Mapping African animal trypanosomosis risk: the landscape approach

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Summary

African animal trypanosomosis (AAT) is a major hindrance to cattle breeding in the Mouhoun River Basin of Burkina Faso. The authors describe a landscape approach that enables the mapping of tsetse densities and AAT risk along the Mouhoun River loop (702 km long) in Burkina Faso. Three epidemiological landscapes were described: the first and most dangerous corresponded to protected forests and their border areas, with a 0.74 apparent density of infectious fly per trap per day (ADTi), the second to a partially disturbed vegetal formation, with a 0.20 ADTi and the third to a completely disturbed landscape with a 0.08 ADTi. Using this risk indicator, the first landscape was 3.92 more risky than the second which was 3.13 more risky than the last. Similar infectious rates were found in all landscapes (approximately 8%) but tsetse apparent densities dropped significantly (p<0.001) in half-disturbed (2.66) and disturbed landscapes (0.80) in comparison to the natural and border landscapes (11.77). Females were significantly younger (mean physiological age of 29 days) only in the most disturbed landscape (p<0.05) than in the two others one (41 days). According to these results, practical implications of stratifying AAT risk and mapping tsetse densities in vector control campaigns are discussed.

Keywords

African animal trypanosomosis, Burkina Faso, Epidemiological landscape, Geographic information system, Remote sensing, Risk assessment, Tsetse.

Mappatura del rischio per le tripanosomiasi africane: l'approccio basato sull'analisi ambientale

Riassunto

Le tripanosomiasi animali africane (AAT) sono il maggior ostacolo all'allevamento bovino nel bacino del fiume Mouhoun River nel Burkina Faso. Gli autori descrivono l'approccio basato sull'analisi ambientale che permette la mappatura della densità di mosche tse-tse e del rischio di tripanosmiasi animale africana lungo l'ansa del fiume Mouhoun in Burkina Faso (702 Km). Sono stati descritti tre ambienti epidemiologicamente rilevanti: il primo e più pericoloso corrispondente alle foreste protette con le loro aree confinanti, con una densità apparente di 0,74 mosche infettanti per trappola al giorno (ADTi), il secondo corrispondente alle foreste parzialmente disturbate dall'attività dell'uomo con una densità pari a 0,20 ADTi ed un terzo corrispondente ad un ambiente completa-mente disturbato dall'attività dell'uomo con un valore pari a 0,08 ADTi. Usando questo indicatore di rischio, il primo ambiente è risultato 3,92 volte più rischioso del secondo che a sua volta è risultato 3,13 più rischioso dell'ultimo. Simili percentuali di infezione sono state ritrovate in tutti gli ambienti (circa l'8%) ma la densità delle mosche tse-tse è risultata molto più bassa negli ambienti disturbati (0,80) e semi-disturbati (2,66) in comparazione con

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gli ambienti naturali ed i confinanti (11,77). Le femmine catturate erano significativamente più giovani (età media fisiologica 29 giorni) solamente nell'ambiente più disturbato rispetto agli altri due (41 giorni). In accordo con questi risultati, sono discusse le possibili applicazioni della stratificazione del rischio per le tripanosmiasi animali africane e della mappatura della densità delle mosche tse-tse nelle campagne di controllo del vettore.

Parole chiave
Ambienti epidemiologici, Burkina Faso, Telerilevamento, Tripanosmiasi animale africana, Tse-tse, Sistema informativo geografico, Valutazione del rischio.

Introduction

In Burkina Faso, like most sub-Saharan West African countries infected by tsetse flies, tsetse and African animal trypanosomoses (AAT) are a major hindrance to cattle breeding (26, 28, 38, 39). Tsetse flies also are cyclic vectors of sleeping sickness in humans. Given the willingness of most African countries to solve the problem, priority areas for control were defined through entomological and epidemiological studies (24) and the Mouhoun River Basin, located in the West African cotton triangle, is considered as a priority area for tsetse and trypanosomosis (T&T) control.

A recent study of the Mouhoun riverine vegetation demonstrated that this river section is constituted of three successive major ecological sections, namely: the tributaries that harbour mainly a Guinean gallery forest, the western branch that harbours a Sudano-Guinean gallery forest and the eastern branch that harbours a Sudanese gallery forest (4). Two riverine tsetse species, *Glossina palpalis gambiensis* Vanderplank 1949 (Diptera, Glossinidae) and *G. tachinoides* Westwood, 1850 were still present in relatively high densities. Their competition and predominance was determined by the riverine forest ecotype, whereas their densities depended on its disturbance level.

During recent decades, prediction models of the presence or abundance of tsetse flies using remote sensing coupled with field environmental data provided by geographic information systems (GIS) have been designed as decision-making tools at various levels (from local to regional) (16, 22, 35, 36, 37), confirming the potential of this approach. The landscape approach consists of trying to predict the properties of the fragmented riverine forest, that is below the imagery's resolution, from the properties of its neighbouring pixels. In the case of riverine tsetse flies, this riverine forest (<10 m in width), is the principal factor that determines their presence and abundance in West Africa (4, 14, 15, 33). It can be characterised from the analysis of peri-riverine soil use classes in buffers of 500 m around the river course. This approach has been developed on a local scale (16) and recently widened to 234 km of the Mouhoun River (eastern branch) (6). It was applied here to the entire Mouhoun River loop, corresponding to 702 km. The aim of the present work was to assess tsetse densities and trypanosomosis risk levels in the various peri-riverine landscapes of the Mouhoun water course in the three ecological sections, using remote sensing data.

Materials and methods

Context and location of the study

In a recent study, crop densities in 500 m buffers around the river course, measured from Landsat images could be positively correlated to the disturbance of the gallery forests, with a negative impact on tsetse densities (6). Three landscapes were discriminated, including a forest, a border and a disturbed landscape (agro-pastoral area). This study assessed riverine tsetse densities and trypanosomosis risk on the eastern branch of the Mouhoun River, harbouring a Sudanese gallery forest. The border landscape was demonstrated to be the area most at risk. The aim of the present study was to extend these results to the basin scale.

The study area, called the Mouhoun River loop, is located north of Bobo Dioulasso (4°17′W, 11°10′N). The study extends from the sources of the Mouhoun (elevation of 500 m, 4°55′W, 11°16′N), west of Bobo Dioulasso through the Sourou Dam at its northern edge (elevation of 260 m, 3°26′W, 12°44′N) to Boromo (elevation of 240 m, 2°55′W, 11°44′N), a town located between Bobo Dioulasso and Ouagadougou. It covers an area of approximately 700 km² along the river course (Fig. 1).

Along the tributaries that harbour mainly a Guinean gallery forest, *G. p. gambiensis* was the predominant tsetse species and its density did not drop significantly with the disturbance of gallery forests; in the western branch, harbouring a Sudano-Guinean gallery forest, both tsetse species were abundant and their densities were negatively correlated with the disturbance level of the gallery. Finally, in the eastern branch, harbouring a Sudanese gallery forest, *G. tachinoides* was the predominant species and the disturbance level of the gallery was negatively correlated to its densities (4).

Entomological and parasitological surveys

Entomological surveys were conducted during the 2002 hot dry season (5). A total of 10% of the river course was sampled, using standardised biconic traps (8) 100-150 m apart, operated from 9.00 h to 16.30 h. The 608 trap locations were recorded using global positioning systems (GPS). Tsetse flies were recorded by species by trap (apparent density per trap and per day or ADT) and sampled for dissection in the field. The proboscis, salivary glands, and mid-gut of part of the flies were examined directly using microscopes in the field. When at least one of these three organs in a fly was infected, all three were stored in distilled water stored at –20°C and analysed by polymerase chain reaction (PCR) at the *Centre de coopération internationale en recherche agronomique pour le développement* (CIRDES) in Bobo Dioulasso, to determine the species of trypanosome involved with monospecific primers of *Trypanosoma vivax*, *T. brucei sensu lato* and *T. congolense* savannah-type (17, 31). The proboscis of the other dissected flies were stored in the same conditions and analysed by PCR (482 flies were tested for trypanosome infection). Downwards, only the mature infections, i.e. those of the proboscis, were used to calculate mature fly infection rates. In addition, the physiological ages of 219 females were determined by dissection of the ovary glands (29).

Ecological surveys

The riverine forest of each trapping site had been previously classed into three disturbance levels using phyto-sociological statements (4). In addition, a semi-quantitative note of abundance (0 = absence, 1 = low, 2 = medium and 3 = high) was attributed to each trapping site for cattle frequentation. The notes were attributed by using direct and footprint observations and by interrogating a native guide.

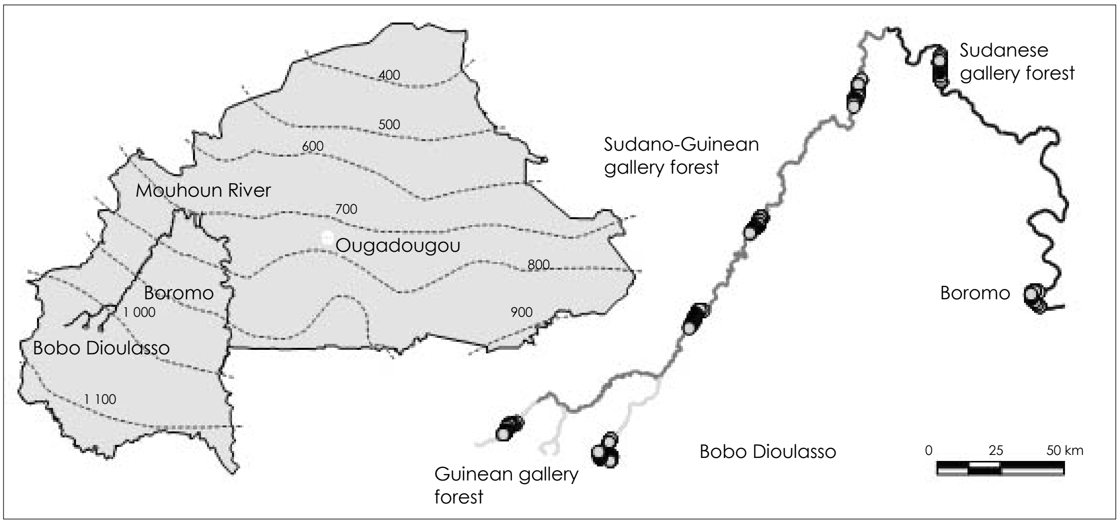

Figure 1
Location of the trapping sites on the three ecological sections of the Mouhoun River

During the ecological surveys, three entomological landscapes were identified in the field (protected forest, border of a protected forest and cultivated and grazed areas) and were registered in all trap locations.

Remote sensing data and methods

Three Landsat 7 enhanced thematic mapper plus (ETM+) images were required to cover the Mouhoun Basin, of which two were from 20 October 1999, Path/Row 196/51 and 196/52 and one from 16 December 2000, Path/Row 197/52. These scenes were cloud-free and had no apparent haze. The river course was digitised from Landsat images using MapInfo® 7.0 software. A buffer of 1 km in width was extracted along the river course and submitted to a supervised classification using a maximum likelihood classifier (Environment for Visualizing Images or ENVI 4.3 software) from a three channel composition (TM4, TM3, TM2). 209 GPS field observations were collected from which training pixels were digitised manually and the 608 trap locations were used to validate the classification. A signature was created for each class. The classifier was run with equal prior probabilities per class and all pixels were classified (0% exclusion). Seven land-use classes were identified (Fig. 2). Standard nomenclature of African vegetation types was used to describe these land-use classes (3).

Statistics

The n-dimensional visualiser tool (ENVI software) was used to control the absence of confusion between the regions of interest (ROIs) = learning areas. The supervised classifications were validated from the calculation of a matrix of confusion and the Kappa coefficient (0.87) (19). The pair comparisons of the classes gave a separability coefficient of between 1.99 and 2, corresponding to an absence of confusion of the pixels allocated within each class (19).

The riverine forests are too small (<10 m) to be seen on a Landsat scene (pixel = 30 m) and are thus analysed through their neighbouring pixels.

The aim of the following landscape classification method was to discriminate clusters corresponding to the entomological landscapes described above (forest, border and disturbed) using the seven vegetal units obtained from the supervised classification of the pixels neighbouring the river course. Points were randomly generated in a distance

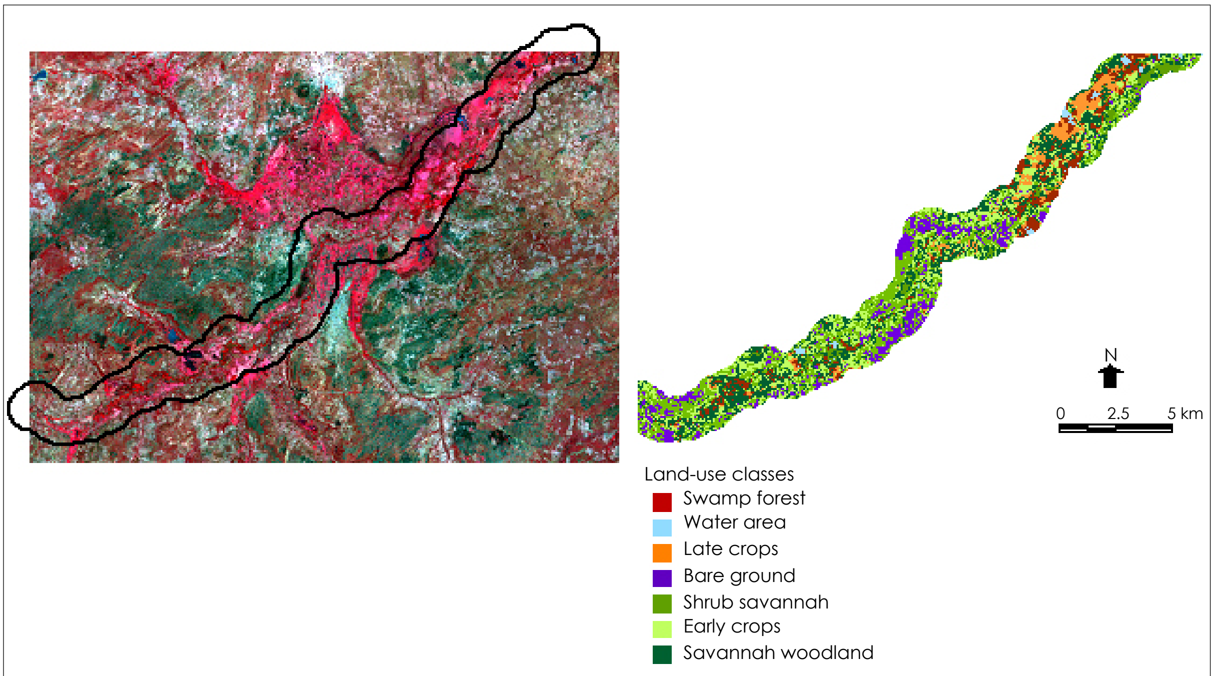

Figure 2
Three Landsat channel composition (TM4, TM3, TM2) and associated supervised classification of a 1 000 m buffer section, Mouhoun tributaries, Burkina Faso

range of 100-500 m from each other (average distance of 300 m) along the river (MapInfo® software, All2pts.mbx), namely: 1 560 points in the Guinean part, 2 354 in the Sudano-Guinean and 920 in the Sudanese part. Within each ecological area, the random points were analysed together to identify clusters of similar neighbourhood. The areas of each land-use unit were calculated in buffers of 500 m around each point and they were reported to the total areas of the buffers to obtain the percentages of each vegetal unit (Fig. 3).

Centred but not scaled principal components analysis (PCA) was performed using the land-use class areas in the 500 m buffers as variables (R 1.6.2 software, ADE4 package) (Fig. 4). Euclidian distances between the river points were calculated between all the points in each ecological area from their coordinates on the two principal axes. Hierarchical cluster analysis was then conducted with the complete agglomeration method (30) using the Classical Multivariate Analysis package (mva package, R software).

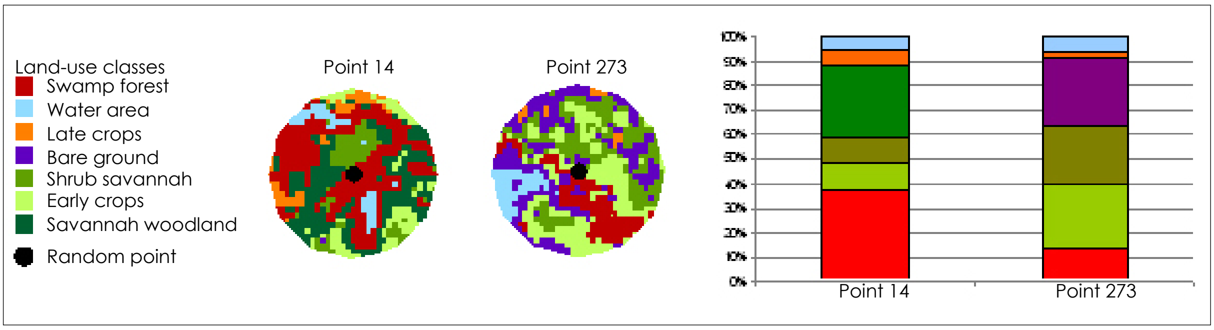

Figure 3
Percentages of seven vegetal units obtained from supervised classification in 500 m buffers around two points randomly generated along the river course

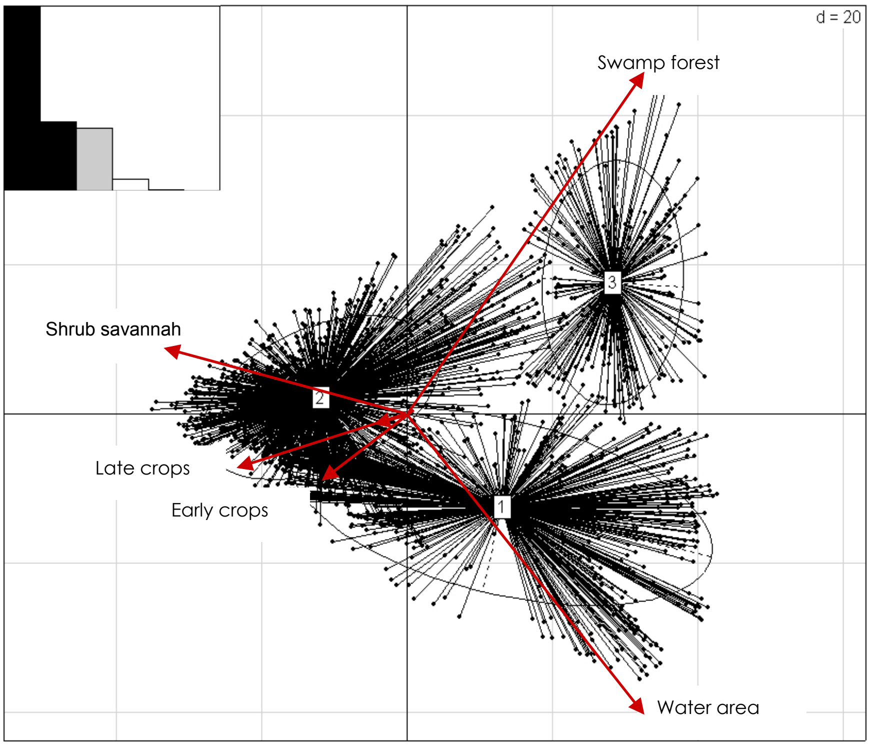

Figure 4
Projection of three distance groups and associated variables
Land-use class areas in 500 m buffers around the river course on the first principal components analysis plan: groups 1 and 2 represent half disturbed landscapes and group 3 a natural landscape

The autocorrelation of tsetse densities between traps was investigated using the Moran I test under the assumption of randomisation (1, 2, 9), applied on neighbouring matrixes, generated with 200 m distance ranges along the river course, from 0 to 2 000 m (Table I), using the spatial dependence: weighting schemes, statistics and models package (spdep package, R software). The method has been extensively described elsewhere (6).

Table I
Results of the Moran test applied to *Glossina palpalis gambiensis* apparent densities with nine neighbouring matrixes corresponding to various distance ranges in the Sudano-Guinean ecological area

Distance range (m)	Statistic	*p*-value
0-200	0.53247	*
200-400	0.37347	*
400-600	0.24817	*
600-800	0.15862	**
800-1 000	0.12436	**
1 000-1 200	0.17520	***
1 200-1 400	0.10374	NS
1 400-1 600	0.09984	NS
1 600-1 800	–0.00811	NS

* *p*<0.001
** *p*<0.05
*** *p*<0.02
NS *p*>0.05

For each epidemiological landscape, the normality of tsetse apparent densities and physiological age distributions were tested using the Kolmogorov-Smirnov test (10). As the distributions of apparent densities were not normal, they were compared together using a Kruskal-Wallis rank sum test (25) and then in pairs using the Steel-type non-parametric multiple comparisons test (npmc package) (32). Fly infection rates were compared using the Chi square test with Yates continuity correction (34). The distributions of physiological ages were normal and their means were thus compared with Student's t-Test with Welch modification to the degrees of freedom, after comparison of their variances with the F test. All statistical analysis were computed with R statistical software (27). The mean number of infectious flies by trap and by day was considered to be proportional to the vectorial capacity (41) and to one of its components, the entomological inoculation rate, corresponding to the product of the vector relative density (modelled by the ADT) by the rate of infectious flies. The relative risks and their confidence intervals represented by the ratio of mean numbers of infectious flies by trap and by day were obtained from bootstrapping in the ADT distributions and from dissected fly samples from each landscape, assuming spatial homogeneity within a given epidemiological landscape (10 000 Monte Carlo simulations, @risk 4.5 software).

Confidence intervals were calculated for a risk α of 5% (18).

Results

From remote sensing landscapes to epidemiological landscapes

In each ecological section, seven land-use classes were identified in the peri-riverine buffers (Figs 2 and 3). Along the tributaries, swamp forests were dominated by *Kahya senegalensis*, *Anogeissus leiocarpus* and *Nauclea latifolia*; along the Sudano-Guinean and Sudanese sections, the predominant species were *Acacia seyal*, *Mitragyna inermis* and *Mimosa pigra*. Savannah woodlands were dominated by *Butyrospermum paradoxum* and *Terminalia laxiflora*. Shrub savannahs were dominated by *Combretum* spp. and *Guiera senegalensis*. Two types of crops could be identified according to the timing of their implementation – early or late during the rainy season - both representing cereals (corn, millet, sorghum) or cotton crops. Bare ground comprised already harvested fields and eroded areas. The final class comprised water areas.

Twelve clusters of similar neighbourhood were identified from hierarchical classification and projected on the first plan of the PCA in each ecological section (the example of three clusters identified in the Sudano-Guinean section is presented in Fig. 4), to control qualitatively their relationship to the variables (land use classes in the 500 m buffers). These landscapes were projected on the map and compared to the entomological landscapes registered on the field, to build the eight final remote sensing landscapes. In the example presented in Fig. 4, landscapes 1 and 2 were merged since they both corresponded to half-disturbed landscapes at various flooding stages. Conversely, landscape 3 was kept apart, corresponding to a natural landscape.

Fly densities were found to be auto-correlated up to a distance range of 1 000 to 1 200 m in the Guinean and Sudano-Guinean sections, of 1 400 to 1 600 m in the Sudanese section (Moran I test, $p<0.05$). Thus fly densities and infection rates between two adjacent remote sensing landscapes could not be considered independent. To take auto-correlation into account and obtain independent epidemiological landscapes, the landscapes of maximal ADT within each ecological area were merged to 1 600 m (in the Sudanese section) and to 1 200 m (in the two others) of the neighbouring landscapes to obtain eight epidemiological landscapes numbered by increasing mean ADT: two in the Guinean ecotype (numbered 3 and 4 in Fig. 5; Table II), three in the Sudano-Guinean ecotype (numbered 2, 5 and 8) and three in the Sudanese ecotype (numbered 1, 6 and 7). The npmc test applied on ADT enabled discrimination of landscape 1 from the others (coded I, $p<10^{-3}$) whereas landscapes 2-4 were merged to create landscape II ($p>0.05$) and landscapes 5-8 were merged to create the last landscape, coded III ($p>0.05$) (Table II; Fig. 5). Downwards, these three independent epidemiological landscapes are considered.

Characterisation of the epidemiological landscapes

Landscapes I, II, and III represented 23%, 56% and 21% of the total river length, respectively, (Fig. 6) and comprised 86, 334 and 188 trap locations, respectively, where the riverine forest disturbance level was previously assessed from phytosociological censes (4). Landscape I harboured the most disturbed gallery, with only 5% of conserved sites, followed by landscape II (27%) and finally landscape III (51%). The surface of swamp forests represented 13% (standard deviation [sd] 7), 16 (sd 16) and 36 (sd 21) of the 500 m buffers in landscapes I, II and III respectively. The percentages of undisturbed sites was thus correlated to the percentage of swamp forests in the buffers ($r^2=0.88$). The percentages of highly frequented sites by cattle were of 64%, 97% and 44% in landscapes I, II and III, respectively.

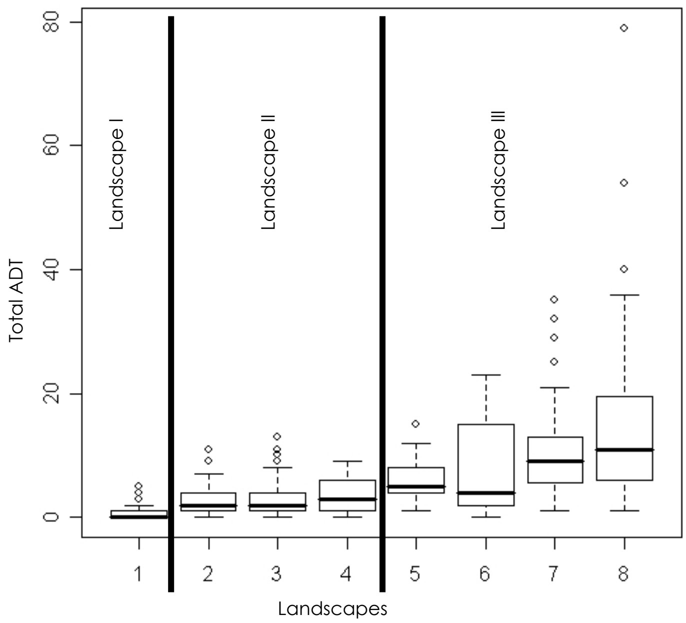

Figure 5
Gathering of three epidemiological landscapes (I, II, III)

Table II
Results of non parametric multiple comparison test on the apparent density of infectious fly per trap per day of the eight epidemiological landscapes

Landscapes	2	3	4	5	6	7	8
1	*	*	*	*	*	*	*
2		NS	NS	*	**	*	*
3			NS	**	**	*	*
4				NS	NS	*	*
5					NS	NS	***
6						NS	*
7							NS

1 disturbed landscape in a Sudanese River section
2 half-disturbed landscape in a Sudano-Guinean River section
3 disturbed landscape in a Guinean River section
4 half-disturbed landscape in a Guinean River section
5 natural landscape in a Sudano-Guinean River section
6 natural landscape in a Sudanese River section
7 half-disturbed landscape in a Sudanese River section
8 half-disturbed landscape in a Sudano-Guinean River section
* $p<0.001$
** $p<0.02$
*** $p<0.05$
NS $p>0.05$

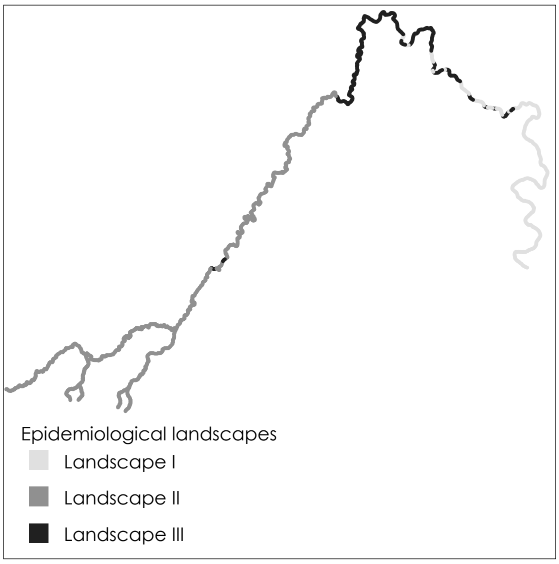

Figure 6
Distribution of epidemiological landscapes along the Mouhoun River course

The tsetse mean apparent densities were significantly higher in landscape III (npmc test, $p<10^{-3}$) (Table III) with ADTs of 11.76 (sd 10.55) than in landscape I and II with ADTs of 0.80 (sd 1.10) and 2.65 (sd 2.54), respectively, and significantly higher in landscape II than in landscape I (npmc test, $p<10^{-3}$) (Table III).

The physiological age of 12, 142 and 65 females were measured in landscapes I, II and III, respectively. The mean age was higher (Student's t-Test, $p<0.05$) in landscape III (42 days old, sd 17.44) and in landscape II (40 days old, sd 17.96) than in landscape I (29 days old, sd 11.76), but not significantly different between landscapes II and III ($p>0.05$).

A total of 60, 225 and 207 flies were dissected in landscapes I, II and III, respectively, to establish the tsetse infectious rates by *T. vivax*, *T. congolense* var. savannah and *T. brucei lato sensu*. The fly infection rates were not significantly different between landscapes (Chi square test, $p>0.05$) (Table IV). *T. vivax* was the predominant species, found in similar infection rates in the three landscapes ($p>0.05$) *T. congolense* savannah type and *T. brucei sensu lato* were not found in landscape I and revealed low infection rates in landscapes II and III (Table IV).

Table III
Comparison of the tsetse fly apparent densities in the epidemiological landscapes using the Steel-type non-parametric multiple comparison test
(npmc package, R software)

Groups compared	Sum of both sample sizes	Statistic	1-sided *p* value	2-sided *p* value
1-2	419	7.25	<0.001	<0.001
1-3	215	12.23	<0.001	<0.001
2-3	464	13.64	<0.001	<0.001

Table IV
Tsetse fly mature infection rates by *Trypanosoma vivax*, *T. congolense* var. savannah and *T. brucei lato sensu* identified by polymerase chain reaction in the epidemiological landscapes

Trypanosome species	Landscape 1	Landscape 2	Landscape 3
T. vivax	0.10 (± 0.04)	0.07 (± 0.02)	0.05 (± 0.01)
T. congolense	0.00	0.01 (± 0.01)	0.02 (± 0.01)
T. brucei lato sensu	0.00	0.01 (±0.01)	0.01 (±0.01)
Sample size	60	225	207

A risk indicator was obtained as the product of fly apparent density distributions by fly mature infection rate distributions, with all trypanosome species together (corresponding to the entomological inoculation rate). This product, representing a mean number of infectious flies by trap and by day was 0.08 (0.02-0.15), 0.20 (0.11-0.30) and 0.74 (0.38-1.16) in landscapes I, II and III, respectively (Fig. 6). In landscape III, the trypanosomosis risk was thus 11.48 (3.66-31.85) and 3.92 (1.72-7.57) times higher than in landscapes I and II, respectively ($p<0.05$, 1 excluded from the 95% confidence intervals). It was 3.13 (1.05-8.46) times higher in landscape II than in landscape I.

Discussion

The use of 500 m buffers around the river course enabled a distinction to be made between epidemiological landscapes of various AAT risks using remote sensing data. Human activities within this distance determined to a large extent the disturbance level of riverine forests, which in turn could be linked to tsetse densities, as was shown previously in the same ecological area (6, 16): while peri-riverine human activities have a negative impact on gallery forest vegetation, swamp forests have a protective action. This riverine neighbourhood could be analysed using Landsat TM images, with a resolution of only 30 m.

The use of the PCA and hierarchical analysis enabled automatic identification of clusters of river points with similar neighbouring features that could be projected on a map using GIS and compared to field data to differentiate units that were representative of entomological landscapes and to merge those that were not, to obtain a supervised landscape classification. The use of spatial autocorrelation then allowed building the epidemiological landscapes, taking into account tsetse dispersal in these fragmented areas. The method used in the present study to predict tsetse densities is more explanatory than former studies, led at a lower resolution (23, 36, 37). The results are in line with a trypanosomosis parasitological survey in cattle conducted in 1999 (40).

Concerning a second epidemiological layer, the hosts, the minimum cattle frequency was observed in the most risky landscape (III). It may be assumed that high cattle frequentation has a negative impact on riverine forests, the most conserved riverine forests also being found in the latter landscape; however breeders have learned to avoid the most dangerous river sections. Although the host density measures were only semi-quantitative, they were obtained very easily and were not time consuming. Moreover, more accurate methods (particularly exhaustive cattle count surveys) were used in the same ecological area, and similar results were obtained (15).

The 1.2 to 1.6 km observed autocorrelation between fly densities may be attributed to the dispersal capacities of riverine flies along the river course (7, 12). The decision to enlarge the most dangerous landscapes of these distances assumed that the majority of tsetse flies which become infected in this landscape would be contained within this distance. This distance is inferior to the median distances measured in a homogeneous conserved Guinean gallery (11), but this can be linked to a higher fragmentation intensity in the study area where a higher mortality rate (in disturbed places) and a heterogeneous distribution of host species could contribute to a reduction of the median distance. The life-span has a dramatic impact on the probability of long-distance movements (7, 20, 21).

The risk indicator selected to approach the vectorial capacity, the number of infectious flies by trap and by day or inoculation rate, suffers from two simplifications: it neither takes into account the life-span of the flies nor their trophic preferences (41). The first simplification could be corrected by calculating the daily mortality rates but the number of flies dissected was insufficient to warrant accuracy, especially in landscape I. However, the mean age in this landscape was significantly lower than in the two others, a factor that also reduced risk in this landscape. Only *T. vivax* was found in this landscape, which is the species with the shorter extrinsic incubation period (about 10 days), in comparison to *T. congolense* and *T. brucei brucei* (14 and 30 days, respectively) (13). The second simplification could be corrected by analysing the origin of the blood meals in the captured flies but, once again, the number of gorged captured flies is generally very low, the traps being more efficient at capturing starved flies. Moreover, since wild fauna has become very scarce in the study area, the considered risk indicator might represent a general threat to domestic hosts (cattle and small ruminants). The present risk classification will be controlled by implementing longitudinal studies in the Mouhoun Basin, as part of the Wellcome Trust 'Fragfly' project. During these more intensive surveys, the real vectorial capacity will be calculated and compared to the entomological inoculation rate.

This rapid risk assessment method enabled the analysis of a river section of 702 km in six months. The present stratification of AAT risk has been used by a development project, the *Projet d'Appui à l'Élevage dans l'Ouest du Burkina Faso* (PAEOB) to identify their priorities areas earmarked for tsetse and AAT control (5).

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