Global Epidemiology, Ecology and Control of Soil-Transmitted Helminth Infections

S. Brooker¹, A.C.A. Clements¹,² and D.A.P. Bundy³

¹Department of Infectious and Tropical Disease, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, UK
²Schistosomiasis Control Initiative, Department of Infectious Disease Epidemiology, Faculty of Medicine, Imperial College, Norfolk Place, London W2 1PG, UK
³Human Development Division, The World Bank, Washington DC 20433, USA

Abstract ........................................... 221
1. Introduction ..................................... 222
2. Transmission Dynamics and the Environment .......... 224
3. Ecological Correlates ................................ 227
4. Predicting Distributions ............................ 231
5. Urbanization ..................................... 232
6. Global Control Strategies ........................... 234
7. Control Applications of GIS/RS ...................... 237
8. Global Distributions ............................... 243
9. Predicted Numbers of Infections .................... 246
10. The Future ...................................... 250
Acknowledgements .................................. 252
References ........................................ 252

ABSTRACT

Soil-transmitted helminth (STH) infections are among the most prevalent of chronic human infections worldwide. Based on the demonstrable impact on child development, there is a global commitment to finance and implement control strategies with a focus on school-based
chemotherapy programmes. The major obstacle to the implementation of cost-effective control is the lack of accurate descriptions of the geographical distribution of infection. In recent years, considerable progress has been made in the use of geographical information systems (GIS) and remote sensing (RS) to better understand helminth ecology and epidemiology, and to develop low-cost ways to identify target populations for treatment. This review explores how this information has been used practically to guide large-scale control programmes. The use of satellite-derived environmental data has yielded new insights into the ecology of infection at a geographical scale that has proven impossible to address using more traditional approaches, and has in turn allowed spatial distributions of infection prevalence to be predicted robustly by statistical approaches. GIS/RS have increasingly been used in the context of large-scale helminth control programmes, including not only STH infections but also those focusing on schistosomiasis, filariasis and onchocerciasis. The experience indicates that GIS/RS provides a cost-effective approach to designing and monitoring programmes at realistic scales. Importantly, the use of this approach has begun to transition from being a specialist approach of international vertical programmes to becoming a routine tool in developing public sector control programmes. GIS/RS is used here to describe the global distribution of STH infections and to estimate the number of infections in school-age children in sub-Saharan Africa (89.9 million) and the annual cost of providing a single anthelmintic treatment using a school-based approach (US$5.0–7.6 million). These are the first estimates at a continental scale to explicitly include the fine spatial distribution of infection prevalence and population, and suggest that traditional methods have overestimated the situation. The results suggest that continent-wide control of parasites is, from a financial perspective, an attainable goal.

1. INTRODUCTION

There are four main nematode species of human soil-transmitted helminth (STH) infections, also known as geohelminths: *Ascaris lumbricoides* (roundworm), *Trichuris trichiura* (whipworm), *Ancylostoma*
_duodenale_ and _Necator americanus_ (hookworms). These infections are most prevalent in tropical and sub-tropical regions of the developing world where adequate water and sanitation are lacking, with recent estimates suggesting that _A. lumbricoides_ infects 1221 million people, _T. trichiura_ 795 million and hookworms 740 million (de Silva et al., 2003). The greatest numbers of STH infections occur in sub-Saharan Africa (SSA), East Asia, China, India and South America.

Chronic and intense STH infections can contribute to malnutrition and iron-deficiency anaemia, and also can adversely affect physical and mental growth in childhood (Drake et al., 2000; Stephenson et al., 2000; Hotez et al., 2004). In recognition of the global health importance of STH infections, there is a renewed global commitment to finance and implement control strategies to reduce the disease burden of STH and other helminths, including schistosomiasis (Fenwick et al., 2003), filariasis and onchocerciasis (Molyneux et al., 2003). The development of effective helminth control is possible because of the availability of proven, cost-effective and logistically feasible intervention strategies. In the case of STH infections, regular periodic chemotherapy, using benzimidazole anthelmintics (BZAs), of school-aged children delivered through the school system is the main intervention strategy (Aswashi et al., 2003; Hotez et al., 2006; Bundy et al., 2006). Understanding where at-risk populations live is fundamental for appropriate resource allocation and cost-effective control. In particular, it allows for reliable estimation of the overall drug needs of programmes and efficient geographical targeting of control efforts (Brooker and Michael, 2000). The precise global distribution of STH infection and how many people are infected and at risk of morbidity however remains poorly defined. This limits how national governments and international organizations define and target resources to combat the disease burden due to STH infection.

A previous review in this series highlighted the potential use of geographical information systems (GIS) and remote sensing (RS) to better understand helminth distributions and their ecological correlates, but also to serve as geographic decision-making tools for identifying areas of particular risk as well as for the design, implementation and monitoring of control programmes (Brooker and Michael, 2000). As an increasing number of large-scale control efforts are underway, it
is timely to assess how the potential of GIS and RS to guide control has been realized in practice. This article begins by describing the scientific basis of how environmental factors affect the biology and transmission dynamics of STH infection. We then show how satellite data can be used to establish and predict species-specific distributions, and how these tools can help shed additional light on the ecology and epidemiology of infection. Next, we describe how these tools have been effectively used within the context of large-scale control programmes. Finally, we adopt a data-driven approach to map the contemporary global distributions of STH infection, and relate these to global human population-distribution data to derive regional and national estimates of population at risk by parasite species. Although focusing on STH infections, examples will also be presented for other helminthiases, including schistosomiasis, filariasis and onchocerciasis.

2. TRANSMISSION DYNAMICS AND THE ENVIRONMENT

To understand and ultimately predict the global distribution of STH infections, it is essential to appreciate their biology, ecology and transmission dynamics. The life cycles of STH infection follow a general pattern. The adult parasite stages inhabit some part of the host intestine (A. lumbricoides and hookworm in the small intestine; T. trichiura in the colon), reproduce sexually and produce eggs, which are passed in human faeces and deposited in the external environment. Adult worms survive for several years and produce large numbers of eggs after 4–6 weeks (Table 1). Eggs can remain viable in the soil for several months (A. lumbricoides and T. trichiura) and larvae several weeks (hookworms), dependent on prevailing environmental conditions. A. duodenale larvae can undergo hypobiosis (arrested development at a specific point in the nematode life cycle) in the human body under certain environmental conditions for several months. Infection occurs through accidental ingestion of eggs (A. lumbricoides and T. trichiura) or penetration of the skin (by hookworm larvae).

As is common for infectious diseases, the transmission of STH infections can be summarized by the basic reproductive number ($R_0$).
**Table 1** Population parameters, development rates and life expectancies of parasites and free-living STH infective stages

<table>
<thead>
<tr>
<th></th>
<th><em>A. lumbricoides</em></th>
<th><em>T. trichiura</em></th>
<th>Hookworm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infected stage</strong></td>
<td>Ova</td>
<td>Ova</td>
<td>Larvae</td>
</tr>
<tr>
<td><strong>Egg production</strong></td>
<td>10,000–200,000</td>
<td>2,000–20,000</td>
<td>3,000–20,000</td>
</tr>
<tr>
<td><strong>Life expectancy</strong></td>
<td>28–84 days</td>
<td>10–30 days</td>
<td>3–10 days</td>
</tr>
<tr>
<td><strong>Adult life span</strong></td>
<td>1–2 years</td>
<td>1–2 years</td>
<td>3–4 years</td>
</tr>
<tr>
<td><strong>Pre-paraty (adult development to sexual maturity)</strong></td>
<td>50–80 days</td>
<td>50–84 days</td>
<td>28–50 days</td>
</tr>
<tr>
<td><strong>Larvae development time to infective stage</strong></td>
<td>8–37 days</td>
<td>20–100 days</td>
<td>2–14 days</td>
</tr>
<tr>
<td><strong>Max. temp. of viable development</strong></td>
<td>35–39°C</td>
<td>37–39°C</td>
<td>40°C</td>
</tr>
<tr>
<td><strong>Basic reproductive number</strong></td>
<td>1–5</td>
<td>4–6</td>
<td>2–3</td>
</tr>
</tbody>
</table>

*a*Data taken from Anderson (1982), Bundy and Cooper (1989) and Crompton (2001).

*b*Data taken from Anderson and May (1991).

*c*Data on *A. lumbricoides* (Seamster (1950); *T. suis* (Beer, 1976); hookworm (Nwosu, 1978; Smith and Schad, 1989)).

This is defined as the average number of female offspring produced by one adult female parasite that attain reproductive maturity, in the absence of density dependent constraints (Anderson and May, 1991). $R_0$ values of between 1 and 6 are estimated, with rates intrinsically highest for *T. trichiura* and lowest for hookworm. In practice, epidemiological studies fail to differentiate between the main hookworm species, *A. duodenale* and *N. americanus*, which will have different epidemiological and ecological characteristics.

Increases in $R_0$ give rise to increases in infection prevalence (percentage of individuals infected) and infection intensity (number of worms per human host). The dynamic processes involved in STH transmission, such as free-living infective stage development and survival, depend on the prevailing environmental conditions (Pavlovsky, 1966; Anderson, 1982). For example, as indicated in Figure 1, free-living infective stages present in the environment develop and die at temperature-dependent rates. Maximum survival rates of hookworm larvae, as indicated by proportion of larvae surviving, occur at 20–30°C (Figure 1a). Experimental studies suggest that maximum development
Figure 1 Relationship between temperature and (a) hookworm survival and (b) development duration. Points indicate experimental data (Seamster, 1950; Beer, 1973; Nwosu, 1978; Udonsi and Atata, 1987) and lines are fits derived from fractional polynomials analyses. Regression details: parasite survival $y = 0.884 + (-22.88x^{-0.5}) + (-7.73\ln(x))$; A. lumbricoides duration $y = 8.601 + (-63.718x^{-2}) + 2.526x^{-3}$; T. trichiura duration $y = 26.079 + 41209.68x^{-2} + (-1715.02x^{-2})$; hookworm duration $y = 3.701 + 40.88x^{-2} + (-46.18x^{-2})$. 
rates of free-living infective stages occur at temperatures between 28 and 32°C, with development of *A. lumbricoides* and *T. trichiura* arresting below 5 and above 38°C (Beer, 1976; Seamster, 1950), and development of hookworm larvae ceasing at 40°C (Udonsi and Atata, 1987; Smith and Schad, 1989) (Figure 1b). It is suggested that *A. lumbricoides* eggs are more resistant to extreme temperatures than *T. trichiura* eggs (Bundy and Cooper, 1989).

Soil moisture and relative atmospheric humidity are also known to influence the development and survival of ova and larvae: higher humidity is associated with faster development of ova; and at low humidity (<50%) the ova of *A. lumbricoides* and *T. trichiura* do not embryonate (Otto, 1929; Spindler, 1929). Field studies show that the abundance of hookworm larvae is related to atmospheric humidity (Nwosu and Anya, 1980; Udonsi et al., 1980).

These differing rates of development and survival will influence parasite establishment in the human host and hence the infection levels. Thus, a climate-induced increase in the rate of establishment, while holding parasite mortality constant, causes the parasite equilibrium to rise (Bundy and Medley, 1992). Although seasonal dynamics in transmission may occur, such fluctuations may be of little significance to the overall parasite equilibrium within communities. This is because the life span of adult worms is typically much longer (1–10 years) than the periods in the year during which *R₀* is less than unity, and *R₀* on average will be greater than 1, maintaining overall endemicity (Anderson, 1982). For all these reasons, spatial variability in long-term synoptic environmental factors will have a greater influence on transmission success and patterns of STH infection than seasonal variability in a location.

### 3. ECOLOGICAL CORRELATES

Given the importance of environmental factors on transmission processes, it is unsurprising that statistical relationships between environmental factors and spatial patterns of infection can be observed. Several studies, some dating back to the early twentieth century, report ecological associations between STH distributions and temperature,
rainfall and altitude (reviewed in Brooker and Michael, 2000). As outlined in Hay et al., (this volume, pp. 37–77), the ability to investigate ecological correlates of infection has been enhanced by satellite imagery, which can provide data from which information about temperature, humidity and vegetation conditions can be derived, and by the use of GIS to overlay multiple layers of data. These tools have been used successfully to describe the environmental factors associated with patterns of STH infection in selected geographical locations, and helped identify the relative importance of different environmental factors in determining geographic distributions (Appleton and Gouws, 1996; Appleton et al., 1999; Brooker et al., 2002a,b, 2003, 2004b; Saathoff et al., 2005).

Here we extend these analyses and investigate the spatial ecology of STH infection across SSA, where surprisingly little is still known about the distributions of STH infection and their underlying environmental determinants. Although intensity of STH infection is a key determinant of transmission dynamics and morbidity (Anderson and May, 1991), prevalence of infection, based on microscopic examination of STH eggs in stool samples, remains the most widely used indicator of infection status and the need for control. We derive estimates of STH prevalence from dedicated surveys, conducted among schoolchildren after 1985 and geo-referenced using global positioning systems. Detailed data are available for Cameroon, Chad, Eritrea, Guinea, South Africa, Tanzania, Uganda, and Zambia, which show that prevalence of *A. lumbricoides* and *T. trichiura* is greatest in equatorial, central and west Africa and southeast South Africa, whereas hookworm has a wider distribution across the continent (Figure 2 is Plate 7.2 in the Separate Color Plate Section). By relating these distributions to satellite-derived environmental data, we can investigate their large-scale ecological correlates.

For each species, a clear relationship exists between prevalence of infection and remotely sensed Land Surface Temperature (LST) (Cracknell, 1997): prevalence of *A. lumbricoides* and *T. trichiura* is generally <5% in areas where LST exceeds 38–40°C, whereas hookworm infection remains highly prevalent throughout the upper end of the thermal range (Figure 3). This is an intriguing observation since experimental studies suggest that each STH species has similar thermal
Figure 3  Relationship between mean LST, estimated from satellite data, and prevalence of STH infection. Estimates are derived for each survey location and data for locations experiencing the same temperature are averaged for presentation. (see legend of Figure 2 for details.)

thresholds (Table 1). The apparent ability of hookworm to survive hotter conditions may be explained in part by the ability of mobile larvae to migrate to more suitable thermal and moisture conditions. In particular, whereas hookworm larvae stages have some limited motility and can move downward into the soil, thereby avoiding desiccation, the ova of *A. lumbricoides* and *T. trichiura* are non-motile, and high surface temperatures will result in ova dying from desiccation (Beaver, 1953).

Some features of helminth life cycles, such as hypobiosis, equip the parasite to survive periods that are unsuitable for transmission. However, hypobiosis only occurs for *A. duodenale* in humans (Schad et al., 1973) and not for *N. americanus*, the hookworm species predominant in SSA (Kilama, 1990) and is therefore excluded here as a possible explanation for hookworm’s apparent wider thermal tolerance. Other species-differences in life history traits may play an important role. It is suggested that the probability of hookworm larvae surviving to infect hosts is enhanced by their more rapid development in the soil (3–10 days) in comparison with *A. lumbricoides* larvae (28–84 days) and *T. trichiura* larvae (10–30 days) (Table 1). This hypothesis is supported by an observed relationship between prevalence and the number of
days in the year that below the thermal threshold (Figure 4). The prevalence of *A. lumbricoides* and *T. trichiura* was generally low in locations where temperatures fall below the thermal threshold for less than 35–40 days, and increased with increasing number of days. Hookworms, however, required a much smaller (8 day) window of thermal suitability for transmission and so were able to persist even when the period available for development was of the order of 10 days.

Finally, a potentially very important factor is the longevity of the adult worm, since the location inside the host is essentially a refuge

![Graph showing the relationship between the proportion of humans infected with worms and the number of days during which temperature was less than 40 °C, which is suitable for survival of free-living STH infective stages: based on observed data for 601 locations from nationwide surveys in Cameroon (Ratard et al., 1991, 1992), Chad (Brooker et al., 2002a) and Uganda (Brooker et al., 2004b). Data were collected in cross-sectional school surveys using similar diagnostic technique (Kato–Katz method) and sampling designs (stratified, random), and encompass a broad range of infection rates. Insert: Relationship between mean LST and number of weeks temperature falls below 40 °C (y = -3.006x + 147.8, r = 0.94, p <0.001). Estimates were derived for each survey location and locations with the same number of days under the thermal threshold were averaged for presentation.](image-url)
from the high external temperatures. Hookworms have a longer adult stage life expectancy (3–4 years) than either *A. lumbricoides* or *T. trichiura* (1–2 years). This implies that hookworms can find refuge from external temperatures for more than twice the length of time of the other species, and are effectively protected from extreme temperatures over a 3–4 year period in appropriate conditions for development. This greatly increases the chances of hookworm transmission stages being deposited and developing in suitable thermal conditions.

4. PREDICTING DISTRIBUTIONS

These analyses have enabled the first continent-wide predictions of infection patterns on the basis of satellite-derived environmental covariates as well as providing insight into the ecology of infection. Predictions of prevalence were based on binomial logistic regression analysis, where, for each location, the response variable contained the total number of positive responses and the total number examined, and the independent variables were satellite-derived mean LST and Normalized Difference Vegetation Index (NDVI) for 1982–1999 (Hay *et al.*, this volume, pp. 37–77) and elevation (http://edcwww.cr.usgs.gov/landdaac/gtopo30/). Models were then cross-validated using a jack-knife procedure (King *et al.*, 2004) and predicted values were compared to observed values using Receiver Operating Characteristics (ROC) analysis (Brooker *et al.*, 2002b). The models for *A. lumbricoides* and *T. trichiura* provided impressive descriptive accuracies of low transmission (prevalence <5%) areas and of areas which would be the target of mass treatment programmes (prevalence >50%) (Figure 2). By contrast, the hookworm model has only moderate accuracy, a probable reflection of the apparent wider distribution of hookworm. The models indicate that prevalence of *A. lumbricoides* and *T. trichiura* is greatest in equatorial, central and west Africa, eastern Madagascar and southeast Africa, whereas hookworm is more widely distributed across the continent. A limitation of this analysis is the use of infection prevalence rather than infection intensity, which has greater relevance to transmission dynamics and morbidity,
but which few studies quantify. There remains the need to investigate geographical heterogeneity in infection intensity.

Satellite data can therefore help define the large-scale distributions of STH infection, which are demonstrated to be influenced by heterogeneity in climate. At smaller spatial scales other factors, including variability in human behaviour, including personal hygiene, as well as differences in sanitation and socio-economic status, have to be considered. For example, in climatically unsuitable areas, microhabitats, influenced by local housing and sanitation, may provide suitable transmission foci, and vice versa. Such microhabitats are commonly found in urban areas.

5. URBANIZATION

In common with many other parasitic infections, STH infections flourish in impoverished areas characterized by inadequate sanitation and overcrowding. It is commonly assumed that *A. lumbricoides* and *T. trichiura* are more prevalent in urban areas whereas hookworm is more often found in rural areas (Crompton and Savioli, 1993). However, comparable data for STH infections in urban and rural settings are remarkably few and those that do exist indicate a more complicated picture. Studies which surveyed similar age groups and socio-economic areas indicate that the prevalence of *A. lumbricoides* and *T. trichiura* differ between urban and rural communities, but in no systematic manner (Table 2). By contrast, hookworm appears to be equally prevalent in both urban and rural settings (Table 2). The precise reasons for the urban–rural dichotomies for *A. lumbricoides* and *T. trichiura* are as yet unclear. Differences in prevalence of *A. lumbricoides* and *T. trichiura* in urban and rural areas may reflect differences in sanitation or population density; socio-economic differences will also play an important role. It is clear that further work is needed to resolve these issues.

By 2007, it is predicted that more than half of the global human population will be urban citizens, most of them living in the rapidly growing cities of Africa, Asia and Latin America (United Nations, 2003). Urbanization often accompanies social and economic
Table 2  Prevalence of STH infections among schoolchildren in urban and rural communities in developing countries. Included studies sought to restrict investigation to areas of similar socio-economic characteristics

<table>
<thead>
<tr>
<th>Setting</th>
<th>Sample size</th>
<th>A. lumbricoides</th>
<th>T. trichiura</th>
<th>Hookworm</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Urban</td>
<td>Rural</td>
<td>Urban</td>
<td>Rural</td>
</tr>
<tr>
<td>Blantyre, Malawi</td>
<td>553 children (3–14 years old)</td>
<td>15.4</td>
<td>0.7</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Pemba, Tanzania</td>
<td>256 children (3–14 years old)</td>
<td>60.6</td>
<td>63.6</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Buea, Cameroon</td>
<td>211 children (8–15 years old)</td>
<td>33.9</td>
<td>56.4</td>
<td>32.3</td>
<td>59</td>
</tr>
<tr>
<td>Rolandia, Brazil</td>
<td>236 children (5–15 years old)</td>
<td>6.1</td>
<td>1.3</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Malaysia</td>
<td>3073 children (&lt;15 years old)</td>
<td>51.7</td>
<td>21.2</td>
<td>65.3</td>
<td>29.1</td>
</tr>
<tr>
<td>Penang, Malaysia</td>
<td>192 children (7–12 years old)</td>
<td>37.4</td>
<td>33.4</td>
<td>100</td>
<td>92</td>
</tr>
</tbody>
</table>
development, with better opportunities for education, adequate living standards and higher incomes. However, overcrowding and lack of adequate water and sanitation in urban slum communities may increase transmission of STH infections. Investigation of the impact of increased urbanization on STH infections together with assessment of the effectiveness of urban helminth control measures in low-income settings is clearly warranted because increased urbanization may promote the transmission of STH infections, especially *A. lumbricoides* and *T. trichiura*.

6. GLOBAL CONTROL STRATEGIES

Recommended drugs for use in public health programmes to control STH infection are the BZAs, albendazole or mebendazole; older drugs including pyrantel pamoate and levamisole are also occasionally used in some developing countries (WHO (World Health Organization), 2002; Utzinger and Keiser, 2004). In areas where STH infections co-occur with schistosomiasis, BZAs are co-administered with praziquantel (PQZ), the major drug used for the treatment of schistosomiasis (Fenwick *et al.*, 2003).

Current efforts to control STH infection, as well as schistosomiasis, focus on the school-age population. It is estimated that between 25% and 35% of school-aged children are infected with one or more of the major species of worms (Bundy, 1997; de Silva *et al.*, 2003). The most intense worm infections and related illnesses occur at school age (Partnership for Child Development (PCD), 1998, 1999).

Infection can result in significant consequences for health and development, affecting growth, promoting anaemia and causing some overt clinical disease, much of which is rapidly reversed by treatment (Warren *et al.*, 1993; Hotez *et al.*, 2006). In addition to these impacts on health and physical development, infected schoolchildren perform poorly in tests of cognitive function; when treated, immediate educational and cognitive benefits are apparent only for children with heavy worm burdens or with concurrent nutritional deficits (Bundy *et al.*, 2006). Treatment alone can neither reverse the cumulative effects of lifelong infection nor compensate for years of missed learning, but
studies suggest that children are more ready to learn after treatment for
worm infections and may be able to catch up if this learning potential
is exploited effectively in the classroom. In Kenya, treatment reduced
absenteeism by one quarter, with the largest gains for the youngest
children who suffered the most ill health (Miguel and Kremer, 2004).

For these reasons, school-age children are the natural targets for
treatment, and school-based treatment delivery programmes offer ma-
jor cost advantages because of the use of the existing school infra-
structure and the fact that schoolchildren are accessible through
schools. An important element of the approach is to minimize the need
for clinical diagnosis, which is often more expensive than the treatment
itself, and to focus on mass delivery of services. Evidence suggests that
mass delivery of deworming is preferable on efficacy, economic
and equity grounds to approaches that require diagnostic screening
(Warren et al., 1993). School-based deworming also has major exter-
nalities for untreated children and the whole community by reducing
disease transmission in the community as a whole (Bundy et al.,
1990).

Recognizing the centrality of school-age children to the response to
helminth infection, in 2001, the 54th World Health Assembly of the
WHO passed a resolution to provide regular deworming treatment to
75% of school-age children at risk (an estimated target population of
398 million) by 2010. School health and nutrition programmes provide
the vehicle for delivering regular but infrequent (every 6 months or
more) anthelmintic treatment to schoolchildren. Operational research
has demonstrated how interventions can be implemented and evaluated
at the country level, for example enabling mass deworming of school-
children (Bundy and Guyatt, 1996; PCD, 1998, 1999; Guyatt et al.,
2001).

A major step forward in international coordination and cohesion
was achieved when a framework to Focus Resources on Effective
School Health (FRESH) was launched at the World Education Forum
in Dakar in April 2000 (World Bank, 2000). Among the early partners
in this effort were UNESCO, UNICEF, the World Food Programme
(WFP), the WHO and the World Bank, with the Education Develop-
ment Centre, Education International and the PCD. The FRESH
framework provides a consensus approach of agreed good practice for
the effective implementation of health and nutrition services within
school health programmes. The framework proposes four core com-
ponents that should be considered in designing an effective school
health and nutrition programme and suggests that the programme will
be most equitable and cost-effective if all of these components are
made available, together, in all schools. The four components also
provide the appropriate mix of interventions for responding to helmi-
nth infection globally: (1) Policy: health- and nutrition-related school
policies that promote the nutrition and health of staff and children
(and promote the role of teachers in delivering anthelmintic treatment);
(2) School environment: access to safe water and provision of effective
sanitation facilities (which helps break the helminth transmission cy-
cle); (3) Education: skills-based education, including life skills that
addresses health and hygiene issues and promotion of positive behaviours
(including promoting handwashing and other hygienic behaviours that
protect against helminth infection); and (4) Services: simple, safe and
familiar health and nutrition services that can be delivered cost-
effectively in schools (such as deworming).

This common focus has encouraged concerted action by the par-
ticipating agencies and has increased significantly the number of
countries implementing school health reforms. The simplicity of the
approach, combined with the enhanced resources available from do-
nor coordination, has helped ensure that these programmes can go to
scale. For example, annual external support from the World Bank for
these actions approaches US$90 million, targeting some 100 million
schoolchildren.

The FRESH framework does not prescribe the design of school-
based deworming programmes, and in practice these are highly
variable and country specific (Bundy et al., 2006). In low-income
countries a public sector model is commonly used, involving the
Ministry of Health in supervising the activity, and the Ministry of
Education in implementing the intervention through teachers. In mid-
dle-income countries, including Indonesia and, historically, Japan and
South Korea, a private-sector model involving non-governmental
organizations delivering treatment that is paid for by the community
has proven sustainable and effective.
GLOBAL HELMINTH ECOLOGY

Whatever the design, identifying which schools and communities require treatment is an essential part of the process, and requires a key role for GIS.

7. CONTROL APPLICATIONS OF GIS/RS

As recently as 5 years ago, applications of GIS and RS in helminthology had only been attempted for schistosomiasis and filariasis (reviewed in Brooker and Michael, 2000; Brooker, 2002). Since then, studies have investigated spatial patterns of STH infection (Brooker et al., 2002b, 2003, 2004b; Saathoff et al., 2005), *Loa loa* (Thomson et al., 2004) and onchocerciasis (Carabin et al., 2003). These studies have focused on the use of RS data to identify ecological correlates of infection and develop statistical models of disease risk. While these applications are attractive research objectives, the challenge remains to apply these geographic tools in the context of large-scale control programmes. Here we examine how GIS and RS have contributed to the design and implementation of helminth control programmes.

Human onchocerciasis or river blindness results from infection with a parasitic filarial worm, *Onchocerca volvulus*, which is transmitted by female *Simulium* blackflies. Blackflies breed in areas close to fast-flowing and well-oxygenated rivers and seldom travel more than 15 km in search of a bloodmeal. This means that high-prevalence communities are located close to breeding sites. Rapid Epidemiological Mapping of Onchocerciasis (REMO), developed by TDR (Tropical Disease Research)/WHO, has been a key geographic tool for the control of onchocerciasis (Ngoumou et al., 1994; Katabarwa et al., 1999). With REMO, it is possible to assess quickly and cheaply, which communities are at high risk of onchocerciasis and where they are located. REMO uses geographical information, particularly the locations of river basins, to identify communities that are likely to be at high risk. A subsample of these communities is then rapidly assessed by screening individuals for onchocercal nodules. This enables communities to be classified into three categories: priority areas which require community-directed treatment with ivermectin; areas which do not require treatment; and possible endemic areas but
which require further investigation. Results of REMO have been effectively incorporated into a GIS to visualize priority areas for mass
distribution of ivermectin and estimate the number of individuals to
be treated (Noma et al., 2002). This has helped the African Pro-
gramme for Onchocerciasis Control (APOC) to prioritize allocation
of resources according to need. The robustness of REMO following
several rounds of interventions remains, however, to be fully inves-
tigated since there has been little validation of the approach since its
initial development.

Severe adverse (and sometimes fatal) encephalopathic reactions
following treatment with ivermectin have been reported in individuals
co-infected with *O. volvulus* and *Loa loa* (loiasis), and as such, there is
an operational necessity to identify areas with a high prevalence of *L.
loa* (Addiss et al., 2003). Thomson et al. (2000, 2004) developed a
spatial model that predicted the prevalence of *L. loa* microfilaraemia
on the basis of satellite-derived environmental data in Cameroon,
with applications for defining areas at-risk of post-ivermectin
*Loa*-related severe adverse reactions. Like onchocerciasis, treatment
strategies have been defined according to levels of endemicity of
onchocerciasis and loiasis. In areas where both diseases are highly
endemic, detailed measures, such as training of medical staff, pro-
vision of medical supplies and heightened surveillance of treated indi-
viduals, are required.

A rapid mapping method has also been developed for lymphatic
filariasis. This disease is caused by the filarial parasite *Wuchereria bancrofti* and is being targeted for eradication by the Global Alliance
for the Elimination of Lymphatic Filariasis (www.filariasis.org). As
with other control programmes, delimitation of endemic localities is an
essential prerequisite for planning control elimination programmes,
based on treatment with diethylcarbamazine (DEC) plus albendazole
or ivermectin plus albendazole. To address this, a method for the
Rapid Geographical Assessment of Bancroftian Filariasis (RAGFIL)
has been developed by TDR/WHO. This is based on the use of a
spatial sampling grid with either 25 km or 50 km between sampled
communities, rapid prevalence assessments using immunochromato-
graphic card tests (ICT) for the detection of circulating antigen from
adult *W. bancrofti* filarial antigenaemia, and geostatistical methods for
predicting the distribution of filariasis throughout the target area (WHO, 1998). Using this method, Gyapong et al. (2002) predicted prevalence in four countries in West Africa, enabling control planning to be initiated. Other analyses suggest, however, that endemic foci can persist within the interstices of the proposed grid and that smaller grids are required (Srividy et al., 2002; Alexander et al., 2003).

The Schistosomiasis Control Initiative (SCI) is currently supporting six countries in SSA to implement national control programmes for schistosomiasis and STH infections, including Burkina Faso, Mali, Niger, Tanzania, Uganda and Zambia (www.schisto.org). In Uganda, where Schistosoma mansoni is widespread, GIS and RS have been employed to classify the country according to different treatment strategies. Regular chemotherapy with PQZ and albendazole is being provided to schoolchildren and other high-risk groups (Kabaterine et al., 2005). Following WHO guidelines, the programme is classifying communities according to three strategies: (1) in communities with a high prevalence (≥50%) schoolchildren are treated every year and high-risk groups, such as fishermen, are treated; (2) in communities with a moderate prevalence (≥20% and <50%) schoolchildren are treated once every 2 years; and (3) in communities with a low prevalence (<20%) chemotherapy is made available in health facilities for treatment of suspected cases. With the use of GIS coupled with satellite and climatic data, geographical analysis found that no transmission of S. mansoni typically occurs in areas of Uganda where total annual rainfall was <850 mm or altitude was >1400 m (Kabaterine et al., 2004). These areas were subsequently set aside without the need for further surveys (Brooker et al., 2004a) (Figure 5). It was also shown that prevalence consistently exceeded 50% in areas within 5 km of Lakes Victoria and Albert, and thus in these areas warranted mass treatment without the need for further surveys. Prospective surveys have validated these predicted classifications (Kabaterine et al., unpublished results).

Outside these two ecological areas, where smaller rivers and water bodies are numerous, it is suggested that individual communities are surveyed using standard parasitological methods (Brooker et al., 2004a). Rapid mapping of communities is based on the Lot Quality Assurance Sampling (LQAS) method (Brooker et al., 2005). Developed
in industry for quality control, LQAS makes it possible to use small sample sizes when conducting surveys among populations (lots), best used in situations where classification of a population is useful and where the emphasis is on decision making (e.g. whether or not to intervene in a particular community) rather than estimation of prevalence and intensity of infection. Field testing showed that a LQAS sampling plan where only 15 children are sampled and a decision to intervene is made if seven children are found to be infected had excellent diagnostic performance, while economic analysis demonstrated that screening using LQAS was more cost-effective than mass treating

![Map showing distribution of S. mansoni in Uganda and classification of the country according to treatment category: (1) mass treatment without further surveys, <5 km from Lake Victoria and Lake Albert (not shown); (2) non-treatment areas, altitude >1400 m or annual rainfall <850 mm (grey areas); (3) and areas requiring further investigation using LQAS (white areas). For further details see Kabatereine et al., (2004) and Brooker et al., (2004a, 2005).](image)

*Figure 5* Distribution of *S. mansoni* in Uganda and classification of the country according to treatment category: (1) mass treatment without further surveys, <5 km from Lake Victoria and Lake Albert (not shown); (2) non-treatment areas, altitude >1400 m or annual rainfall <850 mm (grey areas); (3) and areas requiring further investigation using LQAS (white areas). For further details see Kabatereine et al., (2004) and Brooker et al., (2004a, 2005).
all schools in a single sub-county (Brooker et al., 2005). Based on these findings, LQAS is employed in Uganda to quantify the fine-scale distribution of *S. mansoni* in areas of potential risk. Thus, GIS/RS coupled with field data can target schistosomiasis control from the national to the local level.

Predictive risk-mapping has also been employed to determine target areas for mass treatment in Tanzania (Clements et al., 2006). First, simulation studies were conducted to determine the number of individuals and schools that were required to give a desired level of precision in risk estimates. Parasitological surveys were then conducted in 143 schools in northwestern Tanzania. The proportions of children found to have *S. haematobium* and *S. mansoni* infections were determined for each school and these were used as the outcome variables in separate spatially explicit binomial logistic regression models. The models were developed in a Bayesian framework and included environmental covariates derived from RS and a geostatistical component, using a powered exponential function to describe spatial correlation in the datasets. Models were externally validated against an independently collected dataset from one district within the study area and were used to make spatial predictions for *S. haematobium* and *S. mansoni* risk at prediction co-ordinates, defined by a grid of equally spaced locations and predictions were interpolated to produce a continuous risk surface for the study area as shown in Figure 6a and 6b. (Figure 6a and b are Plates 7.6a and b in the Separate Color Plate Section).

Subsequently, prediction surfaces for *S. haematobium* and *S. mansoni* were combined to make a single intervention map (as the treatment programme and its use of PQZ, makes no distinction between the two schistosome species), consisting of contours that equated to a prevalence of *S. haematobium* or *S. mansoni* of 10% and 50% (Figure 6c is Plate 7.6 in the Separate Color Plate Section). The lower contour (10%) separates areas that would and would not be targeted by the mass treatment campaign and the upper contour (50%) separates areas where mass treatment would only be conducted in school-age children and areas where both school-age children and other high-risk groups in the community would be targeted. Estimates of uncertainty in the spatial predictions help identify the area where further data collection is required.
The experience of SCI in Tanzania and Uganda amply demonstrates the usefulness of GIS/RS as geographic decision-making tools for implementing helminth control at both national scales and local scales. Geographical distributions are continually updated as new epidemiological data are collected, and as intervention reduces the prevalence of infection. Analysis of the cost-effectiveness of the tools, which is germane to their long-term and sustainable use, is currently underway.

The above examples have shown how research and international programmes have led the way in developing the use of GIS/RS for directing control programmes. An important emerging trend is that national governments are beginning to use this approach for designing and developing sustainable national programmes. GIS/RS has been employed by national governments to plan and conduct nationwide rapid epidemiological assessments of STH and schistosomiasis in Chad (Brooker et al., 2002a) and Eritrea (PCD, 2003), and to design and implement national parasite control programmes, in both cases as part of national development programmes with World Bank assistance. In Chad, RS data were used to define seven ecological zones, which were combined with population data in a GIS to define the sample protocol, whereby 20 schools, in different ecological zones were surveyed. This approach substantially reduced the cost of the sample survey, while preserving its utility and effectiveness. The analysis showed that the patterns of hookworm and *S. haematobium* had a close association with the RS/GIS defined ecological zones, and significant relationships with environmental variables; it was correctly predicted that *A. lumbricoides* and *T. trichiura* would not occur in the country. The results from the survey helped the government plan the country's school-based control programme, and resulted in significant cost savings for the programme since it identified the need to target far fewer schools than had first been anticipated. A similar geographical approach was adopted in planning the school health programme in Eritrea (PCD, 2003). Again the sampling methodology proved substantially less expensive, and more practical, than traditional approaches developed without the benefit of GIS/RS. The national survey revealed that infection was highly focal, and that deworming interventions could be precisely targeted, with significant savings in financial and technical resources.
8. GLOBAL DISTRIBUTIONS

The above examples show that, used appropriately, GIS/RS can provide a practical and low-cost tool for designing and implementing sustainable helminth control programmes. GIS has the potential to promote evidence-based priority setting and careful targeting of finite financial resources, resulting in savings in resources and enhancement of sustainability. For this to become a reality, a critical first step is defining the geographical distribution of infection globally.

As with all diseases, there is long history of attempts to define global distributions of STH infections, and provide estimates of numbers infected. A first seminal effort was provided by Stoll (1947), which has been frequently updated (Peters, 1978; Crompton and Tulley, 1987; Bundy and Cooper, 1989; Chan et al., 1994; Brooker et al., 2000; Bundy et al., 2004), with the most recent estimates provided by de Silva et al. (2003).

Since Stoll provided his estimates nearly 60 years ago, efforts to control STH infections and morbidity have varied across different regions of the world. The analysis by de Silva et al., (2003) showed that in certain regions there has been a reduction in STH infection prevalence. In the Americas, for example, there has been a precipitous decline in prevalence and in absolute numbers since the 1960s, a change largely attributable to national treatment programmes coincidental with social and economic development that have brought about improved access to clean water and proper sanitation (Pan-American Health Organization (PAHO), 2000; Ehrenberg et al., 2003). Well-documented declines in prevalence exist for Brazil and Mexico, the two most populous countries in the region (Tay et al., 1976, 1995; Vinha, 1971; PAHO, 2000). Because of the success of control we do not consider the geographical distribution of infection in the region any further although we recognize that there may be small foci of high prevalence which require control activities.

In Asia, several countries, notably Japan, South Korea and Taiwan, have achieved sustained and successful control of STH infections over the last 40 years (WHO, 1996). More recently, a national control programme in Sri Lanka has reduced prevalence to <5%. Control programmes have also been launched in several other Asian countries
including China, Indonesia, Malaysia, Nepal, The Philippines and Thailand. Despite these control efforts, data available for south and southeast Asia suggest the need for effective control (Figure 7). STH

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Prevalence of STH infection by province in Asia. (a) \textit{A. lumbricoides}, (b) \textit{T. trichiura} and (c) hookworm. Horizontal hatched areas indicate areas where sustained control has resulted in prevalence levels of <5%; white areas indicate a lack of data. Data were derived from published surveys or reviews: Afghanistan (Albis Gabrielli, unpublished data), Bangladesh (Hall and Nahar, 1994; Mascie-Taylor et al., 1999), Bhutan (Allen et al., 2004), Cambodia (Simoun et al., 2003; Urbani et al., 2001), China (Xu et al., 1995), India (de Silva et al., 2003), Indonesia (Margono, 2001), Lao PDR (Rim et al., 2003), Malaysia (Singh and Cox-Singh, 2001) Myanmar (Montresor et al., 2004), Pakistan (Government of Pakistan, 1988), Thailand (Anantaphruti et al., 2000, 2002, 2004; Chongsuvivatwong et al., 1994; Kasuya et al., 1989; Nacher et al., 2002; Waikagul et al., 2002), Pacific Islands (Hughes et al., 2004); Vietnam (Anon, 1993; van der Hock et al., 2003). In Cambodia and Myanmar, where empirical data are lacking, prevalence of \textit{A. lumbricoides} and \textit{T. trichiura} was estimated from RS-based prediction models (Brooker et al., 2003).}
\end{figure}
infection remains prevalent in China and India, countries that account for a third of the world's population. The highest prevalence rates are observed for southern China and the northern regions of southeast Asia, and the lowest rates in northern China, northern India and Pakistan. In northern China, *A. lumbricoides* is more prevalent than either *T. trichiura* or hookworm. STH species are also widespread in the Pacific Islands (Hughes *et al.*, 2004).

We suggest that such distribution patterns reflect environmental suitability of STH transmission, especially thermal constraints. Here, this hypothesis is explored by investigating the relationship between prevalence of infection and satellite data for each administrative unit in the Asia region. LST was expressed as the median value for each of a number of 5°C intervals (bins) spanning the full range of temperatures across the region (Figure 8). Median LST is estimated to be <20°C in northern China and >40°C in northern India and Pakistan, where STH infection prevalence is lowest. It appears that *A. lumbricoides* is more widespread in Asia and is able to survive colder temperatures than either *T. trichiura* or hookworm. It can thus be interpreted that these represent the lower thermal limits of STH transmission. Insufficient data were available to adequately explore the upper thermal limits of transmission in the region, as was possible for SSA (Figure 3). The current regional analysis for Asia supports previous studies, which show that heterogeneities in STH infection prevalences are correlated with temperature and humidity in China (Xu *et al.*, 1995; Lai and His, 1996) and southeast Asia (Brooker *et al.*, 2003). The latter study used satellite data to predict prevalence in areas lacking detailed data (Brooker *et al.*, 2003).

While there have been declines in the prevalence of STH infection in the Americas and parts of Asia, estimated prevalence rates for SSA are equivalent to those first estimated by Norman Stoll more than 60 years ago (de Silva *et al.*, 2003). In fact, the prevalence and distribution of STH infection remain largely unknown, because the region has weak disease surveillance systems. The helminthological data that do exist in the formal and 'grey' literature have been collated into a GIS database (Brooker *et al.*, 2000). However, this continental database includes data for only 15% of districts in SSA, with most data on hookworm infection. Furthermore, for reasons outlined
Figure 8  The relationship between prevalence of STH infection in Asia and satellite-derived mean LST for 1982-1999, obtained from NOAA's AVHRR. Prevalence is expressed as median prevalence for each temperature category and the median temperature was calculated for each geographical region; it is recognized that this approach masks the heterogeneity in STH prevalence and temperature within regions, but epidemiological data are not available at finer spatial resolution.

previously (Stoll, 1947; Brooker and Michael, 2000), the inherent variability in the data, because of differences in the timing, methodology and study population, makes it difficult to use these data to reliably define the distribution of STH species. Instead, we have utilized the robust predictions of STH prevalence developed here (Figure 2). These predictions provide perhaps the most detailed description of STH infection in SSA to date.

9. PREDICTED NUMBERS OF INFECTIONS

As indicated, school-based deworming represents the most cost-effective and feasible intervention strategy for STH infections and the greatest need for control exists in SSA. For these reasons, we derive country-specific estimates of school-aged children infected in the region. Consistent with other analyses in this edition, population was estimated from the Gridded Population of the World version 3
(GPW3) global human population distribution for 2005 (Balk et al., this volume, pp. 119–156). Country-specific medium variant population growth rates and proportions of the population aged 5–14 years from the United Nations Population Division – World Population Prospects database (http://esa.un.org/unpp) were used to project this age cohort of the population total to 2005. These population data were spatially related to our species-specific risk models (Figure 2), which were re-sampled at 1 km, the spatial resolution of GPW3. Since the models were developed using prevalence estimates among school-aged children it is assumed that models define prevalence for this age group. For each district, population totals and predicted infection prevalence were extracted and used to estimate numbers of school-aged children infected with each species. Since no clear patterns in urban–rural differences in species prevalence exist (Table 2) no adjustment was made for the effect of urbanization.

Infections from *A. lumbricoides*, *T. trichiura* and hookworm are often found in the same communities and individuals and BZAs, such as albendazole and mebendazole, are broadly effective against all species. In order to estimate the cost of interventions against multiple STH infections, an estimate of the numbers of infections of any species, either single- or multiple-species infections, is required. To quantify the numbers of multiple-species infections we use a validated probabilistic model to predict the prevalence of multiple-species infections for each district for which only overall prevalence data exist (Booth and Bundy, 1995), thereby allowing the number of children infected with any STH species to be estimated.

It is estimated that over 30.7 million African school-aged children are infected with *A. lumbricoides*, 36.5 million with *T. trichiura* and 50.0 million with hookworm. Since many children have multiple infections, it is estimated that 89.9 million are infected with one or more STH species. Forty four per cent of the infections are concentrated in just four countries: in descending order of magnitude these are Nigeria, the Democratic Republic of Congo, South Africa and Tanzania (Table 3). Previous estimates have suggested larger numbers of infections; the most recent estimate suggesting that 53 million school-aged children (5–15 years) are infected with *A. lumbricoides*, 50 million with *T. trichiura* and 47 million with hookworm (de Silva et al., 2003). Previous
Table 3  Estimated numbers of STH infection among school-aged children in SSA by country, 2005

<table>
<thead>
<tr>
<th>Country</th>
<th>School-aged population (1000s)</th>
<th>Estimated numbers of infections (1000s)</th>
<th>Estimated numbers requiring mass treatment based on 50% threshold (1000s)</th>
<th>Total annual per treatment cost (US$ 1000s)³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angola</td>
<td>3666</td>
<td>610</td>
<td>712</td>
<td>1048</td>
</tr>
<tr>
<td>Benin</td>
<td>1737</td>
<td>256</td>
<td>352</td>
<td>399</td>
</tr>
<tr>
<td>Botswana</td>
<td>422</td>
<td>8</td>
<td>10</td>
<td>121</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>3222</td>
<td>30</td>
<td>35</td>
<td>759</td>
</tr>
<tr>
<td>Burundi</td>
<td>1768</td>
<td>309</td>
<td>341</td>
<td>583</td>
</tr>
<tr>
<td>Cameroon</td>
<td>4091</td>
<td>1227</td>
<td>1490</td>
<td>1059</td>
</tr>
<tr>
<td>Cape Verde</td>
<td>111</td>
<td>7</td>
<td>13</td>
<td>44</td>
</tr>
<tr>
<td>CAR²</td>
<td>1014</td>
<td>200</td>
<td>227</td>
<td>256</td>
</tr>
<tr>
<td>Chad</td>
<td>2186</td>
<td>25</td>
<td>27</td>
<td>529</td>
</tr>
<tr>
<td>Comoros</td>
<td>146</td>
<td>72</td>
<td>81</td>
<td>45</td>
</tr>
<tr>
<td>DRC²</td>
<td>14151</td>
<td>4111</td>
<td>4710</td>
<td>3790</td>
</tr>
<tr>
<td>Republic of Congo</td>
<td>839</td>
<td>242</td>
<td>310</td>
<td>201</td>
</tr>
<tr>
<td>Cote d' Ivoire</td>
<td>4399</td>
<td>1400</td>
<td>1783</td>
<td>204</td>
</tr>
<tr>
<td>Djibouti</td>
<td>170</td>
<td>1</td>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>Equatorial Guinea</td>
<td>125</td>
<td>70</td>
<td>81</td>
<td>37</td>
</tr>
<tr>
<td>Eritrea</td>
<td>1020</td>
<td>11</td>
<td>14</td>
<td>324</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>17424</td>
<td>1653</td>
<td>1641</td>
<td>6085</td>
</tr>
<tr>
<td>Gabon</td>
<td>332</td>
<td>155</td>
<td>191</td>
<td>9</td>
</tr>
<tr>
<td>Gambia</td>
<td>353</td>
<td>15</td>
<td>21</td>
<td>99</td>
</tr>
<tr>
<td>Ghana</td>
<td>5326</td>
<td>1330</td>
<td>1699</td>
<td>1300</td>
</tr>
<tr>
<td>Guinea</td>
<td>2226</td>
<td>505</td>
<td>622</td>
<td>584</td>
</tr>
<tr>
<td>Guinea Bissau</td>
<td>330</td>
<td>47</td>
<td>66</td>
<td>84</td>
</tr>
<tr>
<td>Kenya</td>
<td>8835</td>
<td>1134</td>
<td>1158</td>
<td>2682</td>
</tr>
</tbody>
</table>

S. BROOKER ET AL.
estimates at a regional or continental scale have all been based on the approach first established by Stoll in 1947: the prevalence data from the few studies available within a country are used to estimate a mean prevalence for the country as a whole, and then expressed as a product of the estimated number of school-age children in the country. The estimates we present here are the first at this scale to explicitly include the fine spatial variation in distribution of both infection and population, and indicate that the earlier methodology tended to overestimate. It is also worth emphasizing that this level of precision has been achieved affordably only because of the use of GIS/RS: using traditional survey methods to obtain these data would be prohibitively expensive.

The estimates provide a basis for quantifying the financial resources required to support school-based deworming in SSA. It is assumed that mass treatment is only provided in districts where prevalence of any STH infection exceeds 50%, and in these districts treatment is provided to all school-age children irrespective of infection status, according to WHO guidelines on mass treatment (WHO, 2002). Cost analyses estimate that the school-based delivery costs of albendazole or mebendazole, anthelmintics that are effective against all the common STH species, are in the range between US$0.03 and 0.04 per capita (PCD, 1999), while the drug costs are in the range between US$ 0.03 and 0.05 per capita (Guyatt, 2003). Under these assumptions, using the school-based approach to provide a single annual treatment to all school-age children in all districts in Africa where mass treatment is justified would cost US$5.0–7.6 million.

These cost estimates are for maintaining a programme and do not include the higher costs of start-up. Nevertheless they suggest that continent-wide control of parasites is, from a financial perspective, an attainable goal.

10. THE FUTURE

GIS/RS is a powerful tool that has evolved from supporting sophisticated epidemiological research, through a role in directing public health interventions, to now showing a real potential for assisting the
design of sustainable development programmes. The initial epidemiological research was critical to this evolution, because it has provided the evidence for the link between transmission dynamics and the environmental factors that can be detected by RS. Furthermore, as illustrated here, it can provide important new insights into patterns of transmission at a geographical scale that has proven impossible to address using more traditional approaches.

The present analyses have shown that, with the available evidence, GIS/RS can predict patterns of STH transmission, and can do so at a scale that is relevant to the design of national control programmes. Most importantly, this approach is able to achieve this even for areas for which limited empirical data are available and at low cost relative to traditional survey technologies. This approach has the potential to facilitate the design of national control programmes, and the key question now is how best to realize this potential.

The experience of international vertical programmes aimed at controlling lymphatic filariasis, schistosomiasis and onchocerciasis provides some insights, but it is perhaps the examples from Chad, Eritrea, Tanzania and Uganda of national government efforts that more clearly point the way forward. GIS/RS has emerged as a tried and tested and increasingly acceptable technology that can provide national governments with a relatively low-cost approach to surveying and programme design, and which can significantly reduce the cost of practical programmes through more precise geographical targeting and simplifying the processes of monitoring and evaluation. It is important to recognize that GIS/RS can reduce both the upstream (e.g. survey and design) and downstream (e.g. targeting, monitoring and evaluation) costs of programmes, while at the same time enhancing programme effectiveness.

As more use is made of GIS/RS in control, there is a need to assess their cost and cost-effectiveness in targeting control efforts. At present, most funding for their use comes from international agencies and northern researchers. Determining the long-term sustainability of the use of GIS/RS in disease control and how they influence allocation of resources is crucial. It is also important to assess the inherent uncertainties in spatial data (epidemiological and environmental) within a GIS and the propagation of uncertainty in predictions and estimations.
Such research is underway for ecological modelling but similar research is clearly needed for epidemiological applications.

Notwithstanding these issues, the clear message is that this technology should be made available to policy makers and planners at the national level. In terms of helminth control an essential component is to enhance access to the predicted geographical patterns of transmission, such as those described here. As a contribution to improving access, all the maps presented in this text are made available at www.schoolsandhealth.org, and are available separately to individual countries in CD format by request from the same site. In this same spirit we welcome the release of the population and environmental data with this volume.

ACKNOWLEDGEMENTS

We thank the following individuals who have generously contributed data to this review: Henrietta Allen, Chris Appleton, Narcis Kabaterine, Nicholas Lwambo and Antonio Montresor. We are also grateful to Paul Coleman for his contribution to the STH ecological analysis and to Christine Budke, Maiza Campos Ponce, Bob Snow and Anthony Wilson for their comments on this manuscript. SB is supported by a Wellcome Trust Advanced Training Fellowship (#073656) and ACAC is funded by the Schistosomiasis Control Initiative, which receives support from the Bill and Melinda Gates Foundation.

REFERENCES


