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Journal of Ecology and The Natural Environment

January-March 2021
ISSN 2006-9847
DOI: 10.5897/JENE
www.academicjournals.org

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Vol. 13(1), pp. 1-10, January-March 2021
DOI: 10.5897/JENE2020.0871
Article Number: EB67C3866137
ISSN 2006-9847

http://www.academicjournals.org/JENE

Journal of Ecology and The Natural Environment

Full Length Research Paper

Ecological status of a newly impounded sub-saharan reservoir based on benthic macroinvertebrates community (Burkina Faso, West Africa)

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Received 7 December, 2020; Accepted 28 January, 2021

In West Africa, particularly in Burkina Faso, the aquatic ecosystems are under human pressures. Therefore, for long term management of these ecosystems, the managers need baseline data for regular assessment of ecological health condition. In this regard, the structure of the benthic macroinvertebrate community was investigated and the relationship between the environmental variables and biotic indices of the Samandéni reservoir from January to December 2018, after one-year impoundment was explored. The macroinvertebrates were collected with a hand net (25 × 25 cm^2 coverage area and 500 µm mesh) according to the multi-habitat sampling method. Key environmental variables such as temperature, conductivity, dissolved oxygen, pH and total dissolve solids (TDS) were measured *in situ*. High diversity of macroinvertebrates was reported and thirty-four (34) taxa were determined belonging to eight (8) orders dominated by insects (79.41% of all taxa). Good ecological quality of the reservoir was testified by the presence of several sensitive taxa like Ephemeroptera and Trichoptera. The trends of environmental variables also reflect good habitat conditions. The results revealed a strong and negative relationship between some abiotic variables and biotic indices. The finding of this study is of big importance for sustainable management of the Samandéni Reservoir.

Key words: Burkina Faso, macroinvertebrates, monitoring, reservoir, status.

INTRODUCTION

The key global challenge in the 21st century is to maintain the supply of clean water and other aquatic ecosystem services that are of benefit to human's well-being, without affecting biodiversity and ecosystem processes that reinforce their sustainability (Pawlowsky et al., 2018). The effect of climate changes on hydrological and biological dynamics is poorly documented in developing countries (Taniwaki et al., 2017). Therefore, studies on the health of inland aquatic ecosystems are crucial for each nation which must supply water both qualitatively and quantitatively to meet the increasing demands of local populations. Many authors have demonstrated that monitoring water quality by using biological approaches, especially macroinvertebrates communities has greater advantages compared to physical and chemical approaches (Jun et al., 2012; Nyamsi et al., 2014). While

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physical and chemicals measurement required expensive and specialized equipments, and do not provide long-term predictions of environment changes. But benthic macroinvertebrates are recognized as very good indicators, and are the most commonly used (Nyamsi et al., 2014; Kaboré et al., 2016a, c; Gerami et al., 2016; Arimoro and Muller, 2010). This is due to: (a) their sedentary nature, which facilitates spatial analyses of pollution effects, (b) the sensitivity of many common species are well-documented for different types of pollutants (Myers et al., 2011), and (c) the long life cycles of some species, which make them more cost-effective tools to trace pollution effects over longer periods (Heino and Peckarsky, 2014). Habitats degradation, land uses, hydromodification and water pollution can be monitored by assessing benthic macroinvertebrates community structure, and indicators species (Flores and Zafalara, 2012; Kambwiri et al., 2014; Kaboré et al., 2016a; Patang et al., 2018). A large number of biotic metrics/indices have been developed in different countries (Chi et al., 2017; Borja et al., 2013; Dedieu et al., 2015; USEP, 2018; Tampo et al., 2020). However, in developing countries, and particularly in Western African region, the use of biological organisms for monitoring aquatic ecosystems health is still less documented (Kaboré et al., 2016a; Tanon et al., 2020). In Burkina Faso, few studies have addressed the ecological status of the reservoirs. The studies on macroinvertebrates are those of Guenda (1986), Kaboré (2016) and Kaboré et al. (2016a, 2018) that have assessed riverine ecosystems health, and those of Koblinger and Trauner (2013) and Sanogo et al. (2014) on benthic invertebrates' diversity in standing waters. Kaboré et al. (2016a, 2018), Koblinger and Trauner (2013) and Sanogo et al. (2014) mentioned that macroinvertebrates are good indicators of ecosystem conditions (Reyjol et al., 2012; Selvanayagan and Abril, 2016), because they respond to environment disturbances due to human activities. Burkina Faso's last big reservoir is Samandéni, built in 2017 and classified as a Ramsar site in October 2020 (https://rsis.ramsar.org/ris/2439). The dam and associated wetlands provide water for electricity, agriculture and human consumption, while the sparse population plays a major role in enabling the maintenance of biodiversity levels. The vegetation consists of wooded savannah and open forests, combined with dense semi-deciduous gallery forests with trees of up to 40 m in height. The site hosts internationally threatened tree species like the kosso *Pterocarpus erinaceus* and the mahogany *Afzelia Africana* and *Khaya senegalensis*. It also features a diverse range of mammals, waterbirds, fish and reptiles. Minoungou (2020) recorded 40 species of fish, dominated by seven species (*Sarotherodon galilaeus*, *Coptodon zillii*, *Oreochromis niloticus*, *Marcusenius senegalensis*, *Synodontis schall*, *Schilbe intermedius* and *Brycinus nurse*) (Minougou et al., 2020). Globally threatened mammals such as the Hippo (*Hippopotamus amphibious)* and the African elephant (*Loxodonta Africana)* also feature. The increasing human population downstream of the site, increased spread among local communities of water-related diseases, dispersal of hippopotamus herds, impacts of climate change and the lack of stakeholder consultation in its management and development are among the more urgent threats facing the natural resources in the site (https://rsis.ramsar.org/ris/2439). The sustainability of local socio-economic activities reposes on better management of this important reservoir. The present study aims to provide a first database on his benthic macrofauna, one year after its impoundment. The specific objectives were to: (1) evaluate the composition and diversity of benthic macrofauna in the reservoir and (2) explore the relationship between environmental variables and biotic indices as well as describe ecological status using macroinvertebrate community.

MATERIALS AND METHODS

Study area

In Burkina Faso, the climate is characterized by highly irregular rainfall patterns with marked differences between wet and dry seasons which lead to highly chronic water scarcity and episodes of severe drought. The country relies much on reservoirs to produce food (maize, cereals, fruits, vegetables, fish, meat, etc.) for local and national consumptions and sustain socio-economic development in rural area. Following this, a new reservoir named Samandéni reservoir was created in 2017. This study was undertaken in this reservoir, located in the upper Mouhoun catchment (a sub-catchment of the Volta River), with an area of 20,980 km^2 (DGIRH, 2001). The data were collected from January to December 2018 in five sampling stations (Figure 1): Badoville (11°23'55,90''N; 04°34'41,40''W), Dioufoulma (11°23'00,28''N; 04°37'32,41''W), Sadina (11°26'53,22''N; 04°37'43,20''W), Banzon (11°19'59,83''N; 04°46'00,14''W) and Sikorola (11°25'24,55''N; 04°43'19,22''W). The Badoville and Dioufoulma stations are characterized by low human activities, with natural vegetation in the floodplain (e.g. shrubs and trees) typical to the area. Banzon, Sikorola and Sadina stations are characterized by intense activities, such as crops farming, banana plantation, and livestock in the riparian zone. In order to assess the dynamic of the benthic community in the reservoir, four sampling campaign were conducted from January to December 2018. Unfortunately, Dioufoulma, Banzon and Sikorola stations are prohibited during periods of heavy rain by the authorities for safety reasons.

Water variables measurement

At each sampling station, the key water variables such as pH, temperature (°C), electrical conductivity (µS cm^{-1}), dissolved oxygen (DO) (mg/L) and total dissolved solids (TDS) (ppm) were recorded *in-situ* using a portable multi-parameter device (*Hanna Instrument, HI9829*) between 9 and 11 a.m. Each variable was measured in triplicate at each sampling station. Immediately after water variables measurement, the macroinvertebrates were collected.

Benthic macroinvertebrates sampling

The macroinvertebrates were sampled with a hand net (rectangular

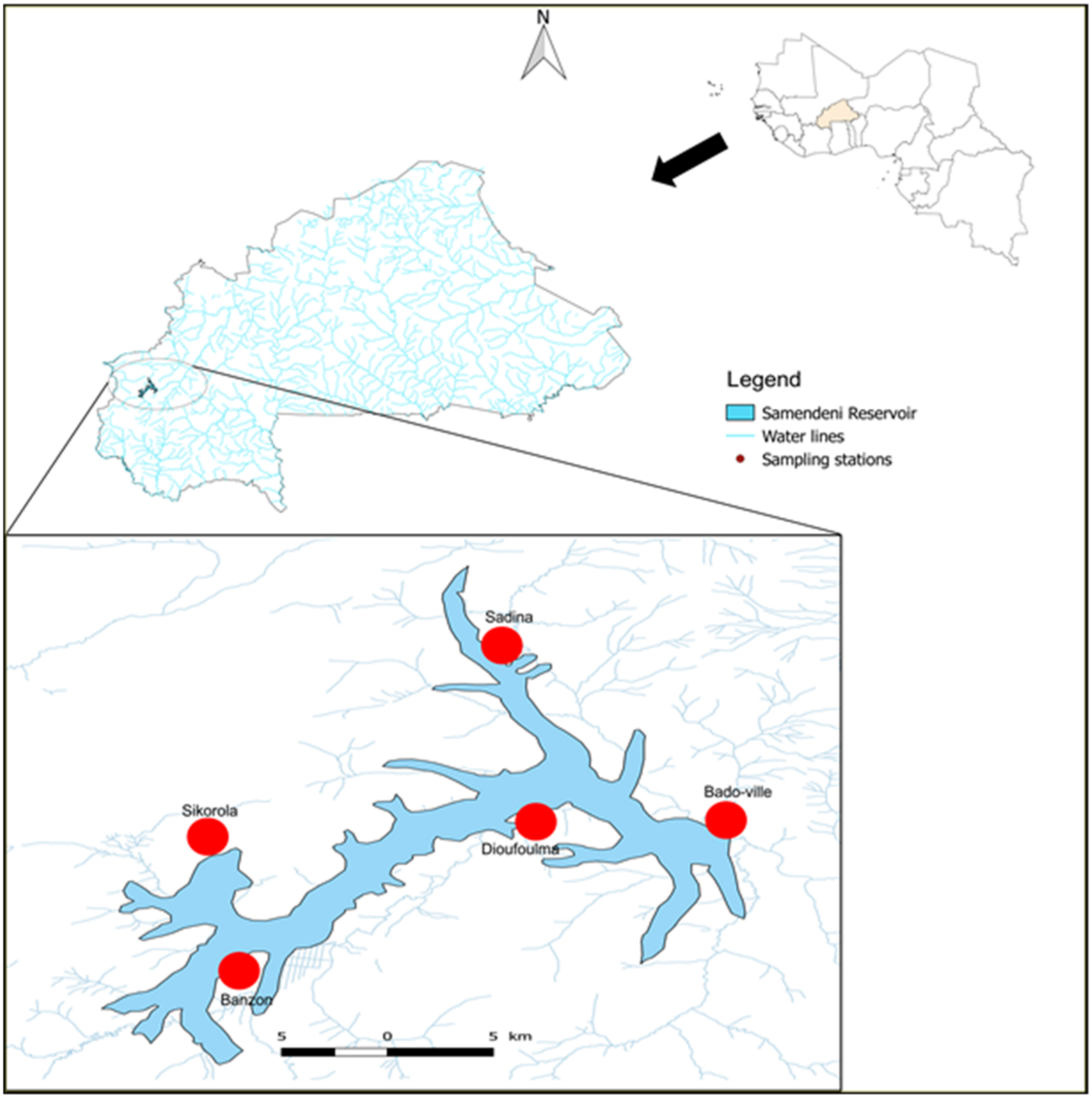

Figure 1. Study area with sampling stations in red dots.

opening: 25 cm x 25 cm, mesh size: 500 µm) according to the multi-habitat sampling approach described in Moog (2007). At each station, a pooled sample, consisting of 20 sampling units was taken from all microhabitats available in proportion to their coverage. The habitats were mainly composed of macrophytes (emerged and submerged plants), sediment (sand, mud, litter) and coarse substrate. Samples were fixed in ethanol (90%), and transported to the laboratory for detailed examination. Prior to sorting out the organisms, samples were sieved and the animals were sorted using a binocular microscope. All taxa were identified to the lowest taxonomic level as possible using taxonomic manuals and keys (Tachet et al., 2003; Moisan and Pelletier, 2008).

Data analysis

The mean and standard deviations, as well as extreme values (minimum and maximum) were calculated for all physico-chemical variables. We used the Kruskall-Wallis test ($p<0.05$) to analyse the variation of physico-chemical variables between sampling stations.

Species occurrences, number of taxa, EOT taxa, relative abundance of some groups (Molluscs, Chironomids, Hemipterans Coleopteran) per station, Shannon-Wiener index (H') and Equitability were estimated to evaluate invertebrates' diversity and abundance. The relative abundance is the percentage of individual particular taxon by total number of all taxa. The Shannon-Wiener

Table 1. Summary statistics of water variables measured in the field for the 5 sampling stations during the study period.

Physicochemical characteristics	All stations (5)		
	Mean	Min	Max
Temp (°C)	25.83 (±2.90)	22.15	33.60
DO (mg/L)	5.68 (±1.18)	4.00	9.00
Cond (µS/cm)	109.69 (±22.20)	50.60	200.00
TDS (ppm)	49.74 (±5.18)	44.00	60.00
pH	7.48 (±0.18)	6.89	7.95

Max= Maximum, Min= Minimum. Value in parentheses indicates the standard deviation.

index (H') (Shannon and Wiener, 1949) and the Equitability (Piélou, 1969), are the common diversity indices which provide information about community composition, rarity and commonness were calculated using respectively formulas (1) and (2).

1) $H' = -\Sigma ((Ni / N) \times \ln (Ni / N)$

where Ni: number of individuals of a given taxa and N: total number of individuals.

2) $E = H' / H\max = H' / \mathrm{Log2}\, S$

where S: number of species observed.

The frequency of occurrence was determined for each taxon following Dajoz (2000): rare (<25%), frequent (25-50%), and very frequent (>50%). To explore relationship between water variables and biotic indices, Spearman correlation was used. Cases of weak correlation (Spearman r <0.5; p> 0.05) were excluded from the final matrix.

Ethical statement

According to the authors, the research was conducted according to ethical standards.

RESULTS

Physico-chemical status of the reservoir

Study stations had slightly warm water temperatures (mean=25.83°C), a neutral pH (mean=7.48), good oxygen contents (mean=5.68 mg/L) and low conductivity (mean=109.69 µS/cm) (Table 1). The highest temperature (27.4°C), pH (7.75) and dissolved oxygen were recorded in Sadina. The highest conductivity (145.33 µS/cm) was found in Sikorola. The Kruskal-Wallis test shows no significant difference (p > 0.05) between the values of pH, temperature, DO and conductivity obtained at the 5 stations.

Taxonomic diversity and occurrence

The Samandéni Reservoir harbor high diversity of macroinvertebrates (Table 2). A total of 34 macro-invertebrate taxa were identified belonging to four classes (Insects, Molluscs, Crustaceans and Annelids), eight (8) orders and 33 families. Insects were the most diversified class with 27 taxa (79.41% of all taxa) followed by the Mollusks (4 taxa). Crustaceans (2 taxa) and Annelids (1 taxa) are the less represented. Eleven taxa (Baetidae, *Caenomedea* sp., *Bezzia* sp., Chironomidae, Coenagrionidae, *Micronecta* sp., *Ranatra linearis*, Dytiscidae, Hydrophillidae, Libellulidae, and *Biomphalaria* sp.) are common to all stations. The high taxonomic diversity (28 and 22 taxa) was found in Bado-ville and Sadina, respectively, while the lowest (14 taxa) in Dioufoulma. Five taxa (*Notonurus* sp., Oligoneuridae, *Ephoron* sp., *Laccotrephes* sp., *Notonecta* sp.) two taxa (*Macrobrachium dux*, Chlorolestidae), one taxon (*Lymnae (Radix) natalensis*) and one taxon (Elmidae) were specifically recorded in Badoville, Sikorola, Sadina, and Banzon, respectively (Table 2).

The Ephemeroptera (Baetidae, *Caenomedea* sp.), Diptera (Chironomidae), Odonata (Coenagrionidae) and Hemiptera (*Micronecta* sp.) were the common taxa (FO>50%) in the reservoir. One taxon of Molluscs (*Biomphalaria* sp.) was very frequent in four stations (Table 2).

Taxa abundances

In total, 2804 individuals of macroinvertebrate were recorded. Overall, the Order of Diptera was the most abundant (28%), followed by Ephemeroptera (25%) and Hemiptera (22%) (Figure 2). In Badoville and Dioufoulma, the Diptera (35.61%) were the most dominant group followed by the Ephemeroptera (29.49%). While in Sadina, the Ephemeroptera (31.48%) were the most abundant group followed by Diptera (22.66%). The results reveal that the Hemiptera and Diptera were well represented in Sikorola and Banzon.

Diversity metrics

Figure 3 showed the variation of metrics (taxa richness, EOT-taxa, % of Chironomidae, % of Molluscs, % of

Table 2. List of benthic macroinvertebrates taxa collected from Samandéni Reservoir during the period of study.

Phylum	Class	Order	Family	Taxa	Bado.	Sadi.	Siko.	Ban.	Diou.
Arthropoda	Crustaceans	Decapoda	Atyidae	*Caridina Africana* Kingsley, 1882	**			**	
			Palaemonidae	*Macrobrachium dux* Lenz, 1910			*		
	Insects	Ephemeroptera	Baetidae	Baetidae	***	***	***	***	***
			Caenidae	*Caenomedea sp.* Thew, 1960	***	***	***	***	***
			Heptageneidae	*Notonurus sp.* Demoulin, 1973	**				
			Oligoneuridae	Oligoneuridae	**				
			Polymitarcyidae	Polymitarcyidae	**				
			Trichorytidae	*Tricorythus sp.* Eaton, 1868	***				
		Trichoptera	Ecnomidae	*Ecnomus sp.* Thomson, 1859	**	**			
		Diptera	Ceratopogonidae	*Bezzia sp*. Kieffer, 1924	***	***	***	*	***
			Chironomidae	Chironomidae	***	***	***	***	***
			Culicidae	Culicidae		**	**	*	
			Tabanidae	*Chrysops* Meigen, 1803	***	**	**	*	
			Psychodidae	Psychodidae				*	
		Hemiptera	Belostomatidae	Belostomatidae	***	***	**	*	
			Coenagrionidae	Coenagrionidae	***	***	***	***	***
			Corixidae	*Micronecta sp.* Kirkadly, 1897	***	***	***	***	***
			Gerridae	Gerridae	**	**	*		
			Naucoridae	Naucoridae	*	**	**		
			Nepidae	*Laccotrephes sp.* Stål, 1866	**				
			Notonectidae	*Notonecta sp.* Linnaeus, 1758	**				
			Ranatridae	*Ranatra linearis* Limnaeus, 1758	**	***	**	*	**
			Veliidae	*Rhagovelia sp.* Mayr, 1865	**	***	***		**
		Coleoptera	Dytiscidae	Dytiscidae	***	***	***	*	***
			Elmidae	Elmidae				*	
			Hydrophilidae	Hydrophilidae	***	***	***	**	***
		Odonata	Chlorolestidae	Chlorolestidae			**		
			Gomphidae	Gomphidae	***	**			**
			Libellulidae	Libellulidae	***	***	***	**	***
Annelids	Clitellata	Arynchobdellida	Hirudinae	Hirudinae	**				**
Molluscs	Gasteropoda	Basommatophora	Thiaridae	Thiaridae	**	**		**	
			Planorbidae	*Biomphalaria sp*	***	***	***	*	***
			Lymnaedae	*Lymnae(Radix) natalensis* Wright, 1966		**			
			Unionidae	Unionidae	**	**			
Total			34	34	28	22	19	18	14

Bado: Badoville; Sadi: Sadina; Siko: Sikorola; Ban: Banzon; Diou: Dioufoulma. ***Very frequent (FO > 50%); **frequent (25% ≤FO ≤50%); *rare occurrence (FO < 25%).

Coleoptera, % of Hemiptera, Shannon-Weiner diversity and Equitability) used to analyse benthic invertebrate's diversity. We found that the indices: total taxa and EOT-taxa, show the same variation. The high values of diversities were found in Badoville and Sadina, while the low values of diversities and EOT-taxa were recorded in Dioufoulma and Banzon (Figure 3a, d). Figure 3b and c show that the percentages of chironomids, molluscs, hemipterans and beetles vary from station to station. In stations where the percentage of Chironomidae is high, that of molluscs is low (Figure 3b). Similarly, in stations where the percentage of hemipterans is high, that of beetles is low (Figure 3c).

Correlations between biological and environmental data

Spearman correlation between metrics and physico-chemical variables (Table 3) indicated that conductivity

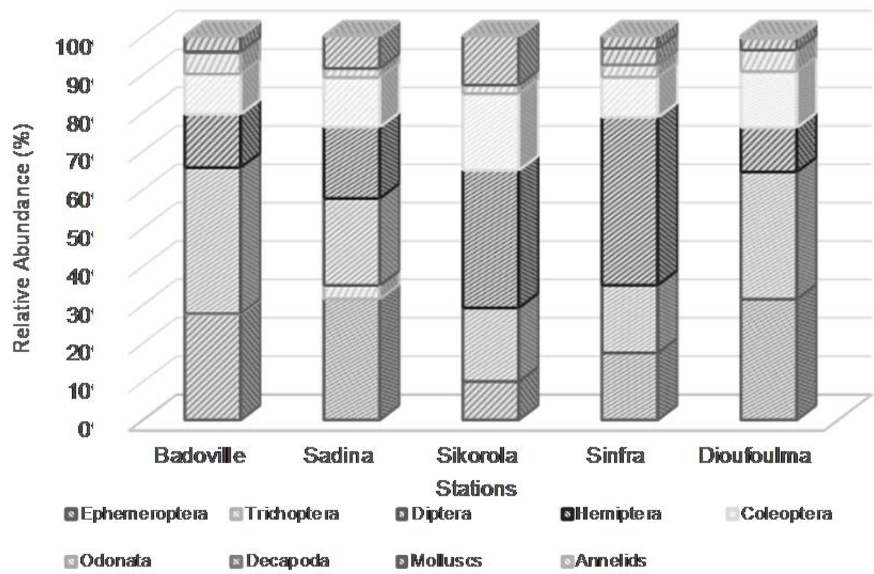

Figure 2. Relative abundance of macroinvertebrate orders encountered in the Samandéni Reservoir.

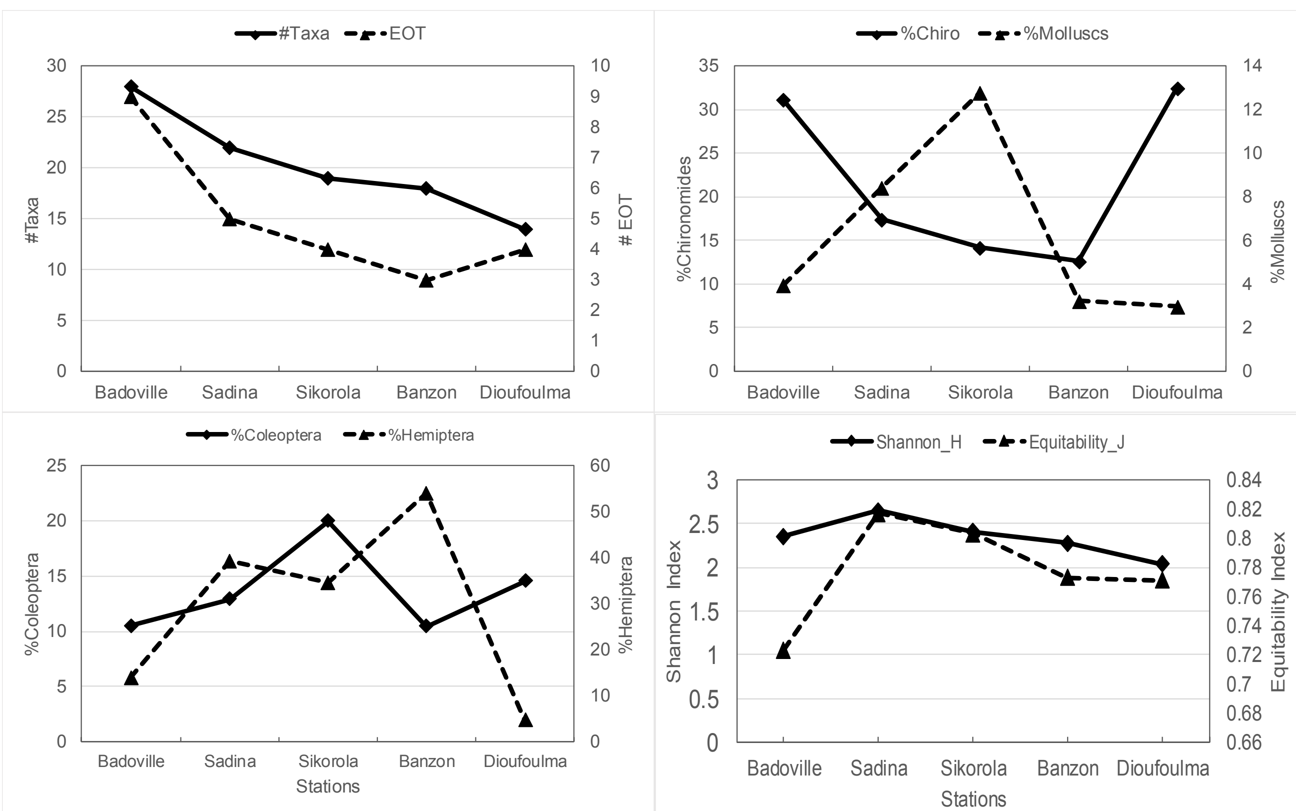

Figure 3. Variation of the biotic indices in the sampling stations.

taxa (Spearman correlation r=-0.97, p< 0.05) and total number of taxa (r=-0.90, p< 0.05) while water pH was highly and positively correlated to EOT-taxa (r=0.87, p< 0.05). The significant positive correlation was also detected between the temperature and hemipterans (r=0.8, p< 0.05). We found that chironomids abundances

Table 3. Correlation Matrix of Water Variables and Biological Index marked with an asterisk (*) =statistically significant (p<0.05).

Water Variable \ Biological Index	Total Taxa	%Chironomidae	%Molluscs	EOT	%Coleoptera	%Hemiptera	Shannon	Equitability
pH	0.6	0.6		0.87*			0.5	
Temp	0.5	-0.5			-0.6	0.8*	0.6	0.5
OD	0.40							0.6
Cond	-0.90*		-0.5	-0.97*			-0.6	
TDS		0.8*	-0.6			-0.5		

16 Insect taxa not identified to species level. Out of 34 taxa in Table 2, only 15 are identified to species level.

was highly and strongly correlated with EOT- were significantly and positively correlated to total dissolved solids (Table 3).

DISCUSSION

Water quality parameters are key factors that influence the life of living organisms in water bodies (Pardo et al., 2012; Hussain and Pandit, 2012). Other studies have underlined the importance of physical-chemical variables for biomonitoring in tropical streams (Thorne and Williams, 1997; Lakew and Moog, 2015). Indeed, authors have demonstrated that the intense land use in riparian zone can deteriorate the quality of water physical and chemical variables (Kaboré et al., 2018; Meulenbroek et al., 2019). In this study, the values of the main physicochemical variables are similar to those obtained by Kaboré et al. (2018) in the reference sites of Burkina Faso. That can be explained by the fact that the riparian zone of the reservoir is slightly impacted by human activities such as agriculture and livestock, hence the good physical and chemical condition of the Samandéni Reservoir. This data can be used as baseline status data to monitor the quality of reservoir habitat.

The diversity obtained (34 taxa) is higher than that obtained by Sanogo et al. (2014) in three reservoirs located in the same Mouhoun catchment. The high diversity of macroinvertebrates found in the present study can be explained by the habitat heterogeneity and suitable conditions due to lower human pressures in the riparian zone. Our results are similar to those reported by Camara et al. (2012) and Kaboré et al. (2016a), who have demonstrated that areas are created to preserve natural resources and wilde animals. According to Kaboré et al. (2016a), Moog (2007), and Selvanayagam and Abril (2016), the variation of the structure of macroinvertebrate community is influenced by the habitat conditions. Here, the lower diversity observed in Dioufoulma, Banzon and Sikorola could be explained by anthropogenic activities such as vegetable crops farming (e.g. using fertilizers and pesticide) in the riparian areas. In contrast, the good ecological condition of Badoville and Sadina stations can justify the hight diversity recorded here.

Our findings showed that insects are the most abundant. That could be explained by the large ability of this group to survive in different types of habitats (Tachet et al., 2010; Mereta et al., 2011), and can also adapt to many feeding strategies in water colunm. This agrees with previous studies on sub-Saharan areas that have proven that the tropical fresh water, harbors a high diversity of macroinvertebrates dominated by insects (Adandedjan et al., 2011; Edia et al., 2013; Sanogo et al., 2014; Kaboré et al., 2016a; Sirima et al., 2017). The presence of macroinvertebrate groups such as Ephemeroptera, Trichoptera and Odonata, recognized as sensitive to pollution, indicates that the Samandéni Reservoir has good ecological conditions (Wahizatul et al., 2013; Kaboré et al., 2016a, b). Other authors (Suleiman and Abdullahi, 2011; Sharma and Chowdhury, 2011) argued that the range of habitats and water chemistry offers basis for a high diversity of freshwater macroinvertebrates. In the same trend, many studies showed that, key sensitive taxa can decline with a decrease of water quality, which is mainly caused by human activities (Flores and Zafalara, 2012; Elias et al., 2014; Morris et al., 2014). 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 and Cummins, 2006). The low electrical conductivity of the reservoir water testifies to its low mineralization due to the weakness of organic matter. The opposite variation in the abundance of Chironomidae and Molluscs may be due to competition between the two groups for habitat and food supply. Indeed, organic matters are used by other Chironomids to build cases. Also, it contributes to improve algae and macrophytes proliferation in water bodies, which constitute an important food resource for mollusks proliferation. In the sites, the variation of the abundances of other macro-invertebrate groups, such as Beetles and Hemiptera reveal that the two groups do not share the same food resources. Thus, according to Kaboré et al. (2016a) and Masese et al. (2014), the Beetles are herbivore-detritivore, while most of Hemipterans are predators. The diversity of taxa sensitive to pollution are parameters most often used to assess the quality of an aquatic environment (Kaboré et al., 2016a; Masese and Raburu, 2017). The same variations observed for the indices: total diversity and EOT taxa in the stations, could be explained by the fact that they reveal the same information on the ecological state of the site. Total-taxa and the EOT index would be more suitable for evaluating the quality of stagnant water than the EPT taxa, which have been recognized as very good indicators of riverine ecosystems integrity (Myers et al., 2011; Kaboré et al., 2016a; Masese and Raburu, 2017; Jerves-Cobo et al., 2017). The absence of plecopterans may be due to the fact that the water in the reservoir is stagnant. The Odonata are considered as important indicators of environmental conditions, as they inhabit both aquatic and terrestrial habitats during their life cycle, and therefore may better reflect disturbance in riparian buffer modification (Goertzen and Suhling, 2013; Oliveira-Junior et al., 2015; Miguel et al., 2015; Monteiro-Júnior et al., 2015). Because the Odonates are predators, according to Stoks and Córdoba-Aguilar (2012) and Nedjwa et al. (2018), their presence can express good diversity of macro-fauna in the water. Here we found also a strong and negative correlation between the electrical conductivity and EOT-taxa. Indeed, the high conductivity is often an indicator of water pollution because it is likely to be affected by different riparian land use types (DeTroyer et al., 2016; Kaboré et al., 2016a, c, 2018; Meulenbroek et al., 2019).

Conclusion

This study provides the first inventory data of macroinvertebrates in Samandéni Reservoir. It harbors the high diversity of macroinvertebrates dominated by insects. We found that EOT-index could be a good indicator of ecological status of standing water bodies, and could be used as monitoring basis tool for the management and conservation of big fisheries ecosystems, particularly in Burkina Faso.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors are grateful to SUSFISH-Plus project (Sustainable Management of Fisheries and Water in Burkina Faso, second party) funded by APPEAR (Austrian Partnership Program for Higher Education and Research for Development) for considerable support for field activities; the ERASMUS + program of the European Union for the Mobility Scholarship (2018-2019), during which this article was written; to Professor P. D. M. Weesie, Member of Science and Society Group, Faculty of Science and Engineering, University of Groningen for his comments to the manuscript; and Dr. Komandan MANO (Université de Dédougou) along with Dr. Idrissa OUEDRAOGO (Université Thomas SANKARA) for their comments on the manuscript.

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Vol. 13(1), pp. 11-17, January-March 2021
DOI: 10.5897/JENE2020.0864
Article Number: 226C8C866191
ISSN 2006-9847

http://www.academicjournals.org/JENE

Journal of Ecology and The Natural Environment

Full Length Research Paper

Regenerating plant species of a highly anthropised tropical forest in Côte d'Ivoire, West Africa

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Received 5 November, 2020; Accepted 8 February, 2021

Haut-Sassandra classified forest (FCHS) lost more than 70% of its forest cover between 2000 and 2011 due to armed conflict and cocoa cultivation. The government is concerned about the future of this forest and whether it can regenerate naturally. Observations likely to uncover plant species that are capable of regenerating the forest were collected through systematic sampling comprising 18 line transects each containing 20 segments. In each segment, it was noted, firstly, the species present and their height and, secondly, the forest cover and the artificial features that reflect human actions. Different observations recorded in the field were processed by frequency analysis in order to find the species able to regenerate easily for a best forest because they belong to a vegetation reconstitution. Principal results showed that the numerous coexistences, in the segments, of the fallow and forest characters in reconstitution mean that fallow land allows for the reconstitution of the forest, in a progressive vegetation sequence. Fifty-nine species appeared capable of naturally regenerating the classified FCHS. This result will help authorities and other deciders to adopt an adequate scenario for this forest management.

Key words: Deforestation, abandoned cocoa farms, forest regeneration, agricultural activity, tropical forest.

INTRODUCTION

Côte d'Ivoire's protected areas and classified forests were higly affected by the armed conflicts from 2002 to 2011 (Barima et al., 2016). During this period, absence of management authority and the paralysis of state institutions had trainee agricultural practices development in classified forest. One of the most typical examples is that of the Haut-Sassandra Classified Forest (FCHS) located in the Centre-West of Côte d'Ivoire. At the beginning of the 2000s, this forest was one of the most relic forests until clandestine farmer’s invasion for cacaoculture causing a high perturbation of this ecosystem (Barima et al., 2016). This forest restoration became a major priority for the administrative and political authorities who engaged some actions for FCHS preservation through the remove of farmers illegaly settled in the forest. This brutal solution has been applied in other Africa’s forests such as the Mont Peko National Park and has been ineffective (Ousmane et al., 2020). In

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order to reconstitute a forest on the FCHS territory, it would be possible to carry out monospecific artificial plantations, for example *Tectona grandis*, but this expensive solution would drastically reduce the diversity of forest species which is the natural ecological potential of this forest. Field observations (Assalé et al., 2016; Barima et al., 2016) suggest that gradual natural regeneration is possible from local forest species as long as they are still present. The question that then arises is: Which species present in the FCHS that can ensure sustainable forest regeneration? To find an answer, the most useful notion is the vegetation sequence which is the set of successive stages of vegetation evolution that can be deduced from observations made in the field (Godron, 2012) and which makes it possible to distinguish between progressive and regressive sequences.

Indeed, in the past, the classified forest was in a state of stabilised dynamic equilibrium where the physiognomy of the forest hardly changed over the years and oscillated around an average situation (Kouamé, 1998; Chatelain et al., 2004). Crop establishment is a regressive crisis so strong that it destroys the regulations that ensured the stability of the forest and replaces them with the regulations imposed each year by the farmers (Godron, 2012). New species then germinate; thanks to the light that reaches the soil. When the cacao farm is then abandoned, the series of successive stages of a 'progressive' vegetation sequence gradually takes place (Akodéwo et al., 2019).

According to previous studies on the establishment of crops in tropical forests (Kouassi et al., 2009; Assalé et al., 2016; Akodéwo et al., 2019), this operation is often described as 'degradation' as if human actions automatically led to a loss of quality compared to an ideal that would be the natural state of the vegetation before the arrival of humans (Arbelot, 1979). To avoid any ambiguity we consider the evolution of vegetation corresponding to forest clearance to be regressive and the sequence of forest regeneration to be progressive (Assalé et al., 2016). This study aims to identify the species capable of initiating the natural regeneration of FCHS. Specifically, it will be focused on (1) determining the features of artificialisation and (2) identifying progressive species by highlighting, by contrast, the "regressive" species established following deforestation.

MATERIALS AND METHODS

Study area

The study area is the Haut-Sassandra Classified Forest, located in the central-western part of Côte d'Ivoire between the departments of Vavoua and Daloa (Figure 1). It covers an area of 102,400 ha. This region is characterised by a humid tropical climate. The average annual rainfall is 688 mm with a minimum of 673 mm and a maximum of 1036 mm. The soils of the FCHS are ferralitic type (Kouamé, 1998). The vegetation of the FCHS belonged to the domain of semi-deciduous humid dense forests with *Celtis* species and *Triplochiton scleroxylon* (Kouamé, 1998).

Data collection

Data collection was carried out in March 2018. For the sampling, 18 line transects were used evenly distributed around the FCHS (Godron, 2012). Each transect is 50 m long and 10 m wide; it is subdivided into 20 segments, 25 m long and 10 m wide, giving a surface area of 250 m² for each segment. Over 5 m on either side of the line marking each transect, the presence of plant species and their height with a dendrometer was noted. The Angiosperm Phylogeny Group III (APG III) has been adopted for the families of plant species.

Human actions and artificial features

Artificialization features" (Godron et al., 1968; Papillon et al., 2008) which reflect human actions were observed in each segment of the transect. Artificial features similar to those proposed by Godron et al. (1968) and Papillon et al. (2008) were used.

In each transect, field observations were recorded in the form of a matrix where the presence of each feature is indicated by the number 1 and the absence by the number 0. Traces of clearing and various crops are clearly the most frequent artificial features; those of forests undergoing reconstitution are less frequent but their number is sufficient to make it reasonable to think that these places can be the basis for forest regeneration.

Data analysis

To find relationships between vegetation and the characteristics of its environment, multivariate methods and in particular factorial correspondence analysis are very often used (Lebreton et al., 1988; Ahmed et al., 2015). These methods give an interesting picture of the statistical proximities between vegetation and its environment, but they do not include tests to calculate the degree of significance of these proximities (Dolédec et al., 1995; Xiaobing and van der Maarel, 1997).

In this case, it is particularly essential to implement precise direct probabilistic tests because the relationships between vegetation and artificial features are less direct than the causal relationships between vegetation and the physical or chemical characteristics of the environment. Moreover, the landscapes in the study area are highly heterogeneous at two scales (Forman and Godron, 1986; Papillon, 1997), and they cannot constitute the infinite universe from which representative samples can be drawn for the inferential estimates presented in the usual statistics manuals. Therefore, the probabilistic tests of frequency analysis (Godron, 2012) which suffer from no estimation bias and which are accurate in the sense of Fisher were used.

A combinatorial calculation makes it possible to directly calculate the probability of finding coexistences (P), without using the law of large numbers and without referring to an infinite and unknown universe, based on Brillouin's formula (1962):

$$Ib = \log_2 1/P$$

where Ib is the amount of information measured in binons and P is the probability of the observed event.

This information is marked with a + sign when the number of coexistences is very high; it is negative and marked with a - sign when there are few coexistences, and it constitutes the ecological profile of the species in relation to the artificial trait. These tests will also be used to find groups of artificialization traits.

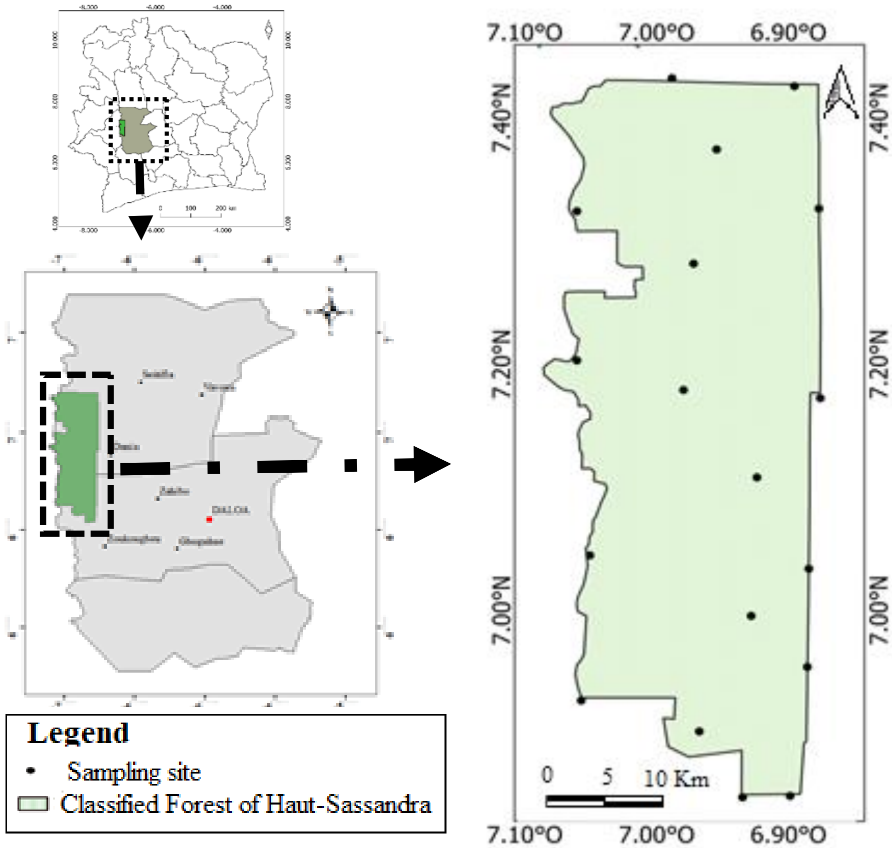

Figure 1. Location of the Haut-Sassandra classified forest in Côte d'Ivoire and sampling sites.

Species and their place in vegetation sequences

The link between the presence of a species and artificialization traits is complex, and it is necessary to see whether each species is predominantly present in segments where numerous traits indicate a regressive sequence or whether, on the contrary, it is present in segments where traces of the forest indicate a progressive sequence.

Criteria for the classification of species

The first species classification criterion (Tr-) is derived from the number of times a species was significantly found in a segment where a regressive human action trait was observed. The second criterion, the opposite of the first (Tr+), is deduced from the number of times a species was observed in a segment where a progressive human action trait such as Fairly conserved forest or forest in recovery was observed. The third criterion (Sc.) comes from the number of times the species has been found under one of the 5 cover classes between 0 and 100%; for this sciaphilia index (the opposite of heliophyte) the species can then be: 1 typical heliophyte, 2 heliophyte, 3 shade-tolerant, 4 shade-preferant, 5 sciaphyte. The fourth and fifth criteria are the mean of the logarithms of the heights (H) of the species and the corresponding variance (var). The synthesis of these criteria gives the regenerating index (I). For this index, the species can then be: 1 very regressive, 2 often regressive, 3 ubiquitous, 4 often regenerating, 5 very regenerating (Godron, 2012).

RESULTS

Artificialization features

A total of 41 artificial features were identified within the FCHS (Table 1). Falling dead trees, burning of tree trunks and crop associations are clearly the most frequently represented artificialization traits with absolute frequencies of 206, 189 and 149, respectively. However, reconstituted forests are less frequent (09), but their number is sufficient to suggest that they can be the basis for forest regeneration. Artificialization features are unevenly distributed in the FCHS and are not independent. Burning affected most of the segments, and resulted in the fall of dead trees on a large number of them. These plantations have been productive enough for a place of denting of the cabosses to be installed. It was noted that the presence of a track that crosses the second segment and the mosaic of crops is installed next to the track.

Regeneration species

A total of 59 plant species belonging to 52 genera and 28

Table 1. Absolute frequency of strokes in Haut-Sassandra classified forest.

Trait	Absolute frequency	Trait	Absolute frequency
Association of cultures	149	Fallow land	43
Burning of tree base	189	Crushing site	5
Camp	3	Little intact edge	1
Chablis	39	Track	32
Yam field	2	Cocoa farm of + 5 years	10
Cassava field	8	1 year cocoa farm	61
Corn field	10	2 years cocoa farm	68
Rice field	6	3 years cocoa farm	59
Falling dead trees	206	4 years cocoa farm	15
Clearing the undergrowth	31	5 years cocoa farm	3
Extraction of firewood	10	Presence of large creepers	1
Forest in reconstitution	9	Well	1
Riparian Forest	2	Cocoa nursery	1
Fairly conserved riparian forest	4	Bare soil	2
Cleared riparian forest	10	Gramineae carpet	2
Intact riparian forest	2	Logging trace	22
Fairly conserved secondary forest	32	Trace of bush fire	4
Secondary forest cleared	20	Herbicide treatment	1
Secondary forest in reconstruction	1	Flooded area	2
Poorly conserved secondary forest	1	Relatively wet area	2
Lightly cleared secondary forest	4		

families were identified from the study area. The seven species-rich families contributed (Fabaceae, Sterculiaceae and Euphorbiaceae) 26% of the total plant species, and the remaining 25 families contributed 74% of the total plant species. These species are capable to regenerating the Haut-Sassandra Classified Forest (Table 2). All species have the number 5 in regenerating idex. They are said to be regenerating and are sufficiently numerous for forest management authorities to search for them in the field to find places where forest regeneration can develop.

DISCUSSION

Artificialization features recorded in the database are not independent of each other and some of them are often found together. The corresponding contingency tables give the most positively related groups of traits. For example, burning the tree base, falling dead trees, 1, 2, 3, 4 and 5 year cocoa plantations, cassava, yam and rice plantations, grass patches and crop association are the most frequent traits and they very often coexist in more than 100 segments. For example, the burning of tree stands and falling dead trees are enough for farmers to establish 1, 2 or 3 year old combination crops and cocoa plantations in more than 50 segments.

The features little cleared secondary forest, trace of bush fire, fairly conserved secondary forest and little conserved secondary forest are often found together in the same segment. This observation confirms that fire is the primary tool for attacking the forest. The fallow and the reconstructed forest found together shows a possibility of reconstructing the forest after fallow. These features also show that fallow land allows a reconstitution of the forest in a progressive vegetation sequence. It is possible that farmers allow fallows to establish themselves because they realise that cultivation leads to a decrease in soil fertility (Kouassi et al., 2009). The classified forest was in a state of stabilised dynamic equilibrium where the physiognomy of the forest hardly changes over the years and hovered around an average situation (Godron, 2012). The installation of crops is such a strong crisis that it destroys the regulations that ensured the stability of the forest and replaces them with the regulations imposed each year by the farmers. New species germinate thanks to the light that arrives on the ground. When the plantation is then abandoned, the series of successive stages of a progressive vegetation sequence gradually takes place. The image that best captures this succession of stages is Figure 2, which shows the states of equilibrium of a log placed in a box with an undulating bottom and shaken by disturbances (Godron, 2012).

This model helps to understand the evolution of the vegetation of a forest after a violent cultivation crisis. The natural primary forests are in the very deep stability trough D, which is very deep, since these forests are

Table 2. List of regeneration species in the Haut-Sassandra classified forest.

Plant species	Familie	Tb	I	Tr-	Tr+	Sc	H	var.
Adenia lobata (Jacq.) Engl.	Passifloraceae	mp	5	-380	81	3	6	2.58
Aidia genipiflora (DC.) Dandy	Rubiaceae	mp	5	-103	35	4	7	3.6
Alafia barteri Oliv.	Apocynaceae	Mp	5	-76	30	4	6	2.14
Alchornea cordifolia Müll.Arg.	Euphorbiaceae	mp	5	-131	28	3	6	2.06
Ancistrocladus abbreviatus Airy Shaw	Ancistrocladaceae	Mp	5	-29	16	3	7	5.18
Baphia pubescens Hook. f.	Fabaceae	mp	5	-842	138	2	6	3.11
Bussea occidentalis Hutch.	Caesalpiniaceae	Mp	5	-147	27	3	8	6.5
Calycobolus heudelotii Heine	Convolvulaceae	mP	5	-95	25	3	6	2.96
Ceiba pentandra (L.) Gaertn.	Bombacaceae	MP	5	-445	56	3	8	11.39
Celtis adolfi-friderici Engl.	Cannabaceae	MP	5	-303	45	3	8	8.08
Celtis mildbraedii Engl.	Cannabaceae	mP	5	-757	89	3	7	5.92
Celtis zenkeri Engl.	Cannabaceae	mP	5	-311	70	3	8	8.74
Centrosema pubescens Benth*.*	Fabaceae	mp	5	-186	32	3	6	2.46
Christiana africana DC.	Tiliaceae	mp	5	-197	66	3	7	4.47
Chrysophyllum giganteum A. Chev.	Sapotaceae	MP	5	-137	32	3	7	5.96
Cnestis corniculata Lam.	Connaraceae	mp	5	-83	14	3	4	0.6
Cissus producta Afzel.	Vitaceae	mp	5	-80	12	3	6	1.62
Cnestis ferruginea DC.	Connaraceae	mp	5	-144	26	3	4	0.57
Combretum racemosum P. Beauv.	Combretaceae	mP	5	-238	47	3	5	2
Cynometra megalophylla Harms.	Fabaceae	mP	5	-26	21	3	8	7.99
Dialium aubrevillei Pellegr.	Caesalpiniaceae	mP	5	-46	14	3	6	6.31
Dioscorea minutiflora Engl.	Dioscoreaceae	G	5	-311	53	3	5	1.24
Dioscorea odoratissima Pax	Dioscoreaceae	G	5	-165	23	4	5	1.72
Dioscorea smilacifolia De Wild.	Dioscoreaceae	G	5	-101	39	4	5	1.54
Diospyros soubreana F. White	Ebenaceae	mp	5	-37	6	2	5	1.23
Drypetes gilgiana Pax	Euphorbiaceae	mp	5	-233	54	4	5	1.21
Entandrophragma utile Sprague	Meliaceae	MP	5	-55	20	3	8	11.68
Eribroma oblongum (Mast.)	Sterculiaceae	MP	5	-120	22	4	7	7.3
Ficus asperifolia Miq.	Moraceae	mp	5	-8	11	4	6	0.75
Funtumia africana Stapf	Apocynaceae	mP	5	-347	52	3	7	4.33
Guibourtia ehie (A. Chev.)	Caesalpiniaceae	MP	5	-416	82	3	7	9.22
Holoptelea grandis (Hutch.)	Ulmaceae	MP	5	-58	28	4	8	12.28
Manniophyton fluvum Müll. Arg.	Euphorbiaceae	mp	5	-59	23	3	6	6.3
Mansonia altissima (A. Chev.)	Sterculiaceae	MP	5	-391	108	3	7	6.61
Mareya micrantha (Benth.)	Euphorbiaceae	mp	5	-157	24	2	7	3.45
Monodora tenuifolia Benth*.*	Annonaceae	mp	5	-223	41	3	5	1.35
Nesogordonia papaverifera (A. Chev.)	Sterculiaceae	MP	5	-1000	156	3	7	8.59
Neuropeltis acuminata (P. Beauv.)	Convolvulaceae	MP	5	-193	44	3	6	5.75
Paullinia pinnata L.	Sapindaceae	mp	5	-83	44	3	6	2.68
Platysepalum hirsutum Hepper	Fabaceae	mP	5	-124	46	4	7	9.29
Pouteria aningeri (A. Chev.)	Sapotaceae	MP	5	-194	27	3	6	3.35
Pterocarpus santalinoides DC.	Fabaceae	mp	5	-22	20	3	7	3.21
Pterygota macrocarpa K. Schum.	Sterculiaceae	MP	5	-47	25	4	8	11.75
Rinorea longicuspis Engl	Violaceae	mp	5	-44	21	3	7	2.67
Sterculia rhinopetala K. Schum.	Sterculiaceae	MP	5	-298	48	3	8	10.36
Streblus usambarensis (Engl.)	Moraceae	mp	5	-276	65	3	5	1.94
Streptogyna crinita P. Beauv.	Poaceae	G	5	-253	61	3	4	0.49
Strombosia pustulata Oliv.	Olacaceae	mp	5	-61	30	4	6	1.93
Strophanthus sarmentosus DC.	Apocynaceae	mP	5	-59	24	3	6	3.45
Terminalia superba Engl. & Diels	Combretaceae	MP	5	-182	25	3	8	9.38
Thaumatococcus daniellii Benth.	Marantaceae	G	5	-114	28	3	5	0.79

Table 2. Contd.

Tiliacora dinklagei Engl.	Mennispermaceae	MP	5	-273	89	3	5	2.95
Trachyphrynium braunianum Baker	Marantaceae	mp	5	-62	46	3	6	1.02
Trema orientalis (L.) Blume	Ulmaceae	mp	5	-307	53	3	6	2.42
Trichilia monadelpha (Thonn.)	Meliaceae	mp	5	-90	26	3	6	2.67
Triplochiton scleroxylon K. Schum.	Sterculiaceae	MP	5	-156	39	3	8	10.96
Xylia evansii Hutch.	Mimosaceae	mP	5	-131	40	3	7	8.03

Tb = Biological type; Tr- = sum of links with regressive features considered negative; Tr+ = sum of links with progressive features considered positive; Sc. = average sciaphilia index; H = average height observed in the field; var. = variance of heights; I = index of the species in the regressive vegetation series (between 1 and 5); MP = megaphanerophyte; mP = mesophanerophyte; mp = microphanerophyte; G = geophyte.

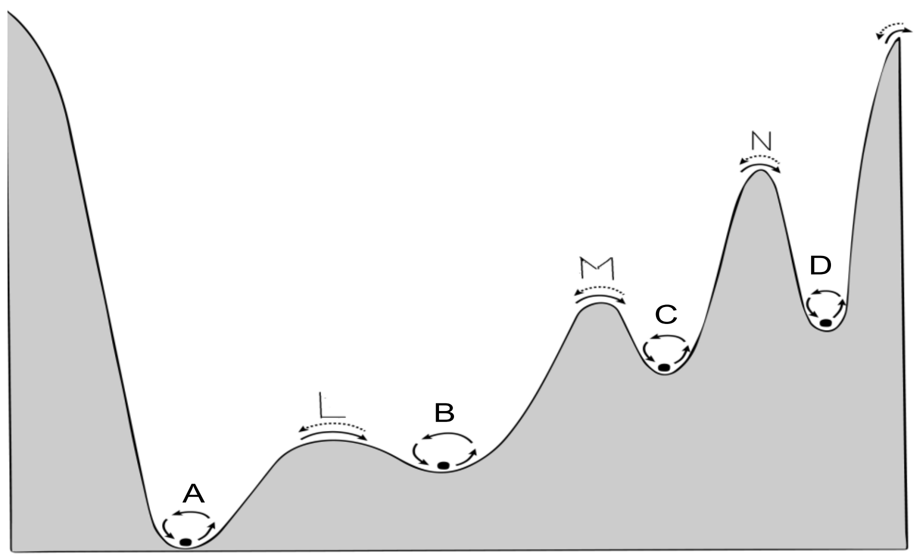

Figure 2. This rollercoaster-shaped model shows how biological systems remain in more or less stable states (A, B, C, D) separated by moments of crisis (L, M, N) for varying lengths of time.

almost unchanging for several centuries. Forests that have just been destroyed to establish food plants follow a regressive sequence that leads them into trough A where the new equilibrium controlled by the farmers is metastable because it can be broken if cultivation is abandoned (Akodéwou et al., 2019); fallow then settles and stabilises for a few years in trough B in a progressive sequence at first. The species in the fallow are not large and trees can gradually establish themselves by disturbing the functioning of the fallow, since their shade will kill species that need sunlight. Very slowly, the forest will resettle and arrive in the C-trough, often passing through some intermediate stages where some transitional species will be temporarily dominant. Hollow C is not identical to hollow D because the species typical of primary forests, called dryads, have disappeared. In studies on the establishment of crops in tropical forests (Assalé et al., 2016; Akodéwou et al., 2019), this operation is often described as 'degradation' as if human actions automatically led to a loss of quality compared to an ideal which would be the natural state of the vegetation before the arrival of humans (Arbelot, 1979). On the contrary, for an agronomist, agriculture is progress and not degradation. It is to avoid this ambiguity that we have said that the evolution of vegetation corresponding to forest clearing (from trough D to trough A) is regressive and that the sequence of forest regeneration is progressive. The problem of forest regeneration after the abandonment of food crops is therefore that of the transition from trough C to trough D. Progressive species capable of initiating natural regeneration of FCHS have been known to be evident. If the crop is abandoned, a sequence of progressive vegetation begins as a prelude to forest regeneration in places where forest species are present. Either because they have survived when the crop was planted, or because they have reestablished themselves through seed germination or the production of shoots, the most significant result of this work is that the progressive species are sufficiently numerous and frequent that the installation of crops in the FCHS has not yet crossed the threshold of irreversibility beyond which forest regeneration would be impossible.

Conclusion

The problem to be solved was whether the FCHS, which lost more than 70% of its forest cover during the 10 years of conflict in Côte d'Ivoire, between 2002 and 2013, and to cocoa cultivation can be regenerated naturally from the species present on the ground. The results showed that the numerous coexistences of fallow land and regenerating forest mean that fallow land allows the forest to regenerate in a progressive sequence of vegetation. Farmers may allow fallows to establish themselves because they realise that cultivation leads to a decrease in sustainable soil fertility. A total of 59 regenerating species have been recorded in the classified forest of Upper Sassandra. They are numerous enough for the forest management authorities to search for them in the field to find places where forest regeneration can develop. The table summarising the relationship of species to the results of human actions shows that there are enough species capable of natural forest regeneration that foresters can find in the field for the forest to reestablish itself. This result is a first step towards ensuring that the authorities responsible for forest management are aware of the measures to be taken to regenerate the forest.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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