Am. J. Trop. Med. Hyg., 54(3), 1996, pp. 304–308

PREDICTIONS OF MALARIA VECTOR DISTRIBUTION IN BELIZE BASED ON MULTISPECTRAL SATELLITE DATA

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Abstract. Use of multispectral satellite data to predict arthropod-borne disease trouble spots is dependent on clear understandings of environmental factors that determine the presence of disease vectors. A blind test of remote sensing–based predictions for the spatial distribution of a malaria vector, *Anopheles pseudopunctipennis*, was conducted as a follow-up to two years of studies on vector-environmental relationships in Belize. Four of eight sites that were predicted to be high probability locations for presence of *An. pseudopunctipennis* were positive and all low probability sites (0 of 12) were negative. The absence of *An. pseudopunctipennis* at four high probability locations probably reflects the low densities that seem to characterize field populations of this species, i.e., the population densities were below the threshold of our sampling effort. Another important malaria vector, *An. darlingi*, was also present at all high probability sites and absent at all low probability sites. *Anopheles darlingi*, like *An. pseudopunctipennis*, is a riverine species. Prior to these collections at ecologically defined locations, this species was last detected in Belize in 1946.

The potential for using multispectral satellite data as an aid in malaria research, surveillance, and control stems from the close relationship of malaria vectors to specific environmental conditions that are detectable with remotely sensed data. *Anopheles* mosquitoes occur in spatial association with specific habitats or, on a larger scale, ecologic zones,[1] and in temporal association with specific patterns of rainfall, humidity, and ambient temperature. For example, larvae of *An. cruzii*, a malaria vector in Brazil, are found in small collections of water in bromeliads. The spatial distribution of *An. cruzii* corresponds to presence/abundance of bromeliads, and the distribution of bromeliads corresponds to the presence of certain forest types and other environmental conditions. Additionally, the species' temporal distribution corresponds to seasonal rainfall.[2] Vector-environment relationships exist for all vector species. The spatial and temporal association of vectors are reflected in the temporal and spatial dynamics of malaria transmission confined to specific environments and seasons.

Our experience, and that reported in published studies, show that satellite data gathered with various sensors and at different resolutions can be used to study the temporal and spatial distributions of disease vectors. Low resolution data, such as those from U.S. National Oceanic and Atmospheric Administration satellites, have been used for general studies of disease vectors in broad climatic zones or regions.[3,4] Higher resolution data from U.S. Landsat and the French Systeme Pour l'Observation de la Terre (SPOT; SPOT data are available from SPOT Image Corporation, 1897 Preston White Drive, Reston, VA 22091-4368) XS (multispectral) sensors have been used to study disease distributions associated with smaller terrestrial features such as villages, rice fields, etc.[5,6] A more complete understanding of how different surface features affect local abundance of specific vector populations is useful for interpreting higher resolution data.

Herein we report a test of multispectral satellite data, in combination with previously characterized environmental determinants, for accurately predicting sites with and without populations of *An. pseudopunctipennis* mosquitoes. In these investigations, we use a paradigm of studies leading to the use of remotely sensed data in predicting vector distributions.[7] Step 1 studies are designed to define the environmental determinants of disease vectors. The objective of step 2 studies is to define the scale for analyzing environmental determinants with satellite data. Step 3 studies can be used to validate analyses of satellite data with in situ (ground truth) data. The associations defined in steps 1, 2, and 3 can then be used to develop predictions (step 4 studies) that are subsequently verified with field studies (step 5 studies). The current research represents a progression of studies as defined in steps 1, 2, 4, and 5. The strong associations of *An. pseudopunctipennis* larvae with specific environmental conditions precluded the need for step 3 studies. Working only with multispectral satellite data, maps, and certain environmental criteria, e.g., amount of forest between houses and waterways, remote sensing specialists developed predictions without benefit of field data or prior knowledge of the study area or vector species. Predictions were based on computer enhancements of SPOT XS satellite data, full image interpretations, and environmental criteria.

MATERIALS AND METHODS

Study site. The study area in central Belize encompasses a northern section of the Hummingbird Highway (Figure 1) that traverses many streams and rivers within the forest-covered foothills of the Maya Mountains.[8] The grid coordinates of specific sampling sites are listed in Table 1.

Environmental criteria. Discriminant analyses of field data showed that increasing altitude and presence of filamentous algae in sun-exposed pools of waterways were critical environmental determinants for the presence of *An. pseudopunctipennis* larvae in the study[9] during the dry sea-

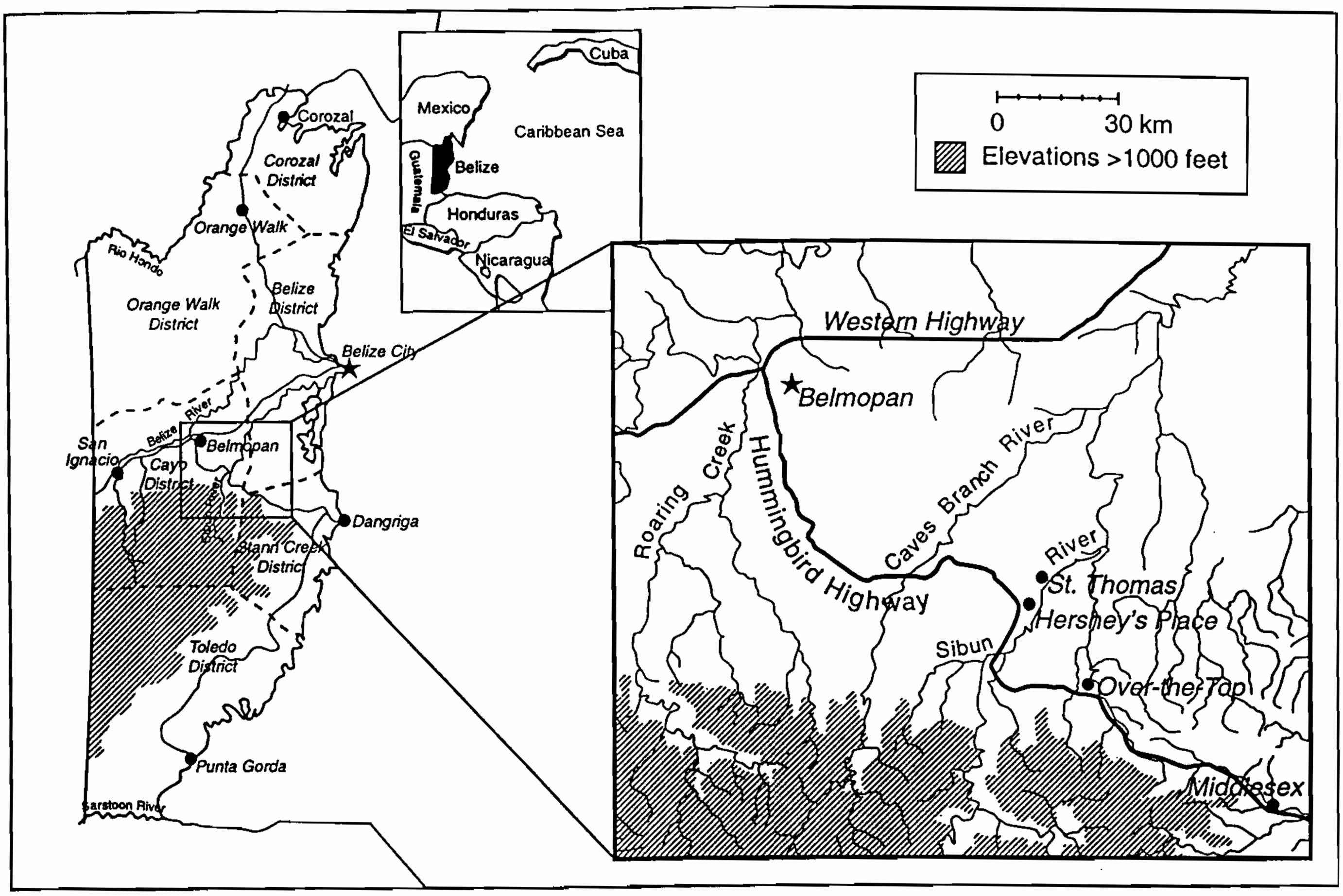

FIGURE 1. Map of Belize depicting the study area along the Hummingbird Highway (see Table 1 for grid coordinates of sample sites).

TABLE 1

Number of *Anopheles* mosquitoes collected from humans in paired indoor:outdoor landing collections and grid coordinates along the Hummingbird Highway of central Belize during April–May 1993 (dry season)

Collecting site	*An. pseudopunctipennis* Indoor:Outdoor	*An. darlingi* Indoor:Outdoor	*Anopheles* spp. Indoor:Outdoor	Grid coordinates (m)*	
				Easting	Northing
High probability sites					
Roaring Creek (#43)†	0:0	8:1	2:0	309,817.9	1,909,001.5
Caves Branch (#11)	1:1	1:3	0:0	317,815.3	1,896,681.2
Caves Branch (#12)	0:2	1:0	0:0	319,564.7	1,896,522.3
Hershey's Place (#14)†	0:2	0:4	3:36	324,609.8	1,895,129.4
St. Thomas (#16)‡	0:0	68:29	10:5	325,938.0	1,896,452.7
Sibun River (#15)	0:4	0:2	1:16	323,930.4	1,893,121.0
Middlesex Village (#30)	0:0	0:2	0:8	339,066.6	1,882,857.8
Middlesex Village (#32)	0:0	0:17	6:36	340,877.4	1,881,908.0
Low probability sites					
Near Silver Creek (#21)	0:0	0:0	0:0	324,287.4	1,890,041.7
Santa Margarita (#22)	0:0	0:0	0:0	326,251.3	1,890,136.0
Near Caves Branch (#7)	0:0	0:0	0:0	312,748.6	1,898,558.7
Armenia (#10)	0:0	0:0	0:0	315,823.7	1,896,332.3
Mile 25 (#28)	0:0	0:0	0:0	335,639.9	1,885,741.4
2 km from Middlesex (#29)	0:0	0:0	0:0	337,271.5	1,884,691.2
San Martin (#2)	0:0	0:0	0:0	312,592.3	1,907,406.5
Western Highway (#39)	0:0	0:0	0:0	311,658.7	1,910,643.4
Near Blue Hole (#13)	0:0	0:0	0:0	322,287.8	1,896,950.2
East of Caves Branch (#8)	0:0	0:0	0:0	314,370.9	1,897,415.0
East of Belmopan (#1)	0:0	0:0	0:0	313,448.9	1,909,252.0
Las Flores (#3)	0:0	0:0	0:0	310,697.6	1,906,436.3

* Map Coordinate System, Universal Transverse Mercator, Zone 16, North America.
† Sampled for two nights, house 14 was *An. pseudopunctipennis*-positive the first night and negative the second; house 43 was negative both nights.
‡ House sampled for three nights.

son, i.e., January through April. These environmental determinants were used in the analysis of SPOT XS data.

Originally eight sites, each for high, medium, and low probabilities for the presence of *An. pseudopunctipennis* were identified through an analysis of SPOT XS satellite and cartographic data. The criteria for site selection included distance of houses from waterways, altitude above specified waterways, and amount of forest between houses and waterways. A linear scoring system was used to categorize a total of 49 sites selected from inspecting image and map data. Only waterways with visible water were included in the analysis. For each of the three criteria list above, a score of 0, 1, or 2 was assigned for high, medium, and low probability sites, respectively. The scoring of sites by distance consisted of 0 for sites that were situated less than 1 km from the waterway, 1 for sites 1–3.5 km from the waterway, and 2 for sites that were at a greater distance than 3.5 km from the waterway. Scores for altitude above waterways were 0 for 0–50 m, 1 for 51–100 m, and 2 for > 100 m. The scoring for amount of forest cover between houses and waterways was 0 for no intervening forest, 1 for partial intervening forest, and 2 for a complete barrier of intervening forest. Sites were then rank ordered by total scores with high probability sites having total scores approximating 0, medium probability sites approximating 1, and low probability sites approximating 2 or above. To reduce requirements for numbers of sampling sites, we later collapsed the medium and low probability sites into a single low probability category.

In the analysis of satellite data, we assumed that the bed of a waterway was exposed to direct sunlight if it was visible in the image. If water also was clearly visible, then we assumed that there were adequate pools for producing enough *An. pseudopunctipennis* mosquitoes to appear in our collections at nearby houses. Visible water would appear in the images as low raster (a single, related, two-dimensionally grouped set of numbers that correspond to a specific area on the ground) values in the near infrared band (band 3). Since houses are critical sampling sites for the presence of adult malaria vectors, the remote sensing specialists attempted to select sites with houses. Areas where the forest had been cut and where there were other signs of intense human activity indicated the presence of houses. In some cases, groups of houses could be identified directly in the SPOT XS image. All of these factors were incorporated into the task of image interpretation.

Multispectral satellite data. Information from two sources was combined into a single 24-bit color image. One source was a multispectral digital image (SPOT XS) from a SPOT imaging system. The surface resolution of the data was 20 × 20 m per pixel. The second source was a set of 1:50,000 scale paper maps. Both sources contained information about land forms, vegetation cover, and other terrain features. The high resolution digital image for the Hummingbird Highway area was obtained on February 15, 1990. The data were collected during relatively cloud-free conditions (about 5% cloud cover). The SPOT XS includes the essential bands in the red light (XS band 2) and in the reflected near infrared (XS band 3) that are essential for mapping vegetation.[10, 11]

The paper maps were published in 1980 by the Directorate of Overseas Surveys and produced under the direction of the Director General of Military Survey, Ministry of Defence (London, United Kingdom). United States users can contact the Director, Defense Mapping Agency Aerospace Center, St. Louis, MO 63118. Computer processing was used to merge the SPOT XS data with the paper map data in a format for expert analysis. The maps were scanned into a Map and Image Processing System (MIPS) on an MS-DOS personal computer. The map and SPOT image data were manipulated with an MIPS (MicroImages, Inc., Lincoln, NE). The MIPS runs on an IBM-compatible personal computer under the Microsoft Disk Operating System (MS-DOS). The maps were scanned at 59.1 dots per cm (150 dots per inch). At map scale, this produced raster cell sizes of 8.5 × 8.5 m. The map data were georeferenced and each raster was aligned to true north by resampling and mosaicing the 36 map parts into one regional map raster. Raster inspection and raster algebra were used to correct variations in detector response and improve display quality.

To visualize the combination of XS and map data, the XS data were resampled to fit the 8.5-m map raster in a raster-based geographic information system (GIS). With the fused XS and map mosaic data on the screen as the displayed georeferenced raster, landscape features were drawn as vector (in the cartographic sense) lines. Since maps can be out of date or in error (positional errors, nonexistent features present, existent features left out, etc.), analysts depended mostly on the visual (displayed) landscape features in the XS colors (red and green) to indicate the presence and location of landscape features. In many cases, the landscape features in the XS image differed from the same features in the map image. Seeing both map and image data at the same time allowed the analyst to find and correct map errors. On the map, many minor waterways appeared to be dry in the XS image. The main indicator of dryness was brightness of band 3. Conversely, the presence of water in any part of a river or stream system appeared dark due to low band 3 raster values (provided the water was not covered by trees). Thus, we were able to trace and classify the rivers and streams in the region. Open visible water (in February) was a criterion that indicated potential for presence of larval habitats. Besides the mapped roads, there were other newer or unmapped roads. The latter could be detected best in XS bands 1 and 2. Analysts classified all vector lines as either major road, minor road, major waterway (with visible water in the dry season), and minor waterway (without visible water).

After the field surveys were completed, the image analysts traveled to Belize and video taped sections of the highway to test the accuracy of their image-based classifications of ground cover into forest, housing, agriculture, open water, e.g., rivers and cleared areas.

Field surveys. After compiling predictions of high and low probability locations, surveillance was initiated on April 30, 1993 to verify the accuracy of site predictions. Surveillance was continued until May 25, 1993. Collections of mosquitoes were conducted at houses in proximity to sites selected by the remote sensing specialists. Each collection consisted of paired indoor/outdoor collections of mosquitoes as they landed on humans from 6:30 PM to 8:00 PM. During each collection period, one collector was seated outdoors and one collector was seated indoors. Oral aspirators were used to collect mosquitoes as they landed on the collector's legs below the knees. Collections were performed by the investigators (DRR, SM, REH, and ER) and experienced technicians with the Ministry of Health. Two teams, one team of two collectors each, were used and 1–2 collections were conducted at each of 20 houses. Mosquitoes collected during this survey were identified and counted.

Numbers of humans and cases of malaria were relatively low along the Hummingbird Highway. Additionally, national malaria statistics were not useful for defining histories of malaria cases in individual households. Consequently, this experiment included no effort to correlate predictions of vector presence with malaria prevalence. Future studies in Belize will place greater emphasis on quantifying vectorial roles and testing predictions against malaria data.

Statistical tests. The hypothesis being tested was that we could use multispectral satellite data to predict which houses would have populations of *An. pseudopunctipennis* mosquitoes. Such houses were defined as being in high probability locations. We did not hypothesize an ability to predict densities of mosquitoes. Consequently, data compiled from this experiment were treated as presence/absence (binary) data. We tested the degree of agreement between the observed distribution and the predicted distribution of *An. pseudopunctipennis* mosquitoes with the chi-square one-sample test. Significance was established at the 0.05 level of probability.

RESULTS

The May 1993 video footage of sections of the Hummingbird Highway were used to assess the accuracy of image-based classifications of ground cover. The five ground cover classes that were used in developing predictions were estimated to be greater than 90% accurate.

North Stann Creek, Sibun River, Caves Branch, and Roaring Creek waterways were predicted to be high probability locations. All other waterways and intervening sites were categorized as low probability locations (Figure 1). In total, collections were conducted at eight houses in high probability and 12 houses in low probability locations (Table 1). We collected *An. pseudopunctipennis* mosquitoes at 50% of the houses in high probability localities. All houses in low probability localities were negative for *An. pseudopunctipennis.* The null hypothesis was that there was no difference between the predicted and actual distributions of *An. pseudopunctipennis*-positive locations. Since the chi-square one-sample test revealed no significant difference ($P > 0.05$) between the observed distribution and the predicted distribution of *An. pseudopunctipennis* mosquitoes, we could not reject the hypothesis.

Finding *An. darlingi* females in collections at all houses in high probability locations was a surprising outcome. Again, as with *An. pseudopunctipennis,* the low probability localities were negative for *An. darlingi* mosquitoes, as well as all other *Anopheles* species.

DISCUSSION

The satellite image used for developing predictions was obtained on February 15, 1990. Although the image was three years old at the time of this test of satellite image-based predictions, the image data were still quite accurate. Video taped data revealed that image-based ground cover classifications were more than 90% accurate. The errors were due to actual changes that occurred in the landscape features due to further development and land abandonment. This is not really a classification error, but is a real change that occurred over the three years between February 15, 1990 and late May 1993. While single houses with thatch roofs could not be detected, there were other indicators of human activities, such as forest clearing.

This test showed that useful predictions of vector presence, and even abundance, over large geographic areas are possible through the use of remotely sensed data. Of our test sites, *An. pseudopunctipennis* was present at 50% of the high probability locations and absent at all low probability locations. Low population densities seem to be a natural characteristic of *An. pseudopunctipennis.*[12] While *An. pseudopunctipennis* was possibly present at all high probability locations, its population densities were clearly below the sensitivity threshold of our collecting effort. Regardless, the finding of no significant differences between the predicted versus actual distributions shows that predictions for the presence of *An. pseudopunctipennis* mosquitoes were generally accurate.

Anopheles darlingi is an important vector in many areas of South and Central America. This riverine species was first reported in Belize in 1940[13, 14] and, prior to the current study, it was last encountered in Belize in 1946.[15, 16] We did not locate populations of *An. darlingi* while sampling a large cross-section of available mosquito larval habitats in Belize during the preceding two years.[9] Indeed, these efforts included some very specific attempts to collect *An. darlingi* larvae in the Hummingbird Highway area. We attribute our success at finally collecting *An. darlingi* to the satellite data used in selecting sites by proximities to rivers with open water. This result demonstrates the value of multispectral data for characterizing specific ecologic settings for malaria vector surveillance.

Overall, our test results reflect the extreme affinity of both *An. pseudopunctipennis* and *An. darlingi* for riverine areas. One might conclude that simple maps depicting rivers could serve for identifying high probability sites for these important vector species. However, maps do not depict current information on roads, areas of cleared forest, changes in agricultural land, the presence of human populations, or the presence of water in waterways. Additionally, maps provide essentially no information on size of waterways or the degree that waterways are open to sunlight.

To improve the cost-effectiveness of malaria control operations, some countries have adopted stratification approaches based on targeting areas for house spraying by history of malaria rates. While stratification increases the cost-effectiveness of spray operations, it may result in houses being sprayed only at locations where cases are detected, which may not be the actual site of malaria transmission. Under such circumstances, malaria transmission will continue unabated after houses are sprayed with insecticide. While the idea of targeting high-risk areas is valid, it seems preferable to target sites for treatment by knowing the locations of malaria vectors, as well as the locations of malaria cases.

Using this approach, in combination with the results of the current study, satisfactory levels of malaria control might be attained by only spraying houses in high probability locations along the Hummingbird Highway during the dry season. However, site selection criteria would need to be modified for spray operations during the wet season. This study demonstrates the value of multispectral satellite data for selecting sampling sites according to strict environmental criteria. Overall, the results of this test show potential for broad applications of multispectral satellite data to malaria research, surveillance, and control.

The malaria control program in Mexico represents a recent example of how the disciplined use of vector control measures can result in marked reductions of malaria cases. In Mexico, after 4–5 years of greatly reduced numbers of houses sprayed for malaria control, a peak number of 116,238 cases of malaria occurred in 1988. The government then increased the numbers of houses sprayed from a previous low of 276,785 in 1985 to 1,887,062 in 1991. This renewed effort succeeded in reducing malaria in Mexico; only 16,170 cases were reported in 1992. Reductions in malaria in Mexico occurred as numbers of malaria cases increased in Belize. In Belize, malaria increased from 10% to 96% from 1988 to 1992, apparently in response to dramatic reductions in numbers of houses sprayed with insecticide (Pan American Health Organization, Washington, DC, unpublished data). Increasing costs of insecticides and spray operations and decreasing numbers of houses sprayed are old trends (Pan American Health Organization, Washington, DC, unpublished data) that will probably continue. To counteract this bleak projection, national programs might still sustain an acceptable level of control by using malaria prevalence and vector ecology data, remote sensing, and GIS to target and prioritize their application of diminishing malaria control resources. This approach to malaria control presupposes an initial investment in hardware, software, training, and field research.

Acknowledgments: We thank Dr. Mel Avemer (Headquarters, National Aeronautics and Space Administration) for support of this research. We are also grateful for assistance with field studies provided by Shilpa Hakre and Linda Reyes (Epidemiological Research Center, Belize City, Belize). We thank Gustavo Escalante and Eugene Lisby (Malaria Vector Control Office, Ministry of Health, Belize) of Cayo District, Belize for assisting with field collections. Suggestions of anonymous reviewers were helpful in improving the manuscript and the reviewers' assistance is gratefully acknowledged.

Financial support: This work was supported by grant R087DB from the Uniformed Services University of the Health Sciences, in part by National Aeronautics and Space Organization grant W-16303 to the Uniformed Services University, and in part by grant DAMD17-90-Z-0013 from the U.S. Army Medical Research and Development Command.

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