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Ecological Distribution Modeling of Two Malaria Mosquito Vectors Using Geographical Information System in Al-Baha Province, Kingdom of Saudi Arabia

Azzam Mohammad Alahmed,[1] Muhammad Naeem,[1]* Salah Mohammad Kheir[1] and Mohamed Fahim Sallam[2,3,4]
[1]*Research Chair of Insect Vector Borne Diseases, Department of Plant Protection, College of Food and Agriculture Science, King Saud University, Riyadh, Saudi Arabia*
[2]*Urban Entomology Laboratory, Entomology and Nematology Department, University of Florida, USA*
[3]*Entomology Department, College of Science, Ain Shams University, Cairo, Egypt*
[4]*Anastasia Mosquito Control District, St. Augustine, Fl, USA*

Abstract.- Malaria is considered as an endemic mosquito borne disease in the Kingdom of Saudi Arabia (KSA). Previous investigations addressed the diseases incidences in KSA, however few studies highlighted the mosquito vectors habitats characterization in regards to ecological variables. Ecological models of mosquito vectors will help in defining potential suitable habitats for their spatial distribution and understanding how much the ecological variables contribute in delineating these suitable habitats. This information will help in developing targeted surveillance and control strategies. Ecological niche modeling was carried out using the evolutionary algorithms implemented in maximum entropy (MaxEnt) to predict the suitable larval habitats of two malaria vectors, *Anopheles gambiae* s.l. and *An. sergentii* (Theobald) in Al-Baha Province, KSA. Climatic and topographical data layers from Worldclim databases and larval occurrence records were used to model the two malaria vectors. Six topographical and four bioclimatic variables were significantly predict *An. gambiae* larval suitable habitat. Both streams covered with vegetation and algae and elevation above sea level were strong predictors of distribution of this mosquito vector. However, for *An. sergentii*, four topographical and ten bioclimatic variables were found to be significant predictors of suitable habitat distribution. Soil and altitude were strong predictors of *An. sergentii* distribution. Also, the linear regression statistical analysis (LM) indicates non linear correlation between TDS/pH and abundance of these two mosquito species.

Keywords: Mosquitoes, *Anopheles gambiae* s.l., *An. sergentii*, malaria, GIS.

INTRODUCTION

In Kingdom of Saudi Arabia (KSA), malaria is an endemic mosquito borne disease (Al-Seghayer *et al*., 1999) and both *An. gambiae* and *An. sergentii* are the main vectors for the disease transmission (Mattingly and Knight, 1956; Abdoon and Alshahrani, 2003). Different ecological factors are contributing in delineating the distribution of mosquito vectors. The combination of these factors is responsible for providing the suitable environments of vector's growth and transmission of diseases. Targeted control of disease vectors is worthwhile to conventional surveillance and control measures (Charlwood *et al*., 2003). Recently, different statistical and geographical information system (GIS) techniques have been applied for the identification of the high-risk areas of vectors and their possible control (Cardoso-Leite *et al*., 2014).

In Al-Baha Province, although no malaria cases have been reported recently, the presence of competent mosquito vectors increase the potentiality of malaria transmission. In the current study we aimed at predicting the ecological suitable habitats of the two malaria vectors, *An. gambiae* and *An. sergentii*, in regards to climatic and environmental variables and to define the substantial contribution of these variables in characterizing the risk areas of malaria transmission to be targeted in surveillance and control strategies.

Authors' Contributions: AMA and MFS designed and conducted the study. MN, AMA, SMK and MFS conducted field visits and analyzed the data. MN drafted the manuscript. SMK and MFS finalized the article.

* Corresponding author: naeem1633@yahoo.com
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MATERIALS AND METHODS

The study area

This study was conducted in Al-Baha Province (longitudes 41° to 42°, and latitudes 19° to 21°), located in the southwestern region of KSA (Fig. 1) between Makkah and Asir with an area of 12,000 km^2 and a population of 500,000 inhabitants (Saudi Geological Survey, 2012). There are two sectors in Al-Baha Province, Al-Sarah (highland) including four districts Al-Aqiq, Al-Mandaq, Al-Qura and Baljurashi and Tihama (low land) including only two districts Al-Mekhwa and Qelwa (Saudi Geological Survey, 2012). Elevation varies between 1,500 and 2,450 m above sea level in Al-Sarah sector (Fig. 2). The annual relative humidity varies between 52% and 67%, and maximum and minimum temperature of 23°C and 12°C, respectively (El-Hawagry *et al*., 2013).

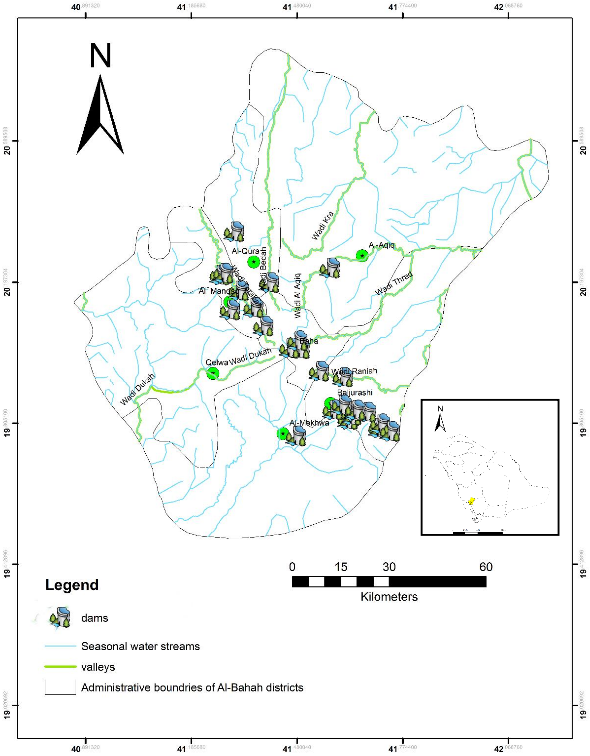

Fig. 1. The study areas in Al-Baha Province, Saudi Arabia with major streams, valleys and dams.

Collection and identification of mosquito larvae

Mosquito larvae were collected for 11 months from December 2013 to November 2014. All potential open and natural breeding sites were sampled and typical mosquito habitats were selected in elevated and lower topographic areas. A standard 350 ml plastic dipper was used for sampling larval mosquito. The coordinates of the collection sites were taken by global positioning system (GPS) (Garmin®, eTrix). After collection all mosquito larvae were put in 80% alcohol. Puri's medium was used for mounting of late third or fourth instars. Species were identified using keys of Al-Ahmed *et al*. (2011a).

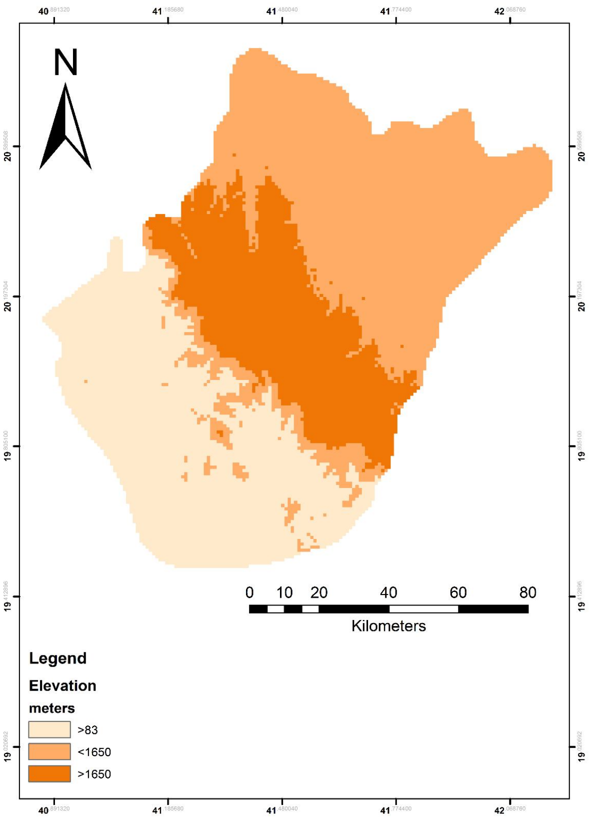

Fig. 2. Elevation map of Al-Baha Province, Saudi Arabia.

The total dissolved salts (TDS) and pH of the breeding water were measured using TDS and pH meters immediately after larval sampling.

Modeling procedures

Our distribution models are niche based which require independent test data as well as appropriate test statistics. For the characterization of mosquito larval habitats, a total of 27 topographical (http://www.diva-gis.org) and bioclimatic layers (11 layers of temperatures and 8 precipitation indices) (Table I) were obtained from WorldClim ver. 1.4 (http://www.worldclim.org) (Hijmans *et al*., 2005). The digital elevation model in ArcGIS toolbox was used to extract the aspect ratio and slope from elevation data layer. It has been believed that both variables, aspect ratio and slope, are good indicators in predicting the land surface characteristics in terms of water runoffs. Also, since land use-land cover (LULC) variables were highlighted in the previous investigation to influence the malaria vectors distribution in Africa, some of these variables were included in our model such as roads (Ahmad *et al*., 2011), which represent the level of urbanization and vicinity to human settlements through the type of roads (vehicle track, primary unpaved, secondary unpaved, secondary paved), vegetation, soil, and dams. The spatial resolution of these bioclimatic layers is at 30 arc-seconds (~1km). All these bioclimatic layers were clipped to match the dimension of Al-Baha Province and saved in ASCII grid format for using in MaxEnt. For clipping these layers, model builder tool of ArcGIS software v. 10 was used. Species distribution modeling was produced using MaxEnt software ver. 3.3. This software only records and produces useful prediction for the species distribution in the study area. The modeling technique uses only occurrence data of mosquito species (Phillips, 2004). The predicted risk probability was categorized into five classes: very low, low, medium, high, and very high. These risk probabilities were calculated using the natural breaks tool in ArcGIS toolbox.

Table I.- Environmental and topographical variables.

Variables	Description
bio1	Annual mean temperature
bio2	Mean Diurnal Range (Mean of Monthly (max temp-min temp)
bio3	Isothermality (Bio2/Bio7) (* 100)
bio4	Temperature seasonality (standard deviation *100
bio5	Max temperature of warmest month
bio6	Min temperature of coldest month
bio7	Temperature Annual Range (BIO5-BIO6)
bio8	Mean temperature of wettest quarter
bio9	Mean temperature of driest quarter
bio10	Mean temperature of warmest quarter
bio11	Mean temperature of coldest quarter
bio12	Annual precipitation
bio13	Precipitation of wettest month
bio14	Precipitation of driest month
bio15	Precipitation seasonality (Coefficient of variation)
bio16	Precipitation of wettest quarter
bio17	Precipitation of driest quarter
bio18	Precipitation of warmest quarter
bio19	Precipitation of coldest quarter
slope	Slope
aspect	Aspect ratio
alt	Elevation in meters
water streams	Streams covered with vegetation
roads	Different types of roads
soil	Soil types
Dams	Dams
vegetation	Annual crop land

Model performance and evaluation

The estimation performance of the model was determined by Area under curve (AUC) values of receiver operating characteristic (ROC) curves (Phillips *et al.*, 2006; Peterson *et al.*, 2008). Predictive performances of all variables were determined by Jackknifing approach (leave-one-out procedure) in Maxent (Pearson *et al*., 2007).

Field validation points

To evaluate the risk maps produced from MaxEnt models for both species, field validation points were collected as independent data sets. Total 41 field validation points were collected for each of *An. gambiae,* and *An. sergentii.* The visited points were selected randomly to represent the five risk probabilities.

Statistical analysis

To evaluate the dependency of larval mosquito abundance on TDS and pH of sampling water habitats, single linear regression model (LM) was used. The Statistical analysis was carried out using the SPSS package version 17 (SPSS Inc., Chicago, Illinois, US).

RESULTS

A total of 2,172 mosquito larvae were

collected during this study in Al-Baha Province from 111 sites. Out of these, 63 (56.76%) sites were positive for mosquito larvae. *Culex* larvae were the most abundant where 995 (45.81%) were collected followed by *Anopheles* 517 (23.80%), *Aedes* 357 (16.44%) and *Culiseta* 303 (13.95%) larvae. Larvae of *An. gambiae* and *An. sergentii* were found to represent 20% and 11%, respectively, of the total **a**nopheline larvae collected. The ranges of TDS and pH of the breeding habitats were 996-1926.4 ppm (part per million) and 6.4-8.8, respectively. The statistical analysis represented a linear correlation between the chemical characteristics (TDS/pH) of breeding habitats and larval abundance of both *An. gambiae* and *An. sergentii* larvae ($P<0.01$). However, R^2 values indicate very low correlation between the abundance of both mosquito vectors and these TDS/pH of the water, where $R^2 = 0.051$ & 0.002 and the regression coefficient was 0.3229 & 0.1942 for *An. gambiae* and *An. sergentii* respectively.

Ecological niche modeling of malaria vectors

There were 10 occurrence records for both mosquito vectors, used in building up the spatial model. The predictive performance for training was found high with an AUC = 0.783 for *An. gambiae* and 0.872 for *An. sergentii*. The fractional predicted area at 10 percentile training presence was 0.526 & 0.221 with test point omission training rate 0.100 & 0.000 for *An. gambiae* and *An. sergentii*, respectively. These points were classified as significantly better than random ($P<0.05$).

Among the 27 bioclimatic and topographic variable layers used for spatial predictions, 10 and 14 variables were found to contribute in spatial prediction of *An. gambiae* and *An. sergentii*, respectively (Table II). A Jackknife test for *An. gambiae* showed that streams covered with vegetation significantly improved the predictive power (36.1%), with an altitude (31.0%), soil (17.2%), slope (4.4%), road (0.5%) and vegetation layers (0.3%). Precipitation and temperature related variables contributed 9.5 % and 1.0 %, respectively (Table II). A Jackknife test for *An. sergentii* showed that the soil significantly improved the predictive power (79.3%), with altitude (10.5%), road (0.1%) and streams (0.1%). The precipitation related variables shared reduce training gain (8.9%). However, temperature related variables contributed only 0.9% in reduced training gain.

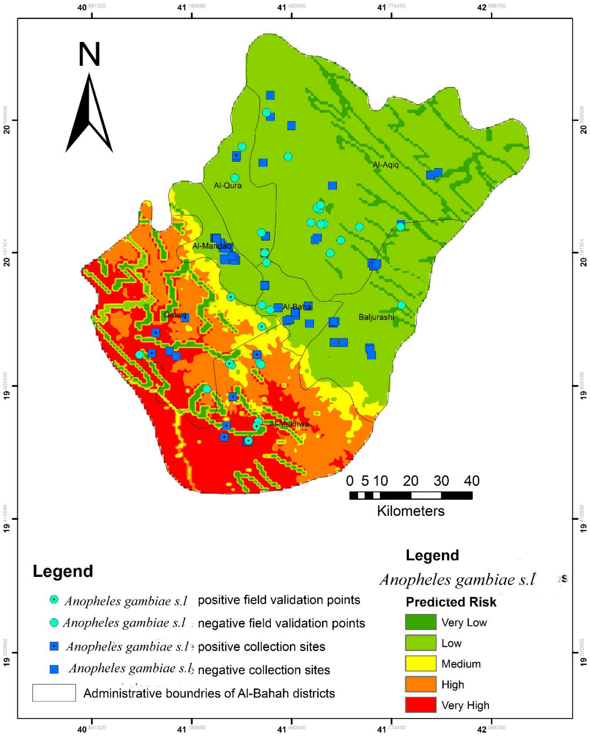

Fig. 3. Predicted suitable habitats for *Anopheles gambiae* s.l Giles in Al-Baha Province

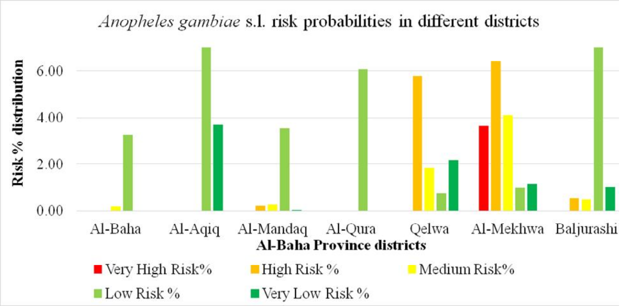

Fig. 4. *Anopheles gambiae* distribution risk in different districts of Al-Baha Province.

The predictive risk map for *An. gambiae* (Fig.3) indicated that "very high" risk areas are present in both Qelwa and Al-Mekhwa districts (low elevations) in Tihama, which demontrates that these districts are highly suitlable habitats for distribution of *An. gambiae* larvae. Also, the distrbution of risk probability in different districts was calculated and it was found that 1815.44 km^2 (15.13 %) at very high, 1556.58 km^2 (12.97%) at high, 827.03 km^2 (6.89 %) at medium, 6839.82 km^2 (57 %) at low and 961.14 km^2 (8.01%) at very low risk (Fig. 4).

Moreover, the predictive risk map for *An. sergentii* **(**Fig. 5) indicated that the central mountainous sector of Al-Baha Province (all the four districts in Al-Sarah) is very suitable for larval distribution. In addition, 1150.05 km^2 (9.58%) was defined as very high, 1264.02 km^2 (10.53%) represents high, 1374.11 km^2 (11.45%) represents medium, 5438.40 km^2 (45.32%) represents low and 2773.42 km^2 (23.11%) represents very low risk areas for *An. sergentii* larval distribution (Fig. 6).

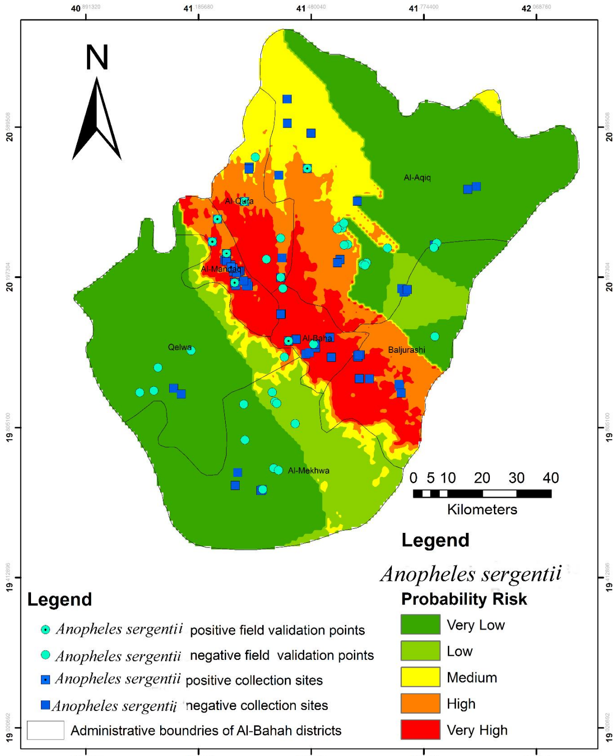

Fig. 5. Predicted suitable habitats for *Anopheles sergentii* in Al-Baha Province.

Field validation of the model

To validate of these models in the field, all sites of Al-Baha Province were visited according to risk classes using a hand held GPS and 41 sites were visited for each species (Tables III, IV). For *An. gambiae*, 67% of sites were positive in very high, 30% in high, 22% in medium, 11% in low risk and no site was detected in "very low" risk areas. As compared to *An. gambiae*, *An. sergentii* have all validation points (100%) in the "very high risk" areas, 67% in high, 50 % in medium, and all sites were negative in low and very low risk areas (Fig.7).

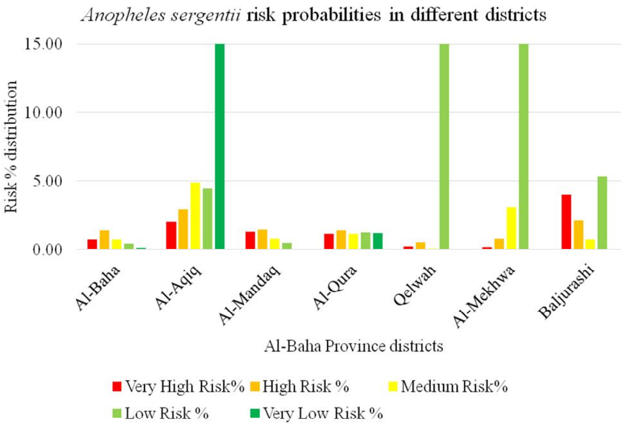

Fig. 6. *Anopheles sergentii* distribution risk in different districts of Al-Baha Province.

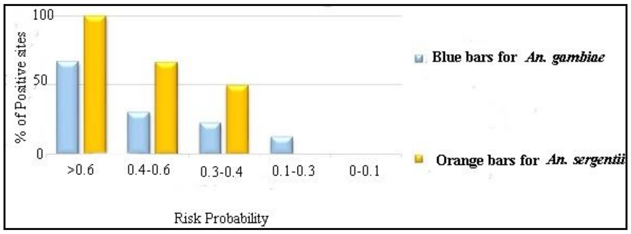

Fig. 7. Field validation of the distribution risk of *Anopheles gambaie* and *Anopheles sergentii* species in response to risk probability produced in MaxEnt model, Al-Baha Province, Saudi Arabia*;* For Y axis indicate % of positive sites; for X axis indicate the risk level for *e.g.*, very high (>0.6), high (0.4-0.6), medium (0.3-0.4), low (0.1-0.3) and very low (0.0-0.1)]

DISCUSSION

Geographic information system (GIS) was proved as a useful tool in predicting maps for the distribution of mosquito vectors and their disease transmission (Kulkarni *et al.*, 2010; Abdel-Dayem *et al.*, 2012). Such technology has been successfully used in different regions (Zhou *et al.*, 2007; Rohani

Table II.- The contribution percentage of the total 27 ecological layers in predicting spatial distribution of *Anopheles gambiae* s.l., and *Anopheles sergentii* in Al-Baha Province, Saudi Arabia.

Species	Variables	Description	% Contribution
An. gambiae s.l.	Streams	Streams with vegetation	36.1
	Altitude	Altitudes	31.**0**
	Soil	Soil	17.2
	Bio14	Precipitation of driest month	9.4
	Slope	Slope	4.4
	Bio9	Mean temperature of driest quarter	0.6
	Road	Different types of roads	0.5
	Bio10	Mean temperature of warmest quarter	0.4
	Vegetation	Vegetation	0.3
	Bio17	Precipitation of driest quarter	0.1
An. sergentii	Soil	Soil	79.3
	Alt	Altitude	10.5
	Bio13	Precipitation of wettest month	5.1
	Bio19	Precipitation of coldest quarter	3.2
	Bio17	Precipitation of driest quarter	0.3
	Bio9	Mean temperature of driest quarter	0.3
	Bio6	Min. temperature of coldest month	0.3
	Bio3	Isothermality (bio2/bio7)(*100)	0.2
	Bio14	Precipitation of driest month	0.2
	Bio2	Mean diurnal temperature range	0.2
	Bio16	Precipitation of wettest quarter	0.1
	Bio7	Temperature annual range (bio5-bio6)	0.1
	Road	Different types of roads	0.1
	Streams	Streams with vegetation	0.1

et al., 2010; Sallam *et al*., 2013) for some Anopheline and Culicine mosquito vectors of diseases. Although, there are no reported cases of malaria at present in Al-Baha, the presence of the mosquito vectors poses a substantial risk of disease transmission. In the current study, we attempted to establish distribution risk maps and produce ecological niche models for *An. gambiae* and *An. sergentii*, using GIS technologies and Maxent software.

Due to the lack of reliable geospatial and seasonal information about the distribution of malaria vectors for Al-Baha Province, a one-year field survey for the collection of mosquito larvae was carried out from natural, open, and accessible water habitats. Previous investigations of Al Baha either sporadic and does not represent the geographic and seasonal variations (Khater *et al*., 2013) or addressed the taxonomic identification or the seasonal abundance of mosquito taxa (Alahmed *et al*., 2011, Al-Ahmed *et al*., 2013).

Despite the presence of different modeling techniques, Maxent was selected for our models due to its accuracy in processing presence only data (Hernandez *et al*., 2006; Phillips *et al*., 2006; Ortega-Huerta and Peterson, 2008). Maxent works on the basic assumption that both fundamental and realized niches coincide (Phillips *et al*., 2006) and that the target species are equally detectable across a study area (Yackulic *et al*., 2012).

In our model, the Jackknife analysis showed that topographic variables shared an increased contribution in predicting spatial distribution of both vectors' habitats as compared to the other variables. Soil types, streams covered with vegetation, and elevation appeared to influence the vertical distribution of *An. gambiae* and *An. sergentii*.

It was represented that water streams with vegetation had the ultimate contribution (36.1%) in predicting *An. gambiae* distribution as compared to the other factors. This may be attributed to richness of this type of water habitats with organic matters that affords food source and protection from direct sunlight and natural enemies (Sattler *et al*., 2005, Alahmed *et al*., 2011b). Our results, was consistent with similar study conducted in Najran Province on

Table III.- **Field validation for the ecological niche modeling of *Anopheles gambiae* s.l (Larval abundance: total number of larvae collected from different risk classes).**

Risk probability	Longitudes	Latitudes	Larval abundance
Very high	41.709	20.321	11
	41.486	20.023	12
	41.166407	20.00604	3
	41.063	19.681	12
	41.333971	20.511253	0
	41.046781	19.53612	0
High	41.378187	19.897571	13
	41.068632	19.901575	6
	41.079567	19.961662	1
	41.624646	20.234883	0
	41.803347	20.04271	0
	41.47	20.482	0
	41.406	20.612	0
	41.353457	19.64419	0
	41.565576	20.33944	0
	41.031979	19.896857	0
Medium	41.456	19.812	5
	41.306955	19.773257	2
	41.406	20.168	0
	41.400425	20.196701	0
	41.385192	19.872744	0
	41.390055	19.868393	0
	41.537	20.288	0
	41.594	20.196	0
	41.679	20.275	0
Low	41.41	19.989	3
	41.391	20.258	0
	41.313	20.419	0
	41.301	20.067	0
	41.392	19.98	0
	41.377	19.687	0
	41.297	19.871	0
	41.304	19.866	0
Very low	41.3819	19.6996	0
	41.575573	20.283641	0
	41.566002	20.282414	0
	41.560805	20.326519	0
	41.554459	20.331414	0
	41.230346	19.796246	0
	41.393	20.043	0
	41.417	20.029	0

statistical modeling of *An. gambiae* in response to the chemical and physical characteristics of their breeding sites (Al-Ahmed *et al*., 2011b). Although the contribution of soil type for *An. gambiae* distribution is only 17.2%, soil type is considered one of the predicting key factors that define the suitable habitats of this mosquito vector (McCann *et al*., 2014).

Table IV.- **Field validations for the ecological niche modeling of *Anopheles sergentii* (Larval abundance: total number of larvae collected from different risk classes).**

Probability	Longitudes	Latitudes	Larval abundance
Very high	41.421	20.031	4
	41.235	20.35	1
	41.259	20.26	1
High	41.222	20.291	3
	41.28	20.183	1
	41.406	20.168	0
Medium	41.47	20.482	5
	41.306	20.396	1
	41.363171	20.244244	0
	41.565576	20.33944	0
Low	41.333971	20.511253	0
	41.400425	20.196701	0
	41.378187	19.897571	0
	41.385192	19.872744	0
	41.3819	19.6996	0
	41.394915	19.694329	0
	41.353457	19.64419	0
	41.554459	20.331414	0
	41.5481	20.324128	0
	41.438114	19.81551	0
	41.306955	19.773257	0
	41.400073	20.300191	0
	41.063	19.681	0
Very low	41.624646	20.234883	0
	41.615858	20.230046	0
	41.62064	20.228337	0
	41.679404	20.274532	0
	41.8081	20.2874	0
	41.800587	20.275416	0
	41.803347	20.04271	0
	41.390055	19.868393	0
	41.575573	20.283641	0
	41.566002	20.282414	0
	41.560805	20.326519	0
	41.304	19.866	0
	41.068632	19.901575	0
	41.031979	19.896857	0
	41.486	20.023	0
	41.166407	20.00604	0
	41.079567	19.961662	0
	41.41	19.989	0

For *An. sergentii*, soil had the greatest contribution in determining the spatial distribution of the suitable larval habitats (79.3%). The response curves produced from MaxEnt represented that the association of suitable larval habitats was linked with the loamy soil type as it provides the necessary nutrients to the larvae of this species (Hua *et al*., 2012). The field evaluation of our model confirmed such association between the loamy soil and suitable larval habitats for *An. sergentii*, which was also widely distributed in the high elevations of the Province.

Elevation contribution was 31% and 10.5% for *An. gambiae* and *An. sergentii,* respectively. Although *An. gambiae* was reported in higher lands in Africa (Minakawa *et al.*, 2002), the most suitable habitats for their larval occurrence was confined to low lands in the current investigation. This may due to the spatial differences in their distribution pattern, which may be impacted by the climatic change. Also, the sampling season and technique should be considered, which may influence the distribution risk map of mosquito vectors either spatially or temporally. Vegetation represented as annual cropland was found to share reduced contribution gain in *An. gambiae* distribution (0.3%).

The climatic variables are considered as the major proxy that affects the distribution of mosquitoes (Lin and Lu, 1995; Murty *et al*., 2010). However, the impact of the climatic variables in Al-Baha Province shared a reduced gain in influencing the spatial distribution of these two mosquito vectors. The reduced share of these factors may be attributed to their interaction with LULC variables. The Jackknife test considers this interaction and estimates the influence of each factor in association of other variables. Climatic factors appeared to have an indirect influence on LULC variables, such as the relationship between vegetation, represented as annual cropland, and the precipitation. Our results confirmed the association between precipitation of driest month (bio14) and driest quarter (bio17) which influenced the distribution of suitable larval habitats. Meanwhile, these suitable habitats were found to be associated with vegetated land in case of both mosquito vectors.

The current investigation is only a start for rigorous and comprehensive ones to be conducted in the entire Kingdom. The significance of presence of these two important malaria vectors in the same Province represents a complicated health problem in malaria transmission in both high and low lands. Further studies in Al-Baha are required to address the temporal distribution and vectorial capacity of such mosquito vectors.

CONCLUSIONS

There is complexity in the ecological system influencing the spatial distribution of mosquito vectors of diseases. This complexity may be attributed to the interaction between different climatic and land use-land cover (LULC) variables in the entire ecosystem. In the current study we tried to investigate the interactions between different climate and environmental factors that may influence the distribution range of two malaria vectors, *An. gambiae* s.l. and *An. sergentii*, in Al Baha Province. We developed distribution risk maps for both malaria vectors in the study area. The jackknife analysis in MaxEnt assessed the percent contribution of each variable in predicting both malaria vectors. The results of the current investigation may help in prompting targeted surveillance and control programs for malaria vectors in Al-Baha Province.

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