Title: Environmental Change and Vector-Borne Disease Transmission: Linking Irrigation to Malaria within Endemic South America

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Abstract: As a vector-borne disease, environmental determinants are a significant factor in the transmission of malaria to human populations throughout the world. The possibility of increased human-vector contact may occur in situations where alterations to the physical landscape result in a habitat favorable for the proliferation of the mosquito vector. Irrigation represents such environmentally-transformative actions capable of affecting the dynamics of malaria, particularly in regions where the disease is endemic. Here, over four decades of available data (1962-2008) from agricultural, healthcare, and population sources are incorporated into an analysis of the role of irrigation on nationwide malaria within those countries comprising the Amazon Forest region of South America for WHO strategy and prevention initiatives. Correlation and regression analyses reveal the presence of a relationship between changes in irrigated area and subsequent disease morbidity among eight of the nine nations of the region. With the exception of Ecuador, these results suggest that the totality of local scale alterations to the environment associated with irrigation development exert a significant influence upon the burden of malaria on the national level. Appreciating this relationship should be a cornerstone to planning and policy decisions involving water resource projects within these countries. The paper concludes with a discussion of other factors, such as migration and deforestation, whose potential to occur synergistically or concomitantly with irrigation produce a multifaceted challenge to effective disease management.

Keywords: Amazon, malaria, irrigation, vector, land use, endemic, morbidity, deforestation

Introduction

Malaria bears the distinction of being one of the most enduring and devastating diseases in human history. It is also one of the most studied – annually, threatening the lives of millions throughout the world. Research has often focused upon medical treatments for infected individuals or upon perfecting methods of vector control through the use of pesticides. There is, however, an aspect of malaria epidemiology that, although studied, has received relatively less scientific attention, which is the role of the physical environment on disease transmission. The question is as follows: Does the condition of the environment influence the spread of the disease? The answer to this question may require understanding how events such as climate change or deforestation result in an increased likelihood of disease transmission. For example, it is possible that changes in temperature or local ecological regime could result in conditions favorable for increased vector-human contact and possibly the spread of malaria (Lindsay and Birley 1996; Walsh *et al*., 1993). In the case of malaria, the vector affected by such changes is the mosquito (genus: *Anopheles*) that transmits the parasitic disease to its human host.

Conditions favorable for the spread of vector-borne diseases, such as malaria, have also been associated with land development projects designed for agriculture or to control local water resources. Irrigation, specifically, has been revealed to contribute to increases in malaria morbidity in a manner similar to deforestation and climate change (Patz *et al*., 2000). Local scale connections between both variables have been demonstrated to occur in various regions throughout the world. For instance, significant linkages were found to exist between an increase in the abundance of certain mosquito species and the presence of irrigated fields for areas of agricultural development within India and Pakistan (Herrel *et al.*, 2001; Tyagi and Yadav, 2001). Within Africa, irrigation development projects may represent a considerable risk to individuals living in areas where previous experience with the disease was relatively low (Ijumba and Lindsay, 2001; Dolo *et al*., 2004). Also, South American research conducted by Roa *et al*. (2002) found a connection between irrigation and the numbers of Anopheles mosquitoes observed at sample sites within Venezuela. In addition, comparisons of mosquito ecology between irrigated areas and residual wooded land conducted by Forattini *et al*. (1993) suggested a link between Brazilian irrigation development and the spread of malaria, which was concluded to be the result of mosquito adaptation to the altered environmental conditions represented by the irrigated system.

Water development schemes, such as irrigation projects, unintentionally influence the transmission dynamics of malaria in nearby communities by altering local ecosystems in such a way that the mosquito populations are allowed to proliferate (Gratz, 1999). Years earlier, these changes were listed by the World Health Organization (WHO, 1992) and included: A) habitat simplification, B) microclimate changes, C) surface water area increases, D) water flow rate changes, and E) rising water tables. If these environmental changes, many of which are hydrologic in nature, affect malaria locally, then perhaps irrigation may also influence the spread of the disease on a larger scale, such as on the national level. If so, then it might be possible to demonstrate a relationship over time in which increases in the extent of irrigated area are accompanied by increases in malaria infections for the population of a given country. Determining the existence of such a relationship could be of considerable importance to politicians, environmental planners, as well as for health officials involved in irrigation and other water resource projects in regions historically at risk for malaria. This includes many nations within the tropical regions of the world, including much of South America. This leads to the purpose of this study, which is to examine nations within the Amazon Forest region of endemic South America to determine if a connection is present between the extent of irrigation within a country and the transmission of malaria among its population.

Countries associated with the Amazon region of South America were chosen as the geographic region of focus for this study due to the presence of several factors that may directly or indirectly work synergistically with irrigation to contribute to malaria morbidity. To some extent, these are all environmental or related factors and include: A) human population growth rate or size, particularly when nations such as Brazil are taken into account, B) tropical climates, which dominate much of the continent, and C) expansive rainforest ecosystems which may be vulnerable to alteration for agricultural development. With the assumption that a link does exist between irrigation and malaria morbidity locally, annual data for both variables covering the majority of the latter half of the twentieth century and beyond were obtained for selected nations on the South American continent where malaria is endemic. These variables were then subjected to a statistical analysis to provide further insight into the historical extent of this relationship on the national level. Later, the results of these tests are discussed as well as their implications for a further understanding of the dynamics between environmental change and malaria transmission.

Methods

Morbidity estimates

Figures obtained for this study include those for malaria morbidity, which is the number of cases of the disease present among the population of a country for a particular year. Global monitoring of malaria is undertaken by the World Health Organization (WHO), which bases its estimates on annual reports received from participating nations. It is possible for instances where the reliability of the submitted data can be called into question, as accurate estimates of morbidity for some nations should not be assumed as certain. In particular, underestimates of the number of malaria cases experienced by a nation for a particular year may be present within the existing dataset. One of the reasons for this during the earlier years of the collection period included considerable resource limitations serving as the principle obstacle to data collection, which may have resulted in an inability to engage in constant surveillance, or for a country to fail to regularly submit complete information when reporting to WHO (1983). Additional hindrances may also be present when attempting to obtain accurate reports on disease morbidity. These include the obvious economic drawbacks within underdeveloped or disadvantaged regions as well as the potential for negative social consequences related to reporting illnesses within certain regions of the developing world (Cash and Vasant, 2000).

Available data on malaria cases originated with the 1962 year of reporting and is published by the WHO and the Pan American Health Organization (WHO, 1983, 1999; PAHO, 2010). Specifically, annual reported figures for malaria were obtained for the study period 1962-2008. Geographically, the available data focused on each nation within South America subject to experiencing endemic malaria and considered at risk for continued significant morbidity, which were Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru, Suriname, and Venezuela (World Resources Institute *et al*., 1998; WHO, 2000b). The geographic proximity of these nations to the Amazon forest is also of prime interest, given the emphasis on the role of environmental change for this study. Correspondingly, each of the nine nations are considered by the WHO as part of the Amazon Forest region for the purposes of malaria control and prevention strategy procedures (PAHO, 2000; WHO 2011).

The varying time between mosquito bite and the first appearance of symptoms was the primary rationale for the national scale focus for this study. International migration was not considered, and the paper limited its scope to the assumption that individuals were infected within the same nation that reported their case. In the event that the number of malaria cases was simply a reflection of the size of the national population, it was determined that the estimated percentage of the population infected with the disease would be used to represent annual morbidity for each country subjected to the analysis. Annual data on population estimates were obtained from figures made available by the Population Division of the United Nations (UN, 2011).

Irrigation data

Irrigation was the variable selected to represent those changes to the environment that could potentially result in the proliferation of the local mosquito population and, subsequently, an increase in the transmission of malaria to humans. Irrigation data on the global and national level is collected by the Food and Agriculture Organization of the United Nations (FAO, 2011). Specifically, annual figures for the extent of irrigated area covering the surface of each nation was obtained for this study; with the period of observation corresponding to that of malaria data (1962-2008). With water resources, the following two points must be briefly mentioned regarding the sources and assessment of data. First, information sources can vary, and may include both official and unofficial sources such as national yearbooks, FAO projects, international research centers, and irrigation master plans. Second, countries occasionally differ on interpretations of what actually is considered irrigated area; with a primary difference being the importance given to the amount land that is equipped for irrigation *verses* that portion of the land that is actually irrigated/wetted FAO (2000). For the purposes of this study, neither consideration was taken into account when utilizing figures for irrigated area. The reason for this being the assumption that significant changes in one or several environmental metrics, such as forest cover, surface relief, soils, or hydrology will take place for areas either newly equipped for irrigation or for those being actively irrigated during a particular year.

Irrigation – Malaria relationship

With annual estimates on the proportion of the population infected with malaria and data for irrigated area obtained over as long a period as possible, comparisons could be made to determine if a statistical relationship between the two variables was present. Specifically, correlation and regression analysis were employed to provide insight into the possible influence of irrigation on the transmission of malaria among the population of each nation within the study area. Because of the differences in the normality of the distribution of the data among nations, both parametric and nonparametric methods were used when applicable. Linear regression analysis using raw data was performed for data representing Brazil, Colombia, Ecuador, and Guyana. For French Guiana, Peru, and Venezuela, where the data was not normally distributed, log-transformations were necessary in order to make the data suitable for linear regression. In the case of Bolivia and Suriname, where the normality conditions of the distribution could not be met, a nonlinear regression model was used. Figure 1 displays a map of those nations comprising the study area.

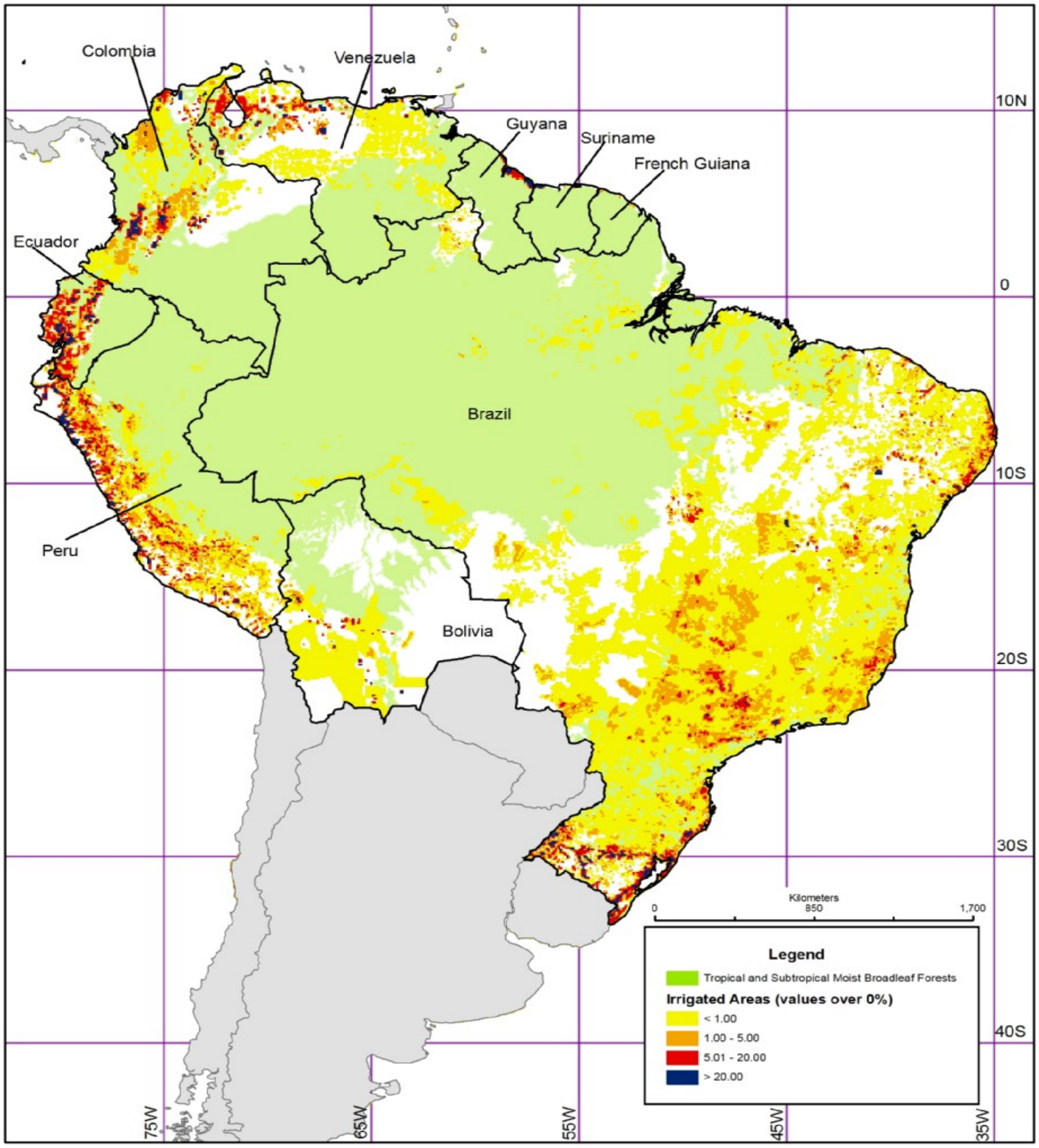

Figure 1. Study area map with irrigated areas and moist broadleaf forests displayed.Tropical and subtropical moist broadleaf forests modified from Olson, D. M, E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, J.A. D'amico, I. Itoua, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, T.H. Ricketts, Y. Kura, J.F. Lamoreux, W.W.Wettengel, P. Hedao, & K.R. Kassem. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. BioScience 51:933-938. Irrigated areas are based on a percentage of 5 minute cell area and have been modified from 1990-2000 data collected by Stefan Siebert, Petra Döll, Sebastian Feick, Jippe Hoogeveen and Karen Frenken. 2007. Global Map of Irrigation Areas version 4.0.1. Johann Wolfgang Goethe University, Frankfurt am Main, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy. Map created using ESRI GIS software.

Results

Bolivia

A nonparametric correlation analysis was performed to determine the possibility of a relationship between trends in the extent of irrigated area and changes in malaria morbidity among the Bolivian population over the 1962-2008 period. The results of a Spearman correlation were significant, and suggested a connection between both variables was present ($n = 47$, $r_s = 0.413$, $p = 0.004$). When a nonlinear quadratic regression was performed, the values of the analysis were mildly significant ($R^2 = 28.8\%$, $F_{2,44} = 10.31$, $p = 0.002$). These results included data for 1998, where the number of malaria cases within the country rose to 73,764 (PAHO, 2010), which was the maximum value over the period of study (Figure 2). This represented an increase of over 43% from the previous year, and an estimated 0.92 population percent infected. However, even when this outlier was removed, a similarly significant relationship remained ($R^2 = 32.5\%$, $F_{2,43} = 11.85$, $p = 0.001$). Morbidity also increased considerably in 1996, but data for this year was neither considered as nor excluded as an outlier. These findings suggest that trends in malaria morbidity within Bolivia have corresponded to some extent to changes in nationwide irrigation over time, with a morbidity maximum in 1998 and a secondary peak occurring in 1996.

Brazil

Not surprisingly, the overall extent of Brazilian irrigation exceeds that of any other nation within South America. For Brazil, data for irrigated area and malaria morbidity was subjected to a parametric correlation analysis. The results of a Pearson correlation were significant, and suggested that a possible relationship existed between both variables over the period of study ($n = 47$, $r_p = 0.661$, $p < 0.001$). The segment of the Brazilian population with the disease peaked in 1991, and it was estimated that over 0.4% of the country was infected with malaria during this year. Irrigation experienced a relatively steady annual increase from 1962-2008, culminating with its maximum value in 2008 (Figure 3). Next, the data was subjected to linear regression, where a significant relationship was displayed between irrigation and morbidity ($R^2 = 42.4\%$, $F_{1,45} = 34.93$, $p < 0.001$). Based on data for the 1962-2008 period, both correlation and regression analyses suggest that malaria has been influenced by irrigation within Brazil over time. In addition, these results were affected by the behavior of irrigation and morbidity from 1978-1989, as both variables experienced consecutive annual increases during this interval.

Colombia

A parametric correlation analysis was performed to assess a possible relationship between irrigation and malaria within Colombia. The analysis encompassed the 1962-2007 period, as figures on the number of malaria cases were missing for the 2008 year, and thus, that year was excluded from the analyses. Values produced from a Pearson correlation were significant, and supported the possibility that a strong relationship exists between the two variables ($n = 46$, $r_p = 0.761$, $p < 0.001$). Although the number of malaria cases peaked in 2001; like Brazil, the estimated percentage of the population infected with the disease reached its maximum in 1991, at 0.54%. The growth of irrigation followed a regular upward trend until 1998; afterwards, stabilizing with no net loss or gain in total area for the remainder of the period of study (Figure 4). Morbidity, however, trended downward during this time. When a linear regression was performed, the analysis was significant and in support of a relationship between changes in irrigation and subsequent malaria infection ($R^2 = 56.9\%$, $F_{1,44} = 60.50$, $p < 0.001$). Despite the behavior of the data during the last decade of the study period, both correlation and regression analyses revealed the presence of a connection between both variables over the period of study.

Ecuador

Data on irrigation and malaria morbidity for Ecuador was subjected to a parametric correlation analysis. Although the Pearson correlation was positive, the analysis was weak and non-significant ($n = 47$, $r_p = 0.257$, $p = 0.080$). The observed pattern of malaria within the country experienced two distinct peaks, in 1969 and 1984, morbidity values of 0.88% and 0.89%, respectively. Irrigation followed a trend similar to that of Colombia, rising in most years until 1998, where total area stabilized and remained unchanged for the duration of the period of study (Figure 5). Linear regression showed a very weak relationship between the behavior of irrigation and the spread of malaria within Ecuador, although the analysis was also non-significant ($R^2 = 4.6\%$, $F_{1,45} = 3.21$, $p = 0.080$). These results suggest that changes in malaria morbidity among the Ecuadorian population have not been linked to changes in the extent of irrigated area within the country.

French Guiana

Missing values for French Guiana were present for several years over the final decade of the study period. Specifically, malaria data for 2002, 2003, 2005, and 2007 was unavailable and, therefore, excluded from the analysis. A nonparametric correlation was performed on both variables and suggested that a relationship between the two was present, with the test for the Spearman analysis being significant ($n = 43$, $r_s = 0.838$, $p < 0.001$). Malaria displayed an upward trend until peaking in 1989, which was the year when morbidity among the population reached its maximum for the country at 5.63% (Figure 6). This makes French Guiana one of three countries within the study area to have a year in which the malaria morbidity maximum exceeded 1%. Afterwards, there was a general decrease in annual morbidity for the remainder of the study period. Trends in irrigation were extremely bland, with two distinct time periods in which total area did not vary. When a linear regression was performed, the analysis was also significant ($R^2 = 62.1\%$, $F_{1,41} = 66.96$, $p < 0.001$). Taking into account that the pattern of irrigated area within French Guiana displayed minor variability, both analyses suggest that a relationship with malaria was present.

Guyana

Parametric correlation and regression analyses were employed to assess a possible relationship between irrigation and malaria within Guyana. Figures on the number of malaria cases were missing for 1967 and 1996; however, which resulted in both years being excluded from the analyses. The results of a Pearson correlation analysis were significant and suggested the existence of a relationship between irrigated area and malaria within the country ($n = 45$, $r_p = 0.820$, $p < 0.001$). Originally, malaria remained relatively low prior to 1985, when a spike in infections that year caused estimated morbidity to exceed 1% (Figure 7). This was the beginning of a pattern in which morbidity remained above this value for the duration of the study period. This included a pronounced peak in 1995, where the estimated percentage of the population infected with the diseased was 8.15%. Linear regression analysis also revealed a possible relationship between irrigation and malaria, with the test being significant ($R^2 = 66.5\%$, $F_{1,43} = 88.21$, $p < 0.001$). This, combined with the results of the correlation analysis, demonstrates the possibility of a link between trends in irrigated area and subsequent malaria morbidity within Guyana over the 1962-2008 interval.

Peru

Figures on irrigated area and morbidity within Peru were examined using a nonparametric correlation analysis. Data for the 2003 and 2005 years was missing, and thus excluded from all analyses. The values produced by a Spearman correlation were significant, and suggested that a relationship between both variables was present from 1962-2008 ($n = 45$, $r_s = 0.891$, $p < 0.001$). The pattern of malaria within the country rose steadily until displaying its sharpest increase from 1991 to 1996, rising from an estimated 0.15% to 0.86%, respectively, over this interval. Two years later, morbidity reached its estimated maximum value in 1998, where approximately 0.97% of the Peruvian population became infected with the disease (Figure 8). The overall trend for irrigation was upward, with total area stabilizing at maximum in 1997 and remaining so throughout the duration of the study period. A linear regression was performed and produced an analysis what was significant ($R^2 = 81.2\%$, $F_{1,43} = 190.92$, $p < 0.001$). These values produced by both correlation and regression suggest that changes in malaria infections among the Peruvian population have been influenced over time by changes in the extent of irrigated land within the country.

Suriname

Several years were excluded from the analysis for Suriname due to an absence of figures for the annual number of malaria cases; specifically, the years of 1993, 1995, 1996, 1997, and 2000 were eliminated from consideration. A nonparametric test was performed on irrigated area and malaria morbidity within Suriname over the study period to determine the possibility of a relationship between both variables. The results of a Spearman correlation suggested the existence of such a relationship, although the analysis was only marginally significant ($n = 42$, $r_s = 0.394$, $p = 0.009$). The pattern of morbidity was erratic, with periodic highs followed by considerable drops in values in subsequent years (Figure 9). The morbidity maximum occurred in 2001, which was also an outlier year, where an estimated 3.6% of the population became infected with the disease. This made Suriname the third nation where malaria incidence among the population for a given year exceeded 1%. Despite occasionally remaining constant over some years, irrigated area experienced an overall increase until stabilizing in 1998. When a nonlinear quadratic regression was used, the analysis was significant ($R^2 = 32.9\%$, $F_{2,39} = 11.07$, $p = 0.005$). In addition, even when the 2001 outlier year was removed, the analysis remained significant ($R^2 = 30.1\%$, $F_{2,38} = 9.59$, $p = 0.007$), and suggested that irrigation has affected the spread of malaria within Suriname over the period of study.

Venezuela

Several years of data were also missing from the Venezuelan dataset, and were excluded from the analyses. These included the years of 2001, 2003, and 2008 for malaria cases reported. A nonparametric correlation analysis was performed and suggested a relationship between irrigated area and morbidity, with the results of the Spearman test being significant ($n = 44$, $r_s = 0.524$, $p < 0.001$). The pattern of malaria within Venezuela shows intervals where infections spike considerably over a short period of time, particularly in the years preceding 1971 and 1988, respectively (Figure 10). The 1988 spike also represented the morbidity maximum for the country, where the percent of the population infected reached 0.25%. Irrigation trends upward until 1989, and afterwards experiences only minor variability in total area. Linear regression also produced an analysis what was significant ($R^2 = 22.3\%$, $F_{1,42} = 13.33$, $p = 0.001$). The results of correlation and regression analyses suggest that the extent of irrigation within Venezuela may have exerted some influence on the pattern of malaria within the country over time.

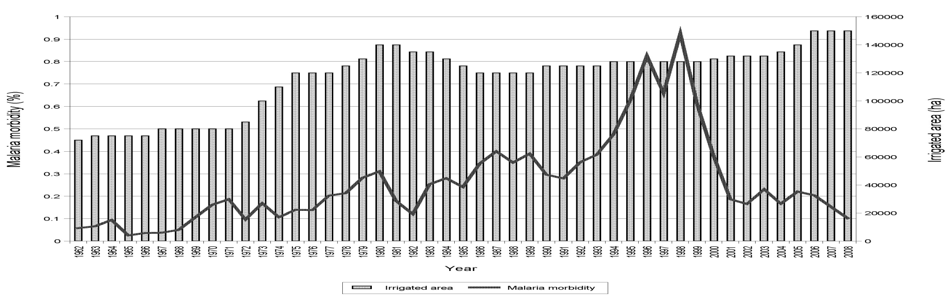

Figure 2. Annual estimates of irrigation and malaria morbidity within Bolivia from 1962-2008.

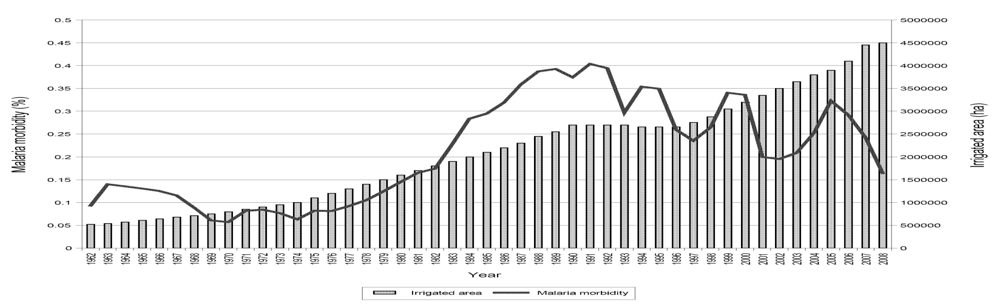

Figure 3. Annual estimates of irrigation and malaria morbidity within Brazil from 1962-2008.

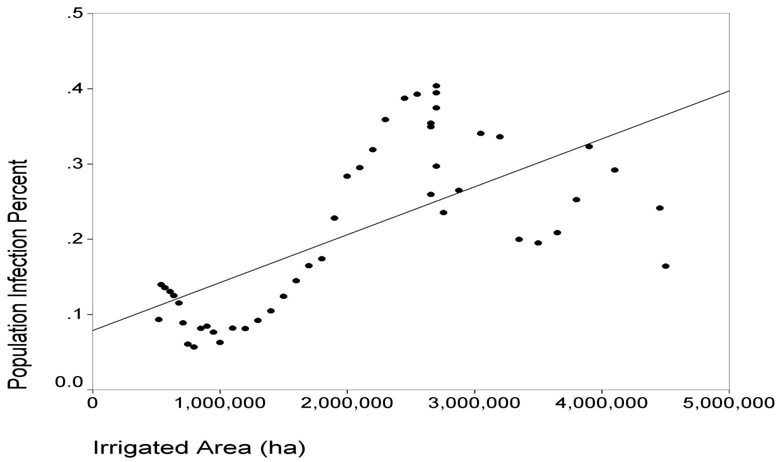

Figure 4. Scatterplot with trendline displaying the relationship between irrigation and malaria infection within Brazil over the 1962-2008 period.

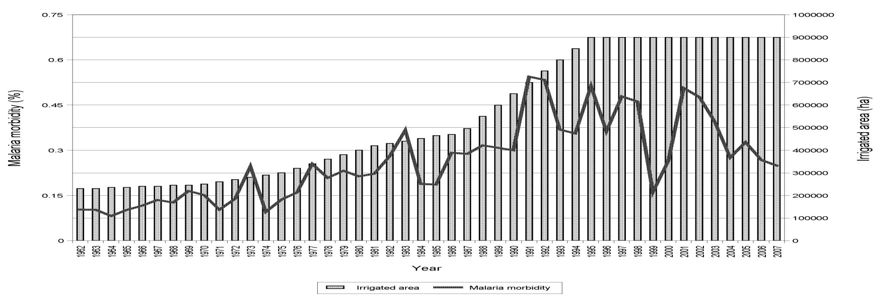

Figure 5. Annual estimates of irrigation and malaria morbidity within Colombia from 1962-2007.

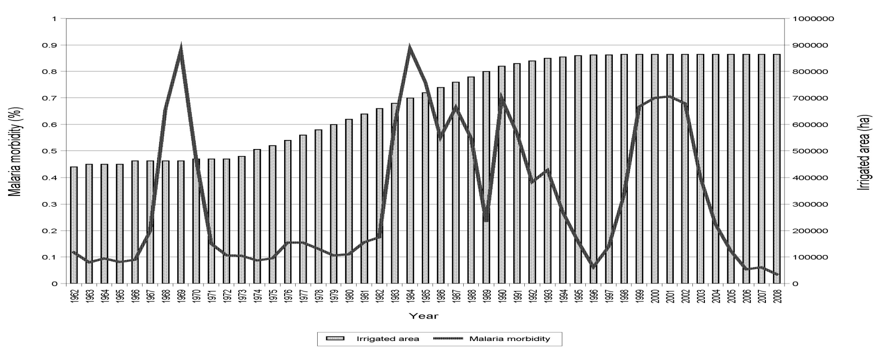

Figure 6. Annual estimates of irrigation and malaria morbidity within Ecuador from 1962-2008.

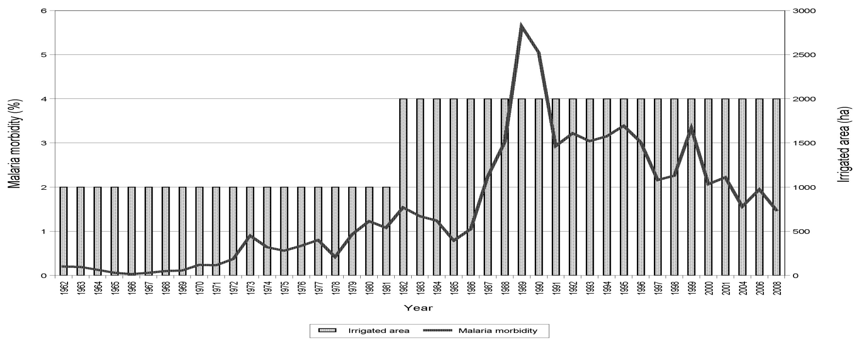

Figure 7. Annual estimates of irrigation and malaria morbidity within French Guiana from 1962-2008.

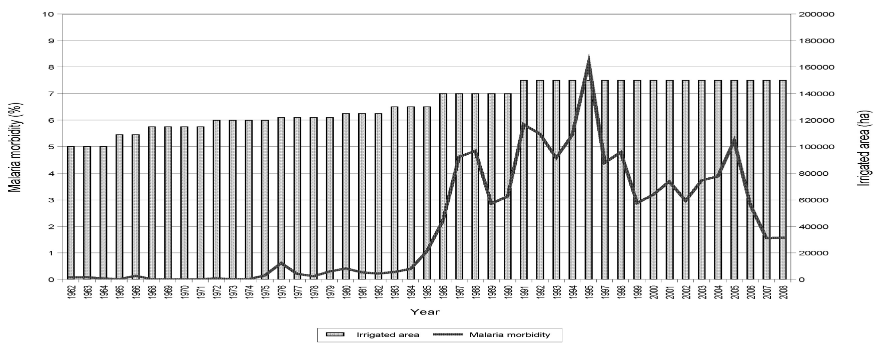

Figure 8. Annual estimates of irrigation and malaria within Guyana from 1962-2008

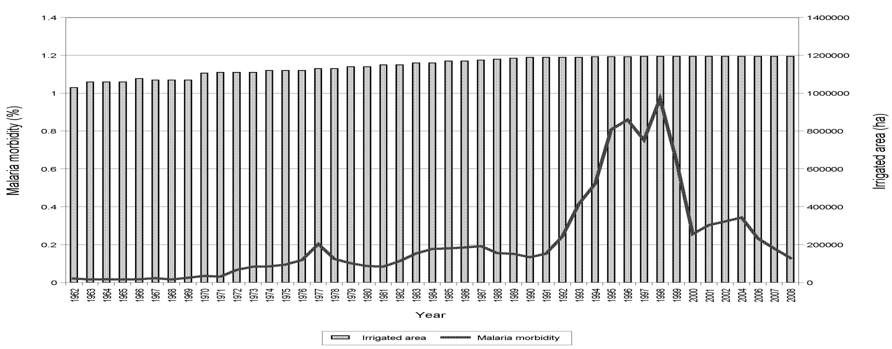

Figure 9. Annual estimates of irrigation and malaria within Peru from 1962-2008

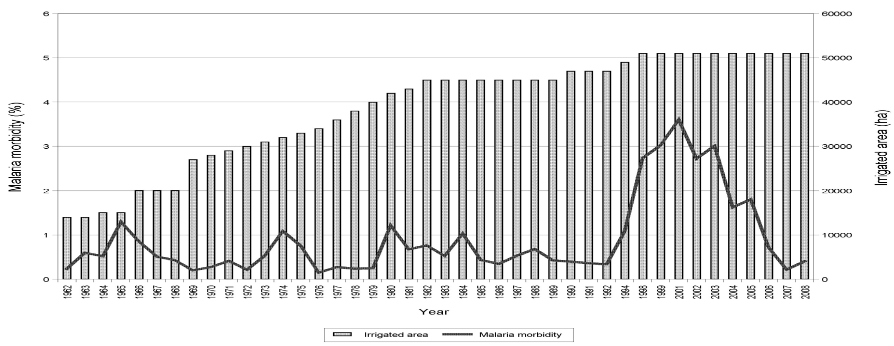

Figure 10. Annual estimates of irrigation and malaria within Suriname from 1962-2008

Discussion

These analyses support the concept that malaria transmission has been influenced by irrigation development in nearly every country associated with the Amazon Forest region of South America. The only exception was Ecuador, where the presence of a weak relationship was discounted due to a lack of statistical significance. For every other country; however, a positive and significant relationship was found to exist between irrigated area and malaria morbidity. French Guiana, Guyana, and Peru are the nations where this relationship appeared to be the strongest; although the extreme lack of variability in irrigated area for French Guiana calls the results for that country into question. French Guiana and Guyana also experienced the greatest single year values for morbidity, as well as the highest average annual morbidity values of any country, at 1.55% and 2.04% of the population infected, respectively. Based on the 1962-2008 data, the relationship between irrigation and malaria was also very strong within Brazil and Colombia over this period. The two most populous countries within the study area, these nations also displayed the lowest average annual rate of increase in malaria cases reported – with Brazil increasing at 5.05% and Colombia at 10.45% annually. After these countries are accounted for, the strength of the relationship abates considerably, yet continues to remain noteworthy and significant for Bolivia, Suriname, and Venezuela.

In addition to local scale environmental factors, such as irrigation, other larger scale phenomenon, including climatic events operating on a global level, may also exert some measure of influence on the transmission of the disease and possibly the pattern of morbidity over the period of study. For instance, the atmospheric and oceanographic variability from normal and subsequent alterations to weather associated with the El Niño-Southern Oscillation (ENSO) may serve as a mechanism which results in an increased risk of vector-borne diseases, including malaria (Kovats, 2000a). Through the observation of data provided by the Climate Prediction Center (CPC, 2011), a comparison is possible between the pattern of ENSO and those years in which malaria morbidity rose sharpest in order to obtain greater insight of the role of climate and weather fluctuations on the dynamics of the disease. Bolivia, Brazil, Ecuador, French Guiana, Guyana, Peru, and Venezuela all suffered their largest increases in malaria during years where El Niño conditions were present. In the case of Bolivia, Ecuador, and Peru, increased precipitation during the 1983 El Niño year was associated with malaria epidemics within each country (WHO, 2000a); although total irrigated area within Ecuador and Peru for that year also increased over the previous year. Also, in addition to El Niño, La Niña conditions prevailed for periods of the years where Brazil, French Guiana, Peru, and Venezuela experienced their maximum annual increase in morbidity, with Colombia experiencing a La Niña-only year.

Although the transmission of vector-borne diseases such as malaria possess linkages to the environment; irrigation, on the other hand, is subject to a host of political and economic factors which can determine the ability to initiate or maintain water development projects. In this fashion, it is those decisions driven by economic concerns that, at least indirectly, possess the potential to affect human health and the spread of malaria. For instance, protecting irrigation systems from continued deterioration can represent a considerable drain upon government budgets, and the lack of availability or willingness to utilize public funds for this purpose is an obstacle faced by many projects throughout the world (Préfol *et al.*, 2006). Internal government structure and organization likewise has the potential to influence the problem similarly. One such example could be found within Brazil, where the past level of cooperation between national agencies responsible for irrigation and water resources, as well as between local and national agencies, was inadequate and served as an administrative obstacle to the efficient allocation and management of water for irrigation and other needs (Saleth and Dinar, 2000). Incomplete regulatory frameworks could result in further vulnerability for individuals affected by water resource schemes in cases where detail is lacking. This is illustrated by the transfer of power by the Colombian government over the RUT Irrigation District, which is located in the southwest region of the country. In this case, no guidelines were established on the amount of water farmers could use to irrigate their fields, which, in turn, led to the possibility that quantities exceeding those needed by crops would be used (Depeweg and Otero, 2004). These issues are certainly not limited to Brazil and Colombia; nevertheless, they are problems that take on special significance for nations where malaria has been endemic.

In addition to the obstacles facing the efficient development of water resources in these countries, understanding the problem of malaria in the context of irrigation development requires an appreciation of the need and motivation to achieve a better quality of life by those living under impoverished conditions. Not surprisingly, agriculture represents one possible pathway towards reaching this goal. Throughout the world, many of the poor reside in rural areas where agriculture provides a means of income and food, and, subsequently, increasing the productivity of irrigated land presents opportunities for economic gain as well as for dealing with the problem of inadequate food supply (K.C. *et al*, 2011). In this sense, the extent of irrigation can be strongly influenced by market forces. When food preferences among the population shift, for instance, it may be necessary for corporations and/or local farmers to correspondingly alter their agricultural activities to meet the new demand. This is demonstrated by the example of past farming practices within the Upper Cañete Valley of Peru, where increased livestock production resulted in a greater demand for feed, which led to local farmers expanding their amount of irrigated area in order to accommodate new crops, such as alfalfa (Weigers *et al*., 1999).

Another well-known form of environmental change prevalent among these nations over the period of study, and much longer, has been deforestation. This is not surprising, and understood, given the abundance of tropical forest ecosystems that cover significant portions of the countries within the study area. As these ecosystems often overlap regions where malaria has been endemic, it may be possible that deforestation has also impacted the disease in a manner similar to that of irrigation. Specifically, changes to the local environment that take place when forest cover is removed can favor the proliferation of the mosquito vector and thus increase the likelihood of infection for human populations (Walsh *et al*., 1993; Lopez and Lozovei, 1995; Patz, 2001; Vittor *et al*, 2006). Also, like irrigation, forest clearing, such as what occurs within the Brazilian Amazon, is also dependent upon economic and political factors that commonly determine land use development, with, for instance, the creation of roads as a part of transportation infrastructure serving as a key indicator of the direction for this activity (Kirby *et al*., 2006). Using deforestation data produced by the Brazilian National Institute for Space Research (INPE, 2002), a glimpse into the 1995 year, where forest loss reached a record high, is possible. During this year, over 29,000 km^2 of Amazon forest was removed, which was a rate nearly double that of the previous year. As expected, the number of malaria cases within Brazil also increased in 1995, albeit slightly, yet the estimated population percent infected with malaria did not. The extent of total irrigated area in Brazil remained unchanged from the previous year as well. However, it should be noted that the dramatic drop in forest cover during the following two years was also accompanied by a decrease in nationwide morbidity within the country.

Given the findings of this paper and the available data, it is clear that multiple forces are in play within the environmental-epidemiological landscape of the study area, where each exerts a significant influence upon the dynamics of malaria, likely occurring over different spatial and temporal scales. In particular, it appears that two forms of land use change – deforestation and subsequent irrigation development – may on occasion operate jointly as a mechanism in which initial deforestation attributed to livestock production and new irrigation necessary to meet the demand for feed crops results in the generation of two separate zones of increased human-vector contact. Focusing upon the Brazilian Amazon, much of the clearing of forest area has been credited to ranching activities and the conversion of forest to pasture by agents operating on larger holdings of land whose actions are driven primarily by market forces (Fearnside, 1993). Therefore, deforestation as a means of creating pasture for the grazing of livestock represents the first phase of this two-part scenario, with the newly cleared area becoming a potential source of disease transmission to humans. The second phase of this process occurs in response to the subsequent necessity to feed the grazing herd. In order to accommodate this new demand, contracted farmers might be required to undertake a shift in agriculture towards crops requiring more intensive irrigation. These agricultural sites may then represent secondary zones of human-vector contact if the intensification of irrigation were translated into an expansion of wetted surface area, and thus greater breeding habitat for mosquitoes carrying the malaria parasite. Ultimately, the sequence of events in this scenario is both initiated by and dependent upon economic or political decisions which could have significant consequences to both human and environmental health in the absence of proper management. As the economic forces driving the removal of tropical forests within the Amazon Basin to satisfy livestock production are expected to continue (Walker *et al*., 2009), the relationship between this form of deforestation and subsequent irrigation in regional malaria morbidity merits further consideration for future modeling and research efforts. This also allows for the possibility that certain conservation plans aimed at protecting forest resources have the potential to limit malaria through the prevention of both deforestation for cattle pasture and the development of associated irrigation schemes in protected areas.

Future patterns of malaria incidence will not only be determined by environmental changes, such as those initiated by new irrigated agriculture, but also on how these changes interrelate with the larger demographic processes taking place within each nation of the study area. Human population movement, for instance, has certainly occurred over the period of study and has likely transformed the pathways in which the disease has been transmitted. By placing people in areas where the chance of contact with mosquitoes infected with the malaria parasite is higher, migration becomes a proximate influence on morbidity, as displayed by research of study sites within the Brazilian Amazon (Marques, 1987; McGreevy *et al*., 1989; Conn *et al*., 2002). Therefore, the affect of out-migration from rural areas of the country could explain some of the behavior of morbidity within the country over the study period. According to census figures, unlike the cities, rural areas of Brazil have experienced decreased population growth for the past five decades (IBGE, 2010). However, the decade of the 1990's displayed the largest drop, with rural areas losing over 4 million people, which outpaced the rate of any other decade by at least 1 million. Calculations by Laurance *et al*. (2001) performed over the 1970-2000 census intervals also revealed that the rural population of the Brazilian Legal Amazon decreased during the 1990's, and was contrary to the high growth rates experienced by the region overall. The mean annual increase in nationwide malaria cases of 1.6 % during the 1990's was also lower than that of any other decade within Brazil, and considerably lower than the 14.9 % mean of the 1980's. It must be noted that total irrigated area was relatively stable and showed little variability for most of the decade as well. One or a combination of these factors could be responsible for the 1990's experiencing the first downward trend in morbidity percent in three decades. In the case of Brazil, out-migration from rural areas may be indicative of a process in which people distance themselves from environmentally transformative actions (e.g. irrigated agriculture, deforestation, etc.) within at-risk zones that could otherwise result in greater susceptibility to disease infection.

Other variables related to population movement may, in certain cases, factor into the pattern of disease displayed by some of the countries within the study area. The number of malaria cases reported in Colombia, for instance, rose dramatically during the 1970's – exceeding 50,000 infections for the first time in 1973 (WHO, 1983), a threefold increase over ten years. This decade marks the beginning of a pronounced upward trend in morbidity percent that continued for the next twenty years. This pattern may be related to the movement of groups of individuals intending to engage in agricultural activities. Specifically, a combination of seasonal out-migration and circulation of peoples descending from the highlands into the lowland areas of the Naya basin had resulted in an increase in malaria incidence, where the sudden boom in population associated with agricultural cultivation and the endemic character of the lowland deltaic zone facilitated the transmission of the disease (Sevilla-Casas, 1993). Nationally, the extent of irrigated agriculture in Colombia climbed during this interval, with total irrigated area experiencing a nearly threefold increase from 1961 to 1990. This rise in nationwide irrigation, in concert with population movement to endemic zones in order to practice seasonal agriculture, likely accounts for the primary variables acting upon malaria morbidity within Colombia during the decades of the 1970's and 1980's.

The task of controlling malaria is undoubtedly a massive endeavor, and one that should be neither underestimated nor underappreciated; particularly, given the complexity of factors that affect morbidity, as demonstrated by the relationship between irrigation and malaria within the study area. Changes in local environmental setting, seasonality, feeding characteristics of the mosquito vector, and its adaptability to change are among the variables to be accounted for as part of an efficient strategy for disease control (Hiwat and Bretas, 2011). This includes understanding the role of irrigation on vector habitat by ensuring that these facilities are maintained effectively in order to limit contact between infected mosquitoes and humans (Martens and Hall, 2000). Either greater awareness of the problem or the success of these methods may at least be partially responsible for the downward trend in morbidity percent over the decade of the 2000's as experienced by the majority of nations of the study area; specifically, as it relates to the decreasing morbidity values for Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, and Suriname observed during this interval. Other measures, such as insecticide-treated materials, indoor spraying, or antimalarial drugs, also merit consideration as mitigating factors depending upon their availability to populations residing within at-risk zones. However, as demonstrated by the situation in Peru, poor interconnectivity between government agencies and a lack of financial transparency often present serious obstacles to the efficient tracking and execution of healthcare operations (Kosack *et al*., 2010).

In summary, the findings of this paper support the concept that irrigation schemes exert a significant influence upon nationwide malaria within the majority of countries of the Amazon Forest region of South America. With the exception of Ecuador, the fact that the remaining eight countries comprising the study area exhibit this relationship suggests the importance of prioritizing adequate maintenance and enacting control programs around either future water resource projects or whenever changes to existing facilities occur. This requires an understanding of the physical and social variables acting upon morbidity, some of which may even work synergistically to intensify the disease within certain endemic populations. Fortunately, recent trends for malaria provide a measure of optimism and hope that future outbreaks will be limited and overall incidence will stabilize at low levels for the majority of nations within the region. However, given the observed patterns of morbidity, where infection rates can vary greatly over relatively small intervals of time – and the need for irrigation or other environmentally-transformative actions necessary to feed growing populations – complacency must be avoided and increased communication between governments and agencies dedicated to the eradication of the disease should be strongly encouraged.

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