MOSQUITO HABITATS, LAND USE, AND MALARIA RISK IN BELIZE FROM SATELLITE IMAGERY

KEVIN POPE,1 PENNY MASUOKA,2* ELISKA REJMANKOVA,3 JOHN GRIECO,4 SARAH JOHNSON,3,6 AND DONALD ROBERTS4

1Geo Eco Arc Research, 16305 St. Mary’s Church Road, Aquasco, Maryland 20608 USA
2Uniformed Services University of the Health Sciences, NASA’s Goddard Space Flight Center, Mail Stop 690.5, Greenbelt, Maryland 20771 USA
3Department of Environmental Science and Policy, University of California, 1 Shields Avenue, Davis, California 95616 USA
4Department of Preventive Medicine and Biometrics, Uniformed Services University of the Health Sciences, 4301 Jones Bridge Road, Bethesda, Maryland 20814 USA

Abstract. Satellite imagery of northern Belize is used to examine the relationship between land use and habitats of the malaria vector, the Anopheles mosquito. A land cover classification based on multispectral Système Probatoire d’Observation de la Terra (SPOT) and multitemporal Radarsat images identified 11 land cover classes, including agricultural, forest, and marsh types. Two of the land cover types, Typha domingensis marsh and flooded forest, are habitats of immature Anopheles vestitipennis, and one, Eleocharis spp. marsh, is the habitat for immature Anopheles albimanus. Geographic information systems (GIS) analyses of land cover demonstrate that the amount of Typha domingensis in a marsh is positively correlated with the amount of agricultural land in the adjacent upland and negatively correlated with the amount of adjacent forest. This finding, coupled with field studies documenting higher soil phosphorus in wetlands adjacent to agricultural fields, supports the hypothesis that nutrient runoff is the cause of higher densities of Typha domingensis in marshes adjacent to fields in northern Belize. Thus, agricultural activities can potentially increase Anopheles vestitipennis habitat and thereby increase malaria risk across a broad region where Anopheles vestitipennis is a malaria vector.

Key words: Belize; land use; malaria; marsh; mosquito; remote sensing; satellite imagery; Typha domingensis.

INTRODUCTION

Natural wetlands in northern Belize provide breeding sites for a variety of Anopheles mosquito species that transmit malaria (Rejmankova et al. 1993, 1995, 1996a, 1998). Malaria is a persistent health problem in Belize, although control efforts in the north have prevented severe outbreaks in recent years. The mean annual malaria infection rate over the last 10 years in northern Belize is ~2%, but some villages have rates as high as 9% (Hakre 2003). Despite this relatively low infection rate, the population of Belize is rapidly expanding, and there is a growing concern that changing land use and demographics in the north may increase malaria risks.

The climate of northern Belize is tropical wet-dry in the Köppen system, with maximum monthly mean temperatures ranging from 29°C to 33°C, humidity 80–88%, and annual rainfall averaging ~1400 mm, most of which falls between May and November. The region is a relatively flat coastal plain with elevations mostly below 20 m, approximately 30% of which is swamp, marsh, or seasonally inundated river floodplains (King et al. 1992). Given this high percentage of wetlands and that the population of northern Belize is largely rural and dispersed, most people live within close proximity to wetlands. Freshwater wetlands in northern Belize include a variety of marsh and forested types. The marshes of northern Belize have been studied extensively (Rejmankova et al. 1993, 1995, 1996a), and three broad types are identified by their dominant macrophyte species: (1) Eleocharis spp. (rush) marsh; (2) Cladium jamaicense (sawgrass) marsh; and (3) Typha domingensis (cattail) marsh. While many marshes contain mixtures of these three species (and other, less common ones), different nutrient and hydro-period tolerances between these three species favor marshes dominated by either Eleocharis cellulosa, Cladium jamaicense, or Typha domingensis (Rejmankova et al. 1995, 1996a). Forested wetlands in northern Belize have been less rigorously studied, but include two main types: (1) gallery forests along the Hondo and New Rivers and (2) swamp forests in the seasonally inundated karst depressions. The seasonally flooded forests...
typically support stands of evergreen and deciduous trees and palms 4–20 m in height (e.g., Wright et al. 1959).

Mosquito larval surveys and oviposition studies in northern Belize confirm that the malaria vector *Anopheles albimanus* breeds in cyanobacterial mats that are common in the *Eleocharis* spp. marsh (Rejmankova et al. 1993, 1996b). These mats can cover 35–75% of *Eleocharis* spp. marsh in the dry season when water levels are low, but drop to 1–15% in the wet season when most mats are submerged (Rejmankova et al. 1996b). Mosquito larval surveys in northern Belize also confirm that the malaria vector *Anopheles vestitipennis* breeds in flooded forests and even more commonly in marshes with tall, dense macrophyte vegetation, which is most typical of the *Typha domingensis* marsh (Rejmankova et al. 1998). Cyanobacterial mats providing habitat for *Anopheles albimanus* larvae occasionally develop within sparse stands of *Cladium jamaicense*, and especially dense stands of *Cladium jamaicense* can provide habitat for immature *Anopheles vestitipennis*. Nevertheless, on a regional scale *Cladium jamaicense* marsh is not a major producer of *Anopheles* mosquitoes. Given these associations between *Anopheles* mosquitoes and *Eleocharis* spp. marsh, *Typha domingensis* marsh, and flooded forests, our satellite remote sensing efforts focused on these three wetland types. Two other malaria vectors in Belize, *Anopheles darlingi* and *Anopheles pseudopunctipennis*, breed mostly in rivers and streams (Manguin et al. 1996, Roberts et al. 1996, 2002), and their larvae are rare in marshes and flooded forests; thus they are not a part of this study.

In this study we address two malaria control issues in northern Belize with the analysis of satellite imagery. The first is to use satellite imagery to map habitats of immature *Anopheles* mosquitoes. The second is to use satellite imagery to determine the degree to which agriculture impacts wetlands where *Anopheles* mosquitoes breed. Our specific objectives are (1) to map land use, *Typha domingensis* marsh, flooded forest, and *Eleocharis* spp. marsh; and (2) to examine the hypothesis that phosphorus runoff from agricultural fields creates higher densities of *Typha domingensis* in marshes adjacent to fields. Several studies in the Florida Everglades have demonstrated that wastewater from agriculture can cause the expansion of *Typha domingensis* (e.g., Davis 1991, Newman et al. 1996, DeBusk et al. 2001, Childers et al. 2003), and satellite imagery has been extremely useful in documenting this change (Jensen et al. 1995, Wu et al. 1997).

**Methods**

**Satellite image cluster analyses**

Our analysis of wetlands and adjacent land use is based on a land cover classification derived from a cluster analysis of *Système Probatoire d’Observation de la Terra* (SPOT) and Radarsat satellite imagery. We acquired a multispectral SPOT image (green, red, near infrared, and shortwave infrared bands) from March 2000 (resampled to 12.5-m pixels to match the Radarsat pixel size) and a series of Radarsat C-band (5.6 cm wavelength) horizontal like-polarized (HH) synthetic aperture radar images from December 1999, January 2000, February 2000, and July 2000. We used a handheld geographic positioning system (GPS) to obtain geographic coordinates of road intersections, which we then used to georeference the SPOT image to a Universal Transverse Mercator (UTM) map base. The Radarsat images were then coregistered to the SPOT image using tie points from prominent landscape features recognizable in both the SPOT and Radarsat images. We then used two passes of a 3 × 3 pixel moving window median filter to reduce the speckle noise in the Radarsat image (Gagnon and Jouan 1997). The combined four-band SPOT and four-date Radarsat image data set was run through multiple iterations of the ISOCLASS clustering algorithm (Tou and Gonzalez 1974) in the TNTmips software package (MicroImages, Lincoln, Nebraska, USA) to produce 75 clusters. These 75 clusters were next grouped into nine classes using the cluster dendrogram, selecting the most distinct groupings based on the relative distances in the dendrogram. We compared the image-based map with field observations (with GPS coordinates) of land cover to assign each class into one of nine provisional land cover types: water, low marsh, medium marsh, high marsh, forest, agricultural type 1 (Ag1), agricultural type 2 (Ag2), agricultural type 3 (Ag3), and urban/bare ground. The process permitted a quick appraisal of the land cover types that could be identified and the degree to which the cluster analysis separated known wetland and land use types. We found that overall the class groupings matched well with known land cover types, but there was notable confusion between some of the wetland and agriculture classes. To address this problem, we reran the ISOCLASS cluster analysis (with 32 clusters) for the areas that corresponded to the four provisional wetland classes (water, low marsh, medium marsh, high marsh) and one agricultural class (Ag3) where most of the apparent confusion occurred. We compared the results of this focused cluster analysis with the field observations and found that the confusion between wetland and agriculture was reduced, but not eliminated.

**Radar detection of seasonal flooding**

Comparison of the wetland land cover classes with our field observations indicates that the *Eleocharis* spp. marsh correlates well with our low marsh class. Nevertheless, the cluster analysis did not separate the *Typha domingensis* marsh from other high marsh types or the flooded forests from other forest types. To address this problem we performed a more detailed analysis of the Radarsat imagery. Our previous radar re-
search noted that flooded *Typha domingensis* marshes typically produce very high C-band HH polarized backscatter due to the double reflection of the radar signal off the vertical stem and water surface (Pope et al. 1997). Examination of the December 2000 Radarsat image revealed that our field observations of *Typha domingensis* marshes matched well with bright (high backscatter) patches in the image. Studies of *Typha domingensis* marshes in Yucatan determined that these marshes produced a mean backscatter of $>0.7$ dB when flooded (Pope et al. 1997), which is higher than any other natural vegetation type in the region (Pope et al. 2001). Therefore, we performed a threshold operation on the December 2000 Radarsat image to identify all pixel values $>0.7$ dB and classified these pixels as of *Typha domingensis* marsh.

Previous radar studies of C-band HH polarized backscatter from flooded forests in Yucatan noted a double reflection of the radar signal off the vertical trunks and water surface, similar to that found in the *Typha domingensis* marshes, but the effect was subdued due to the absorption of the C-band signal by the upper forest canopy (Pope et al. 2001). A backscatter increase of 1–3 dB occurs between dry season non-flooded and wet season flooded forests, with the larger increase coming from forests with continuous flooding (Pope et al. 2001). Larger wavelength radars such as L and P band provide better flood detection in dense forests (e.g., Imhoff et al. 1986, Pope et al. 1994, 2001, Hess et al. 1995), but appropriate images are not available for northern Belize. We extracted backscatter statistics from the non-flooded upland forest in the Radarsat images (several dates) and found that it is relatively constant at $-7.9 \pm 0.2$ dB; hence a flooded forest would be expected to have a backscatter of approximately $-5$ dB. Unfortunately the Radarsat imagery we used in the cluster analysis contained only images from the end (December) and beginning (July) of the wet season, periods when forest flooding is not extensive. Therefore, we obtained another Radarsat image from October 2000 that was acquired only a few days after Hurricane Keith crossed northern Belize and forest flooding was at its seasonal maximum. This image was coregistered and filtered as with the other Radarsat images. We did not use this image in our cluster analysis because it does not cover the entire study area, but it is the only image suitable for identifying flooded forests. We used the forest land cover type produced from the cluster analysis described above to extract a segment of the October 2000 Radarsat image that corresponded to forest. A threshold function was then applied to classify pixels with values greater than $-5$ dB as flooded forest. This segmentation was necessary because, unlike the *Typha domingensis* marsh, the backscatter from flooded forests is not unique, as many non-forest vegetation types produce backscatter values greater than $-5$ dB. A single pass of a $3 \times 3$ modal filter was performed on the binary threshold image ($0 =$ non-flooded, $1 =$ flooded) to reduce the blotchy appearance of the flooded forest in the image. This blotchy appearance may be due to (1) radar speckle, which is a form of noise typical of coherent imaging systems such as radar, (2) uneven penetration of the forest canopy by the C-band radar, (3) patchy flooding in the forests, or (4) a combination of these three factors.

**Classification accuracy assessment**

We assessed the accuracy of our land cover classification for each land cover type of interest to our malaria research by comparing the classification results with field observations (these observations were made independently from the observations used in the initial grouping of ISOCLASS clusters). Our field observations were made in 2002, thus changes in land use and marsh cover may have occurred since the images were acquired in 2000, but on a regional basis these changes are minor. The GPS coordinates were acquired in the field for six sugar cane, six annual crop, six pasture, six forest, six flooded forest, and 14 marsh test sites, each $>1.5$ ha in size. The marsh sites chosen were large tracts and encompassed several marsh types. The flooded forest sites were not flooded at the time of the field selection, but were known to flood each wet season based on earlier observations and the distinctive type of swamp or gallery forest vegetation. A similar approach was applied to the selection of 13 *Eleocharis* spp. marsh sites and 77 *Typha domingensis* marsh sites, although due to the restricted size of these marshes, smaller sites were chosen (0.14 ha for the *Eleocharis* spp. marsh and $>0.6$ ha for the *Typha domingensis* marsh). The test sites were then plotted on the classified image, and the percentage of each class in the site was calculated.

**Field transect analysis**

Using the SPOT-Radarsat classification to locate marshes, field teams selected 40 marsh test sites for transects and made extensive measurements of vegetation, water, and soil parameters and mosquito larvae and pupae populations along each transect. Twenty of the field transects were selected in “impacted” marshes with agricultural fields (sugar cane) adjacent to the marsh, and 20 transects were selected in “unimpacted” marshes surrounded by forest or scrub. All marshes contained at least some *Typha domingensis* (average ranged from 1 to 26% cover). Transects extended 100 m into the marsh measured perpendicular from the edge of the marsh and 100 m in the opposite direction into the adjacent upland.

Vegetation, water, and soil were sampled for chemical analysis at intervals of 0, 10, 25, 50, and 100 m into the marsh in the wet season (August 2001) and at intervals of 0, 50, and 100 m in the dry season (February 2002). Soil samples were also collected in the adjacent uplands. At each interval the percentage of total cover of each major macrophyte species and per-
percentage of live vegetation biomass were estimated using quadrates (Rejmankova et al. 1996a). Plant and soil samples were transported to the University of California, Davis, where they were analyzed for total N, C (both with a Carlo-Erba series 5000 CHN-S analyzer; Carlo-Erba, Milan, Italy), and P (with inductively coupled plasma atomic emission spectrometry [ICP-AES] after microwave acid digestion [Sah and Miller 1992]). Interstitial and surface water samples were analyzed for NH$_4$-N, NO$_3$-N, and soluble reactive phosphorus (SRP) according to standard procedures (Hunter et al. 1993). Significant differences in soil and vegetation parameters between the “impacted” and “unimpacted” marshes were determined using a nested two-way ANOVA. The relationship between environmental variables and plant species densities was assessed with multiple regression analyses and Canonical Correspondence Analysis (CANOCO 4.0; Ter Braack and Smilauer 1988) on transformed species cover and environmental data. Further details on the vegetation, soil, and water analyses are provided by Johnson and Rejmankova (2005).

In order to better define the relationship between marsh macrophyte species and *Anopheles* species, four rounds of larval sampling along the transects were conducted between 2001 and 2003 corresponding with the early wet (August–September), late wet (October–November), early dry (February–March), and late dry (May–June) seasons. Sampling occurred at the same intervals as the vegetation, water, and soils sampling (0, 10, 25, 50, and 100 m). Three collectors spaced 3 m apart sampled for the presence of larvae at each designated distance along the transect. Fifty dips per collector were made with a standard dip cup (Bioquip, Gardena, California, USA). Larvae were placed into 100-mL Whirl-Pak bags (Nasco, Modesto, California, USA), labeled with the transect location and positioning along the transect, and were returned to the field station for processing and identification using keys to larvae of the region (Clark-Gil and Darsie 1983). Pupae that were collected were transferred to separate rearing vials labeled with location data and were allowed to emerge to adults after which time they were identified using keys to the adult mosquitoes of central America (Wilkerson and Strickman 1990). Larvae that were too small to identify were treated in the same manner with the exception of adding a small amount of larval food to the vial until the larvae matured to the fourth instar. Linear correlations (Pearson’s correlation) were calculated between the abundance of each *Anopheles* species and the percent cover of each major macrophyte species at the sampling interval.

The GPS points were taken for the starting point and ending points at the marsh edge for each transect. In some transects a transitional zone (up to 72 m wide) representing a broad ecotone between the perennially flooded marsh and upland was apparent in the field. In these cases, the starting points for the marsh and upland transect were offset by the width of this transition zone. These GPS-derived transect endpoints were imported into ArcGIS (Environmental Systems Research Institute, Redlands, California, USA) and plotted on the SPOT-Radarsat classification. Buffer zones of 25 m were created around the transects to form sampling boxes of $50 \times 100$ m into the marsh and $50 \times 100$ m into the adjacent upland (where present, the transition zone noted above was omitted from the sample) (Fig. 4, upper panel). The buffer zones were exported to Geomatica (PCI Geomatics, Richmond Hill, Ontario, Canada) and a program was used to count the number of *Typha domingensis* marsh pixels in each marsh buffer zone and the number of forest, agricultural, and urban pixels in each upland buffer zone. Linear correlations (Pearson’s correlation) were calculated between the amount of *Typha domingensis* marsh in the marsh transect and the amount of forest and agricultural land in the upland transect.

GIS buffer analyses

We expanded our analysis of marshes and adjacent land use by using geographic information systems (GIS) buffering techniques to examine relationships between *Typha domingensis* marsh and land use on a regional scale. We created buffers around villages and around marshes. To examine the influence of land use on habitats of immature *Anopheles* mosquitoes within the vicinity of villages, we created 3-km buffer zones around 52 village center points (Fig. 1) and measured the amount of land cover within each buffer zone. A 3 km radius was selected to allow for the village size plus an approximate 2-km flight range of the mosquito, based on the 0.5–3.0 km flight range of *Anopheles albimanus* (Hobbs et al. 1974, Lowe et al. 1975) (we lack data for *Anopheles vestitipennis*). Each buffer zone thus represents an approximation of the area that potentially...
produces the Anopheles mosquitoes biting within that village.

In order to create buffer zones around marshes, the marshes on the classification (a raster format) had to be converted to a vector format. The land cover classification map (raster image in Fig. 2) was processed to create an image with only two values; a value of zero represented marsh (all types), and 255 represented...
FIG. 3. Steps in processing marsh classification from raster to vector format. (A) Classification image converted to two values: black for marsh and water pixels; white for all other land cover classes. (B) Image filtered using a 7 × 7 mode filter. (C) Image converted to a vector line format and manually edited to remove all island polygons and rivers. For scale, the width of each image is 17.5 km.

all non-marsh pixels (Fig. 3). This image contained too many marshes to convert to a vector format and included many very small (one- or two-pixel) marshes that we suspected were misclassified. To remove the small marshes, a 7 × 7 mode filter was used on the image (Fig. 3B). After filtering the image, we were able to convert the image to vector format (Fig. 3C). Next we displayed the vector marsh image over a multispectral IKONOS image, which we acquired for the central part of our study area. The IKONOS image was used to edit the SPOT-Radarsat classification, and a number of small marshes that appear to be agricultural fields were removed from the classification. The high-resolution (4-m pixels) of the IKONOS image made it possible to distinguish between agricultural fields and marshes using photo-interpretation techniques (texture, pattern, adjacent land cover type). The edited marsh image contained 112 marshes composed of ≥5 pixels (≥0.08 ha). Marshes boundaries were then buffered with a 25 m wide buffer inside the marsh margin and a 100 m wide buffer outside the marsh margin (Fig. 4, lower panel).

The amount of each land cover type within the village and marsh buffer zones was calculated using the ArcGIS and Geomatica programs. Linear correlations (Pearson’s correlation) were calculated between the amount of Typha domingensis marsh in the buffer inside the marsh and the amount of forest and agricultural land in the buffer outside the marsh. Linear correlations (Pearson’s correlation) were also calculated between the amount of Typha domingensis marsh and each land cover type within the village buffers.

**RESULTS**

**Field transect analysis**

Marshes adjacent to agricultural fields had significantly more Typha domingensis (20% vs. 6% average cover, df-factor = 1, df-error = 353, F = 7.02, P = 0.008) and significantly higher soil phosphorus (~130 μg/cm³ vs. ~85 μg/cm³, df-factor = 1, df-error = 252, F = 57.43, P < 0.0001) than marshes bordered by forest or scrub. Canonical Correspondence Analysis and multiple regression analyses identified soil phosphorus as the variable most strongly affecting macrophyte species abundance, with a positive influence on Typha domingensis (r = 0.68, P < 0.001) and a negative influence on Eleocharis cellulosa (r = −0.29, P < 0.001). See further discussion of these transect results in Johnson and Rejmankova (2005).

The analysis of the mosquito data showed that there was a strong correlation (r = 0.43, P < 0.001) between the densities of Typha domingensis and the densities of immature Anopheles vestitipennis. Immature Anopheles vestitipennis mosquitoes were present in Typha domingensis marshes in all seasons except when the marsh dried out completely in the dry season. By calculating the frequency of larvae by Typha domingensis density it becomes evident that greater than 82% of the larvae occurred at Typha domingensis densities of ≥40% cover. Where larvae did occur at lower densities of Typha domingensis, they were always associated with high overall percentages of macrophyte cover. Anopheles albimanus was positively correlated with cyanobacterial mats (r = 0.58, P < 0.0001). This species was negatively correlated with overall above-water biomass, Typha density, and Eleocharis density, and it occurred most often in sun-exposed areas of the marsh.

**Land cover map**

Results of the cluster analyses and the focused Radarsat analyses of flooded Typha domingensis marshes and forests were combined into a single land cover map.
Fig. 4. Buffer zones around field transects and marshes. The upper panel shows buffer zones 50 m wide and 100 m long centered on the marsh transects. The light gray buffer zone samples marsh vegetation; the dark gray buffer zone samples upland land cover. See the land cover key in Fig. 2. For scale, gray buffer zones are 50 m wide. The lower panel shows buffer zones 100 m outside (green) and 25 m inside (dark blue) marsh boundaries. Marsh not falling within the 25 m buffer zone is shown in light blue. For scale, each green buffer zone is 100 m wide.

(Fig. 2). The results of the classification accuracy assessment are presented in Table 1. Shown in Table 1 are the percentage of the corresponding land cover class found in each test site and the Kappa statistic, which is a measure of the correspondence adjusted for randomness (Congalton and Green 1999). This assessment reveals the following associations. The Ag3 class correlated with 76% of the area identified as sugar cane, although 14% of the annual crop, 21% of the pasture, and 22% of the Eleocharis spp. marsh also correlated with Ag3. Therefore, the Ag3 class reasonably represents sugar cane fields, but there remains some confusion with other agricultural lands and the Eleocharis spp. marsh. The small percentage (6%) of forest in the sugar cane sites is probably not misclassified and reflects trees along the margins of the sugar cane fields. The only significant occurrence of the Ag1 class in our tests was in the sugar cane fields (12%), thus Ag1 can be considered a variant of sugar cane. Nevertheless, examination of the classification map (Fig. 2) reveals large areas classified as Ag1 in the southern part of the study area that are pine savanna. The Ag2 class correlated with 82% of the annual crop, 77% of the pasture, and 3% of the sugar cane. Thus, our classification did not distinguish between annual crops and pasture, but if these two are combined into one land cover type (crops/pasture), there is only minimal confusion with other types. The forest class accurately represents forest, but there is considerable overlap between the forest and flooded forest classes. Our accuracy assessment of all marshes combined demonstrates that there is little confusion (~3%) between this broad category and other non-marsh land cover types. The Eleocharis spp. marsh correlates with our low marsh class (55%).

Associations of Anopheles habitat and land use patterns

The linear correlation (Pearson’s correlation) between the amount of Typha domingensis marsh and land use are presented in Table 2. All three analyses (transect, marsh buffer, village buffer) show the same trend of weak but significant negative correlations between forest and Typha domingensis marsh, compared to weak but positive correlations between Typha domingensis marsh and sugar cane or annual crop/pasture. In general, the strongest correlations were found in the marsh buffer analysis when only marshes with Typha domingensis were included and for the association of Typha domingensis marsh and sugar cane.

Discussion

Our research demonstrates that habitats of immature Anopheles mosquitoes and land cover can be mapped in northern Belize with a combination of dry season SPOT multispectral and Radarsat multitemporal satellite imagery. This result adds to a growing number of recent studies that demonstrate the potential of satellite imagery in malaria assessments (for a recent summary see Rogers et al. [2002]). In general, classification accuracies with Kappa statistics >80% are considered good, 40–80% moderate, and <40% poor (Congalton 1996). The best result for the habitat mapping is for the Typha domingensis marsh (Kappa = 93%), which is a primary habitat for immature Anopheles vestitipennis. The two problematic habitats in our analysis, the Anopheles albimanus habitat (Eleocharis spp. Marsh, Kappa = 51%) and the other Anopheles vestitipennis habitat (flooded forest, Kappa = 27%), were not evaluated well by our accuracy assessment methods because of their heterogeneity. Field studies at the 13 Eleocharis spp. marsh test sites recorded only ~40% cover of Eleocharis cellulosa and associated algal mats.
TABLE 1. Classification accuracy statistics (percentage of sites correctly classified and Kappa statistic) for selected land cover types in northern Belize.

<table>
<thead>
<tr>
<th>Test site</th>
<th>Ag3 (sugar cane)</th>
<th>Ag2 (pasture/crop)</th>
<th>Ag1 Forest</th>
<th>Flooded forest</th>
<th>Eleocharis (low marsh)</th>
<th>Typha</th>
<th>Medium marsh</th>
<th>High marsh</th>
<th>Urban bare ground</th>
<th>Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar cane</td>
<td>76</td>
<td>3</td>
<td>12</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Pasture</td>
<td>21</td>
<td>77</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>Annual crop</td>
<td>14</td>
<td>82</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pasture/crop</td>
<td>18</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Forest</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flooded forest</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>62</td>
<td>34</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>All marsh</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Eleocharis</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Typha</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

Notes: Mean area of all sites in a class was used to calculate percentage correctly classified. Pasture and annual crop were combined into a single class for Kappa statistic calculation. The Kappa statistic is a measure of the agreement, adjusted for randomness, between the land cover predicted in the image classification and that found in the test sites. The Kappa statistic is not given for “all marsh” because test sites combined five (water, Eleocharis marsh, Typha marsh, medium marsh, and high marsh) of the 11 classes.

The remaining 60% was mostly open water and minor amounts of Cladium jamaicense and Typha domingensis. Our classification of the Eleocharis spp. marsh test sites (Table 1) found a mean of 6% water, 14% medium marsh, 2% high marsh, and 2% Typha domingensis (the medium and high marsh types represent mixtures of Cladium jamaicense, Typha domingensis, and Eleocharis spp.). Given this heterogeneity, our classification accuracy of the Eleocharis spp. marsh may be >70%. The 34% correspondence between our flooded forest test sites and flooded forest class is difficult to assess. As noted above, the radar technique for identifying flooded forests produced a blotchy pattern that may in part be an artifact of the technique, but probably also reflects patchy flooding. The latter possibility could not be evaluated directly, since we have no field observations from the date of the Radarsat data. Nevertheless, our wet season observations in other years consistently found that these forests were <50% flooded. If we assume that <50% of the forests in the tests sites were flooded, then our classification accuracy for this class increases to >68%.

Excellent classification results were obtained for the forest (Kappa = 99%) and moderate to good results were obtained for sugar cane (Kappa = 74%) and our combined pasture/crop class (Kappa = 78%). Note also that in our marsh buffer analysis we used an IKONOS image to edit the sugar cane and pasture/crop classes to exclude small erroneous patches of marsh, thus increasing the accuracy of these classes in that specific analysis. The good classification results for land use, coupled with the excellent results for Typha domingensis noted above, give confidence to our assessment of the associations between Typha domingensis marsh and land use based on satellite imagery.

The correlation analyses presented in Table 2 clearly demonstrate that Typha domingensis marsh is more abundant in marshes bordered by agricultural lands than in marshes bordered by forest. The most consistent results are for a positive correlation between Typha domingensis marsh and sugar cane. This finding, based on satellite image analyses, matches the results of the more spatially limited field transect analysis, which also found larger amounts of Typha domingensis in marshes adjacent to sugar cane fields compared to forest or scrub lands. We hypothesize that this association between Typha domingensis and agriculture is the result of phosphorus-laden runoff from agricultural fields into adjacent marshes. This hypothesis is based upon our field transect analyses, which found higher soil phosphorus levels in the marshes adjacent to agricultural fields and a correlation between soil phosphorus and Typha domingensis densities and on the results of studies of similar marsh ecosystems in the Florida Ev-

TABLE 2. Pearson correlation coefficients (r) and significance (P) for the amount of Typha domingensis in a marsh vs. the amount of various land cover types in the adjacent upland.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>n</th>
<th>r</th>
<th>P</th>
<th>Typha vs. pasture/crop</th>
<th>P</th>
<th>Typha vs. sugarcane</th>
<th>P</th>
<th>Typha vs. agricultural land</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transect</td>
<td>40</td>
<td>-0.22</td>
<td>0.18</td>
<td>...</td>
<td>...</td>
<td>0.41</td>
<td>&lt;0.01</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Marsh buffer, all</td>
<td>112</td>
<td>-0.14</td>
<td>0.13</td>
<td>0.17</td>
<td>0.07</td>
<td>0.23</td>
<td>0.01</td>
<td>0.25</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Marsh buffer, with Typha</td>
<td>37</td>
<td>-0.48</td>
<td>&lt;0.01</td>
<td>0.33</td>
<td>0.05</td>
<td>0.35</td>
<td>0.03</td>
<td>0.39</td>
<td>0.02</td>
</tr>
<tr>
<td>Village buffer</td>
<td>52</td>
<td>-0.21</td>
<td>0.14</td>
<td>0.05</td>
<td>0.71</td>
<td>0.23</td>
<td>0.10</td>
<td>0.23</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Notes: Analyses are given for transect, marsh buffer, and village buffer analyses (see text). Significant correlations (P ≤ 0.05) are shown in boldface type.
ergalades (e.g., Craft and Richardson 1997, Doren et al. 1997, DeBusk et al. 2001). Nevertheless, future research is needed in Belize to confirm that Typha domingensis marsh is actually expanding in regions recently impacted by agriculture.

While several of the correlations in Table 2 are highly significant (P ≤ 0.01), the r values are low, indicating that only ~5–20% of the variance (r^2 range 0.05–0.23) in the distribution of Typha domingensis marsh can be explained by larger amounts of agricultural land vs. forests in the catchments. Therefore, current land use is not the dominant factor controlling the distribution of Typha domingensis in northern Belize. Nevertheless, it is surprising that the village buffer analysis produced marginally significant correlations between Typha domingensis marsh and sugar cane (r = 0.23, P = 0.10), which suggests that this association may exist at a regional scale in northern Belize. It is important to note that the highest correlations were found in the analyses that included only marshes that contained some Typha domingensis (Table 2, transects and marsh buffer with Typha). This may reflect the situation in which runoff causes Typha domingensis expansion where it already exists, but has less influence in marshes that lack Typha domingensis to begin with.

Our finding that agricultural land use in northern Belize is associated with higher densities of Typha domingensis, a major habitat for immature Anopheles vestitipennis, has important ramifications for malaria risk in the region. Marshes with sparse or mixed stands of Cladium jamaicense and Typha domingensis (our land cover classes of medium and high marsh) are not favored habitats for immature Anopheles mosquitoes (Rejmankova et al. 1993, 1995, 1996b, 1998). Furthermore, Anopheles albimanus, which breeds in Eleocharis spp. marshes, is a less potent malaria vector than Anopheles vestitipennis (Elliott 1972, Loyola et al. 1993, Achee et al. 2000, Grieco et al. 2002). Therefore, the replacement of Eleocharis spp. marsh and other marsh types with Typha domingensis marsh potentially increases malaria risk by increasing both the abundance and potency of vector species. Thus the expansion and intensification of agriculture throughout the Gulf of Mexico and Caribbean region where Anopheles vestitipennis is a malaria vector may cause a widespread increase in malaria risk. This study demonstrates that satellite image analyses can be used to assess this risk and to provide useful information on the distribution of Anopheles habitats for vector surveillance and control efforts.

ACKNOWLEDGMENTS

This research was funded by the U.S. National Institute of Allergy and Infectious Diseases grant R01 AI49726 and by NASA grant NAG5–12593. We thank the Ministry of Health in Belize for their help and encouragement. Special thanks to Errol Vanzie, Director of Health Services, Belize, and Jorge Polanco, National Epidemiologist, Belize.