The Role of Geographic Information Systems and Spatial Analysis in Area-Wide Vector Control Programmes

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ABSTRACT The success of area-wide interventions aimed at suppressing or eradicating insect populations rests largely on appropriate project planning and implementation - and this is as true in the context of vector-borne diseases as it is within the wider context of insect pest management. In either context, a successful control programme requires accurate knowledge of pre-existing distributions of insects (disease vectors) in time and space, on the appropriate design of insect control strategies, and on the development of suitable frameworks for monitoring and evaluation. Standard disease control operations, such as indoor residual spraying of insecticides or insecticide-treated bed nets for malaria, and the aerial application of insecticides or use of baited traps against the vectors of human and animal trypanosomosis, often include elements of area-wide planning because they target particular disease strata. Genetic control strategies (including the sterile insect technique (SIT)) are more intrinsically area-wide because they target specific vectors over delimited geographical areas delineated by biological criteria associated with colonization or dispersal potential. In either case it is argued that a strong geographical basis to planning and implementation is likely to improve the chances of programme success, as well as making more efficient use of resources and increasing cost effectiveness. Geographic information systems (GIS), global positioning systems (GPS) and remote sensing (RS) are allied technologies that together provide a means of gathering, integrating and analysing spatial data. To date, the application of these tools within traditional and area-wide programmes has been relatively limited, but this seems likely to change, particularly as GIS and GPS are already being used extensively in other areas of agroecological management and research. This paper examines potential areas for the application of GIS and associated spatial tools at various stages of planning and implementation of area-wide programmes integrating the SIT as a primary example, before going on to look beyond the SIT and to a number of examples of infectious diseases where GIS and spatial analysis have, to a greater or lesser extent, been employed within disease control efforts. With the help of these case studies the paper attempts to evaluate the extent to which the hype surrounding spatial tools has been (or can be) justified, and examines the barriers that remain in terms of further expansion of their use.

KEY WORDS spatial analysis, AW-IPM, SIT, geographic information systems, global positioning system, remote sensing, vector control

1. Introduction

Geographic information systems (GIS), remote sensing (RS) and the Global Positioning System (GPS) together represent a set of spatial tools that has commonly been touted as being vital for the proper planning and management of disease control programmes. Proponents of these tools suggest that a strong geographical basis to planning and implementation can improve the chances of a programme's success and increase its cost effectiveness by (1) providing more accurate information on pre-existing distributions of diseases and/or vectors in time and space, (2) contributing to the appropriate design of vector and disease control strategies, and (3) the development of suitable frameworks for monitoring and evaluation.

As a means of assessing the validity of

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these claims, this paper provides an overview of the specific contributions that GIS and associated spatial technologies can make within area-wide efforts to control vector-borne diseases, and assesses the degree to which this potential is being realized. The paper begins with a clarification of what is meant by the term "spatial tools" and describes briefly the core technologies it encompasses. The paper goes on to examine potential (and real) areas of application of spatial tools within a context of area-wide integrated pest management (AW-IPM) programmes integrating the sterile insect technique (SIT) and examines the extent to which spatial tools can aid the process of programme planning and implementation. The paper then goes on to look beyond the SIT, and to a number of examples of infectious diseases where GIS and spatial analysis have, to a greater or lesser extent, been employed within disease control efforts. With the help of these case studies the paper attempts to evaluate the extent to which the hype surrounding spatial tools has been (or can be) justified, and examines the barriers that remain in terms of further expansion of their use.

2. Spatial Tools for Control of Vector-Borne Diseases

Today's spatial "toolkit" includes three main components: GIS, GPS and RS. These are allied and overlapping technologies but are also separate tools in their own right. Within this toolkit, GIS can be defined as computer-based systems capable of capturing, cleaning, filtering, integrating, storing, retrieving, analysing and displaying spatial data. GIS incorporate spatial data and descriptive (attribute) data linked to the mapped features. What makes GIS distinct from other types of database is its ability to analyse data based on their location and spatial characteristics. Thus, while GIS may often be used solely for visualization, their functionality is likely to extend to much more sophisticated forms of spatial and statistical analysis. In this context, spatial analysis refers to the manipulation and transformation of GIS data as a means of extracting additional meaning from them. Common examples of spatial analysis include buffering map features (e.g. to define areas of exposure around vector breeding sites), interpolating between points (e.g. to produce climate "surfaces" from a network of weather stations) and overlaying a number of individual geographical coverages to produce derivative maps (e.g. suitability analysis and risk mapping).

There are a number of ways of getting spatial data into GIS, but arguably GPS and RS offer the most cost effective and flexible approaches. GPS receivers allow the collection of spatial and attribute information for points or more complex features on the ground with an accuracy of between 15 metres and a few centimetres depending on the hardware used. GPS receivers are often used simply to collect spatial data (coordinates) for geographical features, with associated attribute data being recorded separately and manually on survey forms. However, in many cases GPS receiver software now includes programmable data dictionaries, which can be used to capture attribute information directly. Alternatively, some GPS receivers can be linked up to personal digital assistant (PDA) devices or tablet computers. Both approaches greatly increase the speed and efficiency with which GPS data can subsequently be incorporated into existing GIS (Cox and Vreysen 2005).

RS is the process of gathering information about the earth's surface using electromagnetic sensors, typically on board satellites. Sensor data can be used in a relatively raw form, for example to derive land cover classification maps, or can be transformed into indices that constitute direct proxies for environmental variables such as rainfall, land surface temperature and vegetation status. Satellite images give objective, up-to-date assessments of surface conditions over large, sometimes inaccessible areas. Moreover, the repeatability of RS measurements makes RS particularly suitable for monitoring environmental conditions over time. There is now a large variety of multispectral sensor data available – with each sensor offering different advantages in terms of spatial resolution (pixel size), temporal resolution (revisit time) and spectral resolution (the number, width and spacing of the spectral bands used by the sensor). With a number of new satellite sensors due for launch in the next five years it should become increasingly easy to match the specific data requirements of individual disease or pest control programmes with appropriate sources of satellite imagery.

3. The Utility of RS, GIS and GPS in Area-Wide Programmes Integrating the SIT

As set out at the beginning of this paper, the three areas where spatial tools are thought to offer most utility in terms of area-wide programmes are: (1) providing more accurate knowledge of pre-existing vector/disease distributions in time and space, (2) contributing to the appropriate design and implementation of vector/disease control strategies, and (3) facilitating the design of suitable frameworks for monitoring and evaluating control strategies. The following section seeks to translate these somewhat general areas of utility into specific activities relevant to area-wide programmes.

3.1. Knowledge of Pre-Existing Vector and Disease Distributions

Insect pest intervention (and pre-intervention) programmes require accurate, up-to-date information on the spatial and temporal distribution of target insects. GIS-based analysis can be used to bring together a wide range of information sources. These include climate, RS, land use and topographic data, historical data on vector distribution and abundance, disease prevalence, etc. It can also be used to develop modelled or empirical estimates of the temporal and spatial distributions of the pest or disease of concern (Cox and Vreysen 2005). The nature of this GIS exercise, and the data sources used for it, will reflect the stage to which pre-intervention planning has developed. At the very early stages of planning, for example, GIS modelling will almost certainly focus on identifying areas of relatively high risk at the national or regional level, using low spatial resolution environmental data in combination with available historical information on the insects and/or diseases of interest. In other cases, these broad assessments may be more suitable for directing more detailed risk modelling efforts using higher resolution geographic datasets and, possibly, prospective sampling of vectors, to specific areas of interest.

The use of low spatial resolution RS data to predict disease vector distributions at the regional scale began in the early 1990s to correlate distributions of tsetse and incidence of trypanosomosis to spatial variations in climate and vegetation indices – and later also to surrogates of land surface temperature and rainfall (Rogers 1991, Rogers et al. 1996, Robinson et al. 1997, Hendrickx et al. 2001). The outputs of these types of models constituted an important first step in terms of the spatial targeting of the SIT and other area-wide interventions. However, resource and technical constraints may mean that more specific information is required to identify priority areas for intervention or guide future sampling efforts to address levels of genetic variability among target insects, etc.

Regional or national-scale vector distribution models may fail to capture the often localized, patchy distribution of many insect pests in areas where the overall insect population density is low. Locating pockets of high-density populations, while vital for successful insect intervention campaigns, is a major challenge from a spatial analysis perspective. This is because the climate and RS datasets used to predict insect distributions over specific areas are rarely appropriate for work at larger scales. Although a limited number of studies have successfully used high spatial resolution RS data (e.g. from Landsat and Satellite pour l'Observation de la Terre (SPOT) satellites) to identify habitats associated with high insect densities (Rejmankova et al. 1995, Roberts et al. 1996, Kitron et al. 1996), estimates of risk derived from this approach tend to be rather static as in the past it has either not been possible or practical to conduct multi-temporal analysis using these RS products. In future, however, the availability of multi-temporal RS data at respectable spatial resolutions (e.g. Moderate Resolution Imaging Spectroradiometer (MODIS)), should assist the development of dynamic population distribution models for predicting temporal and spatial population dynamics and to link spatial patterns with heterogeneity of habitat.

3.2. The Design and Implementation of Vector/Disease Control Strategies

The availability of temporal and spatial distribution models of the target species at a large spatial scale has implications beyond the design of efficient sampling frames. In particular, such models should facilitate a more efficient deployment of suppression tools as well as a better-targeted release of sterile insects. This increased efficiency should also translate into considerable economic savings in terms of logistics, personnel and sterile insects. A fuller discussion can be found in Cox and Vreysen (2005), but a brief summary of some of the main potential areas of utility for spatial tools is presented here.

In terms of selecting appropriate pre-release population suppression methods, it is worth noting that a variety of methods are often available for different species, but the appropriateness and effectiveness of each will depend on the characteristics of each target area. Spatial analysis can help identify the most appropriate suppression method (or combination of methods) for a given target zone – although the nature of this exercise will vary depending on the target species in question. In the case of tsetse, for example, spatial analysis could be used to (1) evaluate the likely impact of topography, wind velocity and direction, density of tree cover, etc. on the suitability of the sequential aerosol technique (SAT), (2) assess relative livestock and tsetse population distributions and densities in terms of likely impact on the efficiency of the live bait technology, or (3) use demographic data layers and tsetse population distribution models to evaluate likely efficiency or suitability of stationary bait technology (insecticide impregnated targets and traps). Alternatively, it may be possible to model the outcome of different combinations of suppression methods in target areas that are heterogeneous in terms of habitat composition, species composition, host distribution, demography and environment (Cox and Vreysen 2005).

Once an appropriate suppression method has been selected, spatial analysis can be employed directly to guide the suppression strategy, through, for example, determining appropriate sites for the deployment of traps and targets and by indicating required target/trap densities per surface unit in relation to environment and insect distribution. Spatial analysis may also obviate the need for uniform application of control measures such as the SAT over heterogeneous target areas and thereby reduce costs and any associated negative environmental impacts (Cox and Vreysen 2005).

3.3. Suitable Frameworks for Monitoring and Evaluating Control Strategies

Monitoring and evaluation are essential components of any area-wide programme but are time consuming and expensive in terms of materials, logistics and personnel. A careful balance has to be found between "cost efficiency" and the collection of "reliable data", which in most cases equates to restricted monitoring at carefully selected sites (Vreysen 2005). Spatial analysis can assist with the identification and selection of appropriate fixed monitoring sites. Mobile GIS and GPS technology can also make monitoring systems more efficient by allowing data entry in the field, for example using barcode scanners. Perhaps less obviously, spatial analysis can also be used to get "better value" out of available trap data – and a range of spatial analysis techniques employing both geo-statistics and GIS may be valuable at a landscape scale.

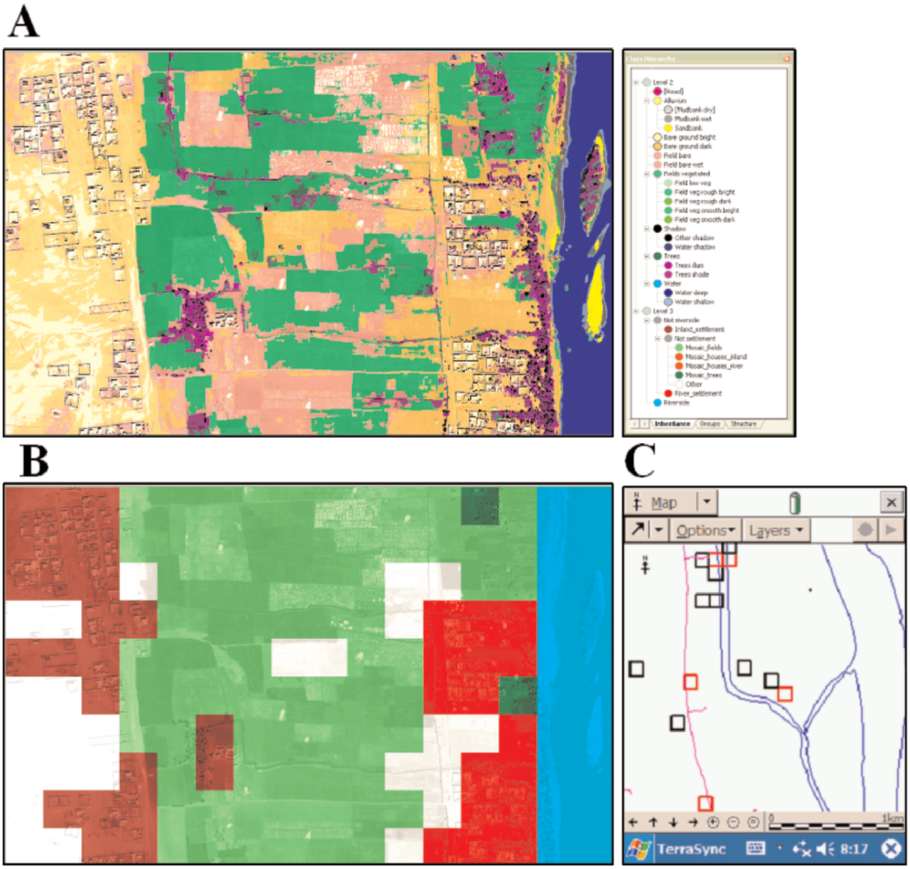

Figure 1. *An illustration of the use of GIS and RS for monitoring abundance of* Anopheles arabiensis *larvae in northern Sudan (Cox, unpublished). In this exercise the task was to generate a sampling approach to yield reliable baseline data on mosquito abundance within two defined reaches of the Nile River. (a) For each monitoring area, high resolution Quickbird RS data were processed using image segmentation and object-based classification techniques to derive land cover maps at sub-metre resolution, (b) which were then generalized to 100 × 100 metre cells conforming to a predefined sampling grid and a limited number of land cover mosaic types. Using these inputs it was possible to generate a random sample of grid squares, stratified by predominant land cover type, to be sampled over the course of a calendar year. (c) For each visit to the study area, field workers were able to upload maps of the specific grid cells to be sampled and use a pocket PC-based GPS/GIS system to navigate to and within the target cells.*

Interpolation procedures, for example, are ideally suited to the analysis of trap data, with output taking the form of contour maps or "surfaces" of insect density.

To date, examples of the application of spatial tools in programme monitoring are rare, but in principle the suitability of GIS for managing and interpreting data from a variety of sources makes it suitable for providing timely feedback on a large number of monitoring indicators (Cox and Vreysen 2005).

3.4. Uptake of Spatial Tools within Area-Wide SIT Programmes

From the information in previous sections it is evident that much of the potential utility attributed to spatial tools remains unproven in the sense that few published examples exist that demonstrate real uptake of the tools themselves. An exception – and an area where GIS and RS have been shown to have most impact – is the modelling of vector, disease and environmental datasets to produce spatial estimates of vector distributions or disease risk (Section 3.1). Of course, not all of this modelling effort has been carried out with SIT-based approaches in mind, and some of the early work was concerned more with methodological development than the utility of the outputs of models themselves. However, the academic nature of this work did ensure that the incremental development of modelling approaches could be tracked through the scientific literature. In contrast, it has been more difficult to assess the uptake of spatial tools with respect to project design, implementation, monitoring and evaluation within AW-IPM programmes (Sections 3.2 and 3.3) because the emphasis on the practical application of the tools, as distinct from their research application, usually precludes widespread publicity of experiences. In other words, in a properly designed programme, spatial tools should ideally be fully integrated tools that operate "under the hood".

That said, it would appear that even anecdotally there are relatively few cases where spatial tools have been explicitly incorporated into ongoing SIT-based programmes. The exceptions are most notably within programmes against the New World screwworm *Cochliomyia hominivorax* (Coquerel) (Philips et al. 2004), tephritid fruit flies (Orankanok et al., this volume), the painted apple moth *Teia anartoides* Walker (Suckling et al., this volume), and most recently, in the development of SIT against *Anopheles* mosquitoes. In such cases, spatial tools have been used primarily to provide navigational guidance and tracking for releases of the sterile insects and for navigation on the ground. In some cases GIS have also been used for mapping trapping sites and monitoring invasion routes (sometimes in real time), such as in the Mississippi boll weevil *Anthonomus grandis* Boheman eradication programme. Less commonly, spatial analysis has been used for selecting trapping sites, most commonly by overlaying grids on topographical maps or satellite images either manually (as historically in the case of the Zanzibar tsetse SIT-based AW eradication project), or more formally within GIS (as in the case of the ongoing SIT feasibility study for *Anopheles arabiensis* Patton in northern Sudan (Fig. 1). This approach is particularly well suited to situations where there is a strong justification for weighting sampling effort according to *a priori* assumptions about the effect of different land use and land cover types on insect distributions. In Panama, for example, Phillips et al. (2004) derived an optimal design of trap networks for monitoring adult New World screwworm flies based on RS-derived forest maps.

There generally seems little evidence for the widespread use of spatial tools for monitoring and evaluation, although within the Programa Moscamed (Guatemala-Mexico), work is ongoing to analyse sterile Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) performance under different environmental conditions, identifying hot spots of persistent high insect density and exploring insect behaviour. Otherwise, the use of GIS/RS as a decision support tool in AW-IPM programmes with an SIT component has so far largely been limited to the spatial display of data and has seldom been applied for planning, implementation of suppression and release programmes or analysis and modelling of the data.

4. Spatial Tools in Non-Genetic Approaches to Disease Control

Much scientific work has gone into geographical modelling of the distribution, abundance and prevalence of diseases and their vectors at a variety of spatial scales (Hay et al. 2000, Lindsay and Thomas 2000, Malone et al. 2001, Elnaiem et al. 2003), while there has been rather less emphasis on incorporating spatial tools directly into control programmes. Arguably, this has particularly been the case for "high-profile" diseases such as malaria, where projects such as the Mapping Malaria Risk in Africa (MARA) collaboration have produced scientific outputs that have reached academic audiences through journal publications (e.g. Craig et al. 1999, Kleinschmidt et al. 2001) and have appeared to play important advocacy roles at international level. However, there is no clear evidence to suggest that these types of products have been used explicitly for planning control activities.

There are probably a number of reasons for this lack of uptake of risk model outputs. Most fundamentally, it is probable that in many cases decision makers simply do not trust the veracity of the models. In view of the methodological and data-related limitations of some published models, in some instances they are probably right not to. In other cases good models may have been produced, but decision makers simply do not find them useful, or even relevant. This is most often the case where modelling has been data-driven, rather than demand-led. Nevertheless, even in situations where researchers have attempted to "second-guess" the needs of policy makers, the results are not always fruitful. In other cases it may be that model results are too generalized from a geographical perspective to influence local-level planning or, conversely, it may be that models using data from specific geographical areas cannot be extrapolated in a reliable way to produce robust predictions of disease and/or vector characteristics over wide areas. It is of course also true that planners may be resistant to new sources of evidence in terms of their decision-making, in which case even highly reliable and pertinent models are likely to be ignored. In this respect it is important that the intended users of risk models are not viewed as "passive" consumers, but are instead brought in as active players in designing and carrying out risk mapping projects.

In reality, direct and productive use of spatial tools has tended to be limited to situations where planning is focused on coordinated disease eradication, or where a single, efficacious intervention is available for a disease and requires targeting. For human onchocerciasis (river blindness), for example, the Rapid Epidemiological Mapping of Onchocerciasis (REMO) developed by the Special Programme for Research and Training in Tropical Diseases/World Health Organization (TDR/WHO), has emerged as an important spatial tool for control planning (Ngoumou et al. 1994, Katabarwa et al. 1999). The Rapid Epidemiological Mapping of Onchocerciasis allows quick and cheap identification of communities at high risk of onchocerciasis using spatial information such as the locations of river basins. High-risk communities are then subsampled and rapidly assessed by screening individuals for onchocercal nodules. This enables communities to be classified into three categories: (1) priority areas which require community-directed treatment with ivermectin, (2) areas which do not require treatment, and (3) possible endemic areas needing further investigation. Results of the Rapid Epidemiological Mapping of Onchocerciasis have been incorporated into GIS to visualize priority areas for community-directed treatment with ivermectin and estimate the number of people needing treatment (Noma et al. 2002). This in turn has allowed the African Programme for Onchocerciasis Control to prioritize allocation of resources according to need.

Rapid mapping method approaches have also been developed for lymphatic filariasis, which is currently being targeted for eradication through the Global Alliance for the Elimination of Lymphatic Filariasis. As with onchocerciasis, identifying endemic localities is an essential first step to carrying out treatment programmes, and the Rapid Geographical Assessment of Bancroftian Filariasis (RAGFIL) was developed by TDR/WHO for this purpose. The Rapid

Geographical Assessment of Bancroftian Filariasis uses a spatial sampling grid with either 25 or 50 kilometres between sampled communities, together with rapid prevalence assessments using immunochromatographic card tests and geostatistical methods (WHO 1998, Gyapong et al. 2002). However, subsequent analyses have suggested that a smaller sampling grid may be required to successfully identify all high-risk communities (Srividya et al. 2002).

Perhaps the most impressive and most up to date example of the use of spatial tools in disease control planning comes from the Schistosomiasis Control Initiative, which is currently assisting the implementation of national programmes for schistosomiasis and geohelminth control in six African countries. In Uganda, where *Schistosoma mansoni* Sambon is widespread, GIS and RS have been employed to classify the country according to treatment strategy. Communities are classified according to three strategies: (1) annual treatment of schoolchildren and high-risk groups with praziquantel and albendazole where schistosomiasis prevalence is above 50%, (2) treatment every second year in communities with moderate prevalence (more than 20% and less than 50%), and (3) health facility based treatment of suspected cases in low prevalence (less than 20%) areas. Spatial analysis using RS data and climate surfaces showed that *S. mansoni* typically occurs only where average annual rainfall is more than 850 millimetres or where altitude is less than 1400 metres (Kabatereine et al. 2004), allowing remaining areas to be excluded from the control strategy. Modelling also showed that prevalence consistently exceeded 50% in areas within five kilometres of major lakes, justifying mass-treatment in villages within these areas without the need for further surveys. In intermediate areas individual communities are surveyed using lot quality assurance sampling (Brooker et al. 2005).

Elsewhere, the Schistosomiasis Control Initiative has used Bayesian geostatistical models to produce validated prevalence surface maps for both *Shistosoma haematobium* (Bilharz) and *S. mansoni* infections in north-western Tanzania with the similar aim of guiding spatially mass-treatment with praziquantel (Clements et al. 2006). Bayesian spatial methods, although rarely applied in the context of vector-borne diseases, offer the distinct advantage of being able to incorporate spatial auto-correlation, as well as uncertainty through the modelling of both observed data and any unknowns as random variables. In this way, Clements et al. (2006) were able to use parasitological data from 143 schools to develop RS-based models for the two infections. Significantly, they were also able to investigate the confidence of the prevalence predictions and thereby inform decision makers on whether sufficient data were collected to exclude areas from mass-treatment.

5. Realizing the Potential of Spatial Tools within Disease Control Programmes

Although this paper in no way constitutes a thorough survey of ongoing area-wide programmes, the process of putting this review together has revealed that, to date, the application of spatial tools within area-wide programmes appears to have been relatively limited. Where spatial tools have been used, work has focused on using existing disease or vector datasets in combination with environmental data to model distributions of vectors and/or their associated diseases. It is likely that these products represent useful first steps in the planning of area-wide programmes (and particularly those aimed at tsetse). However, there is much less evidence for the direct use of GIS, GPS and RS in the planning, implementation, monitoring and evaluation of area-wide programmes. This is somewhat surprising given that these tools have been used extensively in other areas of agroecological management for many years.

Within non-genetic approaches to disease control there has also been a fairly research-oriented focus on spatial modelling of vector and disease risk. Nevertheless, as section 4 demonstrates, there are now a growing number of instances where an explicit spatial framework is being used for targeting public health interventions, and spatial tools have been critical in the development of these approaches. There are now validated instances where spatial tools are providing governments with a relatively low-cost approach to surveying and programme design. This can significantly reduce the cost of practical programmes through more precise geographical targeting and simplifying the processes of monitoring and evaluation. Spatial tools can reduce both the upstream (e.g. survey and design), and downstream (e.g. targeting, monitoring and evaluation) costs of programmes, while enhancing programme effectiveness. At the same time, it should be recognized that the uptake of spatial tools has been far from universal and that, in many cases, this uptake has occurred only very recently.

These findings beg the question of why it has taken so long for spatial tools to be incorporated within disease control programmes. Traditionally, the answer to this has lain in the large economic costs involved in obtaining GIS, RS and GPS hardware and software, in the need to generate spatial datasets from scratch and in a shortage of the necessary skills. However, spatial tools are now becoming increasingly accessible to non-specialists, while increases in computing power mean that even high-level GIS systems can be installed on a standard personal computer. Software costs, once a major disincentive, are now rarely prohibitive, and GIS and RS data are more widely available than ever before. Perhaps it is also significant that some of the "data vacuum" that has hindered the development of spatial disease models in the past is slowly being filled as basic mapping of public health infrastructure improves (e.g. through WHO's Public Health Mapping and GIS Programme (http://www.who.int/health_mapping/about/en/)) and surveillance systems for vector-borne diseases are increasingly incorporating an explicitly spatial dimension (Abeku et al. 2004, Gosselin et al. 2005).

It seems probable therefore, that the uptake of spatial tools will increase markedly over the coming years, and that much of the "hype" surrounding GIS, GPS and RS will be seen to be justified. Indeed, it could be argued that the potential benefits of spatial tools in terms of increasing programme effectiveness and, importantly, cost effectiveness, make it imperative that geographers and others continue to advocate the use of spatial tools for disease control.

6. References

Abeku, T. A., S. I. Hay, S. Ochola, P. Langi, B. Beard, S. J. de Vlas, and J. Cox. 2004. Malaria epidemic early warning and detection in African highlands. Trends in Parasitology 20: 400-405.

Brooker, S., N. B. Kabatereine, M. Myatt, J. Russell Stothard, and A. Fenwick. 2005. Rapid assessment of *Schistosoma mansoni*: the validity, applicability and cost-effectiveness of the lot quality assurance sampling method in Uganda. Tropical Medicine and International Health 10: 647-658.

Clements, A. C. A., N. J. S. Lwambo, L. Blair, U. Nyandindi, G. Kaatano, S. Kinung'hi, J. P. Webster, A. Fenwick, and S. Brooker. 2006. Bayesian spatial analysis and disease mapping: tools to enhance planning and implementation of a schistosomiasis control programme in Tanzania. Tropical Medicine and International Health 11: 490-503.

Cox, J. St. H., and M. J. B. Vreysen. 2005. Use of geographic information systems and spatial analysis in area-wide integrated pest management programmes that integrate the sterile insect technique, pp. 453-477. *In* Dyck, V. A., J. Hendrichs, and A. S. Robinson (eds.), Sterile insect technique. Principles and practice in area-wide integrated pest management. Springer, Dordrecht, The Netherlands.

Craig, M. H., R. W. Snow, and D. le Sueur. 1999. A climate-based distribution model of malaria transmission in sub-Saharan Africa. Parasitology Today 153: 105-111.

Elnaiem, D. E. A., J. Schorscher, A. Bendall, V. Obsomer, M. E. Osman, A. M. Mekkawi, S. J. Connor, R. W. Ashford,

and M. C. Thomson. 2003. Risk mapping of visceral leishmaniasis: the role of local variation in rainfall and altitude on the presence and incidence of Kala-Azar in eastern Sudan. American Journal of Tropical Medicine and Hygiene 68: 10-17.

Gosselin, P., G. Lebel, S. Rivest, and M. Douville-Fradet. 2005. The integrated system for public health monitoring of West Nile virus (ISPHM-WNV): a real-time GIS for surveillance and decision-making. International Journal of Health Geographics 4: 21. http://www.ij-healthgeographics.com/content/pdf/1476-072X-4-21.pdf

Gyapong, J. O., D. Kyelem, I. Kleinschmidt, K. Agbo, F. Ahouandogbo, J. Gaba, G. Owusu Banahene, S. Sanou, Y. K. Sodahlon, G. Biswas, O. O. Kale, D. H. Molyneux, J. B. Roungou, M. C. Thomson, and J. Remme. 2002. The use of spatial analysis in mapping the distribution of bancroftian filariasis in four West African countries. Annals of Tropical Medicine and Parasitology 967: 695-705.

Hay, S. I., J. A. Omumbo, M. H. Craig, and R. W. Snow. 2000. Earth observation, geographic information systems and *Plasmodium falciparum* malaria in sub-Saharan Africa. Advances in Parasitology 47: 173-215.

Hendrickx, G., S. de la Rocque, R. Reid, and W. Wint. 2001. Spatial trypanosomosis management: from data-layers to decision making. Trends in Parasitology 171: 35-41.

Kabatereine, N. B., E. M. Tukahebwa, F. Kazibwe, H. Namwangwe, S. Zaramba, S. Brooker, J. R. Stothard, C. Kamenka, S. Whawell, J. P. Webster, and A. Fenwick. 2005. Progress towards country-wide control of schistosomiasis and soil-transmitted helminthiasis in Uganda. Transactions of the Royal Society of Tropical Medicine and Hygiene 100: 208-215.

Katabarwa, M., A. W. Onapa, and B. Nakileza. 1999. Rapid epidemiological mapping of onchocerciasis in areas of Uganda where *Simulium neavei* sl is the vector. East African Medical Journal 76: 440-446.

Kitron, U., L. H. Otieno, L. L. Hungerford, A. Odulaja, W. U. Brigham, O. O. Okello, M. Joselyn, M. M. Mohamed Ahmed, and E. Cook. 1996. Spatial analysis of the distribution of tsetse flies in the Lambwe Valley, Kenya, using Landsat TM satellite imagery and GIS. Journal of Animal Ecology 65: 371-380.

Kleinschmidt, I., J. Omumbo, O. Briet, N. van de Giesen, N. Sogoba, N. K. Mensah, P. Windmeijer, M. Moussa, and T. Teuscher. 2001. An empirical malaria distribution map for West Africa. Tropical Medicine and International Health 61: 779-786.

Lindsay, S. W., and C. J. Thomas. 2000. Mapping and estimating the population at risk from lymphatic filariasis in Africa. Transactions of the Royal Society of Tropical Medicine and Hygiene 94: 37-45.

Malone, J. B., J. M. Yilma, J. C. McCarroll, B. Erko, S. Mukaratirwa, and X. Y. Zhou. 2001. Satellite climatology and the environmental risk of *Schistosoma mansoni* in Ethiopia and East Africa. Acta Tropica 79: 59-72.

Ngoumou, P., J. F. Walsh, and J. M. Mace. 1994. A rapid mapping technique for the prevalence and distribution of onchocerciasis: a Cameroon case study. Annals of Tropical Medicine and Parasitology 88: 463-474.

Noma, M., B. E. Nwoke, I. Nutall, P. A. Tambala, P. Enyong, A. Namsenmo, J. Remme, U. V. Amazigo, O. O. Kale, and A. Seketeli. 2002. Rapid epidemiological mapping of onchocerciasis REMO: its application by the African programme for onchocerciasis control APOC. Annals of Tropical Medicine and Parasitology 96 Suppl 1: S29-39.

Phillips, P. L., J. B. Welch, and M. Kramer. 2004. Seasonal and spatial distributions of adult screwworms (Diptera: Calliphoridae) in the Panama Canal area, Republic of Panama. Journal of Medical Entomology 41: 121-129.

Rejmankova, E., D. R. Roberts, A. Pawley, S. Manguin, and J. Polanco. 1995.

Predictions of adult *Anopheles albimanus* densities in villages based on distances to remotely-sensed larval habitats. American Journal of Tropical Medicine and Hygiene 53: 482-488.

Roberts, D. R., J. F. Paris, S. Manguin, R. E. Harbach, R. Woodruff, E. Rejmankova, J. Polanco, B. Wullschleger, and L. J. Legters. 1996. Predictions of malaria vector distribution in Belize based on multispectral satellite data. American Journal of Tropical Medicine and Hygiene 54: 304-308.

Robinson, T. P., D. J. Rogers, and B. Williams. 1997. Mapping tsetse habitat suitability in the common fly belt of southern Africa using multivariate analysis of climate and remotely sensed data. Medical and Veterinary Entomology 11: 235-245.

Rogers, D. J. 1991. Satellite imagery, tsetse and trypanosomiasis in Africa. Preventive Veterinary Medicine 11: 201-220.

Rogers, D. J., S. I. Hay, and M. J. Packer. 1996. Predicting the distribution of tsetse flies in West Africa using temporal Fourier processed meteorological satellite data. Annals of Tropical Medicine and Parasitology 90: 225-241.

Srividya, A., E. Michael, M. Palaniyandi, S. P. Pani, and P. K. Das. 2002. A geostatistical analysis of the geographic distribution of lymphatic filariasis prevalence in southern India. American Journal of Tropical Medicine and Hygiene 675: 480-489.

Vreysen, M. J. B. 2005. Monitoring sterile and wild insects in area-wide integrated pest management programmes, pp. 325-361. *In* Dyck, V. A., J. Hendrichs, and A. S. Robinson (eds.), Sterile insect technique. Principles and practice in area-wide integrated pest management. Springer, Dordrecht, The Netherlands.

(WHO) World Health Organization. 1998. Research on rapid geographical assessment of Bancroftian filariasis. World Health Organization TDR/TDF/COMDT/ 98.2, Geneva, Switzerland.