Characterisation of multi-scale of Plasmodium falciparum malaria incidence in children of Camopi, French Guiana, by means of remotely sensed data

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Characterisation of multi-scale patterns of *Plasmodium falciparum* malaria incidence in children of Camopi, French Guiana, by means of remotely sensed data

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Abstract

Malaria remains a major health problem in French Guiana despite the decrease in the number of cases since 2010. A previous study in Camopi, an Amerindian village on the Oyapock River, revealed that *Plasmodium falciparum* malaria incidence was significantly related to landscape features and that its spatial distribution exhibited some obvious patterns. In the present study, we first identified the spatial patterns that exhibit a significant Moran's index of spatial auto-correlation and that significantly explain *P. falciparum* malaria incidence within the multiple linear regression framework. Secondly, we linked these patterns with remotely sensed environmental features. The selected model is composed of five spatial components: three patterns, representing 50.7% of the total variance, are associated with large scale variations of the incidence, and the remaining patterns are associated with local scale variations and represent 28.7% of the total variance. Different hamlet clusters that have specificities in terms of *P. falciparum* malaria incidence rate, environmental characteristics and mosquito control strategies have been identified. The methodology proposed in the present study can provide useful knowledge on the spatial distribution of the *P. falciparum* malaria incidence in Camopi at different scales and on possible explanation of such distribution, as a function of the scale.

Keywords: Remote Sensing, Landscape characterisation, Principal Coordinates of weighted Neighbourhood Matrices (PCNM), Factorial Analysis of Mixed Groups (FAMG), *Plasmodium falciparum* malaria incidence.

1. Introduction

Malaria remains a major health problem in French Guiana despite the decrease in the number of cases since 2010. This French overseas region had in 2008, with Guyana, the most elevated annual parasite index in south America with 15.7 cases per 1000 inhabitants (Carme et al. 2009). Previous studies in Camopi, an Amerindian village on the Oyapock River, highlighted the major contribution of environmental features to the incidence of malaria attacks (Hustache et al. 2007, Stefani et al. 2011a) and the advantages of using remotely sensed data to better and objectively characterise the environment (Stefani et al. 2011b).

Stefani et al. (2011b) already revealed that *Plasmodium falciparum* and *Plasmodium vivax* malaria incidences were, respectively, significantly and slightly related to landscape features. However, the spatial distribution of *P. falciparum* incidence among the 29 hamlets composing Camopi exhibits some obvious patterns (*cf.* Figure 2) that have not been studied yet. Such spatially observable resultants of the eco-epidemiological system depend on environmental, social, demographic and behavioural characteristics as well as on the interactions between these factors at different scales. Consequently, we suggest that a specific study of the spatial properties of the *P. falciparum* malaria incidence in Camopi should be carried out before linking such data with any explanatory variables.

In this context, the objectives of the present study are to first identify the significant spatial patterns of the *P. falciparum* incidence in children of Camopi, and secondly, the relationships of these patterns with remotely sensed environmental features. This two-step approach has been successfully applied to the study of the exposure risk to Chagas disease in a village situated in Bahia state, Brazil (Roux et al. 2011a, 2011b).

In the following, the study area specificity, the epidemiological and environmental data as well as the data analysis methodology are described. We then present the results and discuss them before proposing some perspectives and concluding remarks.

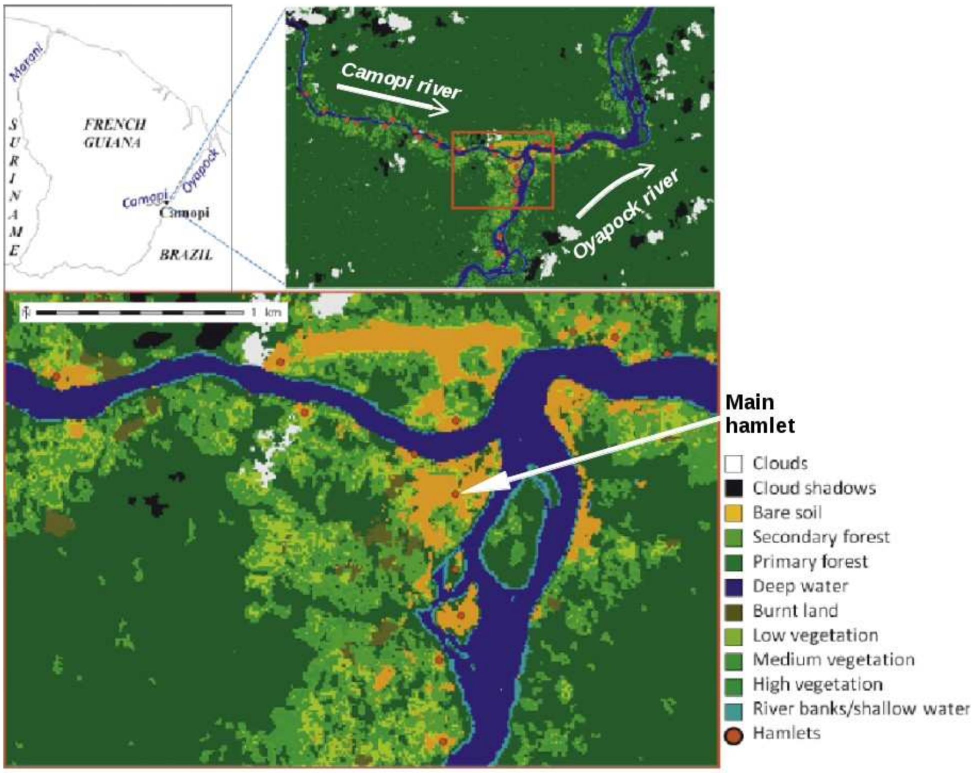

Figure 1: Location of Camopi and land-cover characterisation of the study site, with a magnification of the confluence of the Oypapock and Camopi Rivers (Stefani et al. 2011b).

2. Materials and methods

1.1 Study area

The study was conducted in Camopi, a village on the Oyapock River, which serves as the border between French Guiana and Brazil (Figure 1). This village consists of the agglomeration of a main central hamlet and 28 hamlets within a 15 km2 area. The 1200 registered inhabitants in 2009 were mostly Amerindians of the Wayampi and Emerillon ethnic groups, living on the banks of the Oyapock and Camopi Rivers, respectively. These groups have a traditional lifestyle, practicing subsistence slash and burn agriculture, fishing, hunting and gathering. The people live in wood huts, known locally as “carbets”, which have a roof of palm leaves, steel sheeting or tarpaulin. Nevertheless, modern concrete houses are progressively replacing these traditional dwellings, particularly in the principal hamlet. Camopi is isolated from the inhabited coastal region and the nearest town, Saint-Georges de l’Oyapock, is located at 100 km downstream on the Oyapock River.

1.2 Epidemiological data

Epidemiological data were provided by an open cohort study of children under the age of seven years, followed from January 1st, 2001, to December 31, 2009. A list of all acute clinical malaria episodes, the date of diagnosis and the *Plasmodium* species was established. The reader can refer to Stefani et al. (2011a and 2011b) for details on epidemiological data collection.

Plasmodium falciparum incidence data were then aggregated at the level of each hamlet, as incidence rates at household level would be subject to large errors due to the small number of children per carbet. In this study, we only considered acute clinical malaria episodes associated with *P. falciparum*.

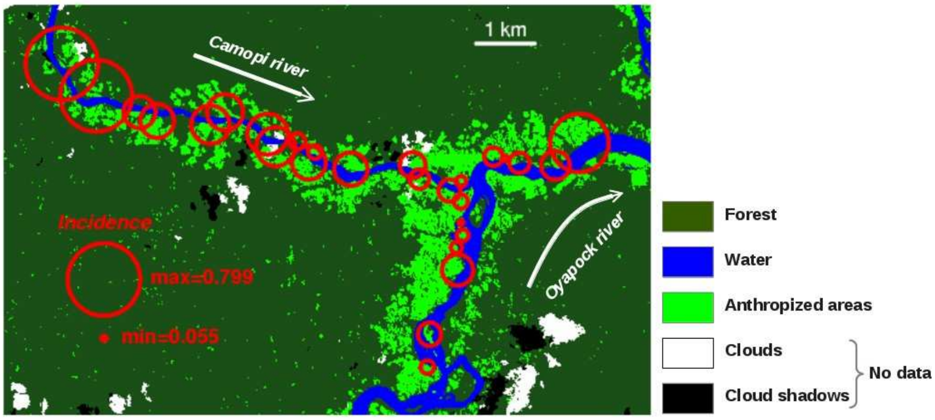

Figure 2: Distribution of the *P. falciparum* malaria incidence in Camopi. Each circle corresponds to a hamlet.

1.3 Remotely sensed data

Land cover/use map: Land cover/use characterisation was based on a 10-meter spatial resolution colour image (copyright CNES/SPOTimage) acquired on August 30th, 2006 by SPOT 5 Satellite and provided by the SEAS-Guyane project (http://www.seas-guyane.org). It was performed by a semi-supervised classification using GRASS GIS 6 software. Photographs taken from the air, with a spatial resolution of 50 cm, acquired by the French National Geographic Institute in 2006 (BD-ORTHO® product), were interpreted by eye, for the labelling of classes identified on the satellite image and for qualitative validation of the classification. In total, nine classes were identified: *primary* and *secondary forest*, *high*, *medium* and *low vegetation*, *body of water*, *burned area*, *bare soil* and *river banks/shallow water* (see Figure 1). *Unfragmented forest* was defined as the unbroken patch (i.e. the set of adjacent pixels belonging to the same class) of primary forest surrounding the village.

Data on rivers and creeks not visible on SPOT 5 satellite images due to their small size and/or the dense vegetation cover were extracted from the BD CARTHAGE® product of the French National Geographic Institute (IGN) and the French Ministry of Environment. BD CARTHAGE® is the hydrographic reference system for France, produced in 2009 for French Guiana by the Regional Direction of the Environment (DIREN) of Guiana and the French National Agency for Water and Aquatic Environments (ONEMA).

All households were geolocalised with a global positioning system (GPS) or by digitalisation from the aerial photographs of BD-ORTHO®.

Landscape characterisation: For each carbet inhabited by a child included in the cohort, the surrounding landscape was characterised within a discoid buffer of 400-meter radius, in accordance with the objective radius selection performed in Stefani et al. (2011b). Extracted descriptive attributes within the buffers were (see Stefani et al. 2011b for details): coverage percentage of each land-cover class, length of the Camopi and/or Oyapock river banks, length of creeks, number of inhabited houses and two measurements of landscape division (Jaeger 2000). Households presenting more than 20% missing data within 400m (presence of clouds and/or cloud shadows) were excluded. One hamlet was removed from the study because of missing data.

In addition to the buffer-based landscape characterisation, we also extracted, for each carbet inhabited by a child of the cohort, the minimum distances to each land cover class, to the creeks, to the other carbets and to the Camopi or Oyapock banks. We defined, for each household, an indicator of landscape “opening”, i.e. the surface of the anthropised area between the household and the surrounding unfragmented forest.

Eventually, landscape features at the carbet level were averaged at the level of each hamlet (Stefani et al. 2011b).

1.4 Complementary field observations and surveys

Information on hamlet characteristics have been collected by field observations and surveys: creation or desertion of the hamlet during the study, total number of carbets and of inhabitants in the hamlet, inundability and frequency of intervention of the county mosquito control service (SDD). Eventually, the distance to the health centre, located in the main hamlet, was also considered.

1.5 Data analysis: multi-scale spatial modelling of the *P. falciparum* malaria incidence

As mentioned in the introduction, we first chose to study the spatial distribution of the incidence data. We identified the spatial patterns that exhibit a significant Moran's index of spatial auto-correlation and that significantly explain *P. falciparum* malaria incidence within the multiple linear regression framework, by applying the following methodology:

1. *Weighted Neighbour Matrices generation*: Five types of neighbourhood structures (here also called graphs) were generated as proposed by Dray et al. (2006): the Delaunay triangulation graph, the Gabriel graph, the relative neighbourhood graph, the minimum spanning tree, and distance based graphs (dnn), considering that two sites i and j are

neighbours if $d(i,j)<=\gamma$. We computed dnn graphs for γ=1300, 1500, 1700, ..., 4500 meters, 1300 meters being the minimum inter-hamlet distance permitting to connect all the hamlets with a minimum vertex degree equal to one, and 4500 being half the maximum inter-hamlet distance.

When two hamlets were connected by a graph edge, the strength of the link was weighted as a function of the inter-hamlet euclidean distance in the geographic space, *d*:

$$f_1 = 1 - \left(\frac{d}{d_{max}}\right)^{\alpha} \quad \text{with } \alpha \in \{1, 2, 5, 10\} \tag{1}$$

$$f_2 = \frac{1}{d^{\beta}} \quad \text{with } \beta \in \{0.1, 0.2, 0.5, 1\} \tag{2}$$

Overall, 168 (21 graphs × 8 weighting solutions) weighted graphs were tested for *P. falciparum* malaria incidence explanation.

2. *Principal coordinates analysis of a neighbour matrix (PCNM)* (Borcard et al. 2004; Dray et al. 2006): The PCNM was computed for the candidate spatial structures previously defined. For each resulting eigenvector, the significance of Moran's I index value was tested with a 999 permutation procedure. Eigenvectors that presented significant spatial auto-correlation ($p < 0.01$) in the sense of Moran's I were retained as proposed by Bellier et al. (2007) and Roux et al. (2011a). The eigenvectors were then sorted into descending order according to their capacity to explain the incidence values, i.e. according to the proportion of explained variance provided by linear regression. Ranked eigenvectors were then entered, one by one, as explanatory variables of the *P. falciparum* incidence, by adopting the multiple linear regression approach. Consequently, as many regression models as eigenvectors were defined, and the corrected AIC (AICc) was computed to select the model that realised the best compromise between variance explanation and parsimony (for procedural details, see Dray et al., 2006). In total, 4468 models were tested and the one providing the lower AICc value was selected.

1.6 Data analysis: environmental characterisation of the spatial patterns of *P. falciparum* malaria incidence

In a second time, we linked the selected eigenvectors (also referred to as *spatial patterns* or *spatial components*) provided by the PCNM, with the hamlet features described in sections 1.3 and 1.4. We chose to apply the Factorial Analysis of Mixed Groups (FAMG) in the same way as in Roux et al. (2011b), i.e. by considering the selected spatial patterns as analysis variables. The FAMG permits to balance the influence of several variable groups (or tables) in the analysis - each group defining a "point of view" or an *a priori* influential factor on the studied phenomenon - and to jointly analyses quantitative and qualitative variables. Table 1 lists the variable groups defined in our study. We then only considered significant variables and modalities for results presentation and interpretation. In fact, for each factorial axis, we first computed the total contributions of the categorical variables by summing the contributions of their modalities and then ranked all the variables in descending order of their contributions. A variable significantly contributed to the axis if it had a cumulated contribution at most equal to 80%. Moreover, a quantitative variable or a modality was well represented on the factorial axis if its quality of representation (cos2) on the axis was superior to 0.1. The reader can refer to Pagès (2002, 2004) and Roux et al. (2011b) for methodological details.

Table 1. List of variable groups and list of variables for each FAMG group.

Group	Variables/Questions(categorical variables)
Spatial model for *P. falciparum* incidence	Selected eigenvectors defining the spatial model for *P. falciparum* malaria incidence
Landscape	Percentage of each land-cover classes, length of the Camopi and/or Oyapock river banks, of creeks; number of inhabited houses; landscape division measures; minimum distances to each land cover/use class, to the nearest creek, the nearest household and the Camopi or Oyapock bank; landscape “opening”
Hamlet features	Creation/desertion of the hamlet during the study; numbers of carbets and inhabitants in the hamlet; inundability; frequency of intervention of the county mosquito control service; distance to the health centre (located in the main hamlet)

2. Results

The selected spatial structure is defined by a distance based graph with $\gamma=2700$m and the f_2 weighted function with $\beta=0.1$. The selected model is composed of five spatial components represented in Figure 3. The cumulated explained variance of the incidence values by the multiple linear regression model is 79.4%. Moran'I spatial autocorrelation of the model residuals is not significant (p=0.79).

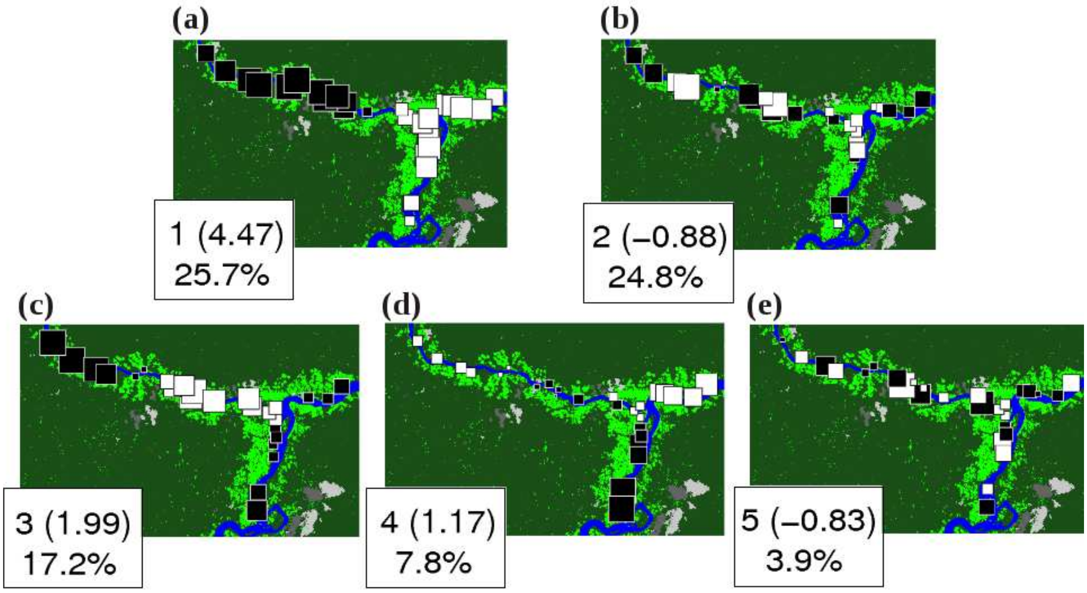

Figure 3. Spatial representation of the eigenvectors for the *P. falciparum* malaria incidence in Children of Camopi. Black and white squares correspond to positive and negative values of the eigenvector components, respectively. The square sizes are proportional to the absolute values of the eigenvector components. The percentage corresponds to the proportions of incidence variance explained by the eigenvectors. The other numbers correspond to the eigenvector rank in the model and to the associated eigenvalue, proportional to the Moran’s I of spatial autocorrelation (Dray et al. 2006).

Three patterns (Figures 3a, 3c and 3d), representing 50.7% of the total variance, are associated with large scale variations of the incidence. The remaining patterns (Figures 3b and 3e) are associated with local scale variations and represent 28.7% of the total variance. The first three spatial components are positively linked with the incidence, whereas the two remaining ones are negatively related.

The first pattern (Figure 3a), explaining nearly 26% of the incidence variance, clearly opposes two regions: the Oyapock river banks and the Camopi river banks. More precisely, the frontier between these two regions coincides with rapids on the Camopi river, constituting obstacles to the navigation upstream “Saut Mombin” hamlet. The third spatial component (17.2% of the incidence variance) opposes the hamlets of the downstream part of the Camopi River with the other ones. The forth spatial component (7.8%) opposes the upstream and the downstream parts of the Oyapock River. The second and the fifth patterns are more difficult to interpret as they correspond to very local variations.

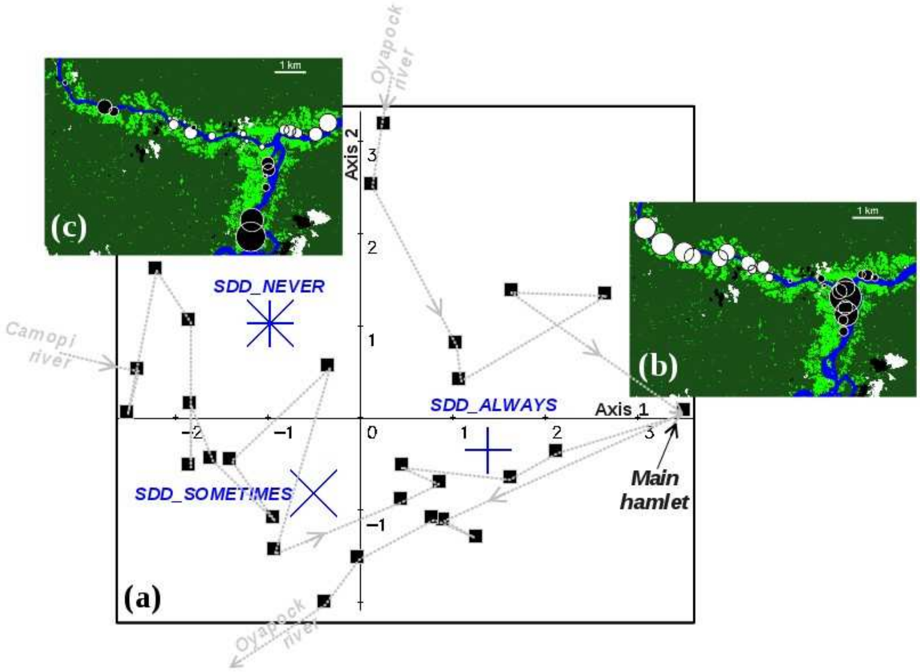

Figure 4. a) Hamlets (black squares) and most significant modalities of categorical variables represented onto the first factorial plane of the FAMG. + and × symbols correspond to the significant modalities related to, respectively, the first and the second axes of the FAMG. Gray arrows link the hamlets along each river. The two maps (b and c) represent, in the geographical space, the hamlet coordinates on the factorial axes (respectively the first and the second axes). Black and white disks are associated with, respectively, positive and negative values. The disk sizes are proportional to the absolute values of the coordinates.

Figures 4 and 5 present the hamlets, the modalities of the categorical variables and the quantitative variables projected onto the first factorial plane of the FAMG, representing 35.5% of the total variance of the data.

The first factorial axis (representing 22.2% of the total variance), explains the first spatial component of the *P. falciparum* malaria incidence (contribution to the axis = 29.5% ; linear correlation coefficient with the axis = 0.85 ; 73.2% of the variance of the variable explained by the axis) (see Figures 4 and 5). It associates the hamlets located upstream Saut Mombin rapids with (see Figure 5): high proportions of *dense forest* and of *high vegetation* within 400m around carbets; high distances to the health centre and (in opposition to the hamlets on the Oyapock river banks and downstream Saut Mombin rapids) low proportions of *bare soil* within 400m, low distances to *high vegetation*, low numbers of carbets and of inhabitants in the village and low number of carbets within 400m. Hamlets located downstream Saut Mombin rapids and on the Oyapock river banks are characterised, by opposition to the hamlets upstream Saut Mombin rapids, by low proportion of *dense forest* and of *high vegetation* within 400m, etc.

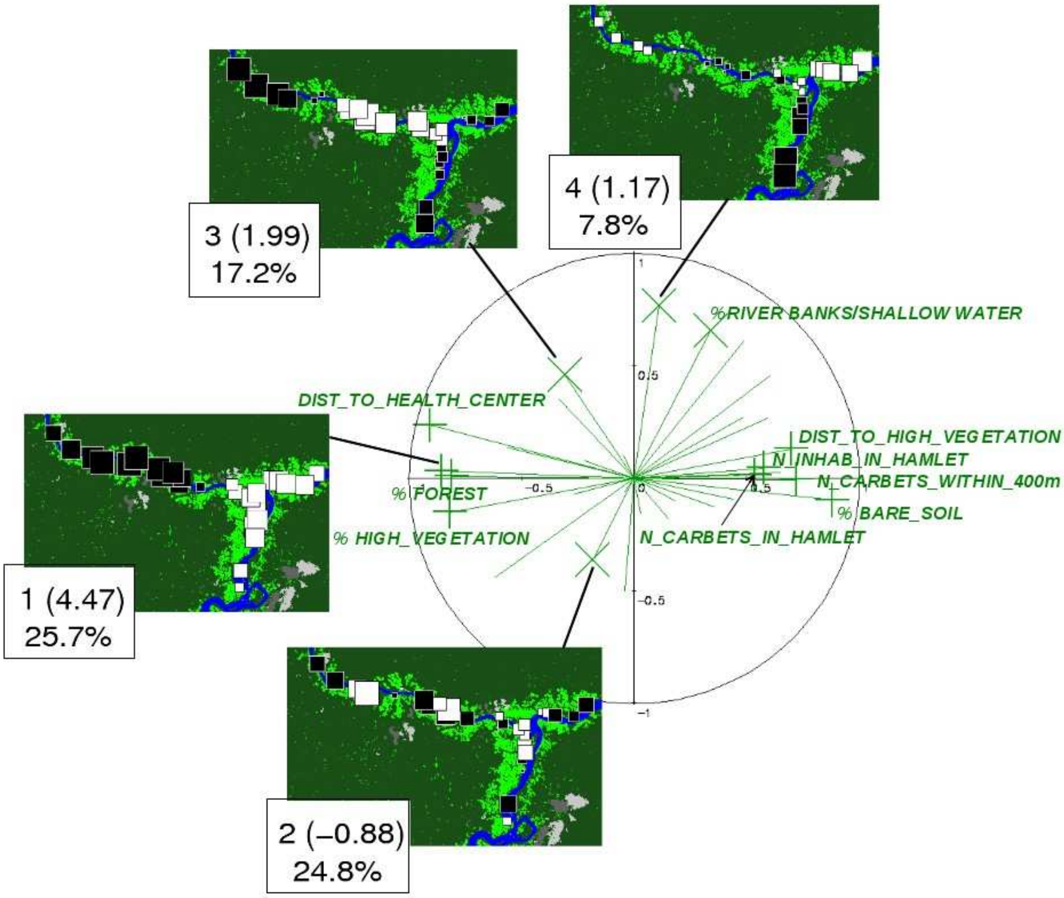

Figure 5. Quantitative variables represented onto the first factorial plane of the FAMG. + and × symbols correspond to the significant variables related to, respectively, the first axis and the second axes of the FAMG.

The second factorial axis (accounting for 13.3% of the data variance) is particularly correlated with the forth spatial component of the incidence (contribution to the axis = 39.5% ; linear correlation coefficient with the axis = 0.77 ; 58.9% of the variance of the variable explained by the axis), and to a lesser extent with the third (resp. 14.2%, 0.46 and 21.2%) and the second ones (8.9%, -0.36 and 13.3%) (see Figures 4 and 5). It essentially opposes the hamlets situated on the Oyapock River downstream the main hamlet with those laying by the upstream Oyapock River (Figure 4). The hamlets situated on the upstream

Oyapock river banks are associated with a high proportion of *river banks/shallow water* within 400m (Figure 5).

The categorical variable *SDD*, corresponding to the frequency of the interventions of the county vector control service, contributes to explain the first and the forth spatial components (Figure 4). In fact, Figure 4 shows that, when “travelling” to the main hamlet along each river, modalities *NEVER*, *SOMETIMES* and *ALWAYS*, corresponding to the frequency of the interventions of the county vector control service, are traversed sequentially.

Eventually, by studying the third and the forth axes of the FAMG, no significant result has been observed according to the defined criteria (section 1.6).

3. Discussion

The study concerns children supposed to be at home, at least out of the school time and especially during the period of high risk of mosquito biting, at the dusk and the dawn and during the night (Girod et al. 2008; Fouque et al. 2010). This has led to the hypothesis that *P. falciparum* malaria transmission occurred in the carbets and/or within the direct peri-domiciliary space. Consequently, this justified the approach that consists in directly linking malaria incidence rates with environmental features.

We did not study the *P. vivax* malaria incidence. In fact, despite the filtering methods proposed in the literature (Hanf et al. 2009), new transmissions associated with *P. vivax* are difficult to distinguish from relapses, and possible induced errors can bias the relationships between environmental factors and incidence. This can explain that *P. vivax* malaria incidence was only slightly related to landscape features in Stefani et al. (2011b).

In the present study, different hamlet clusters have been identified within the Camopi agglomeration. Each cluster defines a district having specificities in terms of *P. falciparum* malaria incidence rate, environmental characteristics and mosquito control strategies:

- District n°1, upstream the “Saut Mombin” rapids, associated with: high incidence rates, high proportions of dense forest and of high vegetation within 400m around carbets; high distances to the health centre, low proportions of bare soil within 400m, low distances to high vegetation, low numbers of carbets and of inhabitants in the village and low number of carbets within 400m. This district is consequently characterised by the preponderance of the dense forest and of high vegetation surrounding the carbets, confirming the relationship between such land cover types and *P. falciparum* malaria incidence in Camopi (Stefani et al. 2011b). Moreover, it is associated with the absence of intervention of the control vector service, which can be explained by the difficulties in ascending the river beyond the “Saut Mombin” rapids;
- District n°2, downstream “Saut Mombin” rapids on the Camopi and along the Oyapock River, associated with: lower incidence rates than District n°1, high proportions of bare soil within 400m, high distances to high vegetation, high numbers of carbets and of inhabitants in the village and high number of carbets within 400m. This confirms the protective effect of a certain degree of urbanisation also identified in Stefani et al. (2011b). District 2 can then be divided into two sub-districts:
  - District n°2a, upstream the main hamlet on the Oyapock River, associated with: relatively low incidence rates for the District n°2; high proportion of river banks/shallow water within 400m. This sub-district seems to be characterised by a high interaction with the Oyapock River. In fact, the hamlets of this sub-district

are either situated on islands or on the Oyapock river banks where the river is particularly sinuous. We can hypothesise that the Oyapock River, with its deep water and its relatively rapid stream, is relatively inefficient in order to produce breeding sites for mosquitoes. Consequently, being surrounded by the Oyapock River appears to be relatively protective. The two hamlets located at the very upstream part of the Oyapock were never visited by the mosquito control service. This proves that the control actions cannot alone explain the incidence rate.

- District n°2b, downstream the main hamlet on the Oyapock River, associated with: relatively high incidence rates for the District n°2 and non-systematic interventions of the control vector service. These hamlets are newer than those upstream.

Only large scale patterns have been explained by the environmental variables. Two reasons can be provided: the environment is effectively only linked with large scale spatial components of the *P. falciparum* malaria incidence in Camopi, or the landscape characterisation method did not permit to explain more local features. In Stefani et al. (2011b), 400 meters was identified as the optimal radius value for characterising the landscape around the carbets regarding the incidence values. However, we can expect that lower radius values could help explaining the relationships between the incidence and the environment at very local scales.

In Camopi, socio-economical and behavioural data were provided by a Knowledge, Attitudes, Practices and Behaviour (KAPB) questionnaire administered to every child's mother (Stefani et al. 2011a). The aggregation of these data at the hamlet level could provide useful information in order to explain local features of the *P. falciparum* malaria incidence distribution.

4. Conclusion

The methodology proposed in the present study can provide useful knowledge on the spatial distribution of the *P. falciparum* malaria incidence in Camopi, at different scales. This study confirms the results already published in Stefani et al. (2011b). However, it spatialised the relations already found and permitted to identified different hamlet clusters that have specificities in terms of *P. falciparum* malaria incidence rate, environmental characteristics and mosquito control strategies. By allowing to formulate hypotheses on places and contexts favorable for malaria transmission, the results can guide the field works, especially with regard to the entomological captures, by specifying priority areas to explore. Moreover, we emphasis the beneficial role of the mosquito control service and highlight the fact that efforts have to be made in order to make the service systematically intervene in isolated hamlet, by reinforce the resources of the vector control. Eventually, further works would permit to identify local socio-economical and behavioural features that could explain the *P. falciparum* malaria incidence distribution at very local scales.

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