Diversity, distribution and habitat requirements of aquatic insect communities in tropical mountain streams (South-eastern Guinea, West Africa)

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Abstract – Considering that knowledge of the biodiversity of a region is the first step toward its conservation and given the paucity of studies on aquatic insects from the Simandou streams, the diversity of these communities was assessed. Aquatic insects were sampled with a hand-net (mesh size: 250 µm) on four occasions between March 2011 and September 2012 at 27 sites. Environmental variables were also recorded. Overall, 129 taxa belonging to 51 families and eight orders were recorded. Multivariate analyses gathered sites into three clusters in regard to aquatic insect composition. The rarefied taxonomic richness showed decreases in association with increasing levels of human impact. Cluster 1 that contained most disturbed sites displayed low taxonomic richness compared with the two others. The highest taxonomic richness was registered in cluster 2 that contained a mixture of upland and lowland sites; the latter remained minimally disturbed. These sites could be considered as reference sites in studies for assessing water quality. Generalised additive models calculated for the most frequent taxa showed that water temperature, dissolved oxygen, conductivity and pH were the incorporated explanatory variables. Therefore, further anthropogenic activities should preserve the surrounding forest in order to preserve the quality of Simandou streams and consequently aquatic biodiversity.

Key words: West Africa / mountain streams / generalized additive models / taxonomic diversity / aquatic insects

Introduction

Streams and rivers are among the most threatened ecosystems of the world (Dudgeon *et al.*, 2006; Hering *et al.*, 2006), particularly those in tropical regions (Boyero and Bailey, 2001). Estimates of the current biodiversity loss in these ecosystems are alarming (Allan and Castillo, 2007). As a result, deterioration of aquatic biodiversity has become one of the main concerns in recent conservation and ecological studies in various parts of the world (Rawi *et al.*, 2013).

Tropical rivers support a rich but incompletely known biota (Tomanova *et al.*, 2006). Therefore, the principal topics of biodiversity studies in this area are taxonomy, species inventory and distribution. Only once

this basic information is established can tropical freshwater systems be viewed in a more holistic manner (Hyslop and Hunte-Brown, 2012). Significant efforts should also be made to develop realistic models of the structure and functioning of pristine or little modified tropical streams (Tomanova *et al.*, 2006). In addition, there is growing interest in Africa for the use of aquatic invertebrates as indicators of water quality and ecosystem changes (Thorne *et al.*, 2000; Dickens and Graham, 2002; Ndaruga *et al.*, 2004; Kasangaki *et al.*, 2006, 2008; Arimoro *et al.*, 2007). Some of the compelling reasons for the apparent popularity of these communities as bioindicators are that they are ubiquitous, species-rich and long-lived. Given their ability to integrate temporal conditions, they provide evidence of environmental conditions over long periods of time (Imoobe and Ohiozebau, 2009).

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In sub-Saharan Africa, tropical forests are increasingly threatened by accelerating rates of forest conversion and degradation (Kasangaki *et al.*, 2008). However, tropical montane cloud forests are ranked among the most important ecosystems for sustaining life in tropical regions (Bubb *et al.*, 2004). Typical for montane areas are first- and second-order headwater streams that offer another vital service to humankind, namely the storage, regulation and purification of water (Bücker *et al.*, 2010). Downstream human populations rely on the supply of a certain amount of quality drinking and irrigation water. All these services depend on healthy ecosystems that are currently endangered by degradation (Doumenge *et al.*, 1995).

In this study, we focussed on mountain streams in the Simandou Range located in the south-east of the Republic of Guinea (West Africa). Long-term biomonitoring surveys of aquatic insects were carried out in several large rivers of West Africa during the Onchocerciasis (River Blindness) Control Programme (Lévêque *et al.*, 2003) and recent studies have been carried out in Ivory Coast (Edia *et al.*, 2010; Kouamé *et al.*, 2011; Diomandé *et al.*, 2014), Ghana (Benbow *et al.*, 2014) and Nigeria (Olomukoro and Ezemonye, 2007; Arimoro *et al.*, 2011). To our knowledge, aquatic insects in streams of Guinea in general and particularly those from the Simandou streams remain largely undocumented. Based on its montane habitats, altitudinal range and relatively intact forest, the Simandou was thought likely to contain a high biotic diversity. In addition, the Simandou Range also harbours potential mineralogical wealth and, in particular, extensive iron ore deposits. Exploratory operations are underway in the area to determine the quality, quantity and location of iron ore resources. Unfortunately, further exploitation of these resources could negatively impact streams and consequently aquatic organisms by increased deforestation, erosion, streambed modification and associated disturbances. It is therefore important to preserve these water resources and maintain their good ecological status (Gama *et al.*, 2014).

Considering that knowledge of the biodiversity of a region is the first step toward its conservation (Heino *et al.*, 2005) and given the paucity of studies on aquatic insects from the Simandou streams and Guinea in general, our objectives were to assess the diversity of aquatic insect communities and the habitat requirements of these communities in this area. We aimed to examine the following topics: (i) patterns of aquatic insect distribution, and (ii) environmental variables best explaining the occurrence of major aquatic insect taxa from these streams.

Materials and methods

Study area and sampling sites

The Simandou Range is located in the southeast of the Republic of Guinea, near its border with Ivory

Coast and Liberia (Fig. 1), close to the town of Beyla. This tropical area is seasonally humid and dominated by the 'West African Monsoon'. The rainy season (1300–1800 mm·year⁻¹) lasts from May to October and the dry season from November to April. Between 90 and 95% of the annual rainfall occurs during the wet season (Extence *et al.*, 2013).

In West Africa, almost the whole of the Guineo-Congolian Region is underlain by Precambrian rock. The landscape is formed by relatively low plateaux and plains interrupted by residual inselbergs and small higher plateaux. The Simandou Range rises above the basement plain by some 600–800 m with the main ridge ranging in elevation from 1250 to 1650 m a.s.l.

Overall, 27 sites were sampled. They were located on tributaries or in the upstream parts of the three main rivers (Milo, Loffa and Diani) belonging to different catchments. The studied streams were selected to cover a range along a disturbance gradient from intact forested sites to degraded sites. The possible degradation (adjacent land use and instream disturbance) was assessed visually by the presence of anthropogenic activities such as farming, habitation, roads, water collection, washing and/or bathing. Site characteristics are summarized in Table 1.

Data collection

Samples were collected on four occasions (*i.e.* two during the rainy season (September 2011 and 2012) and two during the dry season (March 2011 and 2012)) at each site. Aquatic insects were sampled with a multi-habitat approach (Hering *et al.*, 2004). Subsamples were taken over a 30 m reach proportionally to macrohabitat coverage (mineral: mud, silt, sand, stones, bedrock; biotic: floating or submerged macrophytes, bank vegetation, living and fallen wood, algae/periphyton) (Minaya *et al.*, 2013) and were specific to each available habitat at each sampling site. Subsamples were collected starting downstream with a hand-net (mesh size: 250 µm) while manually disturbing the upstream located patches for 1 min. Aquatic insects sorted *in-situ* within each subsample were pooled into samples and preserved in 70% ethanol. They were identified in the laboratory to the finest taxonomic resolution possible by means of the keys in Déjoux *et al.* (1981), Durand and Lévêque (1981), De Moor *et al.* (2003a, b), Day *et al.* (2003) and Stals and De Moor (2007).

At each site and each campaign, dissolved oxygen concentration, electrical conductivity, water temperature, pH and oxidation-reduction potential (ORP) were measured *in-situ* with a YSI Professional Plus meter (YSI Inc., USA). Water samples were collected using 500 mL plastic bottles, transported to the laboratory under cool conditions and were stored at 4 °C for total suspended solids (TSS) analysis. In the laboratory, TSS was determined gravimetrically from GF/F filters after drying (60 °C) to constant weight.

Fig. 1. Location of the study area showing the sampling sites (S1–S27).

Data analysis

Taxon richness was rarefied to avoid any bias related to differences in abundances between samples (Heck *et al.*, 1975). The rarefaction was applied to the total taxonomic richness per site using the lowest abundance (120 individuals for this study) found in all sites as the target number of individuals (Oksanen *et al.*, 2013). Calculations were performed using the *vegan* package (Oksanen *et al.*, 2013) for the R 3.0.2 freeware (R Core Team, 2013).

Correspondence analysis (CA) was used to ordinate the samples according to taxa presence-absence, thus summarizing spatial variability of aquatic insect communities. Between-class CA and permutation tests were carried out to assess the relative extent and significance

of spatial variability (Dolédéc and Chessel, 1989; Baty *et al.*, 2006). The classes of the between-class CA were catchments and sampling sites. The taxonomic similarity between sites was then investigated using Ward's clustering method applied to the between-site CA scores. Between-cluster CA and permutation tests were carried out to assess the relative extent and significance of site clustering. The classes of the between-class CA were clusters. Rare taxa (taxa occurring in less than 5% of the samples) were removed. The analyses were computed with the *ade4* package (Chessel *et al.*, 2004) for the R 3.0.2 freeware.

Indicator values (IndVal) were calculated according to Dufrêne and Legendre (1997) to identify the most discriminant taxa for each site cluster. The statistical significance of the indicator values was evaluated using a

Table 1. Characteristics of the sampling sites.

Stations	Streams	Coordinates (UTM)		Altitude (m)	Category	Disturbance degree	Adjacent land use	Instream disturbance	Population density*
		S	E						
S1	Miya	517 119	963 799	650	Lowland	High	Bridge, road and village	Washing and bathing	High
S2	Miya	514 868	958 207	678	Upland	Moderate	permanent presence of cattle	None	None
S3	Boboiba	514 130	958 365	689	Upland	Low	Riparian forest	None	None
S4	Miya	514 787	956 748	694	Upland	Low	Old rice field	None	None
S5	Loffa	514 915	948 832	762	Upland	Low	Bridge, road	Bridge, road	None
S6	Loffa tributary1	514 216	948 517	780	Upland	Low	Old rice field	None	None
S7	Loffa	518 433	937 509	600	Lowland	Low	Old rice field	Bathing	Low
S8	Loffa tributary2	511 074	944 847	1177	Upland	None	Riparian forest	None	None
S9	Foko	510 091	938 614	852	Upland	None	Riparian forest	None	None
S10	Foko	509 334	939 116	797	Upland	None	Riparian forest	None	None
S11	Soumourou	495 367	943 228	524	Lowland	Moderate	Farming	Washing and bathing	Low
S12	Whisky 2	509 870	942 700	1213	Upland	None	Riparian forest	None	None
S13	Woron	506 004	949 430	572	Lowland	Low	Old rice field	water collection	Low
S14	Worongbê	509 714	950 299	750	Upland	None	Riparian forest	None	None
S15	Woronfi	508 402	951 193	578	Lowland	Low	Riparian forest, old rice field	None	None
S16	Woronfi	508 896	952 353	685	Upland	None	Riparian forest	None	None
S17	Woron tributary	510 601	953 914	906	Upland	None	Riparian forest	None	None
S18	Worongbê	510 430	949 942	801	Upland	None	Riparian forest	None	None
S19	Woron	504 669	948 025	564	Lowland	None	Riparian forest	None	None
S20	Woron	503 090	947 458	544	Lowland	Moderate	Farming, village	Washing and bathing	Low
S21	Soumourou	496 910	944 550	520	Lowland	Moderate	Bridge, road, farming	water collection	Low
S22	Kpolowai	503 095	944 377	534	Lowland	High	Village, farming	Washing and bathing	High
S23	Woronfi	508 085	953 807	702	Upland	None	Riparian forest	None	None
S24	Loffa tributary3	513 923	945 786	871	Upland	None	Riparian forest	None	None
S25	Loffa	518 079	940 531	620	Lowland	None	Riparian forest	None	None
S26	Mala	509 209	957 937	699	Upland	Low	Old rice field	None	None
S27	Loffa tributary4	512 292	947 925	804	Upland	None	Riparian forest	None	None

* Low: discontinuous habitation along the banks; High: continuous habitation.

randomization procedure with 999 permutations (Dufrêne and Legendre, 1997). This analysis was performed using the *indicspecies* package (De Caceres and Jansen, 2013) for the R 3.0.2 freeware.

A preliminary Shapiro test outlined the non-normality of data in some of the clusters. Variations in environmental variables and in rarefied richness between clusters defined by the hierarchical analysis were determined using a Kruskal–Wallis test. When the Kruskal–Wallis test was significant, a Wilcoxon test was used for pairwise comparison. The significance threshold was $P = 0.05$.

Relationships of the most frequent taxa (taxa occurring in at least 50% of the 108 samples (27 sites $\times$ 4 periods) with environmental variables were analysed using GAMs (Hastie and Tibshirani, 1990), with the aim of identifying the main variables influencing their occurrence. All five environmental variables with a pairwise correlation of $r < 0.8$ (Pearson's correlation, $P < 0.05$) (Table 2) were included in the GAMs. In the models, the TSS values were

$\log_{10}(x + 1)$ transformed. Binomial family distributions and log-link functions were used to ensure that all fitted values were positive (Fuentes-Rodriguez *et al.*, 2013). An F -test was used to obtain the significance of the deviance explained by each dropped variable. The contribution of each explanatory variable was expressed as the deviance reduction associated with dropping the variable from the final model (Castella *et al.*, 2001). These models were implemented using the *mgcv* package (Wood, 2014) for the R 3.0.2 freeware.

Results

Taxonomic richness and composition

A total of 129 aquatic insect taxa belonging to 51 families and eight orders were recorded (Appendix). The number of taxa identified at each site ranged from 27 (S11) to 71 (S2). The richest orders of insects were Coleoptera

Table 2. Pearson's correlation coefficient (r) between explanatory environmental variables used in GAMs.

Variable	Code	Temp	Cond	DO	pH	ORP
Water temperature	Temp					
Conductivity	Cond	0.30***				
Dissolved oxygen	DO	−0.36***	−0.22***			
pH	pH	0.19*	0.41***	−0.13		
Oxidation-reduction potential	ORP	−0.34***	0.09	0.16	0.07	
Total sediment suspended	TSS	−0.03	0.09	0.02	−0.01	0.03

*** r significantly different from 0 at $P < 0.001$.* r significantly different from 0 at $P < 0.05$.No asterisk: r not significantly different from 0 ($P > 0.05$). **Fig. 2.** Correspondence analysis of the taxonomic data (CA) showing (a) between-catchment (F1: 18.5.7% and F2: 11.5% of explained variation) and (b) between-site (F1: 16.8% and F2: 9.5% of explained variations) variations, and (c) hierarchical cluster summarising between-site similarities in aquatic insect assemblages. S1–S27: sampling sites, DS: dry season, WS: wet season, 11 and 12: years 2011 and 2012, 1–3: cluster numbers.

(29 taxa) and Ephemeroptera (26 taxa) followed by Odonata (25 taxa). Plecoptera was represented by one taxon (*Neoperla spio*) and was the most abundant order.

Overall, the macroinvertebrate fauna was predominantly composed of ten taxa that were present in more than 50% of the samples: five Ephemeroptera (*Adenophlebiodes* sp., *Diceromyzon* sp., *Caenis* sp., *Labiobaetis* sp., *Afromurus* sp.), one Plecoptera (*Neoperla spio*), two Trichoptera (*Leptocerus* sp., *Hydropsyche* sp.) and two Diptera (Chironominae, *Limnophila* sp.).

The between-catchment CA (Fig. 2a) explained only 3.6% of the total assemblage variation (permutation test, $P < 0.001$). The between-site CA (Fig. 2b) explained 32.6% of the total assemblage variation (permutation test, $P < 0.001$). Hierarchical clustering using the distance calculated by the between-site CA grouped sites into three clusters (Fig. 2c). The sites were clustered according to their taxa composition, and the catchments had no effect. The permutation test on between-cluster CA was significant ($P < 0.001$). Cluster 1 consisted of five sites,

Fig. 3. Box-plots showing differences in rarefied taxonomic richness (calculated for 120 individuals) between site clusters (1–3). Different letters on box-plots denote significant differences between them ($P < 0.05$; Wilcoxon test).

which are the most disturbed by anthropogenic activities, such as agricultural and domestic activities, as they are located close to populated areas (see Table 1). Clusters 2 and 3 were composed respectively of 10 and 12 sites, which are relatively free from disturbance as they are located in unpopulated areas. The Kruskal–Wallis test showed significant differences in rarefied richness between clusters ($\chi^2 = 6.07$, $P < 0.05$, Fig. 3). Cluster 1 displayed the lowest rarefied taxonomic richness and was significantly different from clusters 2 and 3 (Wilcoxon test, $W = 5$, $P < 0.05$). There was no significant difference (Wilcoxon test, $W = 70$, $P > 0.05$) between clusters 2 and 3. However, cluster 2 contained the sites with the highest rarefied richness.

Six taxa had significant indicator values (permutation test, $P < 0.05$) (Table 3): cluster 1 was mainly characterized by *Lestynogomphus* sp., cluster 2 by *Leptelmis* sp. and *Tricorythus* sp., and cluster 3 by *Ephemera* sp., *Afrobrianax ferdyi* and *Chimara* sp.

Environmental characteristics of the site clusters

The variations of environmental variables among clusters are shown in Figure 4. Cluster 3 gathered sites with a relatively high altitude (upland) in comparison with those of cluster 1 (Wilcoxon test, $W = 2$, $P < 0.05$) and cluster 2 (Wilcoxon test, $W = 12$, $P < 0.05$). Cluster 2 contained a mixture of lowland and upland sites (see Table 1).

The highest values of dissolved oxygen were registered in cluster 3 compared with those of cluster 1 (Wilcoxon test, $W = 7$, $P < 0.05$) and cluster 2 (Wilcoxon test, $W = 31$, $P < 0.05$). Conversely, values for water temperature, conductivity and pH in cluster 1 (respectively Wilcoxon test, $W = 42$, 44 and 47.5) and cluster 2 (respectively Wilcoxon test, $W = 112$, 127 and 116) were significantly ($P < 0.05$) higher than those of cluster 3. There were no significant variations of TSS and ORP between clusters (respectively Kruskal–Wallis $\chi^2 = 2.68$ and 2.48, $P > 0.05$).

Taxa relationships with environmental variables

GAMs were significant for five out of the 10 most frequent taxa (Table 4). TSS and ORP never contributed significantly. Water temperature was incorporated in three models (*Adenophlebiodes* sp., *Neoperla spio* and *Limnophila* sp.). Dissolved oxygen was significant in two models (*Neoperla spio* and *Dicercomyzon* sp.). Conductivity and pH were selected as significant predictors once for *Neoperla spio* and Chironomidae, respectively.

The response curves for the significant variables and their confidence bands (twice the standard error) are presented in Figure 5. GAMs for *Adenophlebiodes* sp., *Neoperla spio* and *Limnophila* sp. showed similar trends, incorporating a quasi-linear negative influence of water temperature on the occurrence of the taxa. The contribution of conductivity and pH were also quasi-linear and negative for *Neoperla spio* and Chironominae, respectively. The models for *Neoperla spio* incorporated a quasi-linear and positive response to dissolved oxygen. The influence of this variable for *Dicercomyzon* sp. seemed bell-shaped.

Discussion

To our knowledge, this study represents the first published data on aquatic insects in Simandou streams and one of the very few for the whole Republic of Guinea. The taxonomic richness (129) registered in this study is high when compared with earlier studies from West Africa, particularly in Ivory Coast. For example, Diomandé *et al.* (2009) used an Ekman sampler to collect 50 taxa from one site in the Agnéby River. This difference in taxonomic richness probably reflects differences in sampling methods and habitat coverage as demonstrated

Table 3. Significant indicator taxa (IndVal, $P < 0.05$) for each site cluster.

Indicator taxa	Cluster	IndVal	Probability
<i>Lestynogomphus</i> sp.	1	0.816	0.005
<i>Leptelmis</i> sp.	2	0.827	0.001
<i>Tricorythus</i> sp.	2	0.791	0.001
<i>Ephemera</i> sp.	3	0.866	0.001
<i>Afrobrianax ferdyi</i>	3	0.863	0.001
<i>Chimara</i> sp.	3	0.645	0.03

Fig. 4. Box-plots showing differences in environmental variables between site clusters (1–3). Different letters on box-plots denote significant differences between them ($P < 0.05$; Wilcoxon test).

Table 4. Results of generalized additive models testing the contribution of selected environmental variables to explain the occurrence of the most frequent taxa. For each taxon, environmental variables were kept in models when $P < 0.05$ (in bold).

Taxon	<i>n</i>	<i>P</i>	<i>r</i> ²	Deviance explained (%)	Explanatory variables											
					Temp		Cond		DO		pH		ORP		TSS	
					<i>F</i> -value	<i>P</i>	<i>F</i> -value	<i>P</i>	<i>F</i> -value	<i>P</i>	<i>F</i> -value	<i>P</i>	<i>F</i> -value	<i>P</i>	<i>F</i> -value	<i>P</i>
<i>Adenophlebiodes</i> sp.	76	< 0.05	0.29	38.7	7.19	0.01	2.45	0.12	2.23	0.14	1.10	0.3	0.01	0.96	0.86	0.36
Chironominae	75	< 0.001	0.12	37.5	0.87	0.35	0.43	0.52	3.82	0.05	4.64	0.03	2.04	0.16	3.35	0.07
<i>Neoperla spio</i>	73	< 0.001	0.26	27.5	16.84	0.01	6.29	0.01	5.62	0.02	3.59	0.06	1.23	0.27	0.62	0.44
<i>Diceromyzon</i> sp.	70	< 0.05	0.17	24.1	0.10	0.98	0.32	0.57	5.59	0.02	1.62	0.21	1.19	0.28	0.02	0.90
<i>Limnophila</i> sp.	62	< 0.05	0.13	38.8	5.27	0.02	0.48	0.49	0.03	0.87	1.26	0.26	0.23	0.63	0.51	0.48

See Table 2 for variable codes.

by Maue and Springer (2008). Moreover, this relative high diversity could be due to the fact that the studied areas covered mostly the headwater and mid-streams. Several studies claim high levels of taxonomic richness in these areas (Dieterich and Anderson, 2000; Baptista *et al.*, 2001; Cole *et al.*, 2003; Herlihy *et al.*, 2005). On the other hand, the number of taxa found in the Simandou streams is more similar to that reported, using the same sampling methods, for south-eastern Ivory Coast (124 taxa in eight sites, Edia *et al.*, 2010) and southern Ivory Coast (132 taxa in seven sites, Camara *et al.*, 2012). In the Macaé river basin (Rio de Janeiro, Brazil), Baptista *et al.* (2001) registered 117 taxa. In other tropical regions (Vietnam), the aquatic insect richness (268) obtained by Hoang and Bae (2006) using qualitative and quantitative sampling methods was twice as high as that of our study.

The observed taxonomic richness decreased with increasing levels of human impact in the Simandou streams. Sites (gathered in cluster 1) that were more disturbed by anthropogenic activities (agricultural and domestic activities), and located closer to populated areas, contained lower taxonomic richness. On the contrary, high taxonomic richness was registered in the sites with low human impacts (gathered in clusters 2 and 3). The same pattern was found in temperate (Evans-White *et al.*, 2009), tropical (De Jesus-Crespo and Ramirez, 2011), and mountain stream systems (Miserendino *et al.*, 2008). Site cluster 2 that displayed the highest taxonomic richness contained a mixture of upland and lowland sites, the latter remaining minimally disturbed (Table 1). Thus, in further studies for assessing water quality, such sites could be considered as references. These sites that were suitable for monitoring were characterized by colder water, high oxygen concentrations, low conductivity and low pH and therefore susceptible to rapid modification in the case of mining activities or increased human pressures. These variables were influential and significantly associated with variations in the occurrence of the most frequent aquatic insects in the Simandou streams. The taxa (e.g., *Leptelmis* sp., *Tricorythus* sp., *Ephemera* sp., *Afrobrianax ferdysi* and *Chimara* sp.) associated with these reference sites and the most frequent taxa (e.g., *Adenophlebiodes* sp., *Diceromyzon* sp., *Neoperla spio* and *Limnophila* sp.) could be used as sentinels for alteration of the studied streams. The characteristic taxa associated with relatively unimpacted sites gathered in clusters 2

and 3 were polluo-sensitive (Dickens and Graham, 2002). Except for *Ephemera* sp. and *Tricorythus* sp., the remaining taxa (elmid beetle *Leptelmis* sp., psephenid beetle *Afrobrianax ferdysi* and philopotamid *Chimara* sp.) characteristically occur in the upper reaches of streams in areas of cobbles and boulders (Ward, 1992). The burrower *Ephemera* sp. could also occur in headwater streams (Mellanby, 1963); it lives in tunnels constructed at the water edge. The stout crawler *Tricorythus* sp. inhabits fast flowing streams on rocks or any solid submerged substrate (Gerber and Gabriel, 2002). Belmar *et al.* (2013) also mentioned the preferential occurrence of Philopotamidae and rheophilic Ephemeroptera (such as *Tricorythus* sp.) in headwater streams in Spain.

Our study showed that the Gomphidae *Lestiniogomphus* sp. was closely associated with the most disturbed lowland sites (cluster 1). While it is difficult to explain specifically the fidelity of this taxon in respect to human disturbance, it is known that the family Gomphidae is moderately tolerant to pollution (Dickens and Graham, 2002). Moreover, this gomphid larva is mostly encountered in downstream sites where the substrate is dominated by sand (Allan and Castillo, 2007).

Environmental parameters such as water temperature, dissolved oxygen, conductivity and pH were influential and significantly associated with variations in the occurrence of the most frequent aquatic insects in the Simandou streams. These variables were also dependent upon the altitudinal gradient. The upland forested sites were characterized by low conductivity, low temperature, acidic water and high dissolved oxygen concentration compared with lowland open sites. Moreover, aquatic insect richness was high in upland areas and also decreased with anthropogenic disturbances. As mentioned, the Simandou Range also harbours potential mineralogical wealth and, in particular, extensive iron ore deposits. Exploratory operations are underway in the area to determine the quality, quantity and location of iron ore resources. The exploitation of these resources should incorporate the preservation of the surrounding forest in upstream areas, in order to maintain and preserve aquatic biodiversity and consequently the quality of Simandou streams. Streams with minimally disturbed riparian forest contribute branches and large wood to channels, thereby increasing habitat complexity and habitats that favour increased abundance and diversity of macroinvertebrates

Fig. 5. Generalized additive model (GAM) response curves for the most frequent taxa. Tick marks on the x -axis are observed data points. The y -axis represents the occurrence probability of taxa. Gray bands represent 95% confidence intervals.

(Kaufmann and Faustini, 2012; Ferreira *et al.*, 2014). Moreover, as shown by Rawi *et al.* (2013) for tropical forest streams in the south-western parts of the Malaysian peninsula, all activities involving deforestation have a negative effect on aquatic biodiversity. Similar observations were made by Braun *et al.* (2014) in montane streams in southern Brazil and Suriyawong *et al.* (2015) in Huay Kaew stream at Doi Suthep-Pui National Park (Chiang Mai, Thailand).

Furthermore, intensive ecological research to investigate the drivers regulating the community structure of aquatic insects in Simandou streams is recommended. These investigations should also explore the trait-based approach, which is a powerful tool for studying mechanisms structuring communities including benthic invertebrates.

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* Indicates the presence of taxa.