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Original Article

Analysis of Malaria Endemic Areas on the Indochina Peninsula Using Remote Sensing

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SUMMARY: We applied remote sensing using satellite images capable of obtaining data over a broad range, transcending national borders, as a method of rapidly, precisely, and safely increasing our understanding of the potential distribution of malaria. Our target region was the so-called Mekong malaria region on the Indochina Peninsula. As a malaria index, we used existing distribution maps of total reported malaria cases, malaria mortality, vivax malaria and falciparum malaria incidences, and so forth for 1997 and 1998. We produced monthly distribution maps of a normalized difference vegetation index (NDVI) with values of 0.2+, 0.3+, 0.35+, and 0.4+ using the geographical information system/remote sensing software based on the East Asia monthly NDVI maps of 1997. These maps were overlaid with various malaria index distribution maps, and cross-tabulations were carried out. The resulting maps with NDVI values of 0.3+ and 0.4+ matched the falciparum malaria distribution well, and we realized, in particular, that falciparum malaria is prevalent in regions in which NDVI values of 0.4+ continue for 6 months or more, while cases are fewer in regions with NDVI values of 0.4+ that continue for 5 months or less. It will be necessary in the future to examine the relationship between NDVI values and the habitats of the various vector mosquitoes using high-resolution satellite images and to implement detailed forecasts for malaria endemic areas by means of NDVI.

INTRODUCTION

Malaria has been widespread since ancient times, not only in tropical areas but also reaching into subantarctic zones. The disease has been sufficiently rampant to change human history. Various eradication measures have been carried out since World War II and, currently, the endemic areas are generally limited to tropical and subtropical areas. However, global-scaled climatic variability as well as human movement, the emergence of drug-resistant malarial parasites and vector mosquito strains, and other factors have occurred in recent years, and the number of reported cases has again begun to increase in tropical and subtropical zones. Attention is also being focused on temperate zones where there are new or recurring outbreaks of the disease.

Within the context of unforeseen rapid changes in the natural and social environment, it is important to develop preventative countermeasures to rapidly and precisely detect areas of outbreaks or potential outbreaks of malaria and to forecast expansion in areas in which malaria is endemic. Though there are numerous reports of malaria in East and Southeast Asia at the local, regional, and national levels (1,2), various problems exist, including differences in the methods of collecting data and analyzing the malaria incidence and the number of cases reported; virtually no research, however, is being conducted on a continental level.

Under such circumstances, Nihei et al. (3) have produced maps of past and present malaria distribution and have made forecasts for the near future in East and Southeast Asia by collecting data on the geographical distribution of malaria vectors and malarial parasites as well as data on temperature, rainfall, and other environmental conditions from reports in Japan, China, the Philippines, Indonesia, and other countries. The geographical information system (GIS) has drawn considerable attention in recent years as a means of comprehending and visualizing the current status of emerging and reemerging infectious diseases, especially vector-born diseases (4-8). GIS is gradually being introduced by the World Health Organization as a common practice for infectious disease countermeasures. Remote sensing by satellite image that analyzes regions through integration with GIS is also being used for the rapid and precise study of the environment over extensive areas (9). For the analysis of malaria on the African Continent or at the national level, as seen in the MARA project for mapping malaria risk (10), the normalized difference vegetation index (NDVI), utilizing images from the National Oceanic and Atmospheric Administration (NOAA) meteorological satellite, which is capable of broad-area and real time analyses and is also low in cost, has been used (11-13). Though there are thought to be limits to application of this method to East Asia in light of its high population density and complex topographical, climatic, and other environmental conditions, the use of NDVI, indicating the degree of activity of vegetation over broad regions, is promising with regard to the rapid comprehension of malarial endemicity at present and in the near future in Asia. We developed a database of malaria distribution maps of the Indochina Peninsula using GIS, analyzed the relationship between malaria distribution and NDVI values, and discuss herein the possibility of using GIS

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and remote sensing in the analysis of malaria endemic conditions.

MATERIALS AND METHODS

Malaria incidence data: We refer herein to the number of total reported malaria cases per 1,000, malaria mortality per 100,000 population, and the incidence for all types of malaria, including vivax malaria and falciparum malaria, per 1,000 in 1998 from the various charts relating to Mekong malaria, that is, malaria on the Indochina Peninsula, given in Kidson et al. (14).

Satellite image data: We used 1997 satellite image data capable of analysis by image processing software, and 1996 data to refer to analyses in 1997, from monthly NDVI maps of East Asia in 1996 and 1997 (15,16) calculated monthly based on advanced very high resolution radiometer (AVHRR) data of NOAA meteorological satellites.

Method for calculating NDVI values: There are a variety of vegetation indices that have been developed to help with the monitoring of vegetation. Although a number of vegetation indices have been tried, the one that has received the most attention is the NDVI. In the case of present NOAA-AVHRR, the visible light waveband (0.58 - 0.68 μm) with low vegetation reflectivity was set as band 1 and the near-infrared waveband (0.725 - 1.10 μm) with high vegetation reflectivity was set as band 2. The NDVI was calculated in the following manner.

$$\text{NDVI} = (\text{band 2} - \text{band 1})/(\text{band 2} + \text{band 1})$$

In addition, for the monthly NDVI maps of East Asia, $\text{INDVI} = (\text{NDVI}+1) \times 100$ was used to accommodate them in one-byte integers assigned in the range of 0 - 255.

We used ERDAS Imagine 8.4 (Leica Geosystems, ERDAS, Atlanta, Ga., USA) as image-processing software and ARC/INFO 7.2.1 and ArcView 3.2 and its extension function Spatial Analyst (Environmental Systems Research Institute, Inc. [ESRI], Redlands, Calif., USA) as GIS software.

As the analysis method, the monthly NDVI maps of East Asia were inputted into Imagine by month, and the geographic coordinates were determined. The region from approximately the Equator to 20° north and from 90°- 110° East in the area of the Indochina Peninsula was extracted from the maps covering all of East Asia.

Method for producing monthly distribution maps with NDVI value: We counted the number of months during which an NDVI value of 0.2+ continued and produced distribution maps by the number of months with an NDVI value of 0.2+. We also repeated this task for NDVI values of 0.3+, 0.35+, and 0.4+, respectively, to prepare a total of four maps.

Method for modifying malaria incidence maps to GIS analysis: To overlay the NDVI values from satellite images with the distribution maps of the malaria indices, we digitalized the district boundaries on the map of the Mekong malaria region and input that data into ARC/INFO 7.2.1. in the personal computer. We used equirectangular projection as the projection method, as in the monthly NDVI maps of East Asia, and provided geographical coordinates. In each polygon, we inputted the country name, the total reported malaria cases in 1998, the malaria incidence rate per 1,000 population, malaria mortality per 100,000 (1998), and vivax malaria and falciparum malaria incidence attributes (1998) to develop GIS data for the Indochina Peninsula.

Method of GIS analysis: To compare these maps with NDVI maps, we overlaid the two maps using ArcView and the extension function Spatial Analyst, and quantitatively examined the manner in which they were overlaid by cross-tabulations of both elements. We then examined, in particular, various overlays of the monthly distribution maps indicating values of NDVI 0.3+ and 0.4+ and the distribution maps of each malaria index as indicated by the ratio of various conditions for the entire study area by percentile.

Calculation of the NDVI for agricultural and forest land: To verify the manner in which land use is actually indicated on the Indochina Peninsula, we examined three random points in the Khorat Plateau in central Thailand as agricultural land, and likewise three points in the Annan Mountains, the mountain range that constitutes the border between Vietnam and Laos, as forest land, and then calculated and graphed the average NDVI values from January through December 1997.

RESULTS

Changes in NDVI values by month: Generally speaking, the larger the NDVI value, the higher the vegetation activity level, and at 0.4+ the area is thought to be covered entirely by forest, greenery, or other vegetation. Figure 1 shows the monthly changes in NDVI values in forest and agricultural land on the Indochina Peninsula according to satellite images (AVHRR) in 1997. It is possible to observe changes in NDVI values by month and, thus, agricultural land values indicate lower measures of 0.2 to 0.3 from January to August and higher values of 0.4+ September through November, though the values do not exceed 0.5. Generally, in rice paddies, the values are low at planting time and rise as the rice plants grow, dropping again when the rice is harvested. The NDVI values are higher in forest land than in agricultural land and are 0.5+ throughout the year, dropping to their lowest level in May. NDVI 0.4 is a median value between agricultural and forest land, indicating an intermingling of both environments. NDVI of 0.6 or higher are indicated from September to December.

Distribution maps by NDVI month count: Distribution maps organized according to the number of months with NDVI values of 0.2+, 0.3+, 0.35+, and 0.4+ are all displayed with the same legend to demonstrate the notable differences between the maps. In the distribution map of the number of months with NDVI values of 0.2+ (Fig. 2a), the areas of 10 or more months, displayed in red, occupy 87.9% of the map, almost the entire area, and no regional differences are evident. In the distribution map of the month, with NDVI values of 0.3+ (Fig. 2b), regional differences are prominent,

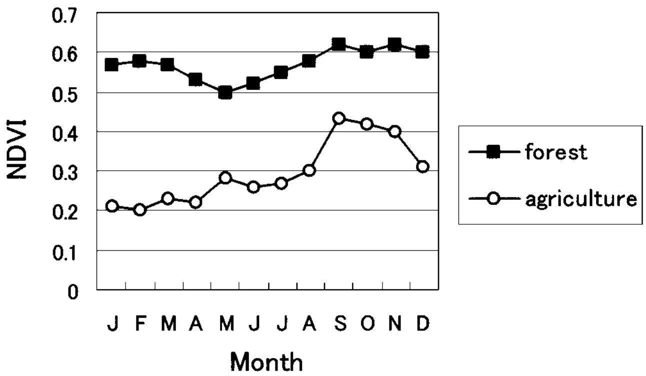


Fig. 1. Monthly changes in NDVI values in agricultural and forest lands on the Indochina Peninsula.

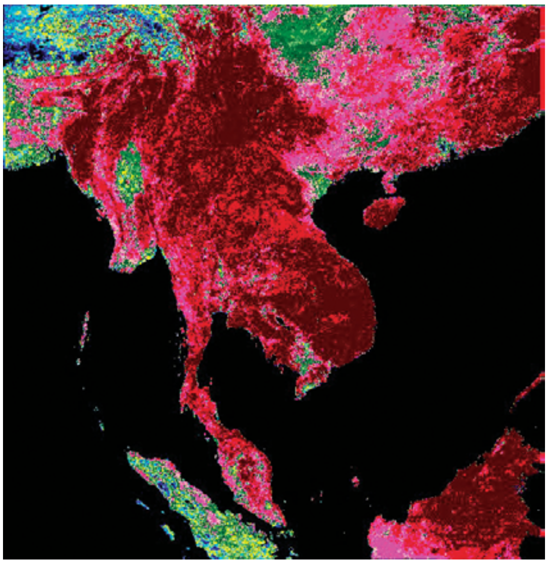


Fig. 2a. NDVI 0.2+

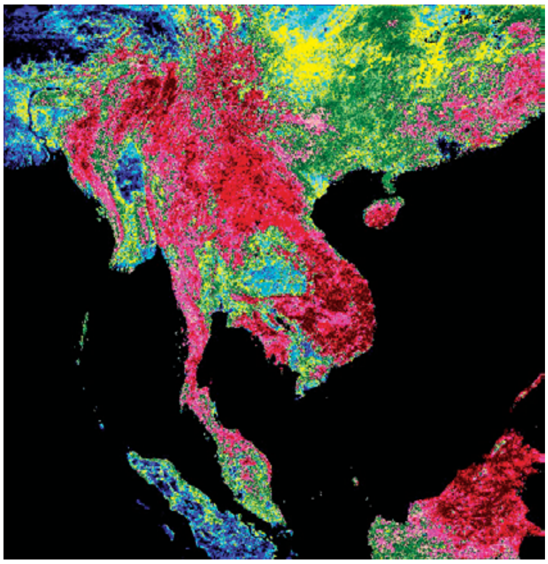


Fig. 2c. NDVI 0.35+

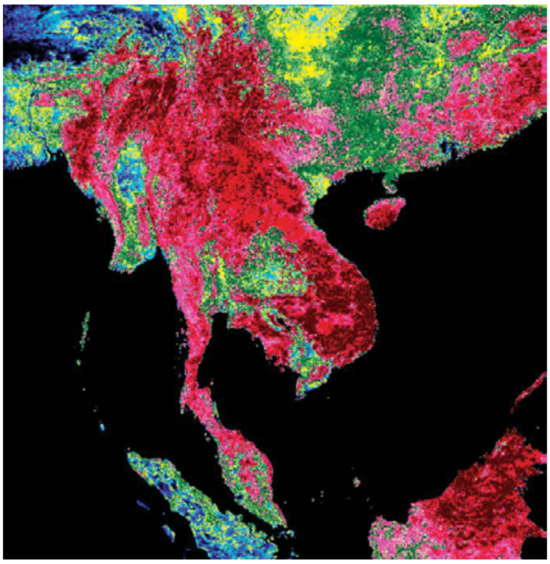


Fig. 2b. NDVI 0.3+

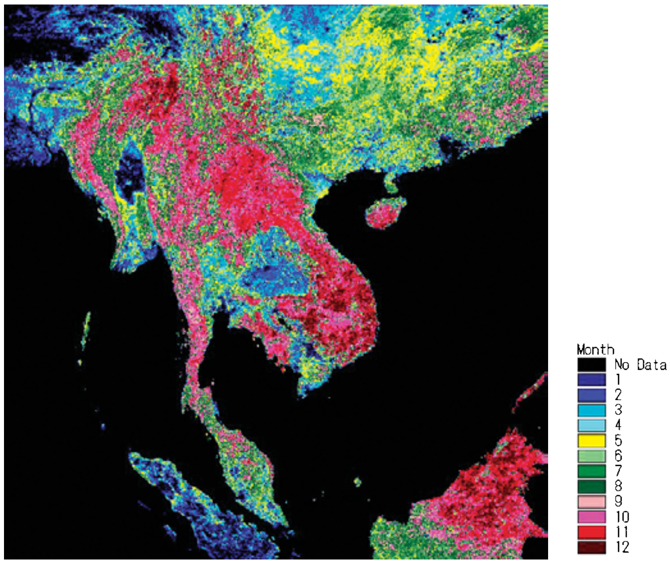


Fig. 2d. NDVI 0.4+

Fig. 2. Distribution map shows the number of months indicating various NDVI values on the Indochina Peninsula.

with 61.6% of the land being covered by areas of 10 or more months. The mountainous region on the border between Vietnam and Cambodia on the Indochina Peninsula was found to be at 11-12 months the mountainous region on the border between Myanmar and Thailand in the west 10 - 11 months, and the northern part of the peninsula along the border between China, Thailand, and Myanmar ranging between 10 and 12 months. The rice paddy fields of Thailand and Myanmar indicate 6 - 9 months and are displayed in green. Analysis of the map for NDVI 0.35+ (Fig. 2c) has been omitted since it is intermediate between 0.3+ and 0.4+. At NDVI 0.4+, there are few areas counted for 10 months, with these accounting for only 31.3% of the overall area, essentially coinciding with a tropical rainforest distribution (Fig. 2d). There are expanses of agricultural areas of 6 - 8 months in green as well as regions of 3 months in blue in areas with two to three rice harvests on the same plot per year in Myanmar, Thailand, and the Mekong River basin. Meanwhile, in China, where development of agricultural land use is vigorously promoted and various crops are cultivated, the number of NDVI 0.4+ ranges from 1-10 months.

Comparison of NDVI maps and malaria indices: We compared Fig. 2b and Fig. 2d, which show the NDVI values of 0.3+ and 0.4+, with the total reported malaria cases (Fig. 3a), the malaria mortality rate per 100,000 (Fig. 3b), the total malaria incidence per 1,000 population (Fig. 3c), vivax malaria incidence (Fig. 3d), falciparum malaria incidence (Fig. 3e), and other indices.

The malaria mortality rate (Fig. 3b) was found to be low in Thailand, Vietnam, and China. There were notable differences, depending on the country, affected by the socio-economical environment, medical treatment and other factors, and it is thought that differences in NDVI do not strongly reflect the mortality caused by malaria. It was therefore eliminated from consideration as a target among the present malaria indices.

In addition, in the distribution maps organized according to the number of months with NDVI values of 0.2+, areas of 10 or more months cover virtually the entire Indochina

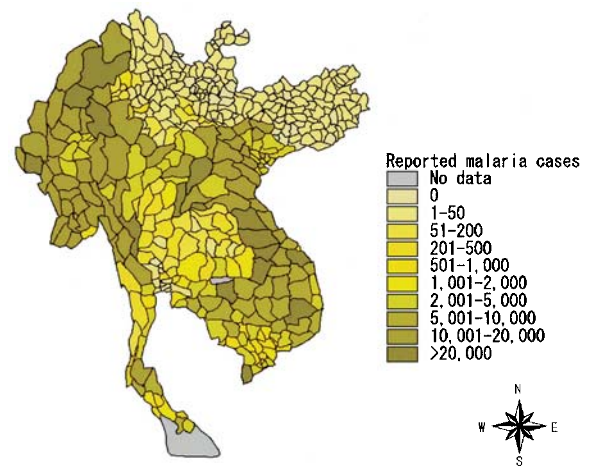


Fig. 3a. Total reported malaria cases in the Mekong malaria region (1998). Modified map originated from Kidson et al. (14).

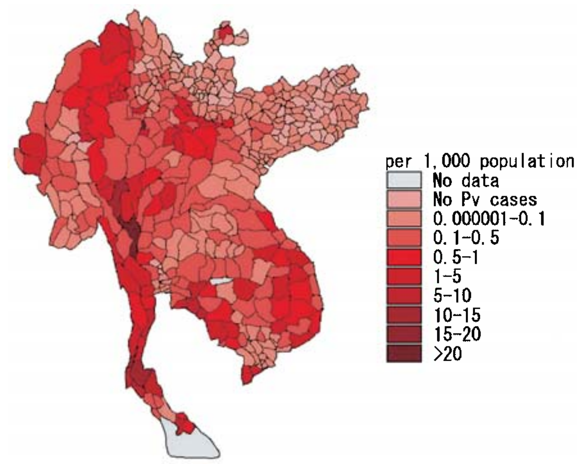


Fig. 3d. Vivax malaria incident per 1,000 population in the Mekong malaria region (1998). Modified map originated from Kidson et al. (14).

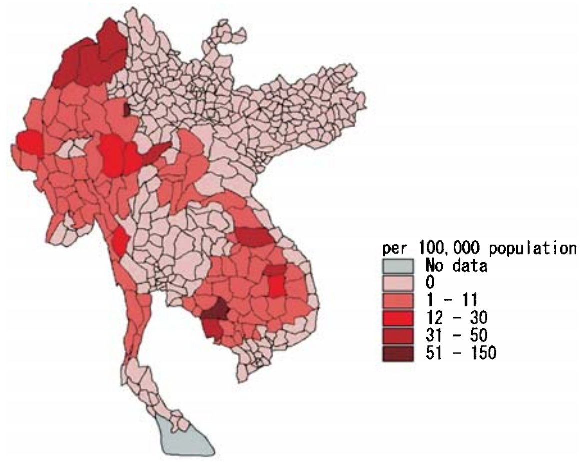


Fig. 3b. Malaria mortality per 100,000 population in the Mekong malaria region (1998). Modified map originated from Kidson et al. (14).

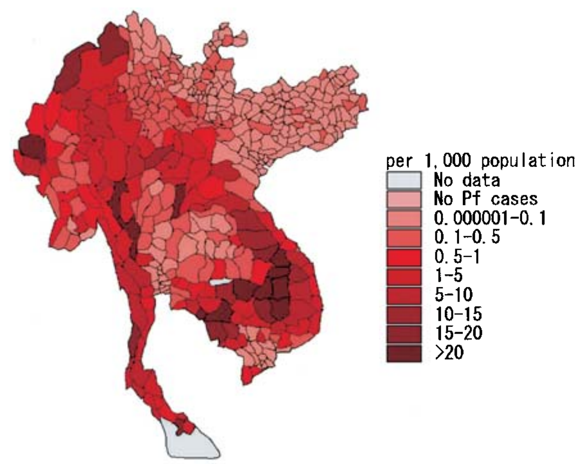


Fig. 3e. Falciparum malaria incident per 1,000 population in the Mekong malaria region (1998). Modified map originated from Kidson et al. (14).

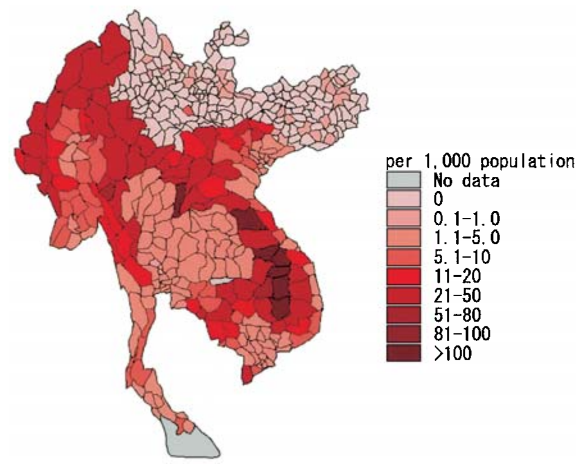
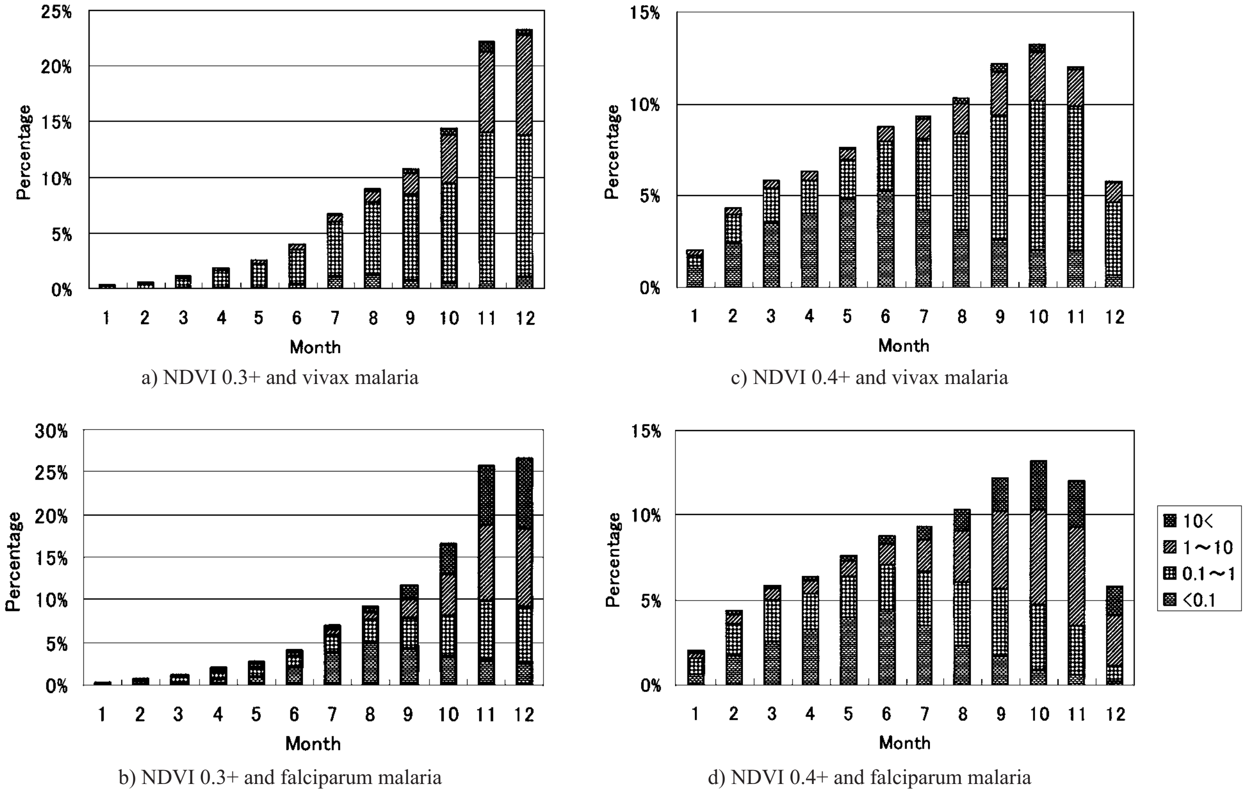


Fig. 3c. Malaria incidence per 1,000 population in the Mekong malaria region (1998). Modified map originated from Kidson et al. (14).

Peninsula and no correlation can be observed with the total reported number of malaria cases, malaria incidence, or other indices. With the exception of China, areas with 10 or more months at NDVI 0.3+ generally coincide with areas with a large number of reported malaria cases. Areas with a month count of 6 or more with an NDVI value of 0.4+ generally coincide with areas having large numbers of reported malaria cases. Therefore, we carried out a cross-tabulation of the maps with NDVI values 0.3+ and 0.4+ and the maps of the number of reported cases, total malaria incidence, and vivax malaria and falciparum malaria incidences. We then accumulated the results and have displayed them on horizontal bar graphs, indicating vivax and falciparum malaria incidence. In all of these maps, the horizontal axis shows the number of months and the vertical axis shows the ratio with the entire survey area as 100% while the legend indicates the distribution of the malaria indices by grade.

As a result of the cross-tabulation, in the distribution maps of the month count with NDVI values of 0.3+ (Figs. 4a, b), areas of 10 or more months account for 60.7% of the total areas, 79.4% of the entire survey area with an incidence of vivax malaria of one or more persons per 1,000 population, and 81.8% of the area with an incidence of falciparum malaria of one or more persons per 1,000. Meanwhile, the areas with a month count of 8 or fewer months with NDVI values of 0.3+ was low at 26.4% and, moreover, the incidences of both vivax and falciparum malaria for the most part were one or less per 1,000.

Likewise, in the cross-tabulation of distribution maps by



a) NDVI 0.3+ and vivax malaria

b) NDVI 0.3+ and falciparum malaria

c) NDVI 0.4+ and vivax malaria

d) NDVI 0.4+ and falciparum malaria

Fig. 4. Results of the cross tabulation of maps with NDVI value 0.3+ and 0.4+ and maps of vivax and falciparum malaria indices by grade.

month count with NDVI values of 0.4+ (Figs. 4c, d), areas with 6 or more months account for 73.2% of the entire survey area. A vivax malaria incidence of less than 0.1 per 1,000 was infrequent, and there was a large ratio in the range of 0.1 or more per 1,000, with 79.4% of the area having an incidence rate of one or more per 1,000. The incidence of less than 0.1 for falciparum malaria was also low, and there was a large ratio of one or more per 1,000, indicating 89.5%, and at 10+ months, in particular, an incidence of one or more per 1,000 accounted for 50% or more. With NDVI values of 0.4+ for 5 or less months, the majority consisted of an incidence one or less.

Thus, overlaying the maps of the vegetation index and falciparum and vivax malaria indices shows that areas with NDVI values of 0.3+ or 0.4+ for half of the year or more indicate a high incidence, while areas of 5 or fewer months have a low incidence. Despite the low number of reported cases, incidence, and other indices, areas with a high month count are included in the case with an NDVI value of 0.3+, but there are few instances where the NDVI value is 0.4+.

DISCUSSION

Along with the development of personal computers and available software, GIS has come to be used for lifeline management and crisis management when disasters occur. There is also global awareness of the importance of GIS techniques in preventive medicine and in providing medical treatment statistics and geographical data. These techniques have been developed based on ArcGIS (ESRI), the most widespread GIS software package in the world, and the applicability is high (17). In the present study, we used the same type of GIS software as well as the remote sensing software ERDAS Imagine, which is capable of integration with ArcGIS. Although meteorological satellite images that can be received twice daily are low in resolution, we used the image data from the general distribution produced by the National Institute for Environmental Studies dated close to the indices of malaria endemicity in order to rapidly obtain results at low cost. The monthly NDVI values are compiled yearly on CD-ROMs, enabling access by anyone to the NDVI values of East Asia. Though there are generally various limitations in comparing malaria endemicity between dry and monsoon seasons, the monthly changes in the NDVI are extremely valuable and effective in analyzing the conditions of malaria occurrence. The NDVI maps are easy to use in processing and mapping the required factors by remote sensing software. This report is the first to compare the various distribution maps relating to malaria endemicity with NDVI values on the Indochina Peninsula, adjusting the map projection on GIS to match the satellite images. Field surveys were also conducted for this study. We have tried to interpret the relationship between the environment and malaria endemicity using satellite data that would otherwise be impossible to attain through ground-based surveys. We furthermore realize that, within the context of the environmental changes that are taking place at global and local scales, our results provide valuable data and methodology for forecasting malaria endemicity in East and Southeast Asia (3), taking the ecological and geographical environment of the malarial parasite into account.

NDVI values indicate annual changes in vegetation activity and the extent of cover reflecting climatic conditions such as temperature and rainfall as well as soil and water conditions. They are therefore used to estimate the type of vegetation (tree or crop species, etc.).

Temperature differences, that is, summer-winter seasonality, affect the activity of vector mosquitoes and malaria endemicity in high-latitude areas. In low-latitude tropical and subtropical areas, the amount of rainfall and the duration of the dry season affect the survival and activity of mosquitoes. In the present study, we conducted analyses of malaria endemicity, taking advantage of the relationship between these climatic factors and the NDVI values themselves, as well as their duration. It is expected that malaria risk areas will expand along with future climatic changes, especially changes in ecosystems due to global warming, and that these analyses will probably be effective in making rapid forecasts (18). It is generally said that regions with NDVI values of 0.35 or 0.4 are related to the distribution of malaria in the MARA program in Africa (4,11,13).

In this report, we examined NDVI values of 0.2+, 0.3+, 0.35+, and 0.4+, taking into account the complex environmental conditions of the Indochina Peninsula. We feel that NDVI values of 0.4+, in particular, indicate a strong correlation to falciparum malaria endemicity in the malaria indices of the Indochina Peninsula. It will be applicable to use these values in the monitoring of vector mosquito habitat expansions and changes due to global warming in the future. NDVI values of 0.4+ indicate geographical differences, and it is easy to distinguish between rice paddies and forests. It will therefore be possible to infer the species of vector mosquito as long as it is possible to clarify the relationship between the mosquito habitat and the NDVI values.

The habitats of vector mosquitoes differ according to the vegetation and the nature of the local environment (19). Satellite images and NDVI are widely used for that reason. The following are some examples of the primary vector mosquitoes in the survey areas: *Anopheles minimus*, which inhabits small rivers in the midst of tropical rainforests overgrown with trees; *An. dirus*, which is found in ponds, wells, and the like in forest shade in hilly areas; *An. sinensis*, which is found in rice paddies in lowland areas; *An. sundaicus*, which inhabits coastal areas; and *An. maculates* and *An. punctulatus*, which inhabit pools, streams, and small rivers in mountainous areas exposed to sunlight (20). *An. dirus* and *An. minimus*, which are found in high mountainous areas and forest land with NDVI values of 0.5+, are highly anthropophilic, and there are many reported cases of malaria in such areas (21). *An. sinensis*, which is found in rice paddies with low NDVI values, is zoophilic and is an important malaria carrier. Malaria also exists in urban areas of developing countries with low NDVI values, and the vector mosquito is *An. stephensi*, which is found in rivers and open wells in the vicinity of urban districts but which is easily eradicated through the use of insecticides. It will be possible to enhance analysis precision by elucidating the relationship between the habitat of the various vector mosquitoes and the NDVI value, and by examining the relationship to malaria distribution. Satellites have been launched by various countries, and it is possible to obtain data of differing precision and content depending on the types of images as well as the resolution, waveband, recurrent orbit days, season, and other factors. It is our intention to interpret NDVI values and to enhance the precision of analysis using satellite images with high resolution from Landsat TM (resolution: 30 m), JERS-1 (18 m), SPOT (10 m), or other satellites (22-28).

There were "false positive" results indicated in areas in which there is malaria risk but low NDVI values, while "false negative" results were also observed in areas with high NDVI values but low malaria indices. These results can perhaps be attributed to the inclusion of areas with complex topographical and climatic conditions, diverse vegetation, and differing NDVI values in province units providing malaria index data. If it was possible to obtain more detailed malaria data, we would probably develop a more detailed satellite image. There are cases in which it is still impossible to ascertain the existence of malaria cases in tropical rainforests in the interior or in regions that are difficult to survey for geographical reasons, while it would be extremely difficult to grasp the conditions of malaria endemicity on a continental level. Our analyses based on NDVI values make it possible to forecast malaria endemicity without direct blood tests, suggesting the potential for policy administrators in those countries experiencing malaria problems.

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