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Geospatial datasets and analyses for an environmental approach to African trypanosomiasis

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Geospatial datasets and analyses for an environmental approach to African trypanosomiasis

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EXECUTIVE SUMMARY

Human and animal trypanosomiases continue to contribute substantially to the overall burden of diseases in sub-Saharan Africa, thus posing a serious hindrance to food security and sustainable rural development in many regions that are infested by the tsetse fly, the vector of the disease.

A number of current initiatives are being used to tackle different aspects of the tsetse and trypanosomiasis (T&T) problem. Multinational projects based on the concept of area-wide integrated pest management (AW-IPM) are being implemented in many affected countries with, for some of the projects, the concurrence of the Pan African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC) initiative. Extensive surveillance and control activities directed against the human form of the disease (also known as sleeping sickness) are carried out by mandated national institutions in collaboration with the World Health Organization (WHO).

A number of research institutes and nongovernmental organizations are also working to curb the T&T problem through demand-driven research and health relief operations. In this context, the Programme Against African Trypanosomiasis (PAAT) plays a central role in setting harmonized criteria, defining guidelines and developing standardized tools and methodologies for strategic interventions and operational decision-making.

This PAAT Position Paper stems from the recognition that geographic information systems (GIS) are becoming increasingly important in all phases of the project cycle, from its initial conceptual elaboration to the final evaluation. The first section of the paper provides a review of state-of-the-art global geospatial datasets that are available in the public domain and that are deemed relevant to assist in T&T decision-making. The review embraces epidemiological and environmental data concerning African trypanosomiases, the tsetse fly, wildlife, livestock, human populations, land cover, surface hydrology and wetlands, elevation, climate and agro-ecological zones. It also includes information on roads, protected areas, georeferenced named locations and satellite imagery. The global datasets described in this section are particularly relevant in light of the transboundary, multinational quality of the T&T problem. The second section investigates the relationship between low- and medium-resolution global datasets and high-resolution local data, using the Mouhoun river basin in Burkina Faso as its study area. The strengths and weaknesses of the different sources of data in the context of T&T decision-making are discussed. The third section presents how GIS, database management systems and image processing software can be used to plan

and implement baseline entomological data collection for a T&T elimination project in Burkina Faso, one of the countries involved in the PATTEC initiative. The final section describes how GIS can be combined with satellite-assisted navigation systems to enhance the execution of a tsetse elimination project, based on the application of the sequential aerosol technique, in the Okavango delta in Botswana. This project was executed in accordance with the AW-IPM approach, which addresses the management of the total insect pest population in a defined, well-demarcated area or region.

Although by no means exhaustive, the review and case studies presented here provide a representative cross section of the possible applications of geospatial datasets and GIS analysis techniques in support of T&T interventions. It is believed that ongoing and future projects against T&T will benefit from the experiences presented in this paper and that these experiences will lead ultimately to more coherent, harmonized and efficient actions.

Acronyms

AAT	animal African trypanosomiasis
ADC	American Digital Cartography inc.
ADT	apparent density per trap per day
AEZ	agro-ecological zones
Agro-MAPS	Global Spatial Database of Subnational Agricultural Land-Use Statistics
AMD	African Mammals Databank
ASCII	American Standard Code for Information Interchange
AW-IPM	area-wide integrated pest management
AWRD	African Water Resource Database
BIL	band interleaved by line
CIAT	Centro Internacional de Agricultura Tropical
CIESIN	Columbia University Center for International Earth Science Information Network
CRU	Climatic Research Unit of the University of East Anglia
DCW	Digital Chart of the World
DEM	digital elevation model
DSMW	Digital Soil Map of the World
DTED2	Digital Terrain Elevation Data Level 2
EROS	USGS Center for Earth Resources Observation and Science
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
ETM+	Enhanced Thematic Mapper Plus
GIS	geographic information system
GLC2000	Global Land Cover database for the year 2000
GLCF	Global Land Cover Facility of the University of Maryland
GLCN	Global Land Cover Network
GLiPHA	Global Livestock Production and Health Atlas
GLW	Gridded Livestock of the World
GLWD	Global Lakes and Wetlands Database
GNS	GEOnet Names Server
GPS	Global Positioning System
GPW	Gridded Population of the World
GRUMP	Global Rural–Urban Mapping Project
GTopo30	Global Topographic 30 arc-second DEM database
HAT	human African trypanosomiasis
HydroSHEDS	Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales
IFAD	International Fund for Agricultural Development
IIASA	International Institute for Applied Systems Analysis

IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IUCN	International Union for the Conservation of Nature
JRC	European Commission's Joint Research Centre
LCCS	Land Cover Classification System
LGP	Length of Growing Period
LOIL	Landsat Orthorectified Image Library
LUT	land utilization type
MERIS	Medium Resolution Imaging Spectrometer
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NGA	United States National Geospatial-Intelligence Agency (formerly NIMA and DMA)
NR	FAO Natural Resources Management and Environment Department
ONC	Operational Navigation Charts
ORNL	Oak Ridge National Laboratory
PAAT	Programme Against African Trypanosomiasis
PAAT-IS	Programme Against African Trypanosomiasis Information System
PATTEC	Pan African Tsetse and Trypanosomiasis Eradication Campaign
RS	remote sensing
SAT	sequential aerosol technique
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SWBD	SRTM Water Body Data
T&T	tsetse and trypanosomiasis
TM	Thematic Mapper
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VPF	Vector Product Format
WCMC	World Conservation Monitoring Centre
WCPA	World Commission on Protected Areas
WHO	World Health Organization
WRI	World Resources Institute

Section 1
Global geospatial datasets for African trypanosomiasis management: a review

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ABSTRACT
Georeferenced datasets and spatial analysis techniques are widely recognized as essential tools to support the planning and implementation of interventions against human and animal diseases, including African trypanosomiases. In this paper we provide a review of state-of-the-art global geospatial datasets that is aimed at assisting scientists, project managers, specialists in geographic information systems (GIS) and decision-makers who are concerned with the problem of African trypanosomiases. The datasets included in this review are selected for their relevance, Africa-wide coverage and, importantly, availability in the public domain. Where deemed appropriate, commercial products or those of restricted distribution, as well as datasets of more limited spatial coverage, are included. Modalities for data access, especially Web sites that allow free data download, are provided. Lastly, possible applications of these datasets in the context of tsetse and trypanosomiasis (T&T) intervention are outlined.

INTRODUCTION
The rationale for this paper is the observation that the geospatial datasets available in the public domain are largely underutilized by the community of technicians dealing with the problem of trypanosomiasis in Africa. We review a selection of GIS datasets that are deemed to be suitable for planning, implementing and monitoring interventions against T&T, as well as supporting research activities. Some databases discussed in this paper have been either produced by or derived from funding associated with the United States Government. Under the United States Freedom of Information Act, unclassified data produced using government funding are subject to eventual release into what is commonly known as the public domain. In broad terms, data released into the public domain cannot be copyrighted, restricted or licensed by the United States Government source entity. For more information on the terminology used in this paper, as well as for a broader review of global geospatial datasets, readers can refer to the FAO publication *An inventory and comparison of globally consistent geospatial databases and libraries* (Dooley, 2005).

AFRICAN TRYPANOSOMIASIS
African trypanosomiasis is an infectious disease that is caused by various species of blood parasites named trypanosomes. The disease affects both people (human

African trypanosomiasis [HAT] or sleeping sickness) and animals (animal African trypanosomiasis [AAT] or nagana).

Animal African trypanosomiasis

There is currently no detailed and consistent spatial dataset of the presence or prevalence of tsetse-transmitted animal trypanosomiasis in sub-Saharan Africa. AAT occurs in 37 sub-Saharan countries covering over 9 million km^2, an area that corresponds approximately to one-third of Africa's total land area. The infection is estimated to threaten over 50 million head of cattle (see page 5). However, global estimates of the affected area and cattle at risk are based not on the presence of the disease itself but rather on the presence of the vector, the tsetse fly. A review of the vast body of literature that addresses the problem of the presence and prevalence of AAT at regional and, in particular, at local scale is beyond the scope of this paper.

Human African trypanosomiasis

Sleeping sickness threatens millions of people in 36 countries of sub-Saharan Africa. HAT takes one of two forms depending on the parasite involved: *Trypanosoma brucei gambiense*, which causes a chronic infection, is found in western and central Africa and accounts for more than 90 percent of reported cases; *T. b. rhodesiense* is found in eastern and southern Africa and causes an acute infection.

Sleeping sickness can occur only in regions in which there are tsetse flies that can transmit the disease; but for reasons that are so far not well understood, many regions infested by tsetse flies are free of sleeping sickness. HAT is a highly focal disease often characterized by distinct outbreaks in a specific area or village. Areas endemic for sleeping sickness receive their names from local geographical features such as valleys, rivers, villages or towns (a continental map of the estimated geographical distribution of active and historical risk areas for HAT is available in Cattand, Jannin and Lucas, 2001).

In 1995, a World Helath Organization (WHO) Expert Committee provided estimates of the population at risk by country (WHO, 1998). The most recent, comprehensive and spatially explicit information on the disease to date, comprising the number of people screened by active case-finding surveys and the number of new cases by country, was published by WHO in 2006 (WHO, 2006) and updated in 2008 (Simarro, Jannin and Cattand, 2008).

In 2007, WHO and FAO, in the framework of the Programme Against African Trypanosomiasis (PAAT), combined their efforts to map sleeping sickness in sub-Saharan Africa by using, as primary source, the vast amount of epidemiological data collated by WHO in recent years (Cecchi *et al*., 2009a). The use of GIS tools and georeferenced, village-level epidemiological data will allow the production of maps that improve substantially on the spatial quality of previous cartographic products of similar scope. The initiative will result in the production of the Atlas of HAT. The Atlas will lay the basis for novel, evidence-based methodologies to estimate the population at risk and the burden of disease, ultimately leading to more efficient targeting of interventions. Preliminary results of the Atlas of HAT initiative are available for central Africa (Cecchi *et al*., 2009a) and western Africa (Cecchi *et al*., 2009b).

THE TSETSE FLY

Mapping the vector of trypanosomiasis, the tsetse fly, is of paramount importance for the control of the disease. Without such mapping, ongoing initiatives for the elimination of the tsetse fly, such as the Pan African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC)[1], are greatly disadvantaged.

Predicted areas of suitability for tsetse flies

The only comprehensive and internationally recognized source for the distribution of the different species of tsetse fly in Africa is the Information System of PAAT (PAAT-IS)[2]. PAAT-IS contains the predicted areas of suitability for the 3 groups of tsetse flies (*fusca*, *palpalis* and *morsitans*) and for 24 tsetse species. All of the distributions have been produced by modelling the assumed presence and absence of the flies, generally using the Ford and Katondo maps (Ford and Katondo, 1975; 1977a; 1977b) modified with more recent information collected from national and international agencies and researchers. The modelling process relies on logistic regression analysis of fly presence against a wide range of predictor variables. The predictor variables include remotely sensed surrogates of climate (vegetation, temperature, moisture), which have been subjected to Fourier processing to provide an additional set of measures related to season and timing for each parameter. Demographic, topographic and agro-ecological predictors are also used. These models are then applied to the predictor images to determine the probability of fly distributions (FAO, 2000). Data are provided at a resolution of 5 km for the whole of sub-Saharan Africa.

For a limited number of regions (Ethiopia, Kenya, South Eastern Africa, Tanzania, Uganda, West Africa) and for a few species, PAAT-IS also provides data at a higher resolution (1 km).

Access to data

PAAT-IS datasets can be downloaded from the PAAT Web site[3] or from FAO GeoNetwork[4] (by searching for the keyword *PAAT*). The maps are also included in the CD-ROM *PAAT-Information System, July 2006*, which can be requested from the PAAT-IS Web page.

Applications within T&T interventions

The PAAT-IS maps of tsetse distribution are particularly useful in support of T&T strategic decision-making at the regional and continental level – for example, in the selection of priority areas for intervention. Continental and regional maps can assist in identifying areas where fly populations are potentially isolated and which are therefore less prone to reinvasion. However, it is important to stress that because of the resolution, the training data utilized, the inherent limitations in the modelling methodologies and the lack of a systematic field-based validation, PAAT-IS maps are less suitable

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1 http://www.africa-union.org/Structure_of_the_Commission/depPattec.htm
2 http://www.fao.org/ag/paat-is.html
3 http://www.fao.org/ag/againfo/programmes/en/paat/maps.html
4 http://www.fao.org/geonetwork/

for guiding the implementation of operations at the field level. For a comparison of PAAT-IS maps with field data on a local scale, see section 2, "Tsetse distribution in the Mouhoun river basin (Burkina Faso): the role of global and local geospatial datasets", in this publication (see page 41).

WILDLIFE

Tsetse flies feed on a number of wild animals that occupy the same habitat. Among them, mammals represent the most important class. Knowledge of the distribution of wild hosts is relevant for trypanosomiasis control. Below we present the most comprehensive data source for the distribution of mammals in Africa.

African Mammals Databank

The African Mammals Databank (AMD) (Boitani *et al.*, 1999) is a GIS-based databank on the distribution of all the large- and medium-sized mammals over the whole African continent (excluding Madagascar). The databank has been implemented by the Italian Institute of Applied Ecology in cooperation with several institutions in Africa. It was designed to collect, store, organize and preanalyse data for the implementation of conservation and management actions in Africa. The databank includes a total of 281 wild mammal species for which a set of data on their distribution and ecology is available.

One product is the "extent of occurrence", which depicts the boundaries of the area in which an observer has a chance of finding individuals of that particular species. The layer discriminates between "certain presence", "uncertain presence", "absence" and "reintroduction". The determination of the expected and possible presence of a species is based on a comprehensive review of the literature.

Other GIS products are based on the modelling of environmental conditions to estimate the suitability or unsuitability of habitats for each species. The categorical–discrete model uses a deductive approach to derive from the literature the environmental preferences of a species. In contrast, the probabilistic–continuous distribution model uses a dataset of known locations of the species to characterize the ecological profile of the species. The characterization is then used to calculate the "ecological distance" of each location within the study area from the preferred ecological conditions of the species.

Access to data

All AMD datasets can be downloaded from the Web site of the Department of Animal and Human Biology[5] of the University of Rome "La Sapienza".

Applications within T&T interventions

The vast majority of favoured tsetse hosts (FAO, 1982) are available within the AMD: bushbuck (*Tragelaphus scriptus*), African buffalo (*Syncerus caffer*), bushpig (*Potamochoerus larvatus*), warthog (*Phacochoerus africanus*), red river

[5] http://www.gisbau.uniroma1.it/amd/

hog (*Potamochoerus porcus*), kudu (*Tragelaphus imberbis*), giraffe (*Giraffa camelopardalis*), porcupine (*Hystrix cristata*), aardvark or antbear (*Orycteropus afer*), giant forest hog (*Hylochoerus meinertzhageni*), hippopotamus (*Hippopotamus amphibius*), eland (*Taurotragus oryx*) and duiker (*Cephalophus* genus).

Among major mammalian hosts of the tsetse, only rhinoceros and elephant are missing from the AMD. The two species of rhinoceros (*Diceros bicornis* and *Ceratotherium simum*) were excluded because data on the last few areas in which they are found are being kept from the public. The elephant (*Loxodonta africana*) was also excluded because an excellent and detailed database in a format very similar to the one proposed by the AMD is kept by the African Elephant Specialist Group of the Species Survival Commission, a programme of the International Union for the Conservation of Nature (IUCN)[6].

LIVESTOCK

Gridded Livestock of the World

The Animal Production and Health Division of FAO developed the Gridded Livestock of the World (GLW) dataset (Wint and Robinson, 2007). The data are produced in Environmental Systems Research Institute (ESRI) grid format at a spatial resolution of 3 arc minutes (approximately 5 km at the equator) for cattle, buffaloes, sheep, goats, pigs and poultry.

For each country, the most recent available livestock census data at subnational level have been collected. These are then converted into densities, excluding land unsuitable for livestock, to provide the "observed" data. The data are then disaggregated based on statistical relationships with environmental variables in similar agro-ecological zones to produce the "predicted" distribution (Figure 1). Pixel values represent densities (number of animals per km^2).

Access to data

These digital maps are available for download at no charge through FAO GeoNetwork portal (by searching for the keyword *GLW*). It is possible to download both "observed" and "predicted" livestock densities; also available for download are the masks of the areas unsuitable for livestock (either monogastric or ruminant) and the predicted density, adjusted to match FAOSTAT totals for the year 2000. The need to adjust the predictions to fixed years (2000 and 2005) stems from the difference between the reference years in the input livestock censuses. The latter are summarized in the GLW metadata.

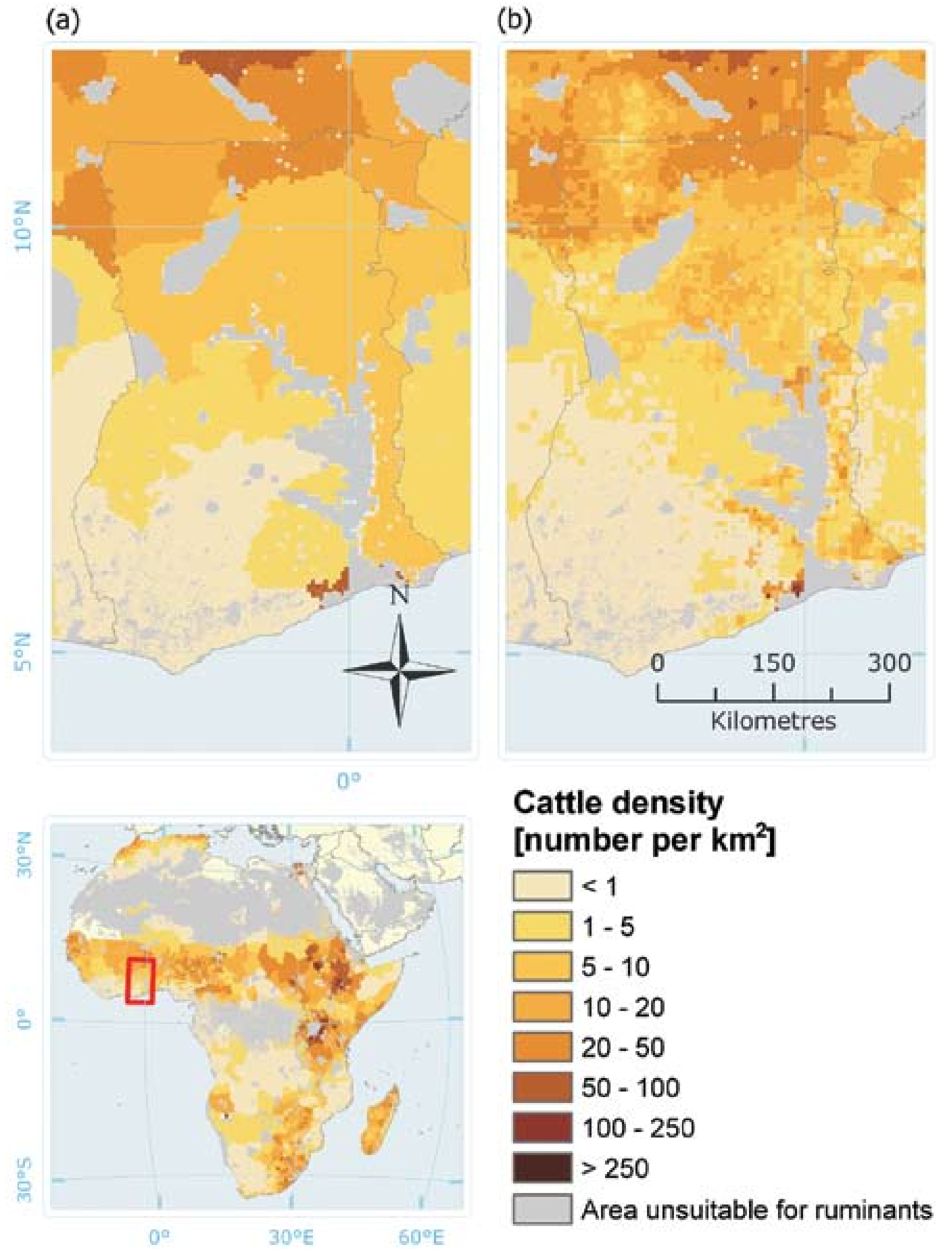
Applications within T&T interventions

Maps of livestock populations can be used in various phases of the T&T decision-making process. We provide here one example concerning the estimation of trypanosomiasis risk.

The maps of cattle density can be combined with maps of tsetse distribution (see page 3) in order to estimate the number of cattle at risk of trypanosomiasis. Even

6 http://www.african-elephant.org/

FIGURE 1
Cattle density in Ghana (number per km²). (a) "Observed density": derived from census data. (b) "Predicted density": based on the observed density, which was disaggregated on the basis of statistical relationships with environmental variables



though the predicted presence of tsetse flies in an area cannot be regarded as a highly accurate indicator of trypanosomiasis challenge, the approach used here is arguably the only viable way to estimate consistently the number of cattle at risk of trypanosomiasis in sub-Saharan Africa. In the present analysis, cattle at risk of trypanosomiasis are considered to be those who live in areas where tsetse flies are predicted to be present. The probability threshold of 50 percent is applied to discriminate areas that are suitable for tsetse from those that are unsuitable, on the basis of the tsetse distributions of the PAAT-IS. The outcomes of this analysis are presented in Table 1.

By using the same input datasets, it is also possible to estimate the proportion of the total cattle at risk challenged by each tsetse fly species (Cecchi and Mattioli, in press).

HUMAN POPULATION

Given the wide variation in the time between and periodicity of national human population censuses, no consistent global database of subnational census data can be identified. The production of raster population distribution or density databases probably represents the most analytically robust approach to producing consistent international or global datasets (Dooley, 2005). The two most relevant raster population distribution or density databases

TABLE 1
Cattle population in tsetse-infested areas (country summary)

Country	Head of cattle in tsetse-infested areas	[%]
United Republic of Tanzania	11 472 000	20.5
Nigeria	6 233 000	11.1
Ethiopia	4 669 000	8.4
Kenya	3 578 000	6.4
Sudan	3 052 000	5.5
Central African Republic	2 984 000	5.3
Burkina Faso	2 858 000	5.1
Guinea	2 829 000	5.1
Cameroon	2 626 000	4.7
Mali	2 438 000	4.4
Uganda	2 310 000	4.1
Benin	1 461 000	2.6
Côte d'Ivoire	1 405 000	2.5
Ghana	1 263 000	2.3
Senegal	1 181 000	2.1
Democratic Republic of the Congo	734 000	1.3
Zambia	592 000	1.1
Somalia	574 000	1.0
Mozambique	553 000	1.0
Others	3 100 000	5.5
TOTAL	55 912 000	100.0

produced to date are the Gridded Population of the World (GPW)/Global Rural–Urban Mapping Project (GRUMP) and the LandScan database.

Gridded Population of the World

The GPW is produced by the Columbia University Center for International Earth Science Information Network (CIESIN) in collaboration with Centro Internacional de Agricultura Tropical (CIAT).

The GPW, now in its third version (GPWv3), consists of estimates of human population in five-year steps from 1990 to 2015 (Balk and Yetman, 2004). The GPWv3 effort utilizes what is most commonly known as a "proportional allocation" or "areal weighting" approach to distribute the population to a grid based on administrative polygons. The number of administrative units used as inputs for the GPW process is constantly improving; for the GPWv3, more than 350 000 polygonal input units were used to construct the grid. A 2.5 minute latitude/longitude cell size is used for the standard GPW global, continental and country-level products (equating to a nominal pixel size of 4.6 km).

Compared with LandScan (see below), GPW uses a much simpler and perhaps more transparent methodology and a higher number of polygonal input units. However, the proportional allocation used by GPW works on the assumption that the population is distributed evenly over the administrative unit; therefore, no attempt is made to account for such important determinants of population distribution as land cover, terrain slope and road networks.

Access to data

The main data products (available at global, continental and country level) are the raw population counts ("Population grid") and the population density per km^2 ("Population density grid")[7]. The raster data are available in a number of formats including American Standard Code for Information Interchange (ASCII), Band Interleaved by Line (BIL), or ESRI's compressed .E00 format for grids.

Global Rural–Urban Mapping Project

The CIESIN has also modelled population based on its urban extent database and GPWv3 inputs into a 30 arc second grid (about 1 km resolution), for its GRUMP population effort. Like GPWv3, GRUMP uses the best or lowest-order population input data available as well as an urban–rural mask. As for GPWv3, population counts and density grids are available, both with and without a United Nations adjustment factor.

Access to data

The GRUMP data products at global and continental levels are available as an alpha release of version 1. The reference years are 1990, 1995 and 2000. In addition to the raw population counts ("Population grid") and the population density per km^2 ("Population density grid"), an "Urban extents grid" allows splitting of the rural and

[7] http://sedac.ciesin.columbia.edu/gpw/global.jsp

urban population. The raster data are available in a number of formats including ASCII, BIL, or ESRI's compressed .E00 format for grids.

LandScan population databases

The LandScan dataset (Dobson *et al.*, 2000; Budhendra *et al.*, 2002) comprises a worldwide population database compiled on a 30 arc second latitude/longitude grid (Figure 2). Census counts (at subnational level) are apportioned to each grid cell on the basis of likelihood coefficients — which are based on proximity to roads, slope, land cover, night-time lights and other information. LandScan has been developed as part of the Oak Ridge National Laboratory (ORNL) Global Population Project for estimating ambient populations at risk. LandScan provides estimates of population counts (no population density product is available); datasets are released annually, with each new release superseding the previous one.

Access to data

After registration and authorization from the provider, the LandScan dataset files are available from the Internet[8] in ESRI grid format by continent and for the world as well as in ESRI raster binary format for the world. The latest version of the product is LandScan 2007.

Applications of human population datasets within T&T interventions

Among the numerous applications one can make of the human population maps are the estimation of the number of people at risk of a disease (Hay *et al.*, 2005) and the identification of areas that are unsuitable for tsetse flies because of the heavy impact that dense human populations have on the natural vegetation that most of the tsetse fly species rely on.

LAND COVER

GlobCover Land Cover

GlobCover is an initiative led by the European Space Agency (ESA) for the production of a land cover map of the world at 300 m resolution. The GlobCover Land Cover product is derived from an automatic and regionally tuned classification of a time series of images acquired by the Medium Resolution Imaging Spectrometer (MERIS) sensor, which is on board the Envisat satellite mission. The time series covers the period December 2004–June 2006. The GlobCover Land Cover v2.2 product (available in the public domain as of 8 December 2008) discriminates the world ecosystems into 22 classes validated by independent experts. A regional product discriminating 46 classes is also available for Africa. The map is compatible with the Land Cover Classification System (LCCS). The LCCS was developed by the United Nations Environment Programme (UNEP) and FAO and is on its way to becoming a standard of the International Organization for Standardization (ISO).

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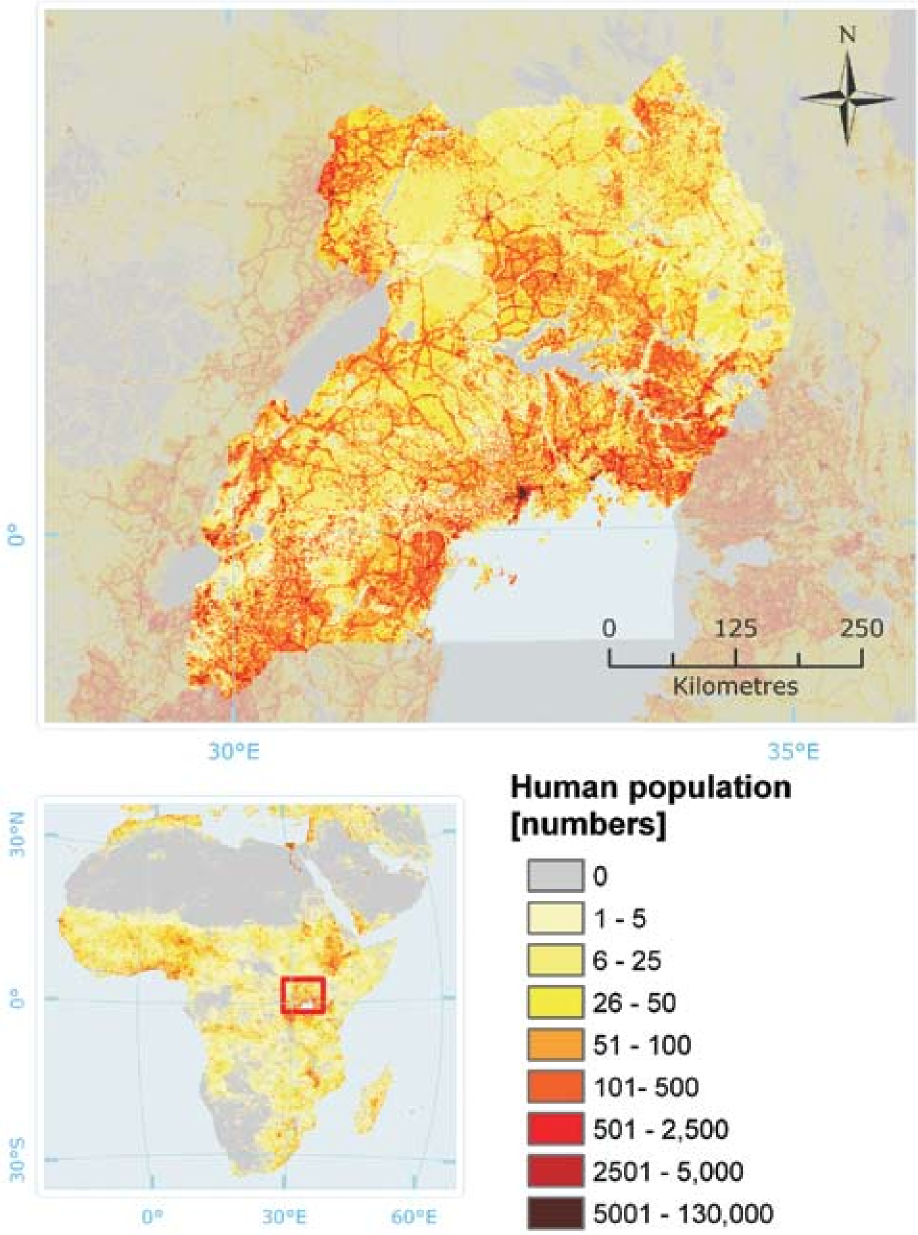
[8] http://www.ornl.gov/sci/landscan/

FIGURE 2
Population distribution in Uganda (LandScan 2007)



Access to data

The GlobCover Land Cover map and other GlobCover products can be downloaded from the ESA Ionia GlobCover Portal[9].

Global Land Cover 2000

The Global Land Cover database for the year 2000 (GLC2000) was produced by an international partnership of about 30 research groups coordinated by the European Commission's Joint Research Centre (JRC). The database contains regional land cover maps with detailed, regionally relevant legends and a global product that combines all regional classes into one consistent legend. The land cover maps are based on daily data acquired between 1 November 1999 and 31 December 2000 from the VEGETATION sensor on board the fourth Satellite Pour l'Observation de la Terre (SPOT) satellite, SPOT4. As with the GlobCover Land Cover map, GLC2000 utilizes the LCCS. One of the regional GLC2000 products covers Africa (Mayaux *et al.*, 2003; Mayaux *et al.*, 2004).

Access to data

All GLC2000 products are available for download from the GLC2000 Web site[10].

Africover

Unlike the vast majority of the geographical datasets discussed in this review, which are global in coverage, Africover deals with regional and national land cover mapping initiatives. Nonetheless, the relevance of the resulting products for T&T management requires that full attention be paid to them.

The purpose of the FAO Africover project was to establish a digital georeferenced database on land cover. The first operational component, the eastern Africa module, generated standardized land cover maps for ten countries[11]. From a methodological standpoint, Africover has promoted the development of the LCCS (Di Gregorio, 2005). It has also given impetus to the Global Land Cover Network[12] (GLCN), a global alliance for the production of standardized, multipurpose land cover data worldwide.

Access to data

The most detailed land cover products generated by the Africover project are the "Full resolution multipurpose land cover databases". The maps are on a scale of 1:200 000 or 1:100 000 for large or small countries, respectively. The FAO Africover Web site[13] distributes public domain, spatially aggregated versions of the full resolution land cover datasets. Three predefined thematic aggregations (agriculture, grassland, woody) are available, all based on the original "Full resolution multipurpose databases". The thematic content of each spatially aggregated dataset is very similar to that of the

[9] http://ionia1.esrin.esa.int/

[10] http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php

[11] Burundi, Democratic Republic of the Congo, Egypt, Eritrea, Kenya, Rwanda, Somalia, Sudan, Uganda and United Republic of Tanzania.

[12] www.glcn.org

[13] www.africover.org

original dataset; specifically, the aggregation is performed at a spatial level, setting a threshold under which the polygons are dissolved into adjacent polygons.

Public domain, aggregated products relating to the eight Africover countries affected by tsetse fly are available though FAO GeoNetwork (Cecchi and Mattioli, 2007). The thematic aggregation, tailored to tsetse habitat mapping, was performed by PAAT to support T&T decision-making (Cecchi *et al.*, 2008a).

Applications of land cover datasets within T&T interventions

An analysis of land cover classification in the context of tsetse habitat mapping is available in "Land cover and tsetse fly distributions in sub-Saharan Africa" (Cecchi *et al.*, 2008b). However, the potential fields of application of land cover maps are much broader, including monitoring of the environmental impacts of intervention strategies and land-use planning in reclaimed areas for sustainable management of natural resources.

SURFACE HYDROLOGY AND WETLANDS

In this section we present the most significant GIS datasets of water-related physical features that are available in the public domain. Even though there is a considerable degree of overlap, the datasets described herein can be meaningfully grouped into three categories: (i) surface water bodies, (ii) rivers and surface drainage and (iii) wetlands.

A comprehensive collection of the available GIS datasets of surface water bodies and wetlands in Africa can be found in the "African Water Resource Database" (Jenness *et al*., 2007), published by the FAO Fisheries and Aquaculture Department, Aquaculture Management and Conservation Service.

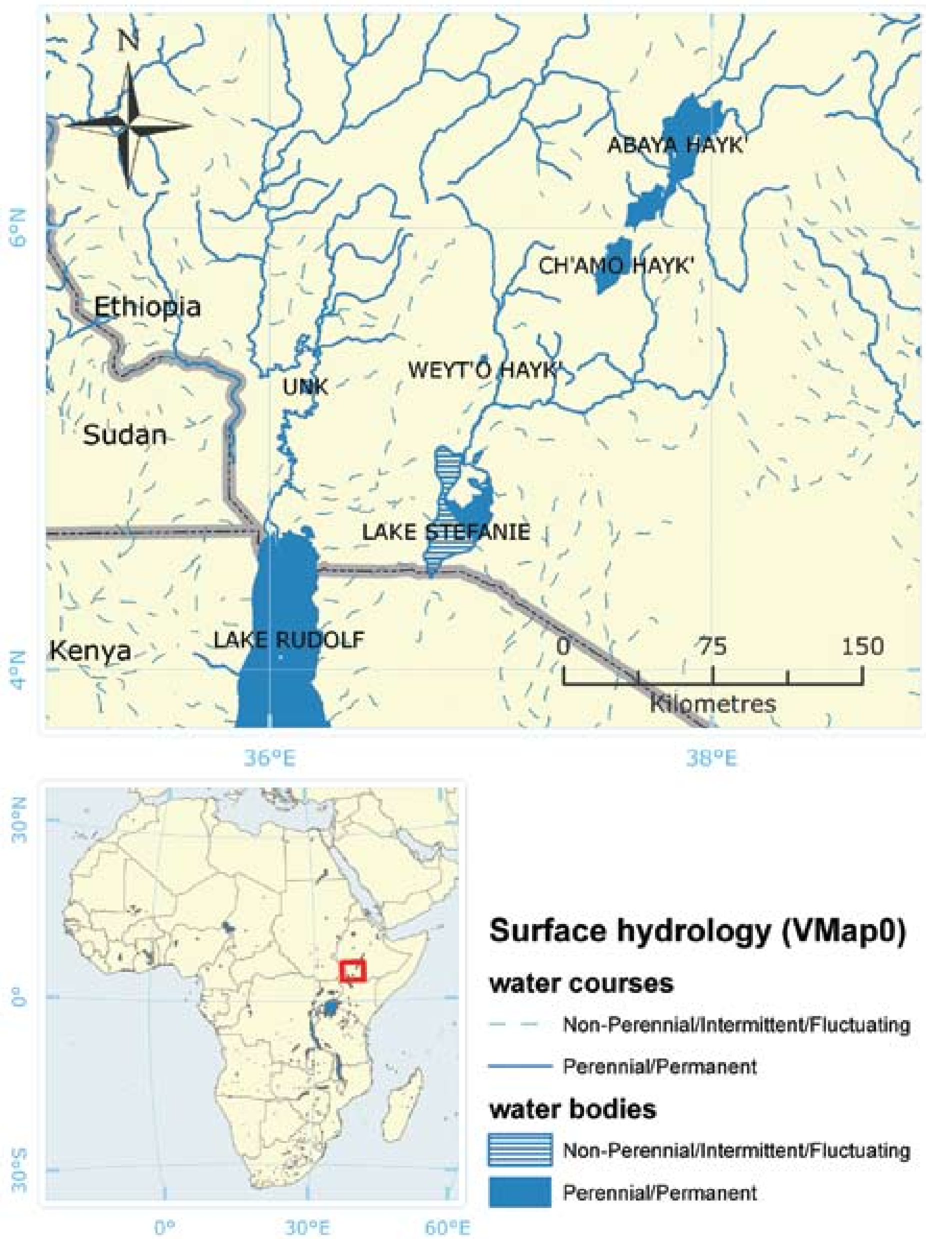
Surface water bodies: VMap0 inland water areas

The Vector Map Level 0 (VMap0) database represents the fifth edition of the Digital Chart of the World (DCW)[14] At a scale of 1:1 M, VMap0 is the largest scale source for surface water bodies at a global level (Figure 3). With regard to Africa, 2 654 out of 24 389 features are named. The hydrological regime is classified as either "perennial/permanent" or "non-perennial/intermittent/fluctuating". The horizontal accuracy of the DCW — and, by extension, that of VMap0 — is 2 040 m at 90 percent circular error.

The VMap0 datasets are based on the Vector Product Format (VPF), the chief limitation of which is the tile structure that segments the features contained in the individual VMap0 data layers. As a result, both analytical and query-based thematic style base mapping often require the further processing of VMap0 data into a more seamless format.

[14] The product is dual named to show its lineage to the original DCW, published in 1992, while positioning the revised product within a broader family of VMap products. VMap0 is a comprehensive 1:1 000 000 scale vector base map of the world. The primary source for the database is the Operational Navigation Chart (ONC) series of the National Imagery and Mapping Agency (NIMA). This is the largest scale unclassified map series in existence that provides consistent, continuous global coverage of essential base-map features (Dooley, 2005).

FIGURE 3
VMap0 Ed.5 inland water areas and watercourses in an area of the Southern Rift Valley in Ethiopia



The “inland water areas” layer is complementary to the “watercourses” layer (see page 15), which is available within the same Vmap0 Ed.5 topical data index “hydrography”. The main limitation of VMap0 (and the DCW) is the lack of overall connectivity between linear features representing rivers and the water bodies data features of the library. However, the lack of connectivity that affects linear features in VMap0 does not represent a major drawback in most studies dealing with tsetse habitat and ecology or with T&T interventions.

Access to data

VMap0 datasets are available in the public domain on the Internet[15]. The VMap0 tiles (four tiles cover the globe) are downloadable as compressed files of about 200 megabytes each. The DCW is also available on the Web[16]. The DCW server allows the download of national subsets — thus providing faster, if less up to date, downloads.

Applications within T&T interventions

Availability of water influences a number of factors that shape the risk of trypanosomiasis, the most important of which is arguably the suitability of the habitat for tsetse fly (especially those of the riverine group), as well as the presence of wild and domestic hosts and human populations. VMap0, which contains a number of named features, is especially useful for the preparation of base maps. It is also useful whenever there is a need to depict the most relevant hydrological elements. However, better spatial delineation of water bodies and drainage networks is now provided by SRTM Water Body Data (see below) and HydroSHEDS (see page 17), respectively.

Surface water bodies: SRTM Water Body Data

The Shuttle Radar Topography Mission (SRTM) provides the most detailed, near-global digital elevation model (DEM) available in the public domain[17] (see page 20).

The SRTM Water Body Data (SWBD) files are a by-product of the data editing performed by the United States National Geospatial-Intelligence Agency (NGA) to produce the finished SRTM Digital Terrain Elevation Data Level 2 (DTED2) data. Ocean, lake and river shorelines were identified and delineated from the 1 arc second (~30 m) DTED2 data (NASA, 2003; NASA/NGA, 2003). The principle guiding the development of SWBD was that water would be depicted as it was in February 2000, the month of the shuttle flight during which the data for the SRTM-DEM were collected. In most cases, two orthorectified SRTM image mosaics were used as the primary source for water body editing. A land cover water layer and medium-scale maps and charts were also used as supplemental data sources (the land cover water layer was derived mostly from Landsat 5 data collected a decade earlier).

The data were subsequently processed by FAO for the African Water Resource Database (AWRD) to provide a seamless and robust derivative. The data layer covers

15 www.mapability.com/info/vmap0_download.html and http://geoengine.nga.mil/

16 http://www.maproom.psu.edu/dcw/

17 http://www2.jpl.nasa.gov/srtm/

Africa and the Arabian Peninsula, and it comprises 38 840 vector surface features of water bodies based on 1:100 000 data. The layer provides nominal analytical/mapping at 1:125 000. The spatial detail of SWBD can be appreciated in Figure 4. It may be interesting to mention that the smallest elements in SWBD have an area of approximately 800 m^2.

Access to data

SWBD can be downloaded from FAO GeoNetwork.

Applications within T&T interventions

In consideration of the unparalleled spatial detail of SWBD, its use can be contemplated in all cases where high-resolution data offer concrete advantages, especially in the planning and implementation of field activities.

Surface water bodies: satellite derivative datasets

Relevant information on surface water bodies can also be derived from satellite-based land cover maps (see page 9). At the global level, the GlobCover Land Cover and GLC2000 products provide land cover datasets that include water bodies as one of the classes. At the regional level, the Africover maps provide for ten East African countries an accurate description of aquatic or regularly flooded areas on a scale of 1:100 000/1:200 000.

Rivers: VMap0 watercourses

As for the surface water bodies discussed on page 12, VMap0 provides the largest scale source for rivers at global level. With regard to Africa, 17 040 out of 146 000 features are named. The hydrological regime is classified as either "perennial/permanent" or "non-perennial/intermittent/fluctuating". The names assigned to the VMap0 Ed.5 linear river features were based on map annotations captured from the Operational Navigation Charts (ONC) (see footnote 14 on page 12) and the gazetteer contained in the GEOnet Names Server (see page 34).

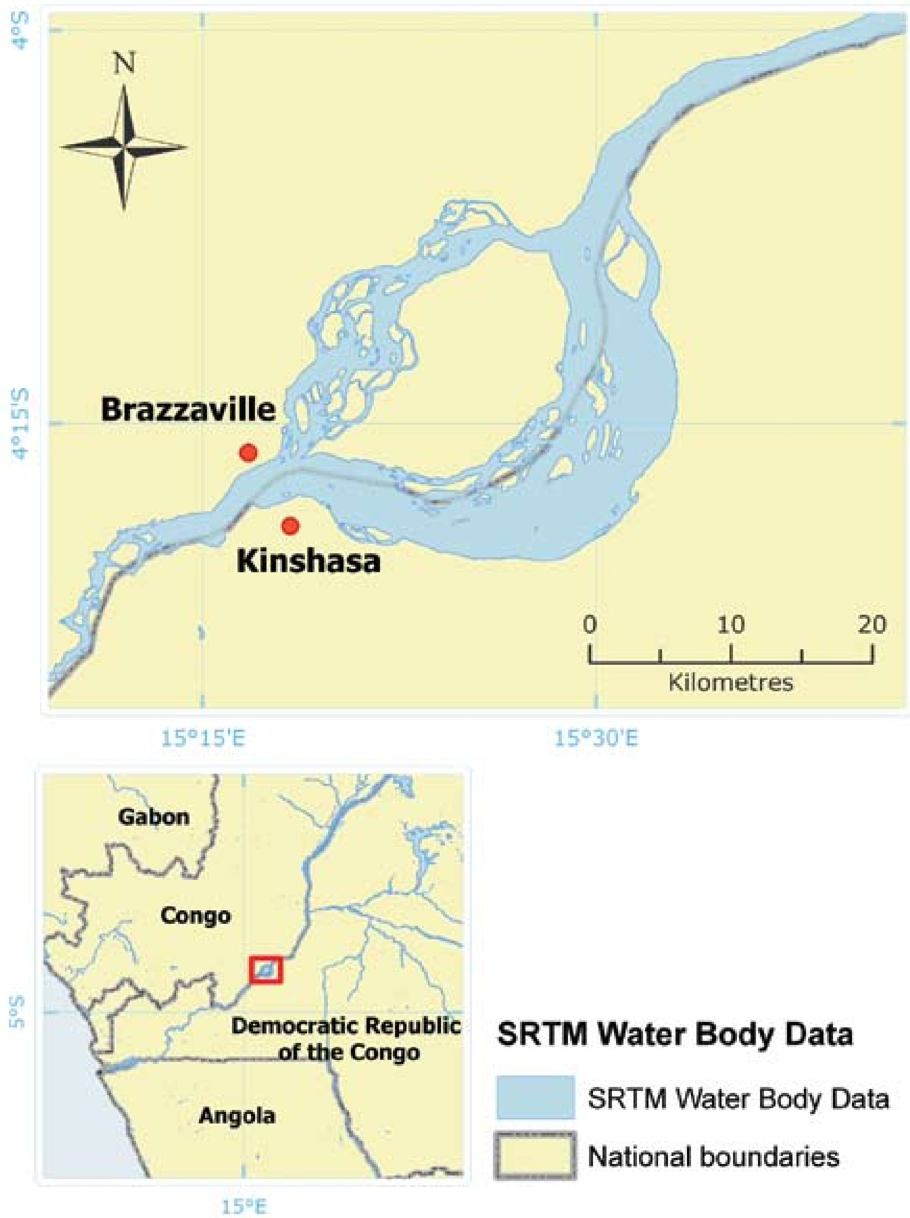
Access to data

Because this is part of the VMap0 data package, watercourses can be downloaded from the same Web sites as the "inland water areas" (see footnote 15 on page 14).

Applications within T&T interventions

The importance of rivers and riparian vegetation in the ecology of tsetse flies, in particular those of the *palpalis* group, is well known. It may be interesting to mention here that VMap0, as opposed to the higher resolution HydroSHEDS drainage network described below, derives directly from digitization of cartographic products and that the hydrological regime (either perennial or intermittent) ultimately stems from direct, if dated, surveys. VMap0 is good at providing a synoptic picture of hydrological features at the regional and global levels; however, for several applications, especially at the local level, it is probably going to be superseded by HydroSHEDS products.

FIGURE 4
SRTM Water Body Data: Congo River near Kinshasa and Brazzaville



Surface drainage: HydroSHEDS

"Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales" (HydroSHEDS)[18] is a set of mapping products that provide hydrographic information for local, regional and global scale applications in a consistent format (Figure 5). It offers a suite of georeferenced datasets (vector and raster) at various scales — including river networks, watershed boundaries, drainage directions and flow accumulations.

HydroSHEDS is based on high-resolution elevation data obtained during a space shuttle flight for the SRTM, operated by the United States National Aeronautics and Space Administration (NASA) (see page 20). HydroSHEDS is currently generating key data layers to support regional and global watershed analyses, hydrological modelling and freshwater conservation planning at a quality, resolution and extent that has previously been unachievable. Available resolutions range from 3 arc seconds (approximately 90 m at the equator) to 5 minutes (approximately 10 km at the equator) with seamless near-global extent. Data for Africa were released in October 2007.

Generally, HydroSHEDS shows significantly greater accuracy than existing global hydrological datasets, and it provides the most detailed global inputs for hydrological GIS applications. However, it does not reach the accuracy of existing high-resolution maps depicting local river networks or remote sensing images that may be available or could be generated on a local basis.

HydroSHEDS drainage network

The HydroSHEDS drainage network (also called river network) is arguably the most important of the HydroSHEDS products for T&T applications. It is a ready-to-use river network derived from 15 arc second (~460 m) drainage direction layers.

For this product, which is delineated from DEMs, only rivers with upstream drainage areas exceeding a threshold of 100 cells are selected. Importantly, however, simple GIS functions allow the derivation of a more detailed drainage network from the 3 arc second drainage direction layer described below.

HydroSHEDS drainage directions

The drainage direction maps distributed with HydroSHEDS define the direction of flow from each cell to its steepest down-slope neighbour. These maps are available at 3 and 15 arc seconds. Derivative products can be generated from the drainage direction maps to show flow accumulations, flow distances, drainage networks and watershed boundaries. Derivatives of the 15 arc second drainage direction map are available for download from the HydroSHEDS Web site (see "Access to data" below); derivatives of the 3 arc second map have to be generated by end users.

Access to data

The whole range of HydroSHEDS products is available from the United States Geological Survey (USGS) HydroSHEDS Web site[19]. The data at the highest

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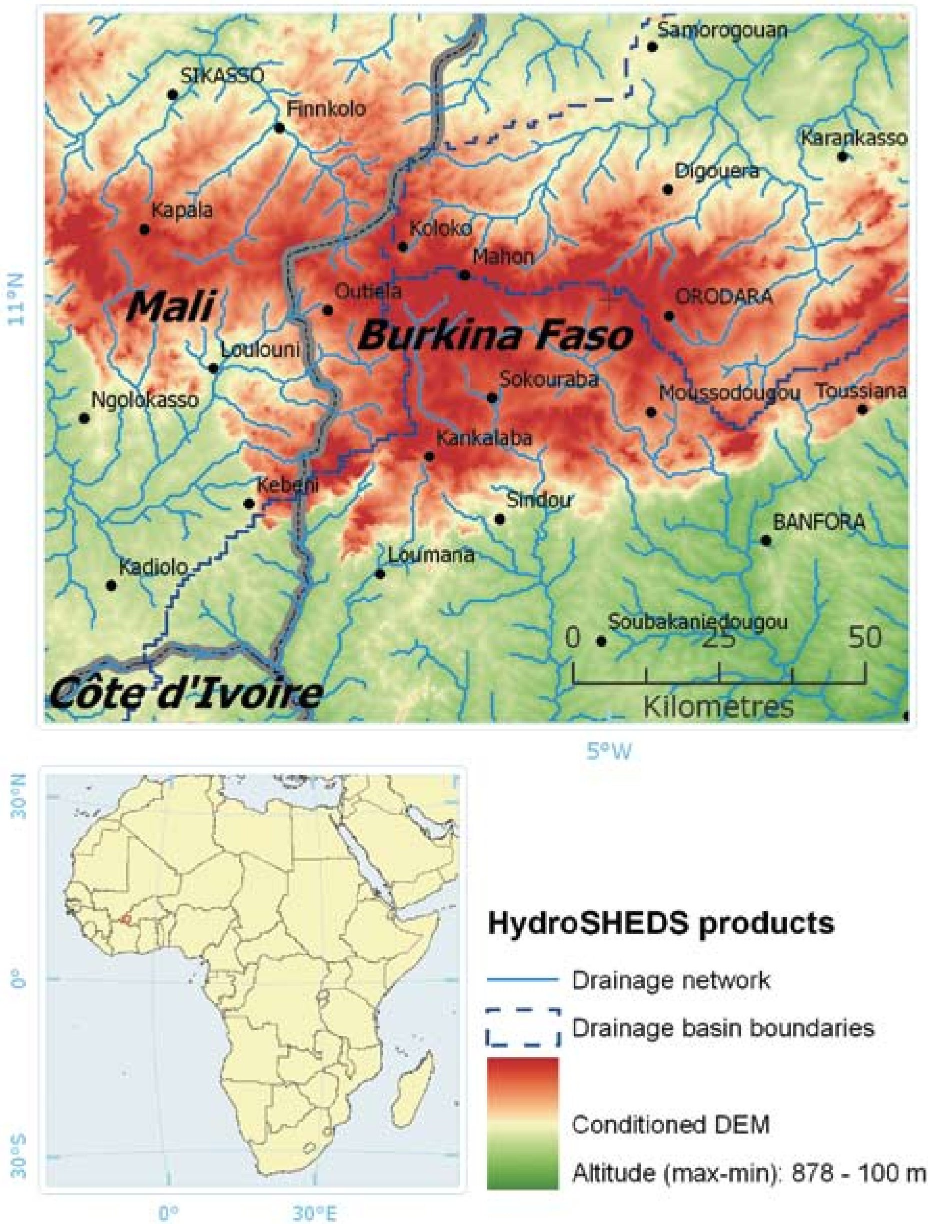
[18] http://www.worldwildlife.org/science/projects/freshwater/item1991.html

[19] http://hydrosheds.cr.usgs.gov/

FIGURE 5
Drainage network, drainage basin boundaries and conditioned DEM at the border between Mali and Burkina Faso (HydroSHEDS)



resolution (3 arc seconds) are available as tiles (5 arc minutes by 5 arc minutes), while the rest of the products are available as seamless mosaics that cover the whole African continent.

Applications within T&T interventions

HydroSHEDS provides a range of products that allow delineation of the drainage network at a resolution that was previously achievable only through digitization of high-resolution maps or satellite imagery. It is important to stress that the concept of a drainage network does not coincide exactly with that of a river network because a drainage network depicts flow-routing pathways rather than the actual presence of water. Obviously, rainfall patterns determine which parts of a drainage network represent temporary or permanent watercourses. Nevertheless, a map of a drainage network can be as useful as a map of permanent watercourses in mapping tsetse habitat because the former depicts areas that do not maintain permanent water yet may sustain vegetation communities favourable to tsetse fly.

HydroSHEDS drainage basin boundaries and watersheds can also be used to identify potential dividing lines between tsetse populations.

Global Lakes and Wetlands Database

The Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004) was created by drawing upon a variety of existing maps, data and information for lakes and wetlands on a global scale (1:1 M to 1:3 M). The database focuses at three coordinated levels on (i) large lakes and reservoirs, (ii) smaller water bodies and (iii) wetlands. The World Conservation Monitoring Centre (WCMC) Wetlands of Africa (see below), the DCW and many other data sources were used.

Because it is up to date, and because of its completeness and scale, GLWD is arguably the best dataset for lakes and wetlands currently available at the global level.

Access to data

GLWD is available for download as three separate layers (two ESRI polygon shapefiles and one ESRI grid)[20]. It is available for non-commercial scientific, conservation and educational purposes.

World Conservation Monitoring Centre Wetlands of Africa

This consolidated coverage of African wetlands was produced for the AWRD from country separates of the World Resources Institute (WRI) African Data Sampler, based on 1:1 M data originally obtained from the WCMC. It comprises 4 404 vector features of wetlands drawn onto ONC charts at 1:1 M by R.H. Hughes and directly related to “A Directory of African Wetlands” (Hughes and Hughes, 1992). More complete information at a national level can be extracted from the AFDS[21].

20 http://www.worldwildlife.org/science/data/item1877.html
21 http://gcmd.nasa.gov/records/GCMD_ADS_WRI.html

Access to data
The consolidated WCMC Wetlands of Africa data can be downloaded from FAO GeoNetwork.

Applications within T&T interventions
This dataset can be considered to be the best reference for wetlands in Africa. Even though it is largely based on the DCW, it may be better equipped to support environmental studies because the cartographic information from the DCW has been reinterpreted from an ecological perspective.

ELEVATION DATABASES

A digital elevation model (DEM) is a topographic surface arranged as a set of regularly spaced x, y, z coordinates where z represents elevation (Figure 6).

Shuttle Radar Topography Mission

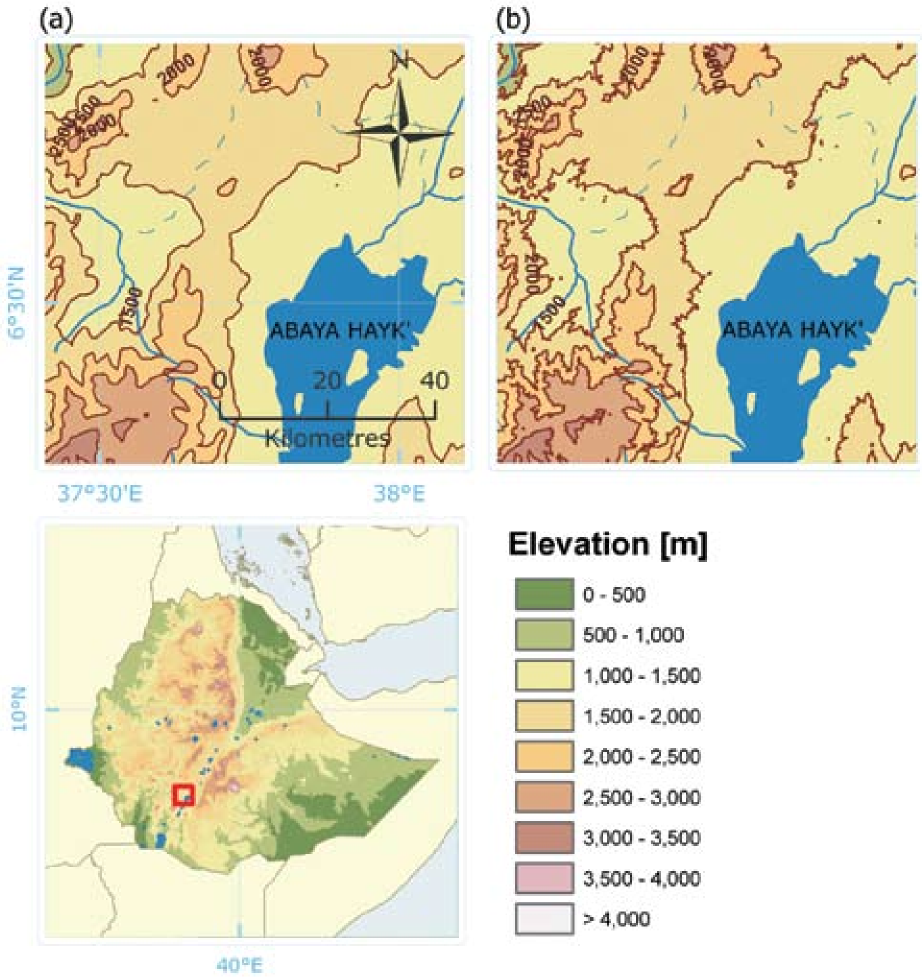
The Shuttle Radar Topography Mission (SRTM) is a joint project between NASA and NGA to map the earth's land surface in three dimensions. It provides the most detailed, near-global products available in the public domain. The SRTM digital elevation data provide a major advance in the accessibility of high-quality elevation data for large portions of the tropics and other areas of the developing world.

The SRTM collected data for over 80 percent of the earth's land surface – that is, for most of the area between latitudes 60° N and 56° S. Worldwide data available to the geospatial data user community include a 3 arc second (~90 m) DEM. The vertical accuracy in the SRTM data is stated to be ±16 m at a 90 percent confidence level. The elevation data are measured with respect to the reflective surface — which may be vegetation, human-made features or bare earth. With regard to water bodies, the ocean elevation is set to 0 m, lakes of 600 m or more in length are flattened and set to a constant height and rivers that exceed 183 m in width are delineated and monotonically stepped down in height.

Access to data
The SRTM datasets are available at different levels of processing from a variety of sources, including the United States Geological Survey (USGS)[22] and the Global Land Cover Facility (GLCF)[23]. The Consultative Group on International Agricultural Research – Consortium for Spatial Information (CGIAR/CSI) disseminates what is arguably the most robust version of the SRTM datasets[24]. The DEM is provided in 5 degree by 5 degree tiles for easy download and use, and all tiles are produced from a seamless dataset to allow easy mosaicking. (Tiles are available in both ArcInfo ASCII and GeoTIFF formats.)

22 http://eros.usgs.gov/products/elevation/
23 http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp
24 http://srtm.csi.cgiar.org/

FIGURE 6
Coloured DEMs and derived contour lines for the area north of Lake Abaya in the Southern Rift Valley (Ethiopia). (a) GTopo30 (30 arc seconds or ~1 km), upgraded with SRTM data (SRTM30), (b) SRTM (3 arc seconds or ~90 m)



Global Topographic 30 arc second DEM database

The Global Topographic 30 arc second DEM database (GTopo30) is a global DEM with a horizontal grid spacing of approximately 1 km; it was derived from several raster and vector sources of topographic information. GTopo30, completed in late 1996, was developed through a collaborative effort led by the USGS Center for Earth Resources Observation and Science (EROS).

For most applications, the detailed and accurate products from SRTM have replaced GTopo30; nevertheless, for certain applications, the high resolution of SRTM may not be necessary, and thus GTopo30 can still prove useful. An updated version of the GTopo30 has been released recently, which uses SRTM data (when possible) in place of the original data (SRTM30).

Access to data

The two main online sources of GTopo30 datasets are USGS[25] and GLCF[26]. The upgraded version of GTopo30 that made use of SRTM data (SRTM30) is also available online[27].

Applications of elevation datasets within T&T interventions

The most obvious application of DEMs concerns the identification of altitudinal limits of tsetse distribution, but DEMs can also assist in the selection of the most appropriate techniques for suppression and elimination of tsetse. Rough terrain — as measured, for example, by DEM-derived slope maps — can pinpoint areas that are unsuitable for either air-assisted sequential aerosol technique (SAT) or field trapping because of accessibility constraints.

CLIMATE

Climatic Research Unit

The Climatic Research Unit (CRU) of the University of East Anglia is arguably the most relevant source of integrated climatological databases. The CRU provides various editions of global gridded datasets relating to climate, time-series and global climate change scenarios. Data resolution ranges from 0.5 degrees (~55 km) to 10 arc minutes (~18.5 km), and the variables available are cloud cover, diurnal temperature range, frost day frequency, precipitation, relative humidity, sunshine duration, daily mean temperature, monthly average daily minimum and maximum temperature (Figure 7a), vapour pressure, wet day frequency and wind speed.

The CRU works closely on a global basis with a number of other institutions and is a primary partner in the Intergovernmental Panel on Climate Change (IPCC), which is jointly coordinated by the World Meteorological Organization and UNEP. More specifically, the CRU is a primary partner of the IPCC Data Distribution Centre.

Access to data

High-resolution gridded data archives can be downloaded from the CRU Web site[28].

WorldClim

WorldClim (Hijmans *et al.*, 2005) is a set of very high resolution (30 arc seconds or ~1 km) global climate layers. The climate elements considered are monthly precipitation as well as mean, minimum and maximum temperatures (Figure 7b). Whenever possible, the input data for interpolation were restricted to records from the 1950–2000 period.

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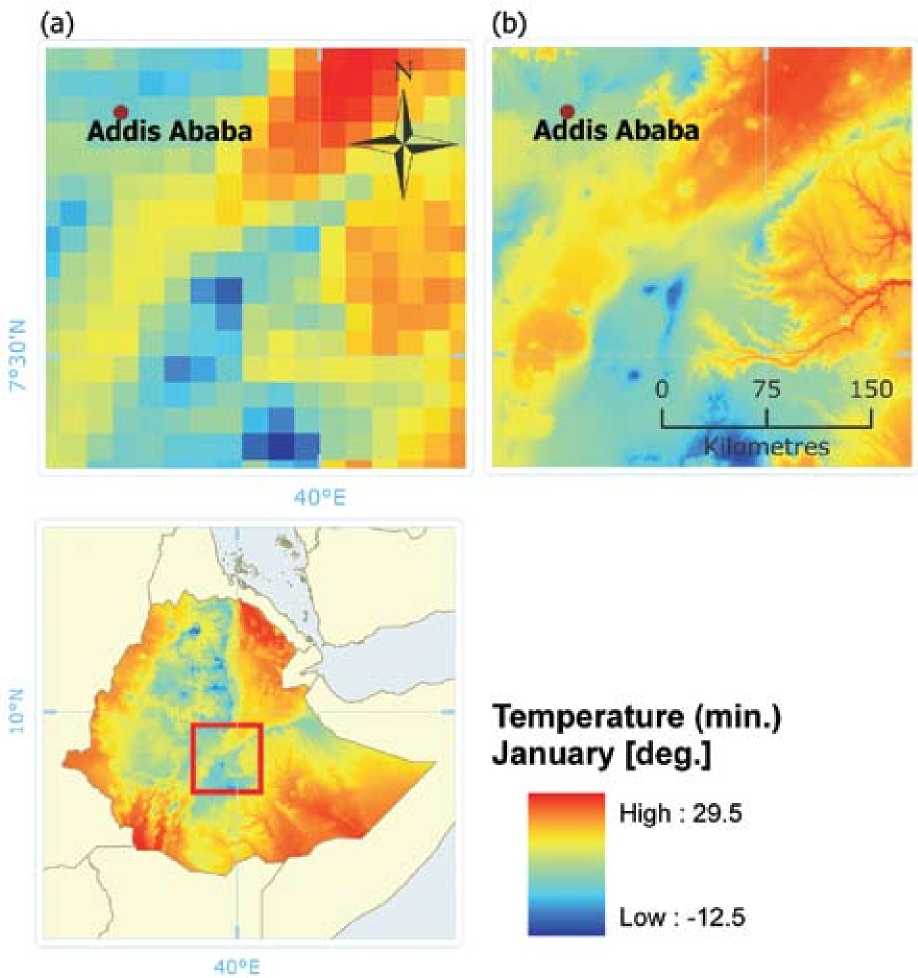
[25] http://edc.usgs.gov/products/elevation.html

[26] http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp

[27] http://www.dgadv.com/srtm30/

[28] www.cru.uea.ac.uk/cru/data/hrg.htm

FIGURE 7
Minimum average temperature during January in the area around Addis Ababa, as depicted by (a) CRU climate grids (10 arc minutes) and (b) WorldClim (30 arc seconds)



High-resolution climate surfaces capture environmental variability that can be partly lost at lower resolutions, particularly in mountainous regions and other areas with steep climate gradients.

Access to data
The data are available for download from the WorldClim Web site[29].

[29] http://www.worldclim.org/

FAO agroclimatic databases and mapping tools

The FAO Natural Resources Management and Environment Department provides the international user community with a set of tools to access and analyse global climatic datasets. For the purpose of this paper, the two most relevant tools are FAOClim and LocClim. The former disseminates climate datasets from thousands of stations worldwide; the latter allows performance of spatial interpolations of agroclimatic data aimed at estimating the value of agroclimatic parameters at a given site based on the observations at neighbouring locations.

FAOClim

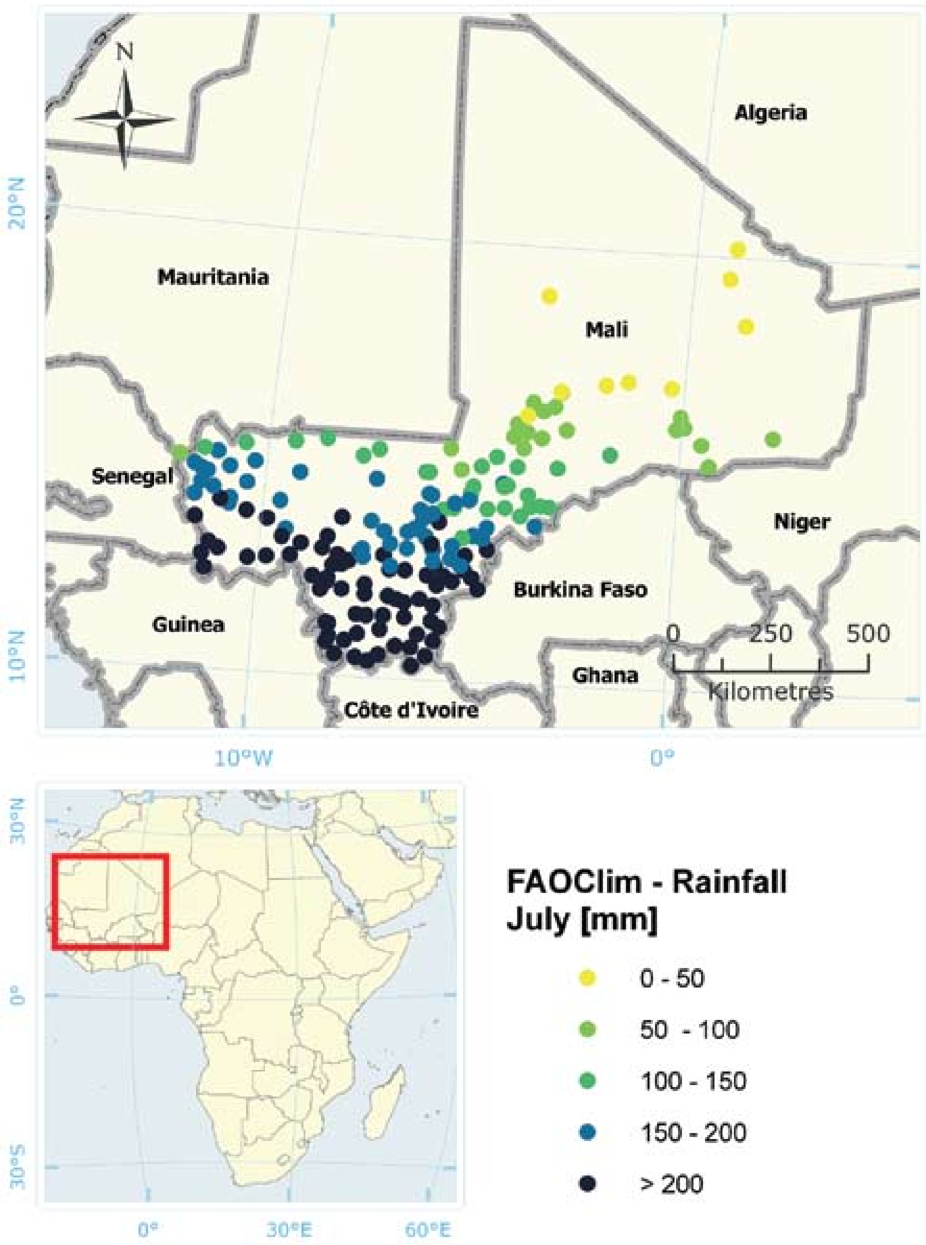
FAOClim is an FAO climate database that covers monthly data for 28 100 stations (over 6 000 in Africa alone) for up to 14 observed and computed agroclimatic parameters (Table 2 and Figure 8).

The database includes both long-term averages (normally from 1961 to 1990) and time series for rainfall and temperature. The data are accessed using two pieces of software: (i) FAOClim, which is used to select data by geographical area, time period and parameter and also to export data for processing by other software packages; and (ii) GeoContext, a program that allows visualisation of the information in map and graph form. The coordinates of the climatic stations allow users to analyse the climatic datasets of FAOClim in a GIS.

TABLE 2
Climate parameters available in the FAO climate database (FAOClim)

Category	Agroclimatic parameter	Units of measurement
Temperatures	Mean minimum temperature	degC
	Mean maximum temperature	degC
	Mean temperature	degC
	Mean night-time temperature	degC
	Mean daytime temperature	degC
Rainfall	Total rainfall	mm
Air moisture	Dew point temperature	degC
	Relative humidity	%
	Vapour pressure	hPa
Potential evapotranspiration	PET – (Penman–Monteith)	mm/month
Wind speed	Wind speed	m/s
Radiation	Global radiation (per day)	cal/cm^2/day and MJ/m^2/day
Sunshine	Sunshine fraction	0 to 1
	Sunshine hours	hours/day

FIGURE 8
Average monthly precipitation during July in Mali, as derived from FAOClim (the FAO climate database)



Access to data
The bulk of the FAOClim data is available on a CD-ROM[30], which also includes querying and mapping applications. The datasets can also be downloaded in tabular format from the Web through the interface FAOClim-NET[31].

LocClim
LocClim (an abbreviation of Local Climate) and its latest development, New_LocClim, are software tools designed to answer commonly asked questions about the climate in locations where no climate observation station exists (Figure 9). Using the stations of FAOClim (described above), New LocClim gives the user full control over the interpolation procedure and allows the user to create climatic maps, graphs and tabular outputs. New LocClim maps can be exported in GIS-compatible formats.

Access to data
New_LocClim can be downloaded from the FAO Web site[32].

Applications of climatic datasets within T&T interventions
Climatic data — especially relative humidity, temperature and rainfall — are used to estimate the suitability of a habitat for tsetse flies. Different studies have found strong correlations between climatic data (e.g. mean annual rainfall) and various parameters of tsetse ecology (e.g. fly density and tsetse daily mortality rates).

AGRO-ECOLOGICAL ZONES

The agro-ecological zones (AEZ) methodology for assessment of land productivity enables rational land management options to be formulated on the basis of an inventory of land resources and an evaluation of biophysical limitations and potentials. The AEZ methodology follows an environmental approach and provides a standardized framework for the characterization of resources relevant to agricultural production according to climate, soil and terrain conditions. It also identifies land utilization types (LUTs) — that is, selected agricultural production systems with defined input and management relationships, and crop-specific environmental requirements. This information forms the basis for a number of applications, such as quantification of land productivity, determination of the extent of land with potential for rain-fed or irrigated cultivation, estimation of the land's capacity to support human populations and multicriteria optimization of the use and development of land resources (FAO, 2002).

Climate, soil and terrain resources

The first resource described in the AEZ methodology is climate. The global climate dataset used was created by the CRU (see page 22). This database comprises a suite

30 http://www.fao.org/NR/climpag/pub/EN1102_en.asp
31 http://geonetwork3.fao.org/climpag/agroclimdb_en.php
32 http://www.fao.org/NR/climpag/pub/en3_051002_en.asp

FIGURE 9

Average monthly precipitation during July in an area of West Africa. The map is based on the FAOClim dataset, interpolated through the FAO New_LocClim software

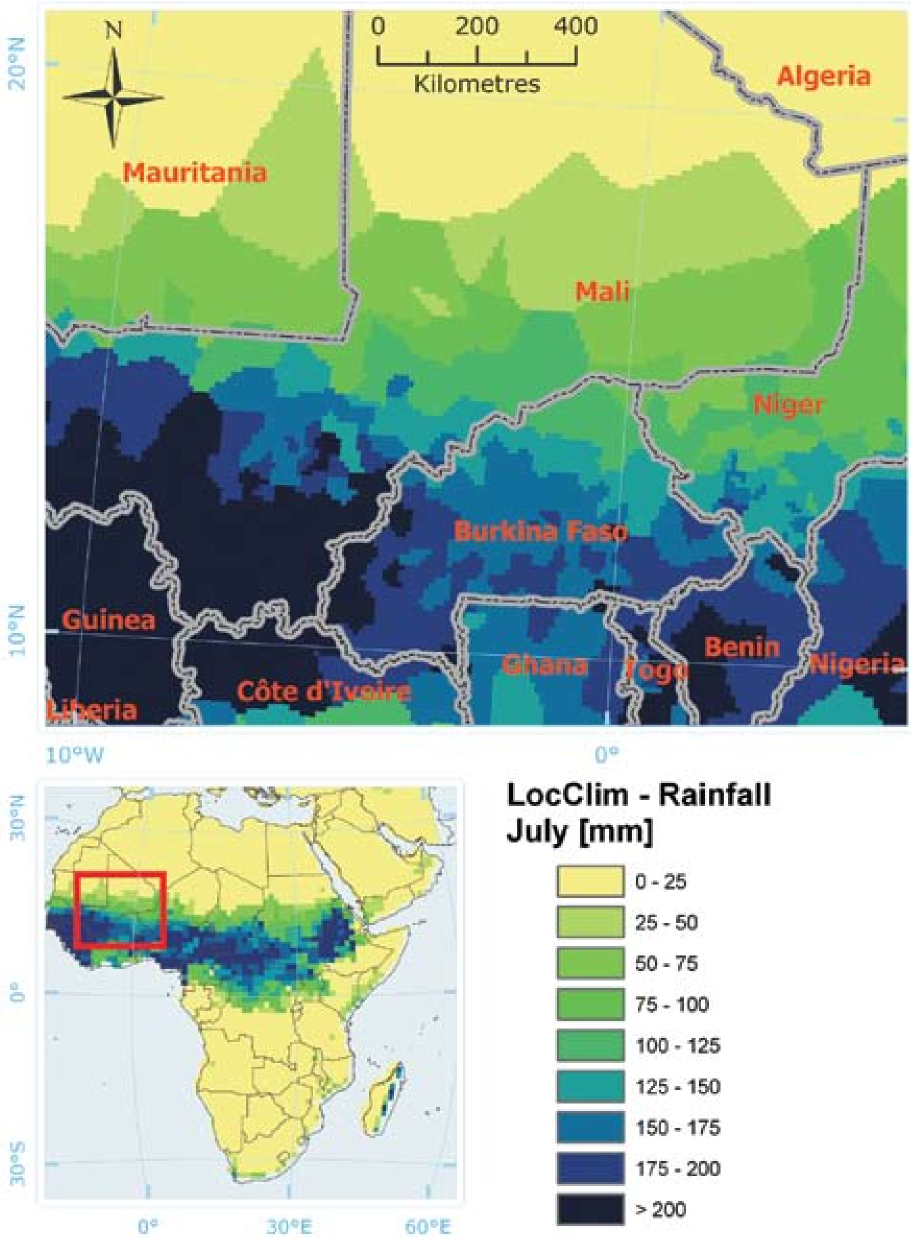


TABLE 3
Climatic variables used in the AEZ methodology to assess land productivity (data provided by the CRU)

Attributes in the CRU climate database
Precipitation
Wet days frequency
Mean temperature
Diurnal temperature range
Vapour pressure
Cloud cover
Sunshine
Ground-frost frequency
Wind speed
Mean monthly climate attributes

of nine climatic variables (Table 3) interpolated from observed station data to a 30 arc minute latitude/longitude grid. Year-by-year historical data, along with details of the 1961–1990 average climate, are available.

Climate data allow calculation of several parameters related to crop growth, development and yield formation. Particularly important is the concept of length of growing period (LGP). The LGP is defined as the number of days when both water availability and prevailing temperatures permit crop growth. Depending on its length, the LGP may allow for no crops or for only one crop per year (e.g. in arid or dry semi-arid tropics), or it may allow the growth of a sequence of crops within one year (e.g. in humid tropics or subtropics).

The second resource considered in the AEZ methodology is soil. The source of soil information used is primarily the digital version of the FAO/UNESCO Soil Map of the World (DSMW) (FAO, 1995). This provides classification of soils according to the FAO/UNESCO 1974 Legend (FAO/UNESCO, 1974). The map is at a scale of 1:5 M and presents soil associations in grid-cells of 5 arc minutes. The composition of soil associations is described in terms of the percentage occurrence of soil units, soil phases and textures. Therefore, each 5 arc minute grid-cell is considered to consist of several land units. Soil data allow calculation of constraints to crop production in relation to soil depth, fertility, drainage, texture and chemicals.

The land resources database is completed by the terrain slopes, which are derived from the GTopo30 database (see page 22). Rules based on altitude differences between neighbouring grid-cells were applied to compile a terrain-slope distribution database (for each 5 minute grid-cell of the FAO DSMW) in terms of seven average slope range classes.

Land utilization types and crop catalogue

In the AEZ methodology, the climate and land resources described in the previous section are combined with information on land utilization types to estimate crop production potential.

According to FAO (1984), "a land utilization type (LUT) consists of a set of technical specifications within a socioeconomic setting. As a minimum requirement, both the nature of the produce and the setting must be specified". Attributes that are specific to particular land utilization types include crop information such as cultivation practices, input requirements, crop calendars, utilization of main produce, crop residues and by-products. In the AEZ methodology, 154 crop, fodder and pasture LUTs are distinguished, each at three generically defined levels of inputs and management (high, intermediate and low).

Access to agro-ecological zones data

The AEZ datasets can be downloaded from the FAO Web site[33] and from the Web site of the International Institute for Applied Systems Analysis (IIASA)[34].

Applications of agro-ecological zones within T&T interventions

The AEZ assessment provides a comprehensive and spatially explicit database of agricultural production potential and related factors. The results that are most directly relevant to the planning of T&T intervention strategies are arguably the crop suitability analyses, which can be used to identify areas with a high potential for agricultural development (both for crop and livestock agriculture). The available crop suitability analyses comprise (i) rain-fed (Figure 10) and irrigated conditions, (ii) maximum attainable yields and long-term achievable yields and (iii) land with cultivation potential based on the consideration of all cereal and non-cereal food and fibre crops/LUTs.

ROADS

VMap0

VMap0 is the largest scale map of roads available in the public domain. Roads are stored in the "Transportation" folder of the VPF file already discussed in the section "Surface hydrology and wetlands" (see page 12). The "Transportation" folder also includes railways, trails, tracks and airports. The VMap0 roads in Burkina Faso are displayed in Figure 11.

Access to data

Being part of the VMap0 data package, VMap0 roads can be downloaded from the same Web sites as the "inland water areas" (see footnote 15 on page 14).

Commercial products

Two global commercial products arguably improve on VMap0 road maps: the ADC

[33] http://www.fao.org/ag/agl/agll/gaez/index.htm
[34] http://www.iiasa.ac.at/Research/LUC/SAEZ/index.html

FIGURE 10
Suitability for rain-fed crops, as estimated through the AEZ methodology

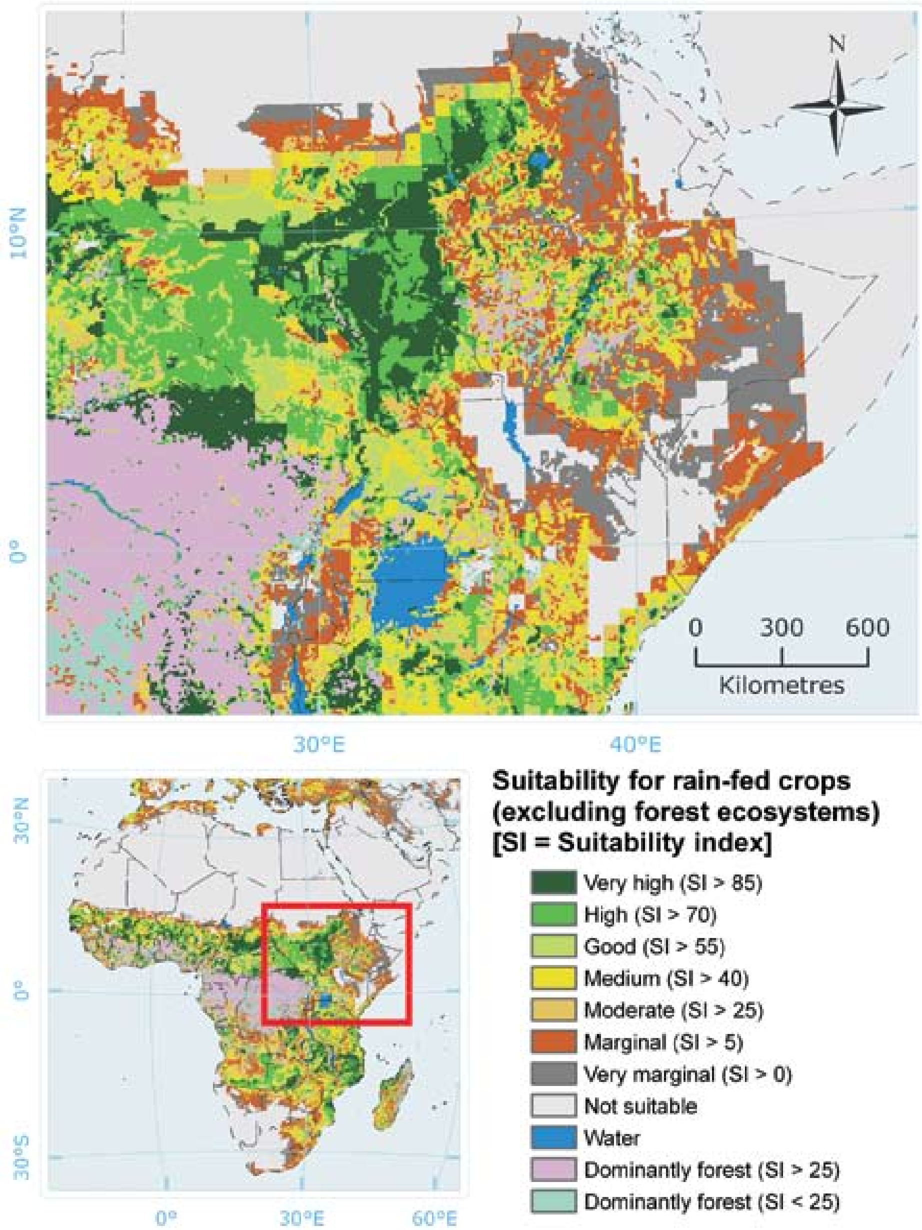
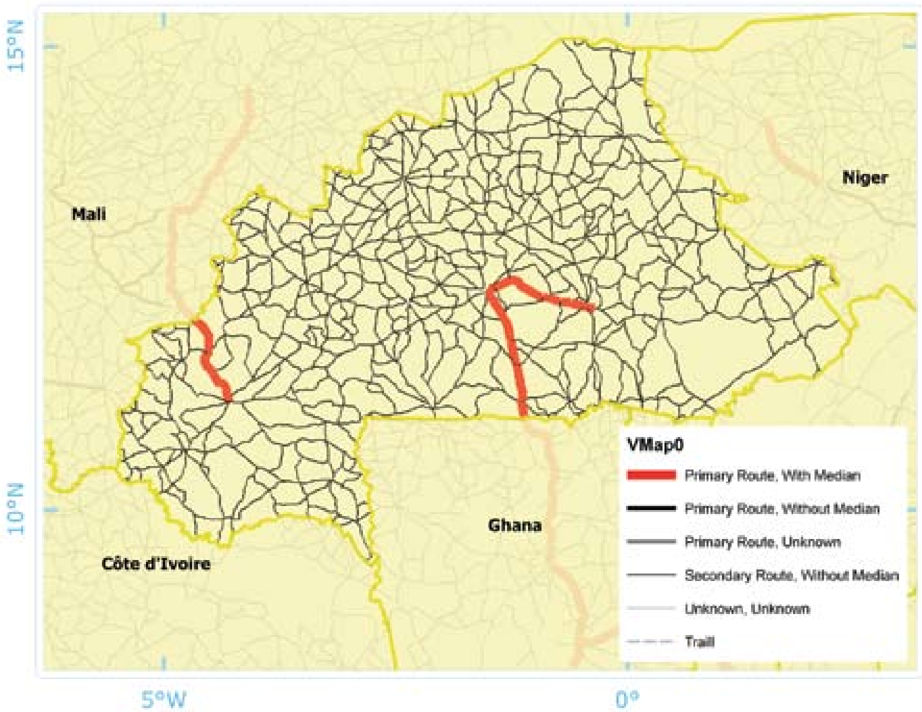


FIGURE 11
VMap0 Ed.5 roads in Burkina Faso



WorldMap Digital Atlas[35] (by American Digital Cartography inc.) and Global Discovery[36] (by Europa Technologies) (Figure 12). However, it must be stressed that for some areas in Africa these products offer no advantage with respect to the public domain VMap0. For a critical review of available datasets and future prospects for public domain global road mapping, see Nelson, de Sherbinin and Pozzi (2006).

Applications of roads datasets within T&T interventions

Road maps can be used to estimate the accessibility of trapping sites. However, the appropriateness of the available VMap0 datasets for the planning of field operations should be evaluated in terms of how up to date, complete and detailed they are. Also, the expansion of commercial activities, as measured by changes in the communication infrastructure, may result in sizeable impacts on tsetse habitat and thus contribute to shaping the pattern of livestock and crop-agricultural activities.

35 http://www.adci.com/products/worldmap/index.html
36 http://www.europa.uk.com/gd.php

FIGURE 12
Screenshot of Google Maps of Burkina Faso (roads are by Europa Technologies)

PARKS, CONSERVANCIES AND PROTECTED AREAS

UNEP – World Database on Protected Areas

The UNEP WCMC, in collaboration with the IUCN World Commission on Protected Areas (WCPA), gathers and reviews the World Database on Protected Areas (WDPA) (Figure 13). The WDPA geospatial data layers provide point and polygon layers of protected areas grouped in two major categories: areas recognized under international law (e.g. "World Heritage Convention" or "Ramsar Convention on Wetlands of International Importance") and areas designated under national legislation. The polygon layers represent the best information available on park boundaries and are, in general, suitable for map scales ranging from 1:1 M to 1:5 M (the differences are due to the multiple sources from which the product is derived).

Access to data

The WDPA database is constantly being updated as new sites are designated and more accurate information is made available. A new release is produced annually and made available for download on the WDPA Web site[37], while the most up-to-date version of the WDPA spatial data layers are available via an Internet Map Server[38]. The WDPA Web site also includes an aspatial relational database (i.e. a tabular database) — which contains information on individual protected areas, their size, IUCN category, history and a number of other attributes. It is searchable but not downloadable via the Internet.

For areas designated under national legislation, the GIS files distributed by WDPA contain indications of data owners and providers at the national level; this information can be used to contact the authorities in charge of managing the national databases of protected areas. These authorities are possibly in a better position to provide the most recent and detailed information for their respective countries.

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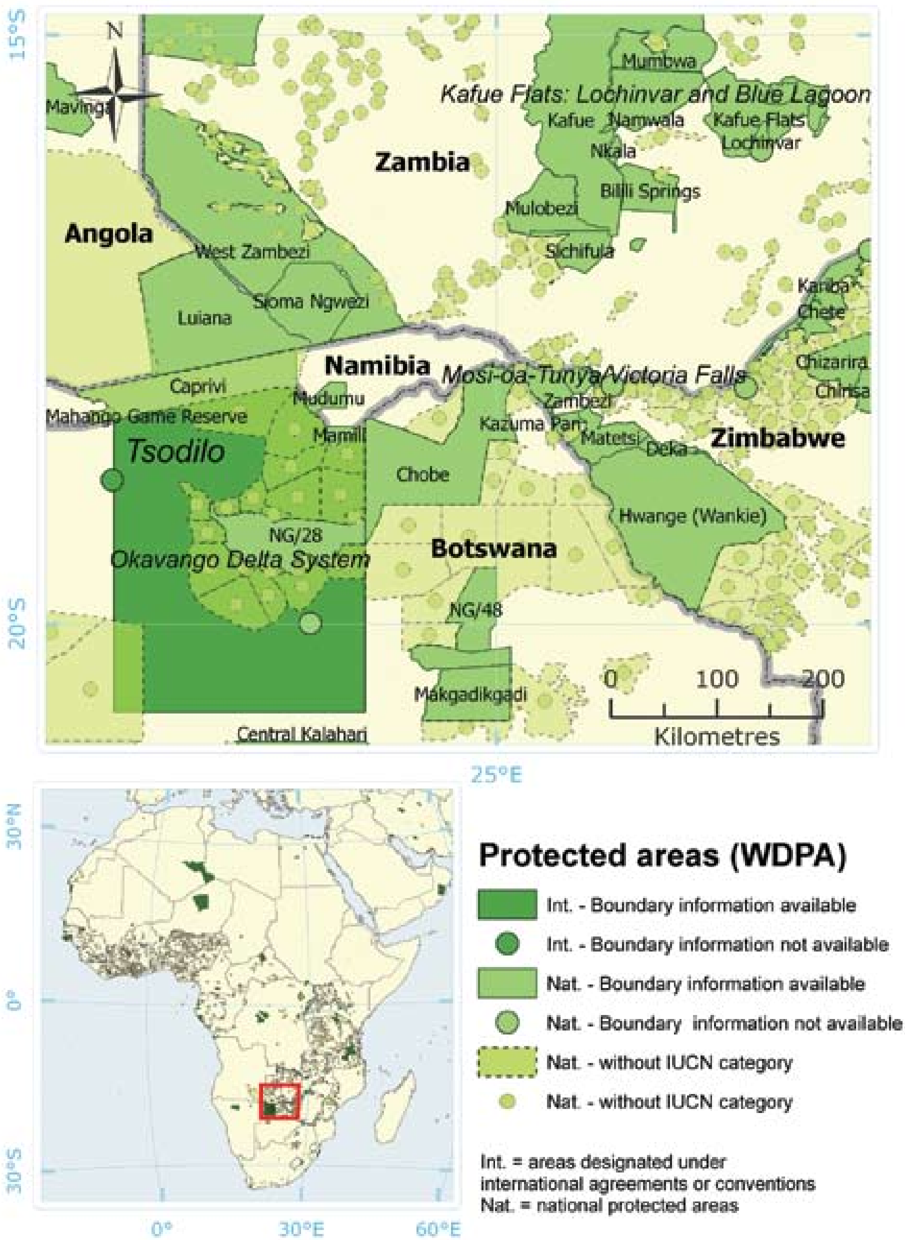
37 http://www.wdpa.org/

38 http://deben.unep-wcmc.org/imaps/ipieca/world

FIGURE 13

Protected areas across the borders of Angola, Botswana, Namibia, Zambia and Zimbabwe, as depicted by the WDPA. The areas for which the boundaries are not available are mapped as circles. Nationally designated protected areas are classified according to IUCN categories



NAMED LOCATIONS

NGA gazetteer – GEOnet Names Server database

The NGA distributes extensive gazetteers of named locations outside the continental United States (Figure 14). Since the late 1990s, the NGA has opted for an Internet-based delivery system that (as of October 2006) gives access to over 6.6 million names and alternative names of cities; prominent structures; hilltops; mountains; mountain ranges; lakes; the confluence of streams; undersea locations; and a range of other types of infrastructural, physiographic, political and cultural features.

The positional information for each location was captured from 1:250 000 source maps. Based on previous processing, the accuracy of many locations has been generalized to the nearest minute, leading to a relative accuracy of ±1 800 m. The accuracy for non-generalized data containing a full coordinate reference in degrees, minutes and seconds would be ±31 m. The database is updated on a continuous basis depending on NGA priorities; however, the frequency for low-priority countries or areas can be measured in decades rather than years.

Access to data

The NGA gazetteer is distributed through the GEOnet Names Server (GNS)[39]. Data can be downloaded in ASCII format either as a global dataset or as national subsets. A complete updated version of the GNS database is posted monthly by NGA.

Other gazetteers

Even though the GNS database provides the baseline for many (if not all) of the gazetteers available either commercially or from private sources, it may be useful to list other online geographical gazetteers that, in some instances, may complement the GNS database.

With the exception of the Alexandria Digital Library Gazetteer, all the gazetteers listed below allow only online searches of individual names; they do not provide for the free download of the full underlying databases.

- Alexandria Digital Library Gazetteer[40]
- Getty Thesaurus of Geographic Names[41]
- Google Maps World Gazetteer (Maplandia)[42]
- Falling Rain Genomics Global Gazetteer[43]
- European Commission Joint Research Centre Digital Atlas[44]
- Microsoft Encarta World Atlas[45]

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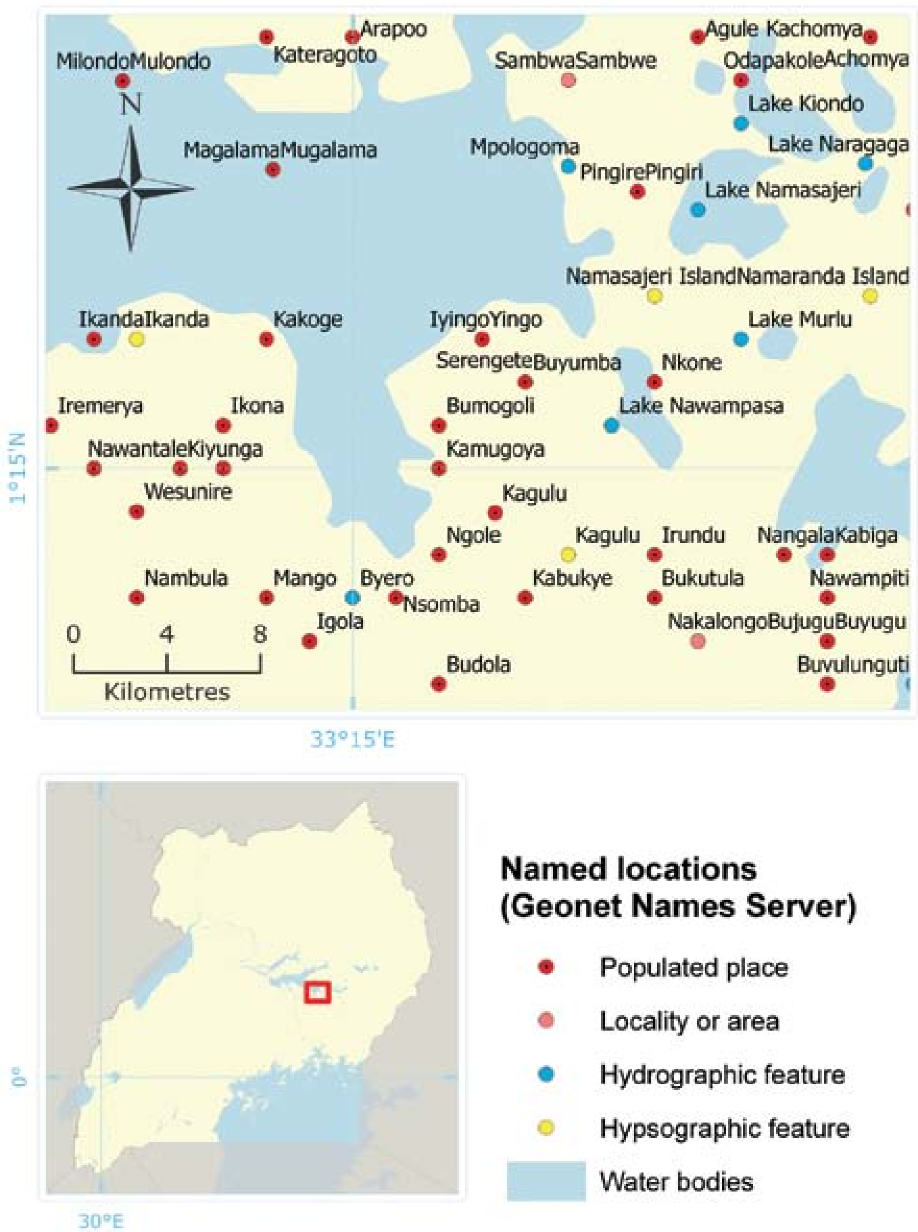
39 http://earth-info.nga.mil/gns/html/
40 http://www.alexandria.ucsb.edu/gazetteer/
41 http://www.getty.edu/research/conducting_research/vocabularies/tgn/
42 http://www.maplandia.com/
43 http://www.fallingrain.com/world/
44 http://dmaweb2.jrc.it/services/dmaexplorer/
45 http://encarta.msn.com/encnet/features/mapcenter/map.aspx

FIGURE 14

Named locations in the area east of Lake Kyoga (Uganda), as derived from the GEOnet Names Server of the United States National Geospatial-Intelligence Agency



Applications of datasets of named locations within T&T interventions

Gazetteers can be used to georeference (or geoposition) survey information that does not contain Global Positioning System (GPS) measurements yet references a named physical location.

SATELLITE IMAGERY

NASA Landsat Orthorectified Image Library

Primarily because the United States Government has provided a source of funding, high-resolution satellite images are available in the public domain as the Landsat Orthorectified Image Library (LOIL). The images in this library have been orthorectified to a common set of control points to enable direct comparisons between locations over the approximately 20-year time period covered by the three sets of reference imagery. The three sets are:

- circa year 2000: Landsat 7 ETM+ (28.5/15 m resolution);
- circa year 1990: Landsat 4/5 TM (28.5 m resolution);
- circa year 1980: Landsat MSS (80 m resolution).

After the orthorectification process, the images from Landsat 4/5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) have a purported positional accuracy of better than 50 m, while the accuracy of the Multispectral Scanner (MSS) imagery is considered to be better than 100 m. Data have been projected into specific Universal Transverse Mercator (UTM) projection systems or zones.

Access to data

Landsat orthorectified image data are available from the University of Maryland's Global Land Cover Facility (GLCF)[46]. Datasets are available in GeoTIFF (uncompressed) and MrSID (compressed, false colour composite) formats[47]. The World Reference System for Landsat satellites, which provides the geographical coverage of each image in a GIS format, can be downloaded from the USGS Web site[48].

Applications within T&T interventions

Medium-resolution satellite imagery can be used in various phases of T&T interventions. For example, Landsat images have been used successfully to map tsetse densities and AAT risk and to define the sampling protocol during the baseline data collection stage.

Given the fairly high resolution of the imagery contained in the NASA-LOIL, these data can be used as image backdrops to support topographic base mapping at scales of 1:250 000 or larger. The maximum viewing scales for this imagery can be approximated as follows: Landsat MSS Imagery, 1:250 000; Landsat TM Imagery, 1:130 000; Landsat ETM+ Pan-Sharpened Imagery, 1:75 000. Given that large-scale topographical base

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46 ftp://ftp.glcf.umiacs.umd.edu/glcf/Landsat and http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp
47 https://zulu.ssc.nasa.gov/mrsid/
48 http://landsat.usgs.gov/tools_wrs-2_shapefile.php

maps commonly use the UTM projection, the imagery comprising the NASA-LOIL is already in a suitable projection system for this use.

GEOSTATISTICAL DATABASES

FAO is the main repository of global forestry, crop, livestock and fisheries statistics via its FAOSTAT Web site[49]. However the only common representations of these data in FAOSTAT are national-level aggregates.

Subnational crop reporting and livestock census data are provided by two relatively recent FAO initiatives: the Global Livestock Production and Health Atlas (GLiPHA)[50] and the Global Spatial Database of Subnational Agricultural Land-Use Statistics (Agro-MAPS)[51].

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The authors would like to thank Joe Dooley (FAO consultant) for his suggestions as well as for the essential information contained in the FAO publication "An inventory and comparison of globally consistent geospatial databases and libraries" (Dooley, 2005). We also extend our gratitude to the staff of the FAO Natural Resources Management and Environment Department (NR) for their assistance.

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49 http://faostat.fao.org/
50 http://kids.fao.org/glipha/
51 http://www.fao.org/landandwater/agll/agromaps/interactive/page.jspx

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Section 2
Tsetse distribution in the Mouhoun river basin (Burkina Faso): the role of global and local geospatial datasets

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ABSTRACT
In this study, we explore the potential of using select global geographic information system (GIS) datasets to map the distribution and densities of riverine tsetse fly at a local scale in the Mouhoun river basin (Burkina Faso). In particular, we analyse the correlation between low-resolution datasets that predict global and regional tsetse distribution and more than 800 trapping scores for *Glossina palpalis gambiensis* Vanderplank and *G. tachinoides* Westwood. The results show that these datasets with global or regional scope, including the Global Land Cover database for the year 2000 (GLC2000), are not suitable for use at a local scale (e.g. in designing baseline data collection protocols for vector control campaigns). On the other hand, higher resolution global datasets available in the public domain, namely the NASA Landsat Orthorectified Image Library (LOIL) and the HydroSHEDS drainage network, have great potential for mapping tsetse habitat when used in process-based models.

INTRODUCTION
In Burkina Faso, as in most sub-Saharan West African countries that are inhabited by tsetse flies, animal African trypanosomiasis (AAT) is a major hindrance to cattle breeding (Itard, Cuisance and Tacher, 2003). Tsetse flies are also cyclic vectors of sleeping sickness in humans, spreading human African trypanosomiasis (HAT). Two riverine tsetse species, *Glossina palpalis gambiensis* Vanderplank 1949 (Diptera, Glossinidae) and *G. tachinoides* Westwood 1850, are still present in considerable densities.

The link between environment and the presence or abundance of vectors of trypanosomiasis is well known, and the use of remote sensing has become an essential tool for the epidemiological analysis of vector-borne diseases (Rogers and Randolph, 1993; Rogers, Hay and Packer, 1996; Robinson, Rogers and Brian, 1997; Hendrickx *et al.*, 1999; de La Rocque *et al.*, 2005). In Burkina Faso, recent studies have demonstrated the relationship between the riverine forest ecotype (and its disturbance level) and the abundance of riverine tsetse. These studies follow a theory regarding the riverine forest ecotype (Morel, 1983) that was later enhanced by the integration of human-driven disturbance (Bouyer *et al.*, 2005).

In this paper, we examine the usefulness of various global and local geospatial datasets to map the habitat, distribution and densities of riverine tsetse, with the ultimate goal of estimating AAT risk at a river basin scale. The types of datasets examined are:

- tsetse distribution (PAAT-IS);
- land cover (GLC2000);
- medium-resolution satellite imagery (Landsat 7 ETM+);
- hydrographic network (HydroSHEDS);
- rainfall (FAOClim).

TSETSE DISTRIBUTION MAPS OF THE PAAT-IS: A COMPARISON WITH FIELD DATA ON A LOCAL SCALE

A recent tsetse elimination initiative has been launched in the Mouhoun river basin within the framework of the Pan African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC), with the financial support of the African Development Bank. The maps that are available in the Programme Against African Trypanosomiasis Information System (PAAT-IS)[1] (see page 3) were used to design the initial area in which baseline data collection would occur. For the Mouhoun river basin, PAAT-IS maps are available at 5 km and 1 km resolutions. These maps consist of probabilities of the presence of different tsetse species. In our case study, the species of interest are *G. p. gambiensis* and *G. tachinoides*. The PAAT-IS maps have been used widely to support strategic decision-making at global and regional levels (e.g. for the selection of priority areas for intervention). However, their potential and limitations for interventions at a local scale have not been evaluated comprehensively.

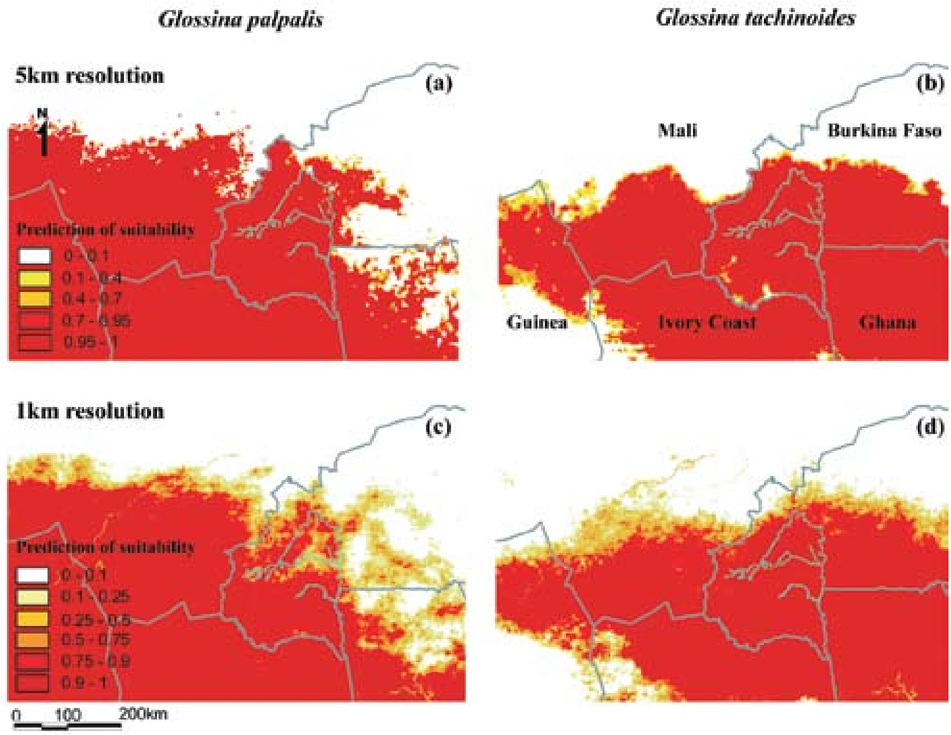
We compared the predictions of the PAAT-IS models to field data collected during various research projects led by the Centre International de Recherche-Développement en zone Subhumide (CIRDES). The most common way to interpret PAAT-IS maps is to assume that tsetse are present in a given area when the probability of suitability is 0.5 (i.e. 50 percent) or greater and that they are absent when the probability is less than 0.5.

Figure 1 shows at resolutions of 5 km and 1 km the predicted areas of suitability for *G. palpalis* and *G. tachinoides*. (It must be noted that the PAAT-IS maps at 5 km resolution, which are available at a continental level, treat the three *G. palpalis* subspecies as a single species.) Figure 2 presents the percentages of trapping sites at which tsetse were actually caught, grouped by class of probability (as derived from the PAAT-IS 5 km and 1 km resolution models, respectively).

The correlation between field data and the 5 km resolution models is poor. In the case of *G. p. gambiensis*, tsetse were found at 32 trapping sites where the probability of suitability, as estimated by the models, was 0.1. Similarly, no tsetse were caught at 3 trapping sites where the estimated probability of suitabilities ranged from 0.6 to 0.9. In the case of *G. tachinoides*, no flies were caught at any sites with a probability of suitability less than 1. If not adequately interpreted, the use of such predictions for

[1] http://www.fao.org/ag/againfo/programmes/en/paat/maps.html

FIGURE 1
Predicted areas of suitability for *G. palpalis* and *G. tachinoides* at map resolutions of 5 km (a and b, respectively) and 1 km (c and d, respectively). Source: PAAT-IS

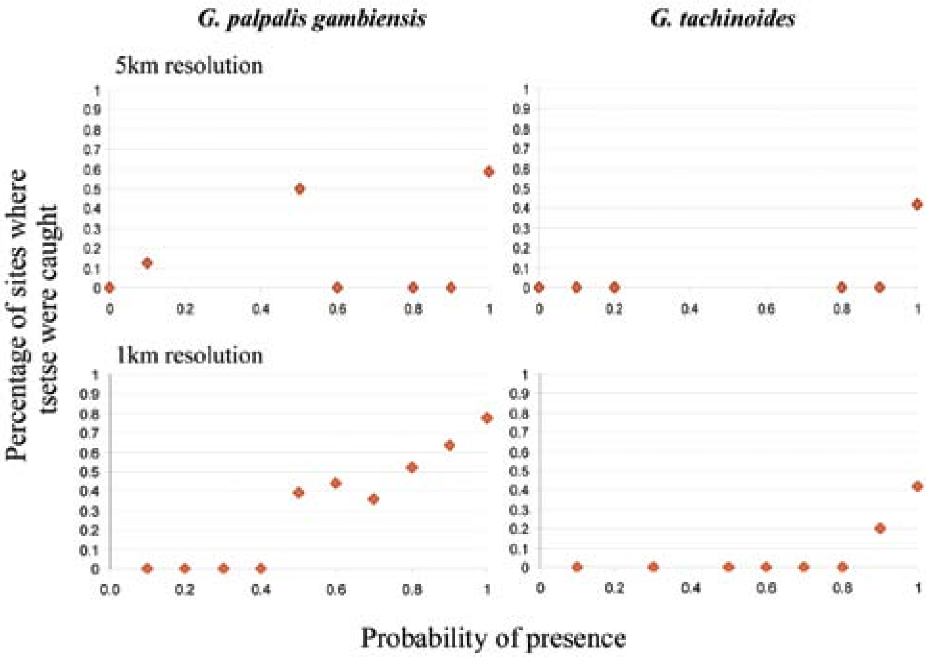


planning the deployment of tsetse traps for baseline data collection would lead to an important overestimation of the sampling area, resulting in significant economic losses (i.e. the funds wasted on misplaced traps).

The predictions at 1 km resolution provide substantially better results than the predictions at 5 km resolution. If a threshold of 0.5 is used to distinguish between absence and presence, the predictions for *G. p. gambiensis* are better than those for *G. tachinoides*. However, if a different threshold is used (e.g. 0.8), the PAAT-IS map for *G. tachinoides* may also prove to be useful.

Even though this case study utilizes field data obtained over a relatively limited geographical area, especially if compared with the global and regional scope of the PAAT-IS maps, it nevertheless demonstrates the limits of PAAT-IS predictions in supporting decision-making at the local level. We argue that when moving on from strategic decision-making towards planning and implementation of field activities at a local level, low-resolution geospatial datasets are inadequate and should only be used with extreme caution. Clearly, the need exists for datasets of higher resolution and for novel analytical methods to map the distribution of tsetse flies.

FIGURE 2
Percentage of 764 trapping sites at which tsetse were caught, grouped by class of probability (as derived from the PAAT-IS 5 km and 1 km resolution models, respectively)



GLOBAL LAND COVER 2000

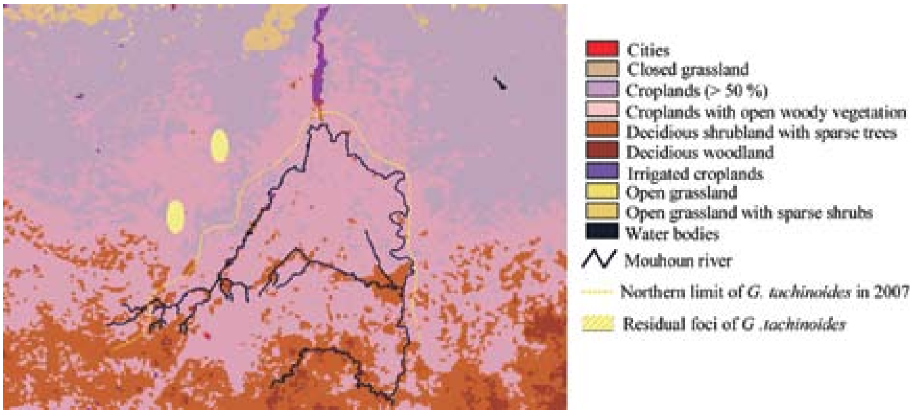
Land cover is arguably the most relevant environmental parameter affecting the suitability of habitat for tsetse flies in that vegetation is either directly or indirectly shaped by soils, climate and human activities. Land cover is also one of the indicators of human intervention on the land most easily detected by remote sensing.

Before the release of the 300 m resolution GlobCover[2] land cover map of the world on 30 September 2008, the 1 km resolution GLC2000[3] provided the most detailed picture of land cover of the earth (see page 9). The GLC2000 land cover classes were found to be statistically correlated with the continental distribution of the three tsetse fly subgenera (*fusca*, *palpalis* and *morsitans*) (Cecchi *et al*., 2008). In particular, 56 percent of the distribution of the *fusca* group and 46 percent of the distribution of the *palpalis* group could be predicted by GLC2000 land cover classes.

We analysed the potential of the GLC2000 to predict the local presence and abundance of *G. p. gambiensis* and *G. tachinoides* (both belonging to the *palpalis* group) in the Mouhoun river basin. As an example, Figure 3 presents the northern limit of the distribution of *G. tachinoides* superimposed on the GLC2000 land cover units. Four

[2] http://ionia1.esrin.esa.int/index.asp
[3] http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php

FIGURE 3
Northern border of the distribution area of G. tachinoides (in yellow) superimposed on GLC2000 vegetation units



units are present within the studied area: "croplands with open woody vegetation", "deciduous shrubland with sparse trees", "croplands (> 50 percent)" and "irrigated croplands". Table 1 shows the mean apparent densities per trap per day (ADT) for both species calculated for the four land cover units, together with the probability of species presence derived from fly catches at 831 trapping sites.

These results are in line with the continental level study, which assigned to the GLC2000 classes in Table 1 a degree of suitability for the *palpalis* group that ranged from low to moderate. Somewhat unexpectedly, the maximum ADTs for both species are observed in the more disturbed units corresponding to "croplands (> 50 percent)". On the other hand, the maximum probabilities of presence are found in classes with a higher proportion of natural vegetation, namely "deciduous shrublands with sparse trees" for *G. p. gambiensis* and "croplands with open woody vegetation" for *G. tachinoides*. Considering that the presence and abundance of tsetse are known to be negatively correlated with the disturbance of riverine forests caused by agriculture (Bouyer *et al.*, 2005), these results call for an explanation.

In Africa, the discrimination of agricultural areas from natural vegetation using satellite imagery of 1 km resolution is quite problematic because of the characteristics of prevailing farming systems and the spatial pattern of croplands. As a result, GLC2000 resolution is probably inadequate to depict the rather small and scattered patches of riverine vegetation that are so important for tsetse fly, especially in this area at the limit of its distribution. This is confirmed by Figure 4, which presents a land cover map at 30 m resolution generated through supervised classification of a Landsat 7 ETM+ scene, as compared with the GLC2000. The forest unit, which is the most important vegetation unit for mapping of tsetse distribution, is completely absent from the GLC2000 and

TABLE 1
Mean apparent density per trap per day (ADT) for *G. p. gambiensis* and *G. tachinoides* (standard deviation in brackets), together with the probability of species presence, in four GLC2000 vegetation units (Mouhoun river basin, Burkina Faso)

GLC2000 units	ADT *G.p.g.*	ADT *G.t.*	Number of traps	Absence of *G.p.g.*	Absence of *G.t.*	Probability of presence of *G.p.g.*	Probability of presence of *G.t.*
Croplands with open woody vegetation	2.79 (5.90)	2.79 (5.27)	574	306	276	0.47	0.52
Deciduous shrubland with sparse trees	2.78 (3.60)	0.56 (1.18)	210	50	144	0.76	0.31
Croplands (> 50%)	6.93 (13.63)	4.26 (14.36)	27	16	16	0.41	0.41
Irrigated croplands	1.80 (2.24)	0.05 (0.22)	20	05	19	0.75	0.05

seems to be have been diluted either in the class “deciduous shrubland with sparse trees” or in “croplands with open woody vegetation”.

Our results confirm the limitations of using coarse resolution global datasets at a local scale and the need for an approach using multiple resolutions to study the link between land cover maps and tsetse habitat.

MEDIUM-RESOLUTION SATELLITE IMAGERY (LANDSAT 7 ETM+)

The previous two sections have highlighted some of the limits of using global datasets at a local scale. We summarize here the methodology and results of a recent study to assess riverine tsetse fly densities and trypanosomiasis risk along the Mouhoun river using medium-resolution satellite imagery (Landsat ETM+) coupled with entomological and environmental field data (Bouyer *et al.*, 2006; Guerrini and Bouyer, 2007; Guerrini and Bouyer, in press). The methodology was based on an initial distinction of three ecological sections along the Mouhoun river (Guinean, Sudano-Guinean and Sudanese gallery forest) and the discrimination of peri-riverine landscape units within a 1 km buffer of the river.

The aim of the landscape classification method was to identify clusters corresponding to three entomological landscapes described in the field (protected forest, border of a protected forest, and cultivated and grazed areas) using seven land-use classes obtained from supervised classification of Landsat 7 ETM+ imagery (Figure 4c). Riverine forests are often too thin (< 10 m) to be clearly detected with Landsat 7 multispectral bands (30 m) and were thus analysed through their neighbouring pixels. Points were randomly generated within each ecological section and then analysed to identify clusters of similar neighbourhoods. The areas of each land-use class were calculated in buffers of 500 m around each point and then expressed as a percentage of the total buffer area (Figure 5).

Clusters of similar neighbourhoods were identified from the hierarchical classification and then matched with the entomological landscapes described in the field. This approach

FIGURE 4

(a) GLC2000 vegetation units, (b) false-colour composition (TM4, TM3, TM2) of Landsat 7 ETM+ scene and (c) associated supervised classification of the northern edge of the Mouhoun river loop (Burkina Faso) within a 1 km buffer of the river. Source: Guerrini and Bouyer, 2007

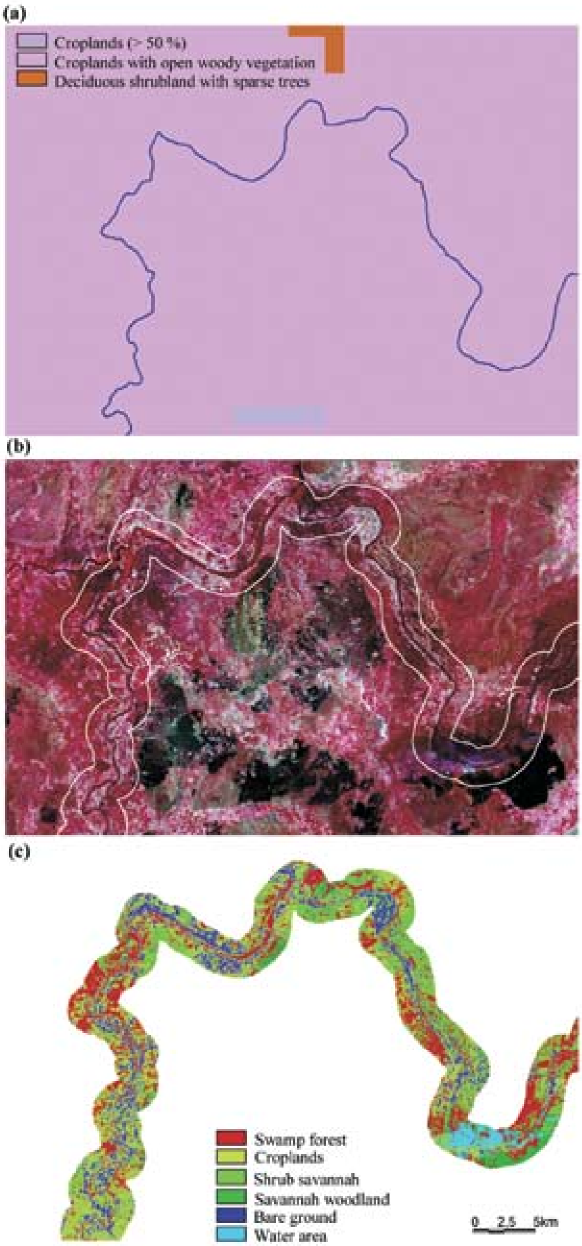
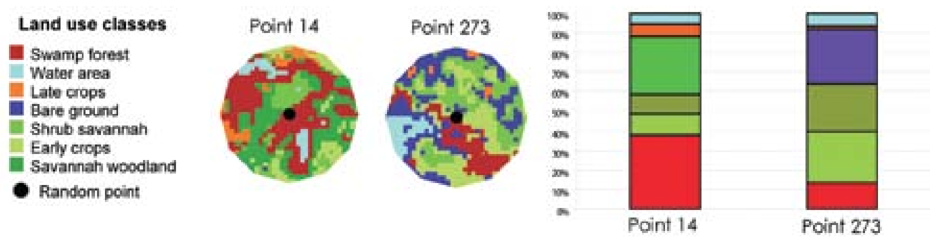


FIGURE 5
Percentages of seven vegetation units derived from supervised classification in 500 m buffers around two points randomly generated along the river course. Source: Guerrini and Bouyer, 2007



allowed classification of the river network into three disturbance levels (disturbed, half-disturbed and natural). The surface of the water around the river course could be used to predict the ecotype of the riverine forest (Guinean, Sudano-Guinean and Sudanese) (Bouyer *et al.*, 2005). Overall, a good classification was obtained for 81 percent of the sites (Guerrini *et al.*, 2008). Figure 6 presents the distribution of these disturbance levels and ecotypes along the Mouhoun river loop.

The ecotype and disturbance levels were matched to obtain homogeneous landscapes in which the ADT of the two species was measured by means of 689 trapping sites (Guerrini and Bouyer, 2007). The ADTs were then mapped along the main course of the Mouhoun river and two of its tributaries (the Leyessa and the Balé), as shown in Figure 6.

Our model predictions were validated against an independent dataset (66 trapping sites). A very good correlation between the model outputs and the field data was observed (Kendall Test results for *G. p. gambiensis*: $T = 0.37$, $z = 4.19$, $p = 2.831e\text{-}05$; Kendall Test results for *G. tachinoides*: $T = 0.39$, $z = 4.67$, $p = 3.036e\text{-}06$).

The method briefly outlined here demonstrates the potential of medium-resolution satellite imagery as a tool in tsetse fly mapping and subsequent assessment of AAT risk at a local level.

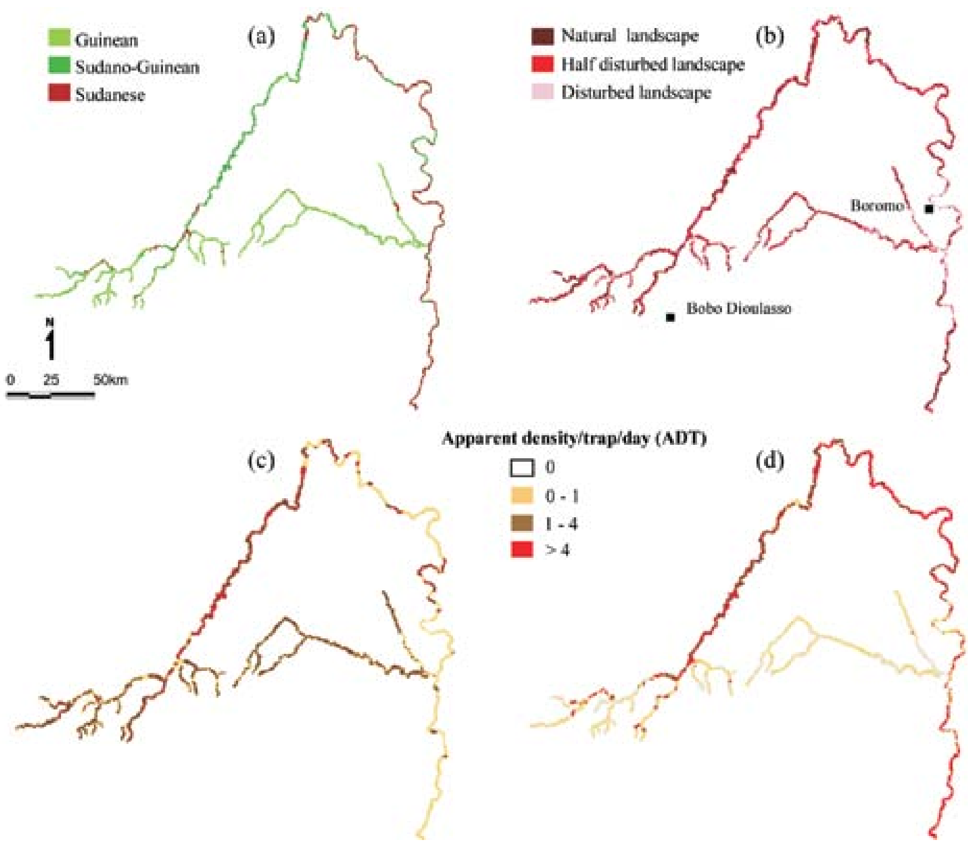
HYDROGRAPHIC NETWORK

A recent study (Guerrini and Bouyer, 2007) compared the HydroSHEDS[4] drainage network (see page 17) with a hydrographic network, digitized from Landsat 7 ETM+ satellite imagery, that was used to map tsetse densities in Burkina Faso. Figure 7 presents the two different sets of vector data.

Although no systematic or quantitative analysis was carried out, visual analysis indicates a very good match between the two datasets. The maximum observed shift was of approximately 0.5 km. Given that the methodology developed to map riverine tsetse densities in Burkina Faso was based on the land-use classification of a 1 km

[4] http://hydrosheds.cr.usgs.gov

FIGURE 6
(a) River ecotypes along the Mouhoun river (Burkina Faso), as derived from water surface analysis. (b) Levels of disturbance derived from swamp forest analysis. (c) ADT of *G. p. gambiensis*. (d) ADT of *G. tachinoides*



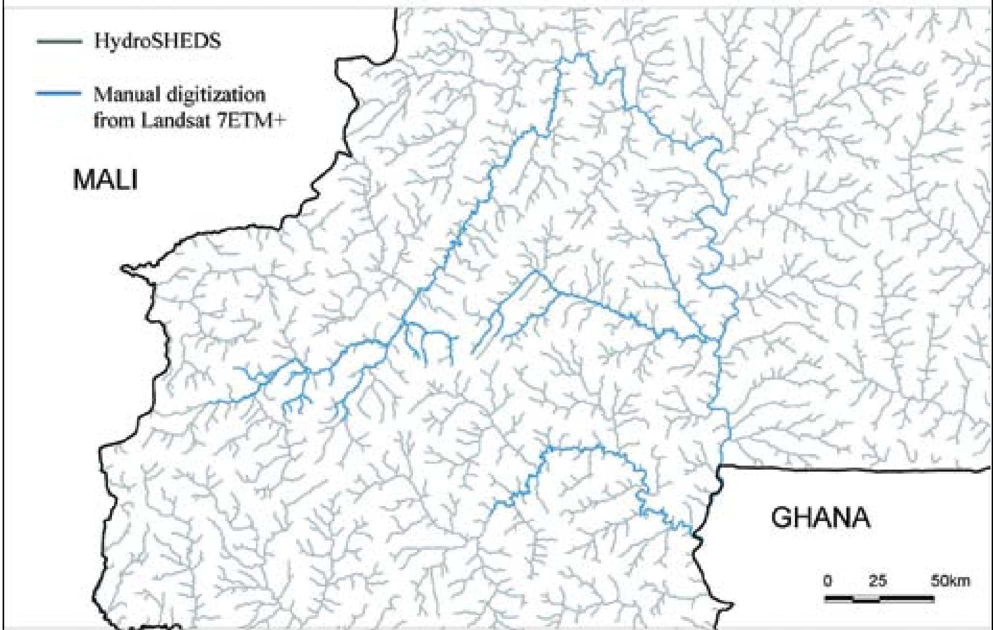
buffer around the river network, HydroSHEDS products could assist in applying this methodology at a broader, possibly regional, scale. Furthermore, HydroSHEDS provides drainage basins (watershed boundaries), which may prove useful in assisting the planning of tsetse genetic surveys. These surveys aim to identify isolated tsetse populations that can be targeted in area-wide control campaigns. It is believed that the potential of HydroSHEDS products to support tsetse and trypanosomiasis (T&T) studies and interventions should be further explored.

ANNUAL RAINFALL

We used the FAOClim[5] database (see page 24) to analyse the evolution of *G. p. gambiensis* and *G. tachinoides* distributional limits between entomological surveys

[5] http://www.fao.org/NR/climpag/pub/EN1102_en.asp

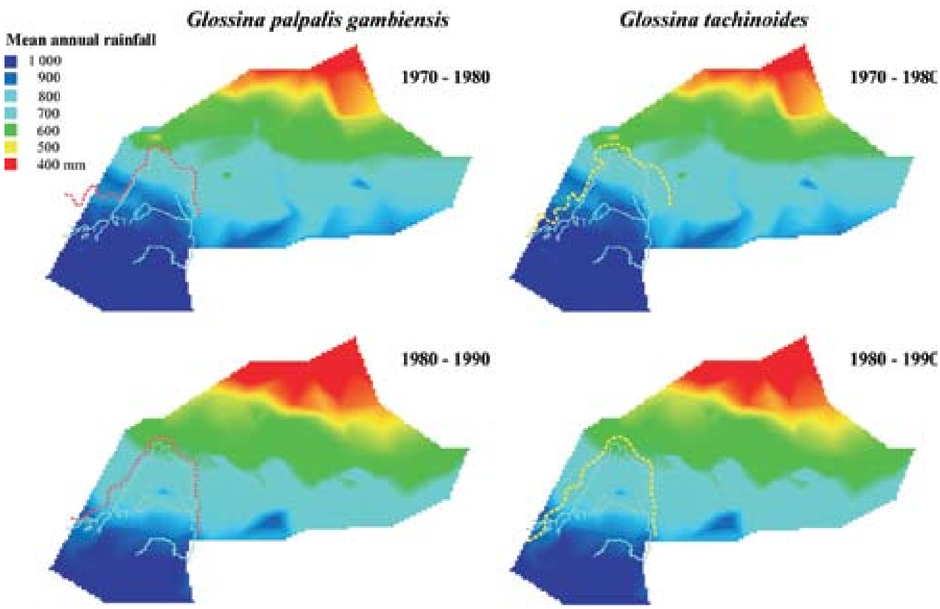
FIGURE 7
The Mouhoun river network, as digitized from Landsat 7 ETM+ images and the HydroSHEDS drainage network



carried out in 1979–1980 (Küpper, 1980) and in 1999–2007 (during various research programmes in which CIRDES was involved). One of the most important climatic factors used to map the density and distribution of tsetse flies is mean annual rainfall, which is positively correlated with indices of vegetation such as the normalized difference vegetation index (NDVI) (Rogers and Randolph, 1991). A map of the decadal mean annual rainfall for two periods (1970–1980 and 1980–1990) was interpolated from 151 meteorological stations in Burkina Faso and compared to the northern limit of tsetse distributions (Figure 8).

Although Figure 8 shows a clear tendency for the isohyets to move southward over time, the limits of the two tsetse species remain at the same latitude, at the top of the Mouhoun river loop. These limits thus seem to depend more on the persistence of the hydrological network than on the annual rainfall. At the same time, no tsetse are found beyond 800 mm of annual rainfall in the absence of permanent rivers or springs (i.e. east or west of the main course of the Mouhoun or springs). Thus, when integrated in multifactorial spatial models, the FAOClim database is likely to be useful in mapping riverine tsetse flies.

FIGURE 8
Decadal mean annual rainfall, as interpolated from 151 meteorological stations in the FAOClim database and northern borders of the distribution areas of *G. p. gambiensis* (left) and *G. tachinoides* (right)



CONCLUSION

A selection of the global GIS datasets presented in the first section of this publication (see page 1) was matched against local entomological and environmental datasets with a view to assessing their potential for supporting T&T interventions.

Datasets at a coarser resolution (the PAAT-IS tsetse distribution maps and GLC2000 land cover map of Africa) predictably showed their limits when utilized at a local scale, thus confirming the need for different approaches to support the planning and implementation of field interventions.

On the other hand, higher resolution global datasets available in the public domain (the NASA-LOIL and HydroSHEDS drainage network) demonstrated their potential for the estimation of disease risk. This potential merits further exploration in the context of T&T problem-solving.

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Section 3
Collection of entomological baseline data in the Mouhoun river basin (Burkina Faso): the use of GIS, remote sensing and GPS

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ABSTRACT
This paper describes how geographic information system (GIS), remote sensing (RS) and Global Positioning System (GPS) technologies were used to plan the collection of entomological baseline data for a tsetse and trypanosomiasis (T&T) elimination project in the Mouhoun river basin in Burkina Faso.

Historical data were collated as the background for data analysis. These data were used to define the survey area and to assess the probability of tsetse fly presence. Existing data and satellite images were used both to determine the sampling and trapping sites and to navigate to the areas used for deployment and release of the traps. For data management, a geodatabase (ArcGIS ArcInfo Desktop) and a relational database (MS Access) were created. The geodatabase was used to compile all geographical data, and the relational database served to integrate field data using a user-friendly interface for technicians. The methodologies and datasets presented in this paper represent essential prerequisites for subsequent project activities, including suppression and eradication of tsetse.

INTRODUCTION
The distribution of tsetse and trypanosomiasis is determined mainly by habitat structure and vegetation types. Tsetse flies live in forests, savannah and riparian woodlands where vegetation provides a suitable climate and habitat for their survival and reproduction. Burkina Faso, like many other tsetse-infested countries in western Africa, suffers subsequent constraints on its agriculture and the livelihood of its rural populations. It is located on a plateau, with most of the country between 300 and 400 m in elevation. It consists of vast plains, broken by occasional low hills. Riverine forest vegetation is predominant in most areas infested by tsetse. The impact of landscape fragmentation on the structure and distribution of a population of Glossina palpalis gambiensis along the Mouhoun (Black Volta) river basin can be traced to human and climatic factors.

Tsetse-transmitted trypanosomiasis is a unique and complex disease that requires strategic study at the continental level. Careful evaluation is necessary of the many different variables that exert a varying influence on its distribution and impact, both geographically and over time. For this reason, GIS, RS and GPS technologies provide powerful tools that can be used to measure a wide range of field parameters essential to sampling, surveys and T&T interventions. GIS has been used principally to predict the distribution and dynamics of different vectors (Lessard *et al.*, 1990), and numerous digital georeferenced databases have been developed to accomplish different tasks. In Burkina Faso, GIS, RS and GPS technologies have been used to define the project area for the collection of entomological baseline data in the Mouhoun river basin and to assist in the implementation of the project to create sustainable T&T-free areas in western Africa under the Pan African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC) initiative.

PROJECT AREA

With the aid of GIS software, the project area was delineated using river basin maps, topographic maps and a map of tsetse fly distribution in Africa (FAO, 2000). The project area was divided into five blocks covering the Mouhoun river basin. The area of each block ranges from 10 000 to 30 000 km^2.

The survey area referred to in this paper is in Block I (Map 1).

Data-mining software used: ArcGIS ArcInfo Desktop 9.0, Erdas Imagine 8.4, MS Access

Three programs were used: ArcGIS ArcInfo Desktop 9.0[1], Erdas Imagine 8.4 and Microsoft Access[2]. The choice of these programs was made according to their individual capabilities and the compatibility among them.

- ArcGIS ArcInfo Desktop is the most widely used GIS (i.e. vector-oriented) software; it is able to handle a geodatabase and has good compatibility with MS Access;
- Erdas Imagine is image-processing software that is oriented to raster datasets, especially satellite imagery; its file format (.img) is easily readable in ArcGIS;
- Microsoft Access is a relational database management system (RDBMS); for this project, it was used to build the database for storing and managing entomological data collected in the field.

Importantly, these three programs are compatible with one another, which facilitated project data management. A key feature of ArcGIS ArcInfo Desktop is its ability to build geodatabases capable of integrating existing data. Various geographical layers in various formats were collected from different sources and subsequently loaded into ArcGIS geodatabases, which stored these layers as “Feature classes” grouped into “Feature datasets”. To fit the needs of the survey, two geodatabases were created: a base maps geodatabase and an entomological data geodatabase.

Base maps geodatabase

Most of the data for the base maps geodatabase were obtained from the Institut Géographique du Burkina. They are in shapefile format in a WGS 84 zone 30 projection and include administrative boundaries, land use/land cover, rivers, etc.

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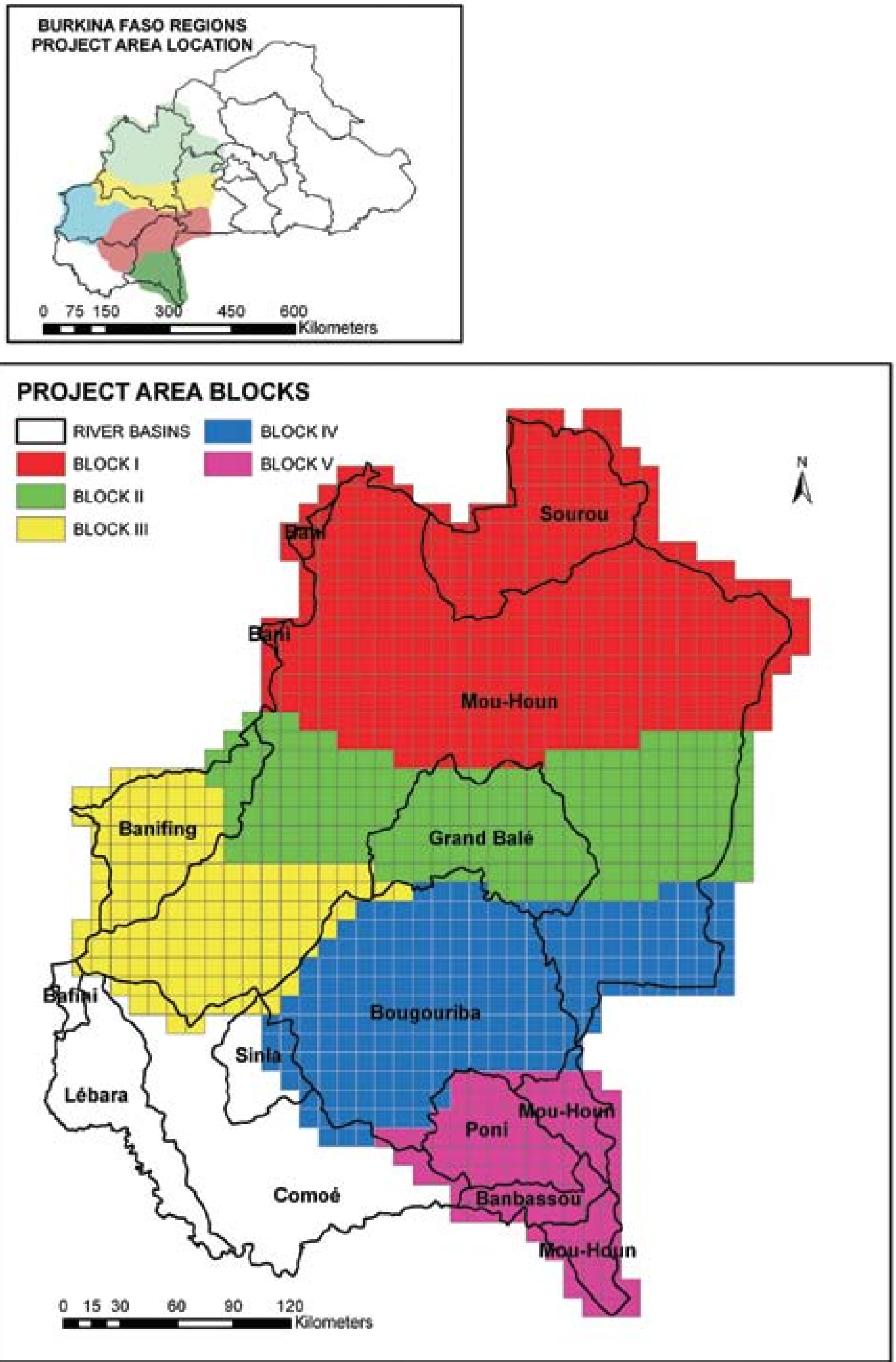
1 http://www.esri.com
2 http://www.microsoft.com

MAP 1
Project area



Entomological data geodatabase

The entomological datasets contained in this geodatabase were collected by different institutions (FAO, Centre International de Recherche Développement sur l'Elevage en zone Subhumide [CIRDES] and the International Atomic Energy Authority [IAEA]) between 1998 and 2005. These data were used for the selection of sampling sites and also for further analysis.

SATELLITE IMAGERY

Satellite images were used to determine suitable habitat for tsetse flies. Two sets of Landsat 7 ETM+ images were used, one acquired in 2000 and another acquired in 2003. Given that the survey area is known to be the habitat of riverine tsetse flies, the satellite images were used to highlight active vegetation along the drainage pattern during the dry season.

Image processing

Of the several image processing techniques used to enhance the depiction of vegetation and other land features (such as bare soil, roads and built-up areas), we chose the false colour composite (FCC) technique and made use of Landsat bands 3, 4 and 5.

In order to increase the spatial resolution, we used two techniques, "Brovey Transform" and smoothing filter-based intensity modulation (SFIM) (Liu, 2000), with panchromatic band 8. This processing gave an FCC pixel resolution of 14.5 m instead of 28.5 m.

DATABASE CREATION

A database was built to integrate the survey data into an RDBMS. The user interface reflects all the parameters contained in the field sheet used by the field survey teams.

The database contains three main tables:

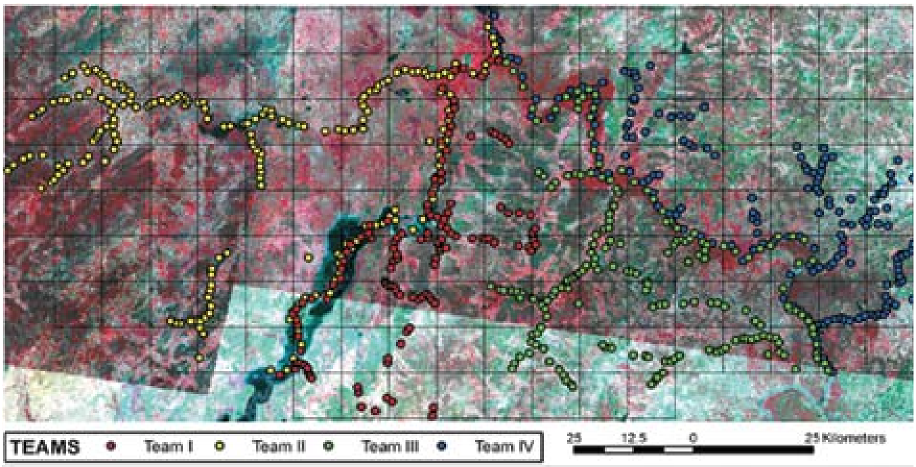
- the "Traps table", whose fields include coordinates (x and y), type of trap, date and time (deployment and release), location (region, villages, etc.) and the composition of the field team (team leader, technicians);
- the "*Glossina* table", whose fields include type of *Glossina* (species), sex and number;
- a final table whose fields include mechanical vectors (species and number).

These tables are linked by the field "trap code", which is the primary key of the "Traps table". A user interface was developed to facilitate data entry in the fields.

TRAINING IN GPS

Field data collection was conducted by four teams consisting of three people each. Each team had a team leader who was responsible for the quality of the data recorded in the field. All participants were trained for four weeks in the use of GPS as well as in the deployment and release of traps. Some individuals were taught how to use the RDBMS database and were required to enter data in cooperation with the team leaders.

MAP 2
Sampling sites allocated to the four teams (Block I)



SELECTION OF SAMPLING SITES AND FIELDWORK

Site identification

The FCC images, base maps and historical entomological geodatabase were manipulated using the ArcGIS program to select sampling sites. A grid of 10 km by 10 km was used as a reference. Within each grid cell, a maximum of 12 points (sampling sites) were selected. These sampling sites were allocated evenly among the four teams (Map 2). The sampling sites were then loaded into GPS receivers.

Fieldwork

Each team was provided with two GPS receivers. Each receiver was preloaded with the coordinates of the team's sampling sites. The teams were instructed to deploy a maximum of two traps in each sampling site. Guided by the GPS receivers, maps and local people, the teams deployed the traps in the sampling sites. The traps remained deployed for 72 hours, at which point the entomological data collection sheets were completed accordingly.

ARCGIS AND RDBMS MANAGEMENT

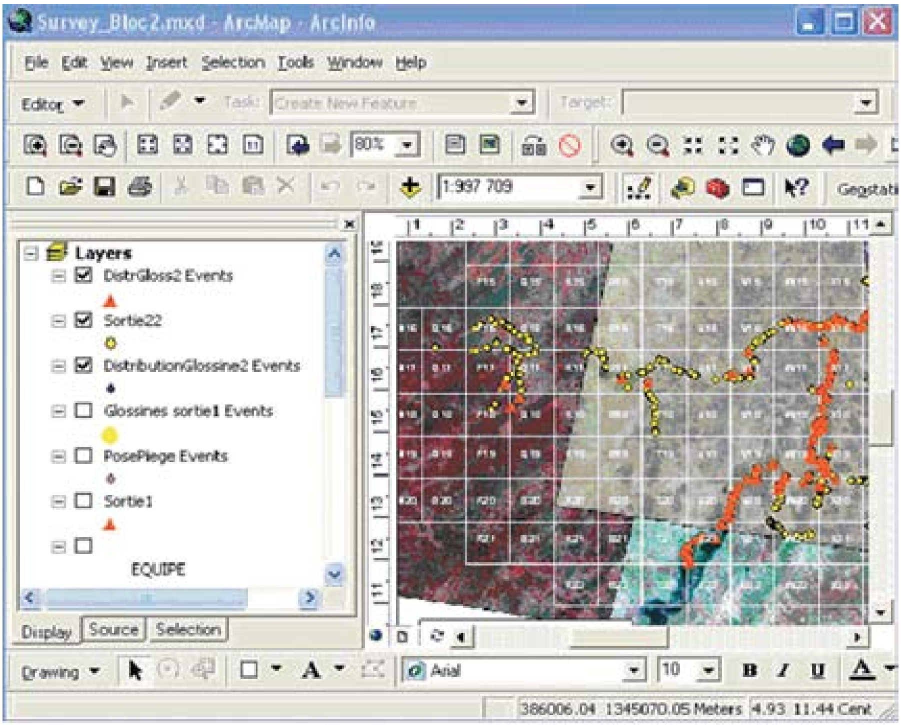
RDBMS and field data integration

Upon returning to the office, each team leader wrote a report and transmitted the entomological field sheets to the database manager, who was responsible for integrating the data into the RDBMS database.

Connection of the RDBMS to ArcGIS

After the field data were entered into the RDBMS database, the ArcGIS program was connected to it via ArcCatalog. (Such a connection enables the ArcGIS program to

FIGURE 1
Screenshot showing the conversion of tables and queries to feature classes



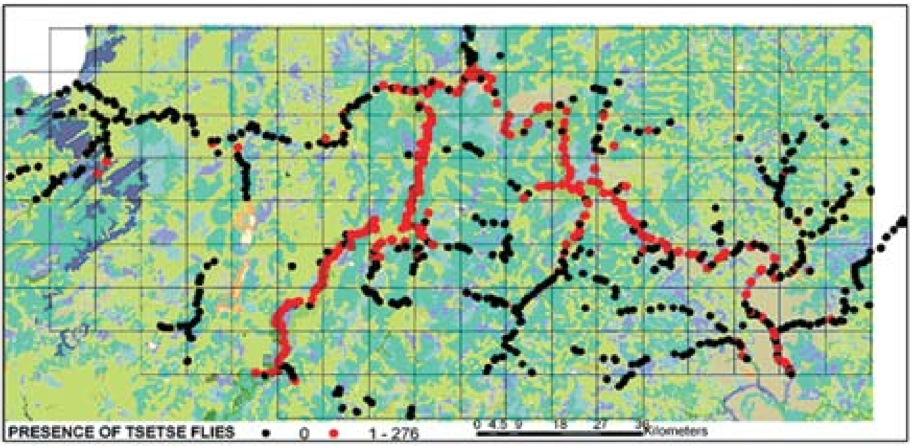
access the tables and queries available in the RDBMS database.) Using ArcMap, the tables and queries were converted into feature classes (layers) (Figure 1). Once this conversion was accomplished, users became able to plot the distributions of tsetse flies (*G. tachinoides* and *G. palpalis*), or any other related query or table, as maps, because geographic *x* and *y* coordinates had been linked to the RBDMS tables (Map 3).

CONCLUSION AND ACKNOWLEDGEMENTS

This paper shows how GIS, RS and GPS technologies have been used in an integrated way to collate entomological data for improved T&T decision-making in Burkina Faso. Historical data have been gathered and compiled in a GIS, satellite images have been acquired and processed and a database has been developed to convert field data into an electronic format.

The key concepts for planning and organizing this work are laid out in the "Collection of Entomological Baseline Data for Tsetse Area-wide Integrated Pest Management Programmes" (Leak, Ejigu and Vreysen, 2008) and the "Tsetse Intervention

MAP 3
Presence of tsetse flies (Block I)



Recording and Reporting System (TIRRS)". These documents have been prepared by the Joint FAO/IAEA Division. The project also received support from FAO/IAEA to organize a workshop to develop a detailed work plan/action plan for the collection of entomological baseline data.

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Section 4
Integrating GIS and GPS-assisted navigation systems to enhance the execution of an SAT-based tsetse elimination project in the Okavango delta (Botswana)

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ABSTRACT
Tsetse intervention using the sequential aerosol technique (SAT) was reintroduced in Botswana's Okavango delta in 2001 and 2002. Previously, only limited results had been achieved with various other techniques. For the first time in the present campaign, geographic information system (GIS) tools were used for operational planning and management of the entire programme. A complementary system of aircraft track guidance was used to ensure precise placement of the insecticide. The system also incorporated a mechanism for verification of the details of spray application. The operation was extremely successful, clearing tsetse flies from an area of approximately 16 000 km^2 over a period of two years with no observed environmental consequences.

INTRODUCTION
In northern Botswana's Okavango delta and fringes, tsetse control has been an important option for controlling tsetse-transmitted trypanosomiasis. Aerial spraying using the SAT (Allsopp, 1990) epitomized Botswana's tsetse control policy during the 1970s and 1980s. Odour-bait technology (Vale and Torr, 2004) replaced the previous SAT in 1991, yet no significant progress was made until 2001 and 2002, when the SAT was reintroduced using a comparatively modern approach (Kgori, Modo and Torr, 2006).

Improved navigation equipment — assisted by a Global Positioning System (GPS), namely the Satloc guidance system — was used to ensure accurate track guidance. Data management and decision support systems, such as geographic information systems (GIS), were also available for data integration. These proved to be indispensable planning tools.

The operation's objective remained the same: to eliminate tsetse completely. This time, however, the results were exceptionally good.

RATIONALE FOR GIS AND SATLOC NAVIGATION
Successful application of the SAT requires formulated insecticide to be applied evenly and systematically along accurate, parallel flight paths, so that a complete blanket of

insecticide drifts through the tsetse habitat (Allsopp, 1990). Complete coverage of the treatment area is crucial, as is accurate and systematic planning and design of the operation in the first place. If areas are missed (as occurs with poor organization of treatment), pockets of tsetse flies will survive. On the other hand, if areas are overdosed, the environmental consequences can be extreme (Merron, 1986).

The Satloc AirStar 98 (CSI Wireless, Calgary, Canada) guidance system was used by all spray aircraft in the present campaign. In addition to guiding the aircraft, the system controlled the insecticide flow rate automatically and thereby ensured uniform application.

Why GIS?

In the Okavango delta, GIS was initially applied in support of the management of tsetse traps and targets in the 1990s through an integrated system that also involved the use of GPS and satellite imagery (Allsopp, 1998; Kgori, 2001). The system guided operations in the field by identifying potentially suitable tsetse areas and by mapping target locations as well as patterns of tsetse distribution.

Eventually, GIS became an integral part of a broader management strategy for tsetse and trypanosomiasis (T&T) intervention in the Okavango delta. It fulfilled the most essential requirement for "visual orientation" in the operational area, which is otherwise a largely inaccessible and difficult working environment. Because of the known usefulness of GIS, it seemed logical to employ GIS in 2001 and 2002 in the operational planning and management of the revamped SAT programme.

Preliminary work and GIS aid

Prior to the commencement of the campaign in 2001 and 2002, input data from routine entomological surveys as well as data relating to target locations, airstrips, tourism camps and access routes (where possible) were recorded accurately using GPS and subsequently archived using the GIS software ArcView 3.2. A base map of the Okavango delta served as a working environment on which to overlay input data. All data were projected using the Universal Transverse Mercator (UTM) coordinate system, zone 34 (map datum WGS 84). This covered the operational area in the Okavango delta adequately.

Unlike an unprojected geographic coordinate system (GCS), UTM applies a system of spatial georeferencing based on a two-dimensional transformation of the earth's surface onto an assumed flat plane. In the UTM system, spatial locations are identified from the perspective of equally spaced horizontal and vertical lines of x and y coordinates. This gives a comparative advantage to UTM-projected base maps with respect to the relaying of relatively accurate spatial georeferencing, both in the GIS environment and on the ground. The UTM coordinate system was particularly well suited to the Okavango project, because its metric units conveniently and accurately measured areas and distances.

Digital imagery of the delta, acquired by the Thematic Mapper (TM) sensor of the satellite Landsat 5, provided a visual perspective of important ecological features in the treatment area, including known habitat islands of tsetse "hotspots". The best tsetse habitats were identified as having the basic requirements of food (i.e. game) – and therefore proximity to water – and shelter (i.e. vegetation). We were concerned with only one tsetse species (*Glossina morsitans centralis*) and therefore did not have to take into account the variability of habitat requirements that might exist in other African regions (e.g. West Africa) where different species coexist.

A false colour composite image made from Landsat bands 2, 3 and 4 was used to highlight vegetation and distinguish suitably dense woodland from open sandy areas, known areas of scrub mopane (C*olophospermum mopane),* etc. The dense woodland was found mostly close to drainage lines, *melapo*[1] or, in some cases, seasonal pans. Nevertheless, suitable vegetation still needed to be differentiated from vegetation associated with permanently flooded areas of papyrus, etc., where there were no flies. To some extent the necessary data, including knowledge of the distributions of game, were obtained from experience and local knowledge. However, the GIS component provided an overlay of historical tsetse survey data (a "habitat-suitability" layer), which assisted in the identification of tsetse "hotspots". This methodology worked particularly well for areas such as Guai, Mombo, Nxabegha, Gubanare, etc.

Following guidance from digital imagery, specific ecological areas were targeted because of their high potential suitability as tsetse habitat. A working estimate of spatial tsetse distribution was then created using GIS. The same procedure was also used to target suitable vegetation. This information, along with data on trypanosomiasis distribution in cattle and horses, was then used to define areas of "potential" fly distribution. At the same time, old and new survey data were used to identify areas of "known" fly distribution. (Throughout the survey period of several years, the area of "known" distribution kept expanding. Right up to the start of the operation, flies continued to be found in "potential" areas outside the "known" distribution.)

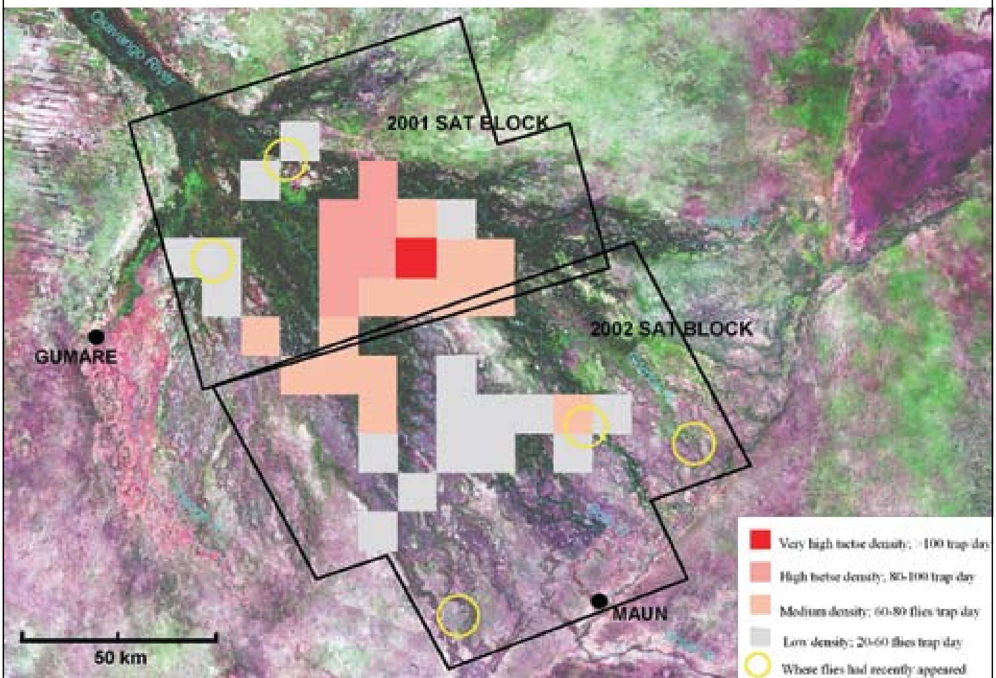
Planning and execution of the project

For visualization of the treatment area, GIS proved to be an indispensable tool. Delimitation of the project area was determined from GIS, which provided precise coordinates that were used to define each individual spray treatment area. This delimitation was based largely on a combination of entomological and parasitological data from the GIS archives. Data depicting the spatial distribution of tsetse were laid over a base map of the Okavango delta to establish accurately the georeferenced distribution pattern. The same approach was used in the evaluation of relevant parasitological data and other project planning parameters to ensure that all known tsetse infestations in the delta were considered within the strategic and operational framework of the project.

In the end, two approximately equal north and south spray blocks were identified (Figure 1), which allowed two successive operations (in 2001 and 2002, respectively) to treat the entire infestations. This approach matched perfectly the underlying strategic and environmental plan for the project, which called for no single area to be treated more than once in succession. Thus, from planning through execution of the project, the

[1] Networks of shallow, diffuse rivers.

FIGURE 1
Distribution and density of tsetse on a Landsat image map of the Okavango delta prior to the 2001 and 2002 SAT operations



technical and visual support provided by GIS was essential to maintaining the strategic focus on project implementation.

Because the northern block included areas where disease incidence was high (Sharma *et al.*, 2001), it was treated first. GIS was instrumental in the planning and management of the target barrier, following the methodology of Allsopp (1998). As a standard procedure, monitoring surveys were georeferenced using GPS and subsequently archived in ArcView for operational analysis. Incidentally, when post-spray tsetse survivors were found after the first application in 2001, it was possible to link the corresponding data to a specific locality within the treatment area using the GIS overlay. As such, only that particular area was circumscribed and singled out for re-treatment — and with relative ease.

BRIDGING THE NAVIGATION GAP

The development of GPS technology in the 1980s and its subsequent adaptation by the aerial agricultural crop spraying industry (to provide an accurate system of aircraft track guidance) signalled both improved air navigation and potential benefits for air-assisted T&T programmes. Along with automated chemical flow control, the accurate and reliable track guidance provided by Satloc GPS navigation underpinned the success of the Okavango SAT programme under review.

Satloc guidance system

Satloc introduced parallel swathe guidance that applies GPS technology to guide aircraft along predefined flight paths. Pioneered for aerial crop spraying in the early 1990s, the system, as used in the Okavango delta in 2001 and 2002, arguably represented the most significant milestone in SAT development since the operations carried out in the 1970s and 1980s.

Once the treatment area and corresponding parameters had been established, these parameters were preprogrammed using the Satloc software, MapStar. A treatable spray area was created and defined using MapStar. The system could then calculate, according to the desired swathe width, the exact positions necessary for a series of successive parallel flight paths over the spray area.

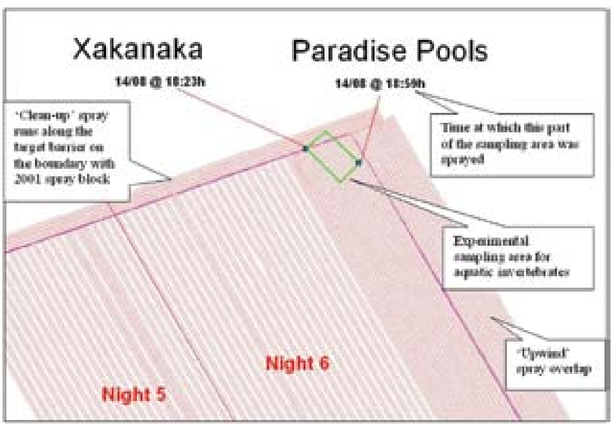
In theory, once a treatable spray area has been firmly established and the swathe size selected, individual flight paths can be flown independently yet accurately. For improved accuracy, onboard Differential GPS (DGPS) is used to guide the aircraft along its predetermined route while details of the flight path are simultaneously programmed into the system. Any risk factors that may influence the associated flight parameters may also be incorporated into the system. With Satloc DGPS, the purported accuracy of the guidance system is typically < 1 m, the most accurate ever used in SAT application.

Integrated data logger

In addition to providing accurate guidance, Satloc has incorporated a data logger that is updated every two seconds and allows flight and spraying statistics to be recorded en route. In this way, every step of the application can be subsequently verified. Using appropriate software, stored information can be retrieved on a personal computer for detailed review. The software package includes the graphic display shown in Figure 2.

FIGURE 2

GIS-derived illustration of Satloc data application in the northern boundary of the 2002 spray block showing accurate positions of the spray runs from corresponding flight logs



GENERAL OUTCOME

For effective management planning and public relations interactions with stakeholders, particularly because tsetse spraying was conducted overnight and in an area primarily used for tourism, a spray protocol for each night was developed using GIS and an overlay of anticipated flight paths. This served to provide advance notice to tour operators in the area who would potentially be affected by the spraying.

Overall, the operational results suggest that the programme was extremely successful. In just two years, tsetse were cleared from 16 000 km^2, and surveys carried out in the five years since the SAT operation ended in 2002 have found no new tsetse. In addition, no signs of cattle trypanosomiasis have been observed anywhere around the delta since 2001, and no cases have been reported from equine safaris operating in the delta. Independent environmental monitoring of the operation did not detect any long-term ecological effects (Perkins and Ramberg, 2004).

SUMMARY AND CONCLUSIONS

Previous SAT operations in Botswana and other countries in the 1970s had much broader parameters than the 2001 and 2002 operation in the Okavango delta under review here. Basic GPS technology, for instance, had not yet been developed, and accurate navigation was still a major problem. Typically, aircraft flew in formation, and pilots judged the spacing between them by eye. Furthermore, there was no mechanism for verifying the application rate of insecticide, and the operations often lacked systematic and coordinated plans.

In contrast, recent campaigns have benefited from the availability of more advanced and innovative management planning systems and strategies, including GIS applications and improved avionic technology. In 2001 and 2002, a decision was made to introduce a new generation of the SAT, enhanced by a host of effective management-support tools. Together with improved Satloc navigation, GIS made a significant contribution to the success of the campaign and thereby set the stage for future programmes to take the SAT to an even higher level of operational efficiency and effectiveness.

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Geospatial datasets and analysis techniques based on geographic information systems (GIS) have become indispensable tools in the planning, implementation and evaluation of a wide range of development programmes, including actions addressing sustainable agriculture and rural development. The growing volume of spatially explicit environmental information, combined with the widening utilization of GIS, allows ecological and socio-economic factors to be integrated more fully into the decision-making process, thus laying the foundation for a holistic approach to development.

This publication provides a cross-section of actual and potential applications of GIS in the context of interventions against tsetse and trypanosomiasis (T&T).

It aims to promote the sharing of knowledge and harmonization of methodologies among the wide range of actors concerned with the T&T problem. In the first section, a selection of geospatial datasets available in the public domain is reviewed through the lens of their possible use within T&T interventions. This review is followed by three case studies from two countries affected by trypanosomiasis (Burkina Faso and Botswana). The case studies provide examples of the application of GIS in operational scenarios and pay particular attention to data collection, management and analysis in the context of area-wide integrated management of tsetse and trypanosomiasis.

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