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Benthic invertebrate assemblages and assessment of ecological status of water bodies in the Sahelo-Soudanian area (Burkina Faso, West Africa)

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Dedication

"It is easy to throw anything into the water, but difficult to take it out"
(Kashmiri proverb quoted by UN-Water)

To:

my daugther Kaboré Adamas Elikya and Yaméogo Elisabeth,

my adoptive mother Tenin Souhmahoro from Côte D'Ivoire,

my mother Zongo Poko and dad Kaboré Tiga Ousmane,

My grateful for your love and Encouragement

Content

Preface

This cumulative dissertation thesis consists of five research articles and a synthesis. It was written in the frame of the APPEAR research project Sustainable Management of Water and Fish Resources in Burkina Faso SUSFISH, contract number 56, project hold by Dipl.-Ing. Dr. Andreas Melcher. It was funded by the Austrian Development Agency (ADA) and implemented by the Austrian Agency for International Cooperation in Education and Research (OEAD). Four Master students; Sebastian Stranzl, Paul Meulenbroek, Daniel Trauner, Thomas Koblinger and two Doctoral students, Mano Komandan and Idrissa Kaboré, worked in this project together.

Abstract

Human activities and the increased demand for freshwater have impaired natural water flow regimes worldwide. Hydrological alterations, desertification, severe pollution, intense urbanization and intensive agriculture are associated with ecological change and are known to have detrimental effects on benthic communities. Efficient monitoring tools to assess how aquatic ecosystems respond to multiple impacts of human activities are urgently needed but still limited in West Africa, especially in Burkina Faso. Comprehensively, this dissertation presents five cumulative scientific publications on the topic "macroinvertebrates in Burkina Faso". This study investigated the benthic macroinvertebrate fauna on a large-scale and provides assessment methods to evaluate the ecological integrity of rivers/streams in West Africa.

The first paper describes the diversity, composition and structure of benthic macroinvertebrate communities in semi-arid rivers of Burkina Faso. We found a high diversity of the benthic macroinvertebrate fauna in semi-arid water bodies, whereas a total of 132 taxa belonging to 57 families from 8 orders of insects that represent 95% of relative abundance have been recorded. The results revealed a strong relationship between midges (Chironomidae), hoverflies (Syrphidae), and mosquitoes (Culicidae), drain flies (Psychodidae), as well as pulmonate snails (Pulmonata) and organic nutriments. In the second publication, we investigated the diversity and ecology of diving beetles (Dytiscidae, Noteridae) and water beetles (Hydrophilidae) of semi-arid rivers and reservoirs in Burkina Faso. We ascertained that aquatic vegetation is the major factor inducing the beetles' richness. A high diversity of water beetles with a total of 60 species belonging to 23 genera was identified in this study, and 24 species were first records for Burkina Faso. The third study explores the potential use of macroinvertebrate communities for bioassessment in semi-arid areas of West Africa. In 29 investigated sampling sites of running waters, 100 taxa from 58 families were recorded. The results also showed that different metrics of diversity, composition and tolerance of macroinvertebrate communities, as well as indicator taxa, showed differential sensitivity to different levels of environmental degradation and a clear trend across the gradient of human impact intensity in terms of land use (protected areas; extensive agriculture; intensive agriculture; urban area). In the fourth publication, the environmental variables (physicochemical, hydro-morphological, and land use) of 44 investigation sites were assessed to identify '*a priori* criteria' in Burkina Faso to describe reference conditions. Therefore an important basis for the development of a bioassessment system based on reference conditions was developed. The results revealed that protected areas can reasonably be considered as credible reference sites as far as they show low impact levels. Finally, in terms of the fifth publication, we tested the multimetric index approach to assess the

ecological status of water bodies in the West African Sahel and upper Sudan ecoregions (BBIMI: Burkina Benthic macroinvertebrate multi-metric index). From the original 46 candidate metrics, after a detailed, comprehensible analysis, five metrics were selected (the core-metrics) for index calculation: "percentage of non-Diptera insects, percentage of tolerant Diptera, number of Ephemeroptera, Plecoptera, Trichoptera (EPT)-family taxa, and two biological indices (ASPT-NEPBIOS and ASPT-BMWP)". The results also showed that BBIMI responded strongly to a gradient of human disturbance.
Within this study important bioassessment tools for the study region were developed. Thus, these cost-effective tools can be used to promote a balance between the use of aquatic resources and the freshwater ecosystem health.

Key words: Benthic macroinvertebrates, ecological status, water bodies, Burkina Faso.

Zusammenfassung

Die gestiegene Nutzung der Binnengewässer durch den Menschen führte zu einer Beeinträchtigung der natürlichen Gewässerökosysteme weltweit. Eingriffe in die Hydrologie, Verlandung, Nährstoffeintrag, Urbanisierung und intensive Landwirtschaft sind mit ökologischen Veränderungen verbunden und haben negative Konsequenzen für aquatische Makroevertebraten. Effiziente Überwachungsinstrumente zur Bewertung des Zustands der Gewässerökosysteme als Reaktion auf multiple menschliche Eingriffe sind dringend notwendig, aber in Westafrika und vor allem in Burkina Faso nur eingeschränkt vorhanden.
Vorliegende Doktorarbeit fast ein Kumulativ von fünf wissenschaftlichen Publikationen zum Thema "Makrozoobenthos in Burkina Faso" zusammen. Die Arbeit versteht sich als Grundlage für die Etablierung eines biologischen Bewertungssystems zur Abschätzung der ökologischen Funktionsfähigkeit von Fließgewässern in Westafrika. Der geographische Schwerpunkt überstreicht die südliche Sahelzone und den nördlichen Sudanbereich im Staatsgebiet von Burkina Faso. Die erste Arbeit beschreibt die Zusammensetzung, Diversität und Struktur von Makrozoobenthos-Gesellschaften in semi-ariden Gewässern Burkina Fasos. Insgesamt wurden 132 Taxa aus 57 Familien nachgewiesen, wobei die Klasse der Insekten 95% der aquatischen Fauna ausmachen. Mittels einer Kanonischen Korrespondenzanalyse konnten Faunengesellschaften in Abhängigkeit von diversen Umweltparametern herausgearbeitet werden, etwa dass die Vertreter der Dipterenfamilien Schwebfliegen (Syrphidae), Stechmücken (Culicidae) und Schmetterlingsmücken (Psychodidae), aber auch die Lungenschnecken (Pulmonata) hervorragende Zeigergruppen für organische Belastung sind. In der zweiten

Publikation wird im Detail auf die Wasserkäferfauna von Burkina Faso, insbesondere das Arteninventar, die Diversität und Biologie der Schwimmkäfer (Dytiscidae, Noteridae) und der Wasserkäfer (Hydrophilidae) in semi-ariden Flüssen und Reservoiren, eingegangen. In 18 untersuchten fließenden und stehenden Wasserkörpern konnten 60 Wasserkäferarten aus 23 Gattungen nachgewiesen werden, wobei es sich bei 24 Arten um Erstnachweise für Burkina Faso handelt. Auf Grund der Habitat-spezifischen Sammelmethode konnte eindeutig nachgewiesen werden, dass untergetauchte Wasserpflanzen und Schwimmpflanzen (wie etwa der Wassersalat *Pistia stratiotes*) die idealen Biotope für Wasserkäfer darstellen. Die dritte Arbeit untersucht die Eignung der benthischen Wirbellose für die Charakteristik der des ökologischen Zustandes von Gewässern in Westafrika. In 29 Fließgewässer strecken wurden 100 Taxa aus 58 Familien ausgewertet. Durch multivariate Verfahren nachvollziehbar belegt, konnten eindeutig abgrenzbare Benthosgesellschaften aus vier unterschiedlich genutzten Landschaftstypen (Schutzgebiete; extensive Landwirtschaft; intensive Landwirtschaft; urbanes Siedlungsgebiet) unterschieden werden. In einer vierten Publikation werden anhand von 44 untersuchten Gebieten in Burkina Faso physikalisch-chemische, hydro-morphologische, und Landnutzungs-Kriterien erarbeitet und beschrieben, auf deren Basis die Ausweisung von Wasserkörpern als, unbeeinflusstes Referenzgewässer“ vorgenommen werden kann. Auf diese Weise wurde eine wichtige Grundlage für die Entwicklung eines auf dem Referenzbedingungsprinzip basierenden biologischen Bewertungssystems geschaffen. In der fünften Veröffentlichung wurde - gleichsam als Sukkus der vorangegangenen Arbeiten – eine Methode zur Beurteilung des ökologischen Zustandes von Fließgewässern der Ökoregionen westafrikanische Sahelzone und nördlicher Sudan erarbeitet, der BBIMI (Burkina Benthic macroinvertebrate multi-metric index). Aus ursprünglich 46 möglichen Maßzahlen und Kenngrößen, den Metrics, wurden nach eingehender, nachvollziehbarer Analyse fünf Messgrößen (die Core-Metrics) für die Indexberechnung ausgewählt: Prozentanteil Nicht-Diptera-Insekten; Prozentanteil toleranter Zweiflügler; Anzahl an Eintagsfliegen-, Steinfliegen- und Köcherfliegen-Arten; sowie zwei biologische Indices (ASPT-NEPBIOS und ASPT-BMWP). Die Ergebnisse zeigten außerdem eine deutliche Reaktion des BBIMIs auf einen Gradienten anthropogener Beeinträchtigungen.

Innerhalb dieser Dissertation wurden wichtige auf Bioindikatoren basierende Bewertungsansätze für das Untersuchungsgebiet entwickelt. Diese kosteneffizienten Ansätze können daher eingesetzt werden, um ein Gleichgewicht zwischen anthropogener Nutzung von Fließgewässern und dem Schutz ihrer ökologischen Funktionen zu gewährleisten.

Schlüsselwörter: Makrozoobenthos, Ökologischer Zustand, Wasserkörper, Burkina Faso

Cummulative synthesis of all articles

Introduction

All life depends on water. Terrestrial as well as aquatic organisms are dependent on water networks and their limnological characteristics. But water of sufficient quality is a limited resource: freshwaters habitats account for less than 1% of the world's water (Gleick, 2000), yet this tiny fraction of global water supports an impressive diversity of aquatic organisms (Dudgeon et al., 2006). In addition freshwaters are natural resources with high economic, cultural, religious, aesthetic, scientific and educational value (Dudgeon et al., 2006). Despite their important roles in support of human populations and their economic activities, most catchments are subject to an array of ecologically unsustainable land-use and development activities (Ollis et al., 2006; Ormerod et al., 2010). Threats to the ecological integrity of river systems are most apparent in arid areas, being particularly severe in developing regions, where increasing water demands resulting from population growth and climate change place excessive stress on freshwater resources (Dugeon, 1992; Davies and Wishart, 2000; Kundzewicz et al., 2007; Dallas and Moore, 2014). Consequently their conservation and management are critical to the interests of all nations and governments.

A thorough scientific knowledge of these valuable ecosystems is an essential prerequisite for developing reliable management tools. This is especially true in many regions of Africa, where ongoing degradation of entire aquatic ecosystems have risen steeply over the years (Strayer and Dudgeon, 2010; Darwall et al., 2011). In West Africa, many countries have to cope with chronic water scarcity and episodes of severe drought. This situation is set to worsen as high population growth rates drive rising water demand to achieve food security. The vulnerability of freshwater habitats and biota increases in response to a range of threats, e.g. overexploitation, water pollution, flow modification, habitat degradation, and exotic species invasion, and, especially, sedimentation due to deforestation, agriculture, human settlements and mining threat (Lévêque et al., 1983; Wood and Armitage, 1997; Dudgeon et al., 2006; Stendera et al., 2012). Specifically in West Africa, according to the IUCN (2008) red list, 26,3% of freshwater fish and 40% of crustaceans are currently threatened and future levels of threat are expected to rise significantly due to a growing population and the corresponding demand of natural resources.

These challenging circumstances create an urgent need for tools to assess ecological health. Such tools are, essential for prioritizing conservation efforts and efficient management of water bodies in these countries. Currently aquatic organisms (e.g. macrophytes, algae, fish, and benthic macroinvertbrates etc.) are used worldwide to characterize the condtion of streams/rivers condition, based on either richness, composition, tolerance or functional composition (Resh et al., 1995; Barbour et al., 1999; Marzin et al., 2012). Among these organisms, the benthic macroinvertebrates are used worldwide because they have several characteristics that make them particularly beneficial (Covich et al., 1999). Unfortunately, current knowledge of benthic macroinvertebrates and water ecosystem health in West African rivers is still very fragmentary (Thorne and Williams, 1997; Yaméogo et al., 2001).

In Burkina Faso, only a few studies have assessed environmental health using benthic macroinvertebrate communities (Guenda, 1985, 1996; Kabré et al., 2002; Sanogo, 2014). At present, no common countrywide benthic macroinvertebrates inventory exits, and the ecological integrity status of rivers and reservoirs is not yet documented. This thesis was conducted to address these knowledge gaps as a part of the APPEAR-sponsored SUSFISH Project (Sustainable Management of Water and Fish Resources in Burkina Faso, www.susfish.boku.ac.at). that aims to “strengthen in-country capacities for science, policy and practice to establish the basis for sustainable fisheries and water management in Burkina Faso”. This research is the first large-scale assessment of benthic macroinvertebrate fauna, which was used to develop national benthic macoinvertebrates-based assessment methods that can serve as tools to evaluate the ecological integrity of water bodies. The achievement of this disertation project is to provide basic knowledge on the benthic invertebrate biota and to develop a diverse set of methodological and technical resources for long-term management and sustainable of water resources.

Thesis outline and objectives

This cummulative dissertation thesis increases the knowledge of the benthic invertebrate's species and their distribution, ecology and the potential use in a biomonitoring program in Burkina Faso. The taxonomy and faunistics aspects were elaborated in close co-operation with taxonomists specialised on the respective taxonomic groups (see Acknowledgements Section), thus contributing to the establishment of an appropriate ecological assessmet methods for long-term water management in Burkina Faso. The specific objectives of this thesis and its articles are:

1. to identify and describe the composition, the diversity of benthic macroinvertebrates in Burkina Faso and determine the environmental factors that influence the macroinvertebrate distribution (Article 1),
2. to investigate the occurrence, distribution and ecology of one specific systematic group, the water beetle families of Dytiscidae, Noteridae and Hydrophilidae, based on the highest available taxonomic resolution of semi-arid waterbodies in Burkina Faso, to test and discuss their response to environmental variables (Article 2),
3. to identify and determine the diversity and distribution of benthic invertebrate taxa in streams of Burkina Faso (Article 3),
4. to test the response of benthic invertebrate taxa to changes in floodplain land use (intensification of agriculture, urbanization) using different metrics related to taxonomic and functional composition (Article 3),
5. to identify and potential indicator taxa for main floodplain land use types (protected areas, extensive and intensive agriculture and urban areas) (Article 3),
6. to develop a reference based evaluation system and to determine reference criteria for human impacts on semi-arid rivers in Burkina Faso (West Africa) (Aricle 4),
7. to select the most sensitive metrics and quantify their deviations from the reference situation, and to evaluate the capacity of the index locally (Aricle 5).

To do so this thesis is divided in two main sections. The first section is a general synthesis "what was done" and introduction, including a brief overview of the study area "West African Sahel and upper Sudan ecoregions" and its surface water resources. In addition, it describes the effects of human impacts on streams/rivers and reviews benthic macroinvertebrates and their usefulness in bioassessement programs. At the end of this synthesis chapter, a general discussion for the study is presented, encompassing all the aspects discussed in the five articles, conclusions and recommendations for future. The second section presents five peer-reviewed research manuscripts.

Research articles overview

Five publications as an first author are considered for this thesis; two of them are already accepted and printed; three of them are still in review in scientific journals. In total 13 co-authors from four rearch institutions supported this work. A total sum of 1,540 sampling units, belonging to 77 sites at 9 larger sampling areas was visited from 2012 to 2015. Sites were located in running waters (n = 66) and reservoirs (n = 11). A total number of more than 33,000 specimens of benthic macroinvertebrates has been collected and determined. Each research article required an individual selection of sites and subsamples according to the scale and requirements of the specific research questions addressed.

The order of articles was choosen to provide a consistant flow done in this doctoral research. The synthesis refers to the following citations of Article 1 to 5:

Article 1: The first paper addresses the diversity, composition and dynamic of benthic macroinvertebrates:

Kaboré I., I. Ouédraogo, L. Tampo, A. Ouéda, O. Moog, W. Guenda, A.H. Melcher. (in review). Diversity, composition and dynamic of benthic macroinvertebrate community in semi-arid rivers of Burkina Faso (West Africa). ***International Journal of Biological and Chemical Sciences***.

Abstract: The benthic macroinvertebrate communities dynamic was investigated in rivers from Burkina Faso in the purpose to analyze 1) the taxonomic composition, 2) the structure of benthic macroinvertebrates community and 3) the composite environmental variables that correspond to the major patterns of this community. The results showed that a total of 132 taxa was recorded and the large majority of these (103 taxa) belonged to 57 families from 8 orders of insects that represent 95% of relative abundance). We also observed some distinct differences relative to the spatial and temporal in the taxonomic composition. The CCA analyse revealed a strong relatisonship between chironomids, Syrphidae, Culicidae, Psychodidae, as well as the Pulmonates molluscs and organic nutriments. These findings showed the sensitivity of benthic macroinvertebrates at different level, which could be attributable to man-induced activities.

Article 2: The second publication conveys on the inventory and the ecology of Coleoptera in Burkina Faso:

Kaboré I., M. A. Jäch, A. Ouéda, O. Moog, W.Guenda and A.H. Melcher (2016). Dytiscidae, Noteridae and Hydrophilidae of semi-arid waterbodies in Burkina Faso: species inventory, diversity and ecological notes. ***Journal of Biodiversity and Environmental Sciences*** *Vol. 8, No. 4:* p. 1-14. ISSN: 2220-6663 2222-3045.

Abstract: Conservation of biodiversity is a major concern due to climate change and pressure from human activities. Knowledge of aquatic insects and their ecology particularly in West Africa is still scanty and fragmented. To fill this gap, we investigated the structure of aquatic beetle assemblages from 18 lentic and lotic water bodies (rivers and reservoirs) in Burkina Faso, and we explored their relationship with environmental variables. Following a multi-habitat sampling approach, all beetles were collected with a hand net, and identified using taxonomic manuals and keys. A total of 11 species of Noteridae in three genera, 27 species of Dytiscidae in 10 genera and 22 species of Hydrophilidae in nine genera were identified in this study. Among these, 24 species are here reported for the first time from Burkina Faso. The species richness was high in the reservoirs with habitats dominated by "water lettuce" Pistia stratiotes (species diversity, sd=11.0±9.00 Shannon Wiener index, H=1.79±1.1) and "reed beds" (species diversity, sd=7.63±1.78; Shannon Wiener index, H=1.51±0.25) in comparison with rivers (sd=2.25±0.75; H=0.35±0.20). The results also showed that the species richness is significantly correlated with vegetation cover. Thus, emergend water plants were found to be the main factor influencing beetles species richness. The observed relationship between vegetation cover and beetle richness may provide significant insights that motivate future efforts in research as well as in habitat conservation measures in West Africa.

Article 3: The third publication delivers on the use of macroinvertebrates for ecosystem health assessment in semi-arid streams of Burkina Faso:

Kaboré I., O. Moog, M. Alp, W. Guenda, T. Koblinger, K. Mano, A. Ouéda, Ouédraogo R., D. Trauner and A.H. Melcher (2016). Using macroinvertebrates for ecosystem health assessment in semi-arid streams of Burkina Faso. ***Hydrobiologia*** 766(1): 57-74. doi:10.1007/s10750-015-2443-6.

Abstract:

Efficient monitoring tools for the assessment of stream ecosystem response to urbanisation and agricultural land use are urgently needed but still lacking in West Africa. This study investigated taxonomic and functional composition of macroinvertebrate communities at 29 sites, each exhibiting one of four disturbance levels ('protected', 'extensive agriculture', 'intensive agriculture' and 'urban') in Burkina Faso and explored their potential for bioassessment. We recorded a total of 100 taxa belonging to 58 families, with the highest richness (16.9 taxa per site) observed in the sites with intensive agriculture and lowest (3.4 taxa) in urban sites. We found a gradual decrease of sensitive EPT taxa and of collector-filterers feeding guild between protected, agricultural and urban sites accompanied by an increase in the relative abundance of tolerant dipteran taxa. Measures of overall taxonomic richness and diversity were mostly efficient in detecting the high impoverishment of the urban sites, while FFG ratios did not deliver consistent results. Finaly, all four land-use types were successfully distinguished by identifying indicator taxa through hierarchical clustering and IndVal index. This work produced an unprecedented faunal inventory of Burkina Faso streams and laid the basis for the development of urgently needed stream assessment tools.

Article 4: The fourth paper describes criteria to define the reference condition in Burkina Faso:

Kaboré I., O. Moog, A. Ouéda, J. Sendzimir, R. Ouédraogo and A. H. Melcher (third revision). Reference criteria for human impacts on semi-arid rivers in Burkina Faso (West Africa). ***Journal of Soil and Water Conservation***.

Abstract: Awareness of sustainable management of water and its biological resources is rising in West Africa, but application of effective tools for biomonitoring and detecting habitats at risk in aquatic ecosystems is limited. In this study, we review bio-indication based on benthic macroinvertebrates and its implications for water resources policy. Especially, we discuss (1) the role of water for livelihoods in semi-arid areas; (2) human-induced stressors, (3) new water quality management implementation based on a sustainable biological monitoring programme based on the reference conditions approach, and (4) provide key environmental descriptors to characterise reference sites by applying the following criteria: physico-chemical, sensoric features, hydro-morphology and land use parameters. Cluster analysis allowed to test the '*a priori* criteria' from 44 areas in Burkina Faso to determine suitable reference areas. The results showed that protected areas can reasonably be considered as credible reference sites as far as they show low impact levels. We recommend that development of bio-indicator standards should be based on the collection and integration of all the available information, especially quantitative, spatially-explicit data, on benthic macroinvertebrates and fish. Rigorous standardization of bio-indicator protocols will make them more easily applicable for management and conservation of aquatic ecosystem resources in Africa.

Article 5: The last paper deals with the development of a multimetric index approach to assess the ecological status of Burkina Faso:

Kaboré I., O. Moog, M. Alp, A. Ouéda, R. Ouédraogo, W. Guenda and A. H. Melcher (second revision). Testing the Multimetric index approach to assess the ecological status of water bodies in the West African Sahel and upper Sudan ecoregions. ***Environmental Monitoring and Assessment***.

Abstract: In the view of the ongoing pressures resulting from agricultural activities and urbanization in the West African Sahel, water management tools based on the knowledge of the ecological status of surface water bodies are urgently needed to preserve aquatic resources. To fill these gaps, the benthic macroinvertebrates communities of Sahel rivers were examined in order to test if the multimetric index approach could be developed to assess the ecological quality of rivers. A total of 66 samples sites fell within two continua ranging from "unimpacted reference sites" and "strongly impaired sites"were assessed during this study. Benthic macroinvertebrate were sampled with a hand net following the multi-habitat sampling approach. Keys environmental parameters, including Physico-chemical parameters, hydro-morphology and land use parameters were qualitatively recorded. More than 45 candidate metrics were evaluated in four categories such as composition metrics, functional feeding metrics, diversity metrics and tolerance measures. We used discriminatory power analysis to exclude unsuitable metrics from the data set. After excluding redundant metrics, five core metrics were selected to compose the BBIMI (Burkina Benthic macroinvertebrate multi-metric index): %Non-dipterans Insect, % Tolerant dipterans and EPT-family taxa, ASPT-NEPBIOS, ASPT-BMWP. The validation of BBIMI was done with the data from 30 samples for environmental variables using standard stepwise model (PCA regression). The result showed that the BBIMI responded to a set of physico-chemical, hydro-morphology and land use parameters associated to a gradient of human pressures affecting the ecological integrity of waterbodies (R^2=0.85; F= 158.8, p=0.000). This work produced an unprecedented effective tool "BBIMI" for biological monitoring and decision making in water management in Burkina Faso case which can be promising for other West African countries.

Burkina Faso and its surface water resources

Burkina Faso is located in the heart of West Africa in the sub-Saharan region (12° 16 ′N, 2° 4′W) (Fig. 1). With an area of 274,200 km² large, Burkina Faso is bordered by the Republics of Niger in the East, Mali in the North and North-West, Côte d'Ivoire in the South-West and Ghana, Togo and Benin in the South (Fig. 1). The climate is tropical semi-arid characterized by high evaporation rate. The 80% of the country is underlain by geological formations composed of Paleoproterozoic granitoids of the baoulé-mossi domain (Metelka, 2011) covered by Neoproterozoic sedimentary rocks in the west, north and southeast and Cenozoic Continental Terminal rocks in the northwest and extreme east. With an approximate 17.5 Million of people (UN DESA, 2012), Burkina Faso is one of the poorest countries in the world, with nearly half the population (46% in 2004) living below the poverty line (Sally et al., 2011). The agriculture sector contributes about 35% to the country's GDP and accounts for about 80% of employment.

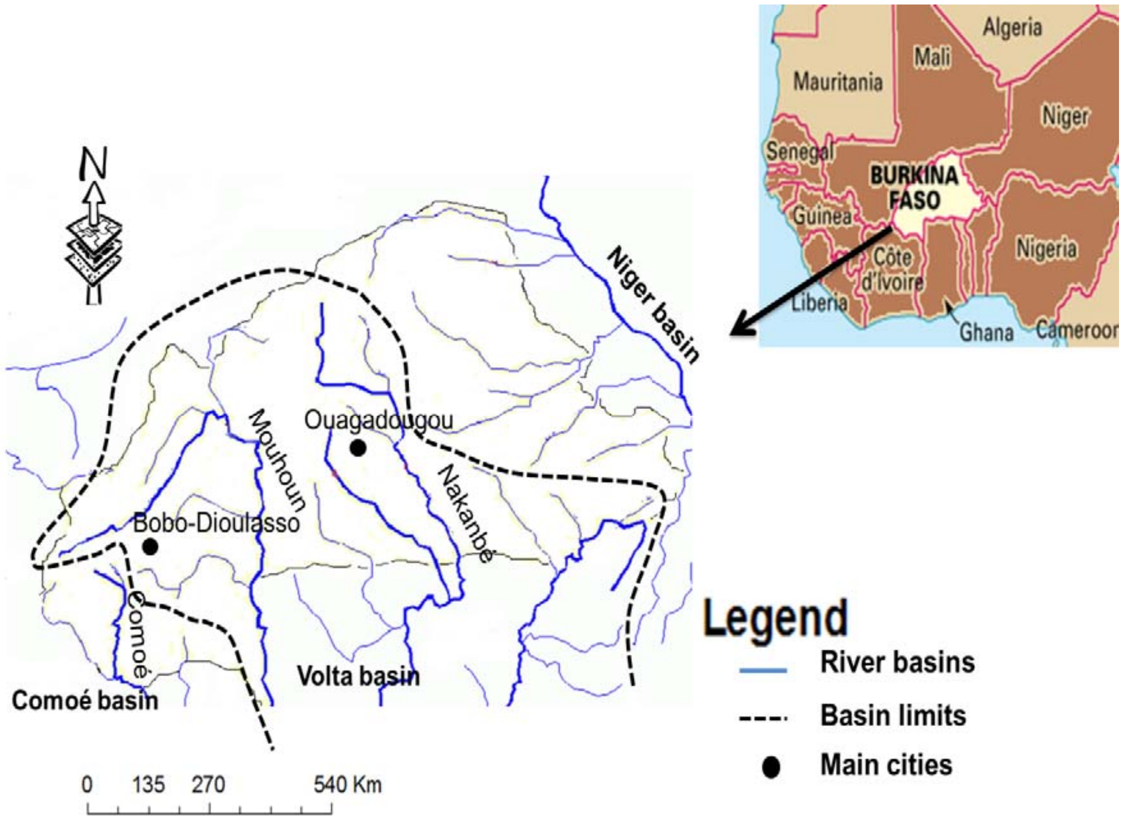

Figure 1 Map of West Africa countries (in peru) showing Burkina Faso. The main river basins and cities are shown.

Burkina Faso is drained by three river basins (Fig. 1): The Volta basin , the 9th largest river basin in sub-Saharan Africa from the 63 transboundary river basins (Opoku-Ankomah , 2000). It covers an estimated area of 400,000 km² and spreads over six West African countries. Almost 85 % of this area spans Burkina Faso (66.8% of the territory) and Ghana (63.7 %) and the remaining 15% stretch across Mali (0.8 %), Togo (47%), Benin (14.2%) and Cote d'Ivoire (2.2%), (Sanwidi, 2007).

Located between the north latitudes of 5°30'N in Ghana, 14°30'N in Mali and the longitudes 5°30'W to 2°00'E, the Volta river basin is drained by three main sub-basins in the north belong to Burkina Faso: Nakanbé (formerly White Volta), Nazinon (Red Volta) and the Mouhoun (formerly Black Volta). The three tributaries flow to join each other at a confluence in the north central region of Ghana and flow downstream through a narrow gorge at Akosombo where a dam built in 1964 for hydropower generation has created the largest man-made lake in the world, Lake Volta (Van de Giesen et al., 2001; FAO, 2005; Ouedraogo, 2010). Mouhoun river with permanent runoff as base flow from the sedimentary aquifers in the western part of the country and Nakanbé downstream, where two hydropower dams Bagré and Kompienga, which have almost perennial flows due to the electricity production from the reservoirs.

The Volta basin receives between 1100 mm (in the south) and 500 mm (in the north) rainfall annually, the rainiest month being August (35% of the precipitations). River discharge is highly sensitive to variations in annual rainfall. The major part of the basin going from the extreme northern Burkina Faso to the northern Ghana is under the monomodal rainfall regime of only 3 to 5 months duration (Sanwidi, 2007). The potential evaporation in the basin varies both temporally and spatially with the northern parts experiencing high annual potential evaporation of 2500 mm, while in the south it is reduced to 1800 mm. Potential evaporation throughout the year usually exceeds rainfall in the basin with the exception of a few months in the rainy season.

Temperatures in the basin vary, from 27°C to 30°C with mean daily temperatures between 32°C to 44°C for daytime and 15°C for nighttime (Sanwidi, 2007). Like temperatures, relative humidity in the basin varies according to locations and periods between 6% in the north during the dry season and 95% during the rainy season in the south of the basin.

The volta basin is especially susceptible to environmental perturbation associated with water scarcity, hydrological variations and overuse due to unpredictable anthropogenic activities affecting the aquatic fauna and water resources.

The Comoé is a perennial river in the extreme south-west of Burkina, covering 6.4% of the territory surface with a surface area of 18,000 km². It is the smallest of the four basins.

Bordering Mali and Côte d'Ivoire, it is located in the Sudanian climatic zone between 9°35', 11°05' N and 3°30', 5°30' W with tropical characteristics and two well-marked seasons: a dry season from November to June and a rainy season from July to October. Annual rainfall varies from 1,200 to 1,400 mm with annual evaporation rate of 2000 m (Kabré et al., 2002). Temperatures in the basin vary, from 24 to 25 °C minimal and 31 to 32 °C the maximal. The area drained by Comoé river is called "Cascades" due to the abundance of water. Dams were also constructed in the area to secure sugar production and also guarantee the municipal water supply to the town of Banfora (Sirima et al., 2009).

Niger Basin covers 30.5% of the national territory; the Niger Basin is located mainly in the northern and eastern parts and covers an area of 83,442 km². Its average annual water potential is the lowest of the country with less than 1 Billion m^3 of which 100 Million m^3 are stored in small and large dams.

This study was undertaken in three rivers including nine sampling areas: Ouagdougou, Koubri, Bagré, Sourou, Nazinga , Boura, Boromo, Bobo-Doulasso and Banfora (Fig.2, also Susfish: http://susfish.boku.ac.at/): the Nakanbé (Volta catchment) in the central part of Burkina Faso (area of 70,000 km²), the Mouhoun (Volta catchment) in the west (92,000 km²) and the Comoé in south-west part of Burkina Faso (18,000 km²) (Fig. 2). Due to the conflict in Mali and for security reasons at the Border we could not sample in the north part of the country "Niger basin".

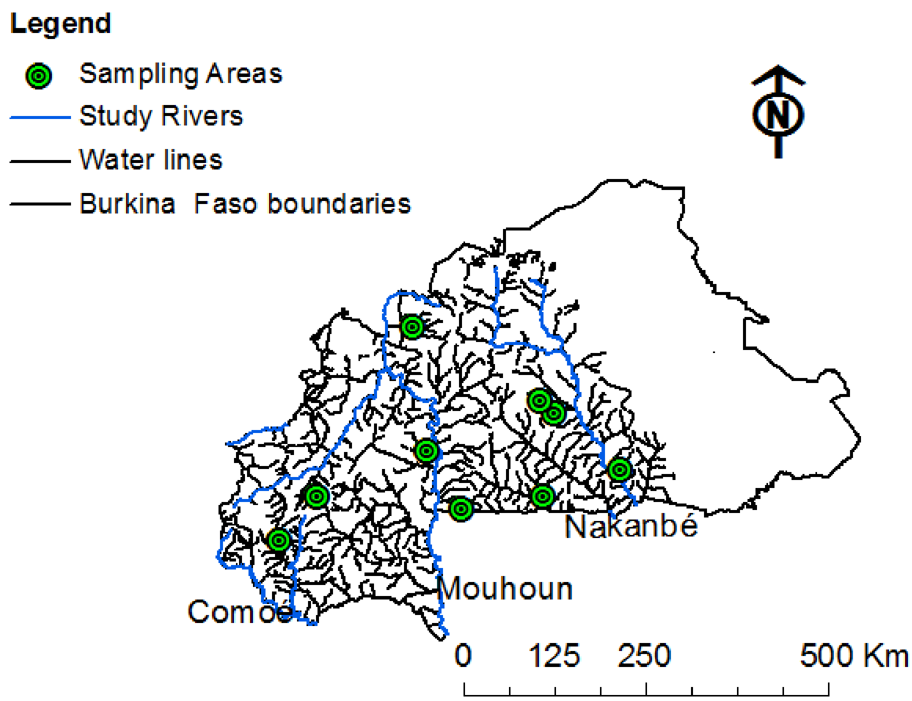

Figure 2 Map of rivers from the Comoe, Mouhoun and Nakanbe chatchment and study areas in Burkina Faso.

Reservoirs

To mitigate the water scarcity, Burkina Faso has built one thousand and five hundreds resrvoirs on seasonal brooks in order to collect water for any use such as irrigation, livestock farming, fishing, hydropower production, domestic needs and others uses (MEE, 2001). Actually more than 80% of the surface water is stocked in artificial reservoirs and the remaining less than 20% in the natural pounds and water courses (Fig. 3). The country relies much on these reservoirs to produce food (maize, cereals, fruits, vegetables, fish, meat, etc.) for local and national consumptions. The total volume of these reservoirs was estimated in 2001 by the GIRE project to be 2.66 Billion m³ of water at their maximum capacity for an approximate total area of 100,000 ha.

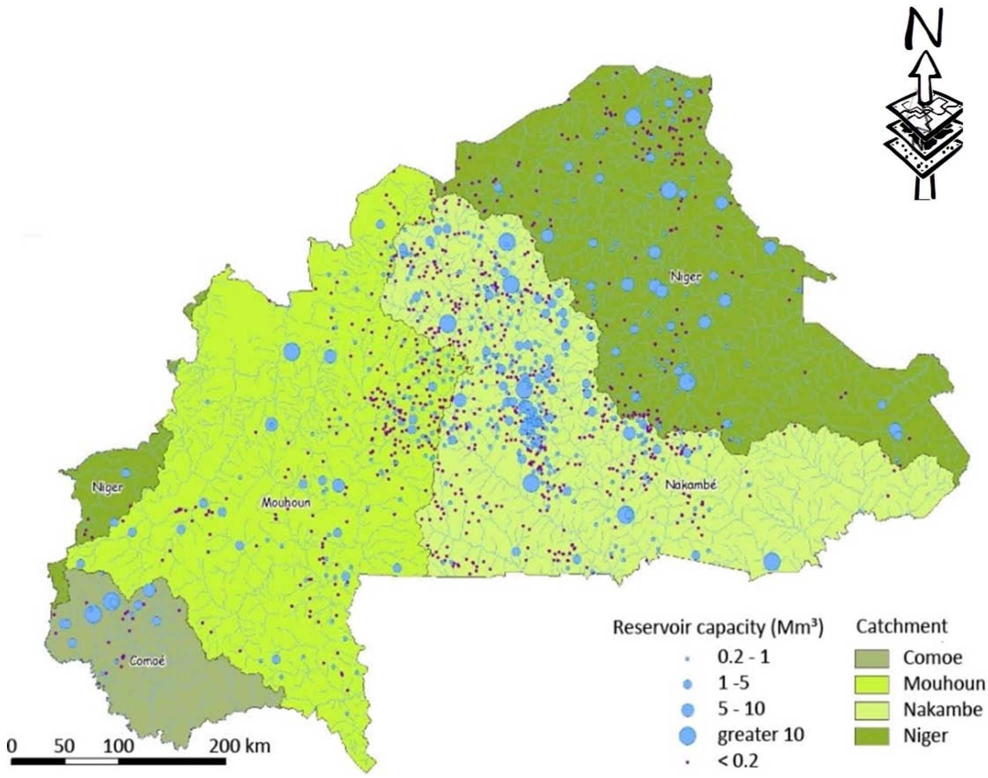

Figure 3 Map of reservoirs in Burkina Faso. Units in million cubic meter (Mm³). (adapted From Cecchi et al. 2009).

The size of the reservoirs ranges from 1 to 25,000 ha, but 60 to 70% of them regularly fall dry, because of their small dimensions (Ouédraogo, 2010). Therefore, fish has become an important protein source. On the other hand, reservoirs are responsible for the spread of new aquatic ecosystems, water borne related diseases and important modifications of the local environment (WHO, 2003; Cecchi et al., 2007; Boelee et al., 2009; UNEP-GEF, 2010). This strategy of reservoir construction is exceptional in this region and makes Burkina Faso one of the leading countries in water resource development in Africa (Fig. 4).

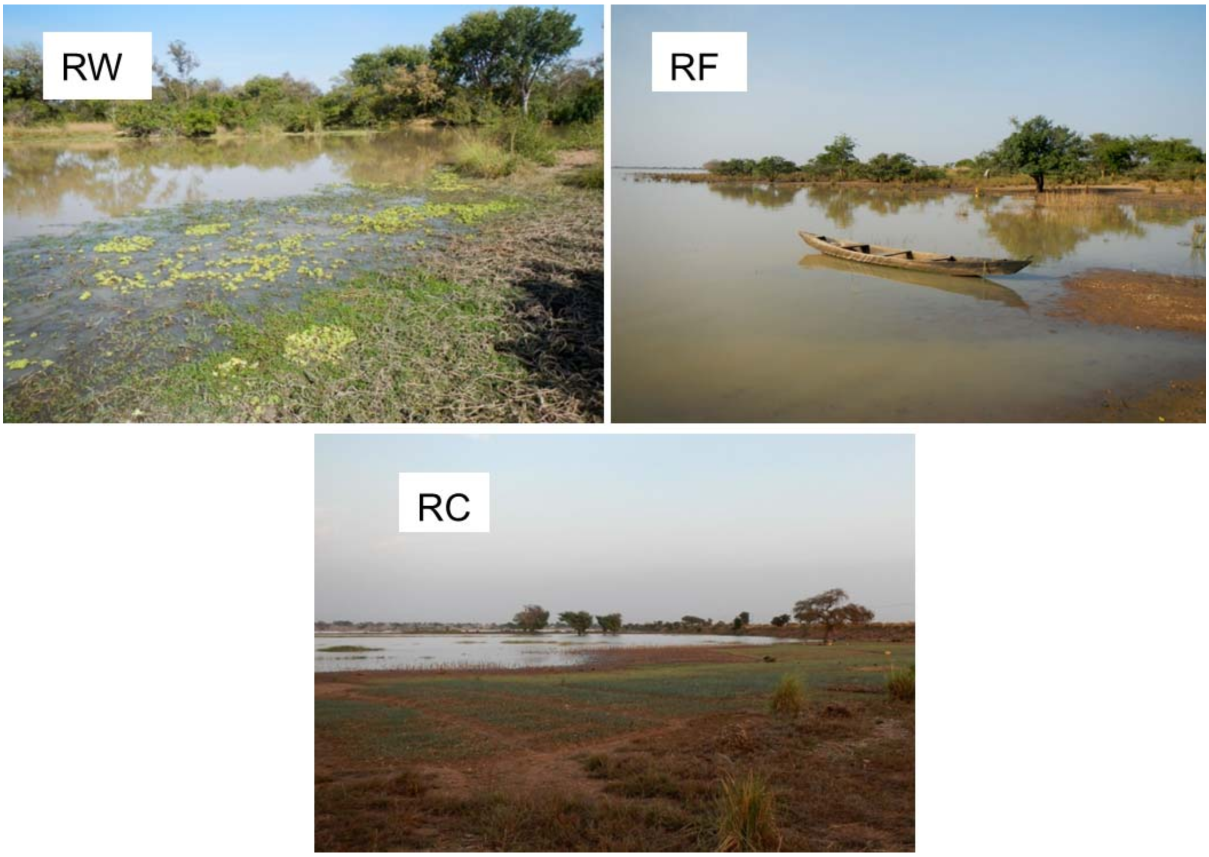

Figure 4 Different uses of reservoirs in Burkina Faso. RW indicates protected reservoir for wild animal at “Nazinga Ranch”- Border to Ghana, RF reservoir with fishing activity and RC reservoir with crops farm south of Ouagadougou.

Streams/rivers ecoregions

Most of Burkina Faso lies within the West Soudanian ecoregion. But at national level, the territory is subdivided into three climatic zones (Fontes and Guinko, 1995; Thiombiano et al., 2006; Newborne and Tucke, 2015):

- The Sahelian sector with a mean annual rainfall lower than 600 mm a high rate of evapotranspiration as well as high temperatures and a short rainy season (2 to 3 months). It is the zone with the lowest rainfall in the country.
- The North-Sudanian sector “Upper Soudanian” has a mean annual rainfall less than 1000 mm, the number of rainy 4 to 5 months. It comprises the most extensive climatic zone as it extends over all of the central part of the country, which is mainly drained by

the Nakanbé. The temperatures recorded are generally mid-range (between 20 and 30 °C).

- The South-Sudanian sector "Lower Soudanian" receives a mean annual rainfall exceeding 1000 mm annually, where the rainy season lasts from 5 to 8 months. This area is marked by low temperature ranges (20-25 °C), drained by Comoé and most part of Mouhoun basin watersheds.

Land use and water pollution

Freshwater biodiversity is threatened by climate and land use (deforestation) change at the global level, and specially in tropical area (Colin and Lauren, 2003; Orgeval and Polcher, 2008; Favreau et al., 2009; WWF, 2010). Freshwater ecosystems depend strongly on physical features such as water quantity, quality, flow and surrounding vegetation, many of the threats to these ecosystems involve activities that alter fundamental physical characteristics. Freshwater ecosystems throughout the world are threatened by human activities that directly alter hydrology system, such as construction of physical barriers to flow, water extraction, and filling or draining of shallow habitats. Pollution of waterways with toxic substances and excessive nutrients, as well as destructive land use practices in areas surrounding freshwater ecosystems, lead to reductions in water quality. Freshwater ecosystems are sensitive not only to water temperature, size, and current, but also to variability in these factors. Rivers, lakes and wetlands are expected to display a wide variety of changes in response to global climate change. In West Africa, the impacts on water bodies are expected to increase due to high levels of economic and population growth in this regions. In Burkina Faso, a major land use for the agriculture is currently intensified. The intense land use impacts on river basins are evident. These pressures often show drastic changes in their river morphology. E.g., the farmland of Nakanbé river in Wayen makes up ~70%, and is expected to increase severely in the future (Mahé et al., 2010). Besides, the agriculture is a major source of nutrients input into the waterbody. Elevated water turbidty and bacterial fecal pollution, as well as chemical substances from mining are also a leading cause of water quality impairment in Burkina Faso (UNEP-GEF, 2010). Effects of those anthropic presures on water ecosystems, benthic macroinvertebrate assemblages and other organisms involve increasing water vulnerability, as well as changing the composition of the community structure, increasing the numbers of opportunistic species, and reducing the general biodiversity and abundance. Especially thesis Article [3] was dealing with this topic.

Freshwater benthic macroinvertebrates

The benthic macroinvertebrates are a diverse array of animals without backbones, which are visible to the eye without the aid of a microscope that inhabit the lake and river bottom (benthal). They include arthropods (insects, arachnids and crustacea), molluscs (bivalves and gastropods), annelids (Oligochaeta and Hirudinea) and other groups like Hydrozoa, Porifera, Kamptozoa, or Bryozoa.

The arthropods

The insects are the most important groups of freshwater living oraganisms. Their bodies are divided into three distinct parts: The head, the thorax and abdomen (Tachet et al., 2003; Sanogo, 2014). The head bears the eyes (compound eyes and ocelli), antennae, and mouthparts. The insect thorax is divided into three parts: the prothorax (pro=first), mesothorax (meso=middle), and metathorax (meta=last). Each of the three thoracic segments contains one pair of legs. Wings are found only by "adults" on the meso- and metathoracic segments. The abdomen has between 6 to 10 segments in most of case.

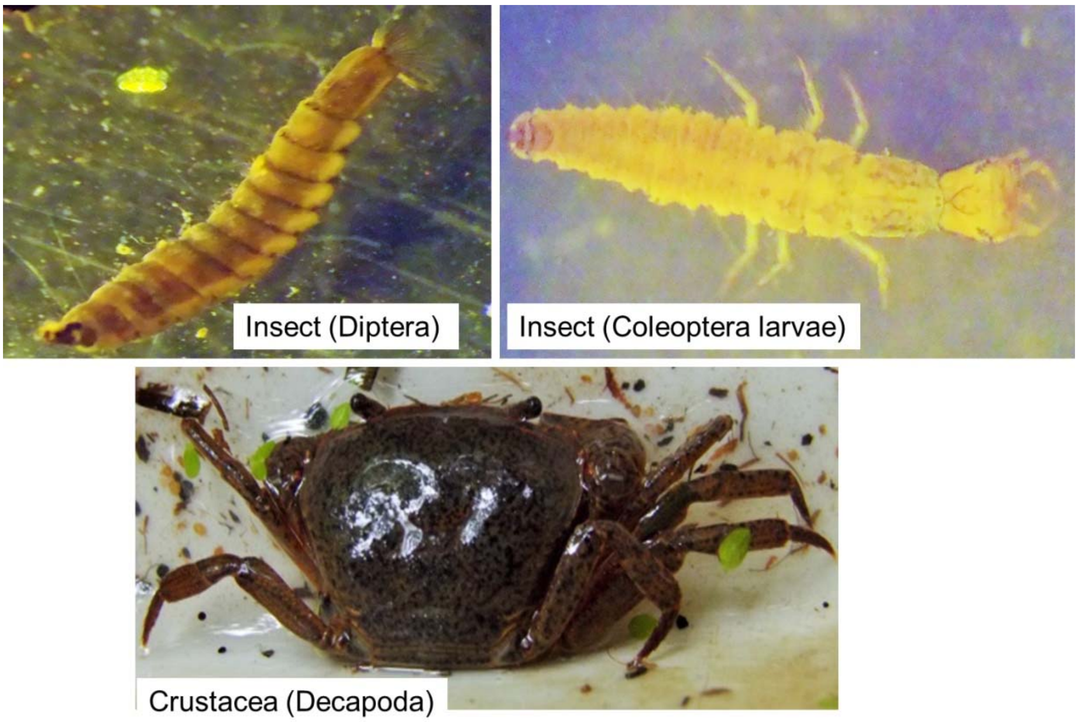

Figure 5 Different Arthropods from Burkina Faso.

The insects include several orders such as Ephemeroptera (mayflies), Odonata (dragonflies and damselflies), Diptera (flies and mosquitoes), Coleoptera (beetles), Trichoptera (caddisflies), Lepidoptera (moths), Plecoptera (stoneflies), Hemiptera (bugs), Neuroptera (lacewings) and Megaloptera (dobsonflies and alderflies). Two groups of arachnids are considered being aquatic or strongly associated with the aquatic habitat: The spiders and mites or hydracariens. They have four pairs of walking legs, two pair of mouthparts and an unsegmented body. The body of a spider is divided into anterior and posterior section by a narrow "waist", whereas the bodies of mites are undivided. Among the crustaceans, the most important groups encountered in the study area are the decapods and the ostracods. The Decapoda have five pair of thoracic pereiopods or walking legs to which decapods owe their name.

Figure 6 Photo of two different molluscs .

Molluscs with one shell (Gastropods) or two shells (Bivalves) are soft-bodied, unsegmented animals that normally live inside a shell (Fig.6). Freshwater snails have a large, ventral muscular foot and a well-developed head bearing a single pair of tentacles (Lévêque, 1980; Mouthon, 1982;). Today the phylum of Mollusca is divided into eight different classes, six of which are exclusive marine (living in the sea). Only bivalves and gastropods have been able to adapt to life in freshwater. The gastropods are more commonly referred to simply as snails but include the limpets and slugs) and the class Bivalvia which includes all the mussels, clams and oysters.

The annelids

The Annelids are characterized by an elongated and cylindrical body divided into ringlike segments. Most annelids have movable bristles called setae, and include earthworms

(Oligochaeta), (Hirudinea), and bristle worms (Polycheta), (mostly marine worms). Leeches are segmented worms characterized by a basic division of the body into 34 segments, of which the seven segments at the posterior end are fused to form a large powerful caudal sucker. The mouth is surrounded by the cephalic sucker formed by the fused ventrales surfaces of the first few segments. The possession of the constant number of body segement and these anterior and posterior suckers distinguishes leeches from the closely-related to Oligochaeta. Most of the leeches are dorso-ventral flattened but due to a complex system of ring-, longitudinal- and diagonal muscles they may have quite variable shapes and are good swimmers. Compared to the earthworms, the aquaitic oligochaeta are much more smaller and more slender.

Figure 6 Photo of Annelids.

Biology and ecology of benthic invertebrates

The biology and ecology of benthic invertebrates (BI) was the main objective of four thesis research articles [1, 2, 3, 5]. It appears that reproduction in arthropods is always sexual. As insects grow from an egg to an adult, they change their body shape (metamorphoses). Most of them fall into the category of either complete or incomplete metamorphosis. For example mayflies, Hemiptera (bugs) dragonflies and damselflies, and stoneflies undergo the more primitive incomplete (or hemimetabolous) metamorphosis with three distinct stages: egg=> nymph=> adult. Beetles and the caddisfly are holometabolous (= endopterygote) insects, which means they undergo a complete metamorphosis: egg=>larva=>pupa=>adult. Aquatic insects have a very wide range of morphological, physiological and behavioral adaptations that allow them to live almost all types of aquatic environment (Tachet et al. 2003; Alba-Tercedor, 2006).

Most aquatic macroinvertebrates conduct gaseous interchange through the tegument (Alba-Tercedor, 2006; WRC, 2007). Most water beetles and bugs obtain oxygen from the air at the water surface. Some groups, such as adult beetle submerged, stored air either under the elytra in a subelytral chamber (e.g. the Hydradephaga), or kept in a bubble on the underside of the body (e.g. the Hydraenidae), while the larvae use the tracheal reservoirs. Adults of several water beetle families (e.g. Dryopidae, Elmidae) and bugs (Aphelocheiride) obtain dissolved oxygen from the water through a “physical gill” or plastron.

Damselflies larvae and Mayflies breathe by means of external gills, but the larvae of the larger, true dragonflies breathe by pumping water in and out of the rectum. Caddisflies breathe dissolved oxygen by diffusion across their soft tissues, and they have a limited ability to cope with low dissolved oxygen by wiggling their bodies within their cases.

Freshwater molluscs differ widely in life-span. The snails may live between one and two decades, whereas the bivalve may reach one or up to 200 years (freshwater pearlmussel). They vary in their reproductive style and may be oviparous (e.g. families Ampullariidae and Pomatiopsidae), viviparous (e.g. Viviparidae) or ovoviparous (e.g. Thiaridae). Members of some genera in the Thiaridae are parthenogenetic functional adults developing from unfertilized eggs (Mouthon, 1982). Pulmonates are oviparous hermaphrodites, with male and female sex organs occurring in the same individual and usually in the same organ (Lévêque, 1980). The mussels belonging to the Sphaeriidae and Corbiculidae are hermaphroditic and viviparous whereas the larger of the Unionidae and Mutelidae may either be separate-sexed or hermaphroditic and viviparous. Pulmonary respiration includes Pulmonates that have a richly vascularized paleal cavity in the mantle, without gills, that function as a “lung”. They are relatively independent of the water’s oxygen because they breathe air directly and live near of the water surface or associated to macrophyte leaves very close to the surface (Mouthon, 1982). Most aquatic worns reproduce sexually , except naidids and tubificids. The worms are hermaphroditic animals, having both testes and ovaries.

Freshwater invertebrates are the small animal inhabitants of the beds (and sometimes the open water), in our streams, rivers, lakes, ponds and wetlands. Insect larvae make up the majority of most freshwater invertebrate communities. The habitat preferences of many of these invertebrates are well known (e.g. freshwaterecology.info). They are essentially composed of lithophilous taxa= stony substrates, psammophilous taxa=sandy substrate, xylophilous taxa=wood dwelling and Phytophilous taxa=aquatic plants. Differences in the physical and chemical characteristics of water can greatly affect the shape and appearance of freshwater macroinvertebrates, even within a small area (Minshall, 1984; Hussain and Pandit, 2012; Singh and Sharma, 2014). Hussain and Pandit (2012) concluded that the composition and distribution of stream macroinvertebrates is governed by numerous physical, chemical and biological factors as well as stream health, which need to be taken into consideration in any study of stream macroinvertebrates.

Functional feeding groups

Feeding approaches are typical traits reflecting the adaptation of species and they could form part of a integrated measure across communities differing in taxonomic composition (Thesis Article [3], Statzner et al., 2001; Heino, 2008). Functional feeding classification of aquatic organisms enriches the knowledge of trophic dynamics in streams and can also serve as useful surrogates for ecosystem attributes (Cummins, 1995; Cummins et al., 2005). Aquatic macroinvertebrates have different adaptations for the aquatic environment that allow them to fit into specific feeding groups (Moog, 1995; Merritt et cummins, 2006). Shredders use chewing mouthparts to bite into large pieces of organic material such as leaf litter and wood, e. g. cranefly larvae, scuds, small-sized stonefliy larvae. They prefer food that has been softened and pre-conditioned by microorganisms (fungi and bacteria) and often leave veins and other finer. Collectors dine on smaller organic particles, usually less than one millimeter in diameter. Sometimes fecal matter left from other organisms may be on the menu. They eat algae and fragments of animals and plants. Filtering collector, capture particles by using a fan (black fly larvae) or spinning a net (free-living caddisfly) made of a sticky substance. Gathering collectors such as mayfly nymphs and beetle larvae are anatomically designed (mouths and appendages) to burrow and live in lower substrate. Scrapers or grazers eat algae from rock and stream surfaces. They are not swept downstream in swift currents because some have suction disks on their abdomens and most are flat. Snails and some mayfly nymphs fall into this category. Predators like dragonfly, damselfly, and stonefly nymphs, are perfectly adapted eating machines. Some capture other aquatic insects by grasping with forelegs and biting and chewing with strong opposable mouthparts. Others use tube-like mouthparts to suck body fluids from their prey (piercers) or just eat their meal whole (engulfers). The parasites live on the body surface or inside the body of another type of organism (known as a host). The parasite obtains nutrition directly from the body of the host (e.g leeches).

Aquatic insects are located in waterways according to what they eat (Vannote et al., 1980). Shredders can be found in upper reaches of streams where there is abundant vegetation. Scrapers prefer open areas or after leaf fall, when sunlight can penetrate the stream and reach the larger substrate to photosynthesize algae. They are typically found in riffles with filtering collectors. Gathering collectors prefer slower areas where sediments are allowed to accumulate. Predators are on the prowl in all aquatic habitats.

Benthic macroinvertebrates biodiversity in West Africa and Burkina Faso

In West Africa, early vast studies on macroinvertebrates was conducted in the 1970s and 80s to evaluate the effects of the application of insecticides on non target macroinvertebrates as a part of onchocerciasis contol programme. Amongst, the reported studies (Dejoux et al., 1981; Yaméogo et al., 1988). These studies have contributed to improve the knowledge of aquatic insects of this region. Thesis Articles [1, 2, 3] deal with that topic.

In the recent years, many studies have been delivered with benthic macroinvertebrate community in west Africa. These studies mainly concerned midst others the inventory of macroinvertebrates in Côte d'Ivoire (Kouadio et al., 2008; Edia Oi et al., 2011; Kouamé et al., 2011; Camara et al., 2012; Yapo et al., 2013), in Togo (Tampo et al., 2015), in Benin (Adandedjan et al., 2011) and in Nigeria (George et al., 2010; Olomukoro and Oviojie, 2015), among others. These studies have demonstrated that West african waterbodies bear a high richness of macroinvertebrates (e.g. Camara et al., 2012 have collected 132 taxa of macroinvertebrates including several "taxa and species" of "Insects , Molluscs , Crustacean and Annelids).

In Burkina Faso, most studies on benthic macroinvertebrates inventory include the studies of Grenier et al. (1960) and Dejoux (1977) who have reported (16) and (25) species of Diptera belong to the family of Simulidae and Chironomidae, respectively. Six species of molluscs "Gasteropd" in the family of Bulinidae were collected by Poda et al.(1994). In the Mouhoun Rivers, Gibon et al. (1994) collected 32 taxa of Trichoptera with eight new species described, Guenda (1996) recorded 97 taxa and Sanogo et al. (2014) have reported 35 taxa. Nevertheless, the systematic knowledge of benthic macroinvertebrates in West Africa, and particularly in Burkina Faso is poorly documented reported by Guenda (pers. comm.).

Biomonitoring and bioassessment

Biomonitoring and bioassessment was the main focus of my Articles [4, 5]. Aquatic ecosystem health cannot be measured directly like human health. Instead, only indicators of health can be measured and, in turn, used to assess the "health" status (Roux et al., 1993; Ollis et al., 2006). Biomonitoring can be subdivided in five categories:

1. Toxicity bioassays are a laboratory-based methodology for investigating and predicting the effect of compounds on test organisms.
2. Behavioral bioassays explore sub-lethal effects of fish or other species when exposed to contaminated water; usually as on-site, early warning systems.
3. Bioaccumulation studies monitor the uptake and retention of chemicals in the body of an organism and the consequent effects higher up the food chain.
4. Fish health studies deal with causes, processes and effects of diseases; and can form a complementary indication of overall ecosystem health.
5. Bioassessments are based on ecological surveys of the functional and/or structural aspects of biological communities.

Quite a large number of living organisms are currently used in biomonitoring programmes including fish, macrophytes, algae, macroinvertebrates etc. (Ellenberg, 1991; Roux et al., 1993; Furse et al., 2006). Many authors have recognized that the limited application of bioassessment in the past has been a major factor responsible for the deterioration of the ecological integrity of rivers and other freshwater ecosystems (Karr and Chu, 2000; Ollis et al., 2006). All over the world, many States have recognized the importance to control pollution and the necessity to restore and maintain biological integrity, to protects species and their habitat. Therfore, many countries are developing at regional/ or national-scale environmental monitoring and natural resources safeguarding programs, including Clean Water Act 1972, Endangered Species Act 1973; South African River Health Programme 1994; South African National Water Act, 1998; DCE 2000 etc. Traditionally, water quality assessment actions have focused on physical and chemical measurements. But nowadays, the use of biological indicators are a key element of environmental and water resource management policies in many countries (Moog and Chovanec, 2000). A biological description offers a holistic view of the state of an ecosystem because biological communities reflect environmental conditions over time and space (Reyjol, et al., 2012). The purposes for bioassessments are varied and include characterizing how populations change across environmental gradients, such as altitude, distance, or substrate changes and how these variables interact. Another purpose is to establish baseline reference conditions for future comparisons (Hering et al., 2006). Bioassessments based on ecological surveys of the functional and/or structural aspects of benthic communities for streams/rivers and lakes are performed to distinguish between impaired sites and sites in natural undisturbed conditions and for characterizing the level of impairment. Learning the effect disturbances on reference communities can help to guide decision making about land use and restoration useful for resource managers, conservationists, politicians and the general public. Dallas and Moore (2014) have demonstrated that the biological assessment in addition to assessment of the available habitats, riparian vegetation, and water quality parameters can greatly enhance the assessment and management of aquatic ecosystems.

Different approaches in bioassessment

Biological community data can be summarised and presented as simple, numeric or categorised indices (Ollis et al., 2006). There are several approaches in the use of biotic indices to assess the ecological status of the water bodies. These indices provide information on the biological status and environment health in a way that is understandable to guide and inform resource managers, decision-makers and the general public. There are four majors groups of indice including diversity indices, similarity/dissimilarity indices, biotic indices and biotic score (UN/ECE, 1995; Sharma and Moog, 1996; Ollis et al., 2006). Its appear that diversity and comparative indices show their limits, while biotic indices and score are widely used in many bioassessment programmes (UN/ECE, 1995; Birk & Hering, 2003; Ollis et al., 2006). They can measure various types of environmental stressors, organic pollution, acid waters etc. E.g. the Saprobic Index is based on the presence of indicator species, which have been assigned saprobic values based on their pollution tolerance to organic inputs. Besides , multivariate and multimetric appraoches are promising upgrading alternative to biotic indices in the bioassessment of watercourses, but multivariate approach suffers from complexities in developing the methodology, understanding and interpreting of results.

Advantages of using benthic macroinvertebrates in bioassessment

Using biotic indicators in bioassessment, especially benthic macroinvertebrates is now common. Kolenati (1848), a citizen of the Austrian Habsburg monarchy, was the first to correctly interlink the absence of Trichoptera larvae to influences by large settlements. Hassal (1850) in London and Cohn (1853) in the old German Empire are credited to be among the first scientists to use aquatic organisms as indicators for water pollution. This led to the description of later widely used communities of aquatic ecosystems by Kolkwitz and Marsson (1902), who developed the first water quality assessment method, the "Saprobic System". Until the 1980s, works from Europe, America and Australia have shown that biological assessment methods which use benthic macroinvertebrates for asssessment of aquatic ecosystems are the most practical ones (Hellawell, 1986; UN/ECE, 1995; Moeykens, 2002). The benthic macroinvertebrates are chosen because they are mostly used worldwide and have several characteristics that make them particularly beneficial for bioassemment 1) they are the most popular indicators and their use dates back to the late 1840ies, 2) they are the major group of organisms in terms of species richness and individual abundance in most waterbodies 3) their life cycles are sufficiently long that they will likely be exposed to pollution and environmental stress 4) sampling the benthic macroinvertebrates assemblage is relatively simple and does not require complicated devices or great effort 5) although they are mobile they have mostly sedentary habits so they are likely to be exposed to pollution or environmental stress 6) the benthic macroinvertebrates biology are well-known and thus sufficient identification keys, ecological data bases are existent and methodological standard.

Discussion

This is an overall discussion of all five research articles. The tropics occur between latitudes 23° north and 23° south. The study of aquatic habitats within the great variety of climatic, geologic, geomorphologic and eco-geographic conditions unique to the tropics is covered in the field of tropical limnology. The applicability of hydro-biological concepts and paradigms, originally developed in the temperate North, to the reality of tropical ecosystems remains a question, especially as a basis for sustainable water management (Dudgeon, 2008; Boulton et al., 2008). These five thesis research articles [1, 2, 3,4, 5] address that question as part of contribute to the knowledge on tropical streams and their benthic invertebrate colonisation.

Based on the most fundamental taxonomic unit – the species -this study revealed a high taxa richness of benthic macroinvertebrate communities in water bodies of semi-arid areas of West Africa. The recorded groups of macroinvertebrates (e.g. Arthropods, Molluscs, and Annelids) tend to be common to those reported in other tropical regions. But, in various types of tropical ecosystems, distribution patterns of species richness may vary among taxa (Pearson and Boyero, 2009, Pearson, 2014). This research addresses ongoing debates on differences between tropical and temperate benthic communities by demonstrating that tropical ecosystems have higher diversity than those in temperate zones (Benbow and McIntosh, 2008; Boyero et al., 2009; Pearson, 2014). Despite the urgent needs created by threats to surface water in the tropical regions, especially West African, studies devoted to macroinvertebrates are still limited. Articles [1, 2, 3] of this thesis address this topic.

Aquatic biodiversity is threatened by habitat degradation, hydrological alterations, water pollution, as well as climate change (Dudgeon et al., 2006; Wallace and Eggert, 2009; Dallas and Moore. 2014). Those threats negatively impact benthic macroinvertebrate communities as well. Our findings showed that benthic macroinvertebrate communities react in predictable ways to different intensities of anthropogenic impairments and thus can be used as valuable bio-indicators. Anthropic pressures affect a variety of zones in aquatic ecosystems, from meso- (riparian zones and land-water interfaces) to micro-scales (the river bed interstices). In Burkina Faso and throughout many countries of the world, rapid urbanization, industrialization, and intensive agriculture are stressing riverine ecosystems (Allan, 2004; Moss, 2008; Strayer and Dudgeon, 2010; Poulton et al., 2015). Like other freshwater plants and animals, human activities affect macroinvertebrate composition, increase the numbers of opportunistic species, and reduce the general biodiversity. Many studies provide strong evidence of impact of human activities on ecological integrity of rivers/streams. With the extent of land use transformation, aquatic trophic structure, also are certain to change. Articles [3, 4] of this thesis address this topic.

The functional composition of benthic macroinvertebrates can vary among sites as well as regions (Cummins et al., 2005; Boyero et al., 2009; Masese et al., 2014), such as those reported in Burkina Faso. In spite of knowledge gaps of tropical rivers /streams, it is clear that these aquatic trophic structures are characterized by complex interactions that are unlikely to be captured adequately by simple generalizations (Boyero et al., 2009), Article [3] specifically addresses this question.

Research globally has shown that benthic macroinvertebrates play important roles in the trophic web, in ecological processes, as well as in bioassessment of environment health in aquatic ecosystems. Research documenting those roles can strengthen water management decisions to maintain the diversity of those organisms. Despite the fact that some species have negative impacts on human health (e.g. Simuliidae and mosquitoes), the numbers of freshwater invertebrates that are pests are very small in comparison to those that are beneficial to humans and the natural world (e.g. Voshell, 2002). These remarkable benefits from benthic macroinvertebrates should encourage politicians and the administrations 1) to include macroinvertebrate-based information on biological water quality into decision frameworks and 2) to formulate outreach programs about biodiversity conservation and natural resources management.

High population growth rates and other threats to aquatic ecosystems and biological resources also endanger basic human and environmental needs that depend on long-term freshwater ecosystem services. This highlights a need for tools to assess the biological integrity and whole aquatic ecosystems health for the sustainable use of resources is currently fundamental. To meet this need this study describes criteria based on physicochemical parameters, hydro-morphological features, land use that can be used as guidelines of reference conditions for the bioassement in Burkina Faso. Our findings suggest the importance of maintaining a range of protected areas hosting a range of sensitive taxa. As far as they show very low impact levels, such areas are crucial for effective conservation of the regional fauna and as reference sites to provide standards for bioindicators. Despite the many ecological risks, both natural and humans, faced by protected areas (Muhumuza and Balkwill, 2013), designation of protected status allows these areas to benefit from better management that preserves near-natural conditions. As such, this study highlights the necessity to mobilize strategies to preserve soil and water in Africa.

The state-of-the-art in bioassessment has not reached a point that is equivalent to the techniques used in physical and chemical monitoring. Bioassessment tools are continuously being developed, modified, and tested to provide quicker and more accurate assessments of the waters. The multimetric approach applied here lies in the same line and seems to be a promising approach for ecological quality assessment in Burkina Faso. But, application of the multimetric method requires time and well-trained personnel. Furthermore, such an index should be tested through time to avoid wrong interpretations associated with the natural, seasonal and temporal variability. These topics are specifically addressed in thesis by Articles [4, 5].

Nevertheless future studies are needed for a more comprehensive understanding of the relationship between hydrology and macroinvertebrate communities, thus contributing to sustainable management of reservoirs and river health when society meets ecology in Burkina Faso.

To do so protocols for a standardize sampling for benthic invertebrates are needed. A guideline for a standardized monitoring of benthic invertebrates for Burkina Faso should be developed in order to build indices based on comparable data. The effectiveness of any index-driven management policies will increase with better knowledge of benthic invertebrates taxonomy, distribution, ecology, and conservation status.

To help to increase the responsibility of local people for their aquatic environments, the development of a simple and easy-to-use water quality evaluation system is necessary. A useful tool for this purpose would be a rapid field assessment tool, such as what has been developed for the Hindukush-Himalaya-Region. Before promoting any new scoring system it is necessary to test it broadly in different regions of Burkina Faso. Improvement and capacity building to identify and classify benthic invertebrates, as well as Fish and in Burkina Faso is required for the future. Managing aquatic ecosystems based on indicator taxa/species will be greatly facilitated by better tools to identify and classify benthic invertebrates in Burkina Faso. This requires development of specific benthic invertebrate’s classification keys for Burkina Faso. For benthic invertebrates this could be done gradually, with simple keys on family level for less experienced users, followed by more detailed ones. Two possible ways (that can be combined) can be used to develop a Biotic Scoring system: 1) adapting an existing method or 2) developing an own methodology to evaluate and describe the ecological status of water bodies. The second idea is feasible for Burkina Faso, but the following activities need to be undertaken. The benthic taxa that are not listed need to be assigned a score; separate systems have to be developed for running water and for reservoirs and the aspect of perennial or intermittent discharge has to be regarded; to be able to apply the reference condition approach eco-geographic regions with similar conditions have to be defined; a sufficient number of test sites needs to be investigated to cover the variety of reference, good, moderate, poor and heavily impacted sites as well as the effects of different stressors and impacts. A special emphasis must be given to adapt the biotic score methodology to classify stagnant waters and reservoirs, as these scoring systems were not designed to assess stagnant or lentic water bodies.

List of possible stressors that should be investigated with respect to their impact on the biota and the ecological balance and functions. The resilience of macroinvertebrates communities is broadly indicated by the persistence of some species in “high pressure” sites and rises questions such as: How does macroinvertebrates species composition change across a range of sites exhibiting a diversity of pressures of different degrees of intensity? Under what conditions and under what kinds of restoration efforts at high-pressure sites do macroinvertebrates communities rebound, and how can we measure different rebound parameters, e.g. maxima, minima, overall dynamics?

Reservoirs represent a unique type of water body on a worldwide scale, but most assessment systems do not provide the option to assess stagnant water bodies, a common situation in Burkina Faso. A method for classification and typology of reservoirs and broad, lentic reaches of rivers needs to be developed that is sensitive to Burkina Faso conditions, where stagnant water bodies are usually under strong agricultural pressures.

Since the impacts of many, different pressures are correlated, future research needs to help us distinguish the impacts of individual pressures on benthic macroinvertebrates taxa. How can we integrate research to distinguish the separate contributions of multiple pressures that degrade average habitats: mining, deforestation, sedimentation, and river bank development? In many reservoir agriculture pollution and urban wastes (sewage) lead to important bloom of saprophytes and algae, which may affect benthic macroinvertebrates diversity. Additionally sedimentation reduces reservoir and river volumes to critical extents, especially toward the end of the dry season, in a way that water quality declines and threatens biota productivity. Other excessive water withdrawals, due to mining and irrigation, reduce the available water volumes within reservoirs at the end of the dry season below thresholds critical to benthic macroinvertebrates and fish capacity to survive and reproduction in West Africa.

Conclusion

In summary, this dissertation investigated the benthic macroinvertebrate assemblages and the ecological status of associated aquatic ecosystems in Burkina Faso. A comparatively high richness of 132 taxa which belong to 57 families have been identified. These results are only a foreshadowing of what research will eventually uncover, since many species are still unknown to the science in West Africa. This thesis could show that among 60 species of Coleoptera that our field research identified, some 24 species are the reported for the first time in Burkina Faso. As with many tropical aquatic ecosystems, especially in Burkina Faso, these preliminary results highlight the need to sustain an intensive research effort to generate conclusive results useful for policy.

This study provided deeper insight into the ecological organization and functioning of aquatic ecosystems in semi-arid West Africa. As such it showed that benthic macroinvertebrate communities are particularly effective as indicators of the health conditions of rivers /streams. Further, the study generated information that can be used to estimate how water ecosystems alterations caused by human activities affect these vital ecosystems. Finally this research established a foundation of data that makes the application of biomonitoring a credible tool for improving strategies of management and conservation of water and river systems in Africa. Specifically, these results can also be used to further improve and then incorporate benthic communities-based monitoring as a tool for the formulation and implementation of policies for the conservation of aquatic ecosystems. Furthermore, they can be used in education (Universities, IUCN, governmental professional school) in the fields of bio-statistics to may help to preservation of biodiversity and management of natural resources in West Africa. Future studies are needed for a more comprehensive understanding of the relationship between hydrology and macroinvertebrate communities, thus contributing to sustainable management of reservoirs and rivers/streams health when society meets ecology in Burkina Faso.

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RESEARCH ARTICLES

ARTICLE #1

International Journal of Biological and Chemical Sciences (**manuscript in review**)

Diversity, composition and dynamic of benthic macroinvertebrates community in semi-arid rivers of Burkina Faso (West Africa).

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Abstract

The benthic macroinvertebrate communities dynamic were investigated in rivers from Burkina Faso in the purpose to analyze 1) the taxonomic composition, 2) the structure of benthic macroinvertebrates community and 3) the composite environmental variables that correspond to the major patterns of this community. The results showed that a total of 132 taxa was recorded and the large majority of these (103 taxa) belonged to 57 families from 8 orders of insects that represent 95% of relative abundance). We also observed some distinct differences relative to the spatial and temporal in the taxonomic composition. The CCA analyse revealed a strong relatisonship between chironomids, Syrphidae, Culicidae, Psychodidae, as well as the Pulmonates molluscs and organic nutriments. These findings showed the sensitivity of benthic macroinvertebrates at different level, which could be attributable to man-induced activities.

Keywords: benthic macroinvertebrates, enviromental variables, dynamic, Burkina Faso

Introduction

The benthic macroinvertebrate assemblages are widely recognised as the most important group in rivers and lakes (Covich et al., 1999). They play a key role for the understanding of the structure and functioning of these ecosystems, due to their wide distribution and limited migration ability and resiliency (Barbour et al. 1999). The benthic macroinvertebrates have been widely used in biomonitoring program, due to several attributes that make them particularly beneficial (Moog et al.,1999; Marzin, 2013). Additionally, they are a primary food source for many species of fish, amphibians and birds (Voshell, 2002). Despite the benefits and the services that they provide to humans, waters health and its living organisms are the most threatened by human activities such as rapid expansion of urban areas and agriculture (Moore and Palmer, 2005; Kaboré et al., 2016). These pressures caused many changes in the structure of macroinvertebrates community and lead to the decline of biodiversity due to habitat fragmentations and the water pollution. This is true in many developing countries. Throught, in tropical area, specially in West Africa, the knowledge on these organism and their ecology is still fragmentary (Sharma et al. 1993; George et al., 2010; Camara et al., 2012; Mesa et al., 20013; Edia et al., 2013). In Burkina Faso, only a few studies have been conducted with benthic macroinvertebrate communities. These studies mainly concerned the inventory of macroinvertebrates in the Mouhoun River (Guenda, 1985, 1996) and the response of benthic macroinvertebrates to anthropogenic interferences (Koblinger and Trauner, 2013; Sanogo et al., 2014; Kaboré et al., 2016). However, the spatial and temporal dynamic changes in macroinvertebrates were not deeply addressed in these studies. The key aims of this present study is to identify and describe the composition, the diversity of benthic macroinvertebrates in Burkina Faso and determine the environmental factors that influence the macroinvertebrate distribution.

Materials and Methods

Study area

The study was undertaken in two main rivers in Burkina Faso: Volta River and Comoé (Fig. 1). Volta River covers an estimated area of 400,000 km² and spread over six West African countries (Sanwidi, 2007). Located between the north latitudes of 5° 30'N in Ghana 14°30'N in Mali and the longitudes 5°30'W to 2°00'E, the Volta river basin is drained mainly by two main sub-basins in the north belong to Burkina Faso: Nakanbé (formerly White Volta) and the Mouhoun (formerly Black Volta). Natural vegetation, mostly savannah grasslands, uses the major part of the rainfall (around 80%) throughout the Volta basin. River volta discharge is highly sensitive to variations in annual rainfall (Sanwidi, 2007). The geological formations of the basin are dominated by the Voltaian system consisted of Precambrian to Paleozoic sandstones, shales and conglomerates. Water resources and agricultural activities in the volta basin are therefore unpredictable. However, 18.6 million people (Barry et al. 2005, Sanwidi, 2007) with an annual growth rate of 2.4% rely on these activities. The Comoé (area of 17,590 km² covering 6.4%) is a perennial river in the extreme south-west of Burkina Faso where the annual rainfall exceeds 1000 mm (Sally et al., 2011). Bordering Mali and Ivory Coast, it is located in the Sudanian climatic zone with tropical characteristics. The basin is drained by the Léraba and Comoé rivers, which are perennial, and by several temporary rivers such as Kodoum, Baoué and Iringou. The total annual surface discharge is estimated at 1.6 billion cubic meters of which 85 million cubic meters are retained by dams. Sampling sites fell within a continuum ranging from low to very high intensity of anthropogenc impacts in the floodplain area (Kaboré et al., 2016). Three sampling campaigns were conducted according to the rivers' hydrology. The first sampling was conducted in 2012 from July to September corresponding to high water flow (Rainy Season), and low water flow (End of Rainy season) from October to December of the same year. The third sampling was conducted from March to June 2014, corresponding at lowest water flow (dry season).

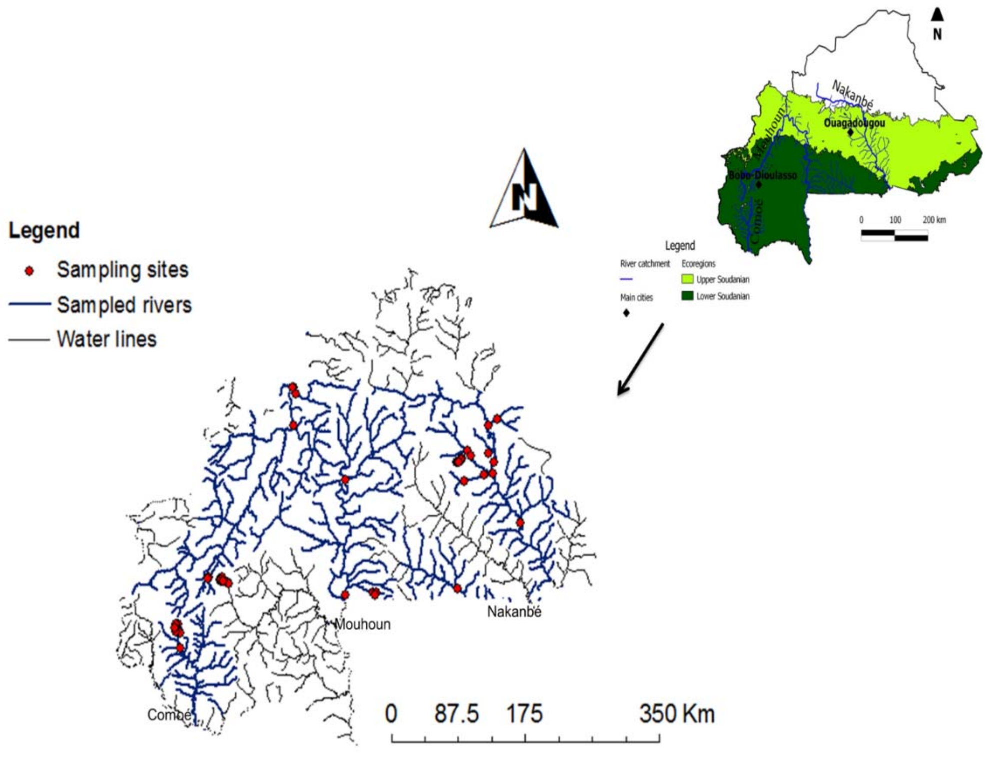

Figure 1 Map of study areas showing the Burkina Faso and the three rivers where the samples were taken.

Physicochemical parameters sampling and analysis methods

In situ parameters such as, pH, electrical conductivity (cond), temperature and dissolved oxygen (O2) were measured with field multimeters (WTW340I) before the macroinvertebrate sampling and, the velocity (m/s) with Global Water Flow Probe FP111. For the other parameters, 1.5 L of water was taken in a plastic bottle , stored on ice for further analysis in the laboratory. Nutrients was determined by molecular absorption spectrophotometry for Nitrate, Ortophosphate, Ammonium. All these parameters were measured in the Laboratoire National d'Anlyse des Eaux" from ,"Ministere de l'Environment et du Development Durable[MEDD] with an accuracy ranking from 1 to 2%.

Benthic macroinvertebrates sampling

The benthic invertebrates were sampled with a hand net (rectangular opening: 25 cm x 25cm, mesh size: 500 µm) according the multi-habitat sampling approach (Moog, 2007). The number and types of microhabitats were recorded. The sampling units were allocated at the investigation site in each habitat composed of Macrophytes (emerged and submerged plants), sediment (sand, mud, litter) and coarse substrate. The sampling started from downstream to upstream , the net was bumped against the bottom substrate to dislodge and collect organisms. The samples were preserved in the alcohol (90%) for detailed examination in the laboratory. Prior to sorting out the organisms, samples were sieved and the animals were sorted. The organisms found were identified with the aid of manuals (Tachet et al., 2003; Merrit et Cummins (1984); Lévêque et Durand (1981) and Moisan et Pelletier (2008). Additionally, we had received taxonomic specialist support.

Data analysis

The total taxa richness (R) was simply taken as a count of number of species present in each site. We used NMS scatter plot of all sampling site to visualize possible predictors of faunal relationships. The diversity indices provide more information about community composition, about rarity and commonness of species in a community. Shannon-Wiener index (H) , Equitability are commonly used to characterize species diversity in a community. Shannon-Wiener Diversity index was expressed following the equation [1], *where pi is the proportion of individuals found in the ith taxon, S is the number of taxa in the samples.*

$$H' = -\sum_{i=1}^{s} p_i \ln p_i \qquad [1]$$

Species equitability or evenness (E) was determined by the equation [2].

$$\text{Equitability (E)} = \frac{H}{\ln S} \qquad [2]$$

Where;

H was the Shannon and weavers index

S was the number of species in samples.

The density is an important tool to measure benthic community production in aquatic ecosystems (Barbour et al., 1996) was also used following the equation [3]

$$D\left(\frac{\text{ind.}}{m^2}\right) = \frac{\text{Total Number of animals}}{\text{Area of samling units}} \qquad [3]$$

We conducted a Kruskal–Wallis ANOVA and Mann-Whitney tests with (SPSS, version 21) followed by pairwise comparison tests to compare taxa richness (R), Shannon-Wiener Diversity (H), equitability (E) and biomass (D) between different Rivers and Seasons, and then between ecoregions. Finally, Canonical correspondence analysis (CCA) was used to define composite environmental variables that correspond to the major patterns of community occurrence.

Results

Physicochemical parameters

Table 1 summarizes the physical and chemical conditions of the study stations.The most sampled sites had warm waters (mean of 29.9). The pH values was slightly alkaline (mean of 7.24), with high conductivity (≥100 $\mu S.cm^{-1}$). Some marked variations in organic concentrations were observed between sampling sites, suggesting anthropogenic pollution and corroborate the use of agricultural fertilizers and urban sewage are believed to increase the concentrations of organic ions in the water bodies.

Table 1 Summary of physicochemical parameters of studied sites

Water variables	Min	Max	Mean
Temperature (ºC) [Tem]	23.30	35.40	29.91 (±2.88)
pH	5.70	9.30	7.24 (±0.68)
Dissolved Oxygen (mg/l) [DO]	1.30	12.70	5.03 (±2.68)
Conductivity (µS/cm) [Cond]	27.50	2480.00	260.19 (±355.60)
Nitrate (mg/l) [Nit]	0.30	38.60	7.69 (±12.36)
Ortophosphate (mg/l) [Orth]	0.00	12.00	2.27 (±3.13)
Ammonium (mg/l) [Amm]	0.00	49.00	3.24 (±6.43)
Water velocity (m/s) [Wvel]	0.00	0.30	0.08 (±0.09)

Benthic macroinvertebrates composition

A total number of 33,357 specimens of benthic macroinvertebrates were collected. Eight orders of insect were recorded in the running water of Burkina Faso (Fig. 2).

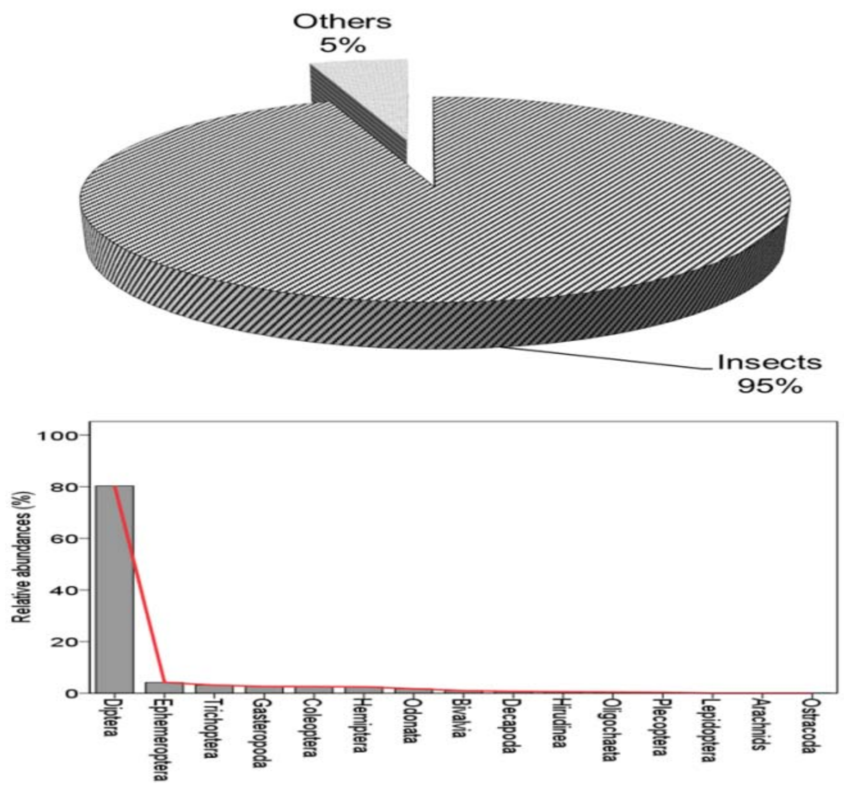

Figure 2 The relative abundances (%) of benthic macroinvertebrate groups.

All the sites were dominated by insects (relative abundance of 95%), represented mostly 80.3% by midges and flies (Diptera). The mayflies (Ephemeroptera) and caddies flies (Trichoptera) made up 7.3% of abundance. The Lepidoptera and Plecoptera, as well as the, Bivalvia, Ostracoda and Arachnida were found in frequencies lower than 0.5%.

Taxa richness

A high diversity of benthic macroinvertebrates with a total of 132 taxa was recorded in this study (Annexe, Table A). A large majority of these (103 taxa) belonged to 57 families from 8 orders of insects: Ephemeroptera, Odonata, Diptera, Coleoptera, Trichoptera, Lepidoptera, Plecoptera and Hemiptera. The remaining 27 taxa belonged to 11 families of Decapoda (Crustacea), Gastropoda and Bivalvia (Mollusca). Coleoptera represented the most diversified group of insects with the following families (taxa): Hydrophilidae (8), Elmidae (7), Dysticidae (6) and the Noteridae (3). They were followed by Diptera (23), dominated by Chironomidae family (4) and Simuliida (4). Within non-insect fauna we found a notable diversity in Molluscs, with several species previously not reported for Burkina Faso. Thus, a total of 15 taxa of gastropod composed of Bulinidae (6), Thiaridae (3), Planorbidae (2), Ampullaridae (2), Lymnaeidae (1) and the Viviparidae (1) were observed. In the Bivalvia class, 3 families including seven species were recorded. Finally, we also found two species of freshwater shrimps belonging to the families Palaemonidae and Atyidae (Appendix Table A1).

Seasonal and spatial variation on benthic macroinvertebrates community

The (Fig. 3) shows NMS analysis with spatial and temporal variation of all sampling sites. The figures did not reveal a clear differences between the watershed (a), Ecoregions (b), Seasons (c) respectively based on the taxa occurrence.

ome distinct differences relative to the basins watersheds could be observed in the taxonomic composition (in I Fig. 4). Thus mean overall taxonomic richness (R= 19.63 ± 3.77) and Shannon-Wiener diversity index (H= 2.00 ± 0.33) were highest in Comoé and reached a minimum of R=8.30 ± 1.05 and H=1.12 ± 0.12 in Nakanbé River (I). While both Nakanbé (means of R= 12.23 ± 1.55, D=446.12 ± 198.69, E= 0.63 ± 0.05) and Mouhoun (means of R= 8.30 ±1.05, D=410.93 ± 126.03, E=0.57 ± 0.05) basins watersheds were distinguished by slightly high overall taxonomic richness, densities , Shannon‑Wiener diversity and Equitability, respectively (see I).

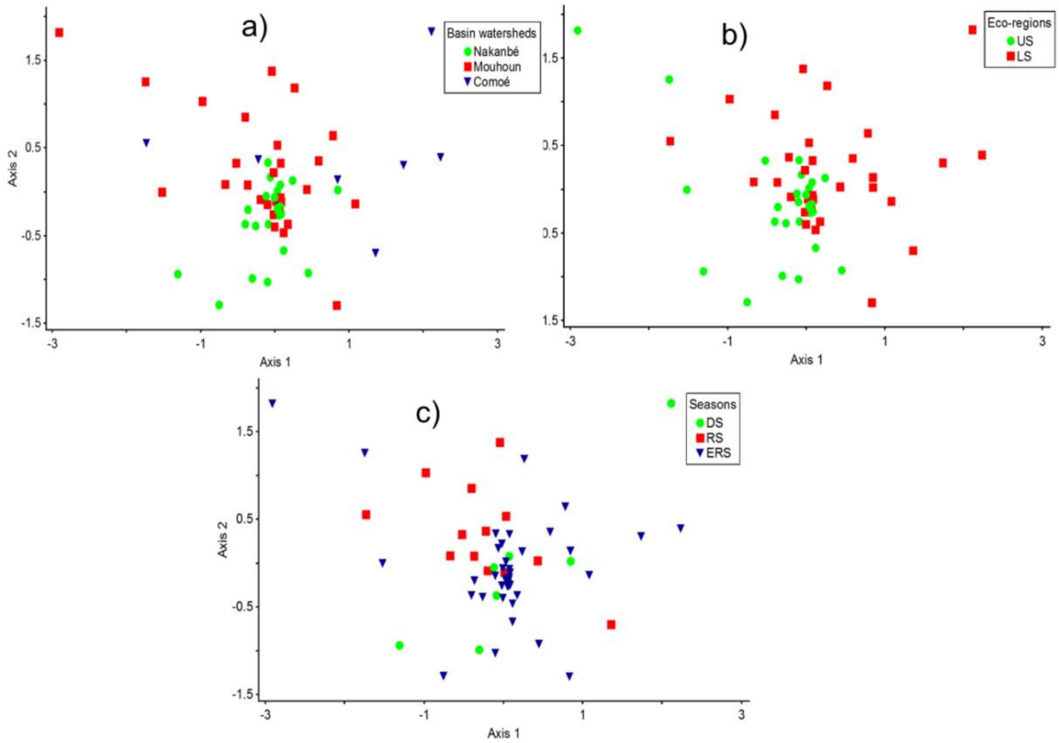

Figure 3 NMS-scatter plot of all samples (N=66) showing the spatial and temporal variation of benthic macroinvertebrates communities (Distance measure: Sorensen (Bray Curtis) using abundances presence-absence transformed. a) = indicates Ecoregions, b) = Seasons and c)= Basins watersheds. (17.57265 = final stress for 2-dimensional solution, 0.00000 = final instability, 194 = number of iterations).

The overall taxonomic richness (mean of R= 12.68 ± 1.40), Shannon‑Wiener index (mean of H=1.51 ± 0.15), Equitability (mean of E= 0.63 ± 0.04) and density (mean of D= 458.53 ± 178.23) tended to increase in Lower Soudanian compared to Upper Soudanian (mean of R= 10.19 ± 1.53, H= 1.2 ± 0.13, E= 0.6 ± 0.04, D= 343.12 ± 106.68, respectively see II of Fig. 4).

In III of Figure 4, the lowest density (mean of D= 82.19 ± 15.69) was recorded in Rainy season while the highest was recorded in Dry season (mean of D= 629.81). In contrast, the high Shannon‑Wiener index (mean of H= 1.6 ± 0.20), taxa richness (mean of R= 13.31 ± 2.04) and Equitability (mean of E= 0.64 ± 0.06) were recorded in the Rainy season. The taxa richness (R=10.31 ± 1.37; 12.44 ± 2.42), Shannon‑Wiener index (H= 1.29 ± 014; 1.39 ±

0.16), Equitability (E= 0.61 ± 0.05; 0.59 ± 0.05) did not reveal a big diffrence between the Dry season and the End of rainy season, respectively (p> 0.05 see III e, f and g, Fig. 4).

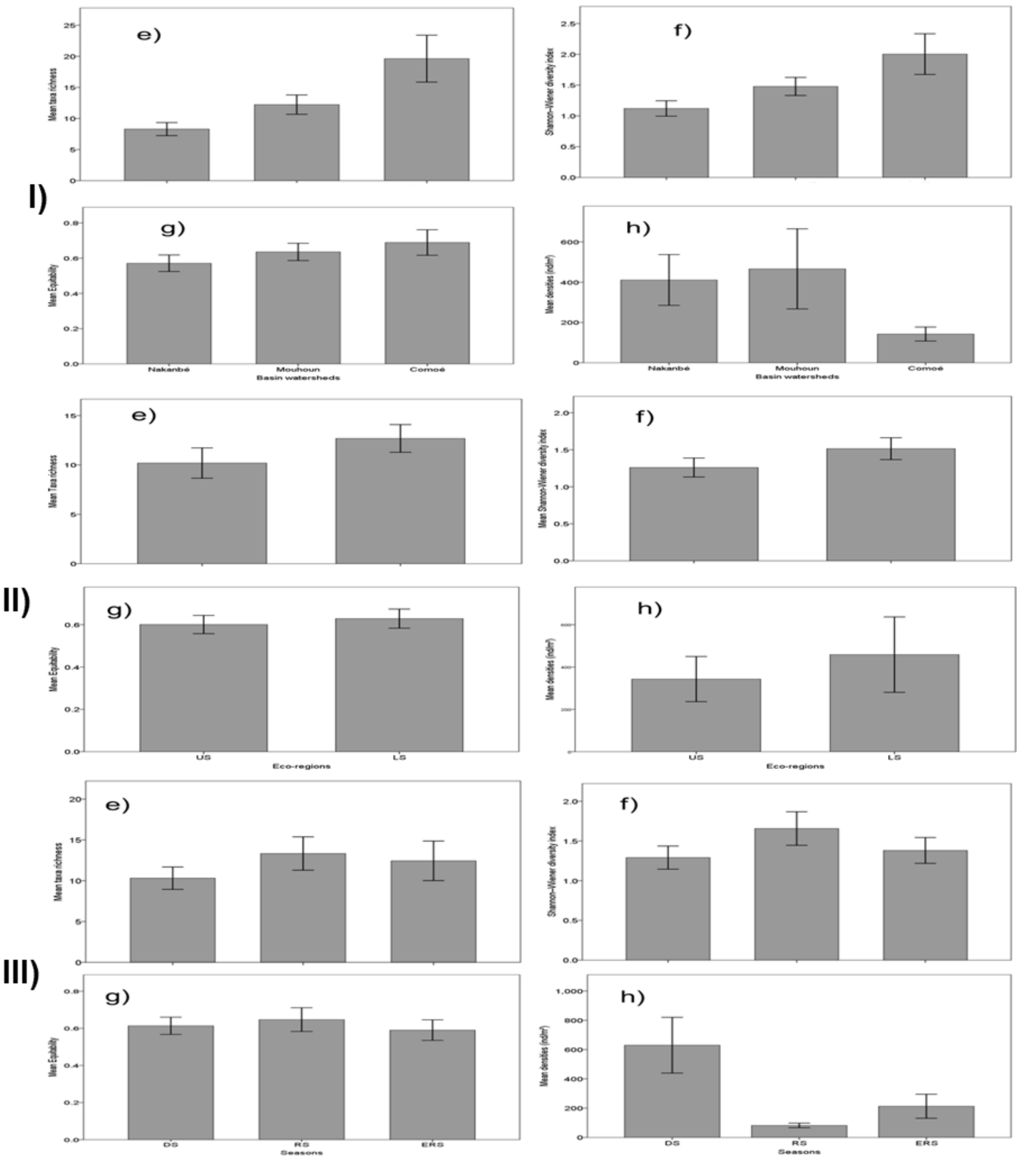

Figure 4 Diagram showing variation of taxa richness (e), Shannon–Wiener index (f), Equitability (g) and density (h) in different basin watersheds. Nakanbé, Mouhoun and Comoé (I), (II) R (e), H (f), E (g) and D (h) between different eco-regions. US: Upper Soudanian, LS: Lower Soudanian and III) R (e), H (f), E (g) and D (h) between different seasons. DS: Dry season, RS: Rainy season and ERS: End of rainy season. Letters above diagrams indicate statistical significance of differences between environmental factor types (pairwise comparison tests): only respective pairs with different alphabetical letters differ significantly (P<0.05).

Influence of physicochemical parameters on benthic macroinvertebrate assemblage

The figure 5 shows the biplots of species and physico-chemical parameters with eigenvalues for axis 1 (0.36) and axis 2 (0.23) explained 59.4% of the variance of overall variables. The first two axes of CCA captured about 82.2% information of species-environment correlations (Monte Carlo test, pvalue <0.05). Thus, nitrate and orthophosphate (r=0.6 all, respectively), ammonium (r=0.7) and the conductivity (r=0.8) are positively related to axis1. The Diptera including Chironomid, Syrphidae, Culcidae, Psychodidae, and the Pulmonates molluscs showed strong correlation with the organic pollution and oppose to Ephemeroptera, Plecoptera and Trichoptera which are correlated with dissolved oxygen and water current.

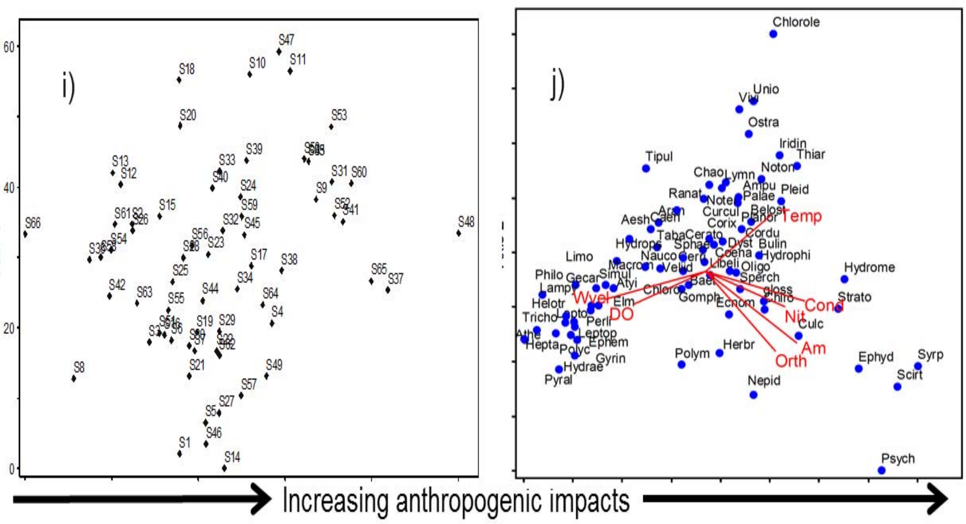

Figure 5 Sites distribution based on taxa occurrence (i) and relationship between physico-chemical variables and benthic macroinvertebrates (j) based on Canonical Correspondance Analysis (CCA). Aran =Araneae, Limo= Limoniidae, Chiro=Chironomidae, Cerato=Ceratopogonidae, Chao=Chaoboridae, Culc=Culicidae, Ephyd=Ephydridae, Tipul=Tipulidae, Strato=Stratomyiidae, Syrp=Syrphidae, Taba=Tabanidae, Athe=Athericidae, Simul=Simuliidae, Psych=Psychodidae, Gecar=Gecarcinucidae, Atyi=Atyidae, Ostra=Ostracoda, Palae=Palaemonidae, Caen=Caenidae, Bae=Baetidae, Ephem=Ephemerellidae, Hepta=Heptageniidae, Leptop=Leptophlebiidae, Tricho=Trichorythidae, Polym=Polymitarcyidae, Ecnom=Ecnomidae, Hydrops=Hydropsychidae, Lepto=Leptoceridae, Philo=Philopotamidae, Polyc=Polycentropodidae, Gomph=Gomphidae, Aesh= Aeshnidae, Chloro=Chlorocyphidae, Chlorole= Chlorolestidae, Coena=Coenagriidae, Cordu=Cordullidae, Libeli=Libelilludae, Macrom=Macromiidae, Curcul=Curculionidae, Dyst=Dysticidae, Elm=Elmidae, Lampy=Lampyridae, Hydrophi=Hydrophilidae, Hydrae=Hydraenidae, Gyrin=Gyrinidae, Noter=Noteridae, Sperch=Spercheidae, Scirt=Scirtidae, Corix=Corixidae, Gerri=Gerridae, Helotr=Helotrephidae, Herbr=Herbridae, Hydrome=Hydrometridae, Belost=Belostomatidae, Nauco=Naucoridae, Nepid=Nepidae, Noton=Notonectidae, Veliid=Veliidae, Pleid=Pleidae, Ranat=Ranatridae, Bulin=Bulinidae, Lymn=Lymnaeidae, Planor=Planorbidae, Ampu=Ampullaridae, Thiar=Thiaridae, gloss=glossiphoniidae, Oligo=Oligochaeta, Perli=Perlidae, Pyral=Pyralidae, Iridin=Iridinidae, Sphae=Sphaeriidae, Unio=Unionidae, Vivi=Viviparidae.

Discussion

Freshwater benthic macroinvertebrates was characterized by the Arthropoda=> Mollusca => Annelida (Akindele and Liadi, 2014; Tampo et al., 2015), as confirmed by this study. This taxonomic list recorded is common to the traditional one reported in freshwaters of Burkina Faso (Guenda, 1996; Sanogo, 2014) and other Afrotropical regions (Edia et al., 2013; Kouadio et al., 2008; Okorafor et al., 2012). Compared to the others studies in some West Africa rivers, Burkina Faso streams appears rich in benthic macroinvertebrates (132 taxa). These results are similar to those reported by Vinson and Hawkins (1996), Camara et al. (2012), Kearns and Stevenson (2012) and Kaboré et al. (2016) who have demosntrated that the sampling technique employed and the types of habitats (e.g. natural habitats, multi-habitats) can explain the high number of taxa found in a given study. The benthic macroinvetrebrates composition presents a strong seasonal and spatial effects which can be justified by the variation of water quantity and mouvement. The year can be divided into three sub- hydrologial periods to characterising the benthic maxroinvertebrates structure. Although we recorded high number of taxa and the lowest biomasse in the rainy season. This may be explained by the fact that the runoff bring a great quantity of foods composed of organic matter, bacteria, phytoplakton and Zooplankton (Ouéda et al., 2007) into the water bodides, which improve food condition for benthic macroinvertebrates. Additionally, the high taxa richness could also be attributed to abundance of macrophytes that enhance environmental heterogeneity , provide protection from predators and reduced competition betweeen species (Uwadiae, 2013; Gong et al., 2000; Kaboré et al., 2016). However the lowest density at the same time is due to enlargement of niche (e.g. expanding of flooded areas). Comparing the three basin watersheds benthic macroinvertebrates, we found that Nakanbé bears the low taxa richness. The similar trend was observed in Upper Soudanian ecoregion mainly drained by Nakanbé River. Melcher et al. (2012) and Ouedraogo (2010) have demonstrated that Nakanbé basin watershed is the most populated and dammed area with intensly anthropogenic activities and urbanisation. As a consequence, these pressures deteriorate water quality and the river systems leading to multiple biodiversity extinctions. The poorer water quality could be attributable to several man-induced activities such as urban runoff to surface river water, the waste dumps into the rivers (Wright et al., 1995; Aggrey-Fynn et al., 2011; Kaboré et al. 2016). The benthic macroinvetebrates may have different levels of sensitivity to pollution and many abiotic factors in the river ecosystems. The high values of conductivity, NO3-, ammonium , orthophoshate and the low values of dissolved oxygen observed in somes sites are indications of deterioration of the water quality as a result of various anthropogenic activities in that sites (Amiro et al., 2010, Tampo et al., 2015). Ouéda et al., 2007 and Kaboré et al., 2016 observed similar trend of organic ions in densely inhabited area and urban streams where wastes (e.g. domestic, industrials and urban) are constantly discharged into the stream/rivers. Which, should justify the relationship between these variables with tolerant taxa such as Syrphidae, Culcidae, Psychodidae, as well as the Pulmonates molluscs that increase with increasing disturbance (Nkwoji et al., 2010; Moya et al., 2012 and Tampo et al., 2015). Throught the sensitive taxa Ephemeroptera (Heptageniidae, Ephemerelliidae), Plecoptera and Trichoptera taxa are often the most abundant insects encountered in sites with a sufficiently high dissolved oxygen concentration and good habitats condition (Arimoro et al., 2010; Shelly et al., 2011).

Conclusion

This study described the benthic macroinvertebrates community dynamic in Burkina Faso. We recorded high taxa richness, indicating that the streams/rivers of Burkina Faso appear very rich. Among the factors potentially important that explain the possible predictors of faunal relationships, we observed some differences in community structure suggesting that environmental factors such seasons, the basins watershed and physicochemical variables could play a key role in distribution of benthic macroinvertebrate in Burkina Faso. In the further study, we will address the role of each available habitats and each physicochemical factors on these aquatic communities to refine our results.

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ARTICLE #2

Journal of Biodiversity and Environmental Sciences (**accepted and printed,** Original version in the annex)

Dytiscidae, Noteridae and Hydrophilidae of semi-arid rivers and reservoirs in Burkina Faso: species inventory, diversity and ecological notes

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Abstract

Conservation of biodiversity is a major concern due to climate change and pressure from human activities. Knowledge of aquatic insects and their ecology particularly in West Africa is still scanty and fragmented. To fill this gap, we investigated the structure of aquatic beetle assemblages from 18 lentic and lotic water bodies (rivers and reservoirs) in Burkina Faso, and we explored their relationship with environmental variables. Following a multi-habitat sampling approach, all beetles were collected with a hand net, and identified using taxonomic manuals and keys. A total of 11 species of Noteridae in three genera, 27 species of Dytiscidae in 10 genera and 22 species of Hydrophilidae in nine genera were identified in this study. Among these, 24 species are here reported for the first time from Burkina Faso. The species richness was high in the reservoirs with habitats dominated by "water lettuce" *Pistia stratiotes* (species diversity, sd=11.0±9.00 Shannon Wiener index, H=1.79±1.1) and "reed beds" (species diversity, sd=7.63±1.78; Shannon Wiener index, H=1.51±0.25) in comparison with rivers (sd=2.25±0.75; H=0.35±0.20). The results also showed that the species richness is significantly correlated with vegetation cover. Thus, emergend water plants were found to be the main factor influencing beetles species richness. The observed relationship between vegetation cover and beetle richness may provide significant insights that motivate future efforts in research as well as in habitat conservation measures in West Africa.

Keywords: Aquatic beetles, vegetation, semi-arid, Burkina Faso, West Africa.

Introduction

Freshwater Beetles constitute the second largest aquatic insect order with about 13,500 species world-wide (Balian et al., 2008; Jäch and Balke, 2008). The Afrotropical Region harbours about 2,700 (Jäch and Balke, 2008). There are, however, major information gaps concerning the knowledge of the invertebrate fauna of West Africa. Several recent surveys carried out in Sierra Leone and Côte d'Ivoire have led to the discovery of many new species, especially in the order of Coleoptera (Franciscolo, 1982, 1994; Castellini, 1990; Reintjes, 2004). Aquatic beetles are abundant in many types of aquatic habitats, which are most sensitive to human alterations (García-Criado et al., 1999). Therefore, aquatic beetles are used as bioindicators of water quality and global climate changes as an outcome of human activities (acidification, climate warming, etc.) and serve as "early warning" organisms detecting possible disturbances and changes in ecosystems (Valladares et al., 1994; Collinson et al., 1995; Moreno et al., 1997; Shepherd and Chapman, 1998; Sánchez et al., 2006; Guareschi et al., 2012). However, rapid population growth, constant desertification and climate change have raised a major concern over the management and conservation of the biological integrity in tropical areas. Thus, the Coleoptera became suitable for assessing the conservation status of the sites (Ribera, 2000; Abellán et al., 2005; Segura et al., 2007). However, ecological studies on Afrotropical beetles are scarce (Reintjes, 2004). As a consequence, our knowledge on the ecology of this group of insects in semi-arid areas is extremely poor, despite the current research initiatives. Among West African countries Côte d'Ivoire has received considerable attention from taxonomists working on Noteridae and Dysticidae (Reintjes, 2004). In Burkina Faso only few studies on aquatic insects have focused on beetles (Guenda, 1996; Kaboré et al., 2016). Our study revealed numerous new species records for Burkina Faso. Qualitative data on beetles were collected in several parts of the country, covering different types of waterbodies. Consequently the key aims of this work were 1) to identify and determine the diversity of Dytiscidae, Noteridae and Hydrophilidae in the sampling area and 2) to test and discuss their response to environmental variables.

Materials and Methods

Study areas

Burkina Faso is located in the heart of West Africa in the Sub-Saharan region (12° 16′ N, 2° 4′W; Fig. 2). The climate is tropical semi-arid with maximal temperatures varying between 24 and 40°C (Ly et al., 2013). Evapotranspiration is between 1,700 to 2,400 mm per year exceeding annual precipitation which ranges from 400 to 1,200 mm (MECV, 2007). The study was undertaken in two local river catchments: the Nakanbé, White Volta catchment (size 70,000 km²), in the central part of Burkina Faso and the Mouhoun, Black Volta catchment (92,000 km²), in the western part of the country. A total of six investigation areas (i.e. Koubri, Nazinga Game Ranch, Bagré, Boura, Sourou and Ouagadougou) termed by Koblinger and Trauner (2013) were chosen, and 18 investigation sites composed of different habitats were sampled (Tab. 1). These habitats were mainly dominated by the following plants species (Fig.1a-d) water lilies "*Nymphea* sp.", Reeds "Typha", water lettuce "*Pistia stratiotes*" and water hyacinth "*Eichhornia crassipes*".

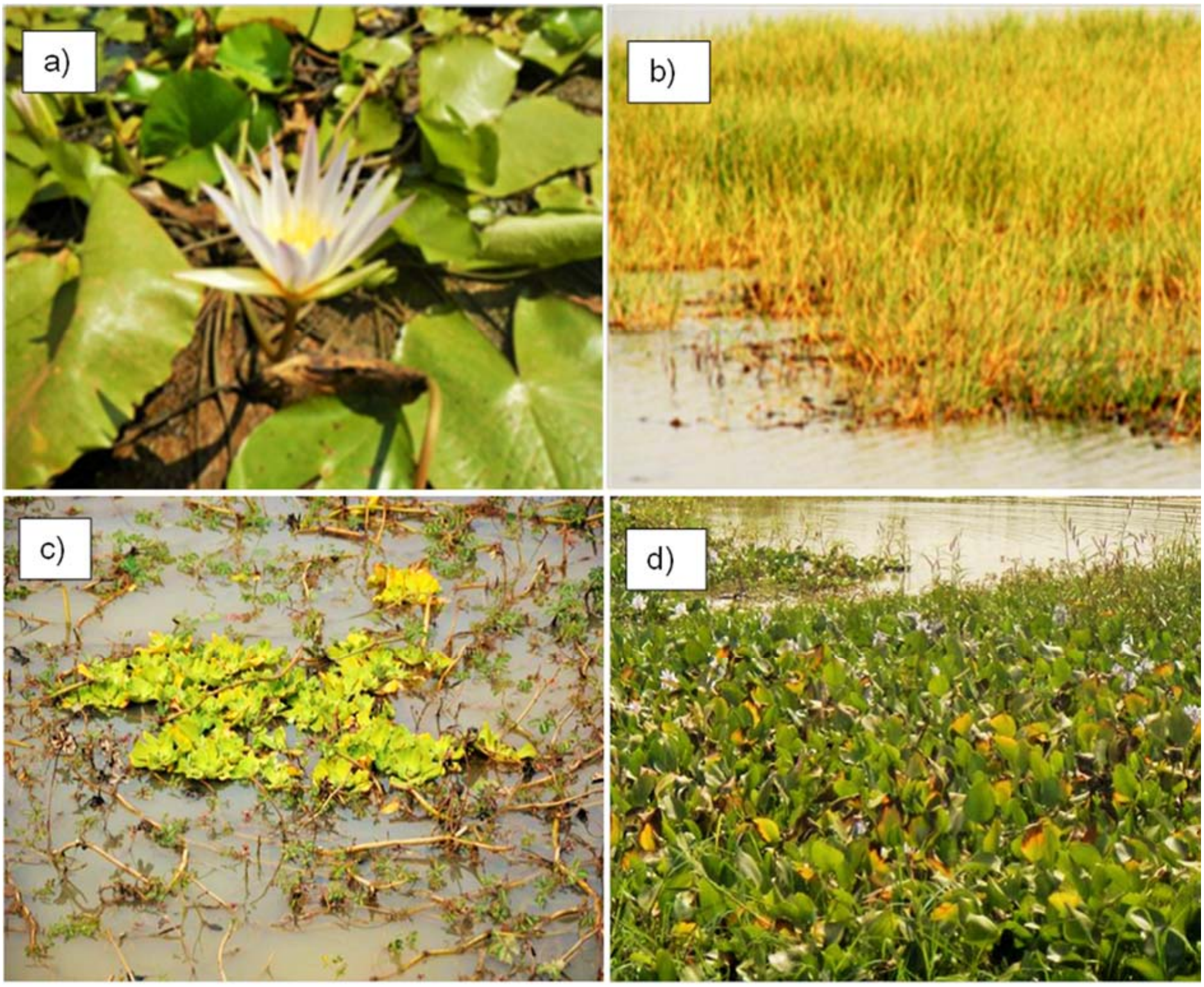

Figure 1 Different types of habitats encountered in the investigation sites. a= water lilies "*Nymphea* sp.", b =Reeds "Typha", c= water lettuce "*Pistia stratiotes*"., d= Water hyacinth "*Eichhornia crassipes.*"

The area of Koubri was described by Melcher et al. (2012) and Koblinger and Trauner (2013) and is located 40 km southeast of Ouagadougou along highway N5. It is located between the latitudes 12° 07' 35.88N & 12° 07' 05.15''N and the longitudes 01° 16' 57.37''W & 01° 26'

08.72''W (WGS84; Google Earth). The sampled reservoirs, Napagbtenga, Poedgo Segda and Noungou, were constructed between 1962 and 1988; their sizes range from five to 430 ha (Ouédraogo, 2010; Melcher et al., 2012).

The Game Ranch of Nazinga is a protected area located in the south of Burkina Faso, 60 km south of the city Ouagadougou close to the border to Ghana. The area is located between the latitudes 11º 03' 04''N & 11º 12' 47''N and the longitudes 01º 23' 25''W & 01º 43'00''W. Eleven (11) reservoirs (18 to 60 ha of large) were created between 1981 and 1987 to improve water supply for wild animals during dry seasons. Among these waterbodies, two reservoirs (Talanga, Kozougou) and one free flowing section (Bodjéro) were sampled (Fig. 1a & 1c).

The Bagré hydro-agricultural dam is located on the Nakanbé River in a large valley about 150 km south-east from Ouagadougou (Villanueva et al., 2006). The large reservoir was created in 1994. The total size and volume have a seasonal fluctuation between 100 and 196 km² and repectively between 0.88 and 1.7 billions m³, whereas the maximum flow rate at the dam is up to 1,500 m³/s (Villanueva et al., 2006).

The Boura reservoir (11° 02' N, 2° 30' W) described by Sanogo et al. (2014) was built in a tributary of Mouhoun River to supply water and an integrated irrigation system for the local population. There are about 40,000 inhabitants in 22 villages close to the dam. Aquatic plants in the reservoir are dominated by "Reeds" (Fig. 1b). This water body was built in 1983 by the National Office of Dams and Irrigation (ONBI) and has a maximum capacity of 4.2 million m³.

The Sourou valley described by Dianou et al. (2011) and Rosillon et al. (2012) is located in the north-west of Burkina Faso. The Sourou River takes its source in Mali. The Sourou valley is especially known for its hydro agricultural installations following the erection of dam valves at the junction of Sourou and Mouhoun rivers in 1984. The construction of the dam increased significantly the stock of water in the Sourou River (600 million m²) through the valley. This availability of water prompted the creation of irrigation systems, hence the importance of the Sourou valley in agricultural production. Three sampling sites (Nianssan 1 and 2, Gouran) have been selected in this area.

The area of Ouagadougou (12° 21′ 26''N, 1° 32′ 7''W), the capital of Burkina Faso, including the sampling sites of Kougri, Bissiga and Korsimoro. This area is characterizd by the tropical climate with average monthly temperatures ranging from 24.5 to 28.8°C. Locally, the mean annual precipitation in Ouagadougou is 740 mm and shows an average of 66 rainy days between April and October (INSD, 2006a). All Bissiga, Korsimoro and Kougri sites are characterized by sediment bed (e.g. mud, sand, fine gravel), whereas the site in Ouagadougou, Reservoir number two, with an area of 226 ha is impacted by *Echhornia* (Fig. 1d).

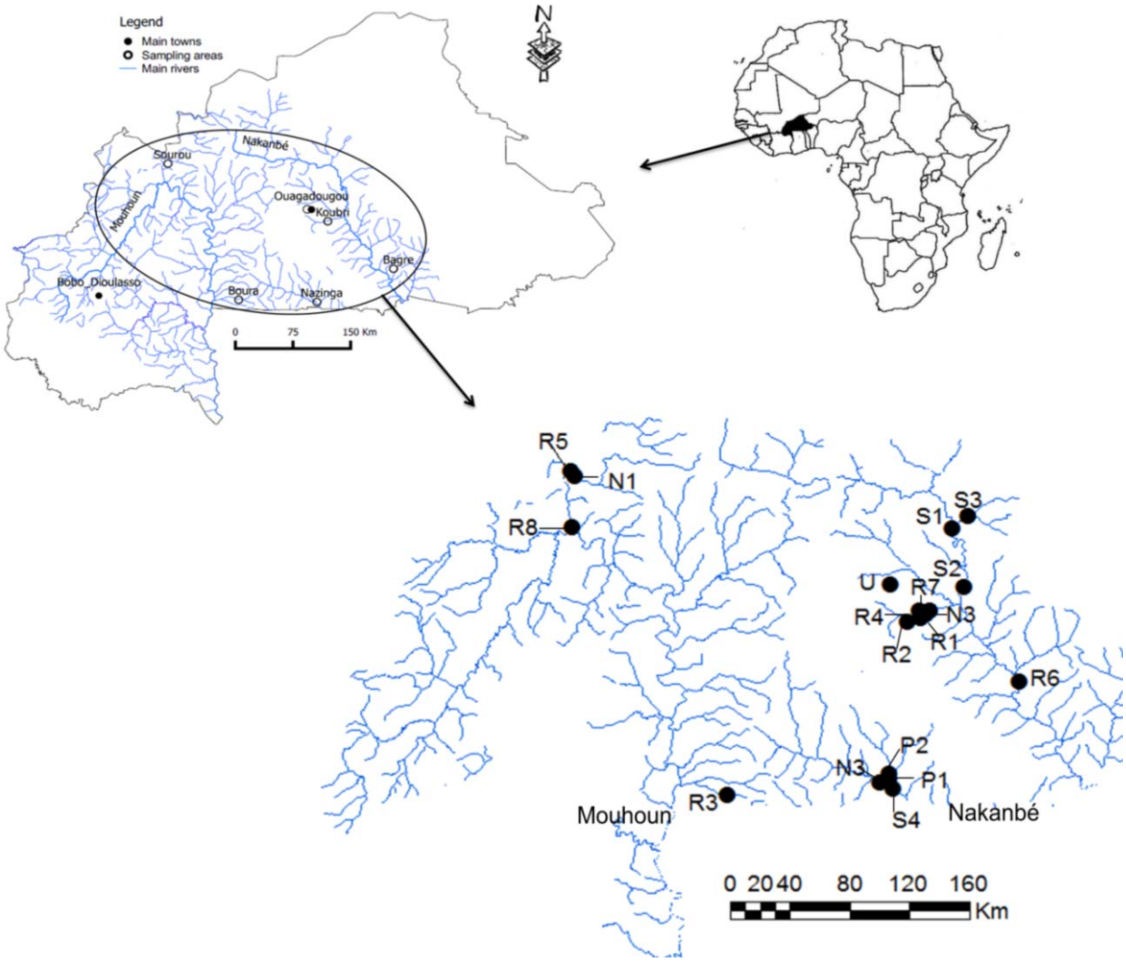

Figure 2 Map of Burkina Faso in West africa showing the location of sampling areas and sampled sites.

Table 1 Summury of the sampling sites charasteristics. Abreviation: W_Tem= water temperature, Cond= Conductivity, DO= desolved oxygen, R= reed, s= sediment, E= *Eichhornia*, N= *Nymphea*, P= *Pistia*

Sites names	Codes	Sampling areas	Latitude (WGS84)	Longitude (N)	Altitude (m)	W_Temp (ºC)	pH	Cond (µS/cm)	DO (mg/l)	Water types	habitat covers	Sampling periods
Napagbtenga	R1	Koubri	12.22111	-1.34901	281	33.5	7.01	50.2	6.2	Reservoir	R	October
Poedgo	R2	Koubri	12.18033	-1.34221	279	32	7	49.8	7.3	Reservoir	R	October
Boura	R3	Boura	11.04914	-2.49964	274	32.7	6.75	52	4.1	Reservoir	R	August
Segda	R4	Koubri	12.22352	-1.28419	276	32	7.17	86.5	4.8	Broken reservoir	R	October
Gouran	R5	Sourou	13.08113	-3.42472	257	34	5.7	98.3	5.7	Irrigation channel	R	October
Beguédo	R6	Bagré	11.774	-0.74651	236	28.8	8	53.5	6.2	Reservoir	R	November
Wedbila	R7	Koubri	12.14926	-1.41818	287	7.95	7.95	58.4	7.4	Reservoir	R	October
Nianssan2	R8	Sourou	12.75463	-3.43418	253	35.4	8.3	127	4.5	Irrigation channel	R	October
Korsimoro	S1	Ouaga	12.82348	-1.04957	282	28.4	7.8	91	4.2	Irrigation channel	S	October
Kougri	S2	Ouaga	12.37811	-1.08075	258	35	7.2	55.6	3.9	River	S	October
Bissiga	S3	Ouaga	12.75083	-1.15056	273	35	7.2	55.6	3.9	River	S	October
Bodjéro	S4	Nazinga	11.09143	-1.50459	269	24.4	8.6	67.8	6.6	River	S	December

Table 1 (continued).

Sites names	Codes	Sampling areas	Latitude (WGS84)	Longitude (N)	Altitude (m)	W_Temp (ºC)	pH	Cond (µS/cm)	DO (mg/l)	Water types	habitat covers	Sampling periods
Kozougou	P1	Nazinga	11.1543	-1.531	273	25.3	8.5	81.2	3.7	Reservoir	P	December
Naguio	P2	Nazinga	11.12763	-1.5834	275	24.4	8.6	67.8	6.6	Reservoir	P	December
Nianssan1	N1	Sourou	13.11078	-3.44917	253	32.6	7.9	196.5	2.4	Irrigation channel	NR	October
Noungou	N2	Koubri	12.20314	-1.30492	278	30.3	7.4	45.1	6.7	Reservoir	NP	October
Talanga	N3	Nazinga	11.18935	-1.52651	275	27.6	7.45	83.6	6.8	Reservoir	N	December
Ouaga	U	Ouaga	12.3909	-1.524	290	27.4	7.2	406	1.65	Reservoir	E	October

Analysis of environmental variables

In order to assess the potential predictors of aquatic beetles from Burkina Faso, beetles and keys environmental descriptors data were collected in 2012 during four months in each of the 18 study sites. The Physico-chemical parameters of water including the temperature (°C), the conductivity (µS/cm), the dissolved oxygen (mg/l) and pH were measured with field multimeters (WTW340I) between eight am and three pm. The dominant habitat plants types (>5% of total area) were qualitatively registered for each site.

Beetle sampling and identification

All beetles were sampled with a hand net (rectangular opening: 25 cm x 25 cm, mesh size: 500 µm), following the multi-habitat sampling approach by (Moog, 2007). A pooled sample, consisting of 20 sampling units, was taken from each habitat or mixed samples on each sampling site. Samples were fixed in 90% ethanol, sieved in the laboratory and the animals have been sorted using a microscope. All taxa have been identified to the lowest taxonomic level as possible. The organisms were identified based on taxonomic manuals and keys by Tachet et al. (2003) and Lévêque and Durand (1981). Additionally direct taxonomic expert support was given by experts from the Natural History Museum Vienna following the most recent revisions. A total collection of all species cited here is deposited and stored in the Natural History Museum Vienna, Austria.

Data analysis

All statistical analyses were performed with the SPSS software (version 21). The typology of investigation sites according to their environmental descriptors was assessed by cluster analysis (Ward method, Ecludian distance). Tested variables were z-standardized prior to the analysis. The relationship between beetles richness and environmental variables was explored using Spearman correlation. The total species richness was simply taken as a count of the number of taxa present in each investigation site. The Shannon Wiener (H') diversity index was expressed following the formulae below, where where p_i is the proportion of individuals found in the ith taxon, S is the number of species in samples.

$$H' = -\sum_{i=1}^{s} p_i \ln p_i \qquad [1]$$

Results

Environmental descriptors

In general most of the study sites had warm water temperatures (mean 30.5 °C), a neutral pH (mean of 7.55), low conductivity (mean 100 µS/cm) and sufficient oxygen contents (Tab. 2). The sampling sites in Ouagadougou receive domestic and industrial wastes. Consequently, high conductivity (406 µS/cm) and low disolved oxygen (1.65 mg/l) were measured in this area.

Table 2 Summary statistics of physico-chemical measured in field for the 18 sampling sites. Abbreviation: Max= Maximum, Min= Minimum. Parenthesis indicate the standar deviation

Physico-chemical descriptors	All sites (n=18)		
	Mean	Min	Max
Temperature	30.43 (±3.52)	24.4	35.4
Conductivity (µS/cm)	97.72 (±85.01)	45.1	406
Disolved Oxygen (mg/l)	5.19 (±1.68)	1.65	7.4
pH	7.55 (±0.73)	6	9

Beetles species richness in Burkina Faso

A high diversity of water beetles with at total of 60 species was identified in this study. Most of them (27 species) belonged to the family Dytiscidae, followed by Hydrophilidae family (22 species) and 11 species of Noteridae were also recorded. Interestingly 24 species (40% of total species) were recorded for the first time for Burkina Faso (Tab. 3). The most frequently occurring species *Helochares* (*Hydrobaticus*) sp. (55%) and *Hydrovatus aristidis* (28%) belong to Hydrophilidae and Dytiscidae families, respectively.

Table 3 List of aquatic main family beetles and species recorded in Burkina Faso waterbodies. (*) first time recorded species in Burkina Faso

Families	Species	Acronyms	R1	R2	R3	R4	R5	R6	R7	R8	S1	S2	S3	S4	P1	P2	N1	N2	N3	U
	Bidessus sharpi Régimbart, 1895*	Bid.sh	+	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Bidessus sodalis Guignot, 1939	Bid.so	-	-	-	-	-	-	+	-	-	-	-	-	-	+	-	+	-	-
	Cybister gschwendtneri Guignot, 1935	Cyb.gs	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydroglyphus dakarensis (Régimbart, 1895)	Hydr.da	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
	Hydrovatus aristidis Leprieur, 1879*	Hyv.ar	+	-	+	+	-	-	-	+	-	-	-	-	-	-	-	-	-	+
	Hydrovatus brevipilis Guignot, 1942*	Hyv.br	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Hydrovatus balneator Guignot, 1954	Hyv.pu	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-		
Dytiscidae	*Hydrovatus cribratus* Sharp, 1882*	Hyv.cr	-	-	-	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-
	Hydrovatus facetus Guignot, 1942*	Hyv.fr	-	+	-	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus parvulus Régimbart, 1900	Hyv.pa	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus pictulus Sharp, 1882*	Hyv.ci	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus regimbarti Zimmermann,1919	Hyv.sp	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus suturalis Bilardo & Pederzani, 1978*	Hyv.sa	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus villiersi Guignot, 1955*	Hyv.vi	-	-	-	+	-	+	+	-	-	-	-	-	-	+	-	-	-	-
	Hyphydrus impressus Klug, 1833*	Hyp.im	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3 (continued).

Families	*Species*	Acronyms	R1	R2	R3	R4	R5	R6	R7	R8	S1	S2	S3	S4	P1	P2	N1	N2	N3	U
	Laccophilus occidentalis Biström et al., 2015*	Lac. oc	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Laccophilus inobservatus Biström et al., 2015*	Lac.in	+	-	-	-	+	-	-	-	+	-	-	-	-	+	-	-	-	-
	Laccophilus? *modestus* Régimbart, 1895	Lac.mo	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
	Laccophilus restrictus (Sharp, 1882)*	Lac.re	-	-	-	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Laccophilus sp. (cf. *restrictus* Sharp, 1882)	Lac.ver	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Laccophilus taeniolatus Régimbart, 1889 *	Lac.ta	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Leiodytes sp.	Lei.sp	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Methles sp.	Met.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Platydytes coarctaticollis (Régimbart, 1894)*	Plat.co	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	+	-	-
	Pseuduvarus vitticollis (Boheman, 1848)	Pse.vi	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Yola cuspis Bilardo & Pederzani, 1979	Yol.cu	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
	Yola nigrosignata Régimbart, 1895*	Yol.nig	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Canthydrus imitator Guignot, 1942*	Can.im	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Noteridae	*Canthydrus koppi* Wehncke, 1883*	Can.ko	+	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
	Canthydrus xanthinus Régimbart, 1895	Can xa.	-	+	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-

Table 3 (continued).

Families	*Species*	Acronyms	R1	R2	R3	R4	R5	R6	R7	R8	S1	S2	S3	S4	P1	P2	N1	N2	N3	U
	Hydrocanthus colini Zimmermann, 1926	Can.col	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Hydrocanthus sp. (near *grandis*)	Can.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Synchortus simplex Sharp, 1882*	Syn.sp	-	-	+	+	-	-	-	+	-	-	-	-	-	+	-	-	-	-
	Synchortus sp. 1	Syn.sp1	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Synchortus sp. 2	Syn.sp2	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Neohydrocoptus koppi Wehncke, 1883*	Neoh.ko	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Neohydrocoptus uellensis (Guignot, 1953)*	Neoh.sp1	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Neohydrocoptus sp.	Neoh.sp2	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
Hydrophilidae	*Allocotocerus* sp.	All.sp	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-
	Amphiops sp. 1	Am.sp1	-	-	+	-	-	-	-	+	-	-	+	-	-	-	-	-	-	-
	Amphiops sp. 2	Am.sp2	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Amphiops sp. 3	Am.sp3	-	-	-	-	+	-	+	-	-	-	-	-	-	-	-	-	-	+
	Amphiops sp. 4	Am.sp4	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Amphiops sp. 5	Am.sp5	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Berosus sp.	Ber.sp	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Coelostoma sp.	Coe. sp	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-

Table 3 (continued).

Families	*Species*	Acronyms	R1	R2	R3	R4	R5	R6	R7	R8	S1	S2	S3	S4	P1	P2	N1	N2	N3	U
	Enochrus sp. 1	Eno.sp1	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Enochrus sp. 2	Eno.sp2	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Enochrus sp. 3	Eno.sp3	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Helochares (*Hydrobaticus*) sp. 1	Hel.sp1	-	-	-	+	-	-	-	-	-	-	-	-	-	-	+	-	-	-
	Helochares (*Hydrobaticus*) sp. 2	Hel.sp2	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
	Helochares (*Hydrobaticus*) sp. 3	Hel.sp3	+	-	-	-	-	+	+	+	+	-	+	-	-	-	+	-	-	+
	Helochares (*Hydrobaticus*) sp. 4	Hel.sp4	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-
	Helochares (*Hydrobaticus*) sp. 5	Hel.sp5	-	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-
	Helochares dilutus (Erichson, 1843)*	Hel.di	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-
	Helochares longipalpis (Murray, 1859)*	Hel.lo	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Helochares pallens MacLeay, 1825*	Helo.pa	+	-	+	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-
	Helochares sp.	Hel.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Paracymus chalceus Régimbart, 1903*	Par.ch	+	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-
	Regimbartia sp.	Reg.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	+	+	-	-	-
Total number of species			**10**	**3**	**11**	**16**	**4**	**2**	**8**	**15**	**5**	**1**	**2**	**1**	**3**	**20**	**4**	**2**	**1**	**3**

Beetles structure in different waterbodies types

The Cluster analysis shows a clear discrimination of investigation sites into five main habitat types (C1 to C5) and their attached cluster groups, which are based on physico-chemical parameters and habitats (Fig. 3). Cluster C1 (R1-R8) indicate semi-aquatic vegetation sites "Reed beds" with water temperature values above 31 ºC. In contrast C2 (S1-S4) are characterized by a high sediment load. C3 (P1-P2) reservoirs covered by aquatic plant "*Pistia*" and having a rather high pH of about 8.55. Finally C4 (N1-N3) is composed of mixed habitat with "*Nymphea*", and C5 (E) represents the single reservoir of *Eichhornia* habitat found in the Ouagadougou

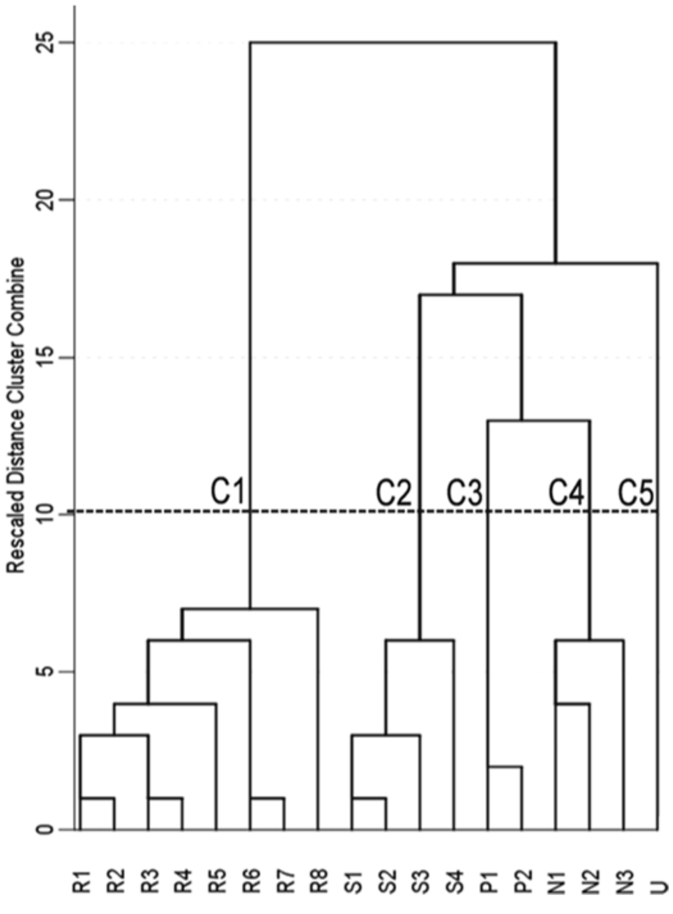

Figure 3 Hierarchical classification of investigation sites related to their environment variables. Four main groups were shown by dendrogram, which C1=R1-R8 indicates "Reed Beds" sites ; C2=S1-S4 sites with sediment substrate, C3 (P1-P2)=reservoirs with *Pistia* cover, and C4 (N1-N3) mixed habitats with *Nymphea*, C5=Ouagadougou reservoirs with *Eichhornia*).

In relation to the identified clusters (groups), some differences related to habitats were observed in the beetle species diversity (Fig. 4). Thus, the species richness per site was high in the reversoirs (C1) coverved by "Reed beds" (mean species diversity, sd=7.63±1.78; mean

Shannon Wiener index, H'=1.55±0.26), and in (C3) covered by *Pistia* (P) (sd=11.00±9.00; H'=1.79±1.10), while rivers with a high sediment load (C2) were dominated by mud, sand, fine gravel (sd=1.75±0.48; H=0.35±0.20) show low species diversity.

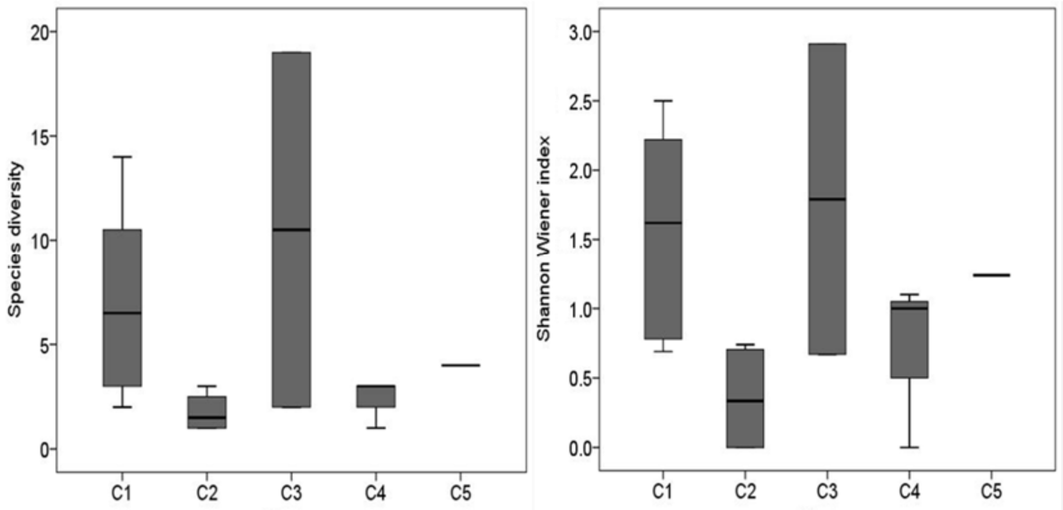

Figure 4 Boxplot showing variation in species richness in diffrent waterbodies types. C1 indicates "Reed Beds" sites ; C2= sites with sediment substrate, C3=reservoirs with *Pistia* cover, and C4 mixed habitats with *Nymphea* and C5=Ouagadougou reservoirs with *Eichhornia*.

Relationship between beetles richness and environmental variables

The relationship between beetles communities and environmental parameters (Table 4) using Spearman correlation test indicated that conductance was positively correlated with the *Eichhornia* cover ($r=0.43$, $p> 0.05$) , and the Hydrophilidae richness ($r=0.37$, $p> 0.05$), and negatively correlated with disolved oxygen ($r=0.63$, $p<0.05$). The water temperature showed negative correlation with *Pistia* cover ($r=0.59$, $p<0.05$). The significant possitive correlations were detected between the pH and *Pistia* cover ($r=0.59$, $p<0.05$). The Reeds cover were significantly correlated to Noteridae richness ($r=0.74$, $p<0.05$, positive); while the button sediment and *Nymphea* cover is negatively correlated to beetles richness.

Table 4 Correlation matrix of physico-chemical parameters and biological index marked with an asterisk (*) = statistically singnificant (p<0.05)

	W_Temp	pH	Cond	DO	W_Eich	W_Reed	W_Nymp	W_Pistia	B_Sed
W_Temperature	1								
pH	-0.449	1							
Conductivity	-0.021	0.227	1						
Disolved Oxygen	-0.02	-0.01	-0.626*	1					
W_ *Eichhornia*	-0.31	-0.09	0.433	-0.43	1				
W_Reed	0.341	-0.5	-0.22	0.31	-0.286	1			
W_*Nymphea*	0.227	0.227	-0.09	0.182	-0.105	-0.419	1		
W_*Pistia*	-0.592*	0.591*	0.045	-0.05	-0.105	-0.419	-0.154	1	
B_Sediment	0.091	-0.02	0.045	-0.27	-0.105	-0.419	-0.154	-0.154	1
Hydrophilidae_taxa	0.103	0.363	0.366	-0.39	0.223	-0.175	-0.023	0.28	-0.16
Dytiscidae_ taxa	-0.262	0.015	-0.08	0.401	-0.127	0.317	-0.209	0.046	-0.21
Noteridae_ taxa	0.17	-0.34	-0.06	0.335	-0.265	0.744*	-0.388	-0.121	-0.39

Discussion

The total number of beetles species (60) collected in this study is higher than the only earlier study conducted by Guenda (1985) who reported 22 species. The big difference can be explained by the diverse types of habitats sampled; nevertheless the species richness of Noteridae (11) and Dytiscidae (27) found in this project is lower compared to those reported from other West African river catchments. Reintjes (2004) and Vondel (2005) reported 95 species of Dytiscidae and 120 species of Noteridae in other Western Africa subregion. The lower number of our species could be due to the fact that: (1) the vast majority of our samples were taken in one river basin, particulary in the central part of Burkina Faso. Extending the sampling to more habitats covering the entire climate gradient from north to south may increase the number of species in these groups; (2) our study covers only four months (i.e. December, October, November and August). Species may be missed, if they are not prevalent in the study area within this period. Despite these restrictions, among the Hydrophilidae four species are newly recorded for Burkina Faso: *Helochares dilutus*, *H. longipalpis* , *H. pallens* *and Paracymus chalceus*. These four species are widely distributed in western, southern, eastern and central Africa (*Helochares longipalpis*, *H. pallens, Paracymus chalceus*). One species (*Helochares dilutus*) does not occur in northern Africa (Fikáček *et al*., 2012). Out of the 15 species of Dysticidae (*Bidessus sharpi, Hydrovatus aristidis, H. brevipilis, H. cribratus, H. cinctulus, H. villiersi, Laccophilus occidentalis, L. inobservatus, L. taeniolatus, L. restrictus Platydytes coarctaticollis*) newly recorded in Burkina Faso, seven species (*Hydrovatus aristidis, H. brevipilis, H. villiers, H. cribratus, Laccophilus restrictus, Yola nigrosignata, Platydytes coarctaticollis, Bidessus sharpi*) are widely distributed in Sub-Saharan Africa (Nilsson *et al*., 1995; Nilsson, 2001; Reintjes, 2004; Vondel, 2005; Bilardo and Rocchi, 2011, 2013; Nilsson, 2013) and two (*Laccophilus occidentalis, L. inobservatus*) are newly reported species (Biström *et al*., 2015) . Based on our knowledge three species of Noteridae (*Canthydrus imitator*, *C. koppi* and *Synchortus simplex, Neohydrocoptus koppi, N. uellensis*) are widely distributed in West Africa, southern, Central and eastern Africa (Reintjes, 2004; Vondel, 2005; Guignot, 1959b; Medler, 1980; Bruneau and Legros, 1963; Legros, 1972; Bilardo and Pederzani, 1978; Nilsson, 2006) even though some of them are found in North Africa (Guignot, 1955a). The current knowledge of the water beetle fauna of Burkina Faso is limited and very scattered, a species list for the country is not available. In West Africa, especially in landlocked areas such as Burkina Faso, the species lists are still fragmentary and certainly far from being complete (Reintjes, 2004).

This study revelead that several parameters determine the water beetles distribution. The vegetation cover and the type of water body are the most important. We provide evidence that the water body type and aquatic plants have much stronger influence on beetles species distribution than physico-chemical variables. The physico-chemical variables do not reveal the distribution of beetle species, but they showed the impact of human activies on water bodies. In this study, we found high conductuctivity and lower oxygen contents associated with the invasive *Eichhornia*. These values for the urban reservoir could be water pollution indicators in line with others works such as Benetti and Garrido (2010) and Pérez-Bilbao et al. (2014). The variation in species richness offers a good basis for the distinction between beetle communities in reservoirs with different types of aquatic plants ("Reeds", *Nymphea* and *Pistia*) and rivers. The Shannon Wiener diversity index and species richness were higher in reservoir sites than rivers. Our findings corroborate several previous ecological aquatic beetle studies which proved that water bodies and type of habitat were determinant variables for various beetle communities (Batzer and Wissinger, 1996; Reintjes, 2004; Gioria et al., 2010; Epele and Archangelsky, 2012; Silva and Henry, 2013; Sanogo et al., 2014). Despite that, the conductivity, pH values and dissolved oxygen values were quite variable among sites, they did not seem to affect water beetle distributions. Such finding is in line with previous studies which pointed out that these variables had little or no influence on aquatic beetles (Arnott et al., 2006; Pérez-Bilbao et al., 2014). The vegetation cover is a key factor driving assemblage compositions, since many water beetles typical of lentic waters only need a few weeks to colonize temporary sites (Picazo et al., 2012). The previous study conducted by Reintjes (2004) showed that the rainfall was highly predictive of beetles taxa richness because they colonized aquatic plants during rainy season. In addition, insects are dependent on the litter deposited as vegetation dies and chemicals secreted by the plants, may also play a role in determining which plants support the greatest numbers and higher diversity of beetles (Fairchild et al., 2000; Menetrey et al., 2005). Gong *et* al. (2000), Albertoni et al. (2007), Silva and Henry (2013) and Koblinger and Trauner (2013) also demonstrated that the macrophytes enhance environmental heterogeneity, provide protection from predators and improve food condition for benthic macroinvertebrates. The negative association between *Nymphea* and beetles species was observed here. Taniguchi found in 2003 that the faunal differences in abundance and especially species richness between different water plants are related to leaf morphology and surface area of the plant that may have an important effect on a plant's ability to support beetles, which agrees with our results. This findings is also reflected in our results, as the structure-poor floating leaves (e.g. the anoxia in the centre of leaves) revealed by far the lowest faunal abundance and taxa richness of some sites. The water body type and vegetation cover are the most important variables in depicting the ecological health of beetles species in semi arid areas.

Conclusion

The knowledge about the water beetle fauna of the West African landlocked countries is limited and very scattered. In this report 24 species are recorded from Burkina Faso for the first time, while thirty six (36) species were already listed by other authors. In West Africa the distribution of aquatic beetles are mostly influenced the by the water body and aquatic plant types. This first result proves the high beetle diversity in Burkina Faso and motivates for further efforts in research as well as effective habitat conservation measures.

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ARTICLE #3

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Using macroinvertebrates for ecosystem health assessment in semi-arid streams of Burkina Faso.

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Abstract

Efficient monitoring tools for the assessment of stream ecosystem response to urbanisation and agricultural land use are urgently needed but still lacking in West Africa. This study investigated taxonomic and functional composition of macroinvertebrate communities at 29 sites, each exhibiting one of four disturbance levels ('protected', 'extensive agriculture', 'intensive agriculture' and 'urban') in Burkina Faso and explored their potential for bioassessment. We recorded a total of 100 taxa belonging to 58 families, with the highest richness (16.9 taxa per site) observed in the sites with intensive agriculture and lowest (3.4 taxa) in urban sites. We found a gradual decrease of sensitive EPT taxa and of collector-filterers feeding guild between protected, agricultural and urban sites accompanied by an increase in the relative abundance of tolerant dipteran taxa. Measures of overall taxonomic richness and diversity were mostly efficient in detecting the high impoverishment of the urban sites, while FFG ratios did not deliver consistent results. Finaly, all four land-use types were successfully distinguished by identifying indicator taxa through hierarchical clustering and IndVal index. This work produced an unprecedented faunal inventory of Burkina Faso streams and laid the basis for the development of urgently needed stream assessment tools.

Keywords: West Africa, bioindication, macroinvertebrates, taxonomic, freshwater, land use.

Introduction

Inland waters are natural resources with high economic, cultural, aesthetic, scientific and educational value (Dudgeon et al., 2006). Their conservation and management are critical to the interests of all nations and governments, and thorough scientific knowledge of these valuable ecosystems is an essential prerequisite for developing reliable management tools applicable locally. This is especially true for many tropical countries, where growing exposure to human activities such as intensive agriculture, dumping of untreated waste and wastewater from settlements and industries cause ongoing degradation of river ecosystems (Dudgeon, 1992; Malmqvist & Rundle, 2002; Strayer & Dudgeon, 2010).

Burkina Faso is a landlocked Sahelian country located in the heart of West Africa, which has to cope with chronic water scarcity and episodes of severe drought. A high population growth rate and rising demand to achieve food security and sustain rural livehoods have resulted in intensification of agriculture (rice and irrigated crop farming, fishing, livestock farming) and accelerating urbanization in Burkina Faso (UNEP-GEF, 2010). As a consequence, the exposure of surface waters to pesticides, chemical fertilizers and pollutants as well as physical modification of the riparian areas (due to e.g. erosion by cattle movement or construction of embankments) have increased over the years, posing a threat to aquatic organisms and water quality (Smith et al., 2009; Melcher et al., 2012).

High human pressure on freshwater ecosystems combined with increasing climatic variability result in an urgent need for tools for the ecological health assessment, essential for prioritizing conservation efforts and efficient management of streams in fast-developing countries such as Burkina Faso. Across the world, stream assessment has previously been based on several biological metrics, that often reflect some combination of parameters: species richness and/or composition, tolerance or functional composition of the aquatic communities. These metrics have proven sensitive to specific impairments to different degrees (Resh, 1995; Barbour et al., 1999). Furthermore, as an alternative, multivariate statistical procedures for community analysis have also been increasingly applied. Based on the latter, methods allowing for instance the identification of indicator species and species assemblages have been developed (Dufrêne & Legendre, 1997).

Due to their important role in freshwater ecosystems (Covich et al.,1999), high diversity as well as the ease and low cost of sampling, benthic macroinvertebrates, have often been used for biomonitoring purposes (Bonada et al., 2006; Carter et al., 2006; Verdonschot & Moog, 2006). The abundance and distribution of benthic macroinvertebrates have been shown to respond to differences in local environmental conditions both in the temperate and in the tropical zones (Jacobsen 1998; Usseglio-Polatera et al., 2000; Kouadio et al., 2008). As a result, macroinvertebrate-based indices have become an important tool for monitoring programs and aquatic ecosystem management, widely implemented in many countries across the world (Barbour et al., 1999; Moog et al., 1999; Carter et al., 2006; Watson & Dallas, 2013). Several authors have, however, emphasized the importance of testing assessment metrics locally (Barbour et al., 1999; Marzin, 2013).

Current knowledge of benthic macroinvertebrates in African rivers is very fragmentary, and documented efforts for development of macroinvertebrate-based monitoring programs have been largely restricted to few countries, primarily in East (Masese et al., 2009a; Masese et al., 2009b; Raburu et al., 2009; Kilonzo et al., 2013) and South Africa (Watson & Dallas, 2013). In West Africa, some studies have delivered assessments of the macroinvertebrate fauna (Yaméogo et al., 2001; Aggrey-Fynn et al., 2011 in Ghana; Camara et al., 2012 and Edia et al., 2013 in Ivory Coast) and some initial efforts have tested the relationship of their diversity to pollution (Thorne & Williams, 1997 in Ghana; Vinson et al., 2008 in Gabon). Similarly, in spite of several previous studies conducted on freshwater macroinvertebrates, an extensive inventory of macroinvertebrate fauna has been missing in Burkina Faso, as many of the former were restricted to narrow advances in the taxonomy of macroinvertebrate communities in a single river (Guenda, 1996) and in some reservoirs (Kabré et al., 2002; Sanogo et al., 2014). These did not provide the quantitative or distributional analysis needed to develop indicators based on benthic macroinvertebrates.

This study was the first to aim for a large-scale assessment of benthic macroinvertebrate fauna in Burkina Faso with the ultimate goal of investigating the potential use of macroinvertebrate-based metrics for the monitoring of the effects of different floodplain land use types. Twenty-nine study sites of different floodplain land use: from protected areas to those used agriculturally and urban areas - were selected. Several analytical approaches were applied to estimate the sensitivity to floodplain land use change of single macroinvertebrate species as well as of functional and taxonomic composition of the community as a whole.

The key objectives of this work were to: 1) identify and determine the diversity and distribution of benthic macroinvertebrate taxa in streams of Burkina Faso; 2) test their response to changes in floodplain land use (intensification of agriculture, urbanization) using different metrics related to taxonomic and functional composition; 3) identify and potential indicator taxa for the four main floodplain land use types (protected areas, extensive and intensive agriculture and urban areas).

Materials and Methods

Study area

Burkina Faso is located in the central part of West Africa (09°20' & 15°03' N; 02°20' E 05°03' W). The climate is tropical and semi-arid with mean temperatures varying between 24 and 35°C (Ouédraogo & Amyot, 2013; Ly et al., 2013) and is characterized by a north-south gradient in rainfall distribution, with high variability in both time and space. Most of Burkina Faso lies within the West Soudanian ecoregion. The Lower Soudanian is characterized by the rainy season of 6 to 8 months (April to October) and an annual precipitation from 1000 to 1200 mm (Sirima et al., 2009). Gallery forests and savanna with trees or shrubs are mainly observed in this area, dominated by *Isoberlinia doka* (Craib & Stapf) or *Isoberlinia. dalzielii* (Craib & Stapf) and *Guibourtia coppalifera* (Bennett) (Guinko, 1984; Guinko, 1997). The Upper Soudanian (US) has a shorter rainy season (June to October) and annual precipitation ranging between 750 to 1000 mm (Thiombiano et al., 2006). Rivers in Upper Soudanian dry out during the dry season. The zone shows a regular rustic savanna and exhibits the highest human densities. Evapotranspiration rates and river flows are extremely sensitive to rainfall variations.

Three main catchments consistute the hydrological network of Burkina Faso: Niger, Comoé and Volta. The study was undertaken in rivers belonging to two of them: the Nakanbé (Volta catchment) in the central part of Burkina Faso (area of 70,000 km²), the Mouhoun (Volta catchment) in the west (92,000 km²) and the Comoé in south-west part of Burkina Faso (18,000 km²). Eleven, four and fourteen sampling sites were selected in these rivers, respectively (Table 1). Floodplain land use types were defined visually by means of field protocol and Google earth map in a standardized manner using land buffer of 1 km diameter (Stranzl, 2014). Field trips were undertaken to confirm the accuracy of this assessment by expert judgment. Sampling sites fell within a continuum ranging from low to very high intensity of agriculture and human population density in the floodplain area. Four major categories of floodplain use were defined and codified as: 'protected' (P), 'extensive agriculture' (EA), 'intensive agriculture' (IA), 'urban' (U) (Fig. 1).

'Protected' areas (n=3) were exposed overall to the lowest levels of human impact and were characterized by a nearly negligible population density (isolated households) and preserved natural riparian vegetation. These were created with the goal of protecting and conserving the wildlife for limited hunting and fishing and maintaining the ecological integrity of the area (Sawadogo, 2006; Ouédraogo, 2010). Sites categorized as 'extensive agriculture' (n=4) were exposed to a low level of human impact, influenced primarily by grazing (pasture) and waste from scattered houses or little villages. In the areas of 'intensive agriculture', the floodplain area was typically converted to land for crop farming. Thus the most destructive change in the riparian zone of these streams was due to the radical modification of the vegetation and application of pesticides and fertilizers, while settlements were limited to single villages. Within this category, streams in areas of three different agricultural uses were sampled: a) irrigated vegetables and seasonal crops farming (n=4); b) fisheries and mixed agriculture (n=4); c) rice farming (n=9). Finally, the sites of the fourth category, defined as "urban" (n=5) were situated in highly urbanized areas (including the areas of major cities of Ouagadougou and Bobo-Dioulasso with population densities of up to 80 inhabitants per km^2 at the study sites), exposed to industrial and other uses including inputs of domestic wastes and river channel engineering.

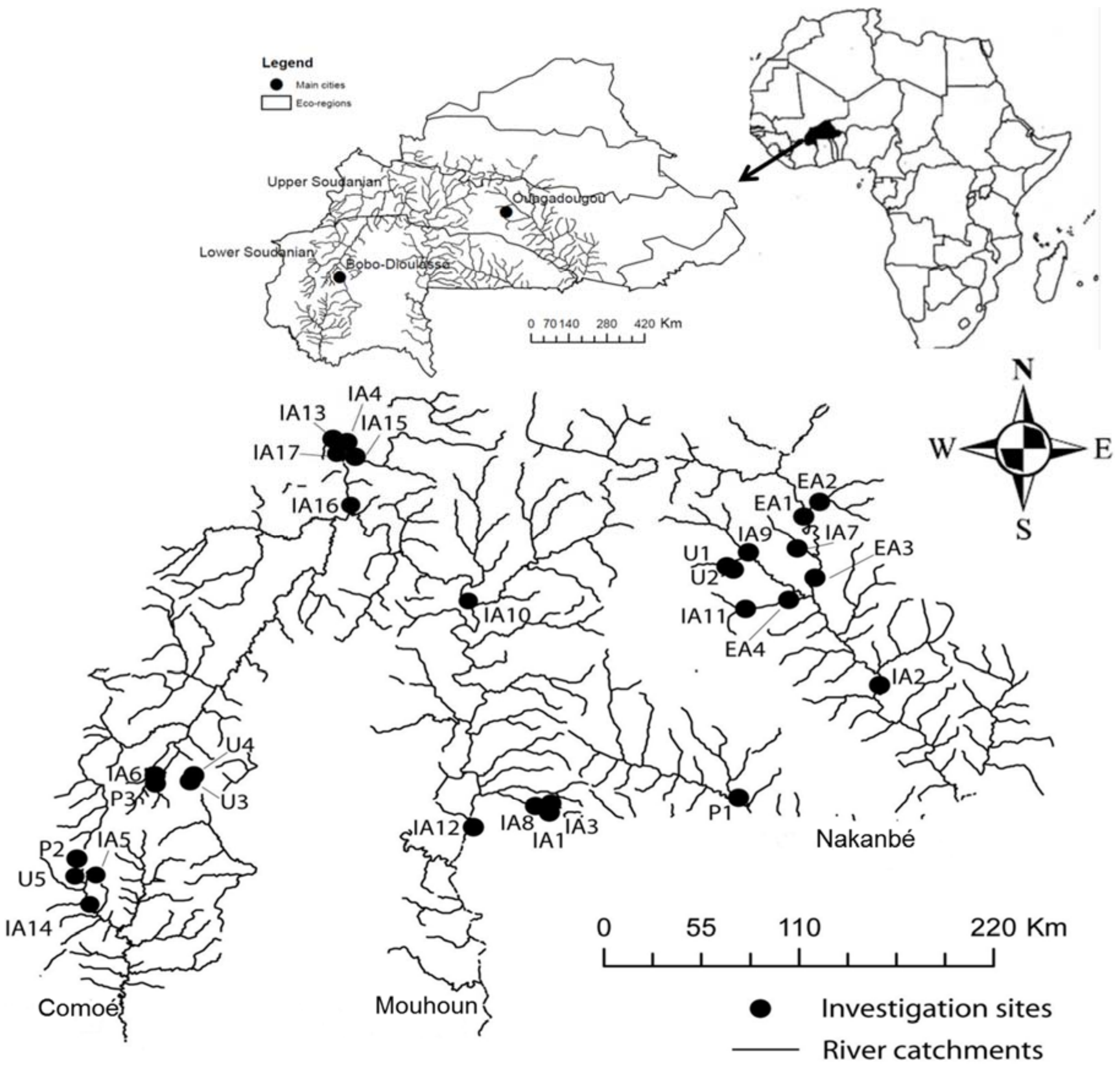

Figure 1 Map of Burkina Faso showing the study area. Circles indicate the sampling sites (after Guinko, 1984). While some of the catchments are shared with other countries, only the part flowing on the territory of Burkina Faso is shown.

Environmental condition of sites

Environmental parameters that are likely to be affected by different floodplain land use types were recorded in the field in order to characterize each sampling site. Temperature (°C), conductivity (µS/cm), dissolved oxygen (mg/l) and pH were measured with field multimeters (WTW340I) between eight and three pm before the macroinvertebrate sampling. The area occupied by the dominant habitat type (>5% of total area) was estimated for each site. The substrate types were recorded according to the categorization based on the grain size (Moog, 2007)

Table 1 Environmental characteristics of the 29 study sites belonging to the river catchments Comoe, Mouhoun and Nakanbé. Dominant habitats are classified as following: megalithal (bedrock) ~size >40 cm, mesolithal (cobbles) ~6 cm< size ≤ 20cm, psammal (sand) ~0.06 mm< size ≤ 2mm, pelal (mud) ~ size> 0.06 mm. P= Protected areas; EA= low agricultural disturbance sites; IA= intensive agriculture sites (IAa = irrigated vegetables and seasonal crops farming; IAb = fisheries and mixed agriculture; IAc = rice farming seasonal crops farming); U = urbanisation, industrial and other uses. LS = Lower Soudanian ecoregion; US = Upper Soudanian ecoregion

Dominant land use	Site	River catchment	Eco-geographic type	Altitude (m)	Water Temperature (°C)	pH	Conductivity (µs/cm)	Oxygen (mg/l)	TDS (mg/l	Water depth (m)	Water velocity (m/s)	Wetted width (m)	Dominant habitat
P1	Bodjéro	Nakanbé	LS	269	24.4	8.6	67.8	6.6	43.4	0.41	0.35	6.65	Mesolithal
P2	Karfiguela	Comoé	LS	320	25.8	10.8	27.5	5.6	17.6	0.52	1	5.6	Megalithal/CPOM
P3	Guingette	Mouhoun	LS	359	29.9	10.19	45.2	6.3	28.9	0.76	0.89	7.3	Mesolithal/Macrophytes
EA1	Bissiga	Nakanbé	US	273	35	7.2	55.6	3.9	35.6	0.53	0.25	29.75	Pelal/Alkal
EA2	Korsimoro	Nakanbé	US	282	28.4	7.8	91	4.2	58.2	0.25	0.02	1.6	Akal
EA3	Kougri	Nakanbé	US	258	31.6	7.64	88.6	4.6	56.7	0.75	0.06	25.56	Pelal
EA4	Peele	Nakanbé	US	261	30.8	7.27	103.2	7.5	66	0.6	0	8.45	Pelal
IA1c	Boura	Mouhoun	LS	269	32.7	6.75	52	4.1	33.3	0.85	0.44	3.75	Techtolithal/Macrophyte
IA2c	Niango	Nakanbé	US	238	23.3	7.55	108.6	4.5	69.5	0.72	0.05	11.2	Pelal
IA3c	Poweri2	Mohoun	LS	277	30.2	7.15	86.5	5.2	55.3	0.75	0.05	7.4	Psammal/Woody debris
IA4c	DI	Mouhoun	US	253	33.9	7.8	158.8	4.7	102	0.55	0.1	na	Pelal/ Macrophyte
IA5c	Tengrela1	Comoé	LS	280	25.3	9.7	28.2	6.6	18	0.62	0.42	6.7	Pelal
IA6a	Kou	Mouhoun	LS	340	26.9	10.7	70.1	4.7	44.8	0.25	0.21	10.9	Psammal/woody debris
IA7a	Nagreogo	Nakanbé	US	273	30.2	6.7	46	3.2	29.4	0.25	0.38	1.7	Akal
IA8a	Poweri1	Mouhoun	LS	280	27.9	7.54	67.6	4.4	43.3	0.6	0.05	6	Psammal /Woody debris
IA9a	Loumbila	Nakanbé	US	281	32.6	7.6	48.2	4.1	30.8	0.45	0.1	8.56	Pelal
IA10b	Bromo	Mouhoun	LS	250	32.6	7.6	88.2	4.1	56.4	0.75	0.6	14.6	Microlithal
IA11b	Segda	Nakanbé	US	276	32	7.17	86.5	4.8	55.3	0.5	0.02	4.7	Pelal/Wood debris
IA12b	Ouéssa	Mohoun	LS	236	30.6	6.9	52.1	7.8	33.3	0.78	0.9	29	Pelal/ Macrophyte
IA13b	Tomaîle	Mouhoun	US	250	31.8	6.5	106	4.2	67.8	0.85	0.26	na	Pelal/ Macrophyte
IA14c	Djaraba	Comoé	LS	263	26.5	9.3	79	5.1	50.5	0.87	0.9	4.5	Mesolithal/Macrophyte
IA15c	Gouran	Mouhoun	US	257	34	5.7	98.3	5.7	62.9	0.45	0.2	2.5	Pelal/ Macrophyte
IA16c	Nianssan2	Mouhoun	US	253	32.6	7.9	196.5	2.4	126	0.6	0.1	5	Pelal/ Macrophyte
IA17c	Nianssan1	Mouhoun	US	253	35.4	8.3	127	4.5	81.3	0.49	0.01	3.2	Pelal/ Macrophyte
U1	Ouaga2	Nakanbé	US	292	31	7.62	353	1.5	226	0.3	0.1	1	Pelal/FPOM
U3	Houet1	Mouhoun	LS	420	25.5	11.6	385	3	246	0.2	0.1	1.85	Megalithal /FPOM
U4	Houet2	Mouhoun	LS	401	32.6	7	460	2.5	294	0.32	0.1	2.5	Pelal/CPOM
U5	Tengrela2	Comoé	LS	305	28.8	10.2	158.7	1.6	102	0.2	0	2.1	Concrete/FPOM
U2	Ouaga1	Nakanbé	US	295	35.4	11.27	491	10.7	314	0.15	0.01	11.5	Concrete/FPOM

Benthic macroinvertebrates: sampling and taxonomy

Benthic macroinvertebrates were collected between July and December 2012, during the period when surface water flow was evident at all study sites. Benthic macroinvertebrates were sampled with a hand net (rectangular opening: 25 cm x 25 cm, mesh size: 500 µm). Following the multi-habitat sampling approach (Moog, 2007), a pooled sample, consisting of 20 sampling units, was taken from all habitat types occupying a minimum of 5% or more of the study area. The number of sampling units allocated to each habitat type was proportional to the areal coverage of the latter. Samples were fixed in 90% ethanol and sieved in the laboratory. The animals were sorted under a microscope and identified to the lowest taxonomic level possible based on taxonomic manuals and keys (Lévêque & Durand, 1981; Merritt & Cummins, 1984; Tachet et al., 2003) and with direct taxonomic expert support (see acknowledgements). The assignment of functional feeding groups was done by expert consensus following Moog (1995), Masese et al. (2014) and Merritt & Cummins (2006).

Data analysis

A constrained canonical correspondance analysis using function *rda* in the package *vegan* (Oksanen et al., 2013) in R (R Core Team, 2013) was conducted on the key chemical and physical variables quantitatively assessed in the study sites to identify major gradients in environmental differences between the sites. Tested variables (mean water temperature, conductivity, oxygen concentration and flow velocity) were z-standardized prior to the analysis. The statistical significance of differences between the land use categories was tested by the 999 permutation procedure and an adjusted R^2 was computed as an unbiased estimate of the explained variance.

To test for the support of the selected site categories in the macroinvertebrate data we first conducted hierarchical cluster analysis using PC-OrRD software (McCune & Mefford, 2006). This analysis was conducted on a presence-absence matrix including all sites and taxa (Flexible Beta value of -0.250, distance measure: Bray–Curtis similarity). The significance of cluster support was assessed with a nonparametric test: Multi-Response Permutation Procedures (Mielke, 1991).

We then used a multimetric approach selecting several indices reflecting either richness, taxonomic or functional composition of the community as suggested for identification of potential indicators of ecosystem health (Resh, 1995; Thorne & Williams, 1997; Barbour et al., 1999). Taxa richness (total number of taxa), percentage of EPT

(Ephemeroptera, Plecoptera and Trichoptera) taxa, percentage of tolerant dipteran insects (following Hauer & Lamberti, 2006; Mandaville, 2002) and Shannon-Wiener diversity index (H'), were calculated for each of the four main land use types. The Shannon-Wiener Diversity index was expressed following the formula [1], where p_i is the proportion of individuals found in the i^{th} taxon, S is the number of taxa in the samples.

$$H' = -\sum_{i=1}^{s} p_i ln p_i \qquad [1]$$

We conducted a Kruskal–Wallis test (SPSS, version 21) followed by multiple comparison testto compare the metrics of richness, diversity and composition between different floodplain land use types.

Furth ermore we also calculated three functional feeding ratios frequently used as indicators of some key functional attributes of stream ecosystem from Vannote et al. (1980) and Merritt & Cummins (2006): 1) 'scrapers to (shredders + total collectors)' ratio (P/R) corresponding to the autotrophy to heterotrophy index; 2) 'shredders to total collectors' ratio corresponding to CPOM to FPOM index and 3) 'predators to prey' ratio reflecting possible top-dow control by predators. The values acquired were compared to threshold ratios applied for both temperate and tropical streams (Cummins et al., 2005; Masese al., 2014). P/R >0.75 would indicate predominantely autotrophic production. CPOM/FPOM > 0.25 would indicate a functioning riparian zone. A predator-prey ratio between 0.1 and 0.2 corresponds to a normally expected predator-to-prey balance.

Finally, we tested for the potential of the macroinvertebrate taxa detected in our study to serve as bioindicators for the four land use types investigated. The Indicator Value (IndVal) was computed for each taxon *i* and category of sites *j* as:

$$IndVal_{ij} = A_{ij} \times B_{ij} \times 100 \qquad [2]$$

where A_{ij} = N $individuals_{ij}$ / N $individuals_i$ is a measure of specificity based on abundance values whereas B_{ij} = N $sites_{ij}$ / N $sites_i$ is a measure of fidelity computed from presence data (Dufrêne & Legendre, 1997). Indicator values range from 0 (no indication) to 100 (perfect indication), the latter corresponding to a case, when all individuals of a taxon are found in a single category of samples and this taxon occurs in all samples of that category (Nahmani & Rossi, 2003). This method permits identification of taxa characteristic of groups of samples defined at different levels of the hierarchical clustering (Dufrêne & Legendre, 1997; Nahmani & Rossi, 2003). Importantly, the same taxon may have different indicator values depending on the level of grouping considered (Nahmani & Rossi, 2003). We used the randomization test to evaluate the statistical significance of each IndVal value for a given taxon with a standard permutation test at the statistical level of 5%. Indicator taxa with IndVal values above the threshold of 25% were retained for the final selection (Nahmani & Rossi, 2003).

Results

Environmental parameters assessed in the study sites varied in relation to floodplain land use (Table 1; see annexe Fig. A1). Sites in protected areas were generally colder and higher in pH and flow velocity (Table 1; see annexe Fig. A1). We could not clearly distinguish between the sites of intensive and extensive agriculture based on the measured environmental variables (see annexe Fig. A1). In contrast, urban sites distinctly differed from all other land use types through enhanced conductivity (up to 490 µSm/cm) and lower width and depth of the water channel (Fig. A1). Canonical correspondence analysis showed a significant association of the variation in environmental parameters with site categories (Annexe $p=0.001$, for RDA1 and $p=0.02$ for RDA2; $R_{adj}^2=0.23$; Tables A1 – A3 in Electronic Supplementary material).

Taxonomic richness of benthic stream macroinvertebrates in Burkina Faso

A high diversity of benthic macroinvertebrates with a total of 100 taxa was recorded in this study (Table A4). A large majority of these taxa (74) belonged to fourty-seven families from eight orders of insects: Ephemeroptera, Odonata, Diptera, Coleoptera, Trichoptera, Lepidoptera, Plecoptera and Hemiptera. The remaining 26 taxa belonged to eleven families of Decapoda (Crustacea), Gastropoda and Bivalvia (Mollusca). Coleoptera (26 taxa of 8 families) represented the most diversified order of insects with the following dominant families: Hydrophilidae (7), Dytiscidae (7), Elmidae (5) and the Noteridae (3). They were followed by Diptera: 15 taxa belonging to nine families. Within non-insect fauna we found a notable diversity in molluscs, with several species previously not reported for Burkina Faso. Thus, a total of 14 taxa of gastropods composed of Bulinidae (5), Thiaridae (3), Planorbidae (2), Ampullariidae (2), Lymnaeidae (1) and the Viviparidae (1) were observed. In the

Bivalvia class, three families including six species were recorded. Finally, we also found two species of freshwater shrimps belonging to the families Palaemonidae and Atyidae.

The most frequently occurring taxa we found belonged to insects and were chironomid subfamilies Chironomini and Tanypodinae, damselflies of the genus *Coenagrion sp.* and mayflies of the genus *Baetis* sp. (the first taxon was present at 90%, the following three taxa at >50% of sampling sites). Several rare taxa potentially sensitive to anthropogenic stress were only found in the protected areas: *Notonurus* sp., *Euthraulus* sp., and *Tricorythus* sp. (Ephemeroptera), *Chlorocypha* sp. (Odonata), *Neoperla spio* (Plecoptera), *Chimarra pétri*, and *Leptocerus* sp. (Trichoptera).

Floodplain land use effects on taxonomic and functional composition of the macroinvertebrate community

Cluster analysis based on macroinvertebrate community composition strongly supported our categorization of the sites based on the floodplain land use (Multi-Response Permutation Procedures, A = 0.197 , p < 0.0001; Fig. 2). Identified clusters at the lowest hierarchical level corresponded to the four categories formulated based on the qualitative assessment of floodplain land use: "protected" (C1), "extensive agriculture" (C2), "intensive agriculture" (C3) and "urban" (C4). P and EA (C1 and C2 respectively) were then clustered together (C5) suggesting their similarity, while urban areas were found most distinct from all the rest of the sites (C4).

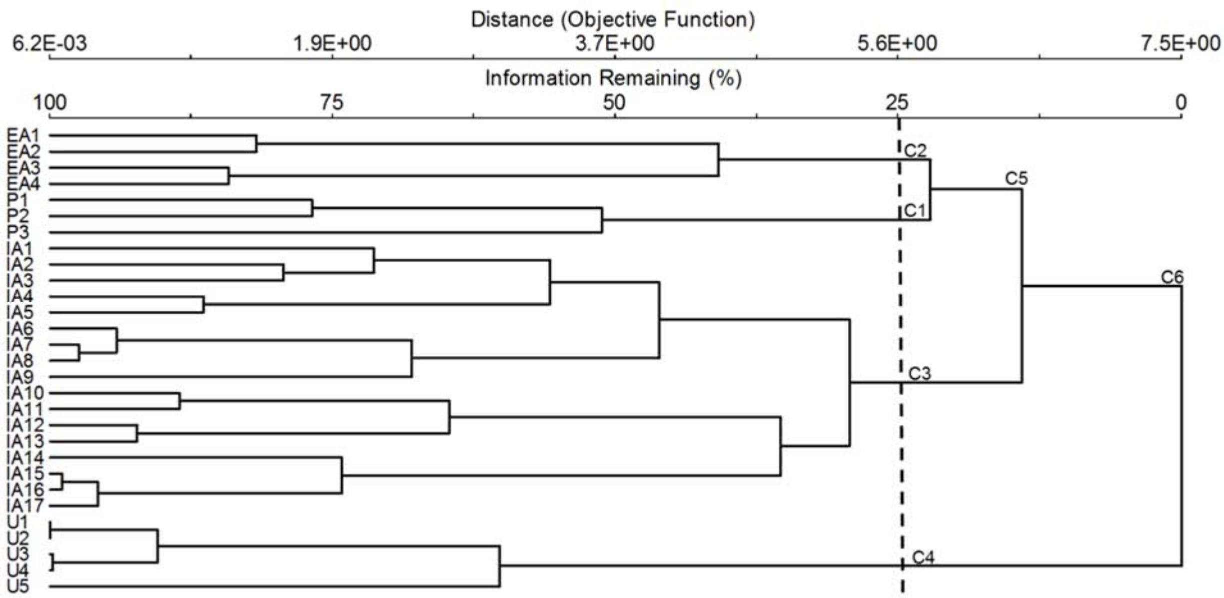

Figure 2 Hierarchical clustering analysis of 29 sites (based on Flexible Beta linkage, value of -0.250, distance measure Bray–Curtis) using a presence/absence matrix. Site names correspond to the different land use types. P = protected area; EA = extensive *agriculture; U = urban sites*

Some distinct differences relative to the floodplain land use types could be observed in the taxonomic and functional community composition of benthic macroinvertebrates (see Tables 2 and A4 for details). Interestingly, different metrics of diversity, composition and tolerance of macroinvertebrate community tested here varied in their sensitivity towards land use change (Fig. 3). The overall taxonomic richness, the percentage of tolerant dipteran taxa (Chironomidae, Syrphidae, Culcidae and Psychodidae), and the Shannon-Wiener Diversity index showed a capacity of clearly detecting only the highest level of benthic fauna impoverishment as found in urban sites (Figs. 3a, c and d). Thus mean overall taxonomic richness per site was highest in sites with intensive agriculture (17.6 ± SE 2.2 taxa per site) and reached a minimum of 3.4 ± SE 0.5 taxa per site in urban sites (Fig. 3). Shannon-Wiener diversity index also tended to increase in agricultural sites, reaching on average 1.9 ± SE 0.2 in the IA sites and then dropped to a minimum of 0.8 ± 0.1 in urban sites. Finally, the fraction of tolerant dipteran taxa consisting of Chironomidae, Syrphidae, Culcidae and Psychodidae showed an increase from average 5.8 ± SE 3.6 % in protected sites to 31.0 ± 6.9 in the agricultural (IA) and 91.6 ± SE 6.3% in the urban streams.

By contrast, metrics based on EPT taxa showed higher sensitivity to different levels of environmental degradation and a clear decrease across the gradient of human impact intensity in terms of land use. Such sensitivity allows one to distinguish between extensive and intensive agriculture (Fig. 3c; Fig. A2). EPT taxa (primarily Baetidae and Hydropsychidae) were highly dominant in the protected areas, making up on average 57.3 ± 14.6% of total abundance (Fig. 3c). While both types of agricultural streams were distinguished by quite high overall taxonomic richness (Fig. 3a), the EPT taxa were represented in EA and IA by a small number of taxa constituting a very low fraction of the overall abundance (18.4 ± SE 7.7% in EA; 3.9 ± SE 1.5% in IA; Fig. 3b) and were completely absent from urban sites.

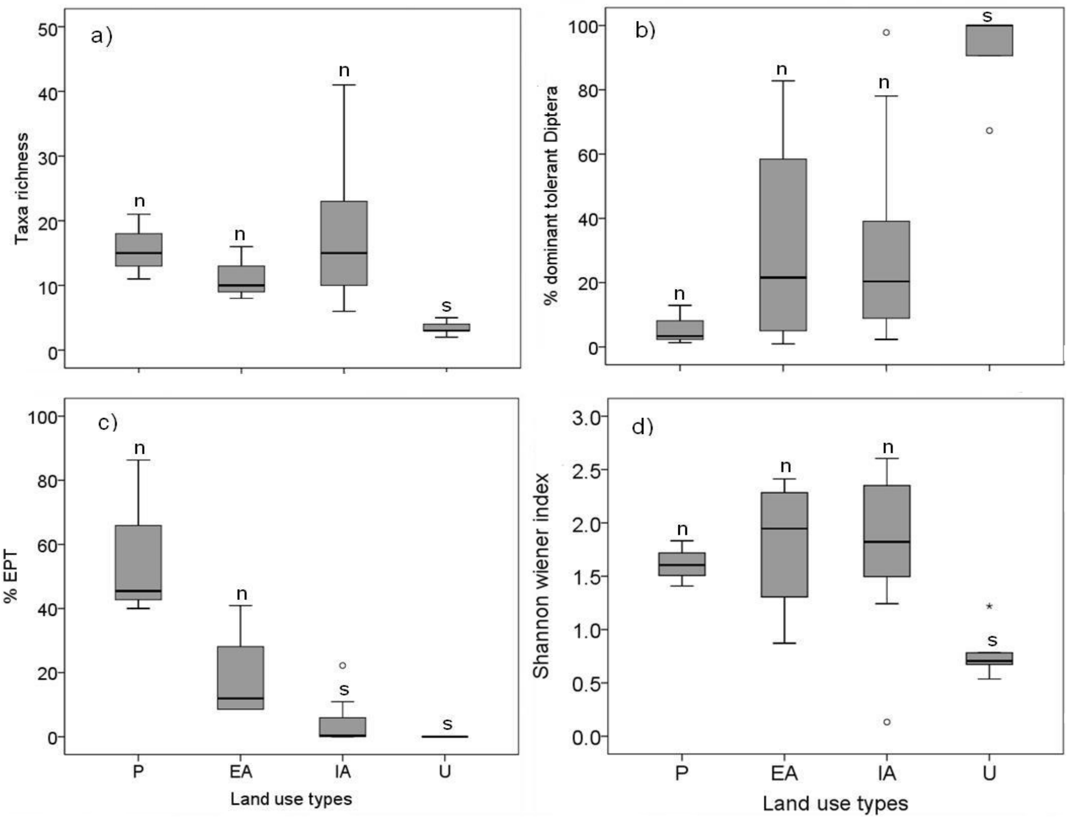

Figure 3 Boxplot showing variation of taxa richness (a), percentages of dominant tolerant dipterans (b), Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa (c) and Shannon Wiener index (d) in different land use types. P: Protected areas; EA: extensive agriculture sites; IA: intensive agriculture sites and U: urban sites. Median value is shown in each box; vertical bars correspond to the minimum and maximum values. Letters above boxplots indicate statistical significance of differences between land use types (pairwise multiple comparison tests): only respective pairs with different alphabetical letters differ significantly ($p < 0.05$).

Variation in the relative abundance of functional feeding groups too reflected differences between the land use types (Fig. 4b). A total of 5,927 individuals (98.5% of the total organisms) were categorized within different functional feeding groups in this study (Table A5). Six major functional feeding groups were recognized (Fig. 4b): predators, shredders, collector-gatherers, collector-filterers, scrapers and parasites. Along a gradient of increasing land use intensity collector-gatherers became a progressively dominant group, covering a range between 38.5% in protected sites and 93.3% in urban sites. Collector-filterers showed the opposite trend, decreasing from an average 49.1% of communities in protected areas to 32.3% in the IA sites, 19.1% in the EA sites and total absence in the urban sites. Scrapers were particularly abundant (19.7%) in the sites with extensive agriculture, and the fraction of predators was at least 3 times higher in agricultural streams compared to 'urban' and 'protected' sites. Shredders were remarkably rare, never reaching over 1% of the total abundance and showing highest fraction in the' protected' sites.

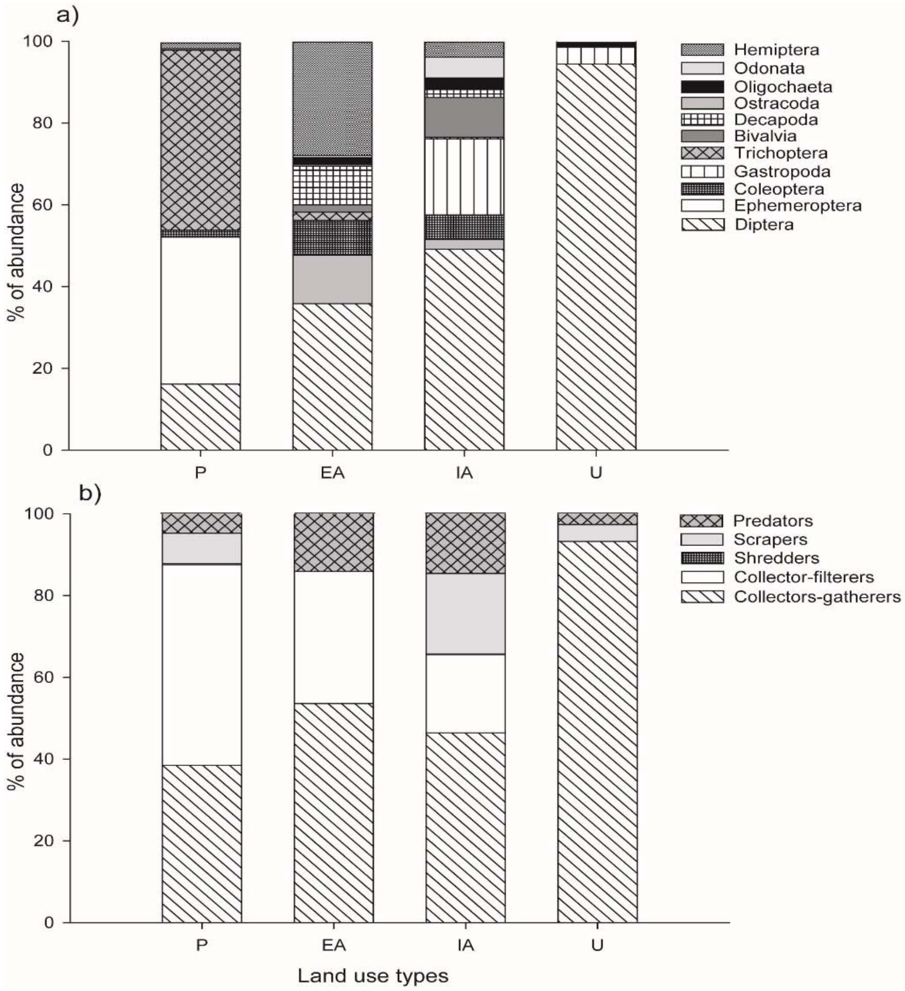

Figure 4 Overall benthic community composition of key functional feeding benthic community: a) taxonomic groups; b) functional feeding groups. P = protected area; EA = extensive agriculture; IA = intensive agriculture; U = urban sites

P/R ratios calculated based on these estimates indicated that most investigated sites were characterised by a rather high level of heterotrophy and thus an overdependence of stream food web on allochtonous material (Table 2). Surprisingly, sites with intensive agriculture with a P/R ratio were close to the expected value of heterotrophy of 0.75, while the P/R ratio was below 0.25 in both protected and urban sites, and scrapers were completely absent in EA sites. CPOM/FPOM ratios were well below 0.1 across all site categories (Table 2) suggesting a very poorly functioning of riparian zone and a deficit of coarse particulate organic matter. Finally, the top-down-control index indicated a relative abundance of predators within expected range in protected sites, a lower than normal abundance of predators in urban sites and a relative overabundance of predators in sites affected by agricultural use (Table 2).

Table 2 Mean values of stream ecosystem attributes derived from ratios of macroinvertebrate functional feeding groups of Burkina Faso' rivers. Standard errors are reported in parenthesis

Land use categories	P/R ratio	CPOM/FPOM ratio	Top down predator control ratio
P	0.25 (0.23)	0.02 (0.01)	0.15 (0.12)
EA	0 (0)	0 (0)	0.42 (0.22)
IA	0.73 (0.42)	0.002 (0.001)	0.44 (0.11)
U	0.10 (0.1)	0 (0)	0.03 (0.03)

Indicator taxa for different land use types

Different land use types could also be distinguished based on calculation of IndVal conducted at different levels of hierarchical clustering, which revealed several taxa as candidate bioindicators in Burkina Faso streams (Fig. 5). Protected areas were distinguished by a particularly high number (20) of potential indicator taxa, of which seven had significant indicator values and included several EPT taxa (*Euthraulus* sp., *Chimarra* sp., *Leptocerus* sp., *Chematopsyche* sp.; Fig. 5). A freshwater shrimp (*Macrobranchium* sp.) and a backswimmer (*Notonecta* sp.) were found to be characteristic of sites with extensive agricultural activities (out of 9 candidate bioindicators). Together with an elmid beetle taxon (*Pseudomacronychus* sp.), *Macrobranchium* sp., also distinguished the combined cluster of protected areas and extensive agriculture from the sites with intensive agriculture (Fig. 5). We found 12 potential indicator taxa for the IA sites of which three (*Appassus* sp., *Coenagrion* sp. and Chironominae) had significant indicator values. These same three taxa as well as *Baetis* sp. were found to be distinguishing the "P+IA+EA" cluster from urban sites. Finally, the analysis identified four taxa indicative of the urban sites of which only *Chironomus* sp. ("red *Chironomus*") had a significant IndVal value (Fig. 5).

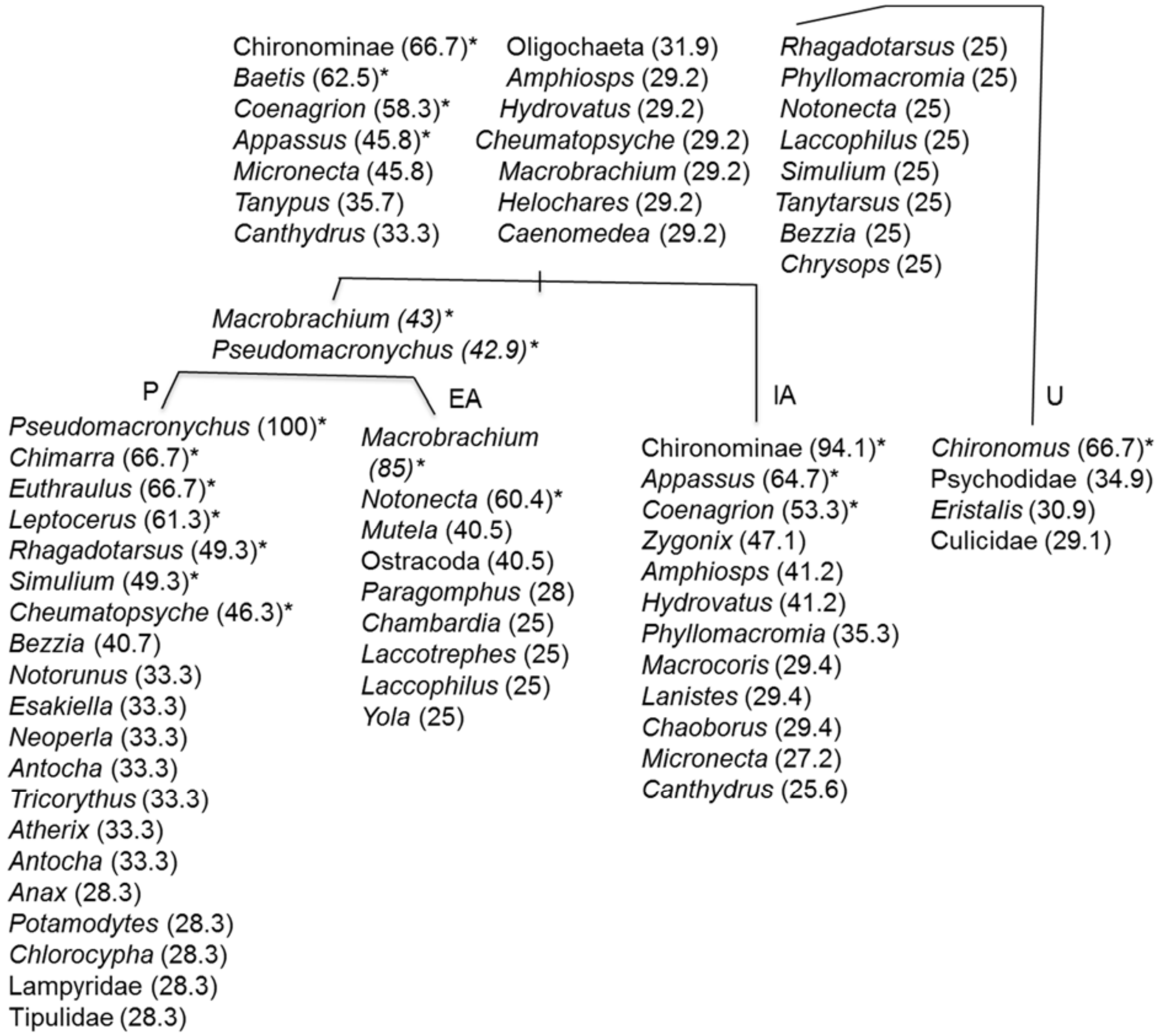

Figure 5 Site typology and associated indicator taxa at different levels of clustering with indicator values in parentheses. Clusters identified by hierarchical clustering analysis correspond to the four land use types. P (C1) = protected area; *EA (C2) = extensive agriculture; IA (C3) = intensive agriculture (C3); U (C4) = urban sites. Indicator taxa shown have IndVal values above 25% (reported in parentheses). Significant IndVal values are marked with an asterisk (p<0.05).*

Discussion

Few studies have previously examined in detail benthic macroinvertebrate fauna of West African streams, and none has covered a geographical scale and variability of sites in terms of human impact comparable to this study. The composition of benthic macroinvertebrate fauna found here confirmed and expanded previous reports from Burkina Faso and neighbouring countries, with which Burkina Faso shares several of its catchments. The number of taxa collected in this study (100) was high when compared to the earlier studies in Burkina Faso streams. For instance, Guenda (1996) reported 94 taxa in his longitudinal study of the Mouhoun river, and Sanogo et al. (2014) collected 35 families during repeated samplings below a dam on a tributary of the Mouhoun river. We also found an prononunced richness of the mollusc community (20 species belonging to 9 families in total). This expands the previous inventories of reported molluscs which have been often limited by a very specific question (e.g. disease transmission studied by Poda et al. (1994), who reported 6 species of molluscs) or a specific geographical area (one river studied by Sanogo et al. (2014), for which 7 families were reported). The high overall taxonomic richness in comparison to other studies reflects the inclusion of both Upper and Lower Soudanian subecoregions into the sampling area , but might also to some extent be explained by covering different habitat types, which has not necessarily been done in previous studies. Furthermore, factors such as the timing and duration of the sampling period may cause the the differences in the estimates of benthic biodiversity as has already been reported for some West African streams (Sanogo et al., 2014). Finally, involvement of taxonomic experts for Decapoda, Coleoptera, Hemiptera and Mollusca in our study allowed more specific identification of taxa, which might have only been determined at a higher taxonomic level and thus not distinguished from each other previously.

Human impact on benthic macroinvertebrate communities: taxonomic composition

The transition from undisturbed to human-dominated landscapes is accelerating in sub-Saharan Africa, and, as a result, is already dramatically affecting watersheds in this region (Kasangaki et al., 2008), especially in Burkina Faso (Melcher et al., 2012). Here we covered several major floodplain land use types present in Burkina Faso: from protected areas to extensive and intensive agriculture and advanced urbanization, testing the potential applicability of macroinvertebrates-based metrics for monitoring human impact on streams.

High variation in the frequency and local abundances of different taxonomic groups of benthic macroinvertebrates offered a good basis for the distinction between benthic communities in the four floodplain land use types, as was confirmed by hierarchical clustering analysis. Importantly, sensitivity to land use change was reflected in different metrics of biotic integrity based on either taxonomic or functional diversity of macroinvertebrates as well as bioindicator approach based on the IndVal index. This confirmed an already previously acknowledged advantage of using several metrics for assessment in that this approach allows to make use of their complementarity and evaluate an entire gradient of degradation in spite of limited sensitivity ranges of single metrics (Thorne & Williams, 1997; Heino, 2008).

Protected areas were clearly distinguished by both high diversity and numerical dominance of the EPT taxa. Most insect taxa belonging to this group have been reported to be highly sensitive to pollution stress (Barbour et al., 1999; Bauernfeind & Moog, 2000). Accordingly, EPT-index has been widely used as an ecological assessment tool (e.g. Barbour et al., 1999), even if single EPT taxa may show a certain tolerance to pollution and thus wide distribution in spite of human impact (e.g. Thorne & Williams, 1997; Kasangaki et al. 2008; Masese et al 2009a). Indeed, in our study, while single EPT taxa (e.g. *Baetis* sp.) were found even in the sites exposed to the effects of intensive agriculture, the patterns in overall taxonomic richness and abundance of the group reflected the expected gradient in pollution. Importantly, EPT-based metrics allowed us to distinguish between extensive and intensive floodplain agriculture, most probably by reflecting the sensitivity of these groups to the variation in pesticides, sediment runoff and organic pollution evident between these two land use types (Sutherland et al., 2002; Kasangaki et al., 2008).

In contrast, neither total taxonomic richness nor Shannon-Wiener diversity index, both frequently used in monitoring programs, allowed us to clearly distinguish protected sites from those with agricultural floodplain land use. Moreover, these metrics rather indicated a trend of increasing taxonomic diversity in both types of the agricultural sites. Similar results have already been reported earlier, associating an increase in macroinvertebrate diversity and total richness to the addition of moderate amounts of pollution (Thorne & Williams, 1997). Here high organic matter (rice, vegetables) and fertilizer input related to intensive agriculture appeared to enhance both algal and macrophyte production (as observed in our study sites) boosting the macroinvertebrate diversity, in particular in molluscs and coleopterans. An additional effect may have been mediated by enhanced habitat heterogeneity due to proliferation of riverside macrophytes, which often positively affects overall benthic macroinvertebrate richness (Gong et al., 2000; Callisto et al., 2001; Ali et al., 2007; Koblinger & Trauner, 2013). Groups such as molluscs, tolerant to many disturbance types (Brenko, 2006; Lévêque, 1972; Idowu et al., 2007; Masese et al., 2014), appear to be particularly successful in profiting from these "positive" agricultural effects, as confirmed by our results.

Finally, all tested taxonomy-based metrics clearly detected the homogenization and drastic impoverishment of benthic fauna in the urban sites, resulting in the strong dominance of tolerant dipteran taxa. Rivers in Burkina Faso are used for manifold domestic activities like drinking, cooking, bathing, and waste disposal (Boyle & Fraleigh, 2003; Ouedraogo, 2010; Koblinger & Trauner, 2013). In the study sites categorized as urban, we observed deposition of polluting domestic and industrial wastes (Fig. A4), which, through water quality deterioration, has been associated with macroinvertebrate extinctions and biodiversity decline (Wright et al., 1995; Ourso, 2001; Allan, 2004; Cook et al., 2009; Ouédraogo, 2010). Furthermore, in urban streams, morphological habitat degradation too may contribute to elimination of certain habitat specialists (Kasangaki et al., 2008). Indeed, mud, fine particulate organic matter and concrete were the dominant types of habitat we found in the urban streams, offering very reduced opportunities in terms of possible ecological niches. This explains a dramatic increase in the percentage of Chironomidae, Sirphidae, Culicidae and Psychodidae, groups commonly considered as tolerant to pollution (Mandaville, 2002; Hauer & Lamberti 2006). Notably while some chironomid taxa are known to be less tolerant or even sensitive to pollution, in our study this family was dominated by Chironomini (in particular, *Chironomus* sp.) and *Tanypus* sp., which have already been shown to be highly tolerant to pollution in other African streams (Odume & Muller, 2011).

Human impact on benthic macroinvertebrate communities: functional composition

While metrics based on taxonomic composition allow an evaluation of diversity or sensitivity of the macroinvertebrate community to a certain stressor, the goal of the functional approach is to characterize ecosystem condition (Cummins et al., 2005). Thus the functional composition of benthic communities is linked to the supply and persistence of particular resources taken up by aquatic food webs and should be responsive to any changes affecting the latter (Merritt & Cummins, 2006). Here we found indications that floodplain land use may drive shifts in the distribution of functional feeding groups in macroinvertebrate communities. The groups feeding on the fine particulate organic matter (collector-filterers and collector-gatherers), often recognized as generalists (Dobson et al., 2002), appeared to be dominant across all sites, a finding consistent with previous reports from African tropical streams (Uwadiae, 2010; Masese et al., 2014). However, the relative importance of these functional groups changed with the intensification of land use: collector-gatherers (primarily midges) became increasingly dominant whereas collector-filterers (mainly caddisflies and bivalves) decreased along the gradient between protected and urban sites. Relying on filtering of particles out of water, collector-filterers are known to be sensitive to increased turbidity and sedimentation (Uwadiae, 2010). Thus increase in both factors due to cattle-driven erosion and organic waste input observed in agricultural and urban streams, is a very probable explanation for the reduction of the relative abundance of this functional feeding group found in our study.

Some further trends were detected for other functional feeding groups. The remarkably low fraction of shredders in all study sites including the protected ones was in accordance with other studies reporting a general scarcity of shredders in tropical streams (Dobson et al., 2002; Wright & Covich, 2005; Arimoro, 2007; Mesa et al., 2013; Christopher, 2014). Several possible explanations for shredder rareness in tropical streams have been offered: from faster microbial processing at higher temperatures (Irons et al., 1994) to lower leaf quality of tropical tree species due to their increased roughness and tannin contents combined with low nutritional value (Wantzen et al., 2002). Furthermore shredders tend to have long life-cycles and are slow colonizers (Jacobsen & Encalada, 1998), life traits that make them unsuitable for living in arid streams with highly variable and unpredictable discharge (Cheshire et al., 2005) as those in Burkina Faso. Even though overall shredder density across all study sites was very low, we did find indications for some differences related to land use types: most shredders were found at the natural sites, while they were missing or nearly missing in the rest of the sites. This decline in relative shredder abundance is most probably related to the removal of vegetation associated with both agricultural and urban land use. Furthermore, we found a particularly high abundance of scrapers (in particular molluscs) in the intensive agricultural sites. Scrapers rely in their feeding on periphyton, thus algal biomass increase due to eutrophication, as discussed above, appears to be the most feasible explanation for their increased importance. Finally, in both types of agricultural sites we also found predators fraction nearly tripled compared to protected and urban sites. Predator abundance appears to be largely driven by prey availability (Petermann et al., 2015) and has already previously been shown to increase in streams affected by human activities (Rawer-Jost et al., 2000). Thus it appears feasible that this trend is related to eutrophication-driven increase in prey abundances.

Across different land use categories we found in stream communities a general deviation from the expected balance in terms of functionality and exchange with the riparian zone, as revealed by using functional group-based surrogate measures of ecosystems attributes. Thus, FFG ratios indicated that, along the studied land use gradient, stream commiunities were characterized by an increased heterotrophy (in all land use categories but

IA) and were at the same time highly sensitive to the presence of fine particulate and not coarse particulate organic matter. Furthermore we found a relative predominance of predators at agricultural sites and a remarkably low top down predator control ratio in sites with urban land use. These results lie in line with previous studies on degradation effects in tropical streams (Cummins et al., 2005; Masese et al., 2014) and further strengthen our conclusions on the effects of artificial human-driven organic matter subsidies and fertilizers to both agricultural and urban streams. Combined with removal of natural riparian vegetation, it appears to lead to a shift in aquatic trophic structure. Altogether, while pointing towards the effects of degradation, FFG ratios did not always allow us to clearly distinguish between different levels of human impact. These metrics appear to be highly affected by the season of the sampling, the correctness of attribution of taxa to functional feeding groups (often limited) and also by whether they are calculated based on abundance or biomass (Masese et al., 2014; Cummins et al., 2005). Furthermore, as the method has been formulated for the temperate zone, threshold values crucial for interpretation of the results, might need to be adjusted for the tropical streams (Cummins et al., 2005).

Human impact on benthic macroinvertebrate communities: indicator taxa

The functional and taxonomic metrics discussed above varied in their sensitivity to human impact and in part were only capable of detecting extreme degradation as in urban streams. By contrast, the indicator taxa approach was successful in distinguishing between categories of human impact at several levels of similarity. We found the highest number of significantly supported indicator taxa in the protected streams. Several of them belonged to EPT taxa, sensitive to the degree of efficient aeration of the sediment and to the availability of specific habitats (Tonkin, 2014; Sweeney et al., 2009). Fewer (two to three) taxa were identified as indicators for each of the two categories of agricultural sites. This points towards taxa tolerant to low-to-moderate levels of pollution and capable of profiting from increasing eutrophication. For example, *Macrobranchium* shrimps in EA sites and Chironominae in IA sites have already been suggested as bioindicators of environmental stress previously (N'Zi et al., 2008; Marques et al., 1999; Lock et al., 2011). Importantly, using these metrics we found that protected sites were the most similar to the sites with extensive floodplain agriculture, while the sites with intensive agriculture were the ones closest to the urban sites. In the latter, only one taxon with significant IndVal values was identified: "red" Chironomus. This is not surprising, as very few taxa survive in these highly polluted environments, and these are typically not urban sites specialists but rather generalists with high tolerance to stream degradation (Ourso, 2001; Konrad & Booth, 2005; Thorne & Williams, 1997). In fact, red-chironomids are considered common and tolerant to a wide array of environmental conditions (Tokeshi, 1995; Barbour et al., 1999; Hooper et al., 2003), and due to possession of haemoglobin, a pigment that transports and stores dissolved oxygen, are known to survive even in highly polluted and oxygen-depleted environments (Moore & Palmer, 2005; Roque et al., 2012).

Conclusions for stream conservation in Burkina Faso

As in many countries across the world, the running waters of Burkina Faso are threatened by multiple impacts of human activities, notably by severe pollution and habitat degradation from intense urbanization and agriculture affecting their temperature regimes, sedimentation processes, riparian vegetation, water physical chemistry and evaporation rates (Aurouet et al., 2005; Munné et al., 2012). These impacts eventually lead to the loss of habitat and water quality, and, hence, negatively affect freshwater fauna. In view of high population growth and thus rising rates of human pressure and habitat degradation, identification of key areas for protection valuable in relation to the presence of specific taxa appears to be crucial for ensuring the long-term regularity of aquatic macroinvertebrate biodiversity (Benstead & Pringle, 2004; Heino, 2008).

Across several types of anthropogenic pressures (grazing by livestock, land farming, urbanization), we developed an extensive inventory of the benthic fauna in Burkina Faso streams and demonstrated that several metrics derived from the composition of the macrobenthic community can efficiently distinguish between land-use related human impacts. Specifically, we found that metrics related to the overall richness and diversity of the macroinvertebrate community as well as its functional composition were capable of identifying the high levels of degradation as observed in the urban sites. Using the specific taxonomic composition of the benthic community one can distinguish between protected and agricultural areas either by focusing on known sensitive groups such as EPT taxa or on indicator taxa. Our findings confirm the importance of maintaining a range of protected areas hosting a range of sensitive taxa and crucial for effective conservation of the regional fauna (Brashares et al., 2001; Muhumuza & Balkwill, 2012). While some further steps needs to be done to refine our results (for instance by taking into account seasonal dynamics of benthic communities or the role of other stressors which have not been addressed here), this work lays a solid basis for development of simple and easily applicable biomonitoring tools for management and conservation of water and rivers systems in West Africa.

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ARTICLE #4

Journal of Soil and Water Conservation (**under third review**)

Reference criteria for human impacts on semi-arid rivers in Burkina Faso (West Africa)

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Abstract

Awareness of sustainable management of water and its biological resources is rising in West Africa, but application of effective tools for biomonitoring and detecting habitats at risk in aquatic ecosystems is limited. In this study, we review bio-indication based on benthic macroinvertebrates and its implications for water resources policy. Especially, we discuss (1) the role of water for livelihoods in semi-arid areas; (2) human-induced stressors, (3) new water quality management implementation based on a sustainable biological monitoring programme based on the reference conditions approach, and (4) provide key environmental descriptors to characterise reference sites by applying the following criteria: physico-chemical, sensoric features, hydro-morphology and land use parameters. Cluster analysis allowed to test the '*a priori* criteria' from 44 areas in Burkina Faso to determine suitable reference areas. The results showed that protected areas can reasonably be considered as credible reference sites as far as they show low impact levels. We recommend that development of bio-indicator standards should be based on the collection and integration of all the available information, especially quantitative, spatially-explicit data, on benthic macroinvertebrates and fish. Rigorous standardization of bio-indicator protocols will make them more easily applicable for management and conservation of aquatic ecosystem resources in Africa.

Keywords: multiple pressures, reference conditions, semi-arid, rivers.

1 Introduction

Burkina Faso is a landlocked Sahelian country located in the heart of West Africa, which has to cope with chronic water scarcity and episodes of severe drought. A high population growth rate and rising demand to achieve food security and sustain rural livelihoods have resulted in intensification of agriculture (rice and irrigated crop farming, fishing, livestock farming) and accelerating urbanization. As a consequence, the incidence of anthropogenic pressures, e.g. exposure of surface waters to pesticides, chemical fertilizers and pollutants as well as physical modification of the riparian areas (due to e.g. erosion by livestock, agriculture or river engineering) has increased over the years, posing a threat to aquatic organisms and water quality (Ouédraogo, 2010; Ouédraogo and Amyot, 2013). Despite the pressing need to preserve these water resources for human demand and to maintain the biotic integrity of riverine ecosystems, few studies (see Guenda, 1996; Sanogo et al., 2014) have addressed the ecological status and biomonitoring of aquatic ecosystems in Burkina Faso. The purpose of biomonitoring in aquatic ecosystems is to evaluate the effect of human activities on biota and the resources they depend on. Several techniques are used in aquatic ecosystem biomonitoring programs, including Saprobic techniques (from Kolkwitz and Marsson, 1902 to Rolaufs et al., 2004), diversity (Metcalfe, 1989), biotic indices and scores (Armitage et al., 1983; De Pauw and Hawkes, 1993; Sharma and Moog, 1996; Dicken and Graham, 2002; Ofenboeck et al., 2010; Kaaya et al., 2015; Lakew and Moog, 2015) multivariate techniques (Norris and Georges, 1993; Rosenberg et al., 2000; Kokes et al., 2006) and multimetric indices (Barbour et al., 1995; Reynoldson et al., 1997; Clarke et al., 2003; Hering et al., 2006).

An important component of the biological assessment of stream conditions using macroinvertebrate communities is an evaluation of the direct or indirect effects of human activities or disturbances (Hering et al., 2006; Moog et al., 2008). Whichever bioassessment approach is adopted, one key issue is the identification of reference sites and reference conditions (Wright et al., 1984; Resh, 1995; Sandin et al., 2001; Ollis et al., 2006). According to Barbour et al. (1996), Roux et al. (1999), Ollis et al. (2006) and Stoddard et al. (2006), the reference condition 1) is defined as “the condition that is representative of a group of minimally disturbed sites organized by selected physical, chemical, and biological characteristics” and 2) represents the expected condition for a particular biotic component and acts as a benchmark with which a monitoring site is compared. With the reference condition approach, the biological community of a potentially stressed waterbody is compared with that of relatively undisturbed reference sites that have similar environmental conditions. However several authors pointed out that reference conditions must be systematically identified because all ecosystems experience some level of human disturbance, and truly pristine sites are virtually non-existent (Thorne and Williams, 1997; Wallin et al., 2003). A number of methods were used to establish the reference condition (Rosgen, 1998; Apfelbeck, 2001). Some of these methods include extensive spatial survey, predictive modelling, historical data, and expert judgment (Dallas, 2000, 2000a; Alonso et al., 2011). Each method of determining the reference condition has its own strengths and weaknesses (Economou, 2002; Sommerhäuser et al., 2003; McDowell et al., 2013), and each method relies on ecosystem classification to some degree (Wallin et al., 2003; Alonso et al., 2011; Johnson et al., 2013).

Many authors have developed'*a priori* criteria'to distinguish a reference site from impaired sites, and these criteria were based on different pressures derived from human activities that can affect ecological conditions (Moog and Sharma, 2005; Du Preez and Rowntree, 2006; Alonso et al., 2011). The criteria selected as'*a priori*' should define the lowest level of environmental disturbance caused by human activities (Stoddard et al., 2006), and most of these criteria should be fulfilled by selected reference sites to clearly define the reference ecosystem as one that is "acceptably healthy" according to current policy goals (Bailey et al., 2004; Alonso et al., 2011). The criteria of appropriate reference sites may vary among regions, water bodies and habitat types. However, the most commonly used criteria include physicochemical parameters, hydro-morphological characteristics, land use pattern and riparian vegetation (Moog and Stubauer, 2003; Nijboer et al., 2004). In developing countries where research resources and historical knowledge are limiting factors, the use of abiotic and riparian vegetation criteria are often used to describe the characteristics of sites in a region that are least and most exposed to stressors (Thorne and Williams, 1997; Moog and Sharma, 2005; Lakew and Moog, 2015).

The present study establishes the basis of a monitoring program by setting criteria to identify what low levels of alteration in environmental variables can still support benthic macroinvertebrate communities. Setting criteria for some observed pressures may not be too difficult and can be approached from different perspectives. For example, the intensity of point source pollution and the magnitude of its impact can be determined by observing the distribution of the sources in a watershed or by direct measurements of the concentration of pollutants in the water column. Similarly, land use patterns in the riparian zone of study sites can be obtained from local land use maps or remote sensing imagery and geographic information systems (GIS). Nevertheless, developing indicators based on quantifying human pressures and their impact levels remains a challenge. It requires detailed analysis of appropriate data sets that rigorously document local conditions. These can consist of current and historical data that help establish trends that have led up to the current health status of the aquatic ecosystem under study and often comprise a diversity of variables under different categories.

2 Water Demand, Water Supply and Policies of Water Management in Burkina Faso

In Burkina Faso, high water demand due to high population growth rate and low management capacity has led to overuse of surface water. The major factors affecting rivers systems are rising urbanisation and agriculture activities. Their combination lowers water quality by depositing untreated domestic waste and pesticides and chemical fertilizers in the rivers and their tributary creeks and channels. In addition, river flow regimes have been altered as increasing water demand required dam construction on rivers to establish a water storage network of reservoirs. These alterations to Burkina Faso catchments and their channels have resulted in new water flow and sediment regimes in the rivers, and hence a net change in their ecological status.

Over the past 50 years a Burkinabe water management institutions have evolved considerably on legislative and administrative levels in response to a series of drought crises. However, water management continues to display a lack of coordination, as it has been only partially effective in adapting to extreme periods of water stress. In the early 1970's, severe droughts struck the Sahel and revealed Burkina's vulnerability to years of low precipitation. Following these droughts, Burkina Faso's water policies have above all been oriented toward ensuring a basic supply for all to minimize the vulnerability to spells of low precipitation (Ministère de L'Environnement et de L'Eau [MEE], 2001; Ministère de L'environnement et du développement durable [MEDD], 2011). The National Office of Dams and Irrigation (ONBI) was then created in 1976, with the aim of harnessing the irrigation potential of the country.

In an on-going response to the threat of droughts in the 1970's and 1980's, Burkinabe water management institutions continued to proliferate (MEE, 2001; MEDD, 2011). The Water Point Committees (CPE) were also formed to facilitate the extension of potable water supplies to rural communities. Attempts were made to consolidate the various institutions in the 1980's, but real institutional integration started in 1990's (MEE, 2001). Influenced by release of the Dublin Principles in the early 1990's, Burkina Faso set out to restructure its water sector with the aid of the World Bank and International Monetary Fund (IMF). In 1995, the government of Burkina Faso created the Water and Environment Ministry (MEE), which then created the General Directorate of Hydraulics (DGH). As a result, water-related activities and interventions in the country achieved much greater organization and coordination (MEE, 2001).

The final stage of reconsideration of the first round of political decisions was reached with the adoption in 1998 of the document on the national policies and strategies of water resources. Together with this, the Gestion Intégrée des Ressources en Eaux (GIRE) project was established in 1999 to integrate water resources management as recommended in the Dublin and Rio international conferences on water and environment. In the same year (1998), the national water law was put into force, and this new water law recognises that basic human and environmental needs should be met (GIRE, 2001). Often in concert with international initiatives, governmental decisions on national water resources management are locally supported by external partnerships and active national/international Non-Governmental Organizations (NGOs)/institutions in the water sector. These initiatives garnered the involvement of many actors and institutions in the water sector of Burkina Faso, including donor institutions (bilateral and multilateral, NGOs and international research projects) national corporate bodies, private companies, research and scientific institutions. Efforts to extend protection to fragile aquatic ecosystems and riverbanks established the Water Law (Assemblée Nationale, 2001). It also defined the river catchment area as the geographical unit of water resources management (Ministère de L'Agriculture de L'Hydraulique et des Ressources Halieutiques [MAHRH], 2003, 2004; United Nations Environment Programme-Global Environment Facility [UNEP-GEF], 2012). Despite an important battery of texts on management of water and its biological resource, governance has proven inadequate to make fisheries sustainable and is badly in need of the biomonitoring tools that can be used to monitor environmental conditions (Ouédraogo, 2010; Sustainable Management of Water and Fish Resources Consortium [SUSFISH], 2015). Importantly, this can help to set ecological objectives to ensure the proper and sustainable management of the resource.

In Burkina Faso, surface water resources are rain-fed. Two seasons, induced by the northward and southward oscillations of the Intertropical Convergence Zone (ITCZ) front, govern water availability in the country: a relatively short rainy season with abundant, patchy rainfall during storm events inducing more runoff than infiltration, and a relatively long dry season where no rainfall occurs but temperatures and evaporation are high. To buffer this temporal variability in Burkina Faso, some 2000 reservoirs (MEE, 2001) regulate water availability for population and livestock. The total volume of these reservoirs was estimated in 2001 by the GIRE project to be 2.66 billion m^3 of water at their maximum capacity with an approximate total area of 100 000 ha. The average annual runoff volume (period 1961-1999) of the national river basins is estimated at 7.5 billion m^3, and the average storage potential of surface water per year is 8.6 billion m^3 (Sandwidi, 2007; MEE, 2007). The water use by consumption in the country was 505 billion m^3/year. Of these, water demand for irrigation was 64%, for domestic needs 21% and for livestock 14% (GIRE, 2001; UNEP, 2010; MEE, 2011).

3 Methodology

3.1 Study area

Burkina Faso is located in the central part of West Africa (09°20'N & 15°03' N; 02°20' E 05°03' W). The climate is tropical and semi-arid with a temperature range varying between maximum (40°C) and minimum (16°C) (Ly et al., 2013; http://www.burkina-faso.climatemps.com/) and is characterized by a north-south gradient in rainfall distribution, with high variability in both time and space. Three main catchments consistute the hydrological network of Burkina Faso (Fig. 1): Niger, Comoé and Volta. Our study was undertaken in rivers belonging to two of them: the Nakanbé (Volta catchment) in the central part of Burkina Faso (area of 70,000 km^2), the Mouhoun (Volta catchment) in the west (92,000 km^2) and the Comoé in south-west part of Burkina Faso (18,000 km^2). In total a 44 investigation areas were selected from these rivers (see suplementary table S). Sampling areas fell within two continua ranging from low to very high intensity of agriculture in one case and of human population density in the floodplain area in the other (Kaboré et al., 2015). Floodplain land use types were defined visually by means of a field protocol and Google earth map. Field trips were undertaken to confirm the accuracy of this assessment by expert judgment. Four major categories of floodplain described in Kaboré et al. (2015) were defined and codified as: 'protected' (P), agriculture': Extensive and Intensive (A), 'urban' (U) and protected areas in the 'urban park' (UP) of Ouagadougou (Bondaz, 2013).

'Protected' areas were exposed overall to the lowest levels of human impact and were characterized by a nearly negligible population density (isolated households) and preserved natural riparian vegetation (Fig. 1). Areas categorized as 'extensive agriculture' were exposed to a low level of human impact, influenced primarily by grazing (pasture) and waste from scattered houses or small villages. In the areas of 'intensive agriculture', the floodplain area was typically converted to land for crop farming. Thus the most destructive change in the riparian zone of these streams was due to the radical modification of the vegetation and application of pesticides and fertilizers, while settlements were limited to single villages. Finally, the areas of the fourth category, defined as "urban" were situated in highly urbanized areas exposed to industrial and other uses including inputs of domestic wastes (Kaboré et al., 2015).

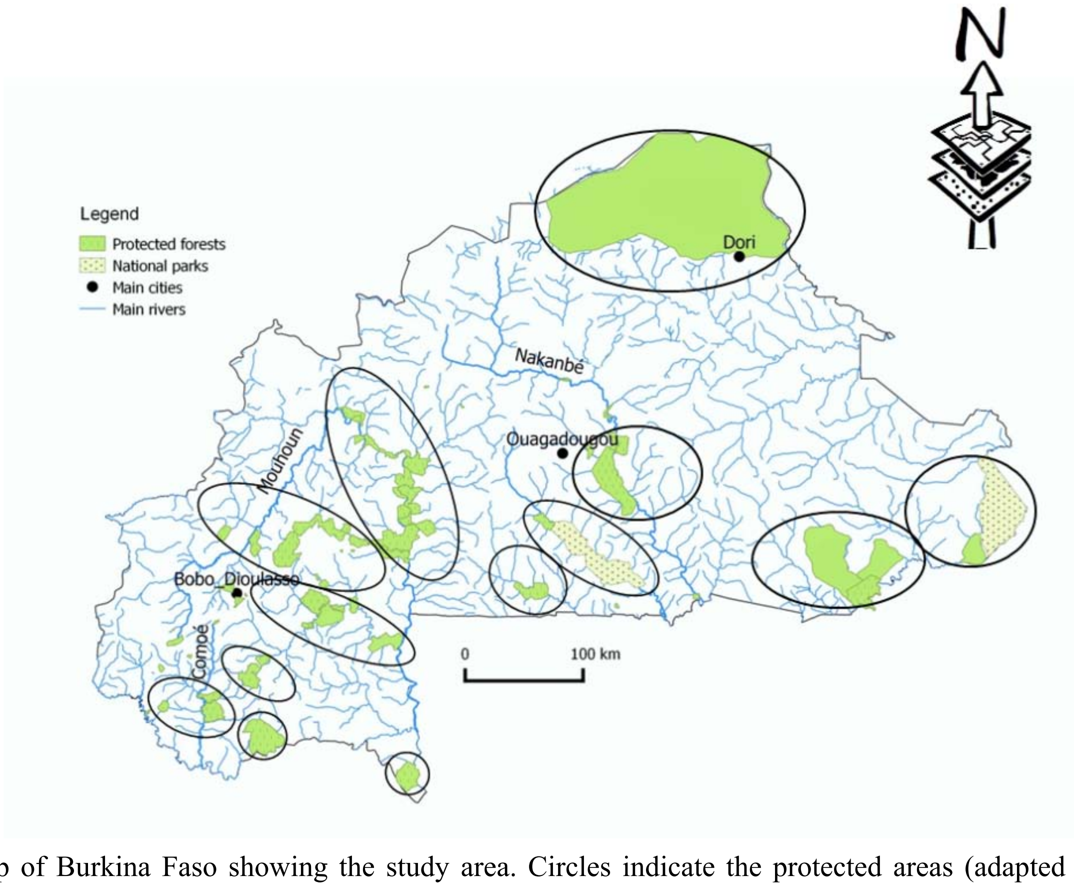

Figure 1 Map of Burkina Faso showing the study area. Circles indicate the protected areas (adapted from BNDT 2009). While some of the catchments are shared with other countries, only the part flowing on the territory of Burkina Faso is shown.

3.2 Environmental Data Sampling

We characterized pressures and developed an overview of driving forces, pressures and possible impacts affecting water body quality in Burkina Faso by compiling a list of human disturbances of rivers based on expert opinion and literature reviews (Ouédraogo, 2010;

MEE, 2011; Koblinger and Trauner, 2013; susfish.boku.ac.at). The interconnected associations used to visualize the impacts of ecosystem alteration on the biological condition of streams and rivers detected in Burkina Faso are shown in Figure 2. The conceptual diagram (Fig. 2) synthesizes evidence of causes and effect in environmental systems where research is conducted to inform policy makers and managers. It offers a basis for objective assessment of available evidence, but also by suggesting potential relations between factors across levels, e.g. driver, impacts, etc.

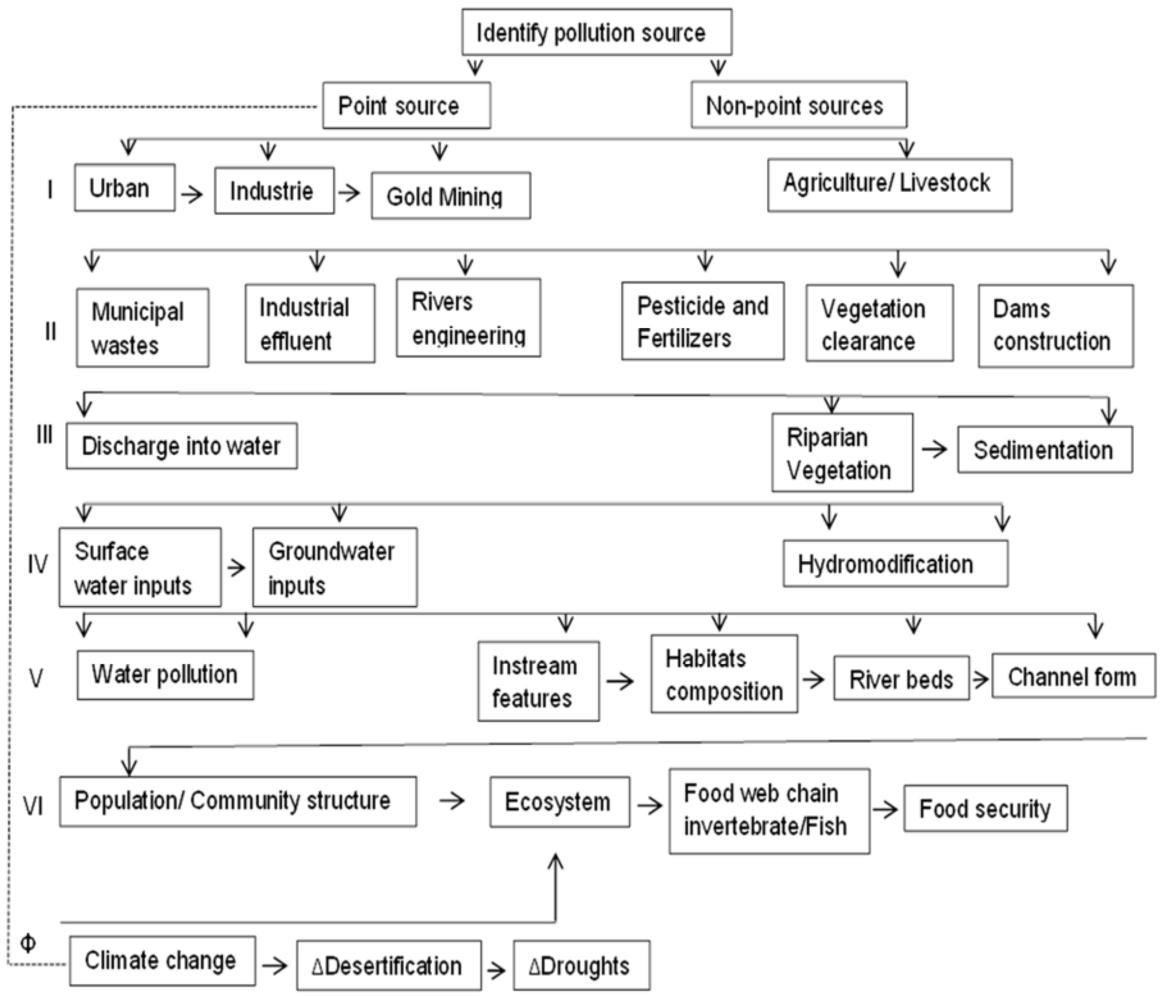

Figure 2 Conceptual diagram. Illustrates interconnected associations used to visualize the impacts of ecosystem alteration on the biological condition of streams and rivers. . (I=Drivers; II=Pressures, III-V= Impacts; VI= Reaction and Φ=natural drivers. Adapted from Ziegler et al., 2015.

Data was recorded at each sampling site on several variables that are likely to be affected by different riparian land use types and thus reflect human impact on Burkina Faso Rivers. The conductivity (µS/cm) and dissolved oxygen (mg/l) were measured with field multimeters (WTW340I). In order to characterize reference sites in this study, we designated investigation sites as 'reference' or 'impaired' based on land use patterns, the degree of habitat degradation as quantified by the protocol (ASSESS-HKH, adapted Susfish, 2012), and variables characterizing hydro-morphological modification (Barbour et al., 1996; Mühlmann, 2010; Lakew and Moog, 2015; Kaboré et al., 2015) as well as expert judgments. "Experts" include people with a profound knowledge on hydro-biological/limnologic topics and a deep insight into local circumstances. Depending on the issue this may include foresters, rangers, fisheries experts, nature conservation management, ministerial, taxonomic scientists or hydro-biologists outside the authors' consortium. For the hydro-morphological characterization, the scoring was conducted using six variables following Mühlmann (2010). Accordingly, a score of 1 was awarded for no or near-to-natural disturbance, 2 for slight disturbance, 3 for moderate disturbance, 4 for strong disturbance and 5 for heavy disturbance. The remaining variable assignments were done by expert consensus following (Korte and Moog, 2006) visually by means of field protocol (Table 1).

Table 1 Variables measured to reflect different pressures on Burkina Faso river systems

Categories	Variables	Characteristic
Morphological pressures	Bed dynamics	Ordinal (5)
	Channel form	
	Bank dynamics	
	In-channel features	
Habitat Pressures	Channel structure	
	Substrate composition	
	Riparian vegetation	
Hydrological Pressures	Hydrograph and discharge regime	Binary (0,1)
	Water extraction for hydropower and industrials uses	
	Water extraction for irrigation	
longitudinal connectivity pressures	Lateral connectivity between river and riparian zone	
	Barrier or reservoir upstream at 50 m of sites	
	Sealing of the river bottom (pavement, concrete)	
Water quality pressures	Point source pollution	Binary (0,1)
	Artificial Eutrophication	
	Known or expected diffusion input.	
	Ferro-sulphide reduction	
	Waste dumping into the river or river banks	
	Foam	
	Water foam (except natural sources)	
	Water turbidity (except natural sources)	
	Water odour	
	Fungi and stuffs	
	Conductivity	Linear
	Disolved oxygen	
	Salinity	

Table 1 (continued).

Categories	Variables	Characteristic
Direct pressures	Cattle washing/watering	
	Livestocks at 100 m of site	
	Sand or gravel excavation	
	Crop farming in the riparian zone	
Riparian land use pressures	Natural or near-natural vegetation cover, e.g. protected areas	Binary (0,1)
	Irrigated agriculture	
	Urbanisation, industry and other uses	
	fishery area	

3.3 Definition of Reference Criteria

From the 34 variables measured in the field, thirty-seven (37) criteria were selected and grouped into six categories: status, hydro-morphological features, physicochemical features, sensoric features, land use, and biological elements. These groups were arranged into thirty-seven categories to describe the reference conditions of semi-arid streams and rivers following other authors and considering the particular condition of study area. We proposed thirty-seven *a priori* criteria that a site has to fulfil to be considered a reference site (Table 2). These thirty-seven criteria include a wide range of human uses and impairments on streams/rivers, and details are given in the following paragraphs that focus on the four main criteria.

Table 2 Summary of the selected criteria for semi-arid streams and rivers

Category	Attributes	Criteria	Conditions	References of tools to be used
Status		1. Protection status	Protected areas	National Law (1997 and 2001)
		2. River bed dynamics	(near to) natural*)	Mühlmann (2010)
		3. Channel form	(near to) natural*)	Mühlmann (2010)
		4.Substrate composition	(near to) natural*)	Mühlmann (2010)
		5. Bank dynamics	(near to) natural*)	Mühlmann (2010)
Hydro morphological features		6. In-channel features	(near to) natural*)	Mühlmann (2010)
	River morphology	7. Channel structure typical to the typology	(near to) natural*)	Hughes (1995)
		8. Dam barrier or reservoir upstream at 500 m of sites	No dam barrier or reservoir**)	Present study
		9. Habitat composition	Representative diversity of substrate composition correspond to related typology**)	Johnson et al.(2013)
		10.Spawning habitats for the natural fish population	(near to) natural***)	Barbour et al. (1996)
		12. Sand or gravel excavation	No**)	Nijboer et al. (2004)
	Hydrological condition	13. Alteration of the natural hydrograph and discharge regime	No alteration****)	Barbour et al. (1996)

Table 2 (continued).

Category	Attributes	Criteria	Conditions	References of tools to be used
		14. Water extraction for hydropower and industrial uses	No****)	Present study
		15. Water extraction for irrigation	No (few exception tolerated if in harmony with nature)**)	Hering et al. (2003)
Physico-chemical features	Point source pollution	16. Point source pollution and Eutrophication	No**), ***)	Hering et al. (2003)
		17. Sign of salinity	No*****)	Present study
		27. Diffuse input	No**)	Nijboer et al. (2004)
Sensoric features		18. Colour and odour	Only natural**)*	Moog, and Sharma (2005)
		19. Foam	Only natural***)	Moog, and Sharma (2005)
		20. turbidity	Only natural***)	Moog and Sharma (2005)
		21. Waste dumping	No**)	Moog and Sharma (2005)
	Physico-chemical	22. Conductivity	<75µs/cm*****)	Present study
		23. Dissolved oxygen	>6.0 mg/l*****)	Present study
	Non-point source poll.	24. Livestock at 100 m of site	No**)	Present study
		25. Cattle watering	No, only wildlife**)	Lakew et Moog (2015)

Table 2 (continued).

Category	Attributes	Criteria	Conditions	References of tools to be used
Land use	Direct water uses	26. washing and bathing	Only minimal activities**)	Hering et al. (2003)
		28. Crop farming in the riparian zone	No**)	Hering et al. (2003)
		29. Riparian zone land use	Natural or near-natural sites; >80% of natural vegetation cover typical to area**)	Bonada et al.(2004)
		30. Extensive agriculture	No**)	Kaboré et al. (2015)
		31. Intensive agriculture	No**)	Kaboré et al. (2015)
		32. Urbanisation, industry and other uses	No**)	Kaboré et al. (2015)
		33. Fishery activity	No evidence**), ***)	Kaboré et al. (2015)
		34. Human settlement in the floodplain area	No**), ***)	Kaboré et al. (2015)
		35. Riparian zone use for recreation	Occasional**)	Kaboré et al. (2015)
		36. Lateral connectivity between river and riparian zone	Natural**)	Richardson et al. (2012)
Biological elements		37. Presence of wild birds and mammals	Possibly (field observation) **), ***)	Barbour et al. (1996)

Legend: *) class 1 of the Mühlmann classification system: **) Yes/No-Information by field trips or written information, Google earth map; ***) Information available from, Ministry of Environment and Sustainable Development, local river authority or other sources (e.g. local fishermen; foresters, natural park guides); ****) Information available at the Water and Environment Ministry or written information; *****) In-situ measurements with probes (e.g. conductivity meter; oxygen meter)

3.3.1 Hydro-morphological Criteria

Developments such as roads, settlements, farm infrastructure, reservoirs, and dams shape our landscape and may have an impact on the ecological functions of water bodies. To visualize those impairments hydro-morphological tools were used to assess physical aspects of water bodies with a focus on habitat structure and hydraulic features. Hydro-morphological properties of streams depend on relations between morphology and hydrology that play a major role in the ecological integrity of flowing water ecosystems (Rosgen, 1998; Mühlmann, 2010). Human modification of natural hydrologic processes disrupts the dynamic equilibrium between the movement of water and the movement of sediment (Poff et al., 1997; Barbour et al., 1999; Dallas, 2000). Indeed, many rivers have been subjected to channelisaton and artificial levee construction, reducing rivers to single-thread channel and isolating them from their floodplain (Mattingly et al., 1993). In this regard, beneficial management programs, including river restoration or holistic engineering, are increasingly expected to maintain and restore ecosystem health while also supporting varied human uses (Barrett et al., 2006; Bernhardt and Palmer, 2011). Therefore, hydro-morphological parameter groups of the sites defined here could be considered suitable as an ensemble that defines the complete set of hydro-morphological conditions necessary for ecosystem functioning. Said parameter groups can be used to translate into explicit and objective criteria. These criteria address all the relevant structural aspects for the preservation of biotic integrity in stream or river systems (Sánchez et al., 2009; Mühlmann, 2010). Thus, many studies have found that key hydrology and channel form parameters can be used as solid basis to guide and improve rivers management strategies and restoration schemes (Bailey et al., 2004; McEnroe et al., 2010; Palmer et al., 2014). In Burkina Faso major human alterations of hydrology and morphology are caused by damming (e.g. reservoir construction), diversion, water abstraction, and river channelization, respectively (Fig. 3a and 3b). High water demands during the dry season accelerate drying out of most streams and decrease the discharge of the few perennial rivers. River channelization and the effects of diversion and water abstraction have significant effects on the downstream environment, as well as channel features. Siltation/erosion of rivers caused by removal of riparian vegetation, gravel extraction and sand excavation constitute majors sources of morphological change. The range of pressure criteria agreed with those reported by the authors that embrace all major pressures affecting surface water ecosystem in the study area.

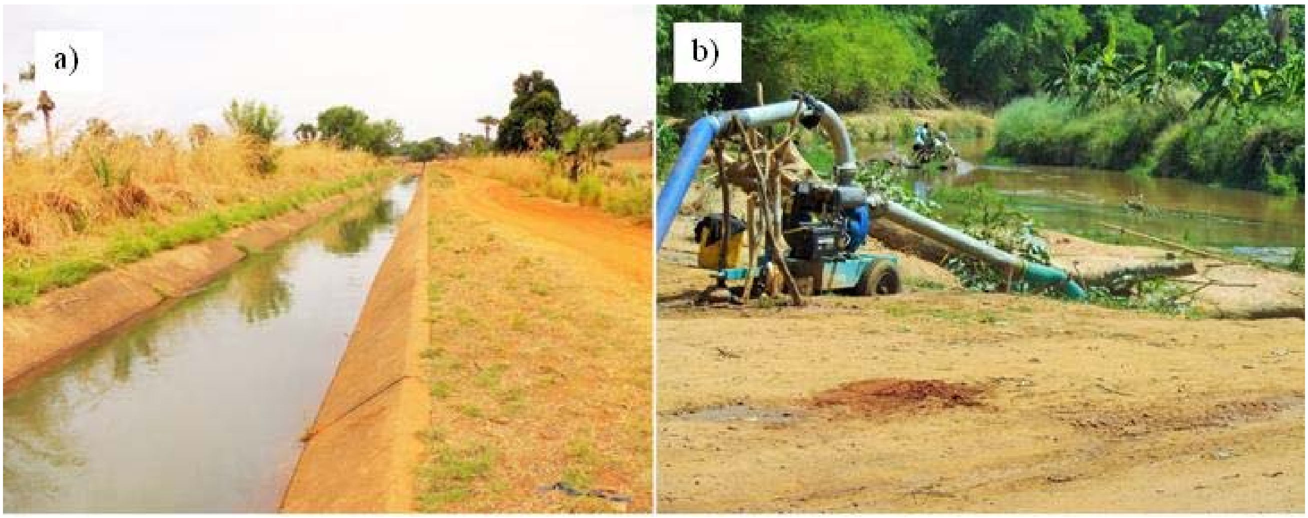

Figure 3 Human pressures on rivers hydro-morphology. (a) =engineering channel and (b) indicates water abstraction by pumping.

3.3.2 Land use and Flooded area cover Criteria

As one of the main drivers of chemical and sediment inputs to surface waters land use influences water quality. However, Bald et al. (2005) have demonstrated that these influences on water quality could be attributed to the transport capacity of the watershed and the influence of riparian buffers. In Burkina Faso, rivers are impaired practically by a variety of uses either aquatic (intense fisheries) or on land, including agriculture, urban, etc. The riparian areas of river basin watersheds are increasingly characterized by intense agricultural usage and human population density (UNEP-GEF, 2010). Burkina Faso officially recognizes the problem of rapid population growth (~3% in 2013) as a major factor for land use changes and depletion of natural resources (MEDD, 2011). Currently major land use changes in the country result from expansion of areas used for crops (e.g. cotton, cashew, etc.), livestock, irrigation and urbanization (Fig. 4c). However, severe negative impacts on benthic macroinvertebrate diversity and drastic change of river morphology are expected due to land use intensification (Cunha et al., 2010; Egler et al., 2012). Riparian vegetation cover is currently restricted to state protected areas, including national parks. 'Protected' areas were exposed to overall lowest levels of human impact, relatively (Fig. 4d). They were characterized by nearly negligible population density (isolated households) and relatively undisturbed riparian vegetation preserved to protect and conserve wildlife for limited hunting and fishing and to maintain ecological integrity (Sawadogo, 2006; Ouédraogo, 2010). In a protected area, small bushes, shrubs and perennial grasses are dominant, but trees are not uncommon. Local riparian vegetation plays a crucial role in nutrient uptake, organic matter and food supply, as well as in river bank stabilization. Increased lateral connectivity between riparian vegetation and flooded areas enlarges the ecological niche for aquatic animals, and by providing more opportunities for food and shelter may constitute a refuge area for a variety of wild terrestrial fauna.

Figure 4 Rivers floodplain use in Burkina Faso. The alphabetical letter (c) = crops farming and (d) indicates protected area.

3.3.3 Physicochemical Criteria

Water quality parameters are key factors that influence the life of living-organisms in water bodies (Bald et al., 2005; Pardo et al., 2012; Hussain and Pandit, 2012). In Burkina Faso numerous water quality problems have been associated with eutrophication caused by nutrient loading from various sources (e.g. domestic washing, crop production and cattle waste). Domestic wastes, including inputs of industrial wastes and other uses, are major factors in urban areas posing a threat to aquatic organisms and water quality (Fig. 5e and 5f). The high concentrations of phosphorus from effluent discharges can cause water quality problems by over-stimulating algal growth that in turn depletes oxygen in the water column. Criteria, such as absence of urban and industrial discharges near to potential reference sites, have to be considered in reference site selection. Other previous studies underlined the importance of physicochemical for bio-monitoring in tropical streams (Thorne et Williams, 1997; Lakew and Moog, 2015). The dissolved oxygen and conductivity, among others measured in water quality assessments are consistent with the overall understanding because expert judgement was used in the definition of categories and the threshold. However, this preliminary approach may help to enrich the debate guiding further study in the region.

Figure 5 Rivers source pollution. The alphabetical letter (e) =domestic waste and (f) =industrial wastes.

4 Testing a Suitable Reference Condition

4.1 Data analysis

All statistical analyses were performed using SPSS software (version 21). In order to support a bioassessment program including reference condition selection in this study, the investigation sites were classified using hierarchical cluster analysis (Ward Linkage Methods, Euclidian distance). Tested variables were z-standardized prior to the analysis. The non-linear discriminant function analysis was then used to test the performance of the clusters (% variance). Each cluster is defined by identification category, and then the pressures were simply recorded as a count of the number of pressures present at each site. With the help of the cluster designations it was possible to show interactions between independent variables to identify the occurrence of pressures with many correlation tests (Gamma, Cramer's V and spearman). All calculation was based on the crosstab analysis following the principles described previously (Melcher et al., 2012); where we tested the independence of both dimensions for all 4-by-4 cells of the cross-table. We used the standardized residuals level of significance proposed by Abdi (2007) and Melcher et al. (2012) to test the statistical significance that was expressed following the formula [1], where t is the number of cells (e.g., t=4*4=16 cells); this means for Table 3:

$$\partial^{*}=\frac{0.05}{16}=0.003125 \qquad [1]$$

The adjusted level of significance is $Z_{\partial*=0.003125;\ \text{one side}} = 2.73$

where

$Z_{\partial*=0.003125;\ \text{one side}} = 2.73$ (Positive $Z_{IJ} > 2.73$ a statistically significant "Typical" (common pressure) and negative, $Z_{IJ} <= 2.73$ a statistically significant "atypical" (uncommon pressures).

4.2 Results

The findings of this study are based on a set of variables that were measured in the field. These variables can be grouped according to seven pressures (morphological, habitat, hydrological, longitudinal connectivity, water quality, riparian land use and direct pressures) that are listed in Table 8 (cited above). The Figure 6 analysis revealed that sites were clustered in four distinct groups, each reflecting a level of pressures. Clusters identified at the lowest, i.e. coarsest, hierarchical level (dotted line Fig. 6) corresponded to the four categories formulated based on multiple pressure assessment of study sites: "protected" (MP1=P1-P8), "intensive agriculture" (MP2=A1-A7), "extensive agriculture" (MP3=A8-A23) which included UP1 & 2 in the same category and "urban" (MP4=U1-U11). Extensive and intensive agricultures sites (MP2 and MP3 respectively) were then clustered together suggesting their similarity in terms of pressure, while urban areas were found to be the most distinct from all the rest of the sites (MP4).

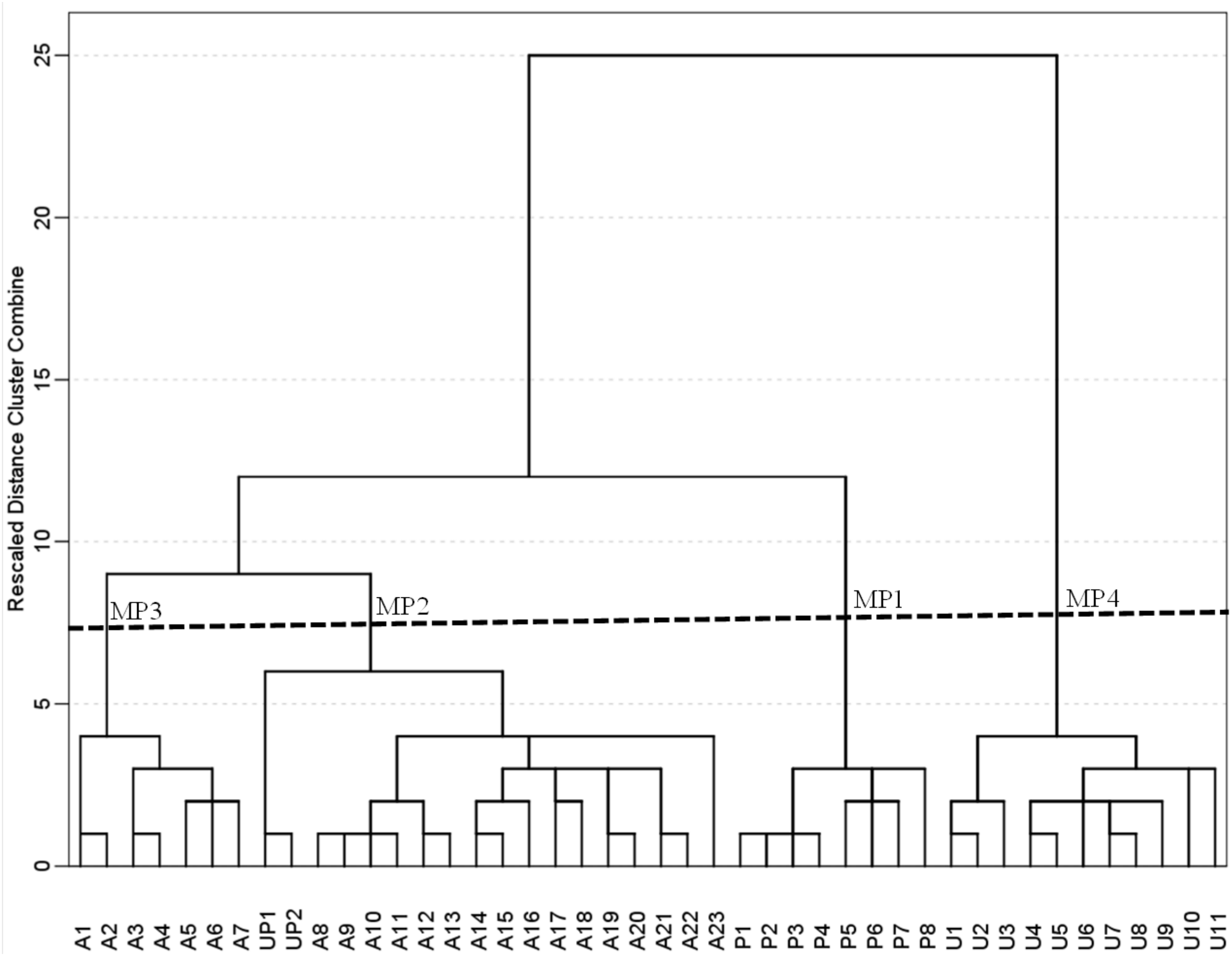

Figure 6 Dendrogram showing the grouping of sites based human pressures. Four main groups were shown by dendrogram which MP1= protected area (reference), MP2= Extensive agriculture, sites, MP3= intensive agriculture and MP4= urban. The explained variance of the discriminant analysis was around 81.8%.

The occurrences of disturbances assessed in the study sites showed a significant association in environmental parameters with site categories (p=0.003 for each site category, table 3). The overall intensity of pressures showed a clear, positive association with site categories (Z_{IJ}> 2.73 and correlation coefficients in Table 3). The site categories showed a clear decrease across the gradient of human impact intensity in terms of hydro-modification, land use and water quality (Table 3). Some distinct differences relative to the pressures could be observed in the categories of sites. The lowest intensity of pressure was typical of protected sites (Z=5.2: Reference "MP1"), followed by the extensive agriculture sites (Good="MP2"). In contrast, the highest intensity of pressure was 'typical 'of the impacted streams sites, e.g. significantly linked with areas affected by human pressures, where the floodplain area was typically converted to land for crop farming or exposed to industrial and other uses including inputs of domestic wastes and river channel channelization. To simplify further analysis, norms used to assess ranges of pressures were quantified using 1) objective statistical methods, 2) field inspections corresponding to *in situ* visual evaluations and 3) expert judgment based on opinions from the scientific community in Table 3. Thus, in absence of purely pristine sites, protected sites were retained as reference after careful checks of the cumulative effects of pressures. These sites were created with the goal of protecting and conserving the wildlife for limited hunting and occasional fishing and maintaining the ecological integrity.

Table 3 Cross-tabulation after cluster and their adjusted residuals to determine type number of affected pressures per group of clusters. (Spearman =0.95, p=0.000: Gamma ß=0.994, p=0.000: Cram v=0.864, p=0.000)

	pressures occurrence		MP1	MP2	MP3	MP4	Total
1	0-2	n	7	2	0	0	9
		Z	**5.2**	-1.3	-1.5	-1.9	
2	3-10	n	1	16	0	0	17
		Z	-1.7	**5.7**	-2.3	-3	
3	11-21	n	0	0	7	2	9
		Z	-1.6	-2.8	**5.7**	-0.2	
4	>22	n	0	0	0	9	9
		Z	-1.6	-2.8	-1.5	**5.8**	
Total		N	8	18	7	11	44

4.4 Discussion

The use of ecological approaches for managing water resources has so far received little attention in West Africa, especially in Burkina Faso, where waters bodies and rivers systems are strongly impaired by human activities. We found evidence of three pressure categories to some degree in nearly all study sites. While these pressures can act singly, in the most cases multiple factors act jointly on water quality. Parameters that can reflect the degree of disturbance include: water temperature, substrate composition, bank and bed stability, sedimentation rate, physical parameters ("e. g." turbidity) and water chemistry (nutrients, contamination). Disturbances of such factors can potentially make the water bodies unsuitable for animals (Aurouet et al., 2005; Munné et al., 2012). As we look from protected areas to urban areas following the coarse categorizations of the study sites, the results show evidence of a levelling of impacts as the number and intensity of multiple anthropogenic pressures accumulate.

While optimal reference sites would represent pristine conditions, this objective is unrealistic in Burkina Faso as it is in most continents north of Antarctica. However, in the absence of patently unimpacted sites, a base level of impact must be defined as a reference level. It is therefore important to select representative reference sites that are least disturbed, because the definition of the reference site has important consequences for development of biological indicators and attainment of threshold values (Hering et al., 2003; Pardo et al., 2012). Here, sites in the protected areas can reasonably be considered as good reference sites as far as they show very low impact levels. These areas show some relatively 'natural' characteristics that are hardly distorted by permanent or significant human disturbances. The designation of protected status allows these areas to benefit from better management that preserves near-natural conditions. Both cluster and cross-table analysis support strongly our conclusion that protected areas can reliably be used as reference sites, and shows the suitability of ordinating these four communities using these classification criteria (Kaboré et al., 2015). The range of different elements used to define such conditions included a wide range of parameters related to the land use, hydro-morphological characteristics and water quality. Our criteria for selecting the reference sites also generally meet the requirements outlined by other authors (Thorne and Williams, 1997; Dallas, 2007; Lakew and Moog, 2015). Here, as the specified environmental features of a protected area, our findings define criteria for what features should be protected and reinforce the need to maintain a range of protected areas for effective biological reference sites. This study yielded a solid first step toward guidelines that scientists throughout West African can now work with to create a single definition of riverine reference conditions. However, Barbour et al. (1999) and Stoddard et al. (2006), among others argue that even if such a single definition is achieved, these criteria could be varied across ecological regions as the characteristics of the landscape and the human use of the landscape. Protected areas enable climate change adaptation and host an important biological diversity crucial for effective conservation of the regional fauna that merits more attention by the competent authorities and scientists. A priori criteria are being increasingly used as cost-effective classification system to calibrate the effects and magnitude of human disturbance on aquatic ecosystems.

5 Conclusion

The running waters of Burkina Faso are threatened by multiple impacts of human activities, notably by severe pollution and habitat degradation from intense urbanization and agriculture. Burkina Faso's legislation recognises that basic human and environmental needs should be met for long-term water ecological services. This study represents the first probe to establish reference condition criteria for the selection of minimally disturbed streams or rivers in the region, and to provide a foundation for ecological status assessment. In view of high population growth and thus rising rates of human pressure and habitat degradation, the identification of key conservation areas e.g. "protected" because they successfully sustain the presence of specific taxa, appears to be crucial for ensuring the long-term sustainability of aquatic biodiversity. This study lays a solid foundation for research to support management by building and sustaining aquatic biodiversity through relatively simple development and application of aquatic biomonitoring tools. Our research demonstrates that such tools could be founded on the reference conditions approach; e.g. a classification system and representative parameters to reflect different degrees of human impact on aquatic ecosystem, for management and conservation of water and rivers systems in West Africa. The authors would like to encourage African limnologists to use their data on biological quality elements (e.g. algae, macrophytes, benthic macroinvertebrates and fish) to refine and test the results of this study to help in the further validation of minimally disturbed sites. This procedure may be very helpful for "early warning" information on hotspots for bio-diversity and conservation. Future improvement of these tools requires integrating science and policy to first, test whether some of the criteria that have been proposed to define reference conditions should be seen as compulsory to classify a site as a reference, and second, for those responsible to formulate and administer policy to commit to long-term monitoring of the integrity of aquatic communities through environmental bio-assessment methods based on the reference condition approach.

Broadly, in Burkina Faso the presence, diversity, trophic level, density and biomass of certain fish and benthic invertebrate genera and species respond negatively to a range of anthropogenic pressures (Melcher et al., 2012; Kaboré et al., 2015). These impacts include over fishing, hydrological alteration, agriculture, water quality, migration barriers, morphological alteration and loss of habitat (Koblinger and Trauner, 2013; Stranzl, 2014; Kaboré et al., 2015). Adequate biological assessment tools enables policy makers and managers to enforce appropriate management plans, and can help to raise public awareness for the protection of water bodies. The reference conditions are a baseline to establish for future comparisons (Hering et al., 2006). Learning the effect disturbances on reference communities can help to guide decision making about land use and restoration useful for resource managers, conservationists, politicians and the general public.

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ARTICLE #5

Environmental Monitoring and Assessment (**under second review**)

Testing the Multimetric index approach to assess the ecological status of water bodies in the West African Sahel and upper Sudan ecoregions

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Abstract

In the view of the ongoing pressures resulting from agricultural activities and urbanization in the West African Sahel, water management tools based on the knowledge of the ecological status of surface water bodies are urgently needed to preserve aquatic resources. To fill these gaps, the benthic macroinvertebrates communities of Sahel rivers were examined in order to test if the multimetric index approach could be developed to assess the ecological quality of rivers. A total of 66 samples sites fell within two continua ranging from "unimpacted reference sites" and "strongly impaired sites"were assessed during this study. Benthic macroinvertebrate were sampled with a hand net following the multi-habitat sampling approach. Keys environmental parameters, including Physico-chemical parameters, hydro-morphology and land use parameters were qualitatively recorded. More than 45 candidate metrics were evaluated in four categories such as composition metrics, functional feeding metrics, diversity metrics and tolerance measures. We used discriminatory power analysis to exclude unsuitable metrics from the data set. After excluding redundant metrics, five core metrics were selected to compose the BBIMI (Burkina Benthic macroinvertebrate multimetric index): %Non-dipterans Insect, % Tolerant dipterans and EPT-family taxa, ASPT-NEPBIOS, ASPT-BMWP. The validation of BBIMI was done with the data from 30 samples for environmental variables using standard stepwise model (PCA regression). The result showed that the BBIMI responded to a set of physico-chemical, hydro-morphology and land use parameters associated to a gradient of human pressures affecting the ecological integrity of waterbodies (R^2=0.85; F= 158.8, p=0.000). This work produced an unprecedented effective tool "BBIMI" for biological monitoring and decision making in water management in Burkina Faso case which can be promising for other West African countries.

Keywords: Multimetric index, running water, West Africa Sahel ecoregion, upper Sudan ecoregion, benthic macroinvertebrates

Introduction

The riverine ecosystems have experienced a long history of human modification of water quality, habitat structure, hydrology regime and hydro-morphological conditions (Allan, 2004; Marzin, 2013) and have therefore become one of the most threatened ecosystem (Dallas, 2000; Wang et al., 2003; Strayer and Dugeon, 2010). In the developing countries, the main causes of water resources degradation and pollution are related to the demographic growth. The greater water demand for industrialisation, urbanization, hydro-power generation, irrigation and stock-water for achieving food security and rural livelihoods have lead to increase water consumption and aquatic ecosystem alteration. A consequence of Mining/ industrial and urban wastes are a source of increased water pollution (Dejoux, 1988; Ouédraogo and Amnyot, 2013). The domestic sewage and run-off from agricultural areas "especially cattle and vegetables farms"(Zimmerman, 1993; Smith et al., 1999; Melcher et al., 2012; Kaboré et al., 2016) are at the base of eutrophication and posing a potential threat to wildlife and human health (Dejoux, 1988; Merata et al., 2013). The rivers provide vital goods and services for communities including water for domestic use, irrigation, industrial use, small business enterprises (e. g. brick making), transportation, electrical power generation, and recreation (UNEP's GEMS/Water Programme, 2008; Merata et al., 2013).
Following the ongoing pressures resulting from agricultural activities and urbanization in the West African Sahel and upper Sudanian ecoregions, the urgent need of water management tools is challenging in the region to preserve aquatic resources.

Across the world, stream assessment has previously been based on several techniques using benthic macroinvertebrates. These techniques include biotic indices such as Saprobic index (Moog et al., 1999), diversity indices (Metcalfe, 1989) and scores system (Armitage et al., 1983; Dickens and Graham, 2002; Ofenboeck et al., 2010) and multimetric indices (Barbour et al., 1999; Thorne and Williams, 1997; Mandaville, 2002) have proven effective in a number of diverse assessment. Currently, the most advanced techniques, including multivariate (Rosenberg et al., 2000; Kokes et al., 2006) and multimetric indices (Barbour et al., 1995; Reynoldson et al., 1997; Karr and Chu, 1999; Hering et al., 2006) have been developed as promising alternatives to biotic indices. The advantages of the multimetric approach combining the sensitivity of many metrics to different aspects. the multimetric indices often reflect combination of parameters and ecological aspects like species richness and/or composition, tolerance or functional composition of the aquatic communities. These metrics have proven sensitive to specific impairments to a different degrees (Resh, 1995; Barbour et al., 1999; Karr and Chu, 1999; Hering et al., 2006). The strength of the multimetric index approach is its ability to integrate information from individual, population, community and ecosystem level (Karr and Chu, 1999; Moog and Sharma, 2005). It could be defined as a "unitless measure which can be used to assess a site's overall condition" , a "flexible tool"(Hering et al., 2006). A multimetric index provides detection capability over a broad range of stressors, by including several characteristics of the sites, and a clear stepwise approaches used by scientist (see Figure 1 adapted from Hering et al., 2006). The fact, that 1) several candidate metrics belonging to different categories are tested, then 2) core metrics chosen of this list 3) The index is validated.

Several authors have emphasized the importance of testing mulimetric index development locally (Barbour et al., 1999; Marzin, 2013). However, Bozzetti and Schulz (2004) have reported that in less developed countries funding is normally insufficient to support long-term studies.The documented efforts for development of benthic macroinvertebrates based mulimetric index have been restricted to few countries, e.g., Namibia (Hay et al., 1996), Kenya (Masese et al., 2009; Raburu et al., 2009, 2009a; Aura et al., 2010), South Africa (Odume et al., 2012), and Ethiopia (Lakew and Moog, 2015). In Burkina Faso there are already indications that benthic macroinvertebrate-based metrics work well and can distinguish well between different impairment types (Kaboré et al., 2016), which offers a basis for a more extensive study and a more targeted testing integrative and cost-effective multimetric for assessing the ecological integrity of the river. The main objectives were; to select the most sensitive metrics and quantify their deviations from the reference situation, and to evaluate the capacity of the index locally.

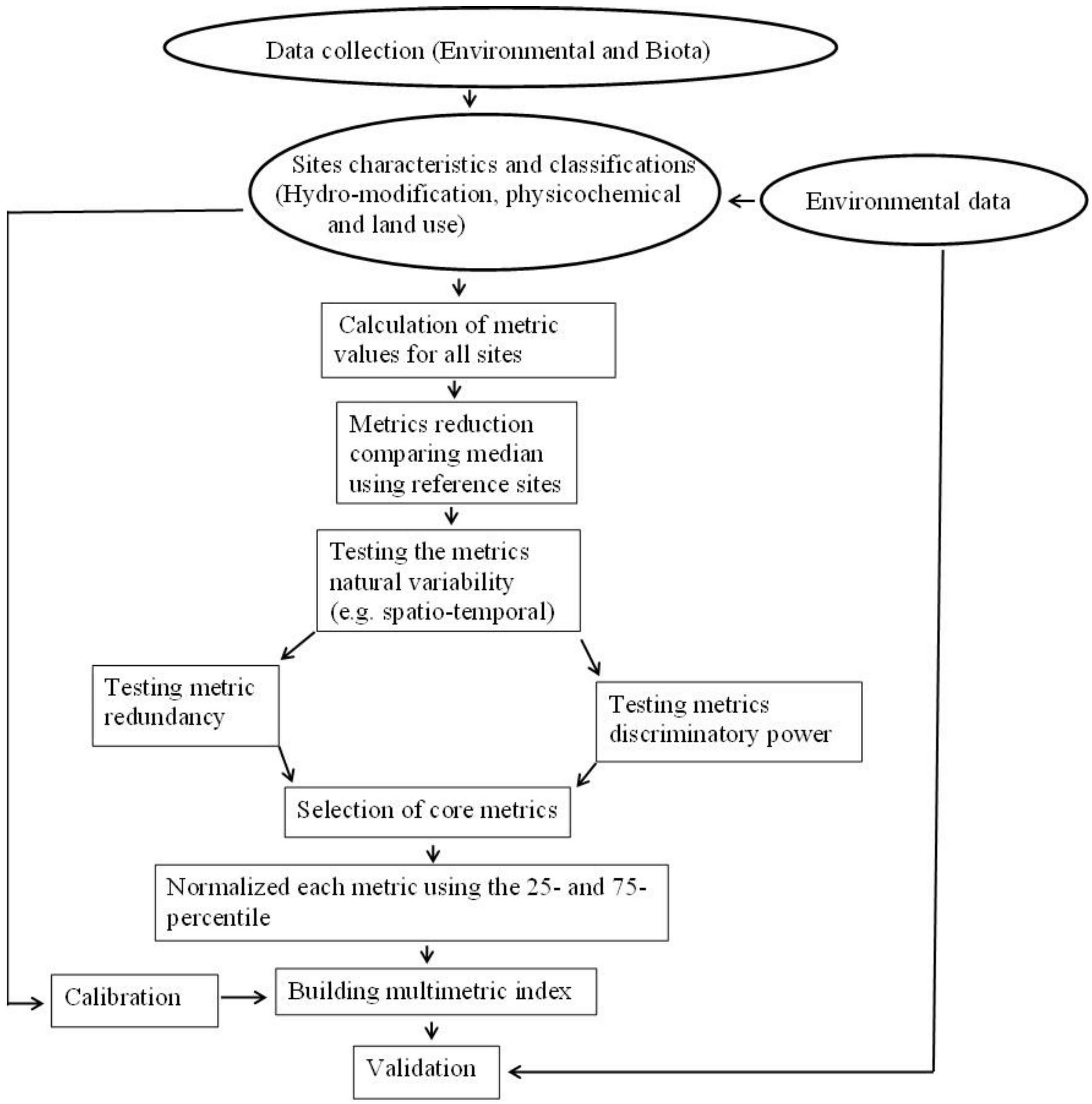

Figure 1 Diagram showing the different steps taken in multimetric index development in the West African Sahel and upper Sudan ecoregions. Ovals represent the pre-steps and squares indicate the steps. (Adapted from Hering et al., 2006).

Methods and materials

Study area

The study was undertaken in three main rivers in Burkina Faso largely described in (United Nations Environment Programme- Global Environment Facility [UNEP-GEF], 2012; Sirima et al., 2009; Kaboré et al., 2016). Nakanbé (formerly White Volta) in the central part of Burkina Faso (area of 70,000 km²), Mouhoun (formerly Black Volta) in the west (92,000 km²) and Comoé in south-west part of Burkina Faso (18,000 km²). Most of the Burkina Faso lie within the West Soudanian ecoregion, but locally according to the difference in climate such as rainfall and phytogeography, the study area was sub-divided in two ecoregions largely described in Kaboré et al. (2016) (Figure 2).

The Volta river including (Nakanbé and Mouhoun) described in (de Condappa, 2008; Sanwidi, 2007; UNEP-GEF, 2012) receives between 1100 mm (in the south) and 500 mm (in the north) rainfall annually, the rainiest month being August (35% of the precipitations). Thus, the discharge is highly sensitive to variations in annual rainfall. The geological formations of the Volta are dominated by the Voltaian system consisted of Precambrian to Paleozoic sandstones, shales and conglomerates. In addition, the Volta comprises Buem formations, Togo series of sedimentary formations, Dahomeyan systems of metamorphic rocks and tertiary formations of the so-called Continental Terminal. The rock basement consists mainly of granites with Birrimian metamorphosed lavas and pyroclastic rocks, Tarkwaian quartzites, phyllites and schists. The Nakanbé and Mouhoun draining the basin volta are ephemeral and therefore dry up during the dry season except the Mouhoun river with permanent runoff from the sedimentary aquifers in the western part of the country.

The Comoé is a perennial river in the extreme south-west of Burkina Faso where the annual rainfall. Natural vegetation, mostly savannah grasslands, uses the major part of the rainfall (around 80%) throughout the basin. exceeds 1000 mm (Sally et al., 2011). The region is one of the more economically vibrant regions of Burkina Faso with several food processing industries installed near Banfora, a town of 70,000 inhabitants on the Abidjan-Ouagadougou road and railway routes (Sally et al., 2011). Comoé River drains an area of 17,590 km² covering 6.4% of the territory surface. Bordering Mali and Ivory Coast, it is located in the Soudanian climatic zone with tropical characteristics. The basin is drained by the Léraba and Comoé rivers, which are perennial, and by several temporary rivers such as Kodoum, Baoué and Iringou. The total annual surface discharge is estimated at 1.6 billion cubic meters of which 85 million cubic meters are retained by dams.

Sampling sites selected within the three basins, ranged from low impaired sites "reference condition" namely protected areas to impaired sites. Due to the lowest levels of human impact and preserving natural riparian vegetation, the protected areas (n=15) were chosen as reference sites. The selected impaired sites (n=51) were converted to land for crops farming and settlements (Kaboré et al., 2016). The references and impaired sites revealed different environmental characteristics (see Table 1). Detailed data sets on environmental variables and benthic macroinvertebrates were collected in two years (2012 and 2014) to test the multimetric appraoch. Three sampling campaigns were conducted according to the rivers' hydrology. The first sampling was conducted in 2012 from July to September corresponding to high water flow (Rainy Season), and low water flow (End of Rainy season) from October to December of the same year. The third sampling was conducted from March to June 2014, corresponding at lowest water flow (dry season). To get a clear understanding on benthic macroinvertebrate data structure, we assessed the spatial and seasonal influences and then data sets was splited in two. Step 1) first 36 sites with macroinvertebrate data were used to calibrate the index using just 2 categories, impaired and reference sites, and then Step 2) 30 other sites experiencing the full range of disturbance (from least impacted reference sites" to "strongly impaired sites) were used to validate the index, after testing the seasonal/annual performance of metrics across all sites.

Table 1 Environmental and physical-chemical variables measured at reference and impaired samples (N=66). In parenthesis are standard deviation values. (*)= significant and (**) indicate non-significant, using Mann-Whitney U-test for reference samples versus impaired. (b) indicates the variables used in the model

Descriptors	Reference (n =15)	Impaired (n =51)	pvalues
Monthly_rainfall (mm) b	91.03 (28.43)	87.31 (17.74)	**
Mean_rainfaill (mm) b	83.72 (18.06)	69.61 (12.72)	**
Monthly_Evaporation (mm) b	172.19 (7.10)	177.85 (4.52)	**
Mean_Evaporation (mm) b	174.51 (6.01)	173.12 (3.48)	**
Monthly_Air_temperature (ºC) b	35.04 (0.88)	36.41 (0.55)	**
Mean _Air _Temperature (ºC) b	34.88 (0.76)	35.62 (0.46)	**
W_Temperature (ºC)b	28.34 (0.65)	30.30 (0.42)	*
pHb	7.17 (0.20)	7.27 (0.10)	**
Conductivity (µs/cm)b	61.05 (6.97)	326.13 (56.89)	*
Disolved Oxygen (mg/l)b	6.66 (0.37)	4.56 (0.41)	*
Nitrate (mg/l)b	2.31 (1.51)	9.75 (1.96)	*
Orthophosphate (mg/l)b	0.39 (0.05)	2.93 (0.49)	**
Ammonium (mg/l)b	1.72 (0.77)	3.71 (1.04)	*
Depth (m)	0.66 (0.05)	1.63 (1.18)	*
Wetted width (m)	7.53 (1.71)	7.69 (1.60)	**
Velocity (m/s)	0.55 (0.07)	0.15 (0.04)	*
Pressures habitat b	1.6 (0.23)	15.98 (1.37)	*

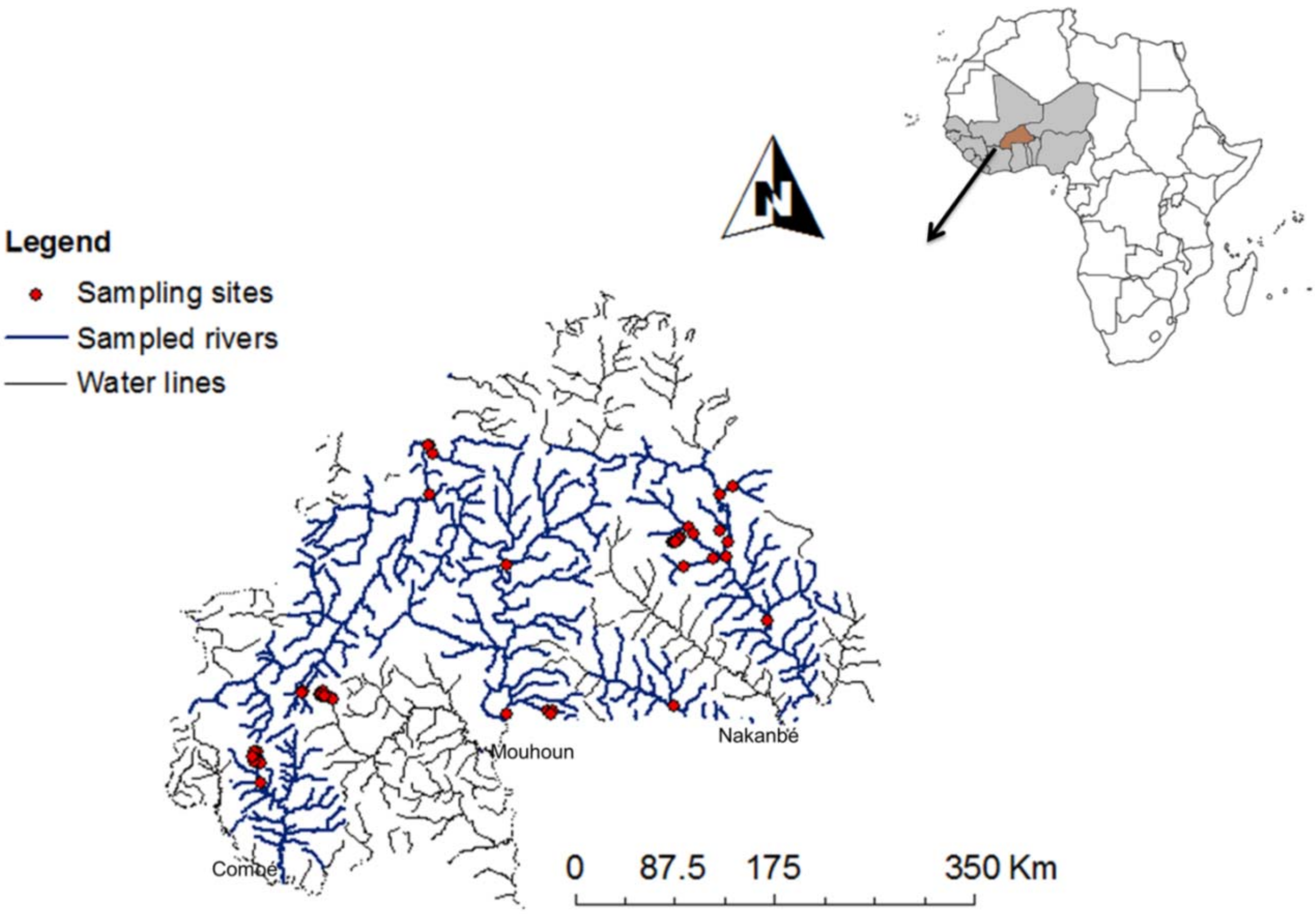

Figure 2 Map of Africa showing the location of Burkina Faso in West Africa. Only, the sampling zone is shown.

Data collection

The environment variables data

Data on several key physico-chemical environmental variables were recorded before the macroinvertebrate sampling to characterize sampling sites. Temperature (°C), conductivity (µS/cm), dissolved oxygen (mg/l) and pH were measured with field multimeters (WTW340I), the velocity (m/s) and water depth and wetted width using Global Water Flow Probe FP111, the tri-weighted measuring tape, respectively at randomly selected transects. The number of measurements (n=8 randomly selected points) was empirically chosen as the smallest statistically relevant quantity (Parasiewicz, 2007). At each site 1.5 L of water was taken in a plastic bottle, stored on ice and sent to the "Laboratoire National d'Anlyse des Eaux" of the "Ministere de l'Environment et du Dévelopment Durable"). Nutrients was determined by molecular absorption spectrophotometry for Nitrate, Ortophosphate, Ammonium. All these parameters were measured in the Laboratoire National d'Anlyse des Eaux" from ,"Ministere de l'Environment et du Development Durable[MEDD] with an accuracy ranking from 1 to 2%. The additional environmental data were gained from the Burkina Faso's national meteorology service (Direction Genérale de la Météo, Ouagadougou): monthly and means annual rainfaill, evaporation and air temperature. The land use pressures, hydro-modification, and water quality, respectively were qualitively assessed in each sampling sites following expert consortium.

Benthic macroinvertebrates collection

Benthic macroinvertebrates were collected in 2012 and 2014 , during the periods when surface water flow was evident at all study sites (beginning and end of the rain seasons, and dry season). Macroinvertebrates were sampled with a hand net (rectangular opening: 25 cm × 25 cm, mesh size:500 µm and sorted following the same protocol as Kaboré et al. (2016). Multi-habitat sampling approach (Moog, 2007) was used , a pooled sample, consisting of 20 sampling units was taken from all habitat types. The animals were mostly identified to the family resolution based on taxonomic manuals and keys (Lévêque and Durand, 1981; Merritt and Cummins, 1984; Tachet et al., 2003) and with direct taxonomic expert support (see acknowledgements).

Selection of reference and impaired sites

In order to establish the benthic macroinvertebrates monitoring program for Burkina Faso running water, we used the reference condition approach, which establishes the basis for making comparisons and detecting use impairment (Barbour et al., 1999; Reece and Richardson, 2000). The reference and impaired sites were chosen following criteria established, as well as Kaboré et al. (2016) based on floodplain use. We characterized sites as reference and impaired based on land use, hydro-modification, water quality. The sites in the protected areas were considered as good reference sites as far as they show very low impact levels. Thirty-seven (37) criteria were selected by an expert consortium and our extensive field trips. The 'a priori' criteria reflect wide range of human uses and impairments on streams/rivers, and that has to fulfil to be considered a reference site (See suplementaryTable A1).

Data analysis

Each component metric of a multiple metric index should be predictably related to specific impacts", and all metrics composing the index should respond to cumulative disturbance which can be use to assess a site's overall condition" (Hering et al., 2006). Importantly, data was analysed in three steps: 1) all metrics are compared between two categories: reference versus impaired "evaluation and calibration", data set 1; 2) Selected 5 metrics are correlated to single environmental variables, 3) BBIMI is regressed against principal components resulting from PCA analysis of environmental variables, dataset 2.

1. Metric calculation

We considered a total of 46 candidate metrics representing various aspects of benthic macro-invertebrate assemblages based on existing knowledge and literature information (Tachet et al., 2003; Barbour et al., 1996). These metrics belonged to four categories such as composition/abundance metrics, sensitivity/tolerance metrics, richness/diversity metrics, and functional metrics that had potential use as biological metrics (Table 2). The selection of those metrics is due to the fact that, they are commonly used in tropical regions and can be linked to the predominant pressures in Burkina Faso.

Table 2 Definition of potential metrics and their response to the impairement

Category	Metrics	Definitions	Expected responses
Tolerance measures	NEPBIOS_score	Nepalese biological scoring system for lowland stream	Decrease
	ASPT _NEPBIOS	Average Score Per Taxa	Decrease
	BMWP_score	biological monitoring working party	Decrease
	ASPT _BMWP	Average Score Per Taxa	Decrease
	SASS_score	South African Scoring System	Decrease
	SASS_ASPT	Average Score Per Taxa	Decrease
	EPT/Chironomidae	Ratio EPT to Chironomidae individuals	Decrease
Richness measures	# ETO	Number of taxa in the insects order of Ephemeroptera (mayflies),Trichoptera (Caddisflies) and Odonata (Damselfly)	Decrease
	# EPT	Number of taxa in the insects order of Ephemeroptera (mayflies), Plecoptera (Stonefly) and Trichoptera (Caddisflies)	Decrease
	# E family	Number of family taxa in order of Ephemeroptera	Decrease
	# T family	Number of family taxa in order of Trichoptera	Decrease
	# P family	Number of family taxa in order of Plecoptera	Decrease
	# O family	Number of family taxa in order of Odonata	Decrease
	# C family	Number of family taxa in order of Coleoptera	Decrease
	# H family	Number of family taxa in order of Hemiptera	Decrease

Table 2 (continued).

Category	Metrics	Definitions	Expected responses
Composition measures	# Decapoda	Number of family taxa in order of Decapoda	Decrease
	# Insect	Number of family taxa in class of Insect	Decrease
	# Bivalvia	Number of family taxa in order of Bivalvia	Increase
	# Diptera	Number of taxa in the order of dipterans	Increase
	# Decapoda	Number of taxa in order of Decapoda	Decrease
	# EPTC	Number of taxa in the insects order of Ephemeroptera (mayflies), Plecoptera (Stonefly), Trichoptera (Caddisfly) And Coleoptera (Beetles)	Decrease
	# EPTO	Number of taxa in the insects order of Ephemeroptera (mayflies), Plecoptera (Stonefly), Trichoptera (Caddisfly) and Odonata (Damselfly)	Decrease
	# BO	Number of taxa in Bivalvia and the insects order of Odonata (Damselfly)	Decrease
	# CO	Number of taxa in the insects order of Coleoptera (Beetles) and Odonata (Damselfly)	Decrease
	# EO	Number of taxa in the insects order of Ephemeroptera (mayflies) and Odonata (Damselfly)	Decrease
	% non-Insects	Percentage composition of non-insects	Increase
	% Non-Diptera Insects	Percentage composition of non- dipteran insects	Decrease
	% dominant tolerant dipterans	Percent of tolerant in order of Diptera (Fly)	Increase
	% EPTESG	Percentage of Ephemeroptera (mayfly), Plecoptera (Stonefly), Trichoptera (Caddisfly) Simuliidae (fly) and Gerridae (bags)	Decrease
	Total Taxa	Overall number of taxa in benthic macroinvertebrate assemblage	Decrease
	% Molluscs	Percentage composition of Molluscs	Increase
	% Oligochaeta	Percentage composition of Oligochaeta	Increase
	% Chironomidae	Percentage composition of Chironomidae	Increase
	Naucoridae/Hemiptera	Ratio Naucoridae to Hemiptera individuals	Decrease
	Paleomonidae/Decapoda	Ratio Paleomonidae to Decapoda individuals	Decrease
	% COP	Percentage composition of Coleoptera, Odonata and Plecoptera	Decrease
	% PT	Percentage composition of Plecoptera and Trichoptera	Decrease
	% H	Percentage composition of Hemiptera	Decrease
	% O	Percentage composition Odonata	Decrease
	% C	Percentage composition of Coleoptera	Decrease
	Density	Number of individual/m²	Variable
Trophic measures	% G/C	Percent of Gatherer-collector functional feeding group	Variable
	% F/C	Percent of Filterer-collector functional feeding group	Decrease
	% SH	Percent of Shredder functional feeding group	Decrease
	% PR	Percent of Predator functional feeding group	variables
	% SC	Percent of Scrapers functional feeding group	variables

2. Metric selection

Two principles were used to identify the core set of candidate metrics selected for the calibration of the Burkina Faso multimetric index. Most of the metrics were expected to decline under perturbation. A) Metrics with many zeros or low values in the reference sites were eliminated because further reduction in values would not be detectable. Furthermore, we used a general rule following Barbour et al. (1996) a median of 15 % or more , and median of 6 taxa or more are minimal thresholds to retain a metric. B) In order to make the index more operational, we further reduced the number of metrics, excluding the ones that were more difficult/costly to examine or to calculate (Baptista et al., 2007). The presence/absence data was used for calculating candidate metric because of the volatile character of the benthic specimens' density (see Barbour et al. 1996). Also the metrics with only very high values in the very few sites (% EPT and % EPTESG, n sites <3) were excluded. The Average Score Per Taxa from South African Scoring System (SASS) was also eliminated from the generation of a multimetric index because (Koblinger and Trauner, 2013) have demonstrated that this South African method excludes many taxa from the study area, and needs to be adapted for West African conditions. We opted to include the EPT taxa number (#EPT] and % tolerant dipteran because they represented different responses to degradation; the first decreases with degradation and the latter increases with impairement, and they are well documented in the tropical region (Thorne and Williams, 1997, Baptista et al., 2007; Sanogo, 2014; Kaboré et al., 2016). For example, trophic metrics, had smaller differences between reference and impaired sites, and were excluded from the index as demonstrated in Baptista et al. (2007) and Kaboré et al. (2016).

Metric selection was conducted based on the 2012 data set (n=36 samples sites) and produced a smaller set of eleven (11) candidate metrics from the 46 potential metrics initially considered (table 3). In addition, to depict the stability of metric (e.g. the seasonal/annual difference across all sites independently of impairment by humans), the selected metrics (11) test was performed using, Mann-Whitney U-test for the years and Kruskal Wallis test for the seasons with treshold of p-value <0.05).

3. Testing metric redundancy and discriminatory power

A correlation analysis was performed in on the two datasets combined to one to check the redundancy of metrics in the information. Strongly correlated metrics could not be used together to determine the impairment, as they contained the same information (Barbour et al., 1996; Hering et al., 2006). In case of high correlation (Spearman $r > 0.8$, $p < 0.01$), one or more redundant metrics were excluded in order to have only one metric representing that information in the index. Then, selected metrics were analysed for discriminatory power in assessing biological impairment. In this step, selection of the final metrics for the integration of multimetric index following two criteria: (1) the statistical significance of metric values differences between "reference" sites and impaired sites using a Mann-Whitney U test (p values of 0.05) and (2) the sensitivity of overlap among interquartile limits (1-3) along with the direction and intensity of the response as the impact increased using box-whisker plots (Barbouret al., 1996). Those metrics that proved to be the most robust following these criteria were considered suitable for the multimetric index. Additionally, the selected metrics were assessed through Spearman correlation for index integration to evaluate the aquatic ecosystem quality in Burkina Faso.

4. Final multimetric index processing

The metrics were normalized using the formula (1) for metrics that decrease with increasing impairment and (2) for metrics that increase with increasing impairment) proposed by (Barbour et al., 1996; Hering et al., 2006). The values were adjusted to a range between 0-10 by applying a simple interpolation (Baptista et al., 2011). The negative values were considered 0, and then the values of each metric are summed to obtain a final score for Burkina Faso multimetric index (BBIMI).

$$\text{Ajusted metric} = \frac{\text{metric value} - 25^{\text{th}} \text{ percentile of impaired sites}}{75^{\text{th}} \text{ percentile of reference sites} - 25^{\text{th}} \text{ percentile of impaired sites}} \times 10 \; [1]$$

$$\text{Ajusted metric} = \frac{\text{metric value} - 75^{\text{th}} \text{ percentile of impaired sites}}{25^{\text{th}} \text{ percentile of reference sites} - 75^{\text{th}} \text{ percentile of impaired sites}} \times 10 \; [2]$$

5. Index validation

The validation of BBIMI was conducted in 30 samples environmental variables (assessed in 2014) judged to be representative of the degradation gradient. A principal component regression using function PCA (Rousseeuw and Driessen, 2000; Walczak and Massart, 1995; Hering et al., 2006) was conducted on the environmental data set quantitatively assessed in the study sites to estimate the values of a response variable at the basis of selected principal components (PCs) of the explanatory variables. The index test was performed by linear regression (Field, 2012) using stepwise method based on selected components. Tested variables were standardized prior to the analysis (Hering et al., 2006). Subsequently, in order to confirm the accuracy of the model, the statistical significance of residual was performed in IC (95%) with Z-residual lie between +1.96 a statistically significant “typical" and -1.96 a statistically significant “atypical" (See also Field, 2012). In addition Durbin-Watson test was performed for p-value range 0 to 4: a value near 2 indicates non-autocorrelation; a value toward 0 indicates positive autocorrelation; a value toward 4 indicates negative autocorrelation. All data analyses were done using SPSS (version 21).

Results

After practical application criteria, a total of 11 metrics were finally retained for the following steps: NEPBIOS_score, ASPT_NEPBIOS, BMWP_score, ASPT_BMWP, # EPT, SASS_score, % Non-dipteran Insects, % dominant tolerant dipterans, Total Taxa, # Insecta and # EPTO (Table 3).

Table 3 Quartile of metrics from data set of first year data of reference samples and reason for first round rejection. Selected candidate metrics are in bold.

Potential metrics	25th%iles	Median	75th%iles	Validity of the metrics (reason for rejection)
NEPBIOS_score	**41**	**73**	**77**	**Valid**
ASPT_NEPBIOS	**5.3**	**6.6**	**7.0**	**Valid**
BMWP_score	**32.3**	**70.3**	**74.8**	**Valid**
ASPT_BMWP	**4.3**	**6.4**	**6.5**	**Valid**
SASS_score	**42.0**	**55.0**	**91.5**	**Valid**
ASPT_SASS	4.5	5.5	6.3	Eliminated (Value low)
EPT/Chironomidae (%)	0.1	13.6	25.3	Values low
#ETO	2.0	5.0	8.0	Values low
#EPT	**2.0**	**3.0**	**6.0**	**Values low**
Density	61.2	108.0	771.2	(volatile value)
% non-Insects	0.0	0.1	33.4	Values low
% Non-Dipteran Insects	**36.8**	**86.6**	**96.8**	**Valid**
% dominant tolerant dipterans	**2.0**	**3.3**	**31.7**	**Valid**
%EPTESG	20.2	60.0	89.8	Eliminate (value low)
Total Taxa	**10.0**	**11.0**	**16.0**	**Valid**
% Molluscs	0.0	0.0	4.1	Values low

Table 3 (continued).

Potential metrics	25th%iles	Median	75th%iles	Validity of the metrics (reason for rejection)
% Oligochaeta	0.0	0.0	0.8	Values low
% Chironomidae	1.3	3.3	26.5	Values low
Naucoridae/Hemiptera	0.0	0.0	20.2	Values low
Paleomonidae/Decapoda	0.0	0.0	26.7	Values low
COP%	4.9	11.6	23.7	Values low
PT%	1.5	5.1	30.7	Values low
H%	0.2	2.2	27.0	Values low
O%	1.3	3.7	9.3	Values low
C%	0.1	7.7	13.3	Values low
# E family	0.5	1.0	1.5	Values low
# T family	0.5	1.0	2.5	Values low
# P family	0.0	0.0	0.5	Values low
# O family	0.5	1.0	4.0	Values low
# C family	1	2	2.5	Values low
# H family	0.5	2	3	Values low
# Decapoda	0	0	1	Values low
# Insects	**7**	**10**	**15.5**	**Valid**
# Bivalvia	0	0	0.5	Values low
# Diptera	1	2	5	Values low
# Decapoda	0	0	1	Values low
# EPTC	2	5	8	Values low
#EPTO	**4**	**6**	**10.5**	**Valid**
#BO	0.5	2	4.5	Values low
#CO	2.5	3	5.5	Values low
#EO	1.5	4	5.5	Values low
#EC	1.5	3	5.5	Values low
%GC	0.6	2.4	16.8	Values low
%F/C	1.4	3.0	28.0	Values low
%SH	0	0	8.3	Values low
%SC	1.4	2	13.6	Values low
%PR	1.4	2.6	5.3	Values low

The comparison beween the years and the seasons using Mann-Whitney U test (pvalues >0.05) and Kruskal Wallis Test (p-values >0.05) based selected metrics did not reveal a clear separation neither between the years, nor among the seasons (Table 4).

Table 4 Discriminatory statistic (P<0.05) within years (Mann-Whitney U) and seasons (Kruskal Wallis Test)

	Years	Seasons
Metrics	Mann-Whitney U (p-values)	Kruskal Wallis Test (p-values)
Sass_score	0.175	0.337
# EPT	0.333	0.619
% Non-dipteran Insects	0.229	0.431
% dominant tolerant dipterans	0.179	0.405
Total_Taxa	0.085	0.222
# Insects	0.195	0.334
NEPBIOS_score	0.089	0.21
ASPT_NEPBIOS	0.537	0.769
BMWP_score	0.196	0.344
ASPT_BMWP	0.219	0.391
# EPTO	0.715	0.655

The redundancy test showed that strong correlations were observed between SASS and total taxa, # Insects, NEPBIOS, BMWP, #EPTO (all R^2= 0.9, respectively, all pvalue <0.05). Others high correlations were reported between BMWP-score and #EPT, Total taxa, # Insects and NEPBIOS-score (R^2=0.89, R^2=0.9, R^2= 0.92, respectively, p-value<0.05). NEPBIOS is also strongly correlated to #EPTO (R^2=0.9, p-value<0.05). Therefore, the SASS, BMWP, NEPBIOS, Total-taxa and #EPTO were considered as redundant eliminated from the integration of the final multimetric index (Table 5).

Table 5 Correlation of benthic metrics. Rejected metrics in bold.** P<0.01

	Sass	EPT	% Non-dipteran Insects	% dominant tolerant dipterans	Total _Taxa	#Insects	NEPBIOS	NEPBIOS _ASPT	BMWP	BMWP _ASPT	EPTO
SASS_score	**1**										
#EPT	0.89**	1									
% Non-dipteran Insects	0.68**	0.56**	1								
% dominant tolerant dipterans	-0.64**	-.549**	-0.82**	1							
Total_Taxa	0.93**	0.74**	0.63**	-0.59**	1						
# Insecta	0.92**	0.73**	0.59**	-0.54**	0.97**	**1**					
NEPBIOS_score	**0.97****	**0.89****	**0.64****	**-0.63****	**0.92****	**0.90****	1				
ASPT_NEPBIOS	0.72**	0.65**	0.64**	-0.59**	0.65**	0.60**	0.76**	1			
BMWP_score	**0.97****	**0.90****	**0.66****	**-0.62****	**0.93****	**0.92****	**0.97****	**0.71****	1		
ASPT_BMWP	0.83**	0.79**	0.68**	-0.67**	0.73**	0.71**	0.82**	0.80**	0.83**	1	
# EPTO	**0.95****	**0.89****	**0.69****	**-0.61****	**0.87****	**0.88****	**0.93****	**0.68****	**0.96****	**0.82****	1

After the discriminatory power analysis, five metrics that have proved to be the most robust following the criteria were selected for being integrated into the Burkina Faso' benthic macroinvertebrate multimetric index (BBIMI): Two Composition metrics (% Non-dipteran Insects and % dominant tolerant dipteran); one Richness metrics (EPT Taxa); Two Tolerance metric (ASPT_NEPBIOS and ASPT_BMWP) (Table 6; Fig. 3).

Table 6 Final metrics selection criteria

	U_test	pvalues	Sensitivity score	Meets the test criteria
% Non-dipteran Insects	20.5	0.001	3	yes
% dominant tolerant dipterans	25.5	0.002	3	yes
# EPT	29	0.002	3	yes
ASPT_BMWP	50	0.039	2	yes
ASPT_NEPBIOS	22	0.001	3	yes
Total_Taxa	75	0.288	0b	no
#Insects	71.5	0.228	0b	no

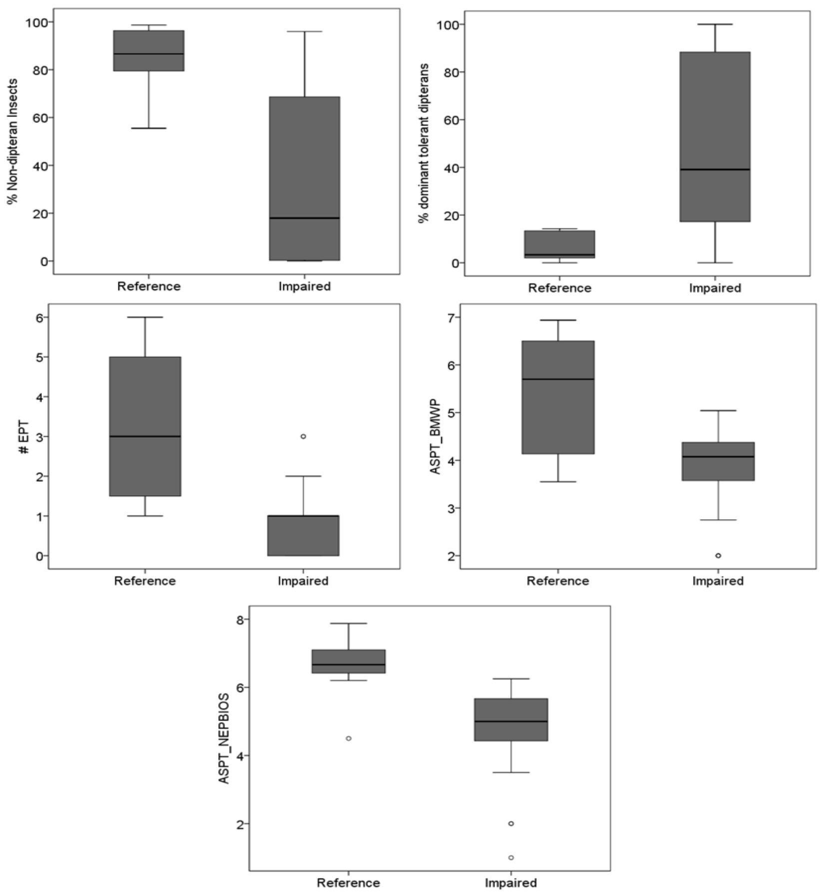

Figure 3 Box- and Whisker plots of each of the 5 core metrics used to discriminate between reference and impaired sites. Median value is shown in each box interquartile ranges (25–75%) percentiles); vertical bars correspond to the minimum and maximum values.

The table 7 showed that the conductivity (µS/cm), the habitat pressures, the nutrients such as Nitrate, Ortophosphate and Ammonium were negatively correlated with %Non-dipteran Insects, #EPT, ASPT_BMWP and ASPT_NEPBIOS, which are positively correlated to dissolved oxygen, water velocity and water depth. While dissolved oxygen, water velocity as well as water depth showed negative correlation with % dominant tolerant dipterans.

The BBIMI score ranges from 0 to 10. The mimimum score of 0 represents the impaired condition, whereas the maximum indicates the reference condition. The BBIMI was quadrisected to provide four ordinal rating for different classification of ecological condition: (Reference condition, BBIMI≥6), (Good, 4≤BBIMI<6), (Poor, 2≤BBIMI<4) and (Bad, <2). Among the 66 samples sites 46 (70%) were correctly classified compared to preclassification by the BBIMI (Kappa=0.29, p<0.05), suggesting that the both pre and post ratings' are similar, with some exceptions.

Table 7 Spearman correlation between selected metrics for index integration and environmental variables. * P<0.05, ** P<0.01. Strong and high correlation between environmental variables and selected metrics are in bold. MoR: monthly rainfaill, MeR: means annual rainfaill, MoEv: monthly evaporation, MeEv: means annual evaporation, MoATem: monthly air temperature, MeATem: means annual air temperature, Wtem: water temperature, Cond: conductivity, DO: Disolved oxygen, Nit: nitrate, Orth: orthophosphate, Am: ammonium, WetW:wetted width Wvel: watervelocity and WDep: water depth and Hab_Pres: habitat pressures

Environmental variables	Metrics				
	%Non-dipteran Insects	%dominant tolerant dipterans	#EPT	ASPT_ BMWP	ASPT_ NEPBIOS
MoR	0.02	0.02	0.07	0.08	0.05
MeR	0.17	-0.15	0.22	0.24	0.15
MoEv	-0.24	0.17	-0.32**	-0.38**	-0.23
MeEv	-0.13	0.17	-0.21	-0.22	-0.14
MoATem	-0.29*	0.24	-0.31*	-0.37**	-0.22
MeATem	-0.26*	0.22	-0.32**	**-0.39****	-0.21
Wtem	-0.04	0.03	-0.28*	-0.29*	-0.34**
PH	0.06	-0.09	0.10	0.16	0.02
Cond	**-0.65****	**0.58****	**-0.71****	**-0.77****	**-0.69****
DO	**0.49****	**-0.39****	**0.53****	**0.53****	**0.54****
Nit	**-0.54****	**0.52****	**-0.55****	**-0.65****	**-0.57****
Orth	**-0.43****	**0.56****	**-0.55****	**-0.53****	**-0.53****
Am	**-0.62****	**0.61****	**-0.73****	**-0.72****	**-0.69****
WDep	**0.48****	**-0.49****	**0.53****	**0.48****	**0.50****
WetW	0.06	-0.08	0.15	0.07	0.08
Wvel	**0.44****	**-0.53****	**0.54****	**0.53****	**0.51****
Hab_Pres	**-0.66****	**0.64****	**-0.78****	**-0.74****	**-0.74****

In the PCAs,the first principal componemt explained 50.3% of the variance and thee second 16.3% (Fig. A1). We can observe the group on the side of first axis made up by the environmental parameters indicating anthropogenic disturbances (Fig. A1 in Electronic Supplementary material). The first PCA axis showed a high correlation with BBIMI, demonstrating a significant response to a gradient disturbance (see Electronic Supplementary Material Tables A2, A3, A4, A5, A6, A7 for more details). Thus, the results from ANOVA (p=0.000, respectively all) supported strongly the realtionship between environmental variables(organic nutriments, and hyrdological pressures) and BBIMI. The R^2 values reported here (R^2=0.85; p=0.000 for validation variables and (R^2=0.67; p=0.000 for calibration variables) showed a significant response to the gradient of disturbance. The both, Durbin-Watson test and standardized residual (~2 and Residual =1.3 for validation samples) indicate that the model is a good representation of our data (see Fig. 4 a , b, c and d).

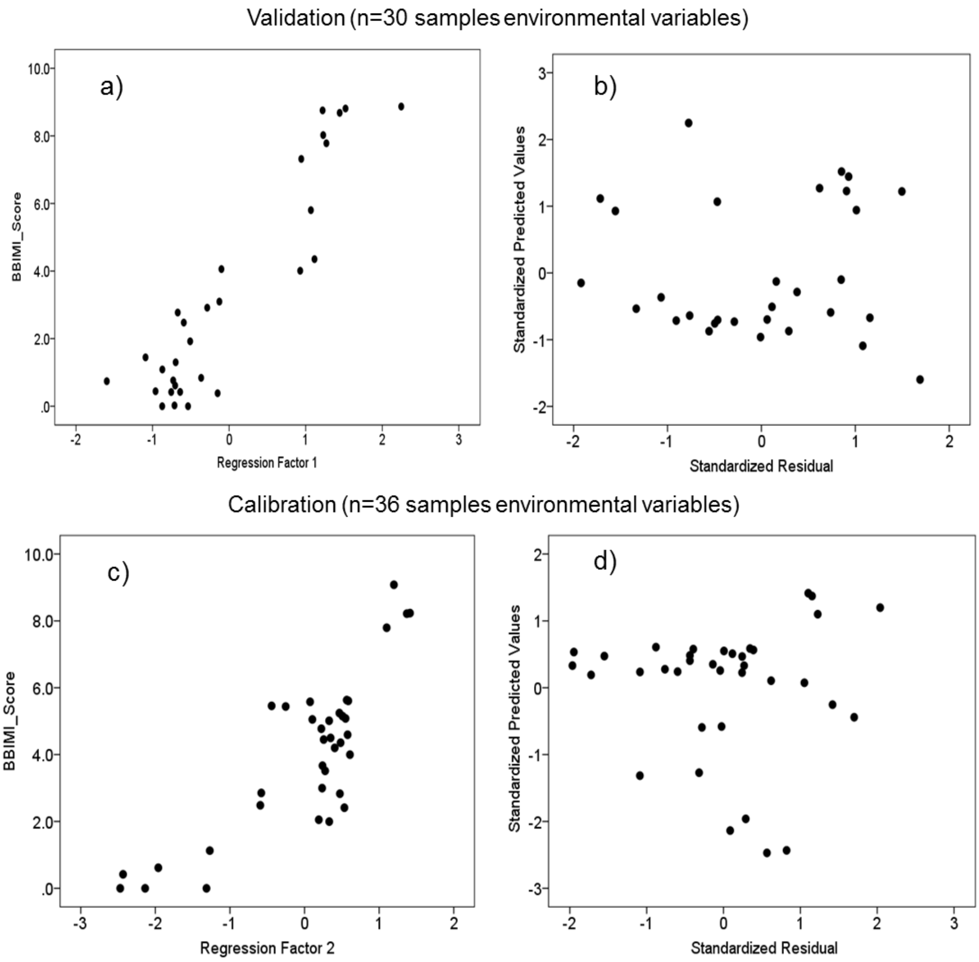

Figure 4 Standard model validation of BBIMI performed with environmental variables. (a, b) indicate model of validation; (c, d): calibration.

Discussion

The transition from undisturbed to human-dominated landscapes is accelerating in sub-Saharan Africa, and, as a result, is already dramatically affecting watersheds in West African Sahel and upper Sudan ecoregions (Melcher et al., 2012; Tampo et al., 2015). Here we covered several major floodplain land use types present in Burkina Faso: from protected areas to extensive and intensive agriculture and advanced urbanization, testing the potential applicability of macroinvertebrates-based multimetric index for monitoring human impact of streams. Many studies findings resulted from the development of benthic invertebrate multimetric index for the running waters in other regions in Europe (Hering et al., 2006), (Mereta et al., 2013; Lakew and Moog, 2015 in Africa), and (Barbour et al., 1996; Baptista et al., 2011, 2007 in America), among others. The most succefful attributes include, %Non-dipterans Insect, ASPT-NEPBIOS, ASPT-BMWP, % Tolerant dipterans and EPT-family. All showed a strong discriminatory power between references and impaired sites. Some metrics were found to be ineffective to determine health of rivers in this regions (Thornes and Williams, 1997; Kaboré et al., 2016).

Kaboré et al.(2016) have demontrated that that taxonomy-based metrics clearly detected the homogenization and drastic impoverishment of benthic fauna in the urban streams, resulting in the strong dominance of tolerant dipteran taxa. The Chironomidae, Syrphidae, Culicidae and Psychodidae, groups commonly considered as predominantly tolerant to pollution (Mandaville, 2002; Kaboré et al., 2016), and showed strong positive correlation with organic nutriment, conductivity, and hydro-modification and land use disturbance. We observed that Chironomini (in particular, Chironomus sp.) were mostly collected fom sites categorized as urban (Kaboré et al., 2016) which have already been shown to be highly tolerant to pollution in other African streams (Odume & Muller, 2011).

The inclusion of the EPT richness in the BBIMI was considered useful, it is good measures that respond to structural changes and a clear response to the impaired gradient in the macroinvertebrate assemblage (Baptista et al., 2011; Poulton et al., 2015). Protected areas that represent “reference conditions” were clearly distinguished by both high diversity and numerical dominance of the EPT-taxa (Kaboré et al., 2016). Most insect taxa belonging to this group have been reported to be highly sensitive to pollution stress (Barbour et al., 1999; Bauernfeind & Moog, 2000). Accordingly, EPT-richness has been widely used as an ecological assessment tool (e.g. Barbour et al., 1999), even if single EPT-taxa may show a certain tolerance to pollution and thus wide distribution in spite of human impact (e.g. Thorne and Williams, 1997; Chutter, 1994; Kasangaki et al., 2008; Masese et al., 2009). Indeed, a previous study investigating the relationship between EPT richness and habitats in Burkina Faso water bodies found that Baetis sp. was found at sites exposed to the effects of intensive agriculture (Kaboré et al., 2016), but the Ephemeroptera include valuable taxa for water quality bioassessment (Imoobe and Ohiozebau, 2009; Emmanuel et al., 2012). The inclusion of Trichoptera was recommended by many authors in the tropical regions for detecting short-term impacts (Kasangaki et al., 2008; Baptisa et al., 2011; Masese et al., 2014), In addition, they are more diversified, abundant and often encounterd in all types of aquatic habitats with a sufficiently good water quality (Guenda, 1996; Merata et al., 2013). Importantly, EPT-based metrics allowed in the previous study to distinguish between extensive and intensive floodplain agriculture (Kaboré et al., 2016), most probably by reflecting the sensitivity of these groups to the variation in pesticides and fertilizer application, sediment runoff and organic pollution (Sutherland et al., 2002; Kasangaki et al., 2008; Ode et al., 2005). In the present study, Plecoptera is represented only by Neoperla sp. (Perlidae). Many studies reported that Perlidae are highly sensitive to environmental degradation (Graf et al., 2002), but Baptista et al. (2007) reported that some genera are partly tolerant to some pressures. We observed that Perlidae were mostly collected from reference sites characterized by natural riparian land use, undisturbed habitat with good hydro-morphology, physico-chemical water quality parameters. It is worthy to consider them as highly sensitive taxa for assessment of West African Sahel and upper Sudan ecoregions rivers (Lakew and Moog, 2015).

The non-dipteran insects have proven to be usefull for detcting the overall increase human presures on waters bodies and rivers systems (Kaboré et al., 2016; Guenda, 1996). Among the non-dipteran insects we found that some taxa of Odonata, Coleoptera, Hemiptera and Lepidoptera are relatively sensitive to pollution and can be used as a good indicator of water quality, even if there is some variation in tolerance to pollution of certain taxa belonging to this group. For example the families such as Elmidae, Gomphidae, Chlorocyphidae and Gerridae were classified among the most sensitive taxa (Kaboré et al., 2016), whereas Coenagrionidae, Hydrophilidae, Corixidae, and Corduliidae are far less sensitive to pollution (Lakew and Moog, 2015; Kaboré et al., 2016). Nevertheless, the non-dipteran insects community has been successfully used as an indicator of habitat and water quality in both lentic and lotic systems (Foote and Hornung 2005). Similar results have already been reported earlier, associating the decrease non-dipteran insects to rising rates of human pressure and habitat degradation (Resh et al., 2000; Megan et al., 2002).

Several versions of ASPT indices have been applied and compared for determining biological water quality in streams (Ferreira et al., 2004; Lewin et al., 2013). Therefore, following the applications in the literature, the ASPT-NEPBIOS and ASPT-BMWP readily give us knowledge on environments polluted by degradable organic matter, and also other types of human impairement (Ofenboeck et al., 2010; Paisley et al., 2013). The performance of ASPT-BMWP and ASPT-NEPBIOS could be due to the fact that: 1) they are extend to geographical application, 2) they are commonly used in bioassessment and biomonitoring of freshwater ecosystems in tropical regions, 3) their orignality to reflect the impact of organic pollution. But many findings have strongly demonstrated that there is still a need for further intensive study and testing of the effectiveness of those indices (Suleiman and Abdullahi, 2011; Koblinger and Trauner, 2013; Zeybek et al., 2014). Thus, these indices may require adaptation for West African Sahel and upper Sudan ecoregions based on its environmental features.

Finally, the level of taxonomic resolution to which organisms are identified is an important and much debated consideration for macroinvertebrate bioassessments (Whittier and Sickle, 2010). Baptista et al. (2011), Stauber and Moog (2000) have demonstrated that the taxonomic resolutions at the genus or species level were found to be valid and sensitive (e.g. greater ability to distinguish least-disturbed from most-disturbed sites). But Carlisle et al. (2007) and Whittier and Sickle (2010) found that the performance differences between the species and family level were not particularly large. In developing countries, West African Sahel and particularly in Burkina Faso due to the limited taxonomic knowledge, as well as the rapidity and cost benefit for managers, family resolution has proven useful in many assessement methods (Thorne and Williams, 1997; Lakew and Moog, 2015).

Due to the difference between seasons that can affect the stability of developed BBIMI, the single metrics were tested because Barbour et al. (1999) and Baptista et al. (2007), Lakew and Moog (2015) argued that the stability multimetric in time and space is fundamental. Our findings revealed that the newly developed BBIMI is stable across seasons (eg. Dry, rainy and end rainy). In addition, we found that macroinvertebrates based indice responded most strongly to gradient of human disturbance, finding consistent with previous reports from tropical (Baptista et al., 2011). Therefore it is a promising tool that can be easily applied to assess the ecological condition of natural stream in Burkina Faso. Land use changes, hydromorphological degradation and general degradation associated to climate change eventually lead to the loss of habitat and water quality,and hence, negatively affect freshwater fauna (Hering et al., 2006a; Kasangaki et al., 2008; Kabore et al., 2016). Long-term studies are needed in these streams/rivers to understand temporal trends of the indice and to differentiate between natural effect and human pressures.

Conclusion and future study

In the present study, by combining the three categories of human pressures, the BBIMI was effective in discriminating reference from impaired sites. The BBIMI showed a strong relationship to a broad range of water quality measures and human disturbances. This study was the first to test the applicability of the multi-metric approach in West African Sahel and upper Sudan ecoregion, and we found that the BBIMI responded appropriately to generalized measurements of disturbance, representing a wide variety of combined stressors, being a suitable and efficient tool to detect environmental impacts.

Our findings indicate that macroinvertebrate communities are very good indicator for assessing ecological integrity of West African Sahel and upper Sudan ecoregions streams. Further study is to take into account river typology, different types of habitats or landscapes or the role of each stressors which have not been addressed here, as well as to extend study to other West Africa region for testing the performance of the index. For instance, this work lays a promising basic tool that provides a biomonitoring tool for management and conservation of water and rivers systems in West Africa. Additionally it delivers reliable information to develop and implement restoration measures by decision makers. On the other hand, as Aschalew & Moog (2015b) argued, the application of the multi-metric method requires time and well trained personnel. Consequently the future activities should also have a focus on the development of a less sophisticated method, eg. a biotic score.

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List of acronyms and abbreviations (alphabetical order)

ADA	Austrian Development Agency
Amm	Ammonium
ANOVA	Analysis of variance
APPEAR	Austrian Partnership Programme in Higher Education & Research for Development
BBIMI	Burkina Benthic macroinvertebrate multimetric index
BNDT	Base nationale de données topographiques
CCA	Canonical correspondence analysis
Cond	Conductivity
CPE	Water Point Committees
CPOM	Coarse particule organic matter
DCE	Directive cadre de l'eau
DGH	General Directorate of Hydraulics
DO	Dissolved Oxygen
E	East
EA	Extensive agriculture
FFG	Functional feeding group
FPOM	Fine particule organic matter
GEMS	Global Environment Monitoring System
GIRE	Gestion Intégrée des Ressources en Eaux
GIS	Geographic information system
HKH	Hindu Kush-Himalayan Region
IA	Intensive agriculture
IC	Confidence interval
IMF	International Monetary Fund
IndVal	Indicator Value
ITCZ	Intertropical Convergence Zone
IUCN	Union Internationale pour la Conservation de la Nature
MAHRH	Ministère de L'Agriculture de L'Hydraulique et des Ressources Halieutiques
MEDD	Ministère de l'Environment et du Development Durable
MEE	Ministère de L'Environment et de L'Eau
mg/l	Milligrams Per Liter
MP	Multiple presures
N	North
NGO	Non-Governmental Organization
Nit	Nitrate
NMS	Non-metric Multidimensional Scaling
OEAD	Austrian Agency for International Cooperation in Education and Research
P	Protected
pH	Potential of Hydrogen
SUSFISH	Sustainable Management of Water and Fish Resources
TDS	Total dissolved solid

Tem	Temperature
U	Urban
UN/ECE	United Nations Economic Commission for Europe
UNEP-GEF	United Nations Environment Programme- Global Environment Facility
W	West
WHO	World Health Organization
Wvel	Water velocity
WWF	World Wildlife Fund
μS.cm-1	Microsiemens per centimeter

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ANNEX: Supplementary tables of Article 1

Table A List of the aquatic benthic macroinvertebrates taxa recorded with their abundances, densities and frequencies in the study area.

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
Arthropoda	Insecta	Coleoptera	Curculonidae	*Stenolophus* sp.	4	4.55	0.05
Arthropoda	Insecta	Coleoptera	Dytiscidae	*Bidessini* sp.	10	3.03	0.12
Arthropoda	Insecta	Coleoptera	Dytiscidae	*Hydrovatus* sp.	136	21.21	1.65
Arthropoda	Insecta	Coleoptera	Dytiscidae	*Laccophilus* sp.	41	15.15	0.50
Arthropoda	Insecta	Coleoptera	Dytiscidae	*Methles* sp.	9	4.55	0.11
Arthropoda	Insecta	Coleoptera	Dytiscidae	*Yola* sp.	9	4.55	0.11
Arthropoda	Insecta	Coleoptera	Dytiscidae	*Neptosternus* sp.	142	7.58	1.72
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia* sp.	16	7.58	0.19
Arthropoda	Insecta	Coleoptera	Elmidae	*Elmis* sp.	20	3.03	0.24
Arthropoda	Insecta	Coleoptera	Elmidae	*Leptemis* sp.	8	4.55	0.10
Arthropoda	Insecta	Coleoptera	Elmidae	*Microdinodes* sp.	3	3.03	0.04
Arthropoda	Insecta	Coleoptera	Elmidae	*Potamodytes* sp.	7	3.03	0.08
Arthropoda	Insecta	Coleoptera	Elmidae	*Pseudomacronychus* sp.	73	15.15	0.88
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis* sp.	14	6.06	0.17
Arthropoda	Insecta	Coleoptera	Gyrinidae	*Orectogyrus* sp.	16	3.03	0.19

Table A (continued).

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
			Hydraenidae	*Hydraenopsis* sp.	6	3.03	0.07
			Hydrophilidae	*Amphios* sp.	28	15.15	0.34
				Berosus sp.	26	7.58	0.32
				Ceolostoma sp.	6	6.06	0.07
				Enochrus sp.	20	7.58	0.24
				Helochares sp.	49	19.70	0.59
				Helocharimorphus sp.	4	1.52	0.05
				Regimbartia sp.	11	6.06	0.13
				Sternolophus sp.	36	4.55	0.44
			Lampyridae	*Lampyridae* sp.	2	3.03	0.02
			Noteridae	*Hydrocanthus* sp.	20	7.58	0.24
				Neohydrochantus sp.	12	3.03	0.15
				Canthydrus sp.	79	15.15	0.96
			Scirtidae	*Scirtidae* sp.	30	3.03	0.36
			Spercheidae	*Spercheus* sp.	21	4.55	0.25
		Diptera	Athericidae	*Atherix* sp.	6	3.03	0.07

Table A (continued).

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
			Ceratopogonidae	*Bezzia* sp.	28	15.15	0.34
			Chaoboridae	*Chaoborus* sp.	14	10.61	0.17
			Chironomidae	Chironomini	4097	43.94	49.66
				Chironomus sp.	15468	33.33	187.49
				Tanypus sp.	126	25.76	1.53
				Tanytarsus sp.	37	9.09	0.45
			Culicidae	Culicidae	3208	25.76	38.88
				Aedes sp.	159	10.61	1.93
			Ephydridae	Ephydridae	195	12.13	2.36
			Limoniidae	*Antocha* sp.	1	1.52	0.01
			Psychodidae	Psychodidae	1508	13.64	18.28
			Simuliidae	*Simulium aureosimile*	2	1.52	0.02
				Simulium adersi	6	1.52	0.07
				Simulium ruficorne	7	1.52	0.08
				Simulium sp.	1516	18.18	18.38
			Stratomyiidae	Stratomyiidae	4	4.55	0.05

Table A (continued).

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
			Syrphidae	*Chrysogaster* sp.	68	1.52	0.82
				Eristalis sp.	314	13.64	3.81
			Tabanidae	*Chrysops* sp.	19	13.64	0.23
				Tabanus sp.	4	3.03	0.05
			Tipulidae	Tipulidae	5	3.03	0.06
		Hemiptera	Belostomatidae	*Appasus* sp.	92	3.03	1.12
				Belostoma sp.	37	9.09	0.45
				Diplonycus sp.	30	16.67	0.36
			Corixidae	*Micronecta* sp.	255	24.24	3.09
			Gerridae	*Limnogonus* sp.	4	6.06	0.05
				Hynesionella sp.	10	3.03	0.12
				Rhagadotarsus sp..	22	16.67	0.27
			Nepidae	*Laccotrephes* sp.	12	3.03	0.15
			Ranatridae	*Ranatra* sp.	7	7.58	0.08
			Notonectidae	*Notonecta* sp.	106	13.64	1.28
			Pleidae	*Plea* sp.	12	4.55	0.15

Table A (continued).

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
			Hydrometridae	*Hydrometra* sp.	19	4.55	0.23
			Helotrephidae	*Esakiella* sp.	100	12.12	1.21
			Naucoridae	*Macrocoris* sp.	28	13.64	0.34
				Naucoris sp.	9	7.58	0.11
			Herbridae	*Herbrus* sp.	6	3.03	0.07
			Veliidae	*Rhagovelia* sp.	71	15.15	0.86
		Ephemeroptera	Baetidae	*Baetis* sp.	926	50.00	11.22
				Centroptilum sp.	86	13.64	1.04
				Cleon sp.	4	3.03	0.05
			Caenidae	*Caenomedea* sp.	73	18.18	0.88
			Ephemerellidae	Ephemerellidae	6	3.03	0.07
			Heptageniidae	*Notonurus* sp.	61	7.58	0.74
			Leptophlebiidae	*Euthraulus* sp.	204	12.12	2.47
			Polymitarcyidae	*Ephoron* sp.	18	6.06	0.22
			Tricorythidae	*Trichorythus* sp.	15	3.03	0.18
		Lepidoptera	Pyralidae	Pyralidae	7	4.55	0.08

Table A (continued).

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
		Odonata	Aeshnidae	*Anax* sp.	2	3.03	0.02
			Chlorocyphidae	*Chlorocypha* sp.	21	6.06	0.25
			Coenagrionidae	*Coenagrion* sp.	108	25.76	1.31
				Enallagma sp.	20	1.52	0.24
				Ishnura sp.	62	6.06	0.75
				Pseudagrion sp.	124	13.64	1.50
			Corduliidae	*Oxygastra* sp.	38	4.55	0.46
				Phyllomacromia sp.	19	10.61	0.23
			Gomphidae	*Onychogomphus* sp.	2	1.52	0.02
				Paragomphus sp.	14	10.61	0.17
				Phyllogomphus sp.	8	3.03	0.10
			Libellulidae	*Orthetrum* sp.	6	3.03	0.07
				Zygonix sp.	130	27.27	1.58
				Bradinopyga sp.	13	4.55	0.16
			Macromiidae	*Macromia* sp.	3	3.03	0.04
		Plecoptera	Perlidae	*Neoperla spio*	99	9.09	1.20
		Trichoptera	Dipseudopsidae	*Dipseudopsis* sp.	4	1.52	0.05

Table A (continued).

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
			Ecnomidae	*Ecnomus* sp.	6	3.03	0.07
			Hydropsychidae	*Cheumatopsyche digitata*	878	16.67	10.64
				Macronematini sp.	2	1.52	0.02
			Leptoceridae	*Leptocerus* sp.	69	10.61	0.84
				Oetis sp.	32	6.06	0.39
			Philopotamidae	*Chimarra petri*	51	3.03	0.62
			Polycentropodidae	Polycentropodidae	4	1.52	0.05
	Malacostraca	Decapoda	Atyidae	*Caridina africana*	135	13.64	1.64
			Gecarcinucidae	Gecarcinucidae sp.	14	7.58	0.17
			Palaemonidae	*Macrobranchium dux*	90	12.12	1.09
	Ostracoda	-	-	Ostracoda	4	6.06	0.05
	Arachnid	-	-	Arachnid	6	6.06	0.07
Mollusca	Bivalvia	Unionoida	Iridinidae	*Aspatharia* sp.	7	1.52	0.08
				Chambardia wahbergi	4	1.52	0.05
				Mutela rostrata	14	6.06	0.17
				Mutela sp.	5	1.52	0.06

Table A (continued).

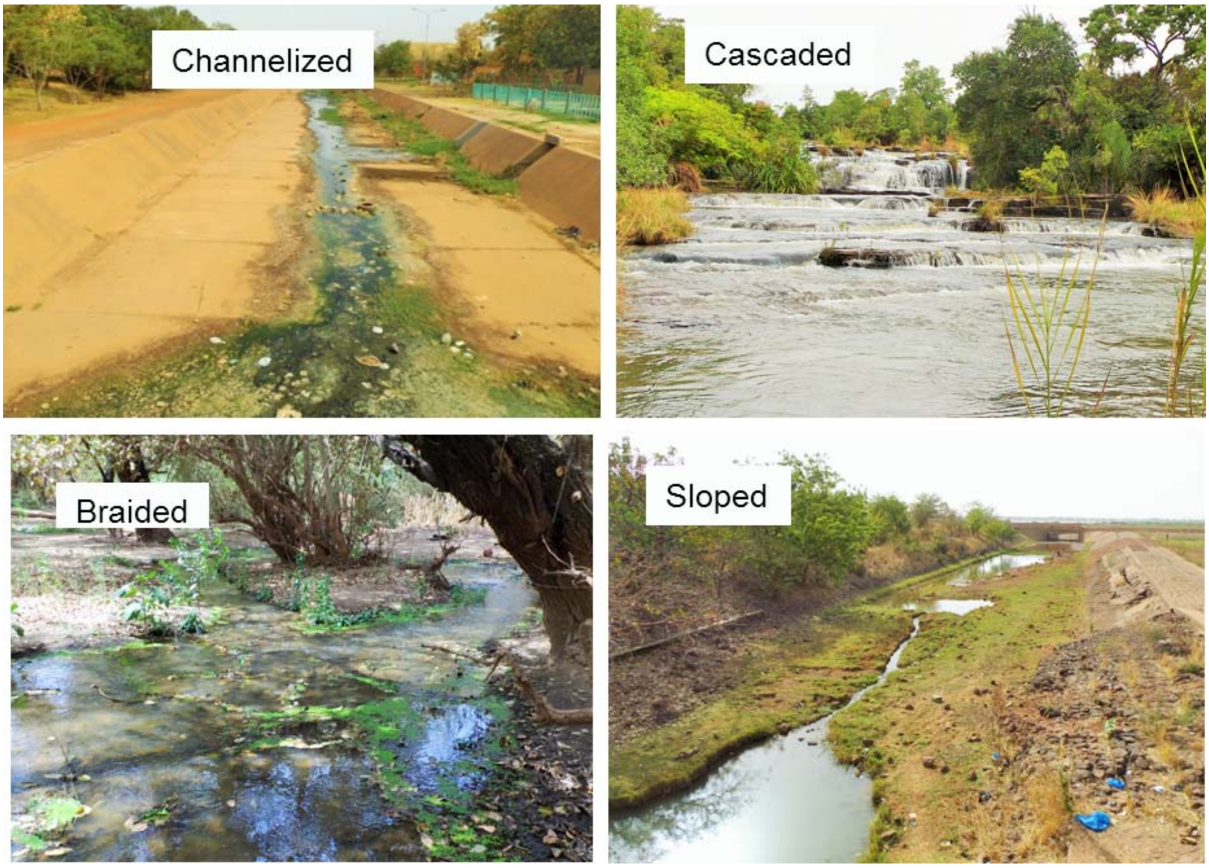
Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
			Unionidae	*Coelatura aegyptiaca*	2	1.52	0.02
				Coelatura sp.	279	4.55	3.38
		Veneroida	Sphaeridae	*Sphaerium* sp.	17	12.12	0.21
	Gastropoda	Archotaenioglossa	Ampullaridae	*Lanistes ovum*	10	3.03	0.12
				Lanistes varicus	23	10.61	0.28
			Lymneidae	*Lymnae natalensis*	46	10.61	0.56
			Planorbidae	*Biomphalaria pfeifferi*	172	13.64	2.08
				Biomphalaria sp.	9	6.06	0.11
				Bulinus camerunensis	30	4.55	0.36
				Bulinus forskali	6	4.55	0.07
				Bulinus globosus	5	4.55	0.06
				Bulinus jousseaumei	23	3.03	0.28
				Bulinus senegalensis	44	12.12	0.53
				Bulinus troncatus	2	1.52	0.02
			Viviparidae	*Bellamya unicolor*	48	4.55	0.58

Table A (continued).

Phylum	Class	Order	Family	*Taxa*	Abundance	Frequency	Density
				Cleopatra bulimoïdes	233	9.09	2.82
		Sorbeochoncha	Thiaridae	*Cleopatra* sp.	212	6.06	2.57
				Potamoda sp.	1	1.52	0.01
Annelida	Clitellata	-	-	*Hirudinea*	182	10.61	2.21
		-	-	*Oligochaeta*	149	28.79	1.81

ANNEX: Supplementary figures of article 1

Figure i Some different types of Rivers encountered in Burkina Faso



Type of habitats sampled

Figure ii Some types of habitats encountered in Burkina Faso

Sampling procedure

Figure iii Field sampling steps. (a) Indicates benthic collection, (b) = pre-sorting, (c) =sample preserved and d) =containers labelled.

Sorting in Laboratory

Figure iv Some steps of benthic macroinvertebrates sorting in laboratory. (a) sorting under microscope (b) Petri dish per each systematic unit

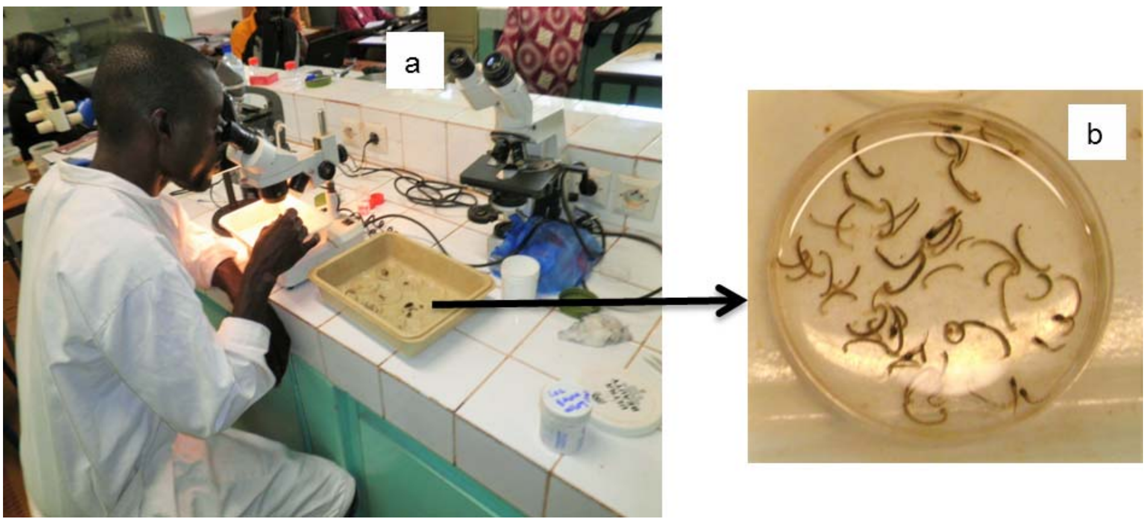
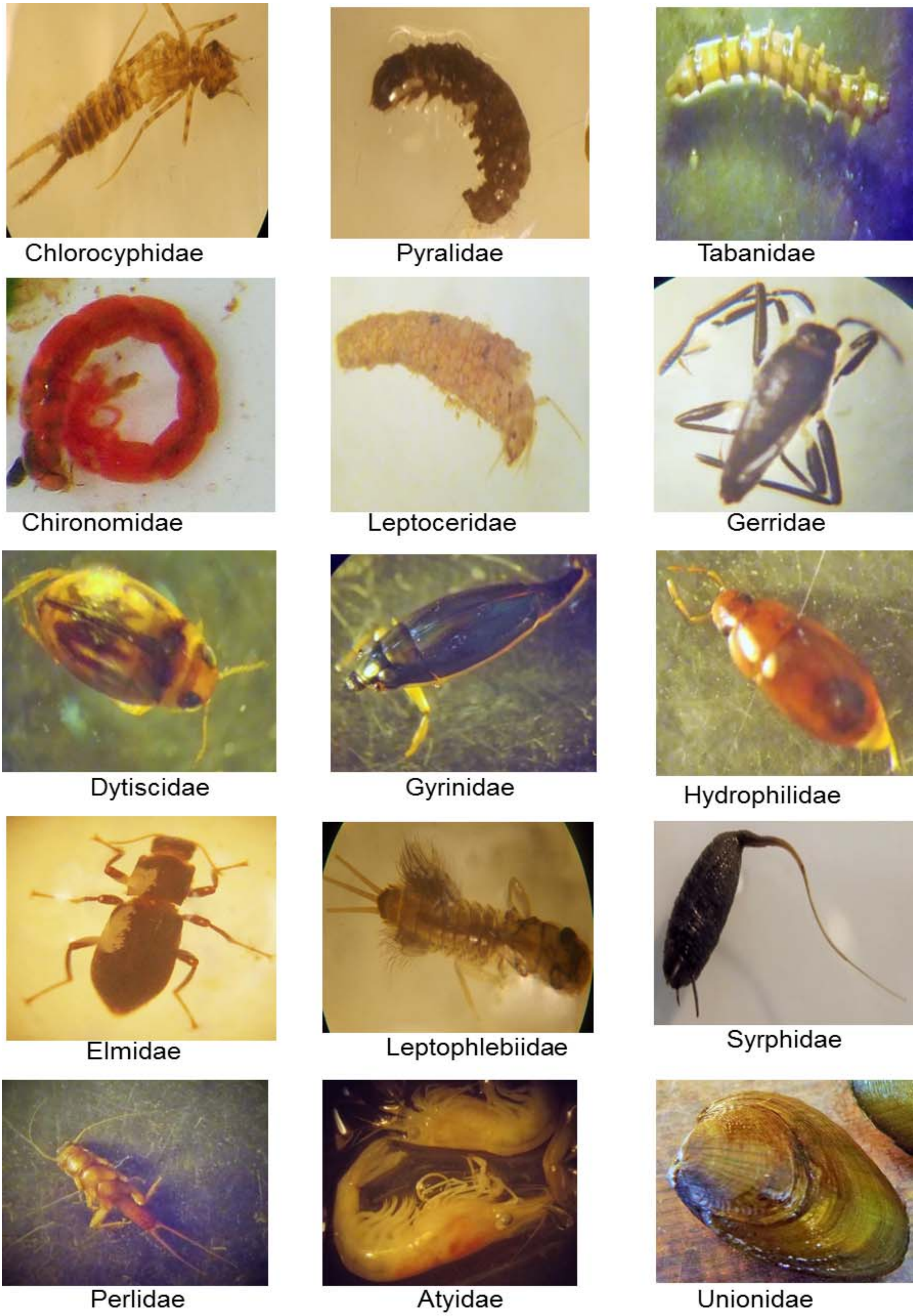


Figure V Some families reported during this study.



Supplementary tables of article 3

Table A1. Output of the constrained canonical correspondence analysis: partitioning of correlations.

	Proportion of variance explained
Total	1
Constrained (land use categories)	0.31
Unconstrained	0.69

Table A2. Output of the constrained canonical correspondence analysis: permutation test for rda under reduced model.

RDA axis	***Df***	***Var***	***F***	***Number of Permutations***	***Pr(>F)***
RDA1	1	1.0771	7.841	999	0.001
RDA2	1	0.4314	3.1405	999	0.016
RDA3	1	0.0574	0.4176	999	0.811

Table A3. Output of the constrained canonical correspondence analysis: variable loadings for single RDA axes.

	RDA1	**RDA2**	**RDA3**
Water temperature	0.13	-0.56	0.00
pH	0.55	0.71	0.07
Conductivity	1.35	-0.02	-0.10
Oxygen concentration	-0.36	0.28	0.18
Water velocity	-0.53	0.35	-0.30

Table A4. List of the aquatic insect taxa found at the twenty nine investigation sites. The (+) indicates the abundance of taxa: sparse (+); abundant (++); highly abundant (+++) and dense (++++). Respective families are reported in bold.

Orders	Taxa	P 1	P 2	P 3	EA 1	EA 2	EA 3	EA 4	IA 1	IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8	IA 9	IA 10	IA 11	IA 12	IA 13	IA 14	IA 15	IA 16	IA 17	U 1	U 2	U 3	U 4	U 5
Diptera	Chironomidae																													
	Chironominae	-	-	-	-	-	-	-	++	++++	+++	++	+	+++	+	+++	+	+	+	+++	+	+++	++	++	-	-	-	-	-	-
	Chironomus sp. (Meigen, 1803)	-	-	-	-	-	+++	+++	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	++	+++	+++	+++	++
	Tanytarsus sp. (Wulp, 1874)	-	+	-	-	+	-	-	-	-	++	-	-	+	-	-	-	-	-	-	-	-	+	-	+	-	-	-	-	-
	Tanypus sp. (Meigen, 1803)	+++	-	+	+	-	-	-	+	-	++	-	-	+	+	++	+	-	-	++	+	+	-	-	-	-	-	++	-	-
	Syrphidae																													
	Eristalis sp. (Latreille, 1804)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	+	+	+	-	-	-
	Culcidae																													
	Aedes sp. (Meigen, 1818)	+++	+	-	-	+	-	+	-	-	-	-	-	-	-	-	-	+	+	-	-	-	+	+	-	++	++	++	++	-
	Limoniidae																													
	Antocha sp. (Sacken, 1860)	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tipulidae (Latreille, 1802)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Ceratopogonidae																													
	Bezzia sp. (Kieffer, 1924)	+	+	-	-	-	+	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Chaoboridae																													
	Chaoborus sp. (Lichtenstein, 1800)	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-
	Psychodidae																													
	Psychoda sp. (Latreille, 1796)	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	+	-	+	+	-	-	-
	Simulium sp. (Latreille, 1802)	+	+++	-	-	-	-	-	-	-	++	-	-	++	+	++++	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tabanidae																													
	Chrysops sp. (Meigen, 1803)	-	-	-	-	+	-	-	-	-	+	-	+	-	+	-	+	-	-	-	-	-	-	+	-	-	-	-	-	-
	Athericidae																													

Table A4 (continued).

Orders	Taxa	P 1	P 2	P 3	EA 1	EA 2	EA 3	EA 4	IA 1	IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8	IA 9	IA 10	IA 11	IA 12	IA 13	IA 14	IA 15	IA 16	IA 17	U 1	U 2	U 3	U 4	U 5
	Atherix sp. (Meigen, 1803)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Stratomyiidae (Latreille, 1802)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Hydrophilidae																													
	Enochrus sp. (Thomson, 1859)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Helochares sp. (Mulsant, 1844)	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	+	+	+	-	+	-	-	-	-	-
	Amphiosps sp. (Erichson, 1843)	-	-	-	-	-	-	-	+	-	-	-	+	-	+	-	-	-	-	-	-	+	+	+	+	-	-	-	-	-
	Ceolostoma sp. (Brullé, 1835)	+	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-
	Helocharimorphus sp. (Kuwert, 1890)	-	+	-	-	+	-	-	-	-	+	-	-	-	-	+	-	+	+	-	-	-	-	-	-	-	-	-	-	-
	Sternolophus sp. (Solier 1834)	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-	-
	Regimbartia sp. (Zaitzev, 1908)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-
	Elmidae																													
	Leptelmis sp. (Sharp, 1888)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coleoptera	*Microdinodes* sp. (Grouvelle, 1906)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Pseudomacronychus sp. (Grouvelle, 1906)	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Stenelmis sp. (Dufour, 1835)	-	-	+	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Potamodytes sp. (Zimmermann, 1919)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
	Dytiscidae																													
	Laccophilus sp. (Leach, 1817)	-	-	-	+	+	-	-	+	-	-	+	+	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Bidessini sp. (Sharp, 1882)	-	-	-	-	-		-	-	-	-	+	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Hydrovatus sp. (Motschulsky, 1853)	-	-	-	-	-	-	-	++	-	-	-	-	-	+	+	-	-	+	-	+	-	+	+	-	-	-	-	-	-
	Laccophilus sp. (Leach, 1817)	-	-	-	+	+	-	-	+	-	-	+	+	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Neptosternus sp. (Sharp, 1882)	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
	Methles sp. (Sharp, 1882)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-

Table A4 (continued).

Orders	Taxa	P 1	P 2	P 3	EA 1	EA 2	EA 3	EA 4	IA 1	IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8	IA 9	IA 10	IA 11	IA 12	IA 13	IA 14	IA 15	IA 16	IA 17	U 1	U 2	U 3	U 4	U 5
	Yola sp. (Gozis, 1886)	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Noteridae																													
	Canthydrus sp. (Say, 1823)	-	-	-	++	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Neohydrocoptus sp. (Satô, 1972)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	-	-	-	-	-	-
	Hydrocanthus sp. (Say, 1823)	-	-	-	-	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-
	Spercheidae																													
	Spercheus sp. (Kugelann, 1798)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	-	-	-	-	-
	Curculionidae																													
	Stenolophus sp. (Dejean, 1821)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Lampyridae (Latreille, 1817)	-	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Gyrinidae																													
	Orectogyrus sp. (Régimbart, 1884)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ephemeroptera	Baetidae																													
	Baetis sp. (Leach, 1815)	++++	-	++	+	+	++	+	-	+	+	-	-		-	++	-	-	-	+	++	++	+	+	++	-	-	-	-	-
	Caenidae																													
	Caenomedea sp. (Thew, 1960)	++	-	-	+	+	++	+	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Heptageniidae																													
	Notonurus sp. (Crass, 1947)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Trichorythidae																													
	Tricorythus sp. (Eaton, 1868)	++	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Leptophlebiidae																													
	Euthraulus sp. (Barnard, 1932)	++	+++	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lepidoptera	Pyralidae (Latreille, 1802)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
Plecoptera	Perlidae																													
	Neoperla spio (Newman, AE, 1839)	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table A4 (continued).

Orders	Taxa	P 1	P 2	P 3	EA 1	EA 2	EA 3	EA 4	IA 1	IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8	IA 9	IA 10	IA 11	IA 12	IA 13	IA 14	IA 15	IA 16	IA 17	U 1	U 2	U 3	U 4	U 5
	Helotrephidae																													
	Esakiella sp. (China, 1932)	-	-	++	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Naucoridae																													
	Macrocoris sp. (Signoret, 1861)	-	-	+	-	+	-	-	-	-	-	-	-	+	-	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-
	Naucoris cimicoides (Limnaeus, 1758)	-	-	-	-	-	-	-	+	-	+	-	-	-	-	-	-	-	+	-	-	+	+	-	-	-	-	-	-	-
	Notonectidae																													
	Notonecta sp. (Linnaeus, 1758)	-	-	-	+	+	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-
	Corixidae																													
	Micronecta sp. (Kirkadly, 1897)	-	-	-	-	-	+++	+	++	-	+	-	-	-	+	+	-	+	+	+	-	+	-	+	-	-	-	-	-	-
	Pleidae																													
	Plea sp. (Leach, 1817)	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
	Ranatridae																													
Hemiptera	*Ranatra linearis* (Limnaeus, 1758)	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-	-
	Gerridae																													
	Limnogonus sp. (Stål, 1868)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	+	+	+	-	-	-	-	-	-
	Rhagadotarsus caprivia hutchinsoni (China, 1931)	-	+	+	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-	-	-
	Veliidae																													
	Rhagovelia sp. (Mayr, 1865)	-	-	-	++	-	-	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Hydrometridae																													
	Hydrometra stagnorum (Limnaeus, 1758)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
	Nepidae																													
	Laccotrephes sp. (Stål, 1866)	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Belostomatidae																													
	Appasus sp. (Amyot & Serville, 1843)	-	-	-	-	-	-	-	-	-	+	+	+	+	-	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
	Belostoma sp. (Latreille, 1807)	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-

Table A4 (continued).

Orders	Taxa	P 1	P 2	P 3	EA 1	EA 2	EA 3	EA 4	IA 1	IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8	IA 9	IA 10	IA 11	IA 12	IA 13	IA 14	IA 15	IA 16	IA 17	U 1	U 2	U 3	U 4	U 5
Odonata	Gomphidae																													
	Paragomphus sp. (Cowley, 1934)	-	+	-	-	-	+	+	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Corduliidae																													
	Phyllomacromia sp. (Selys, 1878)	-	-	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-	+	+	+	+	-	-	-	-	-
	Chlorocyphidae																													
	Chlorocypha sp. (Fraser, 1928)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Coenagriidae																													
	Pseudagrion sp. (Fraser, 1956)	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	++	-	-	-	-	-
	Coenagrion sp. (Kirby, 1890)	-	-	+	-	-	-	-	-	-	-	++	+	+	+	+	-	+	+	+	+	++	+	+	+	-	-	-	-	-
	Aeshnidae																													
	Anax sp. (Selys, 1872)	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Libellulidae																													
	Bradinopyga strachani (Kirby, 1900)	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Zygonix torridus (Kirby, 1889)	-	-	-	-	-	-	-	+	-	-	-	-	+	-	+	+	-	-	-	-	+	+	+	+	-	-	-	-	-
Trichoptera	Leptoceridae																													
	Leptocerus intricatus (Mosely, 1954)	-	+	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Ecnomidae																													
	Ecnomus sp. (McLachlan, 1864)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Hydropsychidae																													
	Cheumatopsyche digitata (Mosely, 1935)	++ ++	+	-	-	+	+	+	-	-	+	-	-	-	+	-		-	-	-	-	-	-	-	-	-	-	-	-	-
	Philopotamidae																													
	Chimarra petri (Gibbs, 1973)	++	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gastropoda	Planorbidae																													
	Biomphalaria sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	-	-	+	+	-	-	-	-	-
	Biomphalaria pfeifferi (Mandahl-Barth, 1959)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	++	-	-	-	-	+	+	-	-	-	-	-	-	-	-
	Bulinidae																													

Table A4 (continued).

Orders	Taxa	P 1	P 2	P 3	EA 1	EA 2	EA 3	EA 4	IA 1	IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8	IA 9	IA 10	IA 11	IA 12	IA 13	IA 14	IA 15	IA 16	IA 17	U 1	U 2	U 3	U 4	U 5
	Bulinus camerunensis (Mandahl-Barth, 1957)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	+
	Bulinus forskalii (Ehrenberg, 1831)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Bulinus globosus (Moreley, 1866)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	+	+	-	-	-	-	-
	Bulinus jousseaumei (Dautzenberg, 1890)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
	Bulinus senegalensis (Müller, 1781)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	++	+	-	-	-	-	-	-	-
	Viviparidae																													
	Bellamya unicolor (Olivier, 1804)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	++	-	+	-	-	-	-	-	-	-	-	-	-	-
	Thiaridae																													
	Cleopatra bulimoïdes (Morelet, 1848)	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	+++	+++	++	-	-	-	-	-
	Cleopatra sp.	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	++	-	-	-	-	-	++++	++	-	-	-	-	-	-
	Potamoda sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	+
	Ampullariidae																													
	Lanistes ovum (Peters, 1854)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Lanistes varicus (Müller, 1774)	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	+	+	+	-	-	+	-	-	-	-	-	-
	Lymnaeidae																													
	Lymnae natalensis (Wright, 1965).	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	-	-	-	-	-
	Unionidae																													
	Coelatura aegyptiaca (Cailliaud, 1827)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Coelatura sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+++	+++	++	-	-	-	-	-
	Iridinidae																													
Bivalvia	*Chambardia wahbergi* (Krauss, 1848)	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mutela rostrata (Rang, 1835)	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	+	-	-	-	-	-	-
	Mutela sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Sphaeridae																													
	Sphaerium (Scopoli, 1777)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	-	-	-	-	-

Table A4 (continued).

Orders	Taxa	P 1	P 2	P 3	EA 1	EA 2	EA 3	EA 4	IA 1	IA 2	IA 3	IA 4	IA 5	IA 6	IA 7	IA 8	IA 9	IA 10	IA 11	IA 12	IA 13	IA 14	IA 15	IA 16	IA 17	U 1	U 2	U 3	U 4	U 5
Decapoda	Atyidae																													
	Caridina africana (Kingsley, 1882)	-	-	-	++	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Palaemonidae																													
	Macrobranchium dux (Lenz, 1910)	-	-	-	++	+	+	+	-	-	-	-	-	-	-	-	-	+	++	+	-	-	-	-	-	-	-	-	-	-
Others	Ostracoda	-	-	-	+	+	-	-	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Oligochaeta	+	-	-	+	-	+	-	-	+	++	+	+	+	+++	+	-	-	-	-	-	-	+	-	-	+	-	-	-	-
	Hirudinea	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Arachnids	+	-	-	-	-	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-

Table A5 List of the aquatic macroinvertebrates functional feeding groups

Taxa	**Functional feeding groups**	**Taxa**	**Functional feeding groups**
Culcidae	C/G	*Hydrovatus*	PR
Anax	PR	Noteridae	PR
Antocha	SH	Nepidae	PR
Psychodidae	C/G	Ampullariidae	SC
Arachnid	PR	Leptoceridae	SH
Baetis	C/G	Gerridae	PR
Viviparidae	SC	*Lymnae*	SC
Belostomatidae	PR	Naucoridae	PR
Bezzia	PR	*Micronecta*	C/G
Planorbidae	SC	Hexaplodinae	C/G
Bulinidae	SC	*Neoperla spio*	PR
Caenidae	C/G	*Notonecta*	PR
Atyidae	CF	*Notonurus*	SC
Coenagrioniidae	PR	Ostracoda	C/G
Irridinae	C/F	Gomphidae	PR
Chaoborus	PR	Corduliidae	PR
Cheumatopsyche	C/F	Pleidae	PR
Chimarra	C/F	Pyralidae	SC
Chironomus.	C/G	Hydrometridae	PR
Chironominae	C/G	*Atherix*	PR
Chrysops	PR	Veliidae	PR
Thiaridae	SC	*Simulium*	C/F
Unionidae	C/F	*Sphaerium*	F/C
Ecnomidae	SH	Curculionidae	SH
Elmidae	SC	Stratomyiidae	C/G
Enochrus	C/G	Tanypodinae	PR
Ephryda	SH	Orthocladinae	C/G
Eristalis	C/G	Tipulidae	SH
Euthraulus	SC	*Trichorythus*	SC
Glossiphoniidae	PA	Libelilludae	PR
Hydrophilidae	SC	Gyrinidae	PR
Laccophilus	PR		

Supplementary figures of article 3

Fig A1 Relationship between site typology and water physicochemical variables measured at benthic sampling (flow velocity, pH, oxygen concentration and water temperature) based on RDA analysis. The two axes accounted for 0.31 of than of among groups dispersion. P=Protected sites, EA= Extensive agriculture, IA= Intensive agriculture, U=Urban sites.

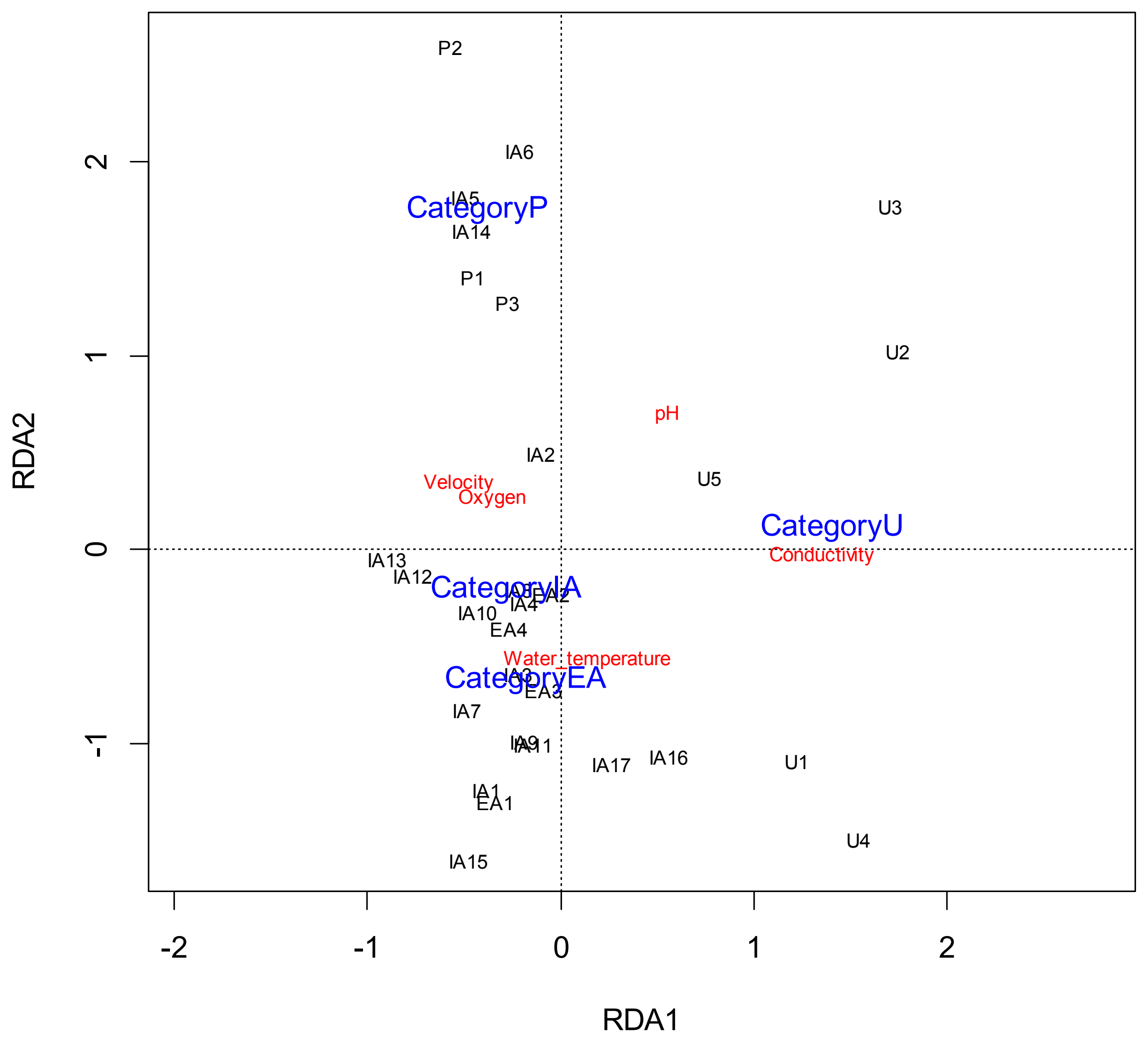


Fig A2 Boxplot showing the variation of EPT-taxa in different land use types. P: Protected areas; EA: extensive agriculture sites; IA: intensive agriculture sites; U: urban sites. Median value is shown in each box; vertical bars correspond to the minimum and maximum values. Letters above boxplots indicate significance of differences between land use types (pairwise multiple comparison tests): only respective pairs with different alphabetical letters differ significantly (p <0.05).

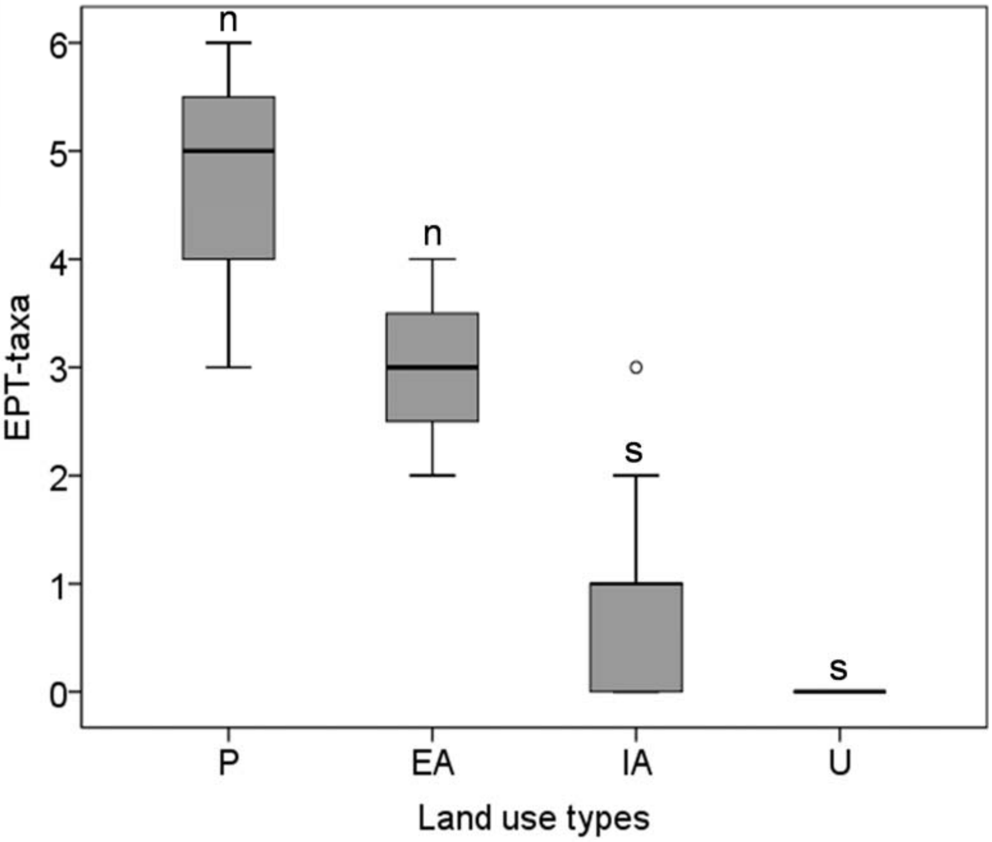


Fig A3 Boxplot showing the variation of non-Dipteran Insects in different land use types. P: Protected areas; EA: extensive agriculture sites; IA: intensive agriculture sites; U: urban stream sites. Median value is shown in each box; vertical bars correspond to the minimum and maximum values. Letters above boxplots indicate significance of differences between land use types (pairwise multiple comparison tests): only respective pairs with different alphabetical letters differ significantly (p <0.05).

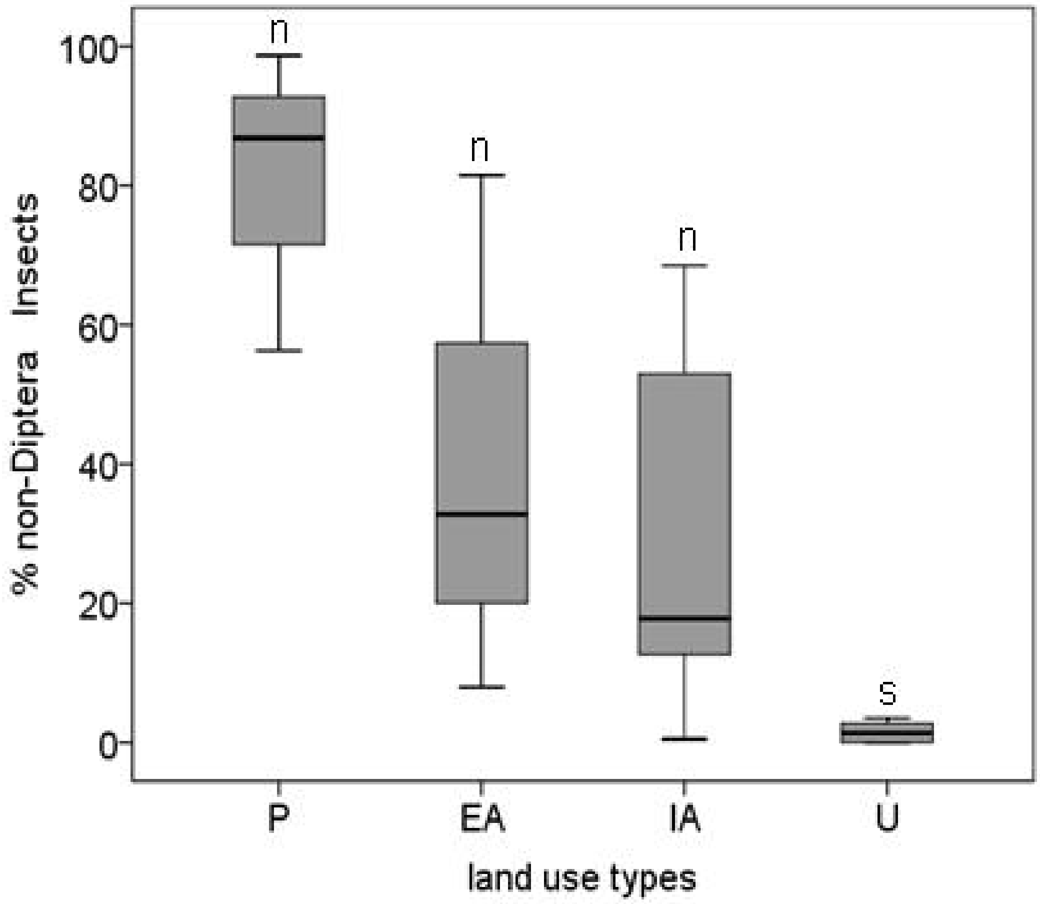


Fig A4 Photos of four riparian land use types: (P: Protected areas; EA: extensive agriculture sites; IA: intensive agriculture sites and U indicate urban stream sites) encountered in the investigations sites.

Supplementary Table of article 4

Table S Characteristics of the 44 study areas belonging to the river catchments Comoé, Mouhoun and Nakanbé. P protected areas, A agriculture sites, UP urban park. LS Lower Soudanian ecoregion, US Upper Soudanian ecoregion

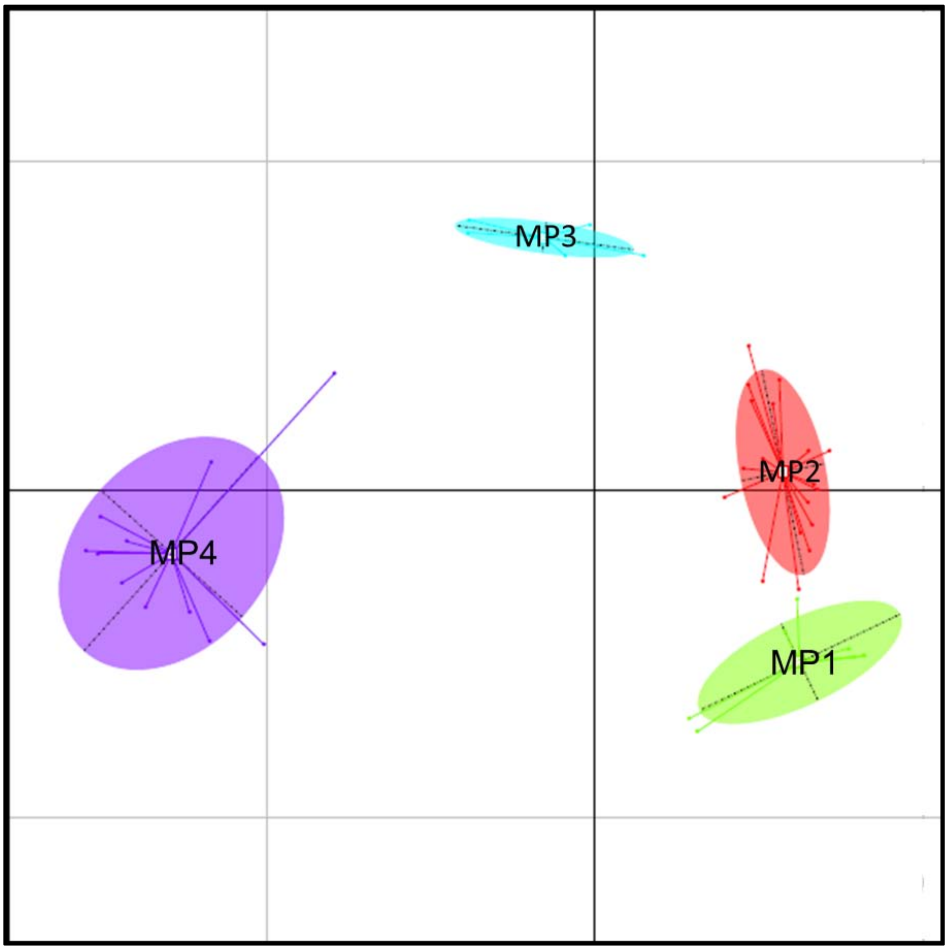
Sites	Dominant land use	River catchment	Eco-geographic types	Latitude (WGS84)	Longitude (N)	Altitude (m)
Karfiguela	P1	Comoé	LS	10.723	-4.823	320
Kou1	P2	Mouhoun	LS	11.187	-4.440	353
Bodjero	P3	Nakanbé	LS	11.091	-1.505	269
Guingette	P4	Mouhoun	LS	11.189	-4.441	359
Bissiga1	P5	Nakanbé	US	12.751	-1.151	273
Koro1	P6	Mouhoun	LS	11.150	-4.207	351
Koro2	P7	Mouhoun	LS	11.146	-4.206	344
Boromo	P8	Mouhoun	LS	12.207	-2.827	250
Nianssan2	A1	Mouhoun	US	12.755	-3.434	253
Nianssan1	A2	Mouhoun	US	13.084	-3.405	253
Korsimoro	A3	Nakanbé	US	12.823	-1.050	282
Peele	A4	Nakanbé	US	12.249	-1.194	261
Boura	A5	Mouhoun	LS	11.049	-2.502	269
Gouran	A6	Mouhoun	US	13.076	-3.406	257
Loumbila	A7	Nakanbé	US	12.495	-1.399	281
Poweri1	A8	Mouhoun	LS	11.049	-2.466	280
Poweri2	A9	Mouhoun	LS	11.028	-2.475	277
Djaraba	A10	Comoé	LS	10.477	-4.775	263
Ouéssa	A11	Nakanbé	LS	11.021	-2.825	236
Lery	A12	Mouhoun	US	12.755	-3.434	263
Tingrela1	A13	Comoé	US	10.654	-4.817	280
Toma île	A14	Mouhoun	US	13.142	-3.451	250
Bissiga2	A15	Nakanbé	US	12.755	-1.152	272
Joint_Nak/Massili	A16	Nakanbé	US	12.266	-1.097	256
DI	A17	Mouhoun	US	13.145	-3.432	253
Segda	A18	Nakanbé	US	12.194	-1.429	276
Kougri	A19	Nakanbé	US	12.378	-1.081	258
Massili	A20	Nakanbé	US	12.443	-1.354	279
Nagreogo	A21	Nakanbé	US	12.475	-1.148	273
Kou2	A22	Mouhoun	LS	11.206	-4.438	340
Niango	A23	Nakanbé	US	11.757	-0.774	238
Bangreweogo1	UP1	Nakanbé	US	12.393	-1.494	294
Bangreweogo2	UP2	Nakanbé	US	12.397	-1.490	288
Houet2	U1	Mouhoun	LS	11.188	-4.287	401
Houet3	U2	Mouhoun	LS	11.172	-4.293	420
Kua	U3	Mouhoun	LS	11.173	-4.259	448
Ouaga1	U4	Nakanbé	US	12.384	-1.496	292
Koko	U5	Mouhoun	LS	11.178	-4.287	420
Dioulassoba	U6	Mouhoun	LS	11.176	-4.298	426
Kadiogo	U7	Nakanbé	US	12.384	-1.516	292

Table S (continued).

Sites	Dominant land use	River catchment	Eco-geographic types	Latitude (WGS84)	Longitude (N)	Altitude (m)
Nianko	U8	Nakanbé	US	12.425	-1.463	285
Houet1	U9	Mouhoun	LS	11.173	-4.296	420
Tengrela 2	U10	Comoé	LS	10.640	-4.773	305
Ouaga2	U11	Nakanbé	US	12.378	-1.501	292

Supplementary Figure of article 4

Fig A1 Hierarchical classification of investigation sites related to their environment variables. The four main groups were shown by dendrogram, which MP1= Protected areas ; MP2-MP3= Extentensive and intensive agriculture area and MP4 indicate urban sites



Supplementary tables of article 5

Table A1 Summary of the selected criteria for determining reference conditions in semi-arid streams and rivers in Burkina Faso

Category	**Attributes**	**Criteria**	**References**
Status		1. Protection status	National Law (1997 and 2001)
		2. Natural river bed dynamics	Mühlmann (2010)
		3. Natural Channel form	Mühlmann (2010)
		4.Substrate composition typical to area	Mühlmann (2010)
		5. Natural bank dynamics	Mühlmann (2010)
Hydro morphological		6. Natural in-channel features typical to the region	Mühlmann (2010)
	River morphology	7. Natural channel structure typical to the typology	Hughes (1995)
		8. No dam barrier or reservoir upstream at 50 m of sites	Present study
	Habitat composition	9. Representative diversity of substrate composition correspond to related typology	Johnson et al.(2013)
		10.Spawning habitats for the natural fish population	Barbour et al. (1996)
		12. No sand or gravel excavation	Nijboer et al. (2004)
	Hydrological condition	13. No alteration of the natural hydrograph and discharge regime	Barbour et al. (1996)
		14. No water extraction for hydropower and industrials uses	Present study
		15. No water extraction for irrigation	Hering et al. (2003)
Physico-chemical features	Point source pollution	16. No point source pollution and Eutrophication	Hering et al. (2003)
		17. No sign of salinity	Present study
		27. Absence of known or expected diffusion input.	Nijboer et al. (2004)
Sensoric features		18. Natural colour and odour	Nijboer et al. (2004)

Table A1 (continued).

Category	Attributes	Criteria	References
		19. Natural foam	Moog, and Sharma (2005)
		20. Natural turbidity	Moog and Sharma (2005)
		21. No waste dumping	Moog, O. and S. Sharma (2005)
	Physico-chemical	22. Conductivity (<75µs/cm)	Present study
		23. Dissolved oxygen (>6.0 mg/l)	Present study
	Non-point source pollution	24. No livestock at 100 m of site	Present study
	Direct water uses	25. No cattle watering	Lakew et Moog (2015)
		26. Minimal washing and bathing activities	Hering et al. (2003)
Land use		28. No crop farming in the riparian zone	Hering et al. (2003)
	Riparian zone land use	29. Natural or near-natural sites, e.g. protected areas (80% of natural vegetation cover typical to area)	Bonada et al.(2004)
		30. No Extensive agriculture	Kaboré et al. (2016)
		31. No Intensive agriculture	Kaboré et al. (2016)
		32. No Urbanisation, industry and other uses	Kaboré et al. (2016)
		33. No evidence fishery activity	Kaboré et al. (2016)
		34. No human settlement	Kaboré et al. (2016)
		35. Riparian zone use for occasional recreation	Kaboré et al. (2016)
		36. Natural maintained lateral connectivity between river and riparian zone	Richardson et al. (2012)
Biological elements		37. Possible Presence of wild Birds and mammals (field observation).	Barbour et al. (1996)

Validation (n=30 samples environmental variables)

Table A2 Output of the model summary

R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change	Durbin-Watson
0.92	0.85	0.84	1.27	0.85	153.49	1	28	0.00	1.73

Table A3 Output of ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	249.02	1	249.02	153.49	0.00
Residual	45.43	28	1.62		
Total	294.45	29			

Table A4 Output of Variance of the error term of the model

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	3.27	0.23		14.06	0.00
REGR factor score 1 for analysis 1	-2.93	0.24	-0.92	-12.39	0.00

Calibration (n=36 samples environmental variables)

Table A5 Output of the model summary

R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change	Durbin-Watson
0.823	0.678	0.67	1.35	0.68	71.52	1	34	0.00	1.55

Table A6 Output of ANOVA

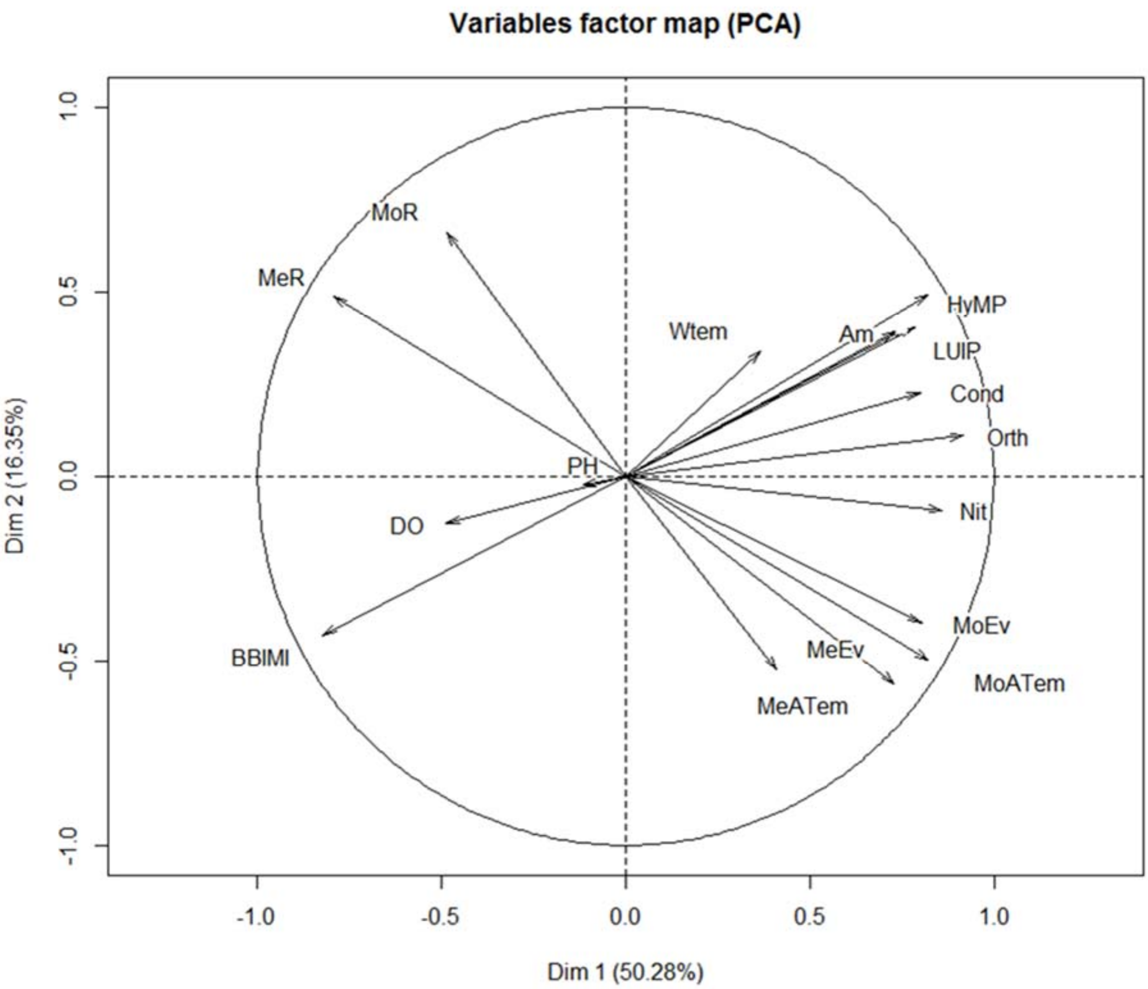
	Sum of Squares	df	Mean Square	F	Sig.
Regression	130.67	1	130.67	71.52	0.00
Residual	62.12	34	1.83		
Total	192.79	35			

Table A7 Output of Variance of the error term of the model

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	3.27	0.23		14.06	0.00
Regression Factor 1	-2.93	0.24	-.92	-12.39	0.00

Supplementary figure of article 5

Fig A1 Principal component analyses (PCAs). First axis grouped environmental parameters used to assess the performance of the index . LUIP: land use pressures, HyMP: hyro-modification pressures, MoR: monthly rainfaill, MeR: means annual rainfaill, MoEv: monthly evaporation, MeEv: means annual evaporation, MoATem: monthly air temperature, MeATem: means annual air temperature, Wtem: water temperature, Cond: conductivity, DO: Disolved oxygen, Nit: nitrate, Orth: orthophosphate, Am: ammonium.



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RESEARCH PAPER

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Dytiscidae, Noteridae and Hydrophilidae of semi-arid rivers and reservoirs of Burkina Faso: species inventory, diversity and ecological notes

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Abstract

Conservation of biodiversity is a major concern due to climate change and pressure from human activities. Knowledge of aquatic insects and their ecology particularly in West Africa is still scanty and fragmented. To fill this gap, we investigated the structure of aquatic beetle assemblages from 18 lentic and lotic water bodies (rivers and reservoirs) in Burkina Faso, and we explored their relationship with environmental variables. Following a multi-habitat sampling approach, all beetles were collected with a hand net, and identified using taxonomic manuals and keys. A total of 11 species of Noteridae in three genera, 27 species of Dytiscidae in 10 genera and 22 species of Hydrophilidae in nine genera were identified in this study. Among these, 24 species are here reported for the first time from Burkina Faso. The species richness was high in the reservoirs with habitats dominated by "water lettuce" *Pistia stratiotes* (species diversity, sd=11.0±9.00 Shannon Wiener index, H=1.79±1.1) and "reed beds" (species diversity, sd=7.63±1.78; Shannon Wiener index, H=1.51±0.25) in comparison with rivers (sd=2.25±0.75; H=0.35±0.20). The results also showed that the species richness is significantly correlated with vegetation cover. Thus, emergend water plants were found to be the main factor influencing beetles species richness. The observed relationship between vegetation cover and beetle richness may provide significant insights that motivate future efforts in research as well as in habitat conservation measures in West Africa.

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Introduction

Freshwater Beetles constitute the second largest aquatic insect order with about 13,500 species world-wide (Balian *et al.*, 2008; Jäch and Balke, 2008). The Afrotropical Region harbours about 2,700 (Jäch and Balke, 2008). There are, however, major information gaps concerning the knowledge of the invertebrate fauna of West Africa. Several recent surveys carried out in Sierra Leone and Côte d'Ivoire have led to the discovery of many new species, especially in the order of Coleoptera (Franciscolo, 1982, 1994; Castellini, 1990; Reintjes, 2004). Aquatic beetles are abundant in many types of aquatic habitats, which are most sensitive to human alterations (García-Criado *et al.*, 1999). Therefore, aquatic beetles are used as bioindicators of water quality and global climate changes as an outcome of human activities (acidification, climate warming, etc.) and serve as "early warning" organisms detecting possible disturbances and changes in ecosystems (Valladares *et al.*, 1994; Collinson *et al.*, 1995; Moreno *et al.*, 1997; Shepherd and Chapman, 1998; Sánchez *et al.*, 2006; Guareschi *et al.*, 2012). However, rapid population growth, constant desertification and climate change have raised a major concern over the management and conservation of the biological integrity in tropical areas. Thus, the Coleoptera became suitable for assessing the conservation status of the sites (Ribera, 2000; Abellán *et al.*, 2005; Segura *et al.*, 2007). However, ecological studies on Afrotropical beetles are scarce (Reintjes, 2004). As a consequence, our knowledge on the ecology of this group of insects in semi-arid areas is extremely poor, despite the current research initiatives. Among West African countries Côte d'Ivoire has received considerable attention from taxonomists working on Noteridae and Dysticidae (Reintjes, 2004). In Burkina Faso only few studies on aquatic insects have focused on beetles (Guenda, 1996; Kaboré *et al.*, 2016). Our study revealed numerous new species records for Burkina Faso. Qualitative data on beetles were collected in several parts of the country, covering different types of waterbodies. Consequently the key aims of this work were 1) to identify and determine the diversity of Dytiscidae, Noteridae and Hydrophilid*ae* in the sampling area and 2) to test and discuss their response to environmental variables.

Material and method

Study area

Burkina Faso is located in the heart of West Africa in the Sub-Saharan region (12° 16′ N, 2° 4′W; Fig. 2). The climate is tropical semi-arid with maximal temperatures varying between 24 and 40°C (Ly *et al.*, 2013). Evapotranspiration is between 1,700 to 2,400 mm per year exceeding annual precipitation which ranges from 400 to 1,200 mm (MECV, 2007). The study was undertaken in two local river catchments: the Nakanbé, White Volta catchment (size 70,000 km²), in the central part of Burkina Faso and the Mouhoun, Black Volta catchment (92,000 km²), in the western part of the country. A total of six investigation areas (i.e. Koubri, Nazinga Game Ranch, Bagré, Boura, Sourou and Ouagadougou) termed by Koblinger and Trauner (2013) were chosen, and 18 investigation sites composed of different habitats were sampled (Tab. 1). These habitats were mainly dominated by the following plants species (Fig.1a-d): water lilies "*Nymphea* sp.", Reeds "Typha", water lettuce "*Pistia stratiotes*" and water hyacinth "*Eichhornia crassipes*".

The area of Koubri was described by Melcher *et al.* (2012) and Koblinger and Trauner (2013) and is located 40 km southeast of Ouagadougou along highway N5. It is located between the latitudes 12° 07' 35.88N & 12° 07' 05.15"N and the longitudes 01° 16' 57.37"W & 01° 26' 08.72"W (WGS84; Google Earth). The sampled reservoirs, Napagbtenga, Poedgo Segda and Noungou, were constructed between 1962 and 1988; their sizes range from five to 430 ha (Ouédraogo, 2010; Melcher *et al.*, 2012).

The Game Ranch of Nazinga is a protected area located in the south of Burkina Faso, 60 km south of the city Ouagadougou close to the border to Ghana. The area is located between the latitudes 11° 03' 04"N & 11° 12' 47"N and the longitudes 01° 23' 25"W & 01°

43'00"W. Eleven (11) reservoirs (18 to 60 ha of large) were created between 1981 and 1987 to improve water supply for wild animals during dry seasons. Among these waterbodies, two reservoirs (Talanga, Kozougou) and one free flowing section (Bodjéro) were sampled (Fig. 1a & 1c).

The Bagré hydro-agricultural dam is located on the Nakanbé River in a large valley about 150 km south-east from Ouagadougou (Villanueva *et al.*, 2006). The large reservoir was created in 1994. The total size and volume have a seasonal fluctuation between 100 and 196 km² and repectively between 0.88 and 1.7 billions m³, whereas the maximum flow rate at the dam is up to 1,500 m³/s (Villanueva *et al.*, 2006).

The Boura reservoir (11° 02' N, 2° 30' W) described by Sanogo *et al.* (2014) was built in a tributary of Mouhoun River to supply water and an integrated irrigation system for the local population. There are about 40,000 inhabitants in 22 villages close to the dam. Aquatic plants in the reservoir are dominated by "Reeds" (Fig. 1b). This water body was built in 1983 by the National Office of Dams and Irrigation (ONBI) and has a maximum capacity of 4.2 million m³.

The Sourou valley described by Dianou *et al.* (2011) and Rosillon *et al.* (2012) is located in the north-west of Burkina Faso. The Sourou River takes its source in Mali. The Sourou valley is especially known for its hydro agricultural installations following the erection of dam valves at the junction of Sourou and Mouhoun rivers in 1984. The construction of the dam increased significantly the stock of water in the Sourou River (600 million m²) through the valley. This availability of water prompted the creation of irrigation systems, hence the importance of the Sourou valley in agricultural production. Three sampling sites (Nianssan 1 and 2, Gouran) have been selected in this area.

The area of Ouagadougou (12° 21′ 26"N, 1° 32′ 7"W), the capital of Burkina Faso, including the sampling sites of Kougri, Bissiga and Korsimoro. This area is characterizd by the tropical climate with average monthly temperatures ranging from 24.5 to 28.8°C. Locally, the mean annual precipitation in Ouagadougou is 740 mm and shows an average of 66 rainy days between April and October (INSD, 2006a). All Bissiga, Korsimoro and Kougri sites are characterized by sediment bed (e.g. mud, sand, fine gravel), whereas the site in Ouagadougou, Reservoir number two, with an area of 226 ha is impacted by *Echhornia* (Fig. 1d).

Beetle sampling and identification

All beetles were sampled with a hand net (rectangular opening: 25 cm x 25 cm, mesh size: 500 µm), following the multi-habitat sampling approach by (Moog 2007). A pooled sample, consisting of 20 sampling units, was taken from each habitat or mixed samples on each sampling site. Samples were fixed in 90% ethanol, sieved in the laboratory and the animals have been sorted using a microscope. All taxa have been identified to the lowest taxonomic level as possible. The organisms were identified based on taxonomic manuals and keys by Tachet *et al.* (2003) and Lévêque and Durand (1981). Additionally direct taxonomic expert support was given by experts from the Natural History Museum Vienna following the most recent revisions. A total collection of all species cited here is deposited and stored in the Natural History Museum Vienna, Austria.

Analysis of environmental variables

In order to assess the diversity for Burkina Faso aquatic beetles, environmental parameters were collected in 2012 over four months in each of the 18 study sites (Tab. 1). The physico-chemical variables include water temperature (°C), conductivity (µS/cm), dissolved oxygen (mg/l) and pH and have been measured *in situ* with field multimeters (WTW340I) between eight am and three pm. The dominating habitat have been qualitatively estimated in each site (Fig. 1a-d).

Data analysis

A grouping (typology) of sampling sites in respect to their environmental descriptors was undertaken by using Ward method cluster analysis (euclidian distance). All variables were z-standardized prior to the analysis. The relationship between beetles richness and environmental variables was explored using Spearman rank correlation. The total species richness was taken as the frequency of the number of taxa present in each investigation site. The Shannon Wiener (H') diversity index was expressed following the formulae below,

$$H' = -\sum_{i=1}^{S} p_i \ln p_i \quad [1]$$

where p_i is the proportion of individuals found in the ith taxon, S is the number of species in samples. All statistical analyses have been performed with IBM SPSS (version 21).

Results

In general most of the study sites had warm water temperatures (mean 30.5 °C), a neutral pH (mean of 7.55), low conductivity (mean 100 µS/cm) and sufficient oxygen contents (Tab. 2). The sampling sites in Ouagadougou receive domestic and industrial wastes. Consequently, high conductivity (406 µS/cm) and low disolved oxygen (1.65 mg/l) were measured in this area.

Table 1. Summury of the sampling sites charasteristics. Abreviation: W_Tem= water temperature, Cond= conductivity, DO= dissolved oxygen, R= reed, S= sediment, E= *Eichhornia*, N= *Nymphea*, P= *Pistia*.

Sites names	Codes	Sampling areas	Latitude (WGS84)	Longitude (N)	Altitude (m)	W_Temp (°C)	pH	Cond (µS/cm)	DO (mg/l)	Water types	habitat covers	Sampling periods
Napagbtenga	R1	Koubri	12.22111	-1.34901	281	33.5	7.01	50.2	6.2	Reservoir	R	October
Poedgo	R2	Koubri	12.18033	-1.34221	279	32	7	49.8	7.3	Reservoir	R	October
Boura	R3	Boura	11.04914	-2.49964	274	32.7	6.75	52	4.1	Reservoir	R	August
Segda	R4	Koubri	12.22352	-1.28419	276	32	7.17	86.5	4.8	Broken reservoir	R	October
Gouran	R5	Sourou	13.08113	-3.42472	257	34	5.7	98.3	5.7	Irrigation channel	R	October
Beguédo	R6	Bagré	11.774	-0.74651	236	28.8	8	53.5	6.2	Reservoir	R	November
Wedbila	R7	Koubri	12.14926	-1.41818	287	7.95	7.95	58.4	7.4	Reservoir	R	October
Nianssan2	R8	Sourou	12.75463	-3.43418	253	35.4	8.3	127	4.5	Irrigation channel	R	October
Korsimoro	S1	Ouaga	12.82348	-1.04957	282	28.4	7.8	91	4.2	Irrigation channel	S	October
Kougri	S2	Ouaga	12.37811	-1.08075	258	35	7.2	55.6	3.9	River	S	October
Bissiga	S3	Ouaga	12.75083	-1.15056	273	35	7.2	55.6	3.9	River	S	October
Bodjéro	S4	Nazinga	11.09143	-1.50459	269	24.4	8.6	67.8	6.6	River	S	December
Kozougou	P1	Nazinga	11.1543	-1.531	273	25.3	8.5	81.2	3.7	Reservoir	P	December
Naguio	P2	Nazinga	11.12763	-1.5834	275	24.4	8.6	67.8	6.6	Reservoir	P	December
Nianssan1	N1	Sourou	13.11078	-3.44917	253	32.6	7.9	196.5	2.4	Irrigation channel	NR	October
Noungou	N2	Koubri	12.20314	-1.30492	278	30.3	7.4	45.1	6.7	Reservoir	NP	October
Talanga	N3	Nazinga	11.18935	-1.52651	275	27.6	7.45	83.6	6.8	Reservoir	N	December
Ouaga	U	Ouaga	12.3909	-1.524	290	27.4	7.2	406	1.65	Reservoir	E	October

Beetles species richness and families in Burkina Faso

A high diversity of water beetles with at total of 60 species was identified in this study. Most of them (27 species) belonged to the family Dytiscidae, followed by Hydrophilidae family (22 species) and 11 species of Noteridae were also recorded. Interestingly 24 species (40% of total species) were recorded for the first time for Burkina Faso (Tab. 3). The most frequently occurring species *Helochares* (*Hydrobaticus*) sp. (55%) and *Hydrovatus aristidis* (28%) belong to

Hydrophilidae and Dytiscidae families, respectively.

Beetles structure in different waterbodies types

The Cluster analysis shows a clear discrimination of investigation sites into five main habitat types (C1 to C5) and their attached cluster groups, which are based on physico-chemical parameters and habitats (Fig. 3). Cluster C1 (R1-R8) indicate semi-aquatic vegetation sites "Reed beds" with water temperature values above 31 °C. In contrast C2 (S1-S4) are characterized by a high sediment load. C3 (P1-P2) reservoirs covered by aquatic plant "*Pistia*" and having a rather high pH of about 8.55. Finally C4 (N1-N3) is composed of mixed habitat with "*Nymphea*", and C5 (E) represents the single reservoir of *Eichhornia* habitat found in the Ouagadougou.

Table 2. Summary statistics of physico-chemical measured in field for the 18 sampling sites. Abbreviation: Max= Maximum, Min= Minimum. Parenthesis indicate the standar deviation.

Physico-chemical descriptors	All sites (n=18)		
	Mean	Min	Max
Temperature	30.43 (±3.52)	24.4	35.4
Conductivity (µS/cm)	97.72 (±85.01)	45.1	406
Disolved Oxygen (mg/l)	5.19 (±1.68)	1.65	7.4
pH	7.55 (±0.73)	6	9

In relation to the identified clusters (groups), some differences related to habitats were observed in the beetle species diversity (Fig. 4). Thus, the species richness per site was high in the reversoirs (C1) coverved by "Reed beds" (mean species diversity, sd=7.63±1.78; mean Shannon Wiener index, H'=1.55±0.26), and in (C3) covered by *Pistia* (P) (sd=11.00±9.00; H'=1.79±1.10), while rivers with a high sediment load (C2) were dominated by mud, sand, fine gravel (sd=1.75±0.48; H=0.35±0.20) show low species diversity.

Relationship between beetles richness and environmental variables

Analyses between beetles communities and their corresponding environmental parameters (Tab. 4) indicated that conductivity was positively correlated with the *Eichhornia* cover (spearman correlation r=0.43, p> 0.05) , and the Hydrophilidae richness (r=0.37, p> 0.05), and negatively correlated with disolved oxygen (r=0.63, p<0.05). The water temperature showed negative correlation with *Pistia* cover (r=0.59, p<0.05). The significant possitive correlations were detected between the pH and *Pistia* cover (r=0.59, p<0.05). The "Reeds" cover were significantly correlated to Noteridae richness (r=0.74, p<0.05, positive); while the buttom sediment (e.g. mud, sand, fine gravel) and *Nymphea* cover is negatively correlated to the beetles richness in general.

Discussion

The total number of beetles species (60) collected in this study is higher than the only earlier study conducted by Guenda (1985) who reported 22 species. The big difference can be explained by the diverse types of habitats sampled; nevertheless the species richness of Noteridae (11) and Dytiscidae (27) found in this project is lower compared to those reported from other West African river catchments. Reintjes (2004) and Vondel (2005) reported 95 species of Dytiscidae and 120 species of Noteridae in other Western Africa subregion. The lower number of our species could be due to the fact that: (1) the vast majority of our samples were taken in one river basin, particulary in the central part of Burkina Faso. Extending the sampling to more habitats covering the entire climate gradient from north to south may increase the number of species in these groups; (2) our study covers only four months (i.e. December, October, November and August). Species may be missed, if they are not prevalent in the study area within this period.

Table 3. List of aquatic main family beetles and species recorded in Burkina Faso waterbodies. (*) first time recorded species in Burkina Faso. R= Reeds, S= sediment, E= Eichhornia, N= Nymphea, P= Pistia.

Families	Species	Acronyms	R1	R2	R3	R4	R5	R6	R7	R8	S1	S2	S3	S4	P1	P2	N1	N2	N3	U
Dytiscidae	*Bidessus sharpi* Régimbart, 1895*	Bid.sh	+	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Bidessus sodalis Guignot, 1939	Bid.so	-	-	-	-	-	-	+	-	-	-	-	-	-	+	-	+	-	-
	Cybister gschwendtneri Guignot, 1935	Cyb.gs	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydroglyphus dakarensis (Régimbart, 1895)	Hydr.da	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
	Hydrovatus aristidis Leprieur, 1879*	Hyv.ar	+	-	+	+	-	-	-	+	-	-	-	-	-	-	-	-	-	+
	Hydrovatus brevipilis Guignot, 1942*	Hyv.br	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Hydrovatus balneator Guignot, 1954	Hyv.pu	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-		
	Hydrovatus cribratus Sharp, 1882*	Hyv.cr	-	-	-	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-
	Hydrovatus facetus Guignot, 1942*	Hyv.fr	-	+	-	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus parvulus Régimbart, 1900	Hyv.pa	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus pictulus Sharp, 1882*	Hyv.ci	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus regimbarti Zimmermann,1919	Hyv.sp	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus suturalis Bilardo & Pederzani, 1978*	Hyv.sa	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Hydrovatus villiersi Guignot, 1955*	Hyv.vi	-	-	-	+	-	+	+	-	-	-	-	-	-	+	-	-	-	-
	Hyphydrus impressus Klug, 1833*	Hyp.im	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Laccophilus occidentalis Biström *et al.*, 2015*	Lac. oc	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Laccophilus inobservatus Biström *et al.*, 2015*	Lac.in	+	-	-	-	+	-	-	-	+	-	-	-	-	+	-	-	-	-
	Laccophilus? modestus Régimbart, 1895	Lac.mo	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
	Laccophilus restrictus (Sharp, 1882)*	Lac.re	-	-	-	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Laccophilus sp. (cf. *restrictus* Sharp, 1882)	Lac.ver	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Laccophilus taeniolatus Régimbart, 1889 *	Lac.ta	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Leiodytes sp.	Lei.sp	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Methles sp.	Met.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Platydytes coarctaticollis (Régimbart, 1894)*	Plat.co	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	+	-	-
	Pseuduvarus vitticollis (Boheman, 1848)	Pse.vi	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Yola cuspis Bilardo & Pederzani, 1979	Yol.cu	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
	Yola nigrosignata Régimbart, 1895*	Yol.nig	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Noteridae	*Canthydrus imitator* Guignot, 1942*	Can.im	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Canthydrus koppi Wehncke, 1883*	Can.ko	+	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
	Canthydrus xanthinus Régimbart, 1895	Can xa.	-	+	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Hydrocanthus colini Zimmermann, 1926	Can.col	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Hydrocanthus sp. (near *grandis*)	Can.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Synchortus simplex Sharp, 1882*	Syn.sp	-	-	+	+	-	-	-	+	-	-	-	-	-	+	-	-	-	-
	Synchortus sp. 1	Syn.sp1	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Synchortus sp. 2	Syn.sp2	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
	Neohydrocoptus koppi Wehncke, 1883*	Neoh.ko	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Neohydrocoptus uellensis (Guignot, 1953)*	Neoh.sp1	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Neohydrocoptus sp.	Neoh.sp2	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
Hydrophilidae	*Allocotocerus* sp.	All.sp	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-
	Amphiops sp. 1	Am.sp1	-	-	+	-	-	-	-	+	-	-	+	-	-	-	-	-	-	-
	Amphiops sp. 2	Am.sp2	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Amphiops sp. 3	Am.sp3	-	-	-	-	+	-	+	-	-	-	-	-	-	-	-	-	-	+
	Amphiops sp. 4	Am.sp4	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Amphiops sp. 5	Am.sp5	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Berosus sp.	Ber.sp	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-
	Coelostoma sp.	Coe. sp	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-
	Enochrus sp. 1	Eno.sp1	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Enochrus sp. 2	Eno.sp2	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Enochrus sp. 3	Eno.sp3	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Helochares (*Hydrobaticus*) sp. 1	Hel.sp1	-	-	-	+	-	-	-	-	-	-	-	-	-	-	+	-	-	-
	Helochares (*Hydrobaticus*) sp. 2	Hel.sp2	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
	Helochares (*Hydrobaticus*) sp. 3	Hel.sp3	+	-	-	-	-	+	+	+	+	-	+	-	-	-	+	-	-	+
	Helochares (*Hydrobaticus*) sp. 4	Hel.sp4	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-
	Helochares (*Hydrobaticus*) sp. 5	Hel.sp5	-	-	-	+	-	-	-	-	-	-	-	-	+	-	-	-	-	-
	Helochares dilutus (Erichson, 1843)*	Hel.di	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-
	Helochares longipalpis (Murray, 1859)*	Hel.lo	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Helochares pallens MacLeay, 1825*	Helo.pa	+	-	+	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-
	Helochares sp.	Hel.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-
	Paracymus chalceus Régimbart, 1903*	Par.ch	+	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-
	Regimbartia sp.	Reg.sp	-	-	-	-	-	-	-	+	-	-	-	-	-	+	+	-	-	-
Total number of species		**10**	**3**	**11**	**16**	**4**	**2**	**8**	**15**	**5**	**1**	**2**		**1**	**3**	**20**	**4**	**2**	**1**	**3**

Despite these restrictions, among the Hydrophilidae four species are newly recorded for Burkina Faso: *Helochares dilutus*, *H. longipalpis* , *H. pallens and Paracymus chalceus*. These four species are widely distributed in western, southern, eastern and central Africa (*Helochares longipalpis*, *H. pallens*, *Paracymus chalceus*). One species (*Helochares dilutus*) does not occur in northern Africa (Fikáček *et al.*, 2012). Out of the 15 species of Dysticidae (*Bidessus sharpi, Hydrovatus aristidis, H. brevipilis, H. cribratus, H. cinctulus, H. villiersi, Laccophilus occidentalis, L. inobservatus, L. taeniolatus, L. restrictus Platydytes coarctaticollis*) newly recorded in Burkina Faso, seven species (*Hydrovatus aristidis,* *H. brevipilis, H. villiers, H. cribratus, Laccophilus restrictus, Yola nigrosignata, Platydytes coarctaticollis, Bidessus sharpi*) are widely distributed in Sub-Saharan Africa (Nilsson *et al.*, 1995; Nilsson, 2001; Reintjes, 2004; Vondel, 2005; Bilardo and Rocchi, 2011, 2013; Nilsson, 2013) and two (*Laccophilus occidentalis, L. inobservatus*) are newly reported species (Biström *et al.*, 2015) . Based on our knowledge three species of Noteridae (*Canthydrus imitator*, *C. koppi* and *Synchortus simplex, Neohydrocoptus koppi, N. uellensis*) are widely distributed in West Africa, southern, Central and eastern Africa (Reintjes, 2004; Vondel, 2005; Guignot, 1959b; Medler, 1980; Bruneau and Legros, 1963; Legros, 1972; Bilardo and Pederzani, 1978; Nilsson, 2006) even though some of them are found in North Africa (Guignot, 1955a). The current knowledge of the water beetle fauna of Burkina Faso is limited and very scattered, a species list for the country is not available. In West Africa, especially in landlocked areas such as Burkina Faso, the species lists are still fragmentary and certainly far from being complete (Reintjes, 2004).

Table 4. correlation matrix of physico-chemical parameters and biological index marked with an asterisk (*) = statistically singnificant (p<0.05).

	W_Temp	pH	Cond	DO	W_Eich	W_Reed	W_Nymp	W_Pistia	B_Sed
W_Temperature	1								
pH	-0.449	1							
Conductivity	-0.021	0.227	1						
Dissolved Oxygen	-0.02	-0.01	-0.626*	1					
W_ *Eichhornia*	-0.31	-0.09	0.433	-0.43	1				
W_Reed	0.341	-0.5	-0.22	0.31	-0.286	1			
W_*Nymphea*	0.227	0.227	-0.09	0.182	-0.105	-0.419	1		
W_*Pistia*	-0.592*	0.591*	0.045	-0.05	-0.105	-0.419	-0.154	1	
B_Sediment	0.091	-0.02	0.045	-0.27	-0.105	-0.419	-0.154	-0.154	1
Hydrophilidae_taxa	0.103	0.363	0.366	-0.39	0.223	-0.175	-0.023	0.28	-0.16
Dytiscidae_ taxa	-0.262	0.015	-0.08	0.401	-0.127	0.317	-0.209	0.046	-0.21
Noteridae_ taxa	0.17	-0.34	-0.06	0.335	-0.265	0.744*	-0.388	-0.121	-0.39

This study revelead that several parameters determine the water beetles distribution. The vegetation cover and the type of water body are the most important. We provide evidence that the water body type and aquatic plants have much stronger influence on beetles species distribution than physico-chemical variables. The physico-chemical variables do not reveal the distribution of beetle species, but they showed the impact of human activies on water bodies. In this study, we found high conductuctivity and lower oxygen contents associated with the invasive *Eichhornia*. These values for the urban reservoir could be water pollution indicators in line with others works such as Benetti and Garrido (2010) and Pérez-Bilbao *et al.* (2014). The variation in species richness offers a good basis for the distinction between beetle communities in reservoirs with different types of aquatic plants ("Reeds", *Nymphea* and *Pistia*) and rivers. The Shannon Wiener diversity index and species richness were higher in reservoir sites than rivers. Our findings corroborate several previous ecological aquatic beetle studies which proved that water bodies and type of habitat were determinant variables for various beetle communities (Batzer and Wissinger, 1996; Reintjes, 2004; Gioria *et al.*, 2010; Epele and Archangelsky, 2012; Silva and Henry, 2013; Sanogo *et al.*, 2014). Despite that, the conductivity, pH values and dissolved oxygen values were quite variable among sites, they did not seem to affect water beetle distributions. Such finding is in line with previous studies which pointed out that these variables had little or no influence on aquatic beetles (Arnott *et al.*, 2006; Pérez-Bilbao *et al.*, 2014). The vegetation cover is a key factor driving assemblage compositions, since many water beetles typical of lentic waters only need a few weeks to colonize temporary sites (Picazo *et al.*, 2012).

Fig. 1. Different types of habitats encountered in the investigation sites. a= water lilies "*Nymphea* sp.", b =Reeds "Typha", c= water lettuce "*Pistia stratiotes*"., d= Water hyacinth "*Eichhornia crassipes*"

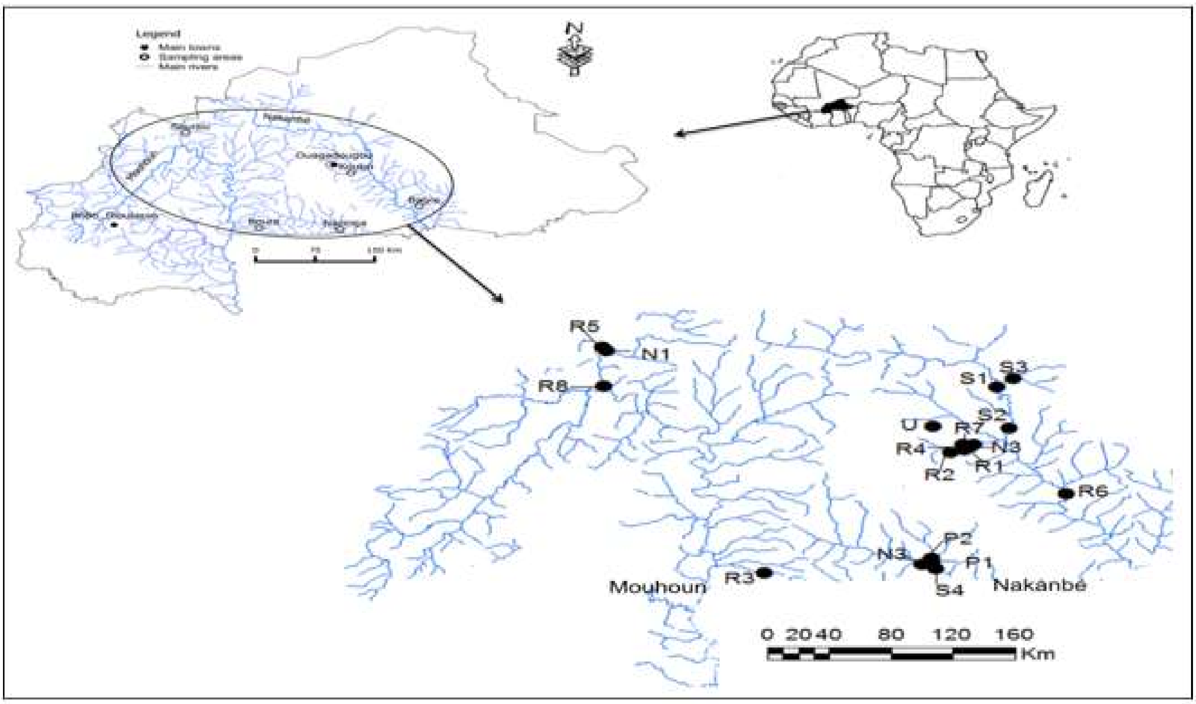

Fig. 2. Map of Burkina Faso in West Africa showing the location of sampling areas and sampled sites.

The previous study conducted by Reintjes (2004) showed that the rainfall was highly predictive of beetles taxa richness because they colonized aquatic plants during rainy season. In addition, insects are dependent on the litter deposited as vegetation dies and chemicals secreted by the plants, may also play a role in determining which plants support the greatest numbers and higher diversity of beetles (Fairchild *et al*., 2000; Menetrey *et al*., 2005). Gong *et al*. (2000), Albertoni *et al*. (2007), Silva and Henry (2013) and Koblinger and Trauner (2013) also demonstrated that the macrophytes enhance environmental heterogeneity, provide protection from predators and improve food condition for benthic macroinvertebrates.

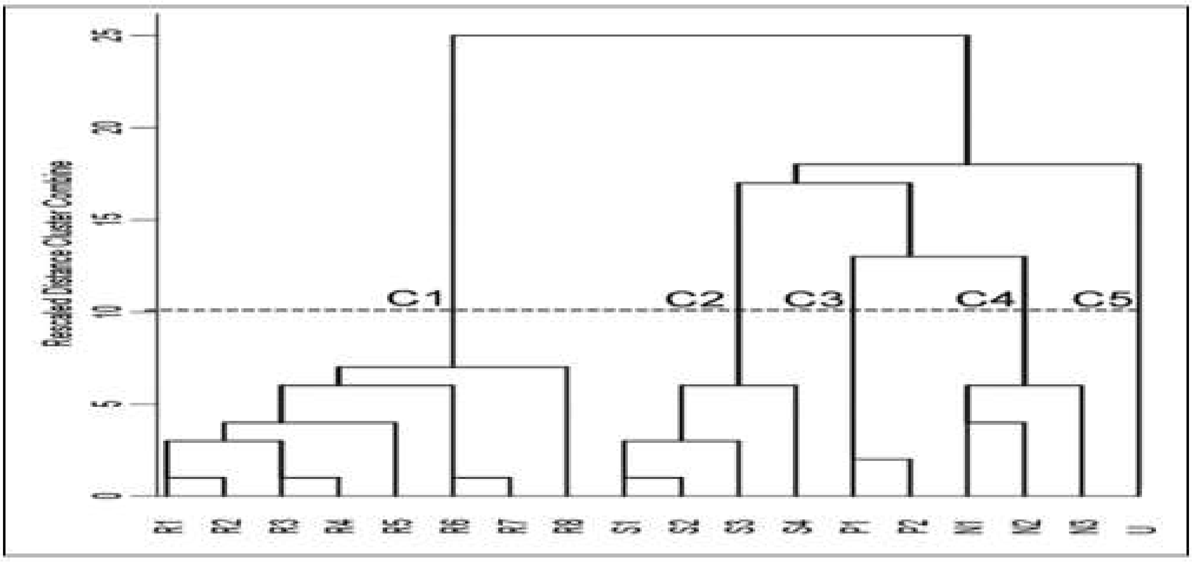

Fig. 3. Hierarchical classification of investigation sites related to their environment variables. Four main groups were shown by dendrogram, which C1=R1-R8 indicates "Reed Beds" sites ; C2=S1-S4 sites with sediment substrate, C3 (P1-P2)=reservoirs with *Pistia* cover, and C4 (N1-N3) mixed habitats with *Nymphea*, C5=Ouagadougou reservoirs with *Eichhornia*).

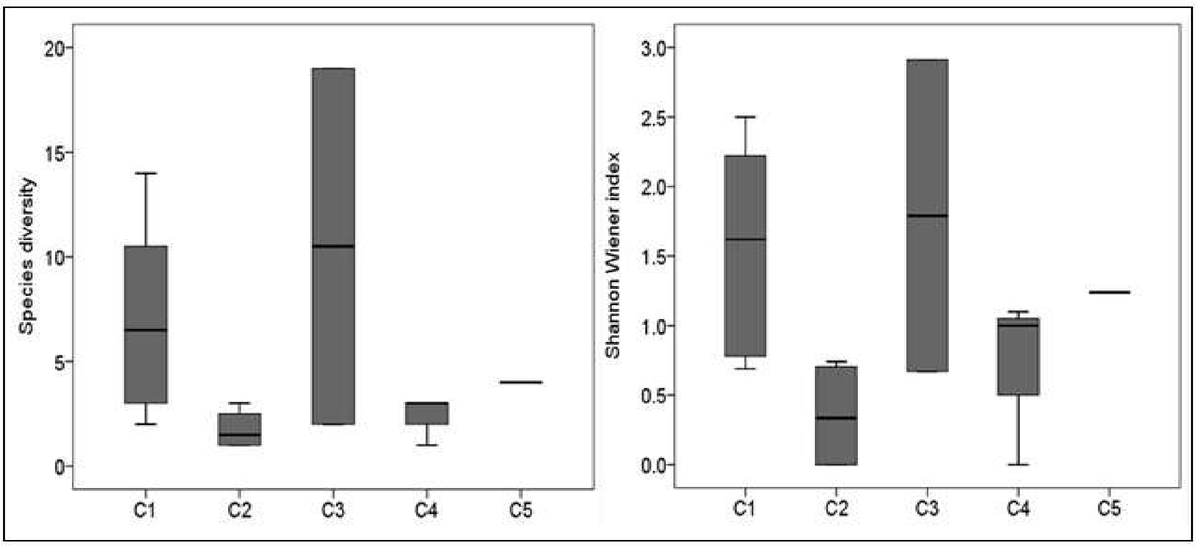

Fig. 4. Boxplot showing variation in species richness in diffrent waterbodies types. C1 indicates "Reed Beds" sites ; C2= sites with sediment substrate, C3=reservoirs with *Pistia* cover, and C4 mixed habitats with *Nymphea* and C5=Ouagadougou reservoirs with *Eichhornia*.

The negative association between *Nymphea* and beetles species was observed here. Taniguchi found in 2003 that the faunal differences in abundance and especially species richness between different water plants are related to leaf morphology and surface area of the plant that may have an important effect on a plant's ability to support beetles, which agrees with our results. This findings is also reflected in our results, as the structure-poor floating leaves (e.g. the anoxia in the centre of leaves) revealed by far the lowest faunal abundance and taxa richness of some sites. The water body type and vegetation cover are the most important variables in depicting the ecological health of beetles species in semi arid areas.

Conclusion

The knowledge of the water beetle fauna in West African landlocked countries is limited and very scattered. In this report 24 species are recorded from Burkina Faso for the first time, which is 40% of the total number, while thirty six (36) species were already listed by other authors. In West Africa the distribution of aquatic beetles are mostly influenced by the water body and aquatic plant habitats. Additionaly a significant direct and indirect impact of human pressures on waters was resulting in a loss of biodiversity. This first result proves the high beetle diversity in Burkina Faso and motivates for further efforts in monitoring, research as well as effective habitat conservation measures.

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PRIMARY RESEARCH PAPER

Using macroinvertebrates for ecosystem health assessment in semi-arid streams of Burkina Faso

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Abstract Efficient monitoring tools for the assessment of stream ecosystem response to urbanization and agricultural land use are urgently needed but still lacking in West Africa. This study investigated taxonomic and functional composition of macroinvertebrate communities at 29 sites, each exhibiting one of four disturbance levels [‘protected’ (P), ‘extensive agriculture’, ‘intensive agriculture’ (IA) and ‘urban’ (U)] in Burkina Faso and explored their potential for bioassessment. We recorded a total of 100 taxa belonging to 58 families, with the highest richness (16.9 taxa per site) observed in the sites with IA and lowest (3.4 taxa) in U sites. We found a gradual decrease of sensitive Ephemeroptera, Plecoptera and Trichoptera taxa and of collector-filterers feeding guild between P, agricultural and U sites accompanied by an increase in the relative abundance of tolerant dipteran taxa. Measures of overall taxonomic richness and diversity were mostly efficient in detecting the high impoverishment of the U sites, while FFG ratios did not deliver consistent results. Finally, all four land use types were successfully distinguished by identifying indicator taxa through hierarchical clustering and indicator value index. This work produced an unprecedented faunal inventory of Burkina Faso streams and laid the basis for the development of urgently needed stream assessment tools.

Keywords West Africa · Bioindication · Macroinvertebrates · Taxonomic · Freshwater · Land use

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Introduction

Inland waters are natural resources with high economic, cultural, aesthetic, scientific and educational value (Dudgeon et al., 2006). Their conservation and management are critical to the interests of all nations and governments, and thorough scientific knowledge of these valuable ecosystems is an essential prerequisite for developing reliable management tools applicable locally. This is especially true for many tropical countries, where growing exposure to human activities such as intensive agriculture (IA), dumping of untreated waste and wastewater from settlements and industries cause ongoing degradation of river ecosystems (Dudgeon, 1992; Malmqvist & Rundle, 2002; Strayer & Dudgeon, 2010).

Burkina Faso is a landlocked Sahelian country located in the heart of West Africa, which has to cope with chronic water scarcity and episodes of severe drought. A high population growth rate and rising demand to achieve food security and sustain rural livelihoods have resulted in intensification of agriculture (rice and irrigated crop farming, fishing, livestock farming) and accelerating urbanization in Burkina Faso (UNEP-GEF, 2010). As a consequence, the exposure of surface waters to pesticides, chemical fertilizers and pollutants as well as physical modification of the riparian areas (due to e.g. erosion by cattle movement or construction of embankments) has increased over the years, posing a threat to aquatic organisms and water quality (Smith et al., 2009; Melcher et al., 2012).

High human pressure on freshwater ecosystems combined with increasing climatic variability result in an urgent need for tools for the ecological health assessment, essential for prioritizing conservation efforts and efficient management of streams in fast-developing countries such as Burkina Faso. Across the world, stream assessment has previously been based on several biological metrics, which often reflect some combination of parameters: species richness and/or composition, tolerance or functional composition of the aquatic communities. These metrics have proven sensitive to specific impairments to different degrees (Resh, 1995; Barbour et al., 1999). Furthermore, as an alternative, multivariate statistical procedures for community analysis have also been increasingly applied. Based on the latter, methods allowing for instance the identification of indicator species and species assemblages have been developed (Dufrêne & Legendre, 1997).

Due to their important role in freshwater ecosystems (Covich et al., 1999), high diversity as well as the ease and low cost of sampling, benthic macroinvertebrates, have often been used for biomonitoring purposes (Bonada et al., 2006; Carter et al., 2006; Verdonschot & Moog, 2006). The abundance and distribution of benthic macroinvertebrates have been shown to respond to differences in local environmental conditions both in the temperate and in the tropical zones (Jacobsen, 1998; Usseglio-Polatera et al., 2000; Kouadio et al., 2008). As a result, macroinvertebrate-based indices have become an important tool for monitoring programmes and aquatic ecosystem management, widely implemented in many countries across the world (Barbour et al., 1999; Moog et al., 1999; Carter et al., 2006; Watson & Dallas, 2013). Several authors have, however, emphasized the importance of testing assessment metrics locally (Barbour et al., 1999; Marzin, 2013).

Current knowledge of benthic macroinvertebrates in African rivers is very fragmentary, and documented efforts for development of macroinvertebrate-based monitoring programmes have been largely restricted to few countries, primarily in East (Masese et al., 2009a, b; Raburu et al., 2009; Kilonzo et al., 2013) and South Africa (Watson & Dallas, 2013). In West Africa, some studies have delivered assessments of the macroinvertebrate fauna (Yaméogo et al., 2001; Aggrey-Fynn et al., 2011 in Ghana, Camara et al., 2012; Edia et al., 2013 in Ivory Coast) and some initial efforts have tested the relationship of their diversity to pollution (Thorne & Williams, 1997 in Ghana, Vinson et al., 2008 in Gabon). Similarly, in spite of several previous studies conducted on freshwater macroinvertebrates, an extensive inventory of macroinvertebrate fauna has been missing in Burkina Faso, as many of the former were restricted to narrow advances in the taxonomy of macroinvertebrate communities in a single river (Guenda, 1996) and in some reservoirs (Kabré et al., 2002; Sanogo et al., 2014). These did not provide the quantitative or distributional analysis needed to develop indicators based on benthic macroinvertebrates.

This study was the first to aim for a large-scale assessment of benthic macroinvertebrate fauna in Burkina Faso with the ultimate goal of investigating the potential use of macroinvertebrate-based metrics for the monitoring of the effects of different floodplain land use types. Twenty-nine study sites of different floodplain land use, from protected (P) areas to those used agriculturally and urban (U) areas—were selected. Several analytical approaches were applied to estimate the sensitivity to floodplain land use change of single macroinvertebrate species as well as of functional and taxonomic composition of the community as a whole.

The key objectives of this work were to (1) identify and determine the diversity and distribution of benthic macroinvertebrate taxa in streams of Burkina Faso, (2) test their response to changes in floodplain land use (intensification of agriculture, urbanization) using different metrics related to taxonomic and functional composition, and (3) identify and potential indicator taxa for the four main floodplain land use types [P areas, extensive agriculture (EA) and IA and U areas].

Materials and methods

Study area

Burkina Faso is located in the central part of West Africa (09°20′ and 15°03′ N, 02°20′ E, 05°03′ W). The climate is tropical and semi-arid with mean temperatures varying between 24 and 35°C (Ly et al., 2013; Ouédraogo & Amyot, 2013) and is characterized by a north–south gradient in rainfall distribution, with high variability in both time and space. Most of the Burkina Faso lie within the West Soudanian ecoregion. The Lower Soudanian is characterized by the rainy season of 6–8 months (April–October) and an annual precipitation from 1000 to 1200 mm (Sirima et al., 2009). Gallery forests and savanna with trees or shrubs are mainly observed in this area, dominated by *Isoberlinia doka* (Craib & Stapf) or *Isoberlinia dalzielii* (Craib & Stapf) and *Guibourtia coppalifera* (Bennett) (Guinko, 1984, 1997). The Upper Soudanian (US) has a shorter rainy season (June–October) and annual precipitation ranging between 750 to 1000 mm (Thiombiano et al., 2006). Rivers in US dry out during the dry season. The zone shows a regular rustic savanna and exhibits the highest human densities. Evapotranspiration rates and river flows are extremely sensitive to rainfall variations.

Three main catchments constitute the hydrological network of Burkina Faso: Niger, Comoé and Volta. The study was undertaken in rivers belonging to two of them: the Nakanbé (Volta catchment) in the central part of Burkina Faso (area of 70,000 km^2), the Mouhoun (Volta catchment) in the west (92,000 km^2) and the Comoé in south-west part of Burkina Faso (18,000 km^2). Eleven, four and fourteen sampling sites were selected in these rivers, respectively (Table 1). Floodplain land use types were defined visually by means of field protocol and Google earth map in a standardized manner using land buffer of 1-km diameter (Stranzl, 2014). Field trips were undertaken to confirm the accuracy of this assessment by expert judgment. Sampling sites fell within a continuum ranging from low to very high intensity of agriculture and human population density in the floodplain area. Four major categories of floodplain use were defined and codified as ‘protected’ (P), ‘extensive agriculture’ (EA), ‘intensive agriculture’ (IA) and ‘urban’ (U) (Fig. 1).

‘Protected’ areas ($n = 3$) were exposed overall to the lowest levels of human impact and were characterized by a nearly negligible population density (isolated households) and preserved natural riparian vegetation. These were created with the goal of protecting and conserving the wildlife for limited hunting and fishing and maintaining the ecological integrity of the area (Sawadogo, 2006; Ouédraogo, 2010). Sites categorized as ‘extensive agriculture’ ($n = 4$) were exposed to a low level of human impact, influenced primarily by grazing (pasture) and waste from scattered houses or little villages. In the areas of ‘intensive agriculture’, the floodplain area was typically converted to land for crop farming. Thus, the most destructive change in the riparian zone of these streams was due to the radical modification of the vegetation and application of pesticides and fertilizers, while settlements were limited to single villages. Within this category, streams in areas of three different agricultural uses were sampled: (a) irrigated vegetables and seasonal crops farming ($n = 4$), (b) fisheries and mixed agriculture ($n = 4$) and (c) rice farming ($n = 9$). Finally, the sites of the fourth category defined as “urban” ($n = 5$) were situated in highly urbanized areas (including the areas of major cities of Ouagadougou and Bobo-Dioulasso with population densities of up to 80 inhabitants per km^2 at the study sites), exposed to industrial and other uses including inputs of domestic wastes and river channel engineering.

Table 1 Environmental characteristics of the 29 study sites belonging to the river catchments Comoé, Mouhoun and Nakanbé

Dominant land use	Sites	River catchment	Eco-geographic types	Altitude (m)	Water temperature (°C)	pH	Conductivity (μs/cm)	Oxygen (mg/l)	TDS (mg/l)	Water depth (m)	Water velocity (m/s)	Wetted width (m)	Dominant habitat
P1	Bodjéro	Nakanbé	LS	269	24.4	8.6	67.8	6.6	43.4	0.41	0.35	6.65	Mesolithal
P2	Karfiguela	Comoé	LS	320	25.8	10.8	27.5	5.6	17.6	0.52	1	5.6	Megalithal/CPOM
P3	Guingette	Mouhoun	LS	359	29.9	10.19	45.2	6.3	28.9	0.76	0.89	7.3	Mesolithal/macrophytes
EA1	Bissiga	Nakanbé	US	273	35	7.2	55.6	3.9	35.6	0.53	0.25	29.75	Pelal/akal
EA2	Korsimoro	Nakanbé	US	282	28.4	7.8	91	4.2	58.2	0.25	0.02	1.6	Akal
EA3	Kougri	Nakanbé	US	258	31.6	7.64	88.6	4.6	56.7	0.75	0.06	25.56	Pelal
EA4	Peele	Nakanbé	US	261	30.8	7.27	103.2	7.5	66	0.6	0	8.45	Pelal
IA1c	Boura	Mouhoun	LS	269	32.7	6.75	52	4.1	33.3	0.85	0.44	3.75	Techtolithal/macrophyte
IA2c	Niango	Nakanbé	US	238	23.3	7.55	108.6	4.5	69.5	0.72	0.05	11.2	Pelal
IA3c	Poweri2	Mouhoun	LS	277	30.2	7.15	86.5	5.2	55.3	0.75	0.05	7.4	Psammal/woody debris
IA4c	DI	Mouhoun	US	253	33.9	7.8	158.8	4.7	102	0.55	0.1	na	Pelal/macrophyte
IA5c	Tengrela1	Comoé	LS	280	25.3	9.7	28.2	6.6	18	0.62	0.42	6.7	Pelal
IA6a	Kou	Mouhoun	LS	340	26.9	10.7	70.1	4.7	44.8	0.25	0.21	10.9	Psammal/woody debris
IA7a	Nagreogo	Nakanbé	US	273	30.2	6.7	46	3.2	29.4	0.25	0.38	1.7	Akal
IA8a	Poweri1	Mouhoun	LS	280	27.9	7.54	67.6	4.4	43.3	0.6	0.05	6	Psammal/woody debris
IA9a	Loumbila	Nakanbé	US	281	32.6	7.6	48.2	4.1	30.8	0.45	0.1	8.56	Pelal
IA10b	Bromo	Mouhoun	LS	250	32.6	7.6	88.2	4.1	56.4	0.75	0.6	14.6	Microlithal
IA11b	Segda	Nakanbé	US	276	32	7.17	86.5	4.8	55.3	0.5	0.02	4.7	Pelal/wood debris
IA12b	Ouéssa	Mouhoun	LS	236	30.6	6.9	52.1	7.8	33.3	0.78	0.9	29	Pelal/macrophyte
IA13b	Tomaîle	Mouhoun	US	250	31.8	6.5	106	4.2	67.8	0.85	0.26	na	Pelal/macrophyte
IA14c	Djaraba	Comoé	LS	263	26.5	9.3	79	5.1	50.5	0.87	0.9	4.5	Mesolithal/macrophyte
IA15c	Gouran	Mouhoun	US	257	34	5.7	98.3	5.7	62.9	0.45	0.2	2.5	Pelal/macrophyte
IA16c	Nianssan2	Mouhoun	US	253	32.6	7.9	196.5	2.4	126	0.6	0.1	5	Pelal/macrophyte
IA17c	Nianssan1	Mouhoun	US	253	35.4	8.3	127	4.5	81.3	0.49	0.01	3.2	Pelal/macrophyte
U1	Ouaga2	Nakanbé	US	292	31	7.62	353	1.5	226	0.3	0.1	1	Pelal/FPOM
U3	Houet1	Mouhoun	LS	420	25.5	11.6	385	3	246	0.2	0.1	1.85	Megalithal/FPOM
U4	Houet2	Mouhoun	LS	401	32.6	7	460	2.5	294	0.32	0.1	2.5	Pelal/CPOM
U5	Tengrela2	Comoé	LS	305	28.8	10.2	158.7	1.6	102	0.2	0	2.1	Concrete/FPOM
U2	Ouaga1	Nakanbé	US	295	35.4	11.27	491	10.7	314	0.15	0.01	11.5	Concrete/FPOM

Dominant habitats are classified as following: megalithal (bedrock) ~ size >40 cm, mesolithal (cobbles) ~ $6 < \text{size} \leq 20$ cm, psammal (sand) ~ $0.06 < \text{size} \leq 2$ mm, pelal (mud) ~ size >0.06 mm

P protected areas, *EA* low agricultural disturbance sites, *IA* intensive agriculture sites (*IAa* irrigated vegetables and seasonal crops farming, *IAb* fisheries and mixed agriculture, *IAc* rice farming seasonal crops farming), *U* urbanization, industrial and other uses, *LS* Lower Soudanian ecoregion, *US* Upper Soudanian ecoregion

Environmental condition of sites

Environmental parameters that are likely to be affected by different floodplain land use types were recorded in the field in order to characterize each sampling site. Temperature (°C), conductivity (μS/cm), dissolved oxygen (mg/l) and pH were measured with field multimeters (WTW340I) between 8 and 3 p.m. before the macroinvertebrate sampling. The area occupied by the dominant habitat type (>5% of total area) was estimated for each site. The substrate types were recorded according to the categorization based on the grain size (Moog, 2007) (Table 1).

Benthic macroinvertebrates: sampling and taxonomy

Benthic macroinvertebrates were collected between July and December 2012, during the period when surface water flow was evident at all study sites. Benthic macroinvertebrates were sampled with a hand net (rectangular opening: 25 cm × 25 cm, mesh size: 500 μm). Following the multi-habitat sampling approach (Moog, 2007), a pooled sample, consisting of 20 sampling units, was taken from all habitat types occupying a minimum of 5% or more of the study area. The number of sampling units allocated to each habitat type was proportional to the areal coverage of the latter. Samples were fixed in 90% ethanol and sieved in the laboratory. The animals were sorted under a microscope and identified to the lowest taxonomic level possible based on taxonomic manuals and keys (Lévêque & Durand, 1981; Merritt & Cummins, 1984; Tachet et al., 2003) and with direct taxonomic expert support (see acknowledgements). The assignment of functional feeding groups was done by expert consensus following Moog (1995), Masese et al. (2014) and Merritt & Cummins (2006).

Data analysis

A constrained canonical correspondence analysis using function *rda* in the package *vegan* (Oksanen et al., 2013) in R (R Core Team, 2013) was conducted on the key chemical and physical variables quantitatively assessed in the study sites to identify major gradients in environmental differences between the sites. Tested variables (mean water temperature, conductivity, oxygen concentration and flow velocity) were *z*-standardized prior to the analysis. The statistical significance of differences between the land use categories was tested by the 999 permutation procedure and an adjusted R^2 was computed as an unbiased estimate of the explained variance.

To test for the support of the selected site categories in the macroinvertebrate data, we first conducted hierarchical cluster analysis using PC-OrRD software (McCune & Mefford, 2006). This analysis was conducted on a presence–absence matrix including all sites and taxa (flexible β value of -0.250, distance measure: Bray–Curtis similarity). The significance of cluster support was assessed with a nonparametric test: multi-response permutation procedures (Mielke, 1991).

We then used a multimetric approach selecting several indices reflecting either richness, taxonomic or functional composition of the community as suggested for identification of potential indicators of ecosystem health (Resh, 1995; Thorne & Williams, 1997; Barbour et al., 1999). Taxa richness (total number of taxa), percentage of Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa, percentage of tolerant dipteran insects (following Hauer & Lamberti, 2006; Mandaville, 2002) and Shannon–Wiener diversity index (H') were calculated for each of the four main land use types. The Shannon–Wiener diversity index was expressed following the formula (1), where p_i is the proportion of individuals found in the ith taxon, S is the number of taxa in the samples.

$$H' = -\sum_{i=1}^{S} p_i \ln p_i. \quad (1)$$

We conducted a Kruskal–Wallis test (SPSS, version 21) followed by multiple comparison tests to compare the metrics of richness, diversity and composition between different floodplain land use types.

Furthermore, we also calculated three functional feeding ratios frequently used as indicators of some key functional attributes of stream ecosystem from Vannote et al. (1980) and Merritt & Cummins (2006): (1) ‘scrapers to (shredders + total collectors)’ ratio (*P*/*R*) corresponding to the autotrophy–heterotrophy index, (2) ‘shredders to total collectors’ ratio corresponding to CPOM–FPOM index and (3) ‘predators to prey’ ratio reflecting possible top-down control by predators. The values acquired were compared to

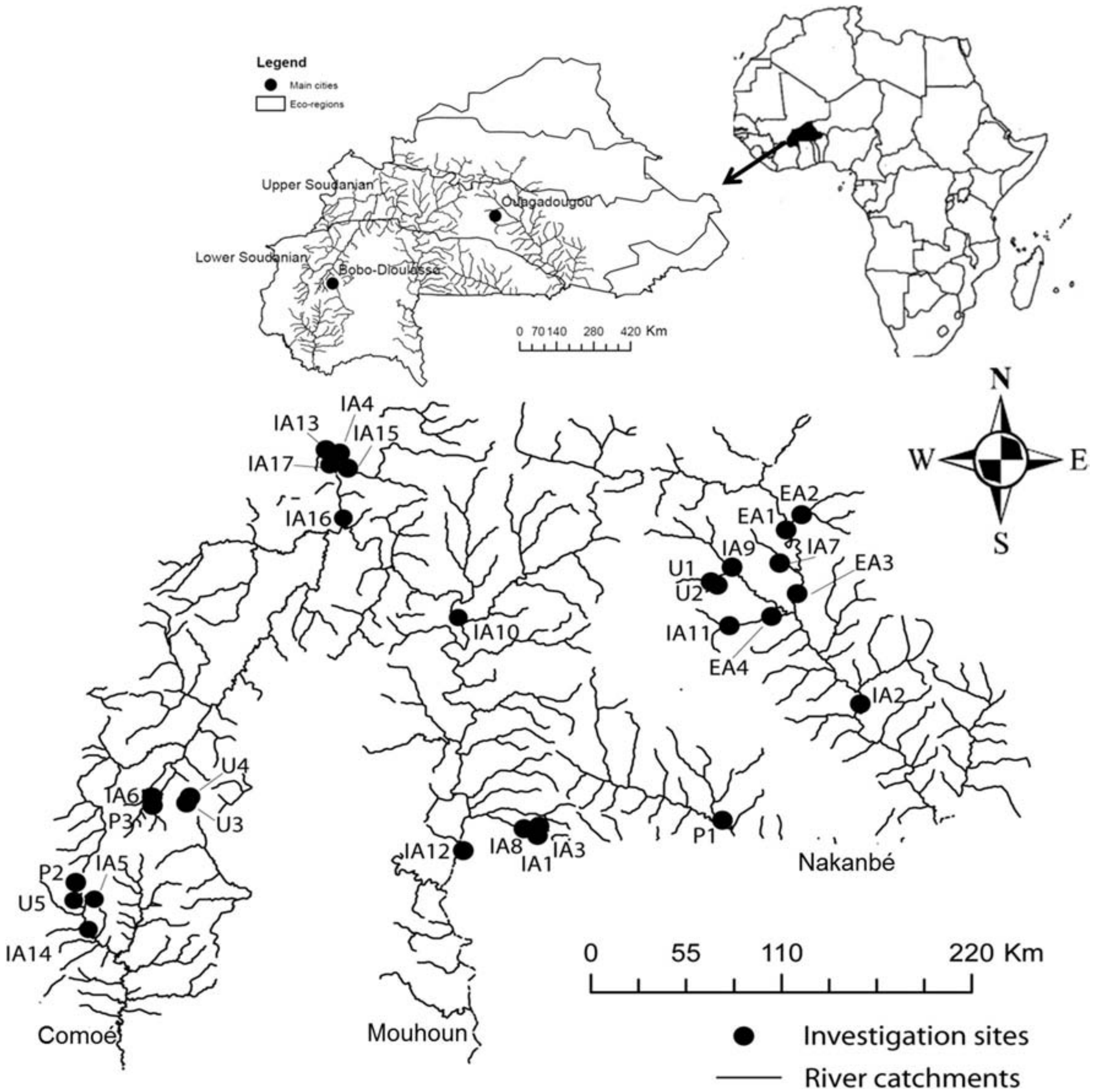

Fig. 1 Map of Burkina Faso showing the study area. *Circles* indicate the sampling sites (after Guinko, 1984). While some of the catchments are shared with other countries, only the part flowing on the territory of Burkina Faso is shown

threshold ratios applied for both temperate and tropical streams (Cummins et al., 2005; Masese et al., 2014). $P/R > 0.75$ would indicate predominantly autotrophic production. CPOM/FPOM >0.25 would indicate a functioning riparian zone. A predator–prey ratio between 0.1 and 0.2 corresponds to a normally expected predator-to-prey balance.

Finally, we tested for the potential of the macroinvertebrate taxa detected in our study to serve as bioindicators for the four land use types investigated. The indicator value (IndVal) was computed for each taxon *i* and category of sites *j* as

$$\mathrm{IndVal}_{ij} = A_{ij} \times B_{ij} \times 100, \quad (2)$$

where $A_{ij} = \mathrm{N\ individuals}_{ij}/\mathrm{N\ individuals}_i$ is a measure of specificity based on abundance values, whereas $B_{ij} = \mathrm{N\ sites}_{ij}/\mathrm{N\ sites}_i$ is a measure of fidelity computed from the presence data (Dufrêne & Legendre, 1997). IndVals range from 0 (no indication) to 100 (perfect indication), the latter corresponding to a case, when all individuals of a taxon are found in a single category of samples and this taxon occurs in all samples of that category (Nahmani & Rossi, 2003). This method permits identification of taxa characteristic of groups of samples defined at different levels of the hierarchical clustering (Dufrêne & Legendre, 1997; Nahmani & Rossi, 2003). Importantly, the same taxon may have different IndVals depending on the level of grouping considered (Nahmani & Rossi, 2003). We used the randomization test to evaluate the statistical significance of each IndVal for a given taxon with a standard permutation test at the statistical level of 5%. Indicator taxa with IndVals above the threshold of 25% were retained for the final selection (Nahmani & Rossi, 2003).

Results

Environmental parameters assessed in the study sites varied in relation to floodplain land use (Table 1; Fig. A1). Sites in P areas were generally colder and higher in pH and flow velocity (Table 1; Fig. A1). We could not clearly distinguish between the sites of IA and EA based on the measured environmental variables (Fig. A1). In contrast, U sites distinctly differed from all other land use types through enhanced conductivity (up to 490 µS/cm) and lower width and depth of the water channel (Fig. A1). Canonical correspondence analysis showed a significant association of the variation in environmental parameters with site categories ($P = 0.001$, for RDA1 and $P = 0.02$ for RDA2; $R^2_{adj} = 0.23$; Tables A1, A2, A3 in Electronic Supplementary material).

Taxonomic richness of benthic stream macroinvertebrates in Burkina Faso

A high diversity of benthic macroinvertebrates with a total of 100 taxa was recorded in this study (Table A4). A large majority of these taxa (74) belonged to 47 families from 8 orders of insects: Ephemeroptera, Odonata, Diptera, Coleoptera, Trichoptera, Lepidoptera, Plecoptera and Hemiptera. The remaining 26 taxa belonged to 11 families of Decapoda (Crustacea), Gastropoda and Bivalvia (Mollusca). Coleoptera (26 taxa of 8 families) represented the most diversified order of insects with the following dominant families: Hydrophilidae (7), Dysticidae (7), Elmidae (5) and the Noteridae (3). They were followed by Diptera: 15 taxa belonging to 9 families. Within non-insect fauna, we found a notable diversity in molluscs, with several species previously not reported for Burkina Faso. Thus, a total of 14 taxa of gastropods composed of Bulinidae (5), Thiaridae (3), Planorbidae (2), Ampullariidae (2), Lymnaeidae (1) and the Viviparidae (1) were observed. In the Bivalvia class, three families including six species were recorded. Finally, we also found two species of freshwater shrimps belonging to the families Palaemonidae and Atyidae.

The most frequently occurring taxa we found belonged to insects were chironomid subfamilies Chironomini and Tanypodinae, damselflies of the genus *Coenagrion* sp. and mayflies of the genus *Baetis* sp. (the first taxon was present at 90%, the following three taxa at >50% of sampling sites). Several rare taxa potentially sensitive to anthropogenic stress were only found in the P areas: *Notonurus* sp., *Euthraulus* sp., and *Tricorythus* sp. (Ephemeroptera), *Chlorocypha* sp. (Odonata), *Neoperla spio* (Plecoptera), *Chimarra pétri* and *Leptocerus* sp. (Trichoptera).

Floodplain land use effects on taxonomic and functional composition of the macroinvertebrate community

Cluster analysis based on macroinvertebrate community composition strongly supported our categorization of the sites based on the floodplain land use (multi-response permutation procedures, $A = 0.197$, $P < 0.0001$; Fig. 2). Identified clusters at the lowest hierarchical level corresponded to the four categories formulated based on the qualitative assessment of floodplain land use “protected” (C1), “extensive agriculture” (C2), “intensive agriculture” (C3) and “urban” (C4). P and EA (C1 and C2, respectively) were then clustered together (C5) suggesting their similarity, while U areas were found most distinct from all the rest of the sites (C4).

Some distinct differences relative to the floodplain land use types could be observed in the taxonomic and functional community composition of benthic macroinvertebrates (see Tables 2, A4 for details). Interestingly, different metrics of diversity, composition and tolerance of macroinvertebrate community tested here varied in their sensitivity towards land use change (Fig. 3). The overall taxonomic richness, the percentage of tolerant dipteran taxa (Chironomidae, Syrphidae, Culicidae and Psychodidae), and the

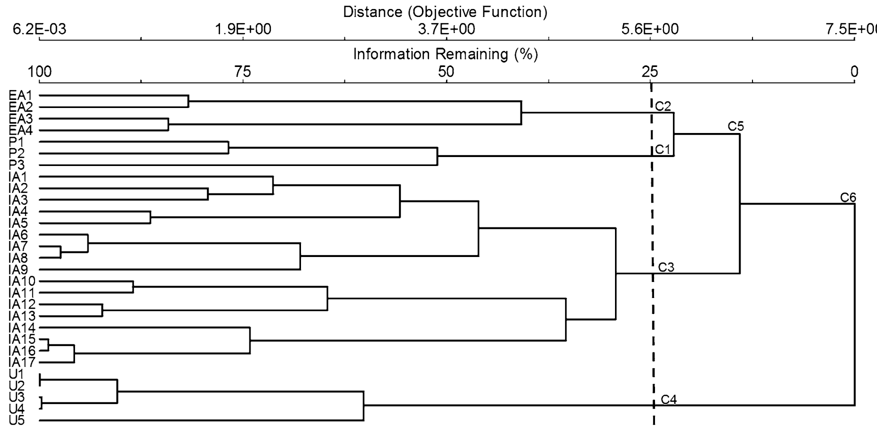

Fig. 2 Hierarchical clustering analysis of 29 sites (based on flexible β linkage, value of −0.250, distance measure Bray–Curtis) using a presence/absence matrix. Site names correspond to the different land use types. *P* protected area, *EA* extensive agriculture, *IA* intensive agriculture, *U* urban sites

Table 2 Mean values of stream ecosystem attributes derived from ratios of macroinvertebrate functional feeding groups of Burkina Faso' rivers

Land use categories	*P*/*R* ratio	CPOM/FPOM ratio	Top-down predator Control ratio
P	0.25 (0.23)	0.02 (0.01)	0.15 (0.12)
EA	0 (0)	0 (0)	0.42 (0.22)
IA	0.73 (0.42)	0.002 (0.001)	0.44 (0.11)
U	0.10 (0.1)	0 (0)	0.03 (0.03)

Standard errors are reported in parenthesis

Shannon–Wiener diversity index showed a capacity of clearly detecting only the highest level of benthic fauna impoverishment as found in U sites (Fig. 3a, c, d). Thus mean overall taxonomic richness per site was highest in sites with IA (17.6 ± SE 2.2 taxa per site) and reached a minimum of 3.4 ± SE 0.5 taxa per site in U sites (Fig. 3). Shannon–Wiener diversity index also tended to increase in agricultural sites, reaching on average 1.9 ± SE 0.2 in the IA sites and then dropped to a minimum of 0.8 ± 0.1 in U sites. Finally, the fraction of tolerant dipteran taxa consisting of Chironomidae, Syrphidae, Culicidae and Psychodidae showed an increase from average 5.8 ± SE 3.6% in P sites to 31.0 ± 6.9 in the agricultural (IA) and 91.6 ± SE 6.3% in the U streams.

By contrast, metrics based on EPT taxa showed higher sensitivity to different levels of environmental degradation and a clear decrease across the gradient of human impact intensity in terms of land use. Such sensitivity allows one to distinguish between EA and IA (Figs. 3c, A2). EPT taxa (primarily Baetidae and Hydropsychidae) were highly dominant in the P areas, making up on average 57.3 ± 14.6% of total abundance (Fig. 3c). While both types of agricultural streams were distinguished by quite high overall taxonomic richness (Fig. 3a), the EPT taxa were represented in EA and IA by a small number of taxa constituting a very low fraction of the overall abundance (18.4 ± SE 7.7% in EA; 3.9 ± SE 1.5% in IA; Fig. 3b) and were completely absent from U sites.

Variation in the relative abundance of functional feeding groups too reflected differences between the land use types (Fig. 4b). A total of 5,927 individuals (98.5% of the total organisms) were categorized within different functional feeding groups in this study (Table A5). Six major functional feeding groups were recognized (Fig. 4b): predators, shredders, collector-gatherers, collector-filterers, scrapers and parasites. Along a gradient of increasing land use intensity collector-gatherers became a progressively dominant group, covering a range between 38.5% in P sites and 93.3% in U sites. Collector-filterers showed the opposite trend, decreasing from an average 49.1% of communities in P areas to 32.3% in the IA sites, 19.1% in the EA sites and total absence in the U sites. Scrapers were particularly abundant (19.7%) in the sites with EA, and the fraction of predators was at least three times higher in agricultural streams compared to 'urban' and 'protected' sites. Shredders were remarkably rare, never reaching over 1% of the total abundance and showing highest fraction in the 'protected' sites.

P/*R* ratios calculated based on these estimates indicated that most investigated sites were characterized by a rather high level of heterotrophy and thus an

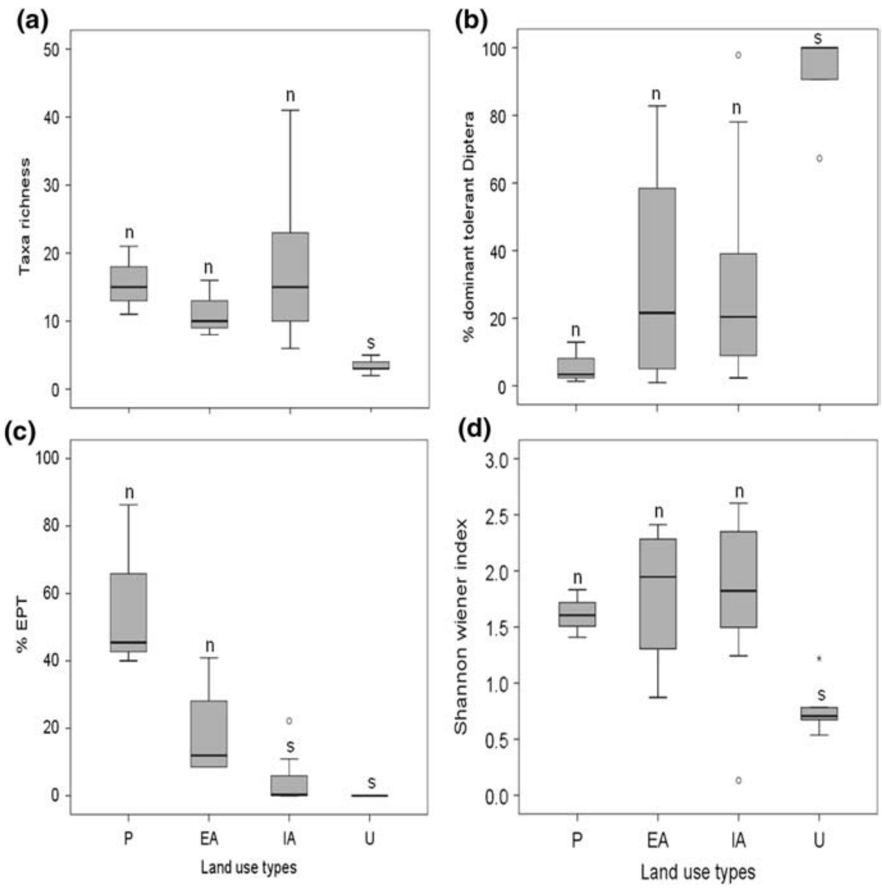

Fig. 3 *Boxplot* showing variation of taxa richness (**a**), percentages of dominant tolerant dipterans (**b**), Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa (**c**) and Shannon–Wiener index (**d**) in different land use types. *P* protected areas, *EA* extensive agriculture sites, *IA* intensive agriculture sites, *U* urban sites. Median value is shown in each *box*, *vertical bars* correspond to the minimum and maximum values. *Letters above boxplots* indicate statistical significance of differences between land use types (pairwise multiple comparison tests): only respective pairs with *different alphabetical letters* differ significantly ($P < 0.05$)

overdependence of stream food web on allochtonous material (Table 2). Surprisingly, sites with IA with a *P*/*R* ratio were close to the expected value of heterotrophy of 0.75, while the *P*/*R* ratio was below 0.25 in both P and U sites, and scrapers were completely absent in EA sites. CPOM/FPOM ratios were well below 0.1 across all site categories (Table 2) suggesting a very poorly functioning of riparian zone and a deficit of coarse particulate organic matter. Finally, the top-down control index indicated a relative abundance of predators within expected range in P sites, a lower than normal abundance of predators in U sites and a relative overabundance of predators in sites affected by agricultural use (Table 2).

Indicator taxa for different land use types

Different land use types could also be distinguished based on calculation of IndVal conducted at different levels of hierarchical clustering, which revealed several taxa as candidate bioindicators in Burkina Faso streams (Fig. 5). P areas were distinguished by a particularly high number (20) of potential indicator taxa, of which seven had significant IndVals and included several EPT taxa (*Euthraulus* sp., *Chimarra* sp., *Leptocerus* sp., *Chematopsyche* sp.; Fig. 5). A freshwater shrimp (*Macrobranchium* sp.) and a back-swimmer (*Notonecta* sp.) were found to be characteristic of sites with extensive agricultural activities (out of nine candidate bioindicators). Together with an elmid beetle taxon (*Pseudomacronychus* sp.), *Macrobranchium* sp., also distinguished the combined cluster of P areas and EA from the sites with IA (Fig. 5). We found 12 potential indicator taxa for the IA sites of which three (*Appassus* sp., *Coenagrion* sp. and Chironominae) had significant IndVals. These same three taxa as well as *Baetis* sp. were found to be distinguishing the "P+IA+EA" cluster from U sites. Finally, the analysis identified four taxa indicative of the U sites of which only *Chironomus* sp. ("red *Chironomus*") had a significant IndVal (Fig. 5).

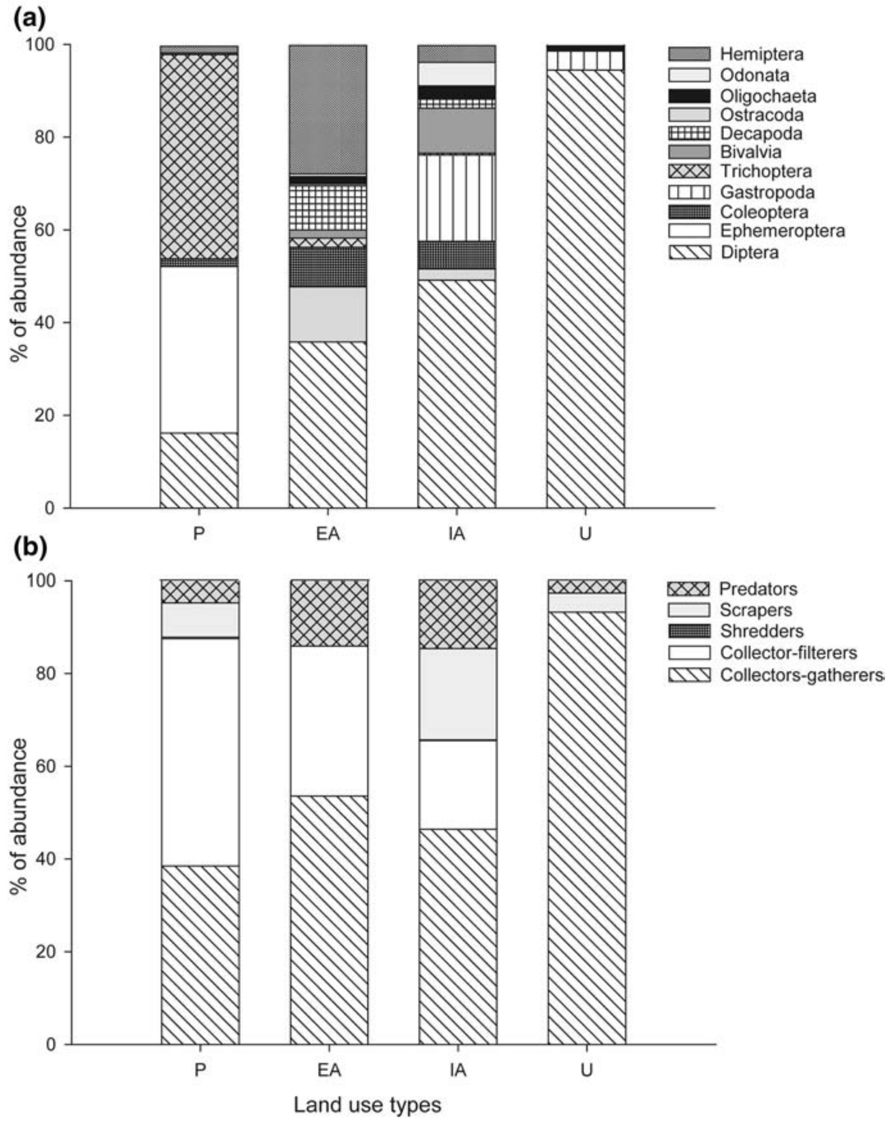

Fig. 4 Overall benthic community composition of key functional feeding benthic community: **a** taxonomic groups, and **b** functional feeding groups. *P* protected area, *EA* extensive agriculture, *IA* intensive agriculture, *U* urban sites

Discussion

Few studies have previously examined in detail benthic macroinvertebrate fauna of West African streams, and none has covered a geographical scale and variability of sites in terms of human impact comparable to this study. The composition of benthic macroinvertebrate fauna found here confirmed and expanded previous reports from Burkina Faso and neighbouring countries, with which Burkina Faso shares several of its catchments. The number of taxa collected in this study (100) was high when compared to the earlier studies in Burkina Faso streams. For instance, Guenda (1996) reported 94 taxa in his longitudinal study of the Mouhoun River, and Sanogo et al. (2014) collected 35 families during repeated samplings below a dam on a tributary of the Mouhoun River. We also found an pronounced richness of the mollusc community (20 species belonging to 9 families in total). This expands the previous inventories of reported molluscs which have been often limited by a very specific question (e.g., disease transmission studied by Poda et al., 1994, who reported six species of molluscs) or a specific geographical area (one river studied by Sanogo et al., 2014, or which seven families were reported).

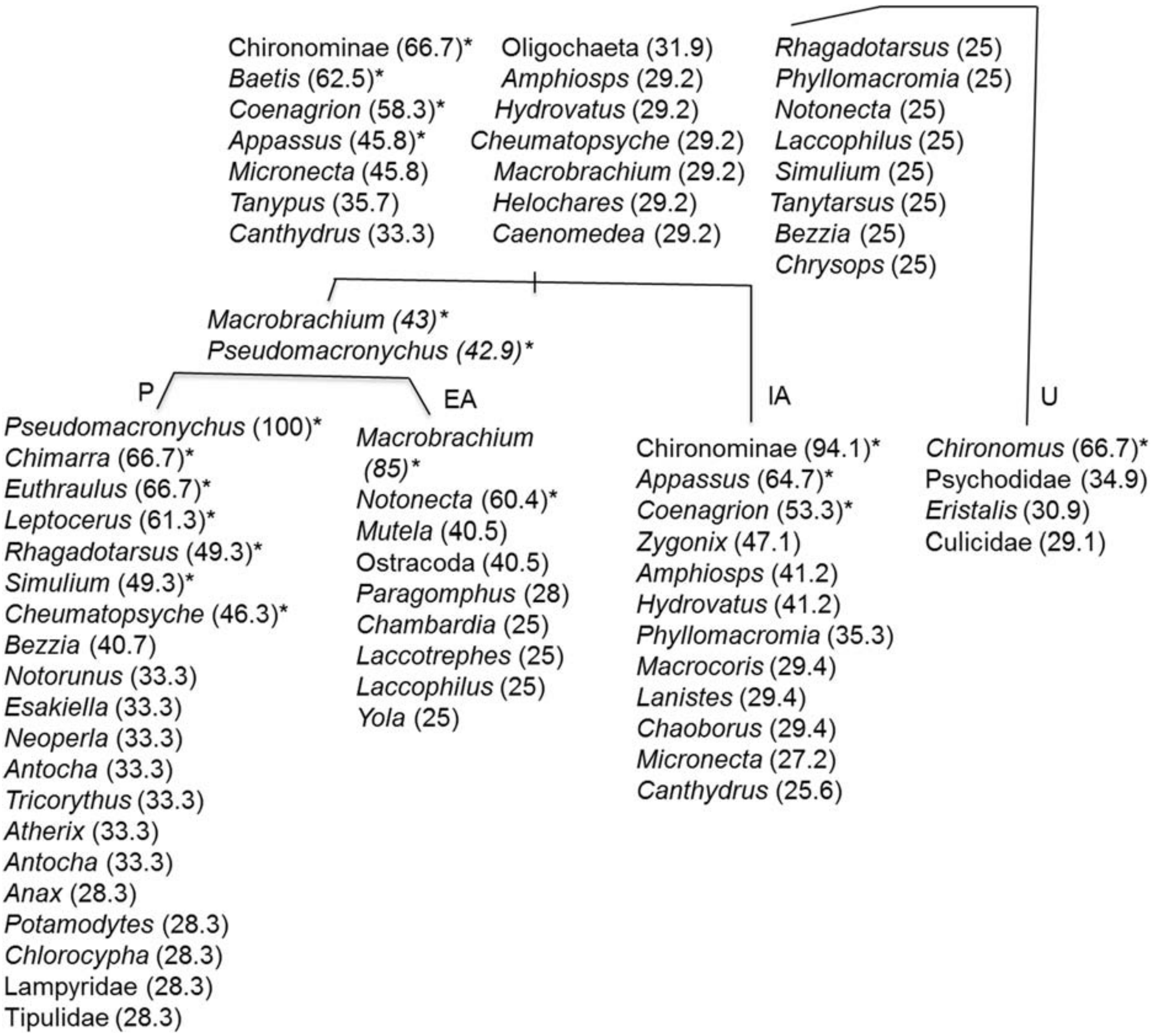

Fig. 5 Site typology and associated indicator taxa at different levels of clustering with indicator values in *parentheses*. Clusters identified by hierarchical clustering analysis correspond to the four land use types. *P* (C1) protected area, *EA* (C2) extensive agriculture, *IA* (C3) intensive agriculture (C3), *U* (C4) urban sites. Indicator taxa shown have IndVal values above 25% (reported in *parentheses*). Significant IndVal values are marked with an *asterisk* ($P < 0.05$)

The high overall taxonomic richness in comparison to other studies reflects the inclusion of both US and Lower Soudanian subecoregions into the sampling area, but might also to some extent be explained by covering different habitat types, which has not necessarily been done in previous studies. Furthermore, factors such as the timing and duration of the sampling period may cause the differences in the estimates of benthic biodiversity as has already been reported for some West African streams (Sanogo et al., 2014). Finally, involvement of taxonomic experts for Decapoda, Coleoptera, Hemiptera and Mollusca in our study allowed more specific identification of taxa, which might have only been determined at a higher taxonomic level and thus not distinguished from each other previously.

Human impact on benthic macroinvertebrate communities: taxonomic composition

The transition from undisturbed to human-dominated landscapes is accelerating in sub-Saharan Africa, and, as a result, is already dramatically affecting watersheds in this region (Kasangaki et al., 2008), especially in Burkina Faso (Melcher et al., 2012). Here we covered several major floodplain land use types present in Burkina Faso: from P areas to EA and IA and advanced urbanization, testing the potential applicability of macroinvertebrates-based metrics for monitoring human impact on streams.

High variation in the frequency and local abundances of different taxonomic groups of benthic macroinvertebrates offered a good basis for the distinction between benthic communities in the four floodplain land use types, as was confirmed by hierarchical clustering analysis. Importantly, sensitivity to land use change was reflected in different metrics of biotic integrity based on either taxonomic or functional diversity of macroinvertebrates as well as bioindicator approach based on the IndVal index. This confirmed an already previously acknowledged advantage of using several metrics for assessment in that this approach allows to make use of their complementarity and evaluate an entire gradient of degradation in spite of limited sensitivity ranges of single metrics (Thorne & Williams, 1997; Heino, 2008).

P areas were clearly distinguished by both high diversity and numerical dominance of the EPT taxa. Most insect taxa belonging to this group have been reported to be highly sensitive to pollution stress (Barbour et al., 1999; Bauernfeind & Moog, 2000). Accordingly, EPT index has been widely used as an ecological assessment tool (e.g., Barbour et al., 1999), even if single EPT taxa may show a certain tolerance to pollution and thus wide distribution in spite of human impact (e.g., Thorne & Williams, 1997; Kasangaki et al., 2008; Masese et al., 2009a). Indeed, in our study, while single EPT taxa (e.g., *Baetis* sp.) were found even in the sites exposed to the effects of IA, the patterns in overall taxonomic richness and abundance of the group reflected the expected gradient in pollution. Importantly, EPT-based metrics allowed us to distinguish between extensive and intensive floodplain agriculture, most probably by reflecting the sensitivity of these groups to the variation in pesticides, sediment runoff and organic pollution evident between these two land use types (Sutherland et al., 2002; Kasangaki et al., 2008).

In contrast, neither total taxonomic richness nor Shannon–Wiener diversity index, both frequently used in monitoring programmes, allowed us to clearly distinguish P sites from those with agricultural floodplain land use. Moreover, these metrics rather indicated a trend of increasing taxonomic diversity in both types of the agricultural sites. Similar results have already been reported earlier, associating an increase in macroinvertebrate diversity and total richness to the addition of moderate amounts of pollution (Thorne & Williams, 1997). Here high organic matter (rice, vegetables) and fertilizer input related to IA appeared to enhance both algal and macrophyte production (as observed in our study sites) boosting the macroinvertebrate diversity, in particular in molluscs and coleopterans. An additional effect may have been mediated by enhanced habitat heterogeneity due to proliferation of riverside macrophytes, which often positively affects overall benthic macroinvertebrate richness (Gong et al., 2000; Callisto et al., 2001; Ali et al., 2007; Koblinger & Trauner, 2013). Groups such as molluscs, tolerant to many disturbance types (Lévêque, 1972; Brenko, 2006; Idowu et al., 2007; Masese et al., 2014), appear to be particularly successful in profiting from these "positive" agricultural effects, as confirmed by our results.

Finally, all tested taxonomy-based metrics clearly detected the homogenization and drastic impoverishment of benthic fauna in the U sites, resulting in the strong dominance of tolerant dipteran taxa. Rivers in Burkina Faso are used for manifold domestic activities like drinking, cooking, bathing, and waste disposal (Boyle & Fraleigh, 2003; Ouédraogo, 2010; Koblinger & Trauner, 2013). In the study sites categorized as U, we observed deposition of polluting domestic and industrial wastes (Fig. A4), which, through water quality deterioration, has been associated with macroinvertebrate extinctions and biodiversity decline (Wright et al., 1995; Ourso, 2001; Allan, 2004; Cook et al., 2009; Ouédraogo, 2010). Furthermore, in U streams, morphological habitat degradation too may contribute to elimination of certain habitat specialists (Kasangaki et al., 2008). Indeed, mud, fine particulate organic matter and concrete were the dominant types of habitat we found in the U streams, offering very reduced opportunities in terms of possible ecological niches. This explains a dramatic increase in the percentage of Chironomidae, Syrphidae, Culicidae and Psychodidae, groups commonly considered as tolerant to pollution (Hauer & Lamberti, 2006; Mandaville, 2002). Notably while some chironomid taxa are known to be less tolerant or even sensitive to pollution, in our study this family was dominated by Chironomini (in particular, *Chironomus* sp.) and *Tanypus* sp., which have already been shown to be highly tolerant to pollution in other African streams (Odume & Muller, 2011).

Human impact on benthic macroinvertebrate communities: functional composition

While metrics based on taxonomic composition allow an evaluation of diversity or sensitivity of the macroinvertebrate community to a certain stressor, the goal of the functional approach is to characterize ecosystem condition (Cummins et al., 2005). Thus, the functional composition of benthic communities is linked to the supply and persistence of particular resources taken up by aquatic food webs and should be responsive to any changes affecting the latter (Merritt & Cummins, 2006). Here we found indications that floodplain land use may drive shifts in the distribution of functional feeding groups in macroinvertebrate communities. The groups feeding on the fine particulate organic matter (collector-filterers and collector-gatherers), often recognized as generalists (Dobson et al., 2002), appeared to be dominant across all sites, a finding consistent with previous reports from African tropical streams (Uwadiae, 2010; Masese et al., 2014). However, the relative importance of these functional groups changed with the intensification of land use: collector-gatherers (primarily midges) became increasingly dominant, whereas collector-filterers (mainly caddisflies and bivalves) decreased along the gradient between P and U sites. Relying on filtering of particles out of water, collector-filterers are known to be sensitive to increased turbidity and sedimentation (Uwadiae, 2010). Thus, increase in both factors due to cattle-driven erosion and organic waste input observed in agricultural and U streams is a very probable explanation for the reduction of the relative abundance of this functional feeding group found in our study.

Some further trends were detected for other functional feeding groups. The remarkably low fraction of shredders in all study sites including the P ones was in accordance with other studies reporting a general scarcity of shredders in tropical streams (Dobson et al., 2002; Wright & Covich, 2005; Arimoro, 2007; Mesa et al., 2013; Christopher, 2014). Several possible explanations for shredder rareness in tropical streams have been offered: from faster microbial processing at higher temperatures (Irons et al., 1994) to lower leaf quality of tropical tree species due to their increased roughness and tannin contents combined with low nutritional value (Wantzen et al., 2002). Furthermore, shredders tend to have long life cycles and are slow colonizers (Jacobsen & Encalada, 1998), life traits that make them unsuitable for living in arid streams with highly variable and unpredictable discharge (Cheshire et al., 2005) as those in Burkina Faso. Even though overall shredder density across all study sites was very low, we did find indications for some differences related to land use types: most shredders were found at the natural sites, while they were missing or nearly missing in the rest of the sites. This decline in relative shredder abundance is most probably related to the removal of vegetation associated with both agricultural and U land use. Furthermore, we found a particularly high abundance of scrapers (in particular molluscs) in the intensive agricultural sites. Scrapers rely in their feeding on periphyton, thus algal biomass increases due to eutrophication, as discussed above, appears to be the most feasible explanation for their increased importance. Finally, in both types of agricultural sites, we also found predators fraction nearly tripled compared to P and U sites. Predator abundance appears to be largely driven by prey availability (Petermann et al., 2015) and has already previously been shown to increase in streams affected by human activities (Rawer-Jost et al., 2000). Thus, it appears feasible that this trend is related to eutrophication-driven increase in prey abundances.

Across different land use categories we found in stream communities a general deviation from the expected balance in terms of functionality and exchange with the riparian zone, as revealed using functional group-based surrogate measures of ecosystem attributes. Thus, FFG ratios indicated that, along the studied land use gradient, stream communities were characterized by an increased heterotrophy (in all land use categories but IA) and were at the same time highly sensitive to the presence of fine particulate and not coarse particulate organic matter. Furthermore, we found a relative predominance of predators at agricultural sites and a remarkably low top-down predator control ratio in sites with U land use. These results lie in line with previous studies on degradation effects in tropical streams (Cummins et al., 2005; Masese et al., 2014) and further strengthen our conclusions on the effects of artificial human-driven organic matter subsidies and fertilizers to both agricultural and U streams. Combined with removal of natural riparian vegetation, it appears to lead to a shift in aquatic trophic structure. Altogether, while pointing towards the effects of degradation, FFG ratios did not always allow us to clearly distinguish between different levels of human impact. These metrics appear to be highly affected by the season of the sampling, the correctness of attribution of taxa to functional feeding groups (often limited) and also by whether they are calculated based on abundance or biomass (Cummins et al., 2005; Masese et al., 2014). Furthermore, as the method has been formulated for the temperate zone, threshold values crucial for interpretation of the results might need to be adjusted for the tropical streams (Cummins et al., 2005).

Human impact on benthic macroinvertebrate communities: indicator taxa

The functional and taxonomic metrics discussed above varied in their sensitivity to human impact and in part were only capable of detecting extreme degradation as in U streams. By contrast, the indicator taxa approach was successful in distinguishing between categories of human impact at several levels of similarity. We found the highest number of significantly supported indicator taxa in the P streams. Several of them belonged to EPT taxa, sensitive to the degree of efficient aeration of the sediment and to the availability of specific habitats (Sweeney et al., 2009; Tonkin, 2014). Fewer (two–three) taxa were identified as indicators for each of the two categories of agricultural sites. These points towards taxa tolerant to low-to-moderate levels of pollution and capable of profiting from increasing eutrophication. For example, *Macrobranchium* shrimps in EA sites and Chironominae in IA sites have already been suggested as bioindicators of environmental stress previously (Marques et al., 1999; N'Zi et al., 2008; Lock et al., 2011). Importantly, using these metrics, we found that P sites were the most similar to the sites with extensive floodplain agriculture, while the sites with IA were the ones closest to the U sites. In the latter, only one taxon with significant IndVals was identified: "red" Chironomus. This is not surprising, as very few taxa survive in these highly polluted environments, and these are typically not U sites specialists but rather generalists with high tolerance to stream degradation (Thorne & Williams, 1997; Ourso, 2001; Konrad & Booth, 2005). In fact, red chironomids are considered common and tolerant to a wide array of environmental conditions (Tokeshi, 1995; Barbour et al., 1999; Hooper et al., 2003), and due to possession of haemoglobin, a pigment that transports and stores dissolved oxygen, are known to survive even in highly polluted and oxygen-depleted environments (Moore & Palmer, 2005; Roque et al., 2012).

Conclusions for stream conservation in Burkina Faso

As in many countries across the world, the running waters of Burkina Faso are threatened by multiple impacts of human activities, notably by severe pollution and habitat degradation from intense urbanization and agriculture affecting their temperature regimes, sedimentation processes, riparian vegetation, water physical chemistry and evaporation rates (Aurouet et al., 2005; Munné et al., 2012). These impacts eventually lead to the loss of habitat and water quality, and hence, negatively affect freshwater fauna. In view of high population growth and thus rising rates of human pressure and habitat degradation, identification of key areas for protection valuable in relation to the presence of specific taxa appears to be crucial for ensuring the long-term regularity of aquatic macroinvertebrate biodiversity (Benstead & Pringle, 2004; Heino, 2008).

Across several types of anthropogenic pressures (grazing by livestock, land farming, urbanization), we developed an extensive inventory of the benthic fauna in Burkina Faso streams and demonstrated that several metrics derived from the composition of the macrobenthic community can efficiently distinguish between land use-related human impacts. Specifically, we found that metrics related to the overall richness and diversity of the macroinvertebrate community as well as its functional composition were capable of identifying the high levels of degradation as observed in the U sites. Using the specific taxonomic composition of the benthic community, one can distinguish between P and agricultural areas either by focusing on known sensitive groups such as EPT taxa or on indicator taxa. Our findings confirm the importance of maintaining a range of P areas hosting a range of sensitive taxa and crucial for effective conservation of the regional fauna (Brashares et al., 2001; Muhumuza & Balkwill, 2012). While some further steps need to be done to refine our results (for instance by taking into account seasonal dynamics of benthic communities or the role of other stressors which have not been addressed here), this work lays a solid basis for development of simple and easily applicable biomonitoring tools for management and conservation of water and river systems in West Africa.

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