Introduction

A geographical information system (GIS) is a computerized system that combines spatial and descriptive data for mapping and analysis (1). One of the main strengths of a GIS is its ability to integrate different types of spatial data. For example, a GIS can be used to map available epidemiological information and relate it to factors known to influence the distribution of infectious diseases, such as climate and other environmental factors. The ability to acquire relevant climatic information, particularly in the tropics, where there is an inadequate infrastructure for the collection of meteorological data, has

| Objective | To design and implement a rapid and valid epidemiological assessment of helminths among schoolchildren in Chad using ecological zones defined by remote sensing satellite sensor data and to investigate the environmental limits of helminth distribution. |
| Methods | Remote sensing proxy environmental data were used to define seven ecological zones in Chad. These were combined with population data in a geographical information system (GIS) in order to define a sampling protocol. On this basis, 20 schools were surveyed. Multilevel analysis, by means of generalized estimating equations to account for clustering at the school level, was used to investigate the relationship between infection patterns and key environmental variables. |
| Findings | In a sample of 1023 schoolchildren, 22.5% were infected with Schistosoma haematobium and 32.7% with hookworm. None were infected with Ascaris lumbricoides or Trichuris trichiura. The prevalence of S. haematobium and hookworm showed marked geographical heterogeneity and the observed patterns showed a close association with the defined ecological zones and significant relationships with environmental variables. These results contribute towards defining the thermal limits of geohelminth species. Predictions of infection prevalence were made for each school surveyed with the aid of models previously developed for Cameroon. These models correctly predicted that A. lumbricoides and T. trichiura would not occur in Chad but the predictions for S. haematobium were less reliable at the school level. |
| Conclusion | GIS and remote sensing can play an important part in the rapid planning of helminth control programmes where little information on disease burden is available. Remote sensing prediction models can indicate patterns of geohelminth infection but can only identify potential areas of high risk for S. haematobium. |

Keywords

Helminths/growth and development; Helminthiasis/epidemiology; Schistosoma haematobium/growth and development; Schistosomiasis haematobia/epidemiology; Ancylostomatoidea/growth and development; Human infections/epidemiology; Ancylostomidae/growth and development; Trichuris/growth and development; Environmental monitoring; Ecology; Information systems; Epidemiologic studies; Chad (source: MeSH, NLM).

Mots clés

Helminthe/croissance et développement; Helminthiasis/épidémiologie; Schistosoma haematobium/croissance et développement; Schistosomiasis haematobia/épidémiologie; Ancylostomatoidea/croissance et développement; Ankylostomiasis/épidémiologie; Ascaris lumbricoides/croissance et développement; Trichuris/croissance et développement; Surveillance environnement; Écologie; Système information; Étude analytique (Épidémiologie); Tchad (source: MeSH, INSERM).

Palabras clave

Helminthes/crecimiento y desarrollo; Helminthiasis/epidemiología; Schistosoma haematobium/crecimiento y desarrollo; Esquistosomiasis haematobia/epidemiología; Ancylostomatoidea/crecimiento y desarrollo; Infecciones por uncinaria/epidemiología; Ascaris lumbricoides/crecimiento y desarrollo; Trichuris/crecimiento y desarrollo; Monitoreo del ambiente; Ecología; Sistemas de información; Estudios epidemiológicos; Chad (fuente: DeCS, BIREME).
been enhanced by remote sensing (RS) techniques that can provide proxy environmental information derived from satellite sensors (2, 3). RS environmental variables have been used to explain the distribution of various infectious diseases, with direct application to disease control programmes (4). Understanding the environmental limits of infection can aid the targeting of national control strategies, as has been demonstrated for onchocerciasis (5) and filariasis (6). For the control of geohelminth and schistosome infections, current WHO recommendations are based on the concept of sample surveys within defined ecological zones (7). There is a need, however, for guidelines whereby health planners can identify such zones and, using population data, develop and conduct rapid and valid epidemiological surveys of different helminth species.

Understanding the environmental limits of infection can also improve our knowledge of helminth biology and epidemiology. Much of our understanding of the environmental sensitivity of helminth species comes from studies undertaken under experimental conditions. For example, experimental studies have identified the temperature at which the development of free-living stages occurs in the shortest time, as well as the minimum and maximum temperatures that represent the thermal limits of development (8). A major disadvantage of this approach is that the extent to which findings can be extrapolated to the field is not known. Some studies have investigated the outdoor development and survival of free-living stages of helminth species (9, 10) but it is not clear how specific they were to the setting in which they were conducted. In contrast, the use of RS environmental observations by satellite sensors allows quantitative measurements of key climatic variables at regular intervals on the regional scale (3). Using Advanced Very High Resolution Radiometer (AVHRR) Pathfinder sensor data, we showed that the prevalence of **Ascaris lumbricoides** and **Trichuris trichiura** in Cameroon rarely exceeded 10% in areas where the RS-derived maximum land surface temperature exceeded 37–40°C (8, 11). Furthermore, field studies in West Africa showed that **Schistosoma haematobium** occurred only throughout the Sahelian zone, because of the adaptation of the host snail **Bulinus senegalensis** to semipermanent water bodies in the Sahel (12–14). Using the same AVHRR Pathfinder sensor data, it is possible to characterize these areas of potential schistosome transmission in Cameroon (11, 15). The correlations between observed disease patterns and RS environmental variables can also be used to extrapolate risk estimates to areas for which no data are available. It is unclear, however, whether predictions developed for one country are useful in describing infection patterns in another, since the environmental factors that influence disease transmission are unlikely to be uniform over large geographical areas (15).

Building on these investigations, we describe how a GIS/RS approach can be used to plan and conduct a rapid epidemiological assessment and to define the environmental limits of helminth species in Chad.

**Methods**

**Remotely sensed proxy environmental data**

In Chad, detailed meteorological observations are available for only five sites (16), which do not adequately capture the range of climatic conditions in the country as a whole. The poor spatial resolution of meteorological data was overcome by using remotely sensed environmental data derived from the AVHRR sensor on the US National Oceanic and Atmospheric Administration’s (NOAA) polar-orbiting meteorological satellites. These data were used to calculate mean annual summaries for 1982–2000 of surface brightness temperatures (expressed as land surface temperature) and photosynthetic activity estimates, expressed as the normalized difference vegetation index. This involved standard procedures of data processing and quality control (2). Minimum, mean, and maximum values of remotely sensed data were used.

The accuracy of RS methods for providing estimates of temperature was investigated in Africa by comparing estimates of land surface temperature with meteorological ground measurements (17, 18). A significant correlation between land surface temperature and ground observations was found, with root mean square errors of around 2°C (17). Thus the correlation between land surface temperature and ground observations is sufficiently strong for practical applications in epidemiological mapping.

**Sampling design**

Stratified sampling by ecological zone overlaid with population data was used to select 20 schools. A map of ecological zones in Africa was derived from the RS environmental data described above. These data, in combination with a digital elevation model of Africa (available from: URL: http://edcwww.cr.usgs.gov/landdaac/gtopo30) and interpolated rainfall surfaces (19) were used to generate 20 ecological zones by means of the unsupervised classification procedures of Earth Resources Data Analysis System (ERDAS) Imagine 8.4™ software. ERDAS implements the iterative self-organizing data analysis technique, which uses Euclidean distance as a similarity measure to cluster data in discrete classes, independently of their geographical location (20, 21).

The resulting ecological map divides Chad into seven ecological zones (Fig. 1a). The map provides an overview of the main ecological variables known to be associated with different patterns and prevalences of helminth infection (8, 11, 15). Overlaying this map with data on population density (22) can help to guide the sample protocol. In the case of Chad, the survey focuses on the populous south-west of the country (Fig. 1b). In this area there are three ecological zones and an urban zone, the latter being the capital, N’Djamena. This is all the information required to target the sampling by ecological zone and population density. Logistical considerations meant that the sample had to be limited to 20 schools situated not more than 30 km from main roads. The number of schools sampled in each zone was proportional to the population. For example, because 10% of the country’s population lives in the tropical zone, two schools were randomly selected.

**Field investigations**

The survey was conducted in November 2000. The target was to randomly select 25 boys and 25 girls aged 9–10 years (class 3). If there were insufficient pupils of this age, additional pupils were sampled from classes 4–7. Many of the schools visited were small, and female enrolment was low. Consequently, it was often necessary to include all the girls in a school in order to achieve the target sample size. In some cases fewer than 25 girls were present. Participation was voluntary and was approved by the local school committee and parents.
A faecal sample was collected from each child and examined using the Kato–Katz method; 10 ml of a urine specimen collected from each child were filtered through a polycarbonate membrane (diameter = 13 mm, pore size = 12 μm; Millipore, Watford, England) and examined microscopically. Each child infected with schistosomes received 40 mg/kg praziquantel and each child infected with geohelminth species received 400 mg albendazole. The geographical location of each school was recorded in the field by means of a non-differential global positioning system (Magellan Systems Corporation, San Dimas, CA, USA) accurate to ±10 m.

Data analysis

\( \chi^2 \) and Student's t-tests were used to assess differences in the prevalence and intensity of infection, by sex. Analysis was also undertaken to investigate how key environmental variables correlated with infection patterns, as determined by the probability that an individual child was infected. Since variables were collected at the individual and school levels, a multilevel approach of logistic regression was employed, accounting for the non-independence of individual observations within schools. In particular, the use of multilevel modelling controlled for the considerable sampling bias in the study towards boys when investigating the environmental correlates of infection. The analysis was performed by means of generalized estimating equations (23, 24) with the \texttt{xgge} procedure (logit link function and binomial distribution specified with robust standard errors, grouped by school) in Stata (Intercooled Stata 6.0, College Station, TX, USA). A forward stepwise procedure was used to screen the included explanatory variables (\( P<0.05 \)).

Validation of RS prediction models for Cameroon

Statistical correlations between epidemiological data and RS environmental data were previously investigated in Cameroon (8, 11). Multivariate logistic regression models were developed to identify the main predictors of helminth prevalence in school-age children exceeding 50% (the WHO-recommended threshold for mass treatment), 20%, and 0%. The significant environmental variables were maximum land surface temperature, rainfall and normalized difference vegetation index (11). No statistically significant model could be developed for hookworm. The statistical models derived from the data for Cameroon were applied to the RS data so as to define the probability of infection prevalence exceeding 50%, 20%, or 0% for the rest of Cameroon. We extended these predictions to Chad and compared them with the field data. This involved taking a 10-km buffer zone around each school and taking the average values of the pixels in each buffer zone (1).

Results

Of the 626 boys and 397 girls examined, over 90% were aged 8–13 years. Of the 1017 children who provided a urine sample, 22.5% were infected with \( S. \) haematobium. The intensity of infection with \( S. \) haematobium lay in the range 1–749 eggs per 10 ml, but generally the children were lightly infected: only 6.1% excreted over 50 eggs per 10 ml. Of the 1000 children who provided a stool sample, 32.7% were infected with hookworm (mean egg count = 180 eggs/g; range by school = 0–694 eggs/g). Both \( S. \) haematobium and hookworm were present in 7.1% of children. Seven children (1%) excreted \( S. \) mansoni eggs in their faeces. No children were infected with \( A. \) lumbricoides or \( T. \) trichiura.

Significantly more boys than girls were infected with \( S. \) haematobium (28.8% vs 12.7%, \( \chi^2 \) test = 35, \( P<0.0001 \)) and hookworm (35.8% vs 28.5%, \( \chi^2 \) test = 5, \( P = 0.03 \)). Boys were also more heavily infected than girls with \( S. \) haematobium (15.6 vs 9.4 eggs/10 ml, \( P<0.05 \)) and hookworm (208 vs 132 eggs/g, \( P<0.02 \)).
Fig. 2 shows the distribution of helminth infections in Chad by ecological zone. The prevalence of *S. haematobium* varied considerably between schools, being highest in the Sahelian zone and the Logone and Chari basins in the west of the country, and lowest in the N’Djamena and tropical zones. Hookworm was most prevalent in the Sudan and tropical zones; there was little or no transmission in the Sahelian zone. Neither *A. lumbricoides* nor *T. trichiura* occurred anywhere in the country at detectable levels.

Table 1 presents infection patterns and their associated environmental variables by ecological zone. Areas of high *S. haematobium* prevalence had low rainfall and high mean land surface temperatures. However, this was also true of N’Djamena, where the prevalence of *S. haematobium* was under 5%. Substantial hookworm infection occurred in the Sudan and tropical zones, whereas there was little or no hookworm infection in N’Djamena or the Sahelian zone, where the mean land surface temperature exceeded 47 °C. Table 2 shows the results of the multivariate analyses as odds ratios for being infected. Boys were 2.4 times more likely than girls to be infected with *S. haematobium*. Mean land surface temperature and rainfall were significantly associated with *S. haematobium* infection. For hookworm, increasing mean land surface temperature was associated with a reduced chance of being infected.

On the basis of models developed in Cameroon (11), we predicted the prevalence of infection category (0, 20, or 50%) for each school surveyed. These models predicted that *A. lumbricoides* and *T. trichiura* would not occur in Chad because the mean land surface temperature exceeds 37 °C throughout the country (8, 11). Such predictions are supported by experimental data: *T. trichiura* eggs take about 28 days to develop at 25 °C, 15 days at 30 °C and 13 days at 34 °C, and do not develop at all above 37 °C (25). The optimal temperature for the embryonation of *Ascaris* spp. is 31 °C (26); 38 °C is lethal (26, 27). These values and the present data confirm an upper thermal limit of around 37 °C for both *A. lumbricoides* and *T. trichiura*.

**Discussion**

The present study on helminth infections in Chad describes the use of GIS and RS to guide a valid rapid epidemiological survey of different helminth species as a basis for developing a national control programme. The study also predicts the environmental limits of several helminth species in the country. The results confirm that *A. lumbricoides* and *T. trichiura* should not occur in Chad because the mean land surface temperature exceeds 37 °C throughout the country (8, 11). Previous studies have failed to identify ecological correlates of hookworm infection (11). Our previous work in Cameroon suggested that this reflected the absence of differential diagnosis of hookworm species or the predominance of behavioural factors. However, the present results suggest that...
hookworm occurs only in the south of Chad and that there is little or no infection in areas where the mean land surface temperature exceeds 47 °C. This distribution pattern probably defines the upper thermal limit of hookworm infection, which is apparently greater than that for A. lumbricoïdes and T. trichiura (37 °C). This species difference in observed thermal limits is corroborated by survey data for Mali (28), where A. lumbricoïdes and T. trichiura occur at negligible levels (<0.5%) and hookworm occurs in areas where the mean land surface temperature exceeds 40 °C. This limit differs from that found in experimental studies showing that egg development stops and death occurs above 35–40 °C (9, 10, 29). For example, Udonsi & Atata (9) showed that at 35 °C the larvae of Nécator americanus all died and that the highest cumulative hatching occurred at 30 °C. Given these findings and allowing for potential error in RS estimates (± 2 °C), the question arises to why hookworms apparently have a thermal limit of 48 °C and why this exceeds that for either A. lumbricoïdes or T. trichiura.

One possible explanation for our findings is that microhabitats provide suitable foci for hookworm transmission in areas of high temperature. However, this argument would be expected to hold also for A. lumbricoïdes or T. trichiura. Alternatively, hookworm might undergo arrested development in order to achieve synchronization with external conditions (30), although this is observed only for Angiostrongylus duodenale, whereas N. americanus is the predominant species in Africa. Another explanation might lie in the differences in the life expectancies of mature worms in the human host: 3–4 years for hookworm and 1–2 years for A. lumbricoïdes and T. trichiura (31). Research is in progress on this hypothesis.

Other helminths

Predictions for Cameroon indicated that S. haematobium could potentially occur throughout the Sahelian zone (11, 15), where transmission take places in areas with semipermanent water bodies and with Bulinus senegalensis as the most likely intermediate host (12). These predictions are much less reliable than those relating to A. lumbricoïdes and T. trichiura. The lack of predictive accuracy for S. haematobium supports the view that it is not possible to make prediction models for schistosomiasis that are applicable at the local level (15). Rather, large-scale models are useful for identifying potential areas of high risk. In particular, they can help to exclude areas where S. haematobium is unlikely to be prevalent and thus indicate areas where local detailed surveys are required so that control can be targeted more precisely. In the present study, all the schools were predicted to be in areas of potential high risk, but local environmental factors presumably determined the actual levels of transmission. For example, the Logone and Chari river basins constitute important foci of schistosomiasis transmission, verifying earlier field studies (32, 33). In these areas, where rice production is common, there are stagnant ponds and irrigation ditches capable of supporting populations of Bulinus globosus and B. truncatus throughout the year (34). These findings illustrate the importance of considering the occurrence of man-made features and other small-scale environmental factors that are not readily detectable in large-scale RS data. A simple questionnaire, administered by teachers to their pupils, can be used to identify individual schools where the prevalence of S. haematobium is ≥50% and therefore warrant mass treatment (35).

Conclusion

The objective of the present national survey was to determine the distribution of helminth infection within the country and to contribute towards planning school-based control programmes, for which purpose it is essential to estimate the target population. The population of Chad in 2000 was estimated to be 8.4 million, of whom 2.4 million were aged 5–14 years. Assuming that the survey results within each zone are representative, they allow the school-age population at risk of schistosomiasis and hookworm transmission to be quantified. On this basis, it is estimated that 1.7 million children in nine districts would be the target for mass treatment for hookworm and that 1.3 million children in eight districts would be the target for a school-based national schistosomiasis control programme, which would include questionnaire screening at the school level. Estimates for school-based programmes suggested that the overall cost per child treated with albendazole for geohelminth control was US$ 0.03 in Ghana and United Republic of Tanzania, and that the costs per child treated with praziquantel for schistosomiasis control were US$ 0.67 and US$ 0.21, respectively, in these two countries (36). Thus it would cost approximately US$ 51 000 for a

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Table 1. Infection prevalences and key environmental variables by ecological zone, Chad

<table>
<thead>
<tr>
<th>Zone</th>
<th>Median infection prevalence (%)</th>
<th>Land surface temperature (°C)</th>
<th>Total rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hookworm</td>
<td>Schistosoma haematobium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>N’Djamena</td>
<td>0.0</td>
<td>2.0</td>
<td>47.9</td>
</tr>
<tr>
<td>Sahelian</td>
<td>3.6</td>
<td>37.3</td>
<td>49.4</td>
</tr>
<tr>
<td>Sudan</td>
<td>44.4</td>
<td>18.0</td>
<td>44.1</td>
</tr>
<tr>
<td>Tropical</td>
<td>76.0</td>
<td>2.0</td>
<td>41.0</td>
</tr>
</tbody>
</table>

Table 2. Details from multivariate analysis used to estimate probability of a child being infected, in 20 schools, Chad

<table>
<thead>
<tr>
<th></th>
<th>Odds ratio</th>
<th>Robust standard error</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schistosoma haematobium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>2.40</td>
<td>0.43</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mean land surface temperature</td>
<td>3.65</td>
<td>1.29</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Rainfall</td>
<td>1.01</td>
<td>0.003</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Hookworm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean land surface temperature</td>
<td>0.70</td>
<td>0.07</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

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* Data on the school-age population for every district were based on 1990 national population forecasts (22), projected to 2001 on the assumption of country- and year-specific inter-census growth rates (See: URL: http://www.census.gov/ipc/www/idbnew.html).
school-based programme of geohelminth control and US$ 273,000–871,000 for a school-based schistosomiasis control programme in Chad.

The present study demonstrates the important role of RS and GIS in planning national helminth surveys, which are an essential prelude to planning the deworming component of national school health initiatives. The use of ecological zone maps is shown to be of value in defining sampling clusters without the need for any ground-based ecological surveys. Multilevel methods are useful in investigating the relationships between infection patterns and environmental variables, and show the importance of temperature in defining the ecological limits of hookworm infection, and of temperature and rainfall in characterizing areas of high prevalence of S. haematobium. We have also shown that RS data can reliably predict the occurrence of geohelminth species. The approach can predict only the potential risk of schistosome transmission, and local questionnaire surveys are needed to target control more precisely. The use of RS data should now be investigated in other epidemiological and ecological settings in order to obtain further validation of the adopted approach. Perhaps more importantly, the challenge for epidemiologists is to demonstrate how this approach is of practical relevance to control programmes.
un análisis jerarquizado, usando ecuaciones de estimación generalizadas a fin de tener en cuenta el agrupamiento a nivel de las escuelas, para investigar la relación entre los modelos de infección y variables ambientales clave.

**Resultados** En una muestra de 1023 escolares, el 22,5% estaban infectados por *Schistosoma haematobium*, y el 32,7% por anquilostoma. Ninguno estaba infectado por Ascaris lumbricoides o Trichuris trichiura. La prevalencia de *S. haematobium* y de anquilostoma mostró una marcada heterogeneidad geográfica, y la distribución observada resultó estar estrechamente relacionada con las zonas ecológicas definidas, y ligada de forma importante a variables ambientales. Estos resultados permiten definir más fácilmente los límites de temperatura de las especies de geohelmintos. Se hicieron predicciones de la prevalencia de las infecciones para cada escuela analizada con la ayuda de modelos desarrollados anteriormente para el Camerún. Estos modelos predijeron correctamente que *A. lumbricoides* y *T. trichiura* no se detectarían en el Chad, pero las predicciones para *S. haematobium* fueron menos fiables a nivel de las escuelas.

**Conclusión** Los SIG y la teleobservación pueden ser instrumentos valiosos para planificar rápidamente programas de lucha anti-helmíntica cuando se dispone de poca información sobre la carga de morbilidad. Los modelos predictivos basados en la tele-observación pueden indicar la distribución de las infecciones por geohelmintos, pero sólo logran identificar las zonas potenciales de alto riesgo de infección por *S. haematobium*.

**References**

20. PMID: 9875775