Spatial Patterns of Malaria Case Distribution in Padre Cocha, Peru

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Abstract

Padre Cocha is a village of 1,400 inhabitants, situated in an area of epidemic vivax and falciparum malaria in the Peruvian Amazon. During the 1997–1998 transmission year, there were 1,157 *Plasmodium vivax* infections and 232 *Plasmodium falciparum* infections diagnosed at the village health post. As part of an ongoing study of malaria transmission in Padre Cocha, the village was mapped using global positioning system (GPS) hardware over the course of one week. Differential GPS correction of locations of all features mapped yielded a positional standard deviation of ±0.2 meters. Mapping of household malaria incidence data revealed areas of consistently high malaria infection density and a central area of low malaria incidence. This pattern suggests that transmission dynamics are heterogeneous within this village of approximately 1 square kilometer. The use of geographic information system (GIS) techniques to explore spatial relationships contributed to generating hypotheses when approaching this previously unstudied site, to exploring patterns of malaria case distribution, and to directing further entomological and epidemiological field work and malaria control measures. Proficiency with the required GPS equipment and GPS/GIS software was achieved by previously inexperienced users during a one-week training session, after which the on-site team was able to continue to use the system to successfully complete the project.

Keywords: malaria, Amazon, *Plasmodium falciparum*, *Plasmodium vivax*, *Anopheles darlingi*

Introduction

Malaria in Peru has undergone explosive growth during the 1990's, particularly in the Amazonian region of Loreto where more than 60% of the cases have occurred (Figure 1). Causes for the epidemic rise in *Plasmodium vivax* (*P. vivax*) and *Plasmodium falciparum* (*P. falciparum*) infections are thought to include the arrival of the highly efficient vector, *Anopheles darlingi* (*An. darlingi*); the dismantling of household residual insecticide spraying programs that took place prior to the 1990's; the changing patterns of river use; and the ecological disruption related to increasing jungle settlement and natural resource exploitation (1,2,3,4).

There has been relatively little study of specific factors related to malaria acquisition and transmission in the Amazon basin, despite the resources that have been

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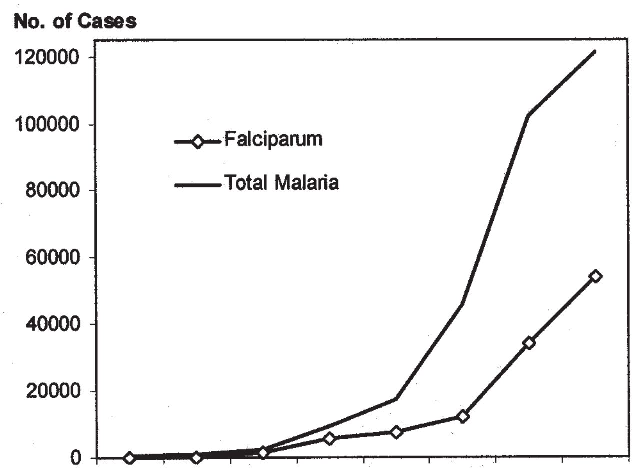

Figure 1 Malaria in Loreto, Peru, 1990–1997.

expended on treatment and control. Studies in Rondônia, Brasil, have shown that malaria is principally related to forest-based occupations such as gold mining and logging (5,6). In the Department of Loreto, Peru, malaria is more common in adults, particularly males, suggesting occupational risk as well (2,3). In other parts of the world, studies have highlighted the heterogeneous nature of malaria incidence and vector distribution within small areas (7,8), as well as the relationships of household malaria risk to vector abundance and distance from vector breeding sites (9,10,11). There have been no studies investigating specific malaria risk factors or spatial relationships in malaria transmission in Loreto to date. As part of an ongoing study of the epidemiology and transmission of malaria in Padre Cocha, Peru, the village was mapped using differential global positioning system (GPS) technology and spatial patterns of the distribution of malaria during the 1997–1998 transmission season were explored.

Materials and Methods

Padre Cocha is a village of 1,400 inhabitants, situated 5 kilometers (km) from Iquitos, the capital of Loreto (Figure 2). The village lies at the side of the Nanay River in a high malaria transmission zone (latitude 3°41'55" S; longitude 73°16'39" W; altitude 122 meters [m]). Between the river and village lies a cocha, a lake fed by the river, which expands and contracts with the river level. The central portion of the village has been cleared; the periphery is ringed by scrub and secondary forest, some of which is inundated during high-water months. Mean annual rainfall is 4.3 m, and the river fluctuates approximately 10 m throughout the year, peaking in April and May. There are 235 households with a mean of 6 occupants (sd=±3). House construction consists of two basic types—traditional boards or logs and thatched roofs, and newer brick and concrete with sheet metal roofs. Malaria is perennial with peak transmission during the wetter months of January through June.

In November 1997, all houses, streets, public buildings, and other features of interest in Padre Cocha were mapped in a five-day period using Trimble ProXR GPS

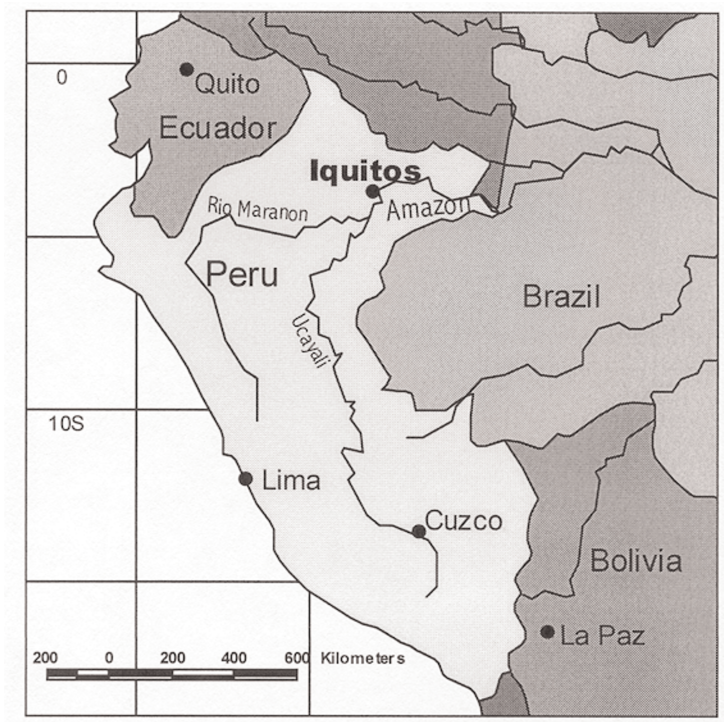

Figure 2 Map of Peru. The study site of Padre Cocha is located 5 km northwest of Iquitos.

receivers. GPS receivers capture radio frequency signals continuously emitted by 21 navigational satellites orbiting the earth at an altitude of approximately 20,200 km (12). During the Padre Cocha mapping, data were received from at least four satellites at any given time, permitting the calculations of latitude, longitude, and altitude. The exact methodology for how position fixes are computed is described in detail elsewhere (12,13).

Error in GPS position determinations arises from several uncontrollable sources, including atmospheric and topographic conditions, orbital and clock error, receiver noise, and most importantly, selective availability, the intentional error component built into the signal of each satellite. Selective availability varies with time and from one satellite to the next. Thus, errors are highly correlated with respect to time if readings are all from the same satellite group, while changes in satellite group members being used to measure positions yield abrupt changes in computed locations. The resultant variation in measurement error can lead to significant compromise of the accuracy of calculated positions. In the absence of adjustment, error in positional accuracy can be as high as 100 m (10,12,13).

To circumvent these sources of errors, post-processing differential correction of locational data, or differential GPS, was employed. For this technique, two receivers storing simultaneous signal information and subject to the same sources of error are required. One receiver is placed at a fixed known location, the base station, while the other is used to record information at remote sites of interest. The data from each receiver are downloaded to a computer program with differential correction capability, are synchronized, and the base station information is used to calibrate the positions recorded by the mobile unit.

For the Padre Cocha mapping, one receiver was placed on the middle of a marker with coordinates previously identified by a US Geologic Service survey at the Peruvian Naval Base in Iquitos (latitude 3°44'05" S; longitude 73°14'25" W; altitude 95.5 m). This receiver served as the base station and collected data continuously, while the second receiver simultaneously recorded village feature positions. The locations of all village point features (houses, shops, public buildings, wells) were measured for two minutes with positional fixes taken at one-second intervals. For line and area features, positions were recorded at three-second intervals as lengths or borders were walked. The perimeter of the cocha was recorded from a canoe paddled around its circumference, using a constant offset from the shore. Each house was assigned a unique household identification number at the time that it was mapped, and information about construction type and the presence of home businesses was also recorded. Pathfinder Office software, version 1.10 (Trimble Navigation, Sunnyvale, CA) was used to perform differential correction of all feature locations and to create a locational database for use in geographic information system (GIS) analyses. In May 1998, new houses erected during the study year were mapped and added to the database.

At the time of the initial Padre Cocha mapping, a community-wide census was performed to obtain basic demographic information. Each identified resident was assigned a unique personal identifier and household address. During the course of the study year, the census database was updated as new residents were identified and former residents moved away. In May 1998, a second village-wide census was performed to verify the completeness and accuracy of all demographic information.

Malaria case data were collected continuously at the Padre Cocha Health Post from August 1, 1997, through July 31, 1998. Individuals with symptoms suggestive of malaria received Giemsa-stained blood smear examinations by experienced Ministry of Health (MOH) microscopists. Those whose blood smears demonstrated malaria parasites were considered cases and were treated in accordance with Peruvian MOH protocols. Information about smear positivity and treatment response was entered into a registry kept at the Health Post, and was subsequently abstracted and entered into an EpiInfo, version 6.04 (CDC, Atlanta, GA), computer database. Individual malaria case data were grouped by the household in which the infection occurred, and incidence for each household was calculated as the number of malaria episodes occurring during a given time period in each home, divided by the number of people residing in that home during that time period. Because there was movement of residents in and out of households during the year, the incidence for the study year was determined by calculating household incidence for each half of the year, and then summing the two six-month incidences. Household incidence for the low-transmission dry season (August–November), high-transmission wet season (December–March) and the transitional season of declining transmission (April–July) were calculated in the same manner.

Entomologic investigations began in Padre Cocha in March 1998. The results of a pilot study of vector abundance performed in late March to July 1998 are the source of data used in this analysis. Adult female mosquitoes were captured at four study stations using indoor and outdoor human landing catches. Mosquitoes were collected by a team of technicians working four consecutive nights from 6:00 PM to 6:00 AM, in twice-monthly cycles. The numbers of female anopheline mosquitoes detected were entered into a computer database by species, parity, and location of capture. The total number of *Anopheles* mosquitoes captured both indoors and outdoors at each station was calculated and used for comparison with the human malaria case distribution for April through August 1998.

ArcView software, version 3.0 (Environmental Systems Research Institute, Inc., Redlands, CA), was used for GIS analysis. The Pathfinder locational database was exported as ArcView shape files, entered into ArcView and then merged with household malaria data exported from EpiInfo in Dbase format. Surface interpolations were performed with ArcView Spatial Analyst in order to make patterns of household-specific malaria transmission easier to interpret. This methodology summarizes information collected for all data points within a fixed distance from a given location; or, for a predetermined number of nearest neighbors, computes the mean or median and applies this smoothed estimate to the entire area under consideration. Observations are weighted proportionally to their distance from the center of the defined area. We used linear weighting and restricted consideration to only those households lying within 50 m of each specified point.

This work was conducted under research protocols approved by the scientific and human use committees of the Walter Reed Army Institute of Research (WRAIR Protocol No. 727) and the United States Army Medical Research Institute of Infectious Diseases (USAMRIID, HSRRB Protocol Log No. A-7421, DoD Protocol No. 30558), and the corresponding ethical review committee of the Direccion Regional de Salud de Loreto. In addition, the studies were conducted under Technical and Scientific Letters of Intention between the US Naval Medical Research Center Detachment (NAMRCD), Lima, Peru, and the Direccion Regional de Salud de Loreto and the Vice-Minister of Health (RM No. 237-97-SA/DM of 5 May 97) for the government of Peru.

Results

Figure 3A shows the map of Padre Cocha using the corrected locations of the November 1997 and May 1998 mappings. The village lies along two main axes with fairly straight streets and house alignments. Figure 3B shows the results of the initial village mapping prior to differential correction. Of note, the cocha appears wrapped over on itself; streets and paths appear crooked and haphazard, and houses have lost relation to each other and the streets. Figure 3C shows readings that were taken at the fixed base station during a five-hour mapping session in November 1997. Rather than showing a single point, the recorded locations follow a randomly meandering line with occasional abrupt changes in direction or position that reflect moments when satellites enter or leave receiving range. The linear pattern signifies that the errors are highly correlated from one reading to the next, and not statistically independent. Thus, readings taken over short periods of time contain approximately the same error term, and averaging them will not eliminate the error. This persistent error is the underlying cause of the inaccuracies that produced the chaotic uncorrected village map. Once differential correction was performed, the mean standard deviation of point feature positions measured in Padre Cocha was 0.2 m (sd=±0.09).

During the study year, there were 232 episodes of *P. falciparum* infections (incidence of 16.6%), 1,157 episodes of *P. vivax* (incidence of 82.6%), and a total of 1,300 independent episodes of malaria of either or both species (incidence of 92.9%). Mean household

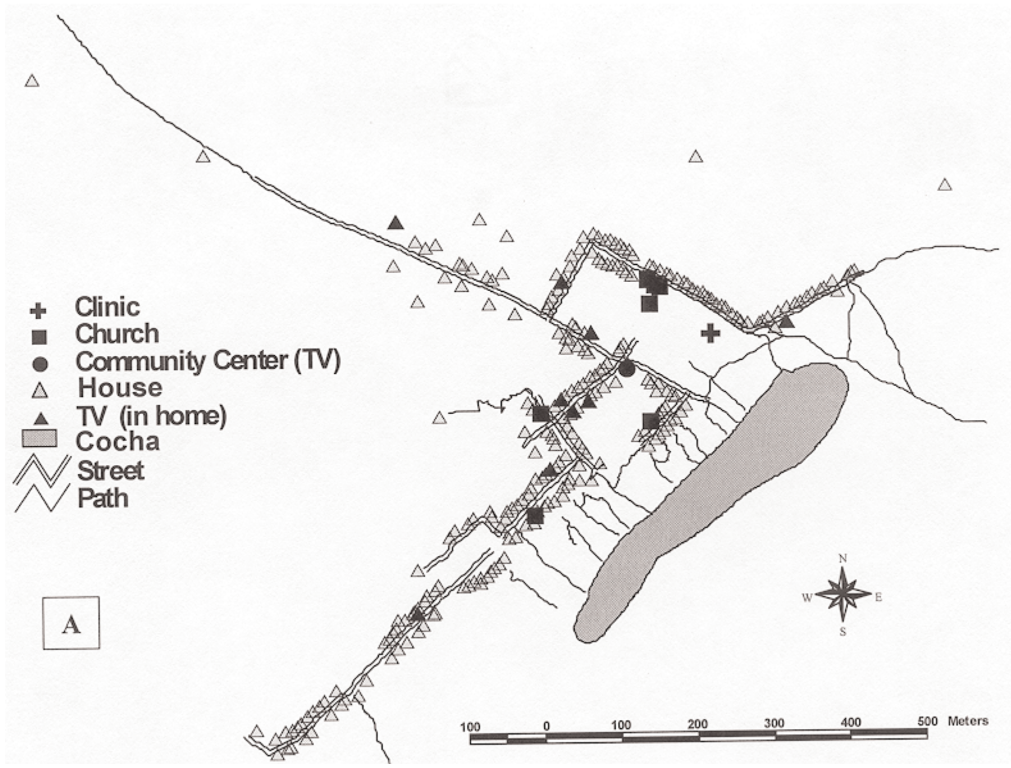

Figure 3A Map of Padre Cocha after differential correction of GPS readings.

Figure 3B Map of Padre Cocha before differential correction.

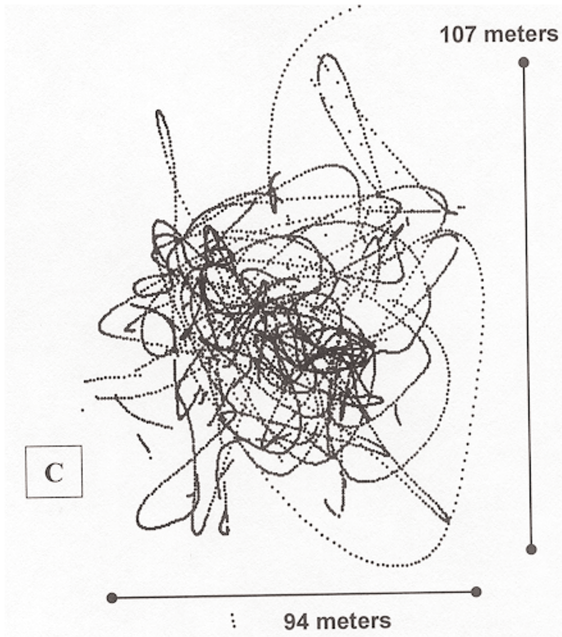

Figure 3C Plot of 5 hours of uncorrected GPS readings at the fixed base station.

incidences for the year were 15.3% for falciparum malaria, 82.1% for vivax, and 96.7% for either or both. Figure 4 shows the monthly distribution of malaria attack rates in Padre Cocha during the study year.

In Figure 5A, the cumulative number of malaria episodes occurring in each household during the study year was mapped using GIS. Several areas appear to have greater

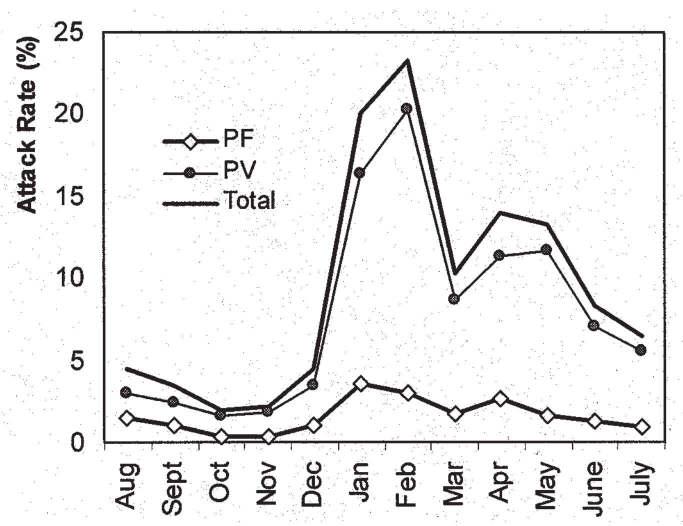

Figure 4 Monthly malaria attack rates in Padre Cocha, 1997–1998.

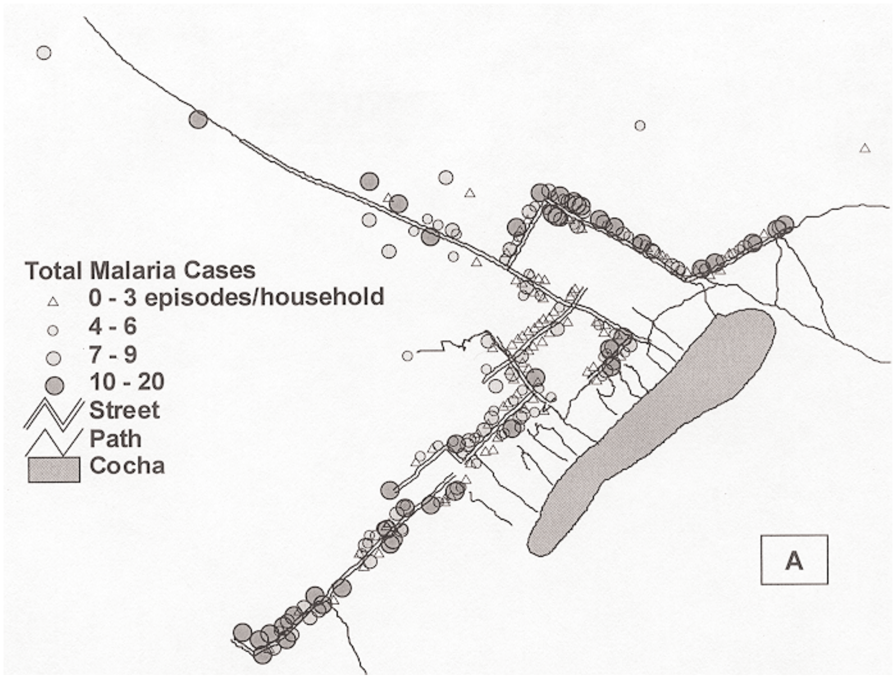

Figure 5A Household distribution of the cumulative number of malaria cases in Padre Cocha, 1997–1998.

concentrations of infections, while one central area appears to have fewer. To control for household size, household incidence was calculated and plotted, and a surface interpolation was performed to determine area incidence distribution. Clusters of high malaria density and the central area of low malaria intensity were confirmed (Figure 5B).

To exclude neighborhood population density as a factor in malaria occurrence, plots and interpolations of household size were performed. These analyses demonstrated a homogenous population distribution in the inhabited areas of the village throughout the year, supporting the conclusion that population density and household size are not significant determinants of malaria distribution. Similarly, altitude variation within the village perimeter was small and did not match the pattern of malaria distribution. Analysis of the spatial distribution of houses of the two construction types also showed a homogenous pattern throughout the village, and analysis of the relationship of household malaria cumulative incidence to house construction type showed no association (one-way analysis of variance: F=0.5; p=0.61).

Figure 6 demonstrates the results of the examination of spatial patterns of *P. vivax* (left) and *P. falciparum* (right) during the three phases of transmission during the year. At the top (sections A and B), the distribution of infections during the dry season from August through November 1997 is shown. The 1997 dry season was unusually prolonged, and little malaria occurred during that time. The middle sections (C and D) depict the dramatic rise in both vivax and falciparum malaria during the wetter months of December 1997 through March 1998. In the lower sections (E and F), the declining in-

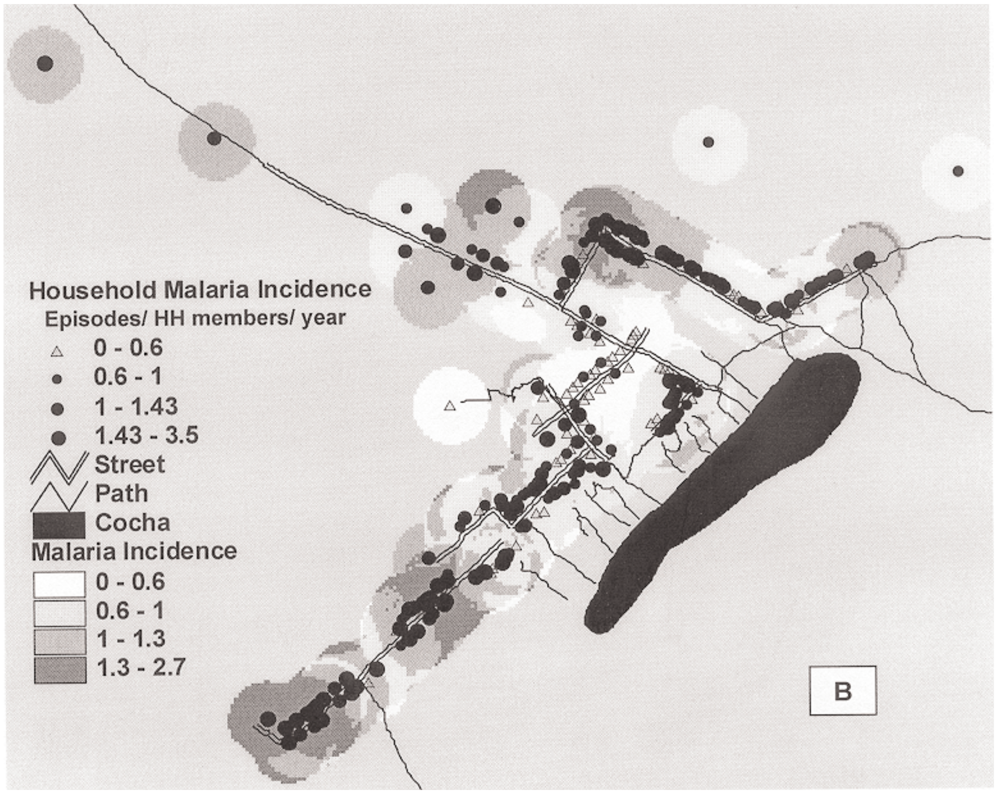

Figure 5B Household malaria incidence and surface interpolation of household incidence demonstrating the spatial distribution of malaria for the study year.

tensity of infections that occurred during the transitional period of April through July 1998 is shown. The general pattern of high and low density clustering noted in Figure 5 was again apparent for each species, and for all three parts of the year.

The results of adult female mosquito collections are displayed in Figure 7. The total number of mosquitoes collected indoors and outdoors at each of the four stations is listed in the legend. Virtually all mosquitoes collected (>97%) were identified as *An. darlingi*. The underlying surface interpolation represents the malaria incidence for the months of April through August 1998, months during which new human malaria infections would likely have been caused by mosquitoes of the same generations as those being captured. Of note, the capture stations with lower total numbers of indoor and outdoor mosquitoes catches were situated in areas of low malaria density, while those with higher numbers of mosquitoes captured were located in high malaria density areas.

Discussion

The use of GPS to map study sites is essential for GIS investigations of spatial relationships between exposure factors and disease occurrence in areas for which accurate maps are not available. Further, when the distances between features are small, differ-

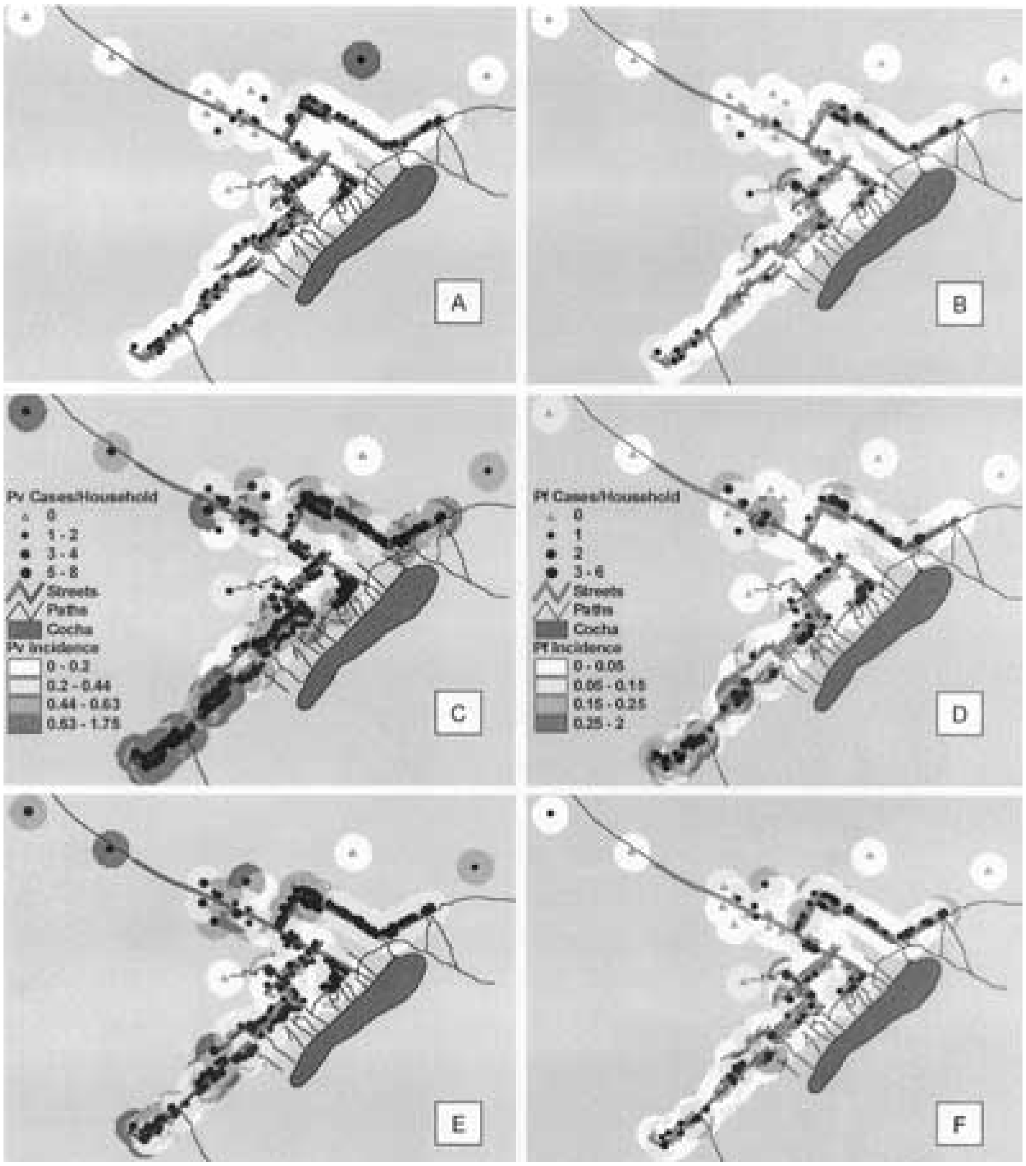

Figure 6 The distribution of cases and incidence of *P. vivax* infections (on left: A, C, E) and *P. falciparum* infections (on right: B, D, F) during the three transmission phases of the study year. A & B depict the dry season of low transmission, August–November. C & D represent the peak transmission period, December–March. E & F show the transitional period of declining transmission, April–July. The scales for cases per household and incidence were held constant throughout the seasons for each species.

ential GPS is necessary for adequate discrimination among sampling units. Our study of malaria distribution in Padre Cocha, Peru, is a good example of the importance and power of this technology. In an area of approximately 1 square kilometer, there was

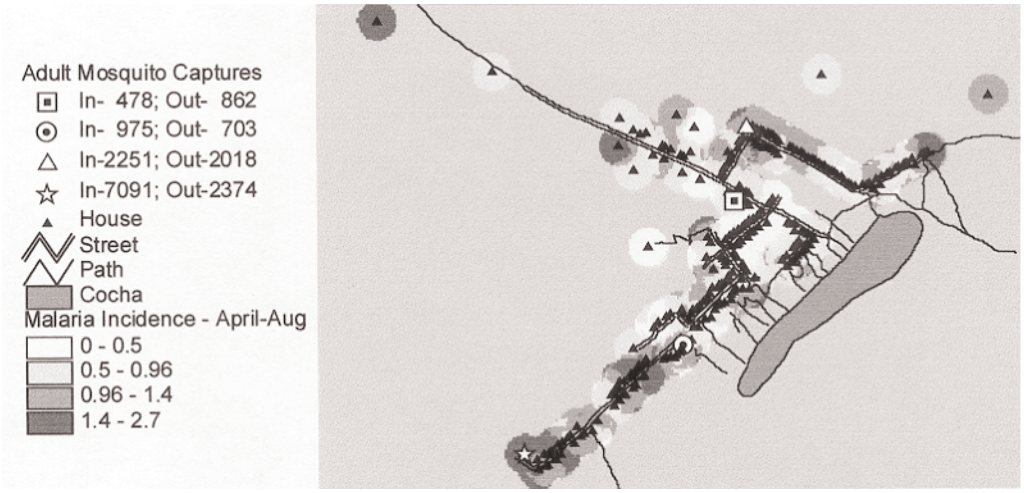

Figure 7 Location of mosquito capture stations and results of adult anopheline mosquito collections, April–August 1998. The underlying distribution of malaria incidence for the corresponding months is also shown.

clear and consistent spatial clustering of high and low malaria infection density. This spatial heterogeneity was true for both malaria species transmitted in the area, and was evident during periods of both high and low transmission.

A number of potential determinants of the distribution of malaria in Padre Cocha were investigated. Population density distribution, neighborhood altitude, and the spatial distribution of house construction type were unassociated with the pattern of malaria occurrence.

An epidemiological study performed during the 1997–1998 transmission year in Padre Cocha examined data about a variety of potential individual risk factors for malaria acquisition (14). Factors significantly associated with malaria incidence included age, working in Padre Cocha or its vicinity rather than elsewhere, time of arising (adults), evening strolling around the village (adults), and evening church attendance (children). The magnitude of associations was modest (range of RRs: 1.22–1.5), and none of these factors had any apparent geographic association with malaria distribution. Television viewing in the evenings was negatively associated with malaria incidence (RR 0.84; 95% CI, 0.73–0.96; p=0.01). Of interest, most of the locations where inhabitants congregate to watch television lie in the central zone of low malaria occurrence and low anopheles captures. Factors unassociated with malaria risk included bedtime, hour of bathing, specific occupation (farmer, fisherman, artisan, etc.), and bednet use. The overall lack of strong risk factor associations to explain the distribution of malaria at the individual or household level argues for the need to identify other factors related to risk, particularly factors with a significant spatial component.

Our analysis of the relationship between entomologic factors and human malaria infections is limited by the preliminary nature of the entomologic data. The finding that capture stations with low total *An. darlingi* catches were located in areas of low malaria infection densities and that, conversely, stations with high total counts were located in areas of high malaria intensity, is suggestive that patterns of vector abundance in and around Padre Cocha are important determinants of the spatial distribution of infections in the village. The entomologic data being collected during the 1998–1999 transmission season, including information about adult mosquito abundance and behavior, and anopheline larval breeding site distribution, will permit a more complete analysis of this hypothesis.

The addition of GPS and GIS technologies to malaria and other vector-borne disease studies affords the possibility of exploring spatial dimensions of disease transmission not easily examined in the absence of these capabilities. Further, the incorporation of these techniques can be performed with a limited addition of time and resources. Our project team consisted of previously inexperienced GPS and GIS users and a consultant who provided one week of training and supervision. All subsequent work was successfully performed by the on-site team.

Village mapping required six separate four- to six-hour sessions, with approximately one hour of subsequent computer time for data downloading and processing. Learning how to set up and operate GPS equipment and software required one didactic and practice session, and then several sessions in the field to attain full confidence in use of the system. Sufficient mastery of GIS techniques to allow the production of basic data maps was achieved within days of introduction to the software. Training by an experienced user on site, while not strictly necessary, greatly simplified the learning process and assured that decisions about base station siting, GPS unit parameterization, mapping plan, and database design were appropriate and efficient.

The single greatest cost in performing the GPS/GIS work at Padre Cocha was that of the GPS equipment and software, which totaled approximately $20,000. Our system was extremely easy to learn and use, and provided accuracies that met our need for analysis within a small area. The very simplicity of the system eliminated any ongoing need for personnel with prior technical training, reducing personnel costs significantly. However, sophisticated GPS units that offer such ease of use are costly, and if site mapping is likely to be accomplished in a few sessions, leasing units may be preferable to purchase. Further, it is now possible to subscribe to a satellite service that can provide real-time differential correction, abrogating the need for a base station unit. Taking advantage of these cost-reducing measures could make the application of GPS/GIS techniques more feasible for projects with limited budgets.

In summary, differential GPS and GIS systems can add critical information to the understanding of malaria transmission and epidemiology. Technologies that are currently available can be used by researchers without specialized backgrounds, and for moderate cost. In our work at Padre Cocha, spatial analysis contributed to generating study hypotheses, to understanding malaria distribution in the community, and to focusing entomologic research and MOH vector control efforts.

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