number was calculated. This index made possible the direct observation of the percentage of influence of each variable on the mosquito abundance. The standard error, *P*-values (significant at <0.001), and confidence intervals were also calculated.

No specific permits were required for the described field study, and no specific permissions were required for the selected locations and activities. The locations in which the research was performed are not privately owned or protected in any way. We confirm that the field study did not involve endangered or protected species.

RESULTS

A total of 11,206 *Anopheles* females was collected, 4,912 of which were *Anopheles pseudopunctipennis*, 1,982 were *Anopheles argyritarsis*, and 1,832 were *Anopheles strodei*. *Anopheles evansae*, *Anopheles rondoni*, *Anopheles nuneztovari*, *Anopheles rangeli,* and *Anopheles triannulatus* were also sampled. Considering each locality separately, the abundance of *Anopheles* species collected at El Oculto was higher than that at Aguas Blancas and San Ramón de la Nueva Orán. At El Oculto, *An. pseudopunctipennis* was more abundant (4,236 specimens), followed by *An. argyritarsis* (n=763), *An. strodei* (n= 763), and *An. evansae* (n=112). At Aguas Blancas, *An. argyritarsis* was the more abundant (1,071 specimens), followed by *An. pseudopunctipennis* (n=572), and *An. strodei* (n=185). At San Ramón de la Nueva Orán, the abundance of *Anopheles* species exhibited a different pattern, with *An. strodei* as the most abundant species (884 specimens), followed by *An. evansae* (n=277), *An. rondoni* (n=254), *An. nuneztovari* (n=177), *An. argyritarsis* (n=148), and *An. pseudopunctipennis* (n=104).

At all three study localities, the relative abundance of *Anopheles pseudopunctipennis,* the main malaria vector in Argentina, was significantly higher during the spring than during either summer or autumn. However, considering each locality, the abundances could vary a little. In Aguas Blancas, this species was markedly most abundant during the spring (Figure 2). A different pattern of abundance was observed at El Oculto, where three decreasing abundance peaks were found: one in the spring, one in the summer, and one in autumn (Figure 3).

A second malaria vector in Argentina, *An. argyritarsis*, was found to be most abundant during the spring at Aguas Blancas (Figure 2). At El Oculto, the species was less abundant but has also showed peaks during spring seasons (Figure 3). The abundance of *An. strodei* fluctuated considerably at all study sites, although it was most abundant during autumn at Aguas Blancas (Figure 2) and at El Oculto during the spring, without disappearing in the winter (Figure 3).

Anopheles strodei was most abundant at San Ramón de la Nueva Orán, showing seasonal fluctuations. The species varied gradually across the entire collection period, but it showed peaks of abundance during spring and autumn (Figure 4). At the same locality, *An. evansae* showed decreasing abundances in the autumn, winter, spring, and summer (Figure 4). *Anopheles rondoni* was the third species more abundant at San Ramón de la Nueva Orán, showing a seasonal pattern with peaks of abundances during summer, followed by autumn and spring (Figure 4).

Values of NDVI and LST were calculated from the MODIS satellite images and overlaid onto the georeferenced field-based data of the three study localities. The database generated for each locality showed the mean, minimum, maximum, and standard deviation values for both NDVI and LST, which were added to a data set containing the number of *Anopheles* mosquitoes collected. LST was a significant predictor of the abundance of *Anophele*s species at all three localities, and NDVI was a significant predictor of mosquito abundance at Aguas Blancas and El Oculto. An analysis of individual study localities revealed that the increase of LST at Aguas Blancas affected *An. argyritarsis* and *An. pseudopunctipennis* by increasing their abundances by 15% and 26%, respectively (Table 1). At El Oculto, an increase of NDVI was related to the abundance of *Anopheles rangeli*, resulting in an increase of >100%. LST was the environmental variable that affected most of the *Anopheles* species at this site, increasing the abundance of *An. pseudopunctipennis*, *An. argyritarsis,* and *An. strodei* by 15%, 21%, and 10%, respectively (Table 2). At San Ramón de la Nueva Orán, the increase in LST affected *An. pseudopunctipennis*, increasing the abundance by 32% (*IRR*=1.325; *SE*=0.066; *CI* 95%=1.158-1.516; *P*-value=0.000) (Figure 7).

Influence of climatic variables

Of the eight climatic variables examined in the analysis, four were found to be significant predictors of the abundance of adult *Anopheles* mosquitoes at Aguas Blancas, three at El Oculto, and none at San Ramón de la Nueva Orán. The mean temperature and mean humidity values were positively related to the abundance of *Anopheles* species at Aguas Blancas, whereas accumulated rainfall was negatively associated with abundance. Wind velocity had little influence on abundance. At Aguas Blancas, the abundance of *An. pseudopunctipennis* and *An. argyritarsis* was positively associated with the mean temperature, showing an increase in abundance of 28% and 22%, respectively, for each degree increase in temperature. The abundance of *Anopheles nuneztovari* was similarly influenced by mean humidity, with an 8% increase in abundance for every 1% increase in mean humidity (Table 1). *Anopheles strodei* was negatively influenced by accumulated rainfall, with a decrease of 1% for each mm increase in rainfall. Wind velocity showed minimal influence on the abundance of this species (Table 1).

At El Oculto, minimum mean temperature was positively associated with the abundance of *An. pseudopunctipennis*, *An. argyritarsis,* and *An. rangeli*, increasing in abundance for each degree increase in minimum mean temperature by 1%, 16%, and 25%, respectively (Table 2). The minimum mean humidity was also positively associated with *An. rangeli,* with the abundance of this species increasing by 11% for every 1% of increase in humidity, but this variable was negatively associated with *An. pseudopunctipennis*, *An. argyritarsis,* and *An. strodei*, which decreased their abundances by 1% (Table 2). Accumulated rainfall was negatively associated with *An. evansae*, which showed a decrease in abundance by 1% for every 1 mm increase in rainfall (*IRR*=0.982; *SE*=0.005; *CI* 95%=0.972-0.993; *P*-value=0.002). There were no significant climatic variables affecting the abundances of *Anopheles* species at San Ramón de la Nueva Orán.

DISCUSSION

Remote sensing data have been used to describe and predict geographical and temporal patterns in vector-borne disease transmission and disease prevalence (Beck et al. 2000, Dambach et al. 2012). Studies detecting larval habitats or the mapping of vector densities as well as studies linking climate and environmental parameters directly to malaria prevalence were made by using remote sensing techniques (Dambach et al. 2012). Satellite images from Landsat, SPOT, and IKONOS have been used to characterize and predict anopheline larval habitats (Rejmankova et al. 1995, Roberts et al. 1996, Pope et al. 2005, Mushinzimana et al. 2006, Diuk Wasser et al. 2007, Munga et al. 2009). This paper addresses the spatial abundance and the temporal patterns of anopheline through the use of remote sensing data. In particular, emphasis has been made on the fact that MODIS NDVI and LST and climate data can obtain information about the influences of environmental variables that could affect the distribution and abundance of *Anopheles* species at the different sampling sites in northwestern Argentina. The Argentinean malarious area has increased land use over time, from a heterogeneous landscape with patches of natural rainforest interspersed with agricultural land including different types of crops. This has resulted in changes of the values of intra- and inter-annual NDVI, LST, and climatic variables that exert their influences directly on the distribution and abundance of *Anopheles* species at each locality, constituting a robust data series to be analyzed.

In the present study, *An. pseudopunctipennis* was the most abundant species principally at El Oculto, with a marked seasonality in the spring. Their major abundance could be related

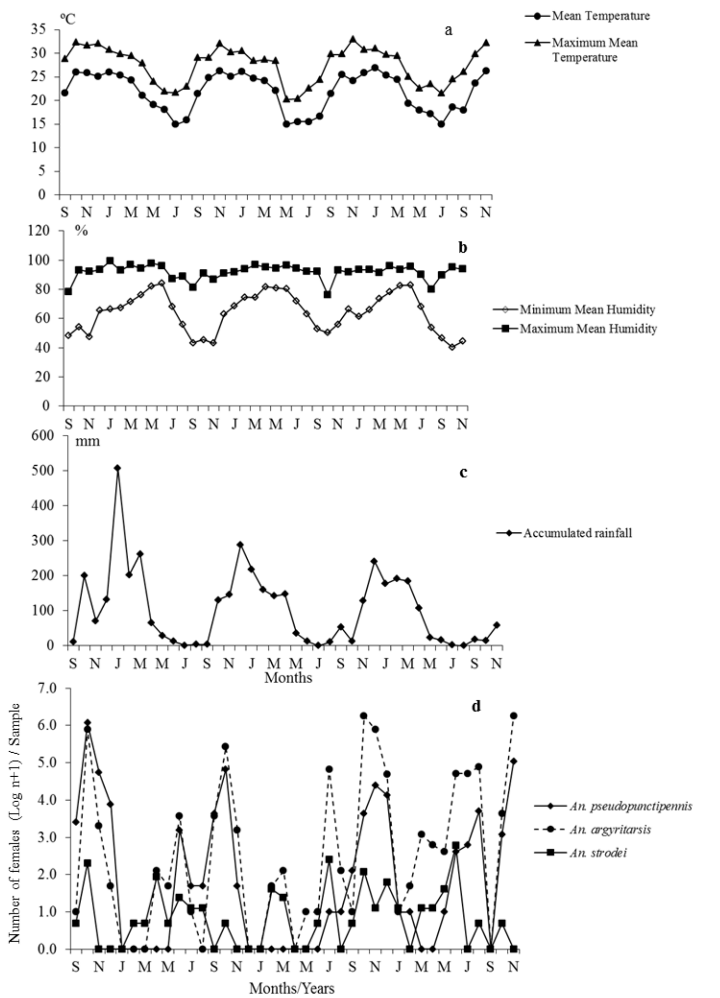

Figure 2. Monthly variation of (a) temperature (mean and maximum mean), (b) humidity (minimum and maximum mean), (c) accumulated rainfall, and (d) number of females (logn+1) of *An. pseudopunctipennis*, *An. argyritarsis,* and *An. strodei* collected in Aguas Blancas, northwestern Argentina.

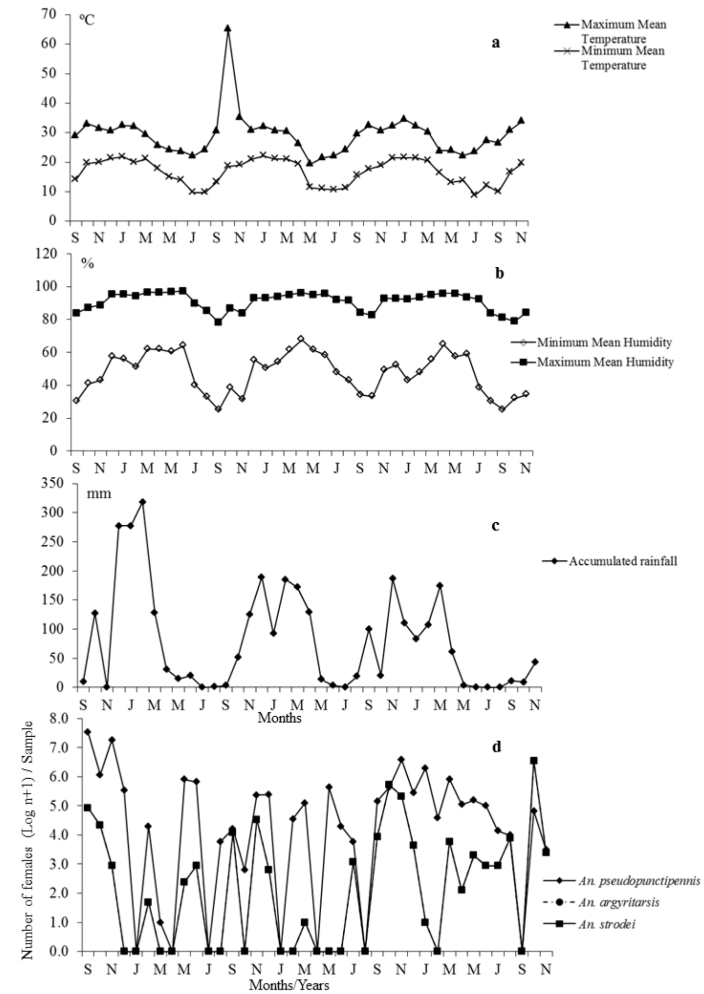

Figure 3. Monthly variation of (a) temperature (maximum and minimum mean), (b) humidity (minimum and maximum mean), (c) accumulated rainfall, and (d) number of females (logn+1) of *An. pseudopunctipennis*, *An. argyritarsis,* and *An. strodei* collected in El Oculto, northwestern Argentina.

to the benign climatic conditions, such as mild temperatures, stable humidity, and low accumulated rainfall. This situation was first reported by Bejarano (1953) and later by Dantur Juri et al. (2003, 2005, 2010a,b). *Anopheles argyritarsis* was the second most abundant species, as it was previously reported by Mühlens et al. (1925) and Dantur Juri et al. (2003, 2005, 2010a,b). This species was also abundant during the spring season, and its abundance could result from the direct impact of environmental changes caused by human activities at this sampling site, which has led to adaptation of this mosquito. Manguin et al. (1993) cited a similar situation in Grenada where *Anopheles argyritarsis* became the most abundant and widely distributed species due to the changes in the geographical distribution of *An. pseudopunctipennis*. In both cases, it appears that environmental changes negatively affected *An. pseudopunctipennis*, decreasing its abundance, only to be replaced by *An. argyritarsis*.

The distribution and abundance of *An. strodei* seems to be similar to that reported by Dantur Juri et al. (2003, 2005), with the highest abundance registered during the spring and autumn at Aguas Blancas, El Oculto, and San Ramón de la Nueva Orán. This species prefers habitats with temperate environmental conditions that are typical of these seasons in the subtropical mountainous rainforest. The moisture held within the canopies of the trees, shrubs, and pastures reduces the amount of sunlight that reaches the soil surface, maintaining the relative humidity and creating a suitable habitat that favors the abundance of *An. strodei* adults.

The accuracy of the multilevel Poisson regression analysis by each sampling site showed a good adjustment. NDVI and LST have affected the distribution and abundance of *Anopheles* species. The IRR values of LST at Aguas Blancas, indicate that this variable was directly related to the increases in abundances of *An. pseudopunctipennis* and *An. argyritarsis.* This explains the seasonal vectors behavior and indirectly predicts future abundance peaks and the potential appearance of malaria cases along the Bolivia-Argentina border.

At El Oculto, where autochthonous malaria cases have been registered, LST IRR values are related to an increase in abundance not only of the main malaria vector *An. pseudopunctipennis* but also of *An. argyritarsis* and *An. strodei*, the first species implicated in the transmission of the disease. At San Ramón de la Nueva Orán,

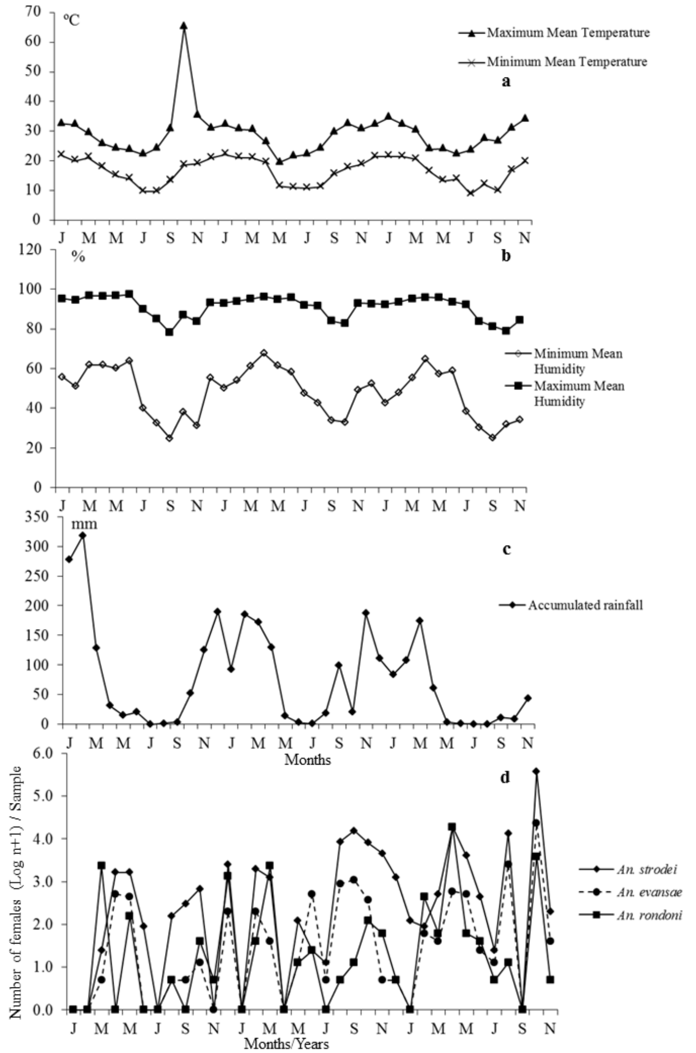

Figure 4. Monthly variation of (a) temperature (maximum and minimum mean), (b) humidity (minimum and maximum mean), (c) accumulated rainfall, and (d) number of females (logn+1) of *An. strodei*, *An. evansae,* and *An. rondoni* collected in Aguas Blancas, northwestern Argentina.

the LST IRR indicated the influence of LST on the increase in abundance of *An. pseudopunctipennis*. LST is used for monitoring vegetation water stress, detecting land surface disturbances and monitoring conditions that allow an environment to become suitable for insect-vector disease proliferation, among other uses (Pinheiro et al. 2006). In our study, LST appeared to be the main environmental variable responsible for the largest abundance of the main malaria vector, *An. pseudopunctipennis*. When this variable increased, there was also an increase in the abundance of this species and for the possibility of malaria transmission along the border of Argentina-Bolivia.

Dambach et al. (2012) have analyzed the effects of environmental variables on the malaria vector densities in rural West Africa, and they found that, while the abundance of *Anopheles* larvae is driven by multiple and interconnected factors (amongst which the NDVI appear) and precipitation events, the presence and abundance of adults of anopheline were negatively correlated to LST and positively to the accumulated rainfall in the preceding 15 days and with the Normalized Difference Pond Index (NDPI).

We have considered not only night LST but also day LST as meteorological factors, and have observed that night LST was not significantly associated with the *Anopheles* adult mosquito density, whereas day LST was negatively associated. The higher day LST produced the lower number of mosquitoes caught, which may indicate higher environmental stress, making it more difficult to survive or search for a blood meal. Higher day LST also has been related to a lower relative humidity, especially during the rainy season. Lower relative humidity implies a less appropriate environment for mosquito survival and blood meal retrieval success (Dambach et al. 2012).

The NDVI IRR values at El Oculto increased by almost 100% of *An. rangeli* abundance in relation to the increase of NDVI value. Similar results were obtained by Lopes et al. (2005) and Lorenço et al. (2011). *Anopheles atroparvus* population density has been directly correlated with NDVI values and temperature providing suitable conditions for mosquito development, both at the larval and adult stages. However, the authors have pointed out that the spatial generalization of the linear relationship encountered between NDVI values and mosquito density should be carefully analyzed and other local conditions/factors/variables explored.

Lorenço et al. (2011) also reported a strong correlation between *Anopheles atroparvus* abundance and NDVI values. NDVI could be used as a pointer of favorable vector habitat conditions as it indicates vegetation cover and, indirectly, water presence. These conditions are necessary for high vector density values as they represent appropriate breeding conditions. By contrast, Jacob et al. (2007) found that NDVI was unable to identify changes in land use and so it was not possible to make inferences regarding the larval abundance and distribution of *Anopheles arabiensis* in paddy fields. In addition, the authors cited several studies (Jackson and Pinter 1986, Myneni et al. 1992) that have found NDVI data to be unstable because they vary according to the soil, sun-view geometry, atmospheric conditions, and the presence of dead material, as well as changes of soil moisture.

Higher values of IRR from the mean temperature were observed at Aguas Blancas in relation to an increase in abundance of *An. pseudopunctipennis* and *An. argyritarsis*. IRR values from the minimum temperature at El Oculto were observed in relation to an increase in the abundance of *An. pseudopunctipennis*, *An. argyritarsis,* and *An. rangeli*. Then, there is a direct relationship between the increase of temperature and the increase of mosquito abundance/density as it was reported by Lopes et al. (2005).

The importance of climatic variables such as temperature in predicting the abundance of vectors, and indirectly, the occurrence of malaria cases, has been highlighted previously by Patz et al. (2000) and Sáez Sáez et al. (2007). These authors all reported that a rise in temperature resulted in faster egg eclosion, a shortened larval period, and the abundance of anopheline adults. In addition, the increase in temperature produced a direct increase of *Anopheles gambiae* adults inside dwellings and an increase in bite rates in the localities where temperatures were the highest (Lindblade et al. 2000). Laboratory tests have also demonstrated that with increasing temperature, the gonotrophic cycle of female *Anopheles albimanus* gradually shortened, reaching a minimum length when the females were exposed to temperatures of 24–30º C (Rúa et al. 2005).

Table 1. Random Effect Poisson Regression of LST and climatic variables for *Anopheles pseudopunctipennis, Anopheles argyritarsis*, *Anopheles strodei*, and *Anopheles nuneztovari* in Aguas Blancas locality, northwestern Argentina (LST: Land Surface Temperature; T° med: mean temperature; WV: wind velocity; P accumulated: monthly accumulated rainfall; H med: mean humidity).

	An. pseudopunctipennis				*An. argyritarsis*				*An. strodei*				*An. nuneztovari*			
Variables	IRR	SE	CI 95%	P-value	IRR	SE	CI 95%	P-value	IRR	SE	CI 95%	P-value	IRR	SE	CI 95%	P-value
LST	1,260	0.074	1.085-1.465	0.004	1,151	0.063	1.014-1.307	0.031								
T° med	1,282	0.096	1.057-1.556	0.013	1,220	0.010	1.195-1.247	0.000								
WV									0.270	0.441	0.111-0.659	0.005				
P accumulated									0.994	0.003	0.988-1.001	0.095				
H med													1,086	0.033	*1.016-1.162*	*0.016*

IRR: Incidence Rate Ratio indicates the influence of each variable in the area; the Standard Error (*SE*) as well as the Confidence Interval (*CI* 95%) and *P*-value were calculated.

Table 2. Random Effect Poisson Regression of NDVI, LST, and climatic variables for *Anopheles pseudopunctipennis, Anopheles argyritarsis*, *Anopheles strodei*, and *Anopheles rangeli* in El Oculto locality, northwestern Argentina (LST: Land Surface Temperature; NDVI: Normalized Difference Vegetation Index; T min: minimum mean temperature; H min: minimum mean humidity).

	An. pseudopunctipennis				*An. argyritarsis*				*An. strodei*				*An. rangeli*			
Variables	IRR	SE	CI 95%	P-value	IRR	SE	CI 95%	P-value	IRR	SE	CI 95%	P-value	IRR	SE	CI 95%	P-value
LST	1,151	0.048	1.045-1.268	0.006	1,211	0.061	1.071-1.370	0.003	1,095	0.040	1.009-1.189	0.031				
NDVI													95.9 E+22	22.45	23.6 E+6-39 E+42	0.018
T° min	1,093	0.046	0.996-1.199	0.060	1,169	0.066	1.024-1.336	0.022					1,256	0.092	1.044-1.512	0.017
H min	0.964	0.015	0.934-0.996	0.027	0.891	0.026	0.845-0.940	0.000	0.962	0.013	0.935-0.989	0.009	1,117	0.032	1.047-1.194	0.002

IRR: Incidence Rate Ratio indicates the influence of each variable in the area; the Standard Error (*SE*) as well as the Confidence Interval (*CI* 95%) and *P*-value were calculated.

During this study, we observed that an increase in accumulated rainfall resulted in a decrease of *An. evansae*. The rise in accumulated rainfall produces the flooding of the bodies of water, resulting in the larval habitats being destroyed, and the abundance of adult mosquitoes would be minor (Dantur Juri et al. 2003, 2010a,b). In contrast, Githeko et al. (2000) and López Vélez and Molina Moreno (2005) cited a rise in accumulated rainfall increases the quantity and quality of mosquito larval habitats and the density of the surrounding vegetation, providing suitable ecosystems for immature mosquitoes.

Lastly, precipitation plays an important role in generating conditions of high relative humidity, which favors not only parasite development within the mosquito but also the survival of female mosquitoes (Sáez Sáez et al. 2007, Rodríguez et al. 2008). In the present study, four *Anopheles* species abundances were affected by minimum humidity. At El Oculto this climatic variable resulted in a decrease in the abundances of *An. pseudopunctipennis*, *An. argyritarsis,* and *An. strodei* and positively affected only *An. rangeli*. This situation was first cited by Dantur Juri et al. (2003, 2010a) in northwestern Argentina that *Anopheles pseudopunctipennis* showed a negative relation with respect to humidity.

Considering the interaction of the environmental factors (Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), temperature, humidity, wind velocity, and accumulated rainfall) and the relationship with the *Anopheles* species in the three sampling sites in northwestern Argentina, different situations have been observed. At Aguas Blancas, not only the increase of LST mainly affects the abundance of *An. pseudopunctipennis* and *An. argyritarsis* producing their increase but also mean temperature which also produces a major increase in their abundances. At El Oculto, there were a greater number of factors interacting; LST produces the increases of *An. pseudopunctipennis*, *An. argyritarsis,* and *An. strodei*, but NDVI increases more than 100% the abundance of *An. rangeli*. These species were also positively influenced by the mean minimum temperature, producing the increase of their abundance. The mean minimum humidity was negatively associated with *An. pseudopunctipennis* and *An. argyritarsis,* producing the decrease in their abundances. At San Ramón de la Nueva Orán, only two climatic factors have been shown to influence the abundance of two species, *An. pseudopunctipennis* and *An. evansae*. The first species was positively influenced, increasing their abundance when the LST increased, but *An. evansae* decreased their abundance when the accumulated rainfall increased.

The interaction between the environmental factors and the association with malaria vectors *Anopheles gambiae* and *Anopheles funestus* in Kenya was reported by Kelly Hope et al. (2009). The authors have found that *Anopheles gambiae* s.s. and *An. arabiensis* were positively correlated with precipitation and negatively correlated with temperature and humidity variables. This contrasts to *An. funestus*, which was negatively correlated with precipitation but positively with temperature, humidity, and NDVI.

In general, differences in vector abundance between localities may not only be subject to environmental variables but also anthropogenic variables (land use). Lopes et al. (2005) have reported that annual land use change was another factor responsible for the *An. atroparvus* population seasonal dynamics. The farming method, with flooding, created an appropriate environment of water availability, when combined with high temperature, allows vegetation to grow at a higher rate in the surrounding areas that sustain high mosquito densities.

Changes in land use of each local environment of the sampling sites can create, or reduce, the number of suitable larval habitats for local vectors that may also affect the abundance and distribution of *Anopheles* species and transmission patterns. In Aguas Blancas, the brick houses are close to the patches of natural rainforest interspersed with crops of corn and bananas and close to different ravines (larval habitats) that cross the road to the Bermejo River. This local environment appears to favor the risk of malaria transmission and the movement of populations between the frontier with Bolivia because trade is the main economic activity. At El Oculto, the poor houses were built alongside the provincial highway between the subtropical rainforest and the subsistence farming that takes place on small plots of land where corn, sweet potatoes, cassava, avocados, mangos, and bananas are cultivated. The presence of different cultivations and the larval habitats situated along the Blanco and Anta Muerta Rivers may be related to the appearance of larval habitats that are more suitable for *Anopheles* species. San Ramón de la Nueva Orán is a city, capital of the department Orán, with important neighborhoods located at the outskirts of the city, close to the piedmont of the rainforest. As a result of the changes in land use, it is observed in the surroundings of the city that agricultural activities increased during the past years, so the area of the native forest decreased. The principal crops are based on sugarcane plots, citrus plants, and tropical fruits (Arroyo 2004). Information about the impact of urbanization, agricultural activities, and changes in climate on malaria transmission is still unknown but becoming increasingly important as reported by Kelly Hope et al. (2009).

In summary, the current analysis produced accurate results that show where and in what proportion environmental and climatic variables affected changes in the distribution and abundance of *Anopheles* species, taking into account the dependence between the *Anopheles* specimens collected from one month to the next and from one year to the next. In this way, it is possible to predict future abundance peaks that can be explained in relation to changes in the environmental and climatic variables. The use of MODIS images with temporal resolution provides a very close approximation in relation to the environmental changes occurring.

Overall, the main assumptions of the paper are that *Anopheles* spp. distribution and abundances depend directly on environmental and climatic conditions and that LST, NDVI, and minimum temperature and humidity could be used to predict when malarial peaks may occur.

Further studies focusing on the effects of environmental variables on the instances of malaria could help to predict future malaria occurrence along the border of Argentina-Bolivia. These studies are relevant considering that Argentina is included in the malaria pre-elimination phase. The results that will be obtained from future studies about the prediction of malaria occurrences can be used to indicate whether vector *Anopheles* species are likely to alter their geographical range, thus also indicating where new cases of malaria are likely to occur.

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