Remote sensing and geographic information systems to predict the density of ruminants, hosts of Rift Valley fever virus in the Sahel

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Summary

Rift Valley fever (RVF) is an acute arboviral disease of domestic ungulates and humans in Africa and the Middle East. Since the first epidemic in 1987, Senegal has been confronted with recurrent episodes of the disease. This study aimed to model spatial distribution of ruminants in the agropastoral area of Barkedji (Senegal) where the disease is enzootic. In this Sahelian ecosystem, livestock distribution mainly depends on the availability of resources. Accordingly, remote sensing and geographic information systems (GIS) were used to seek environmental indicators of livestock density. A high-resolution Landsat image was associated with landscape field data to describe the land-cover. A series of normalized difference vegetation index values gave an estimation of the phytomass. In addition the compounds of herders in the study zone were located and sampled. Three surveys were conducted during the rainy season to record the number of herds in each compound of the sample. All these data were overlaid in the GIS. A discriminant analysis was performed to associate the observed herd density with environmental data and to develop a predictive model for the entire study zone. The final result was a 1-km resolution raster map of herd density during a normal rainy season.

Keywords

Geographic information system, Livestock, Modelling, Pastoral system, Remote-sensing, Rift Valley fever, Senegal.

Telerilevamento e sistemi informativi geografici per prevedere la densità dei ruminanti, ospiti del virus della febbre della valle del Rift nel Sahel

Riassunto

La febbre della valle del Rift (RVF) è una malattia acuta da arbovirus che colpisce gli ungulati domestici e l'uomo presente in Africa e nel medio-oriente. Dalla prima epidemia nel 1987, il Senegal si è dovuto confrontare con ricorrenti episodi di questa malattia. Questo lavoro ha lo scopo di indagare modelli di distribuzione spaziale dei ruminanti nelle aree agropastorali del Barkedji (Senegal) dove la malattia è endemica. In questo ecosistema saheliano, la distribuzione del bestiame dipende principalmente dalla fruibilità delle risorse. In questo contesto, il telerilevamento ed i sistemi

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informativi geografici vengono utilizzati per rintracciare gli indicatori ambientali della densità dell'allevamento. Un'immagine ad alta risoluzione Landsat è stata associata a dati raccolti sul campo riguardo l'aspetto del territorio per descrivere la copertura del suolo. Una serie di valori dell'indice normalizzato di differenze di vegetazione ha fornito una stima della fitomassa. Inoltre le componenti di ciascun allevatore nell'area di studio sono state localizzate e campionate. Tre indagini sono state condotte durante la stagione delle piogge per registrare il numero di allevamenti in ciascun componente del campione. Tutti questi dati sono stati sovrapposti in un sistema informativo geografico. Un'analisi discriminante è stata condotta per associare la densità degli allevamenti osservata ai dati ambientali nonché per sviluppare un modello predittivo per l'intera zona oggetto dello studio. Il risultato finale è stato una mappa-raster ad 1 km di risoluzione della densità degli allevamenti durante una nomale stagione delle piogge.

Parole chiave
Bestiame, Febbre della valle del Rift, Modellizzazione, Senegal, Sistema informativo geografico, Sistema pastorale, Telerilevamento.

Introduction

Rift Valley fever (RVF) is an acute arboviral disease of humans and domestic ungulates. Since its discovery in 1931, the disease has appeared in Africa and the Middle East in many temporally and spatially localised epizootics, sometimes associated with epidemics (34, 35). In cattle and small ruminants, RVF infection causes massive abortions, associated with a high mortality of young animals. The human disease is characterised by the abrupt onset of high fever, severe headache and myalgia. Although the course of disease is favourable in most cases, some patients may develop complicated forms, such as encephalitis and ocular disease (with irreversible after-effects) or fatal haemorrhagic fever (21, 25).

The transmission cycle is initiated and maintained by virus circulation between ungulates and arthropod vectors. More than 30 mosquito species are considered to be potential RVF virus vectors. Among these, the species in which the virus has most often been isolated belong to the *Aedes* and *Culex* genera (10, 12, 30). In opposition to what is usually observed with arboviroses, humans are mainly infected with RVF after handling abortion products or following contact with viraemic animal tissues or fluids at the time of slaughter (6, 37). Animal-to-man contamination by infected biological or mechanical vectors occurs to a lesser extent (14).

In East and southern Africa, RVF outbreaks are correlated with climatic anomalies, i.e. exceptional rainfall, extended in time and space. Models using climatic and satellite indicators have been developed and predict the episodes with accuracy (8, 17, 18, 19). However, in West Africa, those models cannot be applied as the outbreaks observed occurred in arid areas, during low or normal rainfall years (11, 24). For the last few decades, Senegal has often been affected by RVF and the disease is known to be enzootic in Ferlo, a pastoral Sahelian region located in the north-central part of the country (31, 36). The purpose of this paper was to assess the spatial distribution of the principal hosts of RVF, i.e. domestic ruminants, in the study area of Barkedji (Ferlo), using environmental indicators.

Materials and methods

The study zone

The study was conducted in the rural community of Barkedji, in north-central Senegal. The area covers 1 600 km² of Sahelo-Sudanian savannah around the village of Barkedji (14.86731°W, 15.27881°N) (Fig. 1). The relief is composed of a lateritic cuirass partially covered by flattened dunes, stabilised by the vegetation (15). This plateau was eroded by a former affluent of the Senegal River, the Ferlo. It left a large, fossil valley crossing the zone from east to west and sending ramifications to the north and the south. With annual rainfall ranging from 300 to 500 mm, the rural community belongs to the pastoral Sahelian area of Ferlo, characterised by the predominance of annual grass, thorny shrubs and small trees. The climate is characterised by the alternation of a short rainy season (from June to October) and a long dry season when the daily temperature exceeds 40°C. This study was conducted from 2001 to 2003. Compared to the average of the 1961-1990 annual rainfall, taken as the norm, rainfall was considered as normal in 2001 and 2003, and low in 2002.

The study zone is a mosaic of typical Sahelian landscapes, which will be named using their vernacular *Fulani* term, as follows:

- the *seeno* is a bushy steppe growing on a sandy substratum, dominated by *Balanites aegyptiaca*, *Guieria senegalensis*, *Combretum glutinosum* and *Sclerocarya birrea*; this formation is favourable to agriculture and grazing because of the good hydric properties of the sandy soils
- the *sangre* is a bushy steppe growing on the lateritic cuirass; *Pterocarpus lucens*, *Sterculia setigera*, *Commiphora africana*, *Grewia bicolor* are the dominant tree species; low water reserves make this area inappropriate for agriculture, but not for grazing
- the *baldiol* is a tree steppe on argillaceous and hydromorph lowlands, composed of *Acacia seyal*, *Adansonia digitata*, *Balanites aegyptiaca* and *Boscia senegalensis*; the area withstands high pastoral pressure during the rainy season (26).

Nomadic or sedentary people belonging to the Peulh *Fulani* ethnic group mostly populate the area of Barkedji. Their principal activity is livestock breeding, although this may be associated with food crops (20). Peulh herders live in compounds where 3 to 10 families gather and where domestic ruminants are sheltered at night. Herds are constituted of white-dressed gobra zebus, medium-size Peulh-Peulh sheep and Sahelian goats (33). In the Sahel, the distribution of the human population is mostly determined by the availability of resources, especially pasture and water. During the rainy season, nomadic and sedentary herders benefit from the many temporary ponds, flooded by rainfall (32). At this time, transmission of RVF may occur as those ponds also provide shelter for the arthropod vectors (*Aedes vexans*, *Culex poicilipes* and *Aedes ochraceus*). At night, the female mosquitoes leave the pond to hunt and feed on the ruminants sleeping in their night pens (23). Estimating host density is a first step towards

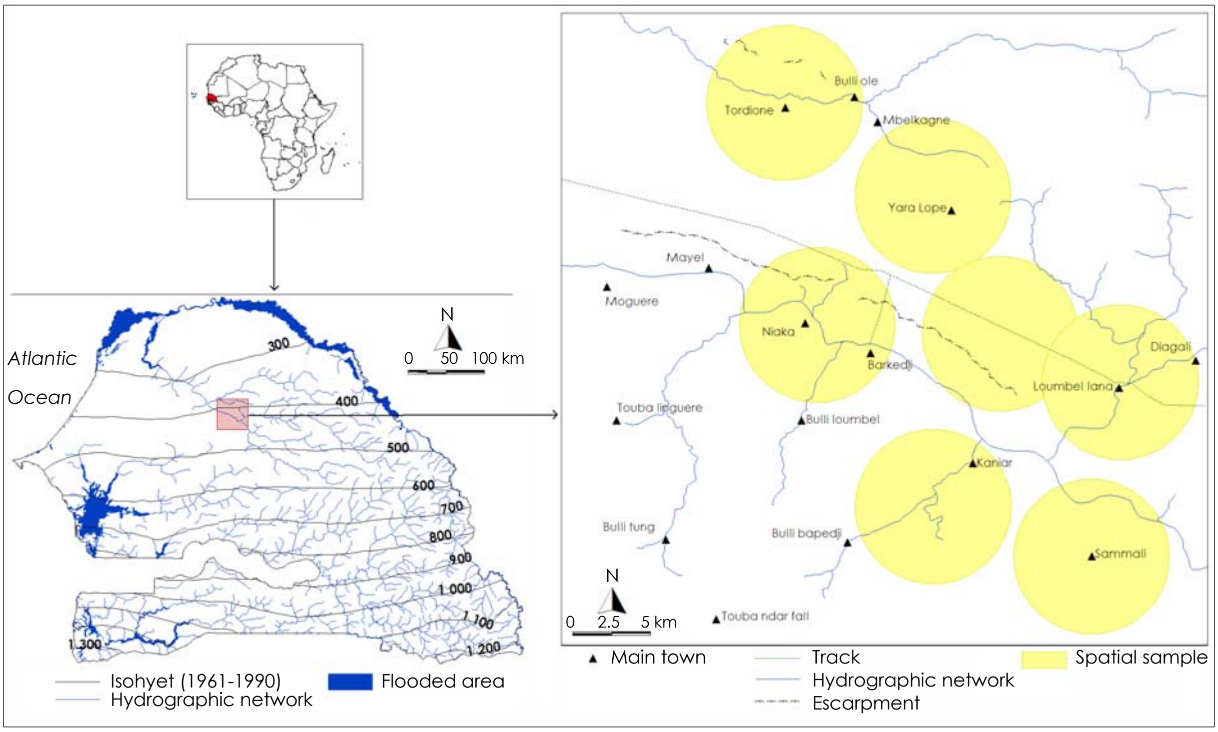

Figure 1
Location of the study zone and spatial sample limits
Source: *Pôle Pastoral Zones Sèches*, Dakar

RVF risk modelling. Consequently, the point of this study was to predict the spatial distribution of compounds and herds during the rainy season, from environmental indicators.

Satellite data processing

A Landsat 7 image, with a spatial resolution of 30 m in multispectral mode and 15 m in panchromatic mode, was provided by the *Centre de Suivi Écologique* (Dakar, Senegal). The two scenes (204-49 and 204-50) covering the study area, were taken in November 1999. The 1999 rainy season was considered normal in comparison to the 1961-1990 'norm'. Pedological and phyto-sociological data were collected in the field during the 2001 rainy season and the 2001-2002 dry season. To describe land cover, a supervised classification of the Landsat 7 image was performed (2). Before classification, the image was submitted in Idrisi® to various processes, namely:

- merging of the panchromatic and multispectral data
- geometric corrections
- enhancement of the contrast (5, 9).

Classification was then performed with four Landsat channels (TM2, TM3, TM4 and TM7). The best classification discriminated six land-cover classes, namely: *seeno*, *sangre*, *baldiol*, damaged bushy steppe, temporary flooded ponds and cultivated or fallow fields. Finally, the 15-m resolution land-cover map was converted into vector format and exported to the MapInfo® geographic information system (GIS).

In addition to the land cover, the vegetation dynamics were assessed using a normalized difference vegetation index (NDVI) time-series. The NDVI monthly values from June to December 2001 were downloaded from the internet of SPOT vegetation site (*Satellite pour l'Observation de la Terre*, www.spot-vegetation.com). These time-series data were synthesised by principal component analysis (PCA), giving an estimate of vegetation dynamics during a normal- rainy season (16).

Herd density modelling

Data collection

A census of the compounds was completed in June 2001 by a team composed of a scientist, a surveyor and a driver. The position of each compound was recorded using a global positioning system (GPS), in the Universal Transverse Mercator projection (WGS 84), zone 28 N. Seven disc-shape, 5 km-radius samples, were then randomly selected for cross-sectional surveys (Fig. 1). In those samples, the same team visited each compound three times during the 2001 rainy season (July, August and October) and noted the family composition, number of herds and status (nomadic or sedentary). In addition, other scientists of our research team located the compounds in another spatial sample of the study zone, as they conducted a serological survey during the 2003 rainy season (7). Their data were used for validation.

Descriptive statistics

An important item when using GIS is to determine what unit should be used to project the spatial data. For this purpose, all the compounds recorded during the 2001 rainy season were gathered in the same spatial layer (after removing the doubles) and submitted to point pattern analysis. The statistical analyses were performed with the R® software. Besag linear function L(r) was preferred to the basic Ripley function (4, 27). The L(r) function was calculated for the real point pattern, i.e. the compounds during the 2001 rainy season and plotted on a graph (Fig. 2). The confidence interval was established using the limits of the L(r) functions calculated for 20 Poisson simulations (1). The Poisson simulations were performed with 244 points, corresponding to the number of compounds recorded in the entire study area. The results of the point pattern analysis showed that the best projection unit was a square pixel of 1 km². In consequence, a grid of 1 600 pixels of 1 km² was drawn in the GIS. All spatial data were projected in this grid for subsequent statistical analysis and modelling.

Before setting up the model, a classical Student test was used to compare nomadic and sedentary compounds, based on their composition and environment (Table I) (16). As the test showed no major difference between the two groups, they were assumed to have similar spatial behaviour and were integrated into the same model.

Spatial modelling

The purpose of this study was to predict the herd density in a normal rainy season, from data collected in a limited sample of the study zone. The method selected was discriminant analysis. Using the GIS geo-processing tools, a set of 19 predictive variables was calculated for each pixel of the grid (Fig. 3), as follows:

- distance to the Ferlo Valley, the nearest track and the nearest permanent water point
- average and standard deviation of the values taken by the four Landsat channels (TM2, TM3, TM4 and TM7)
- average, standard deviation and variety of the land-cover classes
- normalized proportion of *seeno*, *sangre*, *baldiol* and damaged steppe
- value on the first component of the PCA performed on the NDVI data.

The function used to normalise the land-cover proportions p was arcsin$\sqrt{p}$ (3, 13).

The predicted variable d was the observed density of cattle and small ruminant herds, reported in each pixel of the spatial sample. So as to comply with the constraints of the method, d was placed into classes, according to the histogram breaks, as follows:

- low ($d<1$ herd/km²)
- medium ($1\leq d<3$ herds/km²)
- high ($d\geq 3$ herds/km²).

The discriminant analysis was performed with R® on a train set of 347 pixels (half of the spatial sample). Only the most discriminant variables were retained for the final model.

The latter was submitted to inner validation with the 347 remaining pixels. The percentage of correct predictions was calculated 50 times on this test set, and the average was taken as the accuracy.

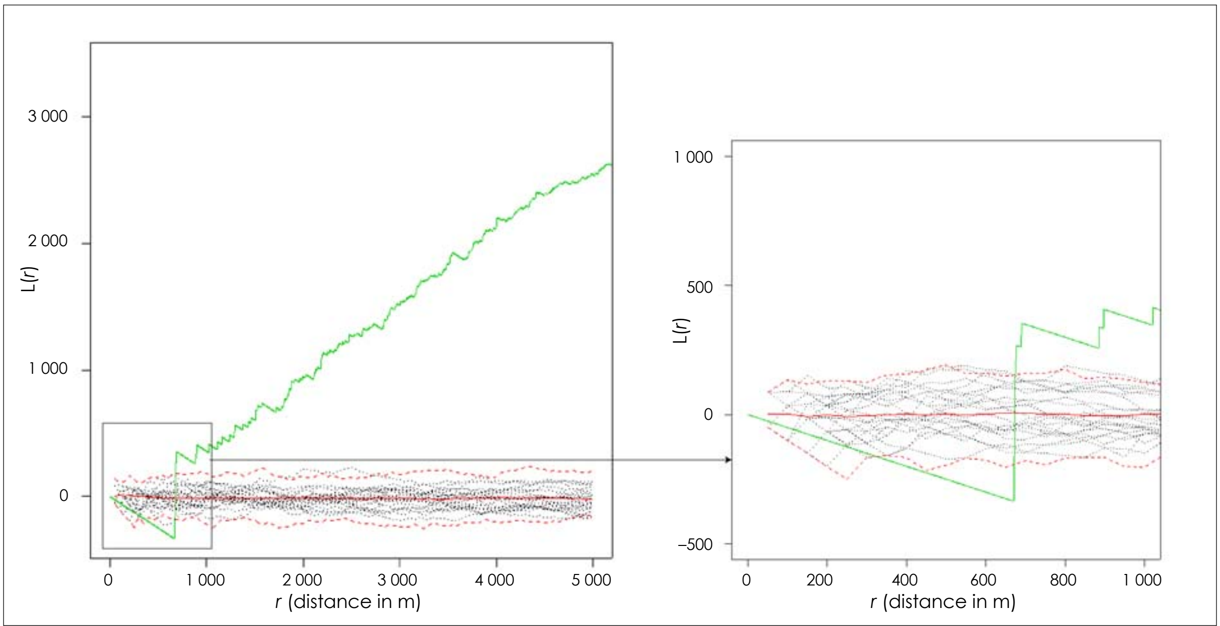

Figure 2
Besag function calculated for the compounds recorded in the spatial sample, during the 2001 rainy season
Plain green line: L(r) function calculated for the real compounds point pattern
Dotted black lines: L(r) functions calculated for the 20 random Poisson point patterns
Plain red line: average of the 20 simulated L(r) functions
Dotted red lines: confidence interval of the 20 simulated L(r) functions
The graph on the right is a ‘zoom’ of the left graph

Table I
Compound composition and close environment: comparison of the mean values for sedentary and nomadic herders

Variable	Description	Sedentary group	Nomadic group	p-value
conc	Number of houses	3.52	2.56	
bo	Number of cattle herds	1.57	1.73	
ppr	Number of small ruminant herds	3.93	3.55	
dpe	Distance to the nearest permanent water point (m)	2 834.60	3 486.78	<0.05
dhy	Distance to the Ferlo Valley (m)	1 154.38	1 501.87	
dpi	Distance to the nearest track (m)	1 181.20	1 040.87	
pse	Proportion of *seeno* in a 1-km radius	0.32	0.36	<0.5
psa	Proportion of *sangre* in a 1-km radius	0.46	0.44	<0.5
pba	Proportion of *baldiol* in a 1-km radius	0.05	0.04	<0.05
pde	Proportion of damaged steppe in a 1-km radius	0.17	0.16	<1

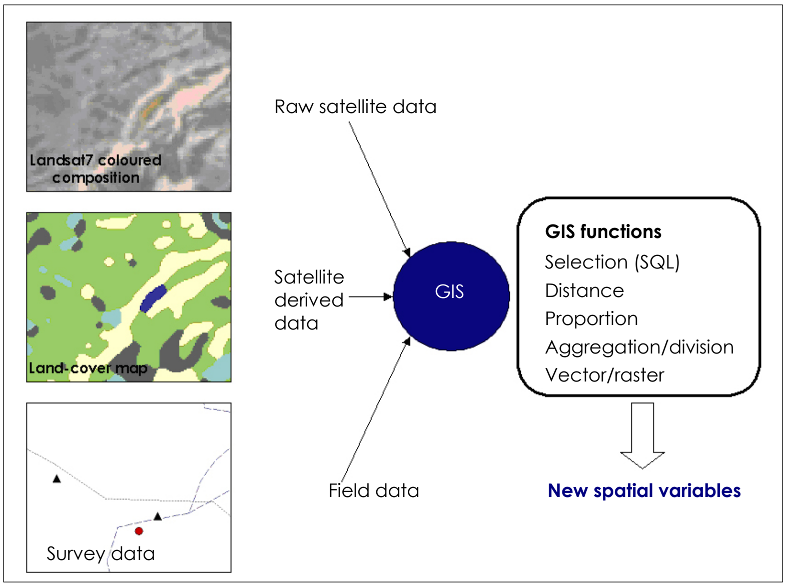

Figure 3
Example of spatial layers association in the geographic information system

The model was then applied to the outside-sample pixels to predict their herd density class. The results were exported to the GIS. To improve visualisation, the inside and outside-sample pixels were merged and the edge effects corrected. A specific colour was assigned to each density class. Finally, an external validation was performed, comparing the predictions to the herd density observed in 2003 in another spatial sample. The percentage of pixels where the predictions matched the real herd density was calculated.

Results

Land-cover map

In November 2001, the study area was mainly covered by two land-cover classes that occupied 52.5% and 30.1% of the total surface, respectively, namely: the *seeno*, in the north-western and south-eastern parts and the *sangre*, in the north-eastern and south-western parts (Fig. 4). Those landscapes, favourable to livestock breeding, generally took the form of wide homogeneous areas, except near the Ferlo Valley where they were shaped as mosaics. The damaged steppe (14.9% of the total surface) was detected around the main

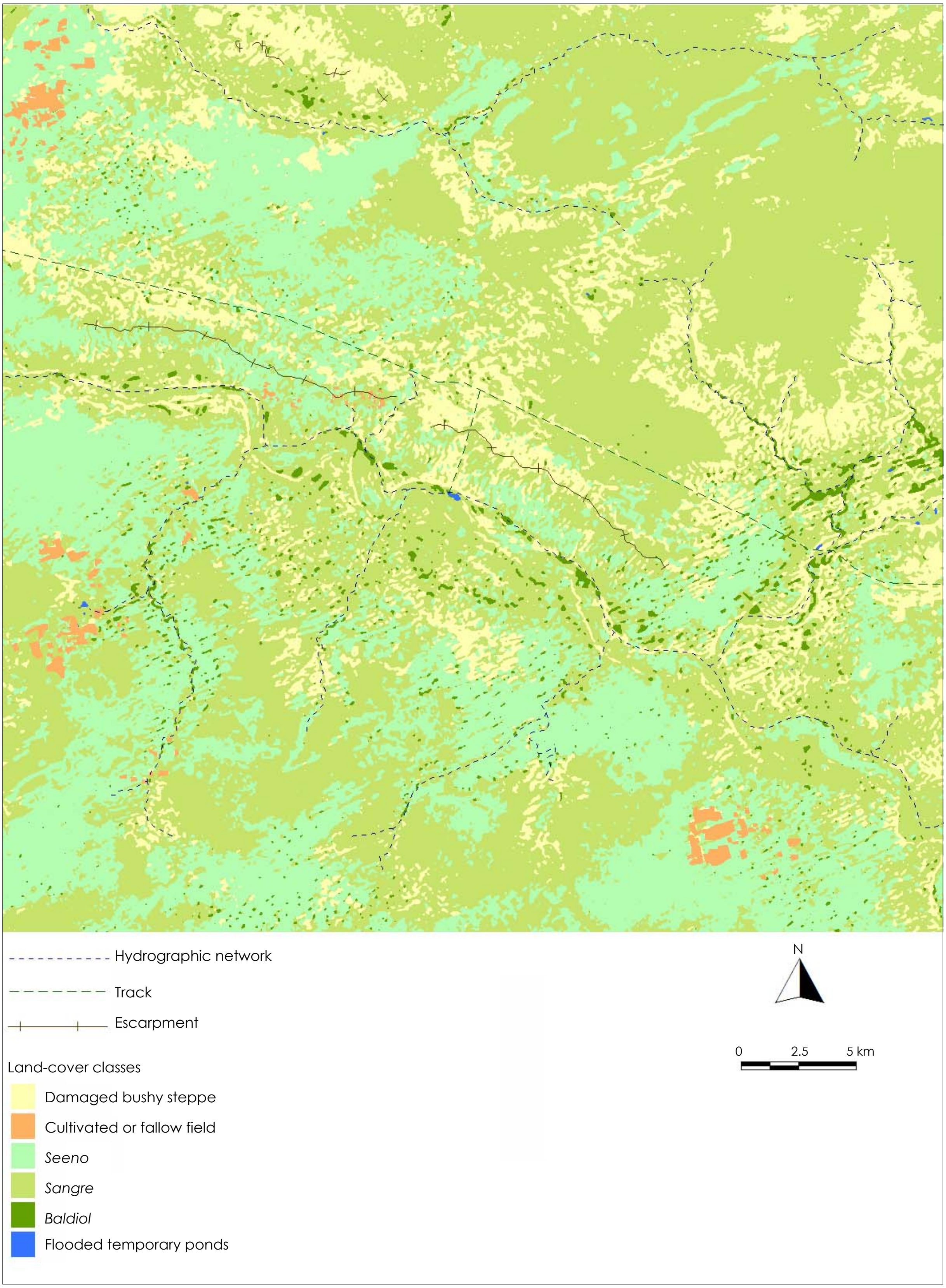

Figure 4
Land-cover map of Barkedji, November 1999
Source: *Centre de Suivi Écologique*, Dakar

tracks and on the valley slopes. The *baldiol* (1.6%) and the large flooded ponds (0.1%), followed the Ferlo Valley and its ramifications. The cultivated parcels, mainly located around the Sammali and Touba Linguere bore-holes, were limited to 0.8% of the total surface.

Spatial distribution of compounds

At a high scale, the compounds first had a random distribution (*r* from 0 to 350 m), then a regular distribution (*r* from 350 m to 700 m) (Fig. 2). When the scale changed, as soon as *r* exceeded 700 m, the L(r) function calculated for the compounds rose above the confidence interval, which meant that the distribution was aggregated.

This analysis showed that at a very high scale, the breeders settle regularly so as to benefit from sufficient space around their compounds. Compound spatial clustering when r rose above 700 m reflected a trend to gather in villages, in places where resources were abundant and easily attainable. These observations determined the modelling scale as follows: 1 km² was considered a relevant unit upon which the spatial data could be projected. Moreover, it is the common observation unit used by geographers. Finally, when the expected results are raster maps, a resolution of 1 km² is the simplest for potential local users.

Herd density prediction

During the 2001 rainy season, 94 compounds were recorded in the spatial samples, among which 53 were sedentary and 41 were nomadic. The mean values of compound composition and close environment variables are reported for each group in Table I. The difference was significant for the following variables: distance to the nearest permanent water point and proportions of *seeno*, *sangre*, *baldiol* and damaged bushy steppe. However, the *p* values were high. Taking into account only the variables with $p<0.05$ led to the conclusion that nomadic herders settled farther from the permanent water points and the *baldiol* than sedentary herders. This may be explained by the fact that, generally, sedentary people settle around bore-holes and wells, for convenient access to water during the dry season. When nomadic people arrive at the onset of the rainy season, some settle in those villages, but most prefer to establish their compound in more isolated places to avoid overgrazing. This slight difference did not justify the use of two specific models. Nomadic and sedentary compounds were consequently united in the same discriminant analysis.

Among the 19 predictive variables initially tested, the six most discriminant were retained for the final model, namely:

- proportion of *sangre* (psa)
- standard deviation of the land-cover classes (sdcl)
- proportion of *baldiol* (pba)
- average of the land-cover classes (mcl)
- proportion of damaged bushy steppe (pde)
- proportion of *seeno* (pse).

The variables means for each herd density class are presented in Table II. The proportion of *seeno* is higher in the medium group than in the other two. This landscape is rather used by sedentary people who possess few herds and who practice livestock breeding and agriculture at the same time. On the contrary, *sangre* is traditionally devoted to stockbreeding and is occupied by nomadic people with numerous herds. The discriminant analysis showed that the proportion of *sangre* was much higher for the 'high' class than for the two other classes. The proportion of *baldiol* was similar for the 'medium' and 'high' classes, and higher than the 'low' class. This result is still in agreement with field observations, i.e. compounds are established close to ponds and humid areas in the *baldiol* landscape. The damaged bushy steppe was more abundant in'high' or 'medium' class pixels, reflecting soil degradation around the compounds.

The herd density map for the entire study zone is presented in Figure 5. Based on the 2001 rainy season data, it reflects a normal situation. Among the 1 600 pixels of the study zone, 1 376 (86%) were classified as 'low herd density', 116 (7.2%) as 'medium herd density' and 108 (6.8%) as 'high herd density'. That is to say that people really occupied 14% only of the available 1 600 km². The high-density clusters were mainly located in the surrounds of the Ferlo Valley (particularly in a polygon

Table II
Means of the six predictive variables of the model, for each herd density class

Herd density class	pse	psa	pba	pde	mcl	sdcl
Low	0.19	0.45	0.01	0.11	2.41	1.19
Medium	0.20	0.44	0.02	0.14	2.43	1.32
High	0.12	0.57	0.02	0.15	2.58	1.30

pse proportion of seeno per pixel
psa proportion of sangre per pixel
pba proportion of baldiol per pixel
pde proportion of damaged steppe per pixel
mcl average of the land-cover classes
sdcl standard deviation of the land-cover classes

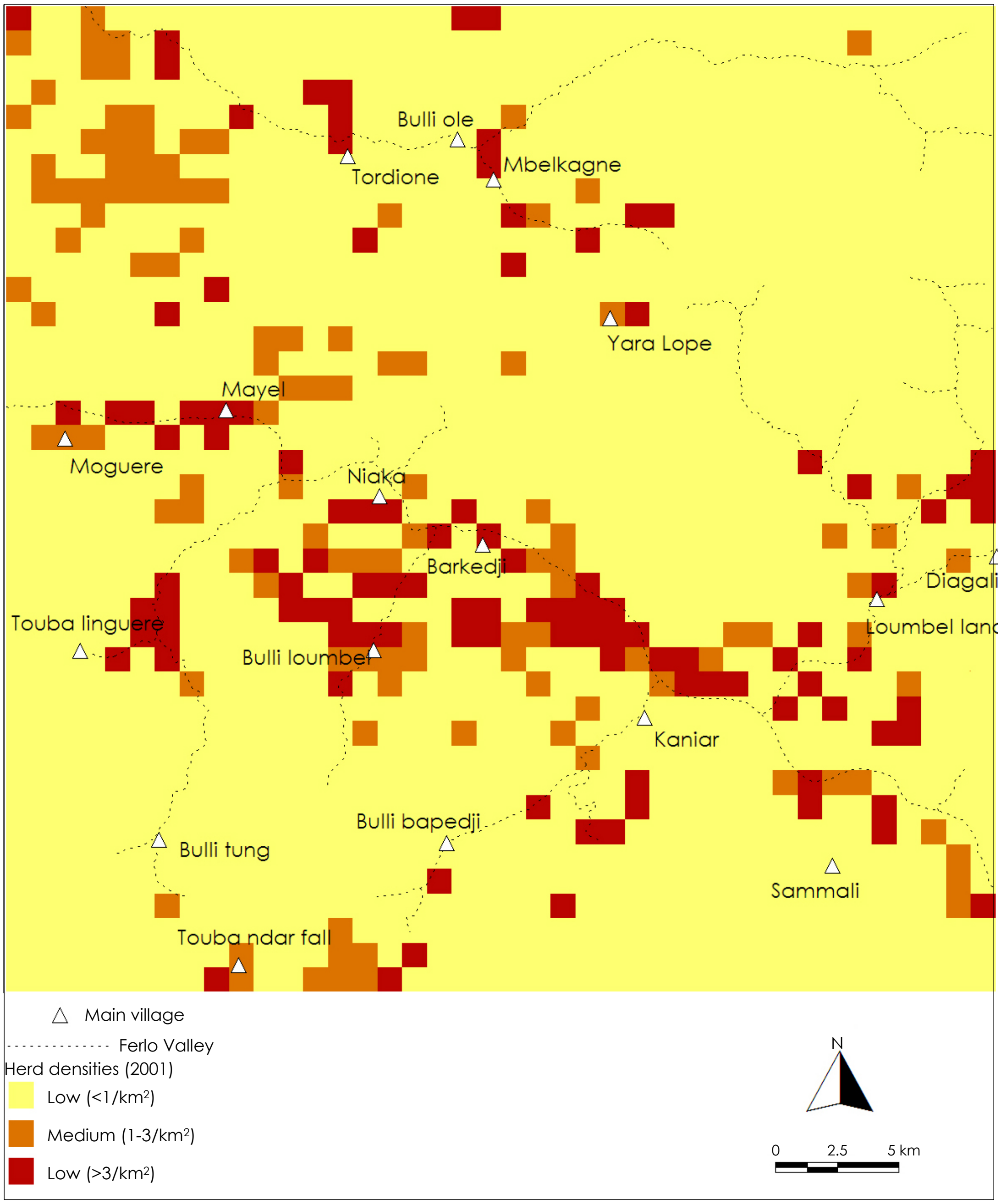

Figure 5
Herd density predicted in Barkedji during the 2001 rainy season

delimited by Niaka, Barkedji, Bulli Loumbel and Kaniar) and secondarily close to bore-holes (Diagali and Touba Linguere) or wells(Mayel, Tordione and Mbelkagne). Two medium-density focuses could be observed, in the north-western part of the area and around the Touba Ndar Fall bore-hole. Otherwise, medium-density pixels were rather isolated or contiguous to high-density pixels.

Validation

The inner validation showed that the model predicted the herd density with 71% accuracy. When overlaying the predictions and the data recorded in the field in 2003, the model fitted the observed herd density in 14 compounds out of 20, corresponding to 70% accuracy.

Discussion and conclusions

In this study, combining in a GIS both remotely-sensed data and field data collected from a limited spatial sample, enabled the prediction of herd density in the entire study area. The most predictive variables were all related to land cover, which proved to be more important than the NDVI variations. Surprisingly, it appears that the composition of the landscape was a better indicator that vegetation dynamics. An explanation for this may be that landscape reflects many environmental factors in the same entity, i.e. soil, vegetation (abundance and species), water resources. On the contrary, the NDVI index is more restrictive since it mainly reflects the rainfall. It was shown to be very relevant in the arthropod abundance assessment (28, 29), but was insufficient for multi-factorial phenomena, such as people or herd densities. In this case, not only the phytomass has an influence, but also the vegetation species, which must respond to the feed requirements of the ruminants. Consequently, land cover appears to be the most relevant indicator.

The accuracy of our model (variation between 70% and 71%, is common when using discriminant analysis. In the 30% of incorrect predictions, the predicted herd density was most often higher than reality.

However, the accuracy of the model can be improved in many ways, as described below.

- Firstly, other models can be considered, particularly multivariable regression analysis models.
- Secondly, other variables relative to people and animal density can be tested, for example elevation, slope, other vegetation indexes etc.
- Thirdly, the working unit can be reconsidered; in our model, the predicted variable was herd density which is less accurate than animal density; this approximation was due to field constraints. In our experience, the number of animals per compound was impossible to obtain in field surveys, both because people pay taxes on the cattle and are traditionally reluctant to count their animals. According to our Peulh surveyor, there was no chance of obtaining the correct animal density figures. In other parts of the Sahel, estimations of animal density are made from the air or by visual counts in compounds (22). Such methods were not possible in this study, so the number of herds had to be taken as an estimator of animal density. If the exact animal density figure can be obtained from later studies, it should be used in the model so as to offer a more accurate estimation of host distribution.
- Finally, the inter-annual herd density variations in the study area were not taken into account. In 2002, field observations revealed that the herd density in the entire study area was much higher than in 2001, although the rainfall was lower than the normal. This increase was related to an unusual inflow of nomadic people, who normally cross the Barkedji area on their way to the Senegal River Valley. In 2002, as rainfall was low, they decided to stay in Barkedji where grazing areas were still available. An additional study, conducted over a longer period, could assess the validity of the model in those particular situations.

This study stresses the importance of remote-sensing and GIS in regard to understanding disease and assessing risk. Spatial tools enable the integration of data taken from the sky and from the field, with powerful geoprocessing and statistical methods. Environmental indicators enable the extrapolation of vector abundance or disease prevalence/incidence in places where field data are not available. Such an approach is particularly interesting in developing countries, as it avoids exhaustive time-consuming and costly field surveys. In addition, GIS tools are powerful for multi-source and multi-scale data analysis. In this study, the choice of the local level corresponded to a desire to understand the Rift Valley fever cycle. This herd density model was part of a larger project that was designed to model the risk of RVF transmission in the rural community of Barkedji, before extrapolating it to the entire Sahelian area of Senegal.

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