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Mapping potential *Anopheles gambiae s.l.* larval distribution using remotely sensed climatic and environmental variables in Baringo, Kenya

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Abstract. *Anopheles gambiae s.l.* (Diptera: Culicidae) is responsible for the transmission of the devastating *Plasmodium falciparum* (Haemosporida: Plasmodiidae) strain of malaria in Africa. This study investigated the relationship between climate and environmental conditions and *An. gambiae s.l.* larvae abundance and modelled the larval distribution of this species in Baringo County, Kenya. Mosquito larvae were collected using a 350-mL dipper and a pipette once per month from December 2015 to December 2016. A random forest algorithm was used to generate vegetation cover classes. A negative binomial regression was used to model the association between remotely sensed climate (rainfall and temperature) and environmental (vegetation cover, vegetation health, topographic wetness and slope) factors and *An. gambiae s.l.* for December 2015. *Anopheles gambiae s.l.* was significantly more frequent in the riverine zone ($P < 0.05$, $r = 0.59$) compared with the lowland zone. Rainfall ($b = 6.22$, $P < 0.001$), slope ($b = -4.81$, $P = 0.012$) and vegetation health ($b = -5.60$, $P = 0.038$) significantly influenced the distribution of *An. gambiae s.l.* larvae. High *An. gambiae s.l.* abundance was associated with cropland and wetland environments. Effective malaria control will require zone-specific interventions such as a focused dry season vector control strategy in the riverine zone.

Key words. *Anopheles gambiae s.l.*, climate, environmental factors, remote sensing.

Introduction

The female *Anopheles* mosquito is an important vector of malaria. In Africa, *Plasmodium falciparum* malaria is the most devastating strain of the disease and is associated with high morbidity and mortality rates (World Health Organization, 2016). This situation is made more severe by the presence of the most effective and efficient vector species, *Anopheles gambiae s.s.* (Giles) and its sibling species *Anopheles arabiensis* (Patton), herein referred to together as *Anopheles gambiae s.l.* Malaria vectors have idiosyncratic habitat preferences. Specifically, *An. gambiae s.l.* prefers shallow, sunlit and transient water bodies without aquatic plants, such as ground depressions that include pools, puddles and hoof prints (Benedict *et al.*, 2010). In addition, *An. gambiae s.l.* is able to survive in wet mud, which consequently enhances its survival in uncertain environments (Dale & Knight, 2008). *Anopheles gambiae s.s.* is adapted to wetter and more humid areas, whereas *An. arabiensis* is adapted to drier climates (Tonnang *et al.*, 2014). The distinct habitat preferences of malaria vectors contribute to the ubiquity of

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their distributions. In Kenya, *An. gambiae s.l.* and *Anopheles funestus* are common vectors in the western highlands and lake endemic zones, whereas *An. arabiensis* and *Anopheles pharoensis* dominate the arid areas of seasonal transmission (Ototo *et al.*, 2015).

The distribution of a mosquito vector is dependent on biotic and abiotic characteristics of the environment. Climate influences risk for malaria, both directly via the development rates and survival of the vector (Paaijmans *et al.*, 2010) and indirectly through changes in vegetation and land surface characteristics (Munga *et al.*, 2009). Rainfall and temperature are important climatic factors influencing the occurrence of malaria vectors. For instance, an increased ambient temperature increases the development rate of mosquitoes (Paaijmans *et al.*, 2010) and consequently increases the risk for malaria transmission. Variability in the frequency, intensity and amount of precipitation also influences mosquito survival (Mamai *et al.*, 2016), densities and distribution as a result of alterations in habitat conditions (Kulkarni *et al.*, 2016). In dry land areas, permanent and localized water sources promote year-on-year low-level larval production by providing 'larval seeds' to newly formed rain-fed habitats (Mala *et al.*, 2011).

Both soil conditions before the onset of rains and vegetation cover influence malaria vector populations (Chaves & Koenraadt, 2010). At a local scale, factors such as soil moisture and land use/land cover changes have been reported to influence the risk for malaria (Chaves & Koenraadt, 2010). Soil moisture levels have been used to determine the number of infective bites on human hosts (Chaves & Koenraadt, 2010). Other studies have used vegetation health to detect suitable conditions for mosquito development (Dambach *et al.*, 2012). Likewise, vegetation growth stages play a considerable role in determining mosquito vector abundance (Juri *et al.*, 2014). Irrespective of the association with rainfall, vegetation has heterogeneous effects on mosquito abundance because it provides both suitable habitats for immature stages and shade, which discourages mosquito production (Juri *et al.*, 2014). Slope is an additional hydrological factor influencing the suitability of breeding habitat (Hanafi-Bojd *et al.*, 2012). These environmental factors affect the spatial distribution of mosquito vectors.

The distribution of mosquito vectors, their biological adaptation and presence in a particular environment are the major factors influencing malaria epidemiology. In Kenya, malaria is responsible for 18% of hospital visits (U.S. Agency for International Development, 2016) and in Baringo County it accounts for 11% of outpatient consultations (Kenya Inter-Agency Rapid Assessment, 2014). The county has a substantial malaria burden as a result of its unique geophysical formations and the occurrence of different eco-climatic conditions. Data on the prevention or control of malaria are also limited, although malaria is among the most prevalent diseases in Baringo (Baringo County Government, 2014). The high prevalence of malaria may be attributable in part to the environmental determinants of malaria vectors, given the prevailing heterogeneous conditions. This calls for particular attention to explore the influences of climatic and environmental conditions on malaria vectors and risks. This study focused on investigating the relationships between climate and environmental conditions and mosquito abundance, and on modelling *An. gambiae s.l.* larval distribution in Baringo County. Understanding these dynamics is central to the prevention of malaria epidemics and the associated losses because such understanding provides decision-making tools to reduce vulnerability.

Materials and methods

Study area

Baringo County, Kenya lies between the latitudes of 00°26′ N and 00°32′ N and the longitudes of 36°00′ E and 36°09′ E. The county is classified into four ecological zones based on altitude, vegetation type and climatic characteristics. These zones are identified as highland (1500–2300 m a.s.l.), mid-altitude (1000–1500 m a.s.l.), riverine (1100–1200 m a.s.l.) and a lake ecosystem (lowland, < 1000 m a.s.l) (Fig. 1). The riverine and lowland zones were selected during this study in view of their overlapping climatic and altitudinal conditions. Daily air temperatures range between 16 °C and 42 °C and mean monthly minimum and maximum temperatures are 20 °C and 35 °C, respectively. Average annual rainfall ranges from 300 mm to 600 mm.

Climatic and environmental factors

The climate data used in this study were remotely sensed Climate Hazards Group infrared precipitation with station (CHIRPS) rainfall and land surface temperature (LST). Environmental factors assessed included vegetation cover, vegetation health, topographic wetness (TW) and slope. Moderate resolution imaging spectroradiometer (MODIS) LST (http://iridl.ldeo.columbia.edu/SOURCES/.USGS/.LandDAAC/.MODIS/.1km/.8day/.version_005/.Aqua/.EAF/) and precipitation raster data (http://iridl.ldeo.columbia.edu/SOURCES/.UCSB/.CHIRPS/.v2p0/.daily-improved/.global/.0p05/.prcp/datafiles.html), both at 5-km resolution, were obtained from the International Research Institute/Lamont–Doherty Earth Observatory (IRI/LDEO) climate data library. A multi-spectral, radiometrically corrected Landsat 8 image with 30-m spatial resolution for Baringo County for 27 December 2015 was acquired from http://glovis.usgs.gov. The date was screened and selected based on minimum cloud cover at the scene. A supervised land cover classification was conducted using a random forest algorithm. The normalized difference vegetation index (NDVI) map generated from the Landsat image was used to assess the vegetation health of the study area. Topographic wetness derived from the Landsat image was used as a proxy for moisture content. The TW index is a suitable proxy for soil moisture and an important environmental factor influencing the durations and frequencies of mosquito breeding habitats (Wiebe *et al.*, 2017). Area slope was generated from the Shuttle Radar Topography Mission (SRTM) digital elevation map (DEM) with 30-m resolution obtained from the National Aeronautics and Space Administration (NASA) website (https://lpdaac.usgs.gov/dataset_discovery/measures/measures_products_table).

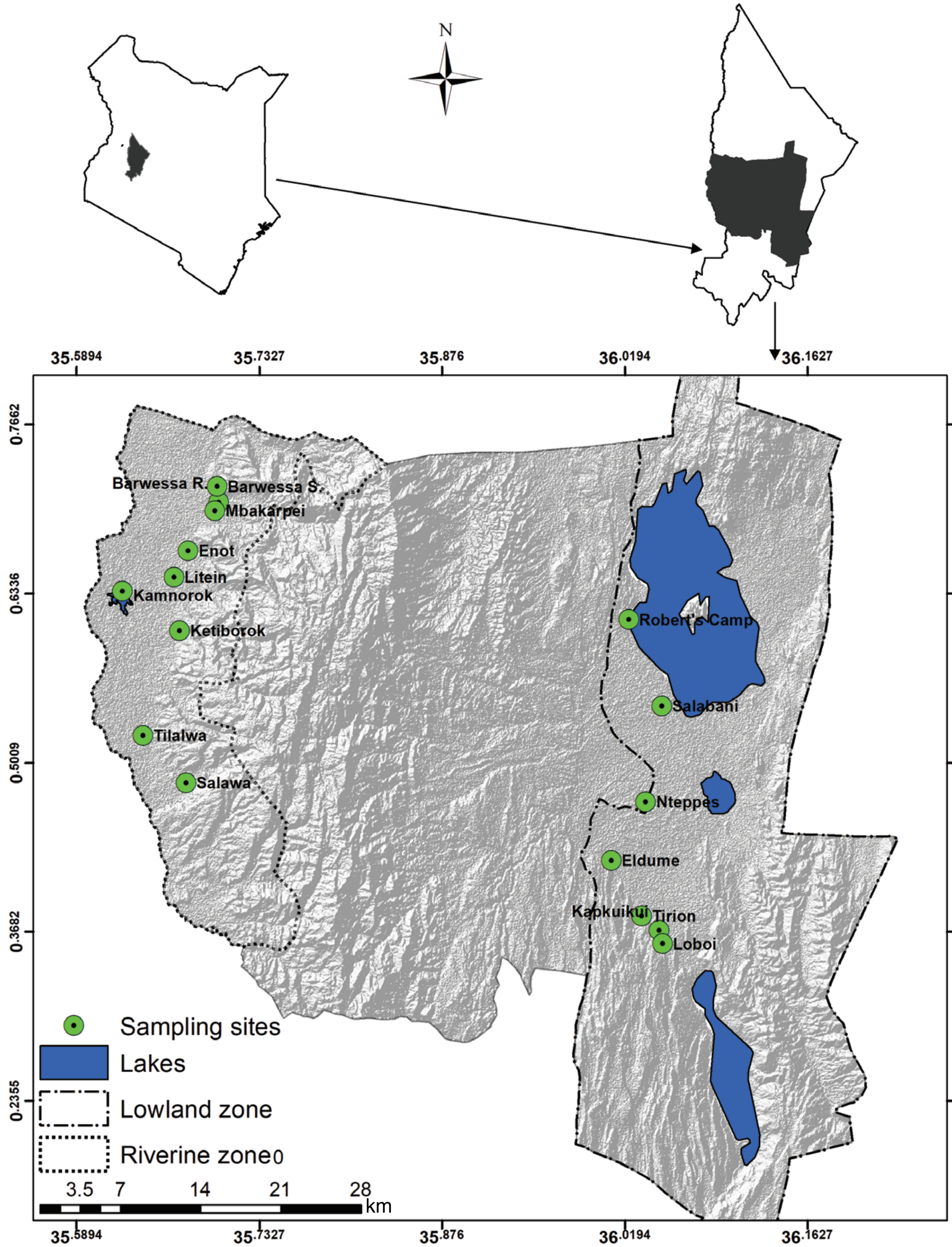


Fig. 1. Map of Kenya showing Baringo County. The study area (in grey) is enlarged to show the selected ecological zones and mosquito larvae sampling sites. [Colour figure can be viewed at wileyonlinelibrary.com].

Fig. 2. Various habitat types sampled for the presence of mosquito larvae. [Colour figure can be viewed at wileyonlinelibrary.com].

Entomological survey

Sixteen sampling sites were purposively selected based on availability and access. In the riverine zone, nine sites including Salawa, Tilalwa, Ketiborok, Mbakarpei, Litein, Kamnarok, Enot, Barwessa secondary and Barwessa River were selected. In the lowland zone, the seven sites sampled were Kapkuikui, Loboi, Salabani, Robert's Camp, Nteppes, Eldume and Tirion. Mosquito larvae were collected once per month for a period of 13 months from December 2015 to December 2016. In each ecological zone, permanent and transient breeding habitats were sampled for the presence of *Anopheles* species. Permanent habitats included lake edges, river fringes, canal overflows, swamp edges, drains, pan dams and water pits. Transient habitats were hoof prints, rain pools and concrete tanks (Fig. 2). In each habitat, 10 dips were taken using a standard 350-mL dipper (Service, 1993). A pipette was used in shallow habitats in which dippers could not be used. Habitat characteristics such as water depth, turbidity and the presence of aquatic plants were recorded. All larvae samples were preserved in 95% ethanol for later identification. Immature anopheline mosquitoes were identified morphologically to species level using keys provided by Highton (1983) and Gillies & Coetzee (1987). The identification of larvae was confirmed by experts from the Division of Vector-Borne Diseases in Marigat, Baringa County.

Data analysis

The random forest classifier was used to perform a supervised vegetation classification. First, training samples were selected from the Landsat image. Each pixel was given a class label from each tree, and the relative frequency of a pixel's class allocation from the multiple trees was used as a measure of classification confidence. The image was analysed using ERDAS Imagine 2015 (Erdas, Inc., Norcross, GA, U.S.A.) and R Version 3.2.2 (R Foundation for Statistical Computing, Vienna, Austria). The accuracy of land cover types was verified by ground truthing.

Six spectral bands from radiometrically corrected Landsat imagery were used in deriving the TW values for the study area. Tasselled cap transformation was applied to the bands based on coefficients. The values were standardized by a rescaling factor creating a range of 0–1, where 1 represented areas of high wetness and 0 represented areas of low wetness. A non-parametric Wilcoxon signed-rank test was used to compare abundances of mosquito larvae in lowland and riverine zones during January–December 2016. Larvae collected during December 2015 were used in modelling species distribution and were not included in the analysis of monthly trends.

A generalized linear mixed model with negative binomial regression was used to model the relationships between climatic and environmental factors and *An. gambiae s.l.* larvae abundances. Two-tailed correlation analysis was used to determine individual variables associated with *An. gambiae s.l.* larvae. Six predictor variables, including temperature, rainfall, TW, vegetation cover, vegetation health and slope, were used to build the model. All predictor variables were standardized to values ranging between 0 and 1 and resampled to 100 m to enable comparison. Saaty pairwise comparison enabled the ranking of land cover classes. The best model was selected based on the lowest Akaike information criterion (AIC) value. All statistical analyses were conducted in R Version 3.2.2.

Results

Spatial distribution of climatic and environmental factors

Figure 3 shows spatial distribution of rainfall, temperature, TW and slope. High levels of rainfall were observed in the highland and riverine zones, whereas the lowest level was recorded in the lowland zone. Low minimum temperature coincided with high rainfall (Fig. 3A, B). Low TW values (> 0.29) were observed in the riverine zone compared with the lowland zone (Fig. 3C). Similarly, high TW values coincided with low minimum temperatures. Both the lowland and riverine zones had area slopes of $< 7\%$ (Fig. 3D).

Landsat image classification generated eight land cover types comprising dense forest, sparse forest, wooded grassland, open grassland, annual crops, wetland, open water and bare land (Fig. 4A). Wooded grassland was the dominant vegetation type (36.4%, 305 518 acres). Sparse forests, open grassland and dense forests covered 18.3% (153 383 acres), 11.7% (97 897 acres) and 10.5% (88 296 acres) of land, respectively. Cropland (9.4%, 78 925 acres) was present in the lowland zone and wetlands (4.0%, 29 989 acres) were found in both the riverine and lowland zones. Open water (7.0%) included major lakes such as Lake Baringo, Lake Bogoria, Lake 94 and Lake Kamnarok. Bare land together with settlement covered the least area (3.0%). High NDVI values coincided with areas dominated by forest and cropland and low NDVI values were noted in areas with open grassland (Fig. 4B).

Entomological data

A total of 3460 mosquito larvae belonging to 11 species were collected during December 2015 to December 2016. Of these, 31% (1067) were *Anopheles* mosquitoes. The frequency of *An. gambiae s.l.* was significantly higher in the riverine zone than in the lowland zone ($W = 13$, $Z = -2.04$, $P < 0.05$, $r = 0.59$). In the lowland zone, the *An. gambiae s.l.* population showed a distinct seasonal pattern, with peak abundances occurring during May–July and December–January coinciding with the long rains and dry seasons, respectively. However, in the riverine zone, *An. gambiae s.l.* populations were present virtually throughout the year with peaks during April–June, as well as during February, September, November and December (Fig. 5).

Anopheles gambiae s.l. was found in 13 habitats consisting of marshes, river fringes, lake edges, canals and pan dams (Table 1). *Anopheles gambiae s.l.* was found in transient habitats such as rain pools and hoof prints, and in isolation in a water pit in the riverine zone. Further, *An. gambiae s.l.* was not found in an abandoned fish pond in which other species were present.

Effects of environmental factors on distributions of An. gambiae s.l. *species*

Rainfall, slope and vegetation health were significant factors influencing the distribution of *An. gambiae s.l.* larvae (Table 2). An increase in rainfall was associated with increased *An. gambiae s.l.* larvae ($b = 6.22$, $P < 0.001$, $\text{AIC} = 180.7$). Slope was also a significant environmental factor influencing the occurrence of mosquito larvae: an increase in slope negatively influenced the occurrence of *An. gambiae s.l.* larvae ($b = -4.81$, $P = 0.012$, $\text{AIC} = 180.7$). This study found a negative association between vegetation health and *An. gambiae s.l.* larvae ($b = -5.60$, $P = 0.038$, $\text{AIC} = 180.7$). Further, TW and vegetation cover had non-significant positive influences, whereas minimum temperature was negatively associated with the presence of *An. gambiae s.l.* larvae.

Figure 6 shows the spatial distribution of *An. gambiae s.l.* larvae in the region. The areas in dark red show high abundances of larvae, particularly in the riverine zone in comparison with the lowland zone. In the lowland zone, high larval abundance was associated with cropland and wetland. In the riverine zone, high abundance was associated with open grassland and wetland.

Discussion

Different land cover types have varied soil water input capacities. In Baringo County, high wetness values observed in croplands may have been attributable to irrigation activities enhancing surface moisture content. This finding is corroborated by Wang *et al.* (2013), who found high moisture levels in croplands compared with grassland in Yangjuangou, China. The gentle slope ($< 7\%$) in both zones suggests the potential for high levels of water accumulation and the possibility of flooding. Area slope and TW are correlated hydrological variables often associated with mosquito breeding habitats (Hanafi-Bojd *et al.*, 2012). Slope influences area drainage, water velocity and accumulation, whereas TW affects the occurrence and duration of larval

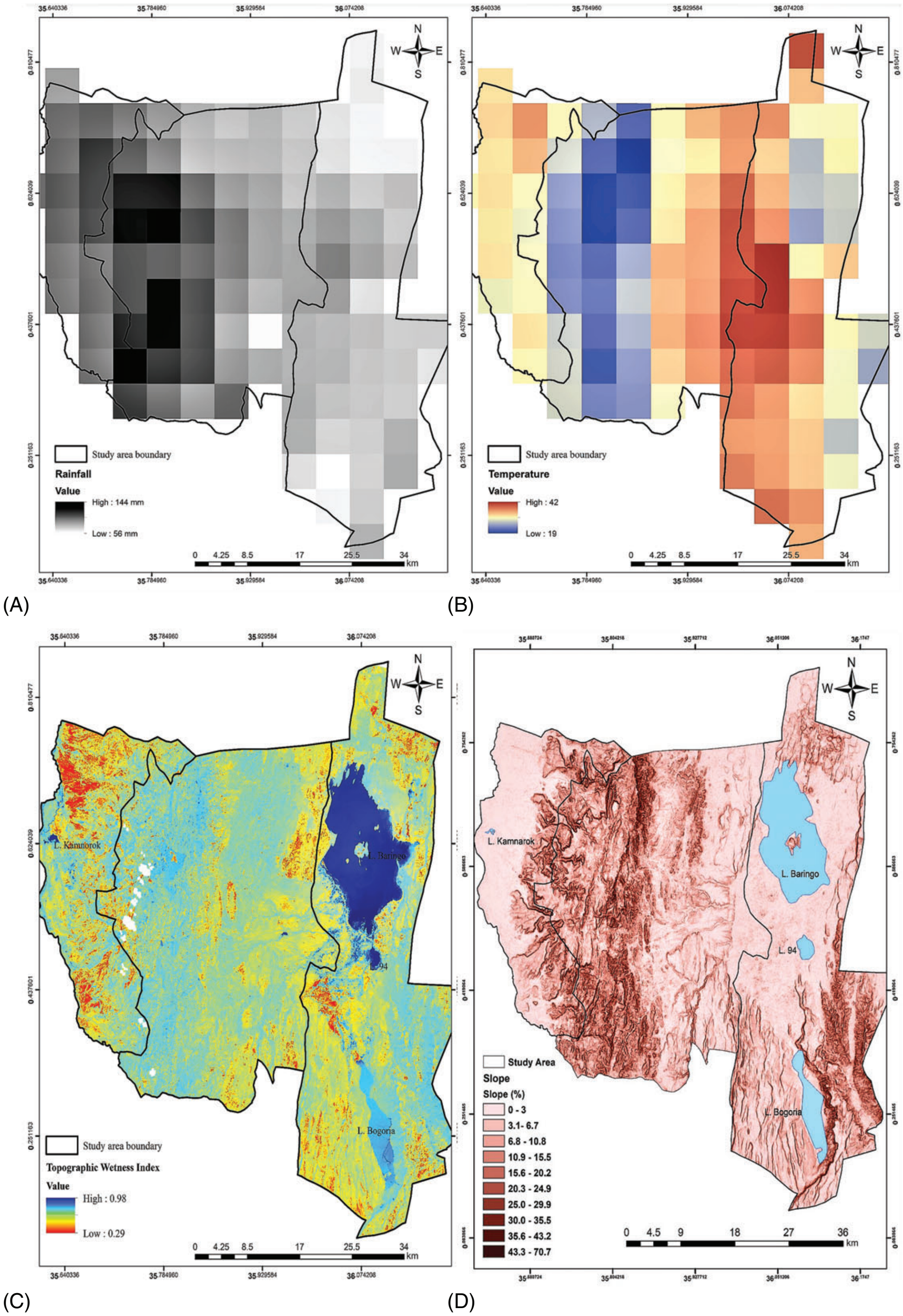
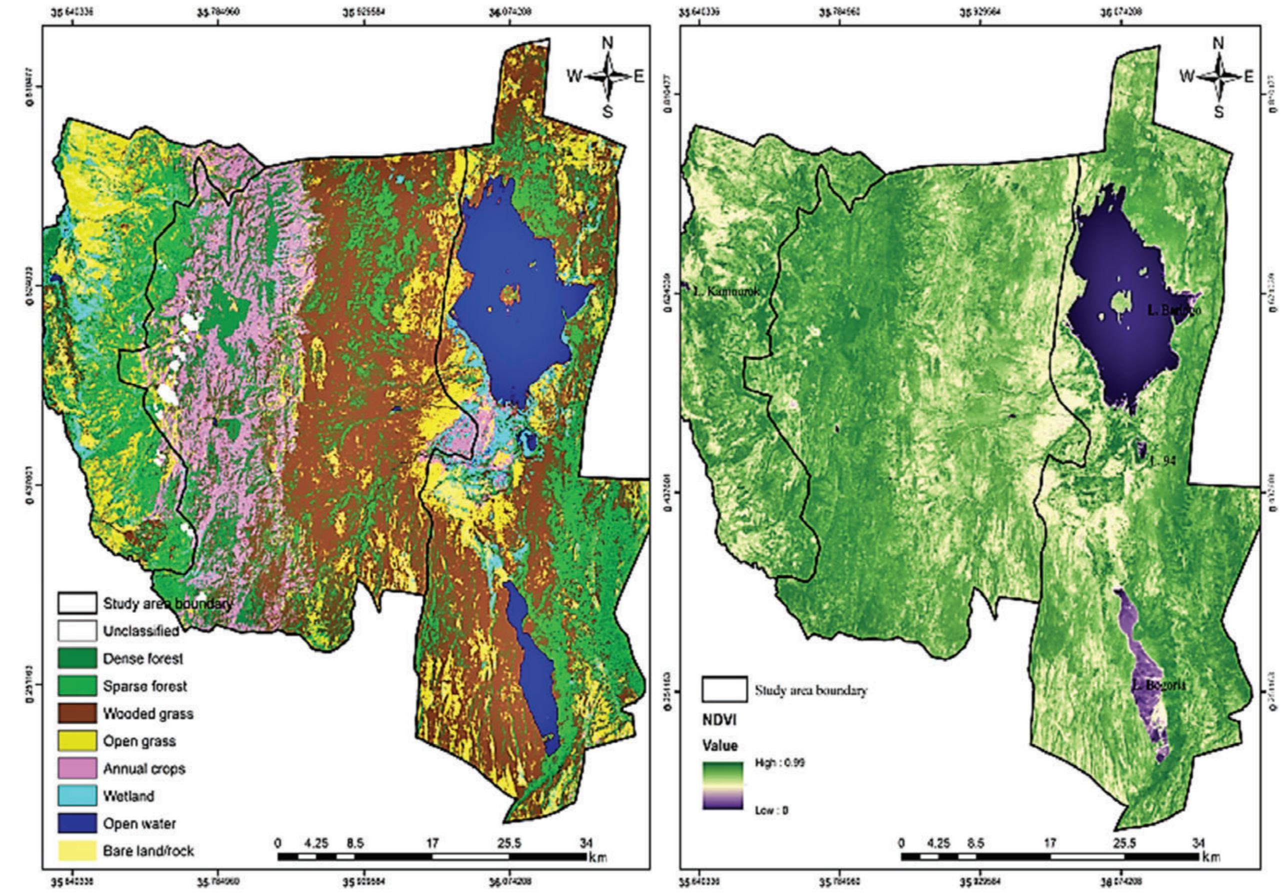


Fig. 3. Spatial distribution of (A) rainfall, (B) temperature, (C) topographic wetness and (D) the study area slope. [Colour figure can be viewed at wileyonlinelibrary.com].



(A) (B)

Fig. 4. (A) Land cover types and (B) vegetation health in the study area interpreted from a Landsat image. NDVI, normalized difference vegetation index. [Colour figure can be viewed at wileyonlinelibrary.com].

habitats, conditions likely to promote high *Anopheles* productivity (Nmor *et al.*, 2013).

Anopheles gambiae s.l. was abundant in the riverine zone compared with the lowland zone, which suggests that the risk for malaria is higher in this zone in comparison with the lowland zone. High *An. gambiae s.l.* abundance observed almost year-round in the riverine zone implies that malaria transmission may not be seasonal, as previously thought. The presence of high vector abundances during the dry season (December, January and February) suggests a possibility of dry season malaria transmission. This finding agrees with Mala *et al.* (2011), who found high abundances of *An. arabiensis* (a sibling species of *An. gambiae s.l.)* during dry seasons in the lowland areas in Baringo County. A recent study found high *P. falciparum* infection during the dry season in the riverine zone (Omondi *et al.*, 2017). This could be attributable to the presence of a dry season vector resulting in significant rates of malaria transmission.

Consistent with the present study, Arum *et al.* (2010) found *An. gambiae s.l.* to be widely distributed in marshes, canals and ditches in lowlands of Baringo. In Ethiopia, Kibret *et al.* (2014) found mosquito habitats to be confined to marshes and leaking canals during the dry season, indicating the roles of these habitats in sustaining a year-round presence of *Anopheles* mosquitoes. Similarly to natural breeding habitats, human-made habitats such as pan dams, puddles and culverts support *An. gambiae s.l.* larvae populations (Mattah *et al.*, 2017). This implies that environmental management practices such as the draining of rain pools and the maintenance of irrigation canals and ditches can potentially reduce abundances of malaria vectors in this region. The absence of *An. gambiae s.l.* in an abandoned fish pond could be attributed to deep water conditions that discouraged *An. gambiae s.l.* production.

This study showed high *An. gambiae s.l.* abundances in areas dominated by croplands and wetlands, which suggests that irrigation activities may feed habitats that support year-round mosquito activity in the lowland zone. According to Kibret *et al.* (2014), pools and leakages from irrigation canals promote high *An. gambiae s.l.* densities. An earlier study attributed high occurrences of *An. gambiae s.l.* in farmland to optimal abiotic conditions, and further stated that these conditions support faster mosquito development (Munga *et al.*, 2006). By contrast with the lowland zone, high levels of *An. gambiae s.l.* abundance were associated with open grassland in the riverine zone. This finding is

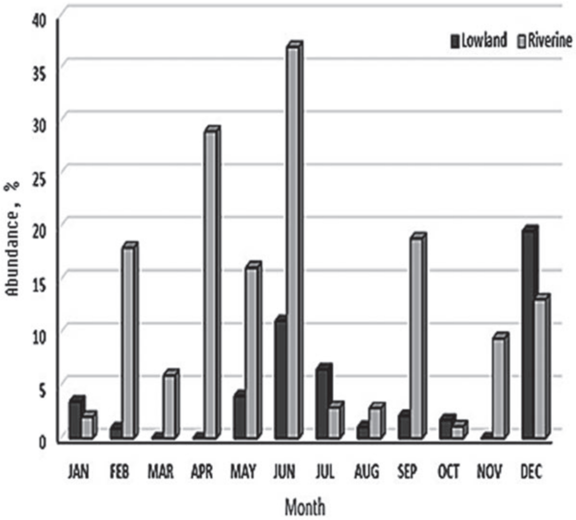


Fig. 5. Monthly distribution of *Anopheles gambiae s.l.* in the lowland and riverine zones during January–December 2016.

Table 1. Presence (+) or absence (−) of *Anopheles gambiae s.l.* in different habitat types during January–December 2016.

Habitat type	*An. gambiae s.l.*
Barwessa River	+
Barwessa secondary (water pit)	+
Mbakarpei River	+
Enot (marsh)	+
Litein canal	+
Kamnorok (lake margin)	+
Ketiborok River	+
Tilalwa dam	+
Salawa River	+
Robert's Camp (lake margin)	+
Salabani (lake margin)	+
Nteppes (canal)	+
Eldume (canal)	−
Tirion (canal)	+
Kapkuikui (marsh)	+
Loboi (canal)	−

consistent with observations by Kweka *et al.* (2015), who reported higher larval abundances in pasture than in other land cover types. The strong association of larval abundance with grassland is probably attributable to the oviposition attraction of *An. gambiae s.l.* species to grass-dominated breeding sites (Asmare *et al.*, 2017). It is evident that different land cover types play various roles in the spatial distribution of *An. gambiae s.l.* mosquitoes.

The distribution of *Anopheles* mosquitoes is influenced by multiple interconnected factors that vary in space (Dambach *et al.*, 2012). In this study, rainfall, slope and vegetation health had significant influences on *An. gambiae s.l.* larvae distribution. An increase in rainfall was associated with increased larval abundances, which is consistent with the findings of studies conducted on the Kenyan coast (Walker *et al.*, 2013) and in West Africa (Dambach *et al.*, 2012). Rainfall directly influences mosquito survival and densities (Mamai *et al.*, 2016) and may act as a proxy for the presence of larval habitats (Wiebe *et al.*, 2017). Like the present study, a study in Ghana found a negative association between slope and larval distribution (De Souza *et al.*, 2010). Recently, Wiebe *et al.* (2017) developed predictive maps showing the distributions of the *Anopheles* sibling species in Africa and showed that temperature, TW and slope were the best predictors for *An. gambiae s.l.* distribution in Africa. The variations in significant predictors of *Anopheles* distribution may be attributed to the use of different models and spatial scales. In the present study, vegetation health negatively influenced the occurrence of mosquito larvae, which suggests that shade provided by vegetation may negatively affect *An. gambiae s.l.* larval production (Munga *et al.*, 2006; Dambach *et al.*, 2012).

Table 2. Factors affecting the occurrence of *Anopheles gambiae s.l.* larvae.

Predictors	Estimate	*P*-value
Intercept	− 0.85	0.86
Vegetation cover	0.29	0.67
Vegetation health	− 5.60	0.038 *
Rainfall	6.22	0.00041‡
Temperature	− 0.58	0.68
Topographic wetness	2.15	0.76
Slope	− 4.81	0.012 *

Significance level: $*P < 0.05$; $†P < 0.01$; $‡P < 0.001$.

Conclusions

This study sought to investigate the environmental predictors of the distribution of *An. gambiae s.l.* larvae using a negative binomial model. The results reveal that rainfall, slope and vegetation health significantly influence the occurrence of *An. gambiae s.l.* larvae. The results further show that croplands and wetlands may sustain a year-round presence of the malaria vector in the region. Effective malaria control will require zone-specific interventions, such as a focused dry season vector control protocol in the riverine zone.

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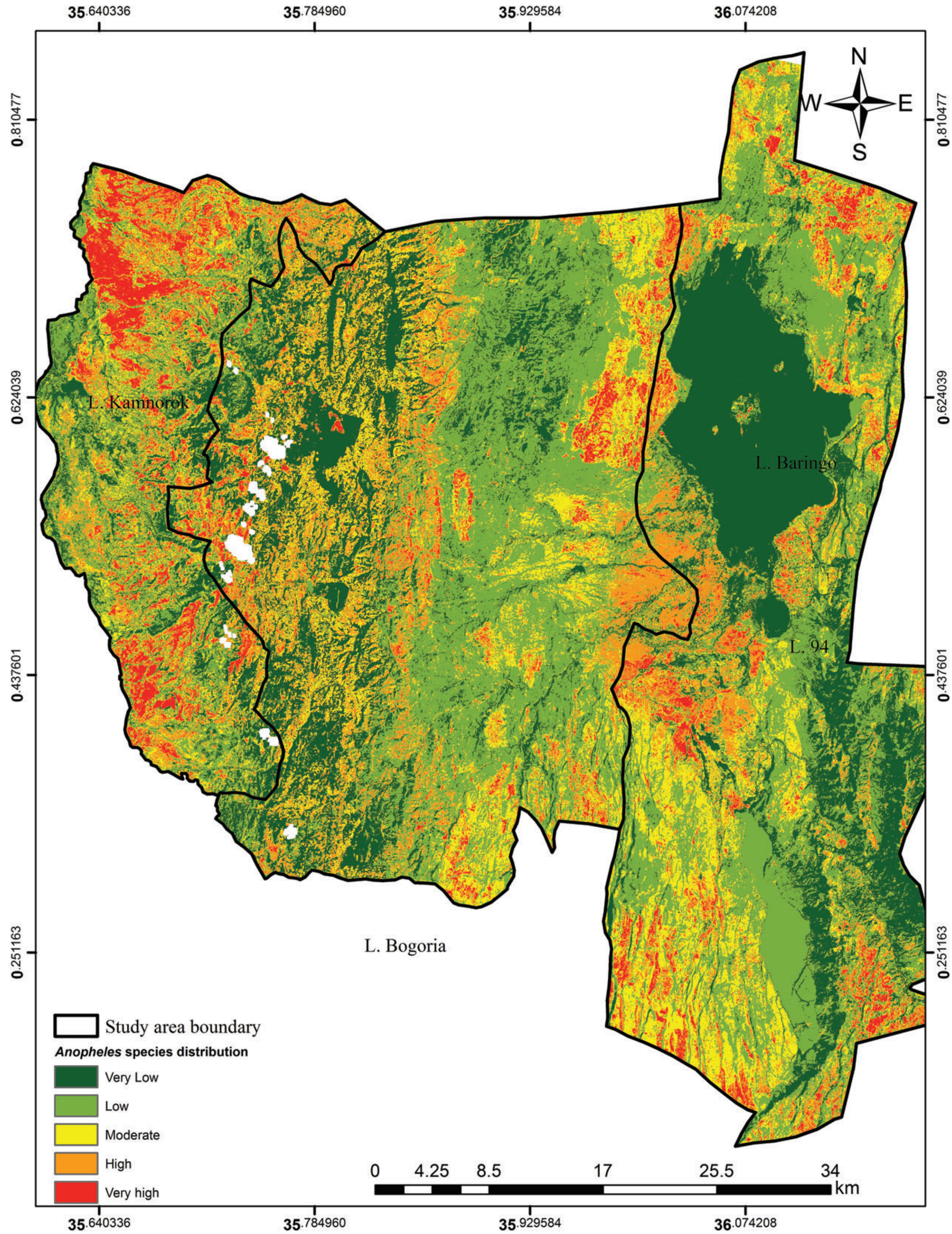

Fig. 6. Predicted spatial distribution of *Anopheles gambiae s.l.* larvae in the study area. White patches are areas with cloud cover. [Colour figure can be viewed at wileyonlinelibrary.com].

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