# Spatial analysis of the distribution of tsetse flies in the Lambwe Valley, Kenya, using Landsat TM satellite imagery and GIS

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## Summary

**1.** Satellite imagery, geographic information systems (GIS) and spatial statistics provide tools for studies of population dynamics of disease vectors in association with habitat features on multiple spatial scales.

**2.** Tsetse flies were collected during 1988–90 in biconical traps located along transects in Ruma National Park in the Lambwe Valley, western Kenya. Fine spatial resolution data collected by Landsat Thematic Mapper (TM) satellite and reference ground environmental data were integrated in a GIS to identify factors associated with local variations of fly density.

**3.** Statistical methods of spatial autocorrelation and spatial filtering were applied to determine spatial components of these associations. Strong positive spatial associations among traps occurred within transects and within the two ends of the park.

**4.** From satellite data, TM band 7, which is associated with moisture content of soil and vegetation, emerged as being consistently highly correlated with fly density. Using several spectral bands in a multiple regression, as much as 87% of the variance in fly catch values could be explained.

**5.** When spatial filtering was applied, a large component of the association between fly density and spectral data was shown to be the result of other determinants underlying the spatial distributions of both fly density and spectral values. Further field studies are needed to identify these determinants.

**6.** The incorporation of remotely sensed data imagery into a GIS with ground data on fly density and environmental conditions can be used to predict favourable fly habitats in inaccessible sites, and to determine number and location of fly suppression traps in a local control programme.

*Key-words*: geographic information system, remote sensing, spatial statistics.

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## Introduction

Tsetse flies are the vectors of animal and human trypanosomiasis, among the most serious diseases of cattle and people in Africa, and inhibit agricultural development in large parts of subsaharan Africa (Ford 1971; Rogers & Randolph 1986). Due in part to characteristics of the trypanosome parasites, control of these diseases is likely to depend largely on the management of tsetse populations. From an epidemiological point of view, successful fly population management will reduce the number and/or infection rate of flies below a transmission threshold.

Several species of tsetse and trypanosomes are responsible for disease transmission. Even for the same species of vector and parasite, spatial heterogeneity in environmental conditions results in local

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differences among fly populations and transmission dynamics that may defeat attempts at global modelling and control strategies of trypanosomiasis.

The Lambwe Valley in western Kenya (Fig. 1) supports large numbers of *Glossina pallidipes* Austen and infections of *Trypanosoma brucei* (Allsop, Baldry & Rodriguez 1972; Otieno & Darji 1985; Turner 1986; Wellde 1989). In addition to a high prevalence of nagana in cattle, and a history of human sleeping sickness, this is one of the remaining two sites in Kenya where persistent transmission of Rhodesian sleeping sickness occurs (Willet 1965; Baldry 1972; Wellde 1989). The ecology of tsetse and trypanosomiasis in the Lambwe Valley has been studied extensively (Turner 1986; Wellde 1989). The Lambwe Valley includes a national park with large game populations, surrounded by human settlements with domestic livestock. Extensive thicket and woodland in the valley and surrounding escarpments are infested with *G. pallidipes*.

Remote sensing is increasingly applied to studies of vector-borne diseases (Barinaga 1993; Hugh Jones 1989; Washino & Wood 1994), both in studies of vast areas using coarse spatial resolution data (Linthicum *et al.* 1987; Perry *et al.* 1990; Rogers & Randolph 1991; Rogers & Williams 1993), and in local studies using fine spatial resolution data (Washino & Wood 1994; Beck *et al.* 1994). Geographic information systems are increasingly used in studies of vector-borne diseases for data management and analysis (Dister *et al.* 1993; Kitron, Bouseman & Jones 1991; Kitron *et al.* 1994; Lessard *et al.* 1990; Guthe 1993; Beck *et al.* 1994; Glass et al. 1994).

Rogers & Randolph (1991) and Rogers & Williams (1993) discussed the application of coarse spatial resolution (1 km$^2$) AVHRR (advanced very high resolution radiometer) satellite data to explain fly distribution on a continental scale throughout Africa. Based on photosynthetic activity assessed through satellite imagery, and using a GIS, they linked the biological characteristics of tsetse populations with disease prevalence on a regional scale in West Africa. They further applied remote sensing and GIS to explain the distribution of tsetse and trypanosomiasis in other parts of Africa.

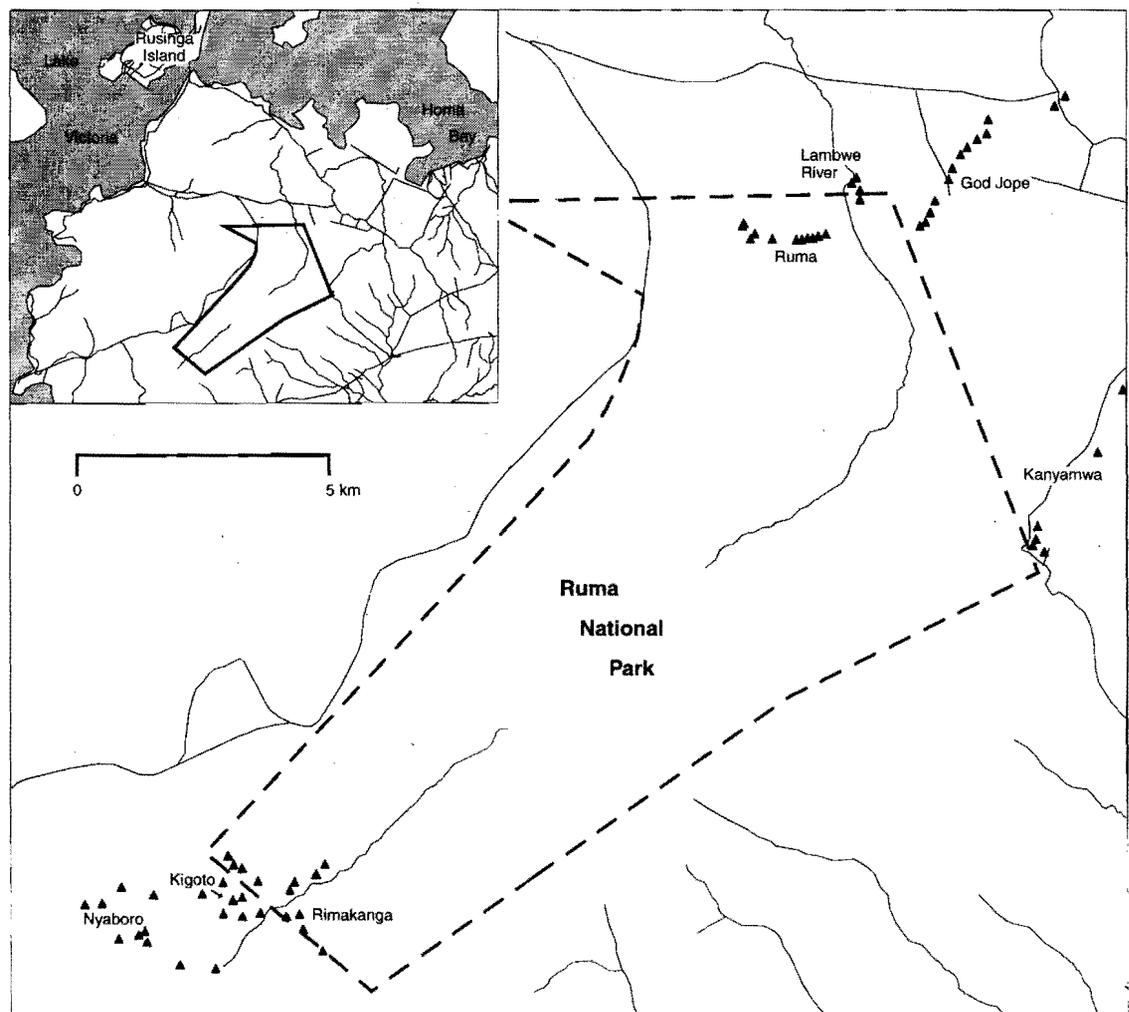In our study, we used the finer resolution (30 ×

Fig. 1. The Lambwe Valley and Ruma National Park with locations of tsetse attraction traps in transects used during 1988–90. Inset shows location of Ruma National Park in western Kenya.

30 m) Landsat Thematic mapper (TM) data and reference ground environmental data in Arc/Info GIS to identify factors associated with local variations of fly density in the Lambwe Valley, Kenya. We further applied the geostatistical techniques of spatial autocorrelation and filtering to determine the spatial components in these associations. The application of geostatistical methods to epidemiological studies is still in its infancy, although several methods have been summarized (Hungerford 1991; Roberts, Ravlin & Fleischer 1993), and applied to some vector-borne diseases (Hungerford 1991; Kitron *et al.* 1992). Our goal is to apply these methods to local control programs of tsetse and trypanosomiasis.

## Materials and methods

The study area was located in the 300 km² Lambwe Valley, South Nyanza Province in Western Kenya. A 120 km² game reserve, Ruma National Park, is located in the south end of the valley (Fig. 1). Land cultivation and grazing of domestic cattle from surrounding settlements take place around the park. Detailed descriptions of the Lambwe Valley, its ecology and demography have been published (Wellde 1989).

Large-scale analog maps from the Survey of Kenya (1:50 000) served as a basis for digitizing roads, park boundaries and hydrology into a GIS. A 185 × 170 km scene of Landsat 5 Thematic Mapper (TM), centered around the Lambwe Valley and dated 19 November 1989, was acquired. The resolution of these data are 28·5 × 28·5 m. Thirty control points (prominent land features) were located using a hand-held Magellan global positioning system (GPS), and used to georeference the TM data to subpixel precision. ERDAS image processing software was used for manipulation of the satellite data.

Flies were collected in Lambwe Valley by ICIPE personnel during 1988–90 in biconical attraction traps (Challier & Laveissiere 1973), located along transects inside and adjacent to thickets and wooded areas. At the north-east part of the park, traps were placed in Ruma thicket, in a transect running to God Jope hill, and along both sides of the Lambwe River (Fig. 1). At the south-eastern edge of the park traps were placed in Rimakanga thicket, Nyaboro thicket and the Kigoto area (Fig. 1). Additional traps were located in a conifer plantation on the Kanyamwa Escarpment north-east of Ruma National Park, where colonization of *G.pallidipes* has taken place (Turner 1981).

In 1991 and 1992, habitat descriptions and photographs were prepared for trap sites. Measurements of percentage closure (proportion of trap site faced by thicket), trap distance from thicket, and size of nearest thicket provided ground reference for validation of some satellite classification indices, and could be associated directly with catch data. A GPS was used to determine geographic coordinates for 67 trap locations for which catch data were available. Trap

locations were overlaid on the processed satellite image using ARC/INFO GIS. Spectral data from all seven TM bands were averaged for the nine pixels centered around each of the 67 trap locations with GPS coordinates. Consequently, the values for each spectral band per trap represent an average over an 85·5 × 85·5 m area.

Traps were checked daily for 6–31 days per month, and the average daily fly catch per trap was calculated each month. Traps were ranked according to average daily fly catch each month for each year and for the 3-year period. Both actual catch data and ranked catch data were used to analyse the spatial and temporal distribution of flies, and to associate fly density with selected remotely sensed and ground measured variables.

The seasonal distributions of catch in 60 traps with monthly data for one or more of the years 1988–90, and which could be associated with both ground data and remotely sensed data, were analysed in detail. For each month, a ranking of the average daily fly catch was made across all traps with data for a given year and for the 3-year period. The consistency in ranking of traps defined a spatial pattern which could be tested for associations with spectral and ground data (see below). We selected data from one month, December, which was closest to the time of year when the satellite image was taken (late November), and for which correlations of fly density with environmental parameters were typically high, as well as for May (when fly densities were high, at the end of the wet season), and for average annual catch.

The spatial pattern of fly distribution and its association with environmental factors was determined using Moran's *I* (Cliff & Ord 1973) measure of spatial autocorrelation. A standard normal variable derived from these measures, $Z(I)$, can be easily interpreted. A $Z(I)$ significantly larger than zero indicates that high or low values of a given variable are spatially aggregated. Significant spatial autocorrelation of two correlated variables suggests that a third variable may be responsible for at least some of the association between the two variables.

The degree of association of fly density with ground measures and remotely sensed data was calculated using correlation measures, and simple and multiple regression. To separate the spatial component from the association of fly density with spectral data, we used a spatial filtering technique developed by Getis (1990, 1995). This technique is based on measurements of spatial concentration around individual points (trap locations in this case) as described in Getis & Ord (1992) and Getis & Franklin (1987). These measurements are used to screen out the spatial autocorrelation of a variable (e.g. catch per trap, spectral values of a given band) through the generation of two new variables. These two variables describe the spatial component (association among trap locations), and the non-spatial component (association among catch

values with no relation to the spatial position of traps), with the sum of these two components equal to the original variable.

Spatial filtering is applied because part of the relationship between values (fly catch per trap) may be related to physical proximity, so that proximal values may not be independent. The independent association of these values with environmental data (as measured using ground-referenced remote sensing parameters) can only be quantified when the spatial effects are removed. Thus, the application of spatial filtering to the data on fly densities and TM band values allowed us to control for the effect of spatial association, and to calculate the relative contribution of spatial and non-spatial components in the distribution of fly catch among traps. We then applied multiple regression that included the spatial and non-spatial components as independent factors.

## Results

### SEASONAL DISTRIBUTION OF CATCH

The mean daily fly catch per trap was highly variable between samples taken from the same trap in different months (Table 1). In 1988, fly catch was highest in February, followed by April, and remaining high through July; it was lowest in November–December. In 1989, catch was highest in March, followed by February, and remaining relatively high through June; it was lowest in July, August, November and in Jan-

Table 1. Monthly distribution and standard error of average daily fly catch in tsetse attraction traps in Lambwe

| Month | 1988 ($n = 39$) | 1989 ($n = 29$–30) | 1990 ($n = 16$) |
|---|---|---|---|
| Jan | 237·4 | 4·8† | 7·5§ |
| | (60·7) | (1·7) | (1·4) |
| Feb | 612·3 | 15·4* | 32·9 |
| | (157·6) | (2·6) | (8·4) |
| Mar | 292·9 | 20·9 | 17·4 |
| | (60·8) | (3·4) | (5·5) |
| Apr | 389·3* | 15·0 | 22·6 |
| | (81·6) | (2·7) | (5·7) |
| May | 216·5* | 15·2 | 15·5 |
| | (36·2) | (2·4) | (4·2) |
| Jun | 316·2 | 12·5 | 12·0 |
| | (58·5) | (2·7) | (3·7) |
| Jul | 197·0 | 6·9‡ | 5·9 |
| | (35·5) | (1·5) | (2·0) |
| Aug | 35·0 | 8·6 | 8·1 |
| | (8·6) | (2·0) | (3·6) |
| Sep | 28·2 | 12·4* | 7·3 |
| | (8·6) | (3·3) | (3·3) |
| Oct | 18·5 | 9·0 | 9·9 |
| | (6·3) | (2·4) | (4·4) |
| Nov | 8·2 | 6·1 | 11·3 |
| | (2·4) | (1·5) | (4·3) |
| Dec | 4·3 | 9·7 | 6·5 |
| | (8·2) | (2·1) | (2·5) |

*$n = 33$; †$n = 11$; ‡$n = 23$; §$n = 8$.

uary (when only 11 traps were monitored). In 1990, catch was highest in February, followed by April; it was lowest in July and December. Thus, in all 3 years, fly density declined in July or August following the beginning of the dry season in June, and peaked in the long wet season of February–May.

The ranking of traps with regard to average fly catch per month remained consistent throughout the year. Correlations among the ranked fly catch values in the various months were positive and highly significant each year. For 1988, correlations ($r$) were always $> 0.6$ ($P < 0.0001$). For 1989, correlations ($r$) were always $> 0.7$ ($P < 0.01$), except for April with correlations with other months as low as 0·6 ($P < 0.05$), and excluding January, when only four traps were positive. For 1990, correlations were very high ($r > 0.8$, $P < 0.0001$), somewhat lower for July and December with other months ($r > 0.6$, $P < 0.01$), and even lower for July with December ($r = 0.52$, $P < 0.05$).

Monthly weather data (total rainfall, minimum and maximum temperature) were received from nearby weather stations (Fig. 1) in Mbita Point (1988, 1989) and Rusinga Island (1988, 1990). The stations indicate high correlations of rainfall, minimum and maximum temperature between the two stations ($r = 0.94, 0.86$ and $0.95$, $P < 0.01$, respectively).

In 1988, the total rainfall was 1239 mm in Mbita Point and 1265 mm in Ruesinga; rainfall was highest in March through May, with relatively little rain during the rest of the year, except for September. In 1989, the total rainfall was lower (668 mm in Mbita), with highest rainfall in March through May and in November. In 1990, total rainfall was 837 mm in Ruesinga, with rainfall again highest in March through May, and low during the rest of the year. The average monthly maximum temperature was consistent in all 3 years (27·4–27·7 °C), while the average minimum temperature was similar in 1988 and 1989 (20·5–20·8 °C), but lower in 1990 (18·4 °C).

When each year was considered separately, correlations (using Spearman rank correlation) were significant only in 1990, when the average monthly fly catch was positively correlated with rainfall ($r = 0.069$, $P < 0.05$) and negatively correlated with minimum temperature ($r = -0.68$, $P < 0.05$). When data from all 3 years were considered together, fly catch was positively correlated with rainfall ($r = 0.55$, $P < 0.01$), and negatively with minimum and maximum temperature ($r = -0.56$, $P < 0.01$ in both cases). Using time lags to correlate fly density with rainfall 1–2 months earlier, did not provide additional significant correlations.

### SPATIAL DISTRIBUTION OF FLIES

For 60 traps (28 in 1988, 17 in 1989 and 15 in 1990), the average daily catch for each month was ranked. Annual relative rank of each trap (Fig. 2) was cal-
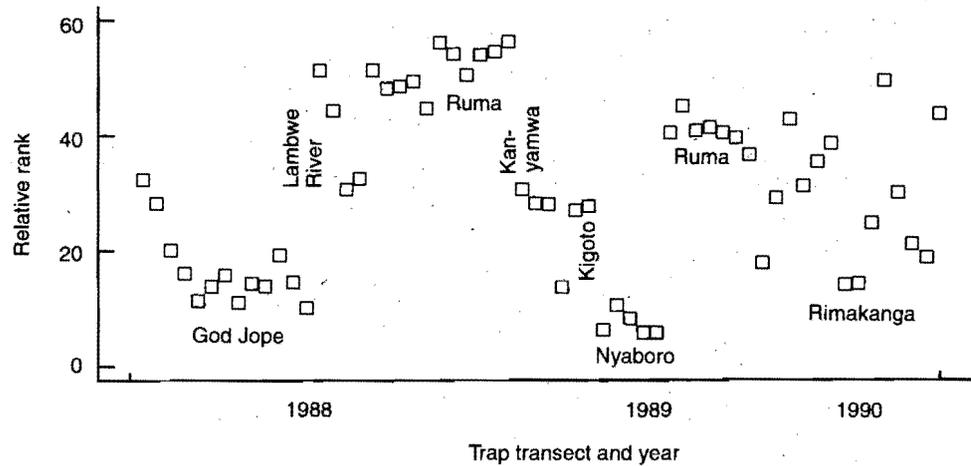
**Fig. 2.** Average relative ranking of monthly fly catch in all traps in Lambwe (1988–90). For each trap, the relative rank was calculated as the annual average of its monthly rankings. Trap values are arranged along the *x* axis according to their number in a transect, with transects arranged alphabetically within each year.

culated as the average of monthly ranks. When traps were grouped by transect, traps within transects had similar relative ranks, with the exception of Rimakanga Thicket (Fig. 2). In Ruma Thicket, with data for 2 years, average rank of traps was similar for both 1988 and 1989. This similarity of catch within transects is associated with transects being located in relatively uniform habitats. Traps in Rimakanga transect were located at various distances from the thicket, and were less uniform. Differences between transects were significant as measured by one-way ANOVA ($F = 28.8$, $P < 0.0001$ for average annual catch; and ranging from 15.3 to 230.9 for monthly catches, $P < 0.0001$ for each month). The average ranking of each transect was measured using the Kruskal–Wallis test (Table 2). Differences in ranks between transects were significant ($w = 47.0$, $P < 0.0001$ for average annual rank of monthly catch; *w* ranging from 39.7 to 56.1 for monthly catches, $P < 0.0001$ for each month). Fly catch was highest in Ruma Thicket, and lowest in Nyaboro and God Jope thickets, with intermediate values in Kigoto, Lambwe River and Rimakanga. Thus, both high and low densities of tsetse occurred at both ends of the valley.

The distribution of fly catch among traps was fur-

ther studied through Moran's *I* measure of spatial autocorrelation. A significant positive spatial auto-correlation was found among all traps, as well as when the northern and southern traps were considered separately, or when trap data for different years was not combined (Table 3). Thus, neighbouring traps tended to be ranked similarly with regard to fly catch, and spatial proximity of traps *per se* is a factor that contributes to this positive relationship between catch values in neighbouring traps.

More precise information on the spatial relationship can be determined using corellograms, which can pinpoint the degree of association over distances and determine the distance beyond which spatial association has no further influence. This was done each year for both the actual catch data and for the ranking of catch by trap. The results were similar, and the data for the ranked fly catch is presented in Fig. 3.

In 1988, when only data from the northern end of the valley was considered, Moran's *I* peaked at 0.8–1.0 km for December (when several traps were empty), and at 2.0–2.5 km for May and for the average

**Table 2.** Ranking of average daily trap catch in Lambwe by transects, using the Kruskal–Wallis procedure (W = 47.0, P < 0.0001)

| Transect (year) | Sample size | Average rank |
| --- | --- | --- |
| God Jope (1988) | 13 | 15.8 |
| Lambwe River (1988) | 4 | 41.5 |
| Ruma (1988) | 11 | 54.1 |
| Kanyamwa (1989) | 3 | 28.3 |
| Kigoto (1989) | 3 | 19.3 |
| Nyaboro (1989) | 5 | 3.2 |
| Ruma (1989) | 6 | 42.1 |
| Rimakanga (1990) | 15 | 30.1 |

**Table 3.** Spatial autocorrelation of catch of tsetse flies in attractant traps in Lambwe, 1988–90

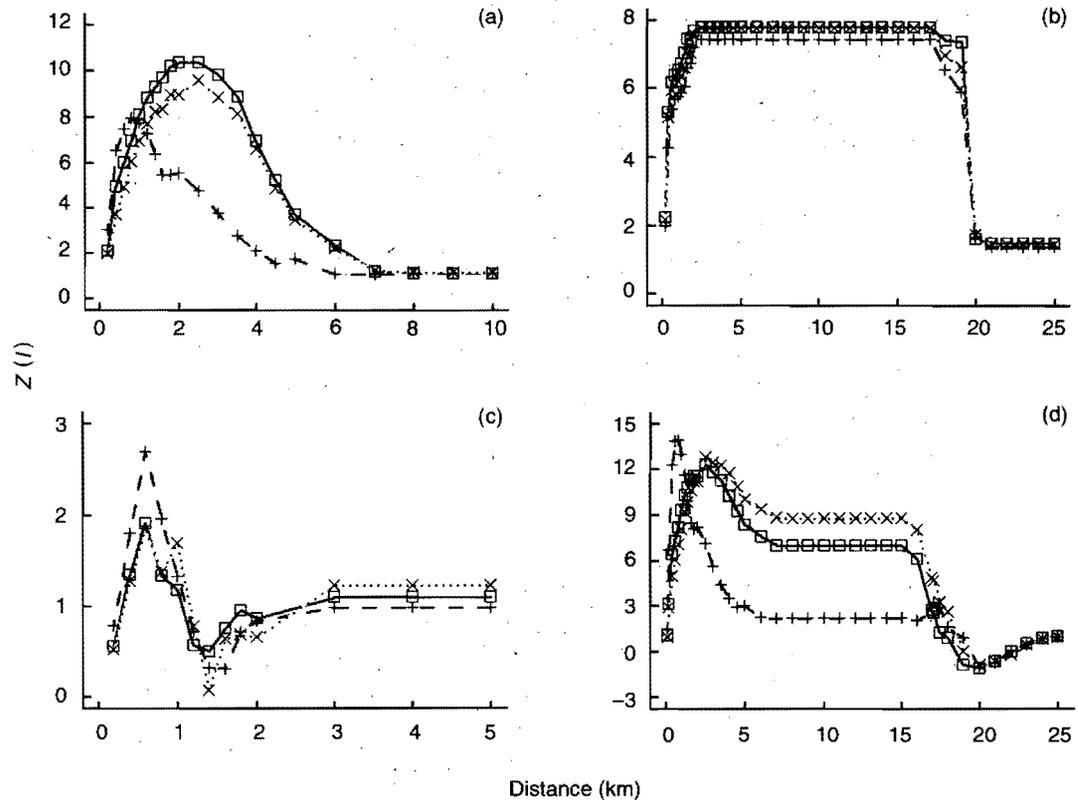| Groups of traps | Number of traps | Moran's *I* | *Z*(*I*) |
| --- | --- | --- | --- |
| All traps (1988–90) | | | |
| Daily average | | 1.06 | 8.36 |
| December | 60 | 1.21 | 9.50 |
| May | | 0.74 | 5.88 |
| North Lambwe (1988) | | | |
| Daily average | | 0.82 | 3.67 |
| December | 28 | 0.98 | 4.33 |
| May | | 0.60 | 2.73 |
| South Lambwe (1989–90) | | | |
| Daily average | | 0.55 | 3.36 |
| December | 23 | 0.77 | 4.56 |
| May | | 0.61 | 3.70 |

**Fig. 3.** Spatial autocorrelation of fly catch (as measured by standardized Moran's *I*) over distance for each year and for the 3-year period. (a) 1988 (north Lambwe); (b) 1989 (north and south Lambwe); (c) 1990 (south Lambwe); (d) 1988–90 (north and south Lambwe). Average (––□––); December (–– + ––); May (···· × ····).

monthly catch (Fig. 3a). These distances approximate the mean and median distances among traps (1·5 km and 1·3 km respectively in December, 2·5 km and 2·3 km otherwise). In 1989, the distances (mean, 10·4 km; median, 17·5 km) among traps were much higher, because traps from both the northern and southern edges of the valley were monitored. Spatial autocorrelation was uniformly high over a large range of distances (2·5–17 km), indicating a strong positive spatial association among traps within the two edges of the park (Fig. 3b). The sharp drop at 17 km is a result of lack of spatial association between the two edges of the park. In 1990, when only one thicket (Rimakanga), in the southern part of the valley was considered, Moran's *I* peaked within a very short distance (0·6 km), below the average distance among traps (mean of 1·2 km, and median of 1·1 km; Fig. 3c). This indicates a very strong spatial effect between proximal traps in this less uniform transect.

When data for all 3 years were grouped together, spatial autocorrelation was very high ($Z(I) > 12$) peaking at 0·6–0·8 km for December, when several traps were empty, and at 2·5 km for May and for the average monthly catch (Fig. 3d). Values of spatial autocorrelations among traps were high over a large range of distances. This was particularly notable during May and for the average monthly catch, with spatial autocorrelation values remaining high over distances of 0·6–16·0 km. The mean distance among

traps from all 3 years was 10·5 (similar to 1989), but the median distance was lower (8·0 km), since more traps were located at each of the two edges of the park. The range of highly significant positive values of $Z(I)$ suggests that a strong positive spatial association among traps occurs within transects and within the two ends of the park, but not necessarily across the whole study area. Data from traps between the two trap concentrations at the edges of the park could provide a more complete determination of the pattern of spatial association.

### ASSOCIATION OF FLY CATCH WITH FIELD DATA

Of several measures used to characterize each trap location on site, percentage closure (proportion of area surrounding trap that was covered with brush or woody vegetation) emerged as most significant and showed highest correlations with fly catch. For all years, fly catch was significantly correlated with closure each month ($P < 0·01$), except for June 1988 and April 1989 ($0·1 > P > 0·05$). Other measures that showed positive correlations with fly catch included size of thicket around the trap and, to a lesser extent, degree of ground coverage by shrub and distance of the trap from the thicket. All of these measures are associated with the extent of ground cover around

**Table 4.** Correlations of ranked fly catch values and ground measures in Lambwe for 1988 and 1988–90

| Measure | r for 1988 (n = 28) Dec. | Av. | r for 1988–90 (n = 60) Dec. | Avg. |
|---|---|---|---|---|
| Closure (%) | 0·67** | 0·65** | 0·79** | 0·69** |
| Thicket extent | 0·57* | 0·64** | 0·61** | 0·68** |
| Distance | 0·44+ | 0·35 | 0·46** | 0·40* |

$+ P < 0.05$; $* P < 0.01$; $**P < 0.001$.

traps. Table 4 provides a summary of the rank correlations of three ground measures with the trap catch in December and May and with average annual trap catch both for 1988 and for the 3-year period. The correlation with percentage closure was always the highest, reaching $r^2 = 0.62$ in December when all 60 traps were considered.

### ASSOCIATION OF REFERENCE GROUND DATA WITH SPECTRAL DATA

The significance of association of fly density with spectral data requires translation of remotely sensed data to the ground level, and are dependent on the spatial unit selected for analysis. Correlation between spectral values of bands and ground measures most closely associated with fly catch are summarized in Table 5 for 1988 and for the 3-year period. The highest correlations were found for bands 7 and 3 with percentage closure. Correlation with the extent of the thicket and distance from the thicket were also significant, particularly for the 3-year period. Correlations with the normalized difference vegetation index (NDVI) were not as high as with the individual band values. It is possible that measures of soil and vegetation moisture, or other ground measures, which were not available, could have provided additional significant associations.

### ASSOCIATION OF FLY CATCH WITH SPECTRAL DATA

Correlations of several bands and band ratios with fly catch were highly significant. Table 6 summarizes the correlations of all spectral bands and NDVI with the

December, May and average catch for 1988 and for 1988–90. In 1988, correlations were highest with bands 7,6 and 5; in 1988–90 with bands 7,5 and 3. The mid-infrared bands, 7 and 5, are associated with vegetation moisture and with soil moisture. Band 3 (Red) is associated with chlorophyl absorption, and is useful for discrimination of vegetation type. The thermal band 6 (which has a different spatial resolution of $120 \times 120$ m vs. $28.5 \times 28.5$ m for the other six bands) is used in vegetation stress analysis and soil moisture discrimination (Lillesand & Kiefer 1994; Washino & Wood 1994). The correlation of catch with band 6 was highest in 1988, but this was not repeated in other years.

Overall, band 7 emerged as being consistently highly correlated with fly catch. Band 7 is associated with moisture content of soil and vegetation, which are documented determinants of fly density and survival (Rogers 1979; Rogers & Randolph 1986, 1991; Rogers & Williams 1993). The correlations with band 7 were higher than with the best ground measure (percentage closure) in 1988, but not for all years together. When looking at band ratios, correlations were highest with ratios which include band 7. For 1988, B7:B1 showed a slightly higher correlation than B7 alone ($r = -0.76$ for Dec. and $-0.80$ for the average monthly catch), but overall there was no convincing reason to use band ratios over simple band values. The commonly used NDVI, which is associated with photosynthetic activity, was less highly correlated with fly catch than several bands and band ratios.

When several bands and band ratios are considered together using backward stepwise multiple regression, an even larger proportion of the variance in catch values can be explained (Table 7). In all cases, band 7 and/or the ratio of band 7 and band 1 was included in the regression equation. Band 1 was also commonly included, and bands 6, 3 and NDVI were included several times (Table 7). The correlation was as high as $r^2 = 0.87$ in 1989, $r^2 = 0.88$ for the average catch in 1988, and exceeded 0·6 in all cases.

### FILTERING OF SPATIAL EFFECTS

To separate the spatial effects of the association of fly density with spectral values, we filtered the spatial effects from the associations of fly catch per trap and

**Table 5.** Correlations of ground measures and spectral data in Lambwe for 1988 and 1988–90

| Measure | r for 1988 (n = 28) B3 | B5 | B7 | NDVI | r for 1988–90 (n = 60) B3 | B5 | B7 | NDVI |
|---|---|---|---|---|---|---|---|---|
| Closure (%) | 0·54* | 0·49* | 0·56* | −0·49* | 0·65* | 0·57* | 0·57* | −0·49* |
| Thicket extent | 0·37+ | 0·49* | 0·43+ | −0·29 | 0·49* | 0·43* | 0·45* | −0·38* |
| Distance from thicket | 0·42+ | 0·42+ | 0·40+ | −0·41+ | 0·37* | 0·37* | 0·37* | −0·37* |

$+ P < 0.05$; $*P < 0.01$.

**Table 6.** Correlations of TM band values and fly catch in Lambwe for 1988 and 1988–90

| TM Band | r for 1988 (n = 28) | | | r for 1988–90 (n = 60) | | |
|---|---|---|---|---|---|---|
| | Dec. | May | Av. | Dec. | May | Av. |
| 1 | −0·13 | 0·24 | 0·03 | −0·42** | −0·32+ | −0·32+ |
| 2 | −0·17 | 0·15 | −0·05 | −0·41* | −0·19 | −0·27+ |
| 3 | −0·57* | −0·30 | −0·52* | −0·63** | −0·30+ | −0·47** |
| 4 | 0·51* | 0·18 | 0·41+ | 0·45** | 0·14 | 0·27+ |
| 5 | −0·67** | −0·54* | −0·72** | −0·63** | −0·19 | −0·47** |
| 6 | −0·80** | −0·81** | −0·91** | −0·36* | 0·05 | −0·25 |
| 7 | −0·74** | −0·53* | −0·75** | −0·68** | −0·28+ | −0·52** |
| NDVI | 0·59** | 0·26 | 0·51** | 0·59** | 0·24 | 0·40* |

$+ P < 0.05$; $*P < 0.01$; $**P < 0.001$.

the reciprocal of the values of band 7 for each trap location. For December, May and the average catch for each year, and for the 3 years together we screened out the spatial component of the distribution of values of spectral bands, percentage closure, and of the number of flies per trap. The resulting new variables were used to assess the role of the spatial and non-spatial components of the association between fly catch and spectral data. The multiple regression of catch values on the two components of B7 was always higher than the simple regression on B7 (Table 8). The *t*-values indicate that the spatial component contributed more to the association, but that a significant spatially independent association exists for the December and the average catch in 1988 and in 1988–90. Thus, a large component of the association between monthly catch and values of band 7, is the result of other deter-

minant(s) underlying the spatial distribution of fly density and spectral values.

## Discussion

The emphasis on local variations in fly distribution and the use of fine resolution satellite data complement the studies of Rogers and his colleagues (Rogers 1991; Rogers & Randolph 1991; Rogers & Williams 1993), who associated coarse resolution (1 km²) AVHRR satellite data with tsetse and African trypanosomiasis distribution on a coarse scale. They found significant correlations of fly mortality rates and fly size with mean monthly NDVI values in west Africa. They further correlated NDVI values with seasonal changes in numbers of human trypanosomiasis disease cases in East Africa. The success of their work is based on extensive ground studies and analysis of the biological and environmental determinants of tsetse population dynamics and vectorial capacity (Rogers 1979; Rogers & Randolph 1984, 1986).

**Table 7.** Variables included in stepwise multiple regression of ranked fly catch in Lambwe on TM band values (with *t* values for each variable, and the correlation coefficient $(P < 0.01$ in all cases)

| Year | Month | Variables (*t*-values) | r² |
|---|---|---|---|
| 1988 | Dec | B1 (−2·7), B6 (−3·3), B7 (2·2), B7/B1 (−2·0) | 0·71 |
| 1988 | May | B3 (−2·1), B6 (−6·3), B7/B1 (3·4) | 0·75 |
| 1988 | Average | B3 (−3·6), B6 (−8·3), B7 (3·1) | 0·88 |
| 1989 | Dec | B1 (−7·3), B4 (2·4), B7 (3·7) | 0·87 |
| 1989 | May | B2 (−2·25), B3 (−2·5), B5 (3·8), B7 (2·5), B7/B1 (−2·7) | 0·87 |
| 1989 | Average | B1 (−3·6), B6 (−1·8), B7 (2·8), B7/B1 (−2·3) | 0·87 |
| 1990 | Dec | B1 (2·2), B7 (−5·1), NDVI (−3·0) | 0·63 |
| 1990 | May | B1 (2·2), B7 (−5·0), NDVI (−2·9) | 0·62 |
| 1990 | Average | B1 (2·9), B7 (−4·9), NDVI (−2·4) | 0·63 |

**Table 8.** Multiple regression of ranked tsetse catch values in Lambwe on reciprocal TM band 7-values separated into a spatial (NB7) and non-spatial (LB7) component. The *t*-values for the two components and the correlation coefficient of the multiple regression are listed. For comparison, the correlation efficient from a simple regression with the composite B7 is also given

| Month | *t*-value for | | r² | r² with B7 |
|---|---|---|---|---|
| | MB7 | LB7 | | (unseparated) |
| Dec 1988 | 3·1* | 7·5** | 0·67 | 0·55 |
| May 1988 | −0·8 | 6·4** | 0·65 | 0·29 |
| Average 1988 | 2·2+ | 10·1** | 0·79 | 0·56 |
| Dec 1989 | −1·0 | 7·4** | 0·80 | 0·35 |
| May 1989 | 0·7 | 6·4** | 0·75 | 0·49 |
| Average 1989 | 1·1 | 7·7** | 0·82 | 0·34 |
| Dec 1988–90 | 5·0** | 9·1** | 0·58 | 0·47 |
| May 1988–90 | 0·3 | 3·7* | 0·22 | 0·08 |
| Average 1988–90 | 2·2+ | 6·9** | 0·47 | 0·27 |

$+ P < 0.05$; $*P < 0.01$; $**P < 0.001$.

Rogers (1991) emphasized the need for utilizing fine spatial resolution data without neglecting the essential ground studies that enabled him to reach the conclusions mentioned above. Rogers & Williams (1993) further caution that to benefit from advances made in GIS, a better understanding of spatial and temporal determinants of vector and parasite distributions is necessary. They do, however, welcome the return of the spatial component to epidemiological studies that is made possible with the advent of GIS and satellite imagery.

Although our understanding of the determinants of tsetse distribution on a large scale has advanced significantly, we are still limited in our understanding of temporal changes in risk of transmission of trypanosomiasis. We are also limited in our ability to translate coarse-scale data to assist local fly surveillance and control efforts.

Our study was intended as a step to assist local efforts to survey, predict and control risk factors for animal and human trypanosomiasis. We concentrated on a correlation study of spectral data with fly density as measured through trap catch. The high correlations between trap catch and band values are especially striking given that trap locations were selected prior to (and independent of) this study to maximize fly catch. This suggests that when less optimal locations are considered, correlations are likely to be even higher.

Further understanding of the association of ground measures with spectral data will assist in better interpretation and possible extrapolation of our results. Because all of our ground measures were related to the extent of vegetation cover around the traps, the importance of other ground measures (e.g. soil type, vegetation type, etc.) and their association with spectral data could not be assessed. A more detailed characterization of the trap environment is necessary. This is further supported by the results of the spatial analysis, which indicated that the association of fly catch with spectral values is due largely to a spatial association.

Statistical spatial analysis of the type reported here is new to parasitological and epidemiological studies. Yet, when studying associations between environmental determinants of vector distribution and risk factors for disease transmission, such an analysis is valuable. A finding such as ours, that the association at a given time is largely spatial, suggests that common factors are responsible for large components of the observed distribution of spectral values and tsetse density in the Lambwe Valley. In contrast, a large non-spatial component in the association may suggest a more direct link, and a possible biological mechanism which determines the association.

The high correlations of fly catch with remotely sensed fine resolution satellite data do suggest that satellite imagery may be a useful tool for predicting local variations in fly density. Specifically, the incor-

poration of satellite imagery into a GIS-based surveillance program can be used to predict favourable fly habitats in inaccessible sites. A GIS provides an information management tool that allows for the association of remotely sensed environmental data and ground-gathered (reference) data with data on fly population dynamics, host distribution, human agricultural practices, trypanosomiasis infection rates, etc. Analytical techniques applied to the composite database can be used to explain and predict fly distribution and to target effective disease control measures. One potential use is the determination of the optimal number and location of fly monitoring and suppression traps based on probable fly density and available ground reference data.

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