

Characterization of phytoplankton assemblages in a tropical coastal environment using Kohonen self-organizing map

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Abstract

This study was aimed at understanding the main abiotic environmental factors controlling the distribution patterns of abundance and composition of phytoplankton (size less than 10 μm) assemblages in the coastal waters of south-eastern Côte d'Ivoire. Data were collected during two cruises, in January (low-water period) and October (high-water period) of 2014. A total of 67 species were identified and assigned to Bacillariophyceae (49%), Cyanophyceae (21%), Chlorophyceae (13%), Euglenophyceae (10%), Dinophyceae (4%) and Chrysophyceae (3%). Three biotic zones (I, IIA and IIB) were distinguishable on a Kohonen self-organizing map after an unsupervised learning process. The diatom genera *Eunotia* sp., *Navicula* sp. and *Actinopterychus senarius* are significantly associated with I, IIA and IIB biotic zones, respectively. A clear seasonal cum salinity trend was apparent in phytoplankton distribution patterns. Turbidity and nitrate levels were the main abiotic factors controlling phytoplankton distribution in I, the upland tidal regions of the lagoon. In regions along the lagoon–sea continuum, phosphate and turbidity exert the most control during the low-water season (IIA), while total dissolved solids control phytoplankton distribution during the high-water season (IIB). These are climate-sensitive parameters whose concentrations depend on prevailing hydroclimatic processes. Therefore, seasonality can have important consequences on phytoplankton community and inadvertently the productivity of these systems.

Key words: coastal environment, Kohonen self-organizing map, phytoplankton, tropical

Résumé

Cette étude avait pour but de comprendre les principaux facteurs environnementaux abiotiques affectant les schémas de distribution de l'abondance et de la composition des assemblages de phytoplancton (de taille inférieure à 10 μm) dans les eaux côtières du sud-est de la Côte d'Ivoire. Les données ont été collectées au cours de deux croisières, en janvier (période de basses eaux) et en octobre (hautes eaux) 2014. Soixante-sept espèces ont été identifiées et assignées aux Bacillariophycées (49%), Cyanophycées (21%), Chlorophycées (13%), Euglénophycées (10%), Dinophycées (4%) et Chrysophycées (3%). Trois zones biotiques (I, IIA et IIB) étaient discernables sur une carte auto-adaptative de Kohonen après un processus d'apprentissage non supervisé. Les diatomées des genres *Eunotia* sp., *Navicula* sp. et *Actinochyptus senarius* sont significativement associées respectivement aux zones biotiques I, IIA et IIB. Il y avait une tendance nette saison-salinité dans les schémas de distribution du plancton. Les taux de turbidité et de nitrates étaient les principaux facteurs abiotiques contrôlant la distribution du phytoplancton en zone I, la zone du lagune située au-dessus des marées. Dans les régions se trouvant le long du continuum lagune-mer, ce sont les phosphates et la turbidité qui exercent le maximum de contrôle pendant la saison de basses eaux (IIA), tandis que c'est le total des solides dissous qui contrôle la distribution du phytoplancton pendant la saison de hautes eaux (IIB). Ce sont des

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paramètres climato-sensibles dont la concentration dépend des processus hydro-climatiques dominants. C'est pourquoi la saisonnalité peut avoir d'importantes conséquences sur la communauté des phytoplanctons et, incidemment, sur la productivité de ces systèmes.

Introduction

Phytoplankton constitutes the most important biological community in any aquatic system (Price, 2001). These microscopic plants form the base of the aquatic food web with prime linkages to fisheries productivity (Pezennec & Koranteng, 1998; Djagoua *et al.*, 2006). Therefore, changes in their composition can influence the biological structure of aquatic systems. Their patterns of distribution are strongly influenced by the physical and chemical properties of their host waters (Suthers & Rissik, 2009), hence their use as water quality indicators (Sahu *et al.*, 2012). Phytoplankton abundance, diversity and distribution patterns in tropical coastal systems at land–sea interface are largely dependent on the physical conditions (flow regimes) of the system (Castel, Caumette & Herbert, 1996). In the coastal zone of Côte d'Ivoire, authors (Dandonneau, 1971; Seu-Anoï *et al.*, 2013) have shown that the phytoplankton assemblage at any particular time is dependent on the alternating continental (fluvial and precipitation) and marine hydrologic regimes.

The Ivorian coastal zone makes up 1% of national landmass of 322,462 km². It encompasses several coastal lakes (Dadié, Labion, M'bakré) and interlinked lagoons (Grand-Lahou, Ébrié and Aby) that together occupy an area of 1200 km² (Durand & Chantraine, 1982). Of these, the Ébrié lagoon, the largest in West Africa, has a surficial area of 566 km² (Varlet, 1978). Data on phytoplankton assemblages on this important reservoir of biodiversity are limited. Some authors (Dandonneau, 1971; Iltis, 1982) have described phytoplankton assemblages and their seasonal distribution patterns in this environment. Recently, Seu-Anoï *et al.*, 2013; made a first attempt at describing the abiotic factors controlling phytoplankton distribution in a large area of the Ébrié lagoon based on redundancy analyses, information fundamental to resources management (Park *et al.*, 2003). This study is, therefore, a follow-up on their works using the Kohonen self-organizing map, an artificial neural network, ANN technique combined with multivariate statistical analyses

to explore the relationship between algal taxa and environmental abiotic variables in these environments.

The Kohonen self-organizing map (SOM) is an ANN technique based on unsupervised learning algorithm (Kohonen, 1995, 2001). In comparison with other ordination techniques (PCA, CCA, RDA) previously used in characterizing ecological communities (Brogueira, Do Rosário Oliveira & Cabeçadas, 2007; Okogwu & Ugwumba, 2013; Seu-Anoï *et al.*, 2013), SOM is a more effective tool for cluster visualization and patterning of nonlinear relations in high-dimensional complex data sets such as species abundance data with high number of zero values (Park *et al.*, 2007). Other advantages of this method over conventional ordination techniques can be found in Bullinaria (2004) and Astel *et al.* (2007). This technique has wide applications and has been used successfully to characterize phytoplankton distribution patterns in different environments (Bandelj *et al.*, 2008; Krasznai *et al.*, 2010; Niamien-Ebrottie *et al.*, 2013), in other ecological studies to elucidate biotic community–environment association (Lek *et al.*, 2005; Oh *et al.*, 2007) and even in biomedical sciences and other industrial applications for the structuring and pattern recognition in complex multidimensional data (Kohonen *et al.*, 1996; Serrano-Cinca, 1996; Yu *et al.*, 2006; Astel *et al.*, 2013). Furthermore, correlations in qualitative terms can be detected between input data layers (variables) displayed in the output neurons of the component plane (Westerlund, 2005).

Material and methods

The study area

The Ébrié lagoon is the largest lagoon in West Africa (Fig. 1). It has a length of 140 km, maximum width of 7 km and an average depth of 4.8 m (Varlet, 1978). The lagoon is a large reservoir of biodiversity with 153 species of fisheries, of which 33 are endemic (Baran, 2000). It is bounded to the west by the Azagny National Park (a national park since 1981 and designated a Ramsar site since 1996) (Evans and Fishpool, 2001), where it is in contact with the Grand-Lahou lagoon via the Azagny canal, dug up in 1939 to facilitate the exploitation of manganese (Pagès, Lemasson & Dufour, 1979). In its eastern borders, the lagoon is in contact with the Aby lagoon via the Assinie canal, dug up in 1955 (Durand & Chantraine, 1982). The Ébrié lagoon catchment is drained

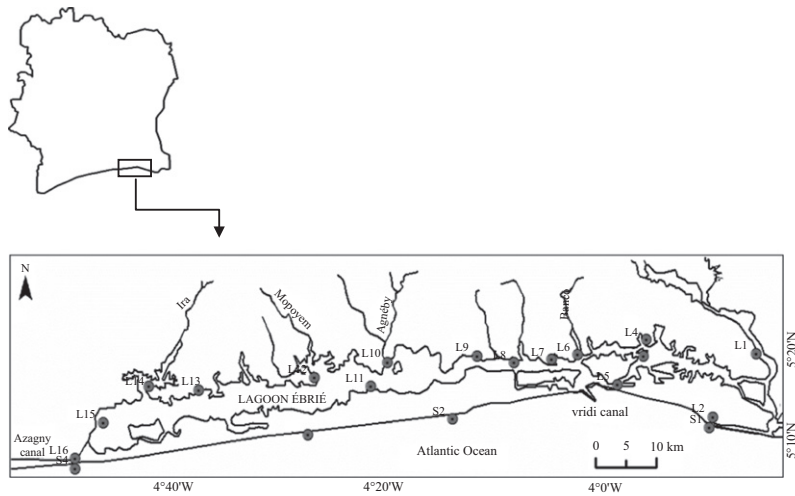


Fig 1 Map of the study area showing sampling points. The first letters, L and S, represent samples from the lagoon and the Atlantic shorelines, respectively

by six rivers: the Ira, Mopoyem, Agnéby, Banco, La Mé and Comoé from west to the east, together they account for over 90% (9.85 billion m^3 per annum) of its freshwater input (Varlet, 1978). The month of September marks the peak discharge period of these rivers whose source is from the north of the country with Sudanian savannah or Guinean climate characterized by unimodal rainfall pattern. Direct precipitation accounts for a smaller fraction (1.1 billion m^3 per annum). Permanent exchanges with the sea in its central parts via the artificial Vridi canal dredged in 1950 (Pagès, Lemasson & Dufour, 1979). This accounts for its 38 billion m^3 per annum sea water input. Conversely, the ocean receives approximately 50 billion m^3 per annum of mixed water sources via the lagoon (Varlet, 1978).

The climate of the area is subequatorial (tropical wet and dry) with bimodal character (Fig. 2). Two rainy seasons, long rainy season (April to July) and short rainy season (September to November), are intercepted by two periods of dry season: long dry season (December to

March) and short dry season (August). The mean annual precipitation is 1704 mm (1970–2014 average) with monthly maximum up to 450 mm for the month of June. Mean annual temperature is 26.4°C (1970–2014 average) with March as the hottest month (27.8°C) and August as the coolest month (24.3°C) of the year. Relative humidity is high with mean values of 83%.

The lagoon lies at the focal point of two distinct geologies, to the north are Mio-Pliocene sedimentary rock layers and to the south are Quaternary marine sands. For more details on this environment, one can refer to Dufour *et al.* (1994) and Koné *et al.* (2009).

Phytoplankton sampling, identification and enumeration

Twenty sampling points were chosen randomly from the Ébrié lagoon and the inshore of the South Atlantic Ocean. Sixteen sampling sites were randomly selected on the Ébrié lagoon and labelled L1, L2, L3, L4, L5...L16 from east to west, while four sampling sites labelled S1, S2, S3 and S4

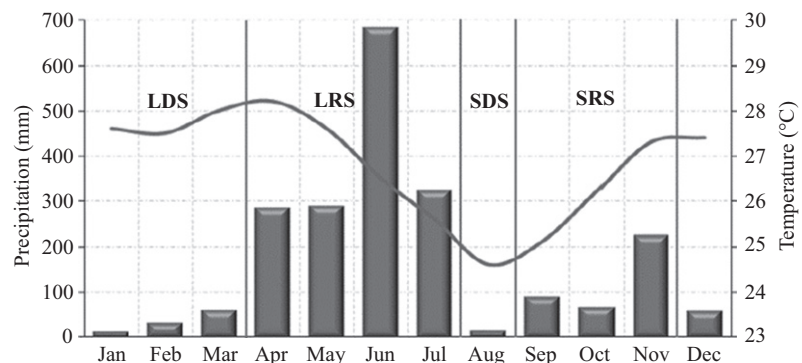


Fig 2 Climate diagram of the Abidjan synoptic station (5°15'N, 3°56'W): LDS implies long dry season; LRS, long rainy season; SDS, short dry season; and SRS, short rainy season (source: national meteorological station, SODEXAM)

were chosen along the inshore environment. Each site was sampled twice, once in January (low-water period) and again in October (high-water period) of 2014. These sum up to 40 sets of observations. Phytoplankton were harvested using plankton net of 10 µm mesh size. Concentrates were collected into 50-mL dark brown polyethylene bottles and fixed in Lugol's iodine solution in a ratio of 1 : 100. One-millilitre aliquot was mounted on a Malassez double-grid haemocytometer and counted under a Zeiss microscope. Species identification was to species level where possible from works of authors (Foged, 1966; Compère, 1991; Krammer & Lange-Bertalot, 1991; Cocquyt, Lange-Bertalot & Kociolek, 1998; Ouattara, 2000; Komárek & Anagnostidis, 2005). Cell enumeration was following the procedures of Schoen (1988).

Abiotic environmental variables

Nine abiotic environmental variables were measured at each site: surface water temperature (°C), pH, dissolved oxygen (mg L⁻¹) and total dissolved solids (TDS) using multiparameter handheld sensors (HANNA HI-9878; HANNA Instruments, Texas, USA). Turbidity (NTU) was measured by spectrometry with a WAGTECH turbidity meter. The slope value (%) was derived from digital elevation map. Nutrient (nitrate, NO₃⁻ (mg L⁻¹), hydrogen phosphate, HPO₄⁻ (mg L⁻¹) and silicate, SiO₃²⁻ (mg L⁻¹)) analyses were by spectrophotometry (Lange CADAS 100, Altmann Analytik, Germany) at the Steinmann-Institut, University of Bonn, Germany.

Data analyses–SOM map

Rare species (13 taxa) were excluded from all statistical operations based on a 1% relative abundance. In this study, hierarchical SOM (Miikkulainen, 1990; Lampinen & Oja, 1992) was chosen over other conventional gradient analyses to pattern phytoplankton community dynamics, as the latter failed to detect significant structures/patterns in the data owing to the large number of zero counts. Hierarchical SOM is a dimensionality reduction technique that reduces *n*-dimensional input vectors to two-dimensional neurons or maps (Chattopadhyay, Dan & Mazumdar, 2012). After the convergence of the SOM algorithm, clusters among units of the SOM map are visualized on a hierarchical clustering tree (Miikkulainen, 1990; Vesanto & Alhoniemi, 2000). As a first step, sampling points were clustered into groups based on biological data, and a second step relates the resulting

clusters to environmental abiotic variables. The SOM consists of two different computational units, input and output layers connected by computational weight vectors. In this study, the data set (abundance values of 54 taxa from 20 sampling sites, studied over two seasons) was log-transformed (ln(x + 1)), conditioned with nine measured environmental predictors (temperature, dissolved oxygen, pH, turbidity, total dissolved solids, slope, nitrate, phosphate and silicate) and trained with an unsupervised batch map learning rule. The list of taxa and acronyms are given in Table 1. The output neurons display a two-dimensional 4 × 3 (12 nodes) map units on hexagonal lattice. The 4 × 3 map size was selected after several iterations. Initial map size was determined by heuristic formula (MATLAB SOM Toolbox):

$$\text{Map units} = 5 * n^{0.5431},$$

where *n* is the number of records in the data set. For details on the SOM algorithm for ecological applications, one can refer to Lek, Giraudel & Guégan (2000), Kohonen (2001) and Park *et al.* (2003). The quality of training algorithms was assessed by quantization error (QE) for map resolution and topographic error (TE), a measure of the map's ability to accurately represent the input layers (topology preservation). Although there exists no reference value for QE and TE (Astel *et al.*, 2013), after the machine learning process, the map size with the minimum quantization error value and zero topographic error is selected. Low QE values denote good maps (Kaski & Lagus, 1996), while a zero TE implies perfect topology preservation (Pözlbauer, 2004). Subsequently, divisive clustering tree (dendrogram) of the input variables is formed based on the similarity of the weight vectors of the neurons (map units) (Miikkulainen, 1990). Multivariate pairwise statistics were employed to determine the statistical significance of the relationships.

Community indices

Jaccard similarity index, SC_j (Jaccard, 1912), was used to check classification consistency and assess similarities between clusters. It is computed as

$$SC_j(A, B) = \frac{A \cap B}{A \cup B}$$

where *A* intersection *B* is the number of species two samples have in common, and *A* union *B* is the number of species represented by both samples. A maximum value of

1.0 indicates maximum similarity, that is all species present in A are also found in B. In terms of biodiversity conservations, areas with low values are treated as top priority as they tend to preserve more biodiversity.

Other studied community indices are taxa richness, Shannon index, H' (Shannon & Weaver, 1949) to assess the diversities of each community, computed as

$$H' = - \sum_{i=1}^s \frac{n_i}{n} \ln \frac{n_i}{n}$$

where s is the number of species in a sample, ' n_i ' is the number of individuals of species i in a sample and ' n ' is the number of individuals in a sample.

Community dominance index, CDI (Krebs, 1994), to determine the percentage of abundance contributed to a community by two most abundant species. It is calculated as

$$CDI = 100(n1 + n2)/N$$

where $n1$ and $n2$ are the abundances of the two most common species and N is the total abundance. Index values range between 0 and 100. High values represent less diverse and highly disturbed communities. Finally, indicator value index (IndVal, Dufrière & Legendre, 1997) was determined for each cluster to identify indicator species using the *indicpecies* package (ver. 1.7.1) of De-Cáceres & Legendre (2009). The indicator value of a

species i with respect to cluster j is the sum of the specificity (A) and fidelity (B), scaled to 100, that is

$$\text{IndVal}_{ij} = 100A_{ij} \times B_{ij}$$

Specificity (A_{ij}) is the ratio of the mean abundance of species i in cluster j and the sum of means of the same species over all group. A maximum value of 1 is attained if the species occur only in that cluster. Fidelity (B_{ij}) is the proportion of sites in which species i is present within cluster j . Maximum value of 1 occurs when species i occur in every site in the cluster j . Only taxa with more than 25% indicator value were retained as indicator species (Dufrière & Legendre, 1997). The statistical significance was tested using a permutation test.

Results

Original data set

The original data set consists of 40 samples from 20 sampling sites (Ébrié lagoon and inshore of the Atlantic Ocean) in two seasons (low- and high-water period). Sixty-seven taxa were identified with cell densities (cells mL^{-1}) ranging between 25000 and 5.65×10^6 for sampled sites. These were assigned to Bacillariophyceae (49%), Cyanophyceae (21%), Chlorophyceae (13%), Euglenophyceae

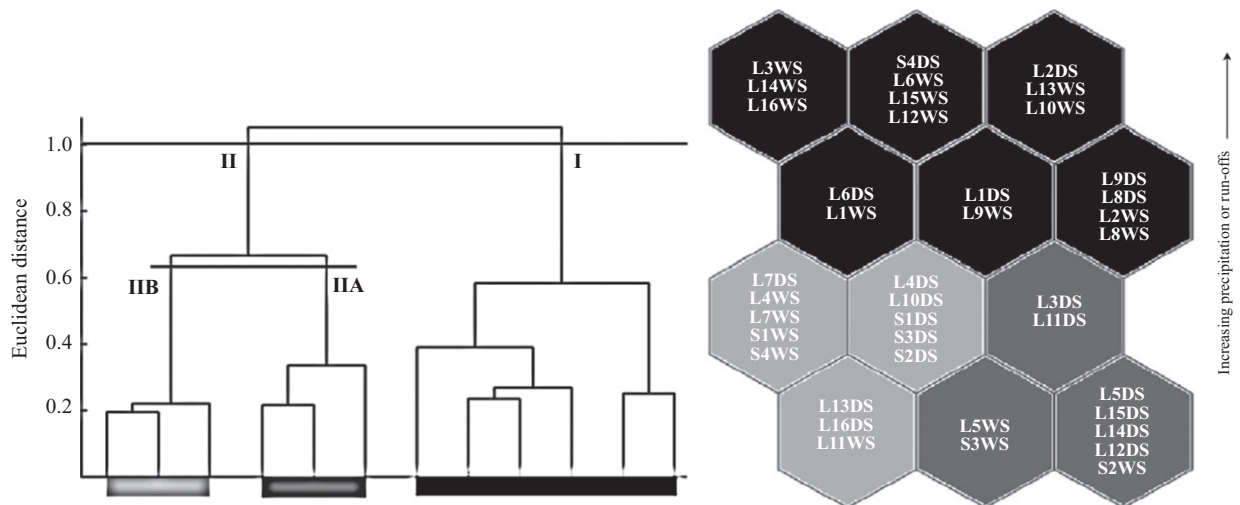


Fig 3 Dendrogram (clusters between virtual map units) (left image) projected onto SOM map (right image) consisting of 12 hexagons, representing neurons. Shading intensity indicates the different clusters. The first letters of the names represent study sites: L: Ébrié lagoon and S: the inshore environment, respectively, while suffixes DS and WS represent the low- and high-water periods (sampling seasons), respectively

(10%), Dinophyceae (4%) and Chrysophyceae (3%). Total cell densities ($\times 10^6$ cells mL^{-1}) of 18.78 and 34.23 were recorded on the Ébrié lagoon for the low- and high-water period, respectively, while mean cell densities ($\times 10^6$ cells mL^{-1}) of 1.1 and 1.60 were recorded for the inshore waters for same period. Only 54 taxa contributing more than 1% to overall abundance were retained for statistical computations. After the learning process, the trained SOM lattice partitioned the original data set into three new biogeographical zones (clusters I, IIA and IIB) based on taxa abundance data, displayed by a dendrogram and hierarchical cluster projected onto a SOM map (Fig. 3).

SOM patterning of Phytoplankton assemblages

A map of 12 units was arranged in a 4×3 grid with QE of 1.603 (minimum value) with a TE of zero, after the machine learning process. SOM results in two major clusters (I and II) at a high linkage distance of 1.0. Two subclusters IIA and IIB were observed in cluster II at a linkage distance of 0.62 (Fig. 3). Clusters were highly related to seasonality and salinity gradient (Fig. 4). Cluster I (upper part of the map) grouped samples collected from the lagoon during the high-water period. Cluster IIA (lower right area) consists of a high percentage of samples from the central and western end of the lagoon during the low-water period and samples from inshore waters during the high-water period. Cluster IIB (lower left area) consists mainly of samples from the eastern end of the lagoon and the inshore environment. Spatial heterogeneity was more pronounced during the low-water period relative to the high-water period. Temporal patterns were also apparent in floristic composition (taxonomic diversity) within clusters. During the high-water period, 30% of the coastal waters fell within the cluster I category, while for clusters IIA and IIB, it was 30% and 40%, respectively. Conversely, during the high-water period, the biogeographical areas of cluster I expanded (60%) at the expense of clusters IIA (25%) and IIB (15%), respectively.

Abundance and diversity

Maximum cell densities (28.6×10^6 cells mL^{-1}) were recorded in regions of cluster I. Total cell densities ($\times 10^6$ cells mL^{-1}) were 7.45 and 17.08 for clusters IIA and IIB, respectively. Cell densities of the taxa within each cluster were summed up to six classes: Bacillariophyceae

(diatoms), Cyanophyceae (cyanobacteria), Chlorophyceae (green algae), Dinophyceae (dinoflagellates), Euglenophyceae (euglenoids) and Chrysophyceae (golden-brown algae). Although diatoms were the most species-rich and diverse taxa, the cyanobacteria were, however, the most abundant. This is because of the ability of some variants to form long chains of filamentous cells. The orders Oscillatoriales, Chroococcales and Nostocales dominated the cyanobacteria community. Fig. 4 shows the taxa characteristics of each cluster. The taxa *Phormidium foveolarum* Gomont, *Navicula* sp., *Nitzschia* sp., *Cyclotella meneghiniana* Kützing, *Cocconeis* sp., *Monoraphidium convolutum* (Corda) Komárková-Legnerová, *Eunotia* sp., *Euglena* sp. and *Gyrosigma attenuatum* (Kützing) Rabenhorst showed ubiquitous distribution and were present in all biotic zones. Species contributing less than 1% to cell abundance (rare species) in cluster I are *Surirella* sp., *Scenedesmus* sp., *Gyrosigma acuminatum* (Kützing) Rabenhorst, *Entomoneis* sp., *Nitzschia* sp., *Trachelomonas* sp., *Trachelomonas volvocina* Ehrenberg, *Netrium* sp., *Ulnaria ulna* (Nitzsch) Compère, *Melosira* sp., *Trachelomonas planctonica* Svirenko, *Navicula* sp., *Encyonema silesiacum* (Bleisch ex Rabenh.) Mann in Round, *Hantzschia* sp., *Amphora commutata* Grunow, *Cocconeis* sp., *Coscinodiscus asteromphalus* Ehrenberg, *Cyclotella* sp., *Gyrosigma* sp., *Closterium* sp. and *Monoraphidium convolutum* (Corda) Komárková-Legnerová in order of decreasing relative abundance. Rare species in cluster IIA are *Amphora commutata* Grunow, *Orthoseira* sp., *Ceratium* sp., *Gyrosigma* sp., *Gymnodinium* sp., *Strombomonas* sp., *Trachelomonas* sp., *Cocconeis* sp., *Surirella* sp. and *Closterium* sp., while rare species recorded in cluster IIB are *Melosira* sp., *Navicula* sp., *Orthoseira* sp., *Phacus* sp., *Monoraphidium convolutum* (Corda) Komárková-Legnerová, *Encyonema silesiacum* Bleisch ex Rabenh.) Mann in Round, *Diploneis ovalis* (Hilse) Cleve, *Cyclotella* sp., *Coscinodiscus asteromphalus* Ehrenb., *Gyrosigma* sp., *Strombomonas* sp., *Euglena* sp., *Cocconeis* sp., *Nitzschia* sp., *Pinnularia* sp., *Ceratium* sp. in order of decreasing relative abundance. Jaccard's community index confirms the dissimilarity between clusters. Values were 0.25 (between clusters I and IIA), 0.33 (between clusters I and IIB) and 0.37 (between clusters IIA and IIB). Cluster IIA, with the highest CDI (63.42%), is the least species diverse group. This is followed by clusters I (CDI: 49.83%) and IIB (CDI: 42.31%). The two most abundant species in each cluster are *Phormidium foveolarum* Gomont and *Aulacoseira granulata* (Ehrenberg) Simonsen (cluster I); *Pseudanabaena* sp. and *Phormidium foveolarum* Gomont (cluster IIA);

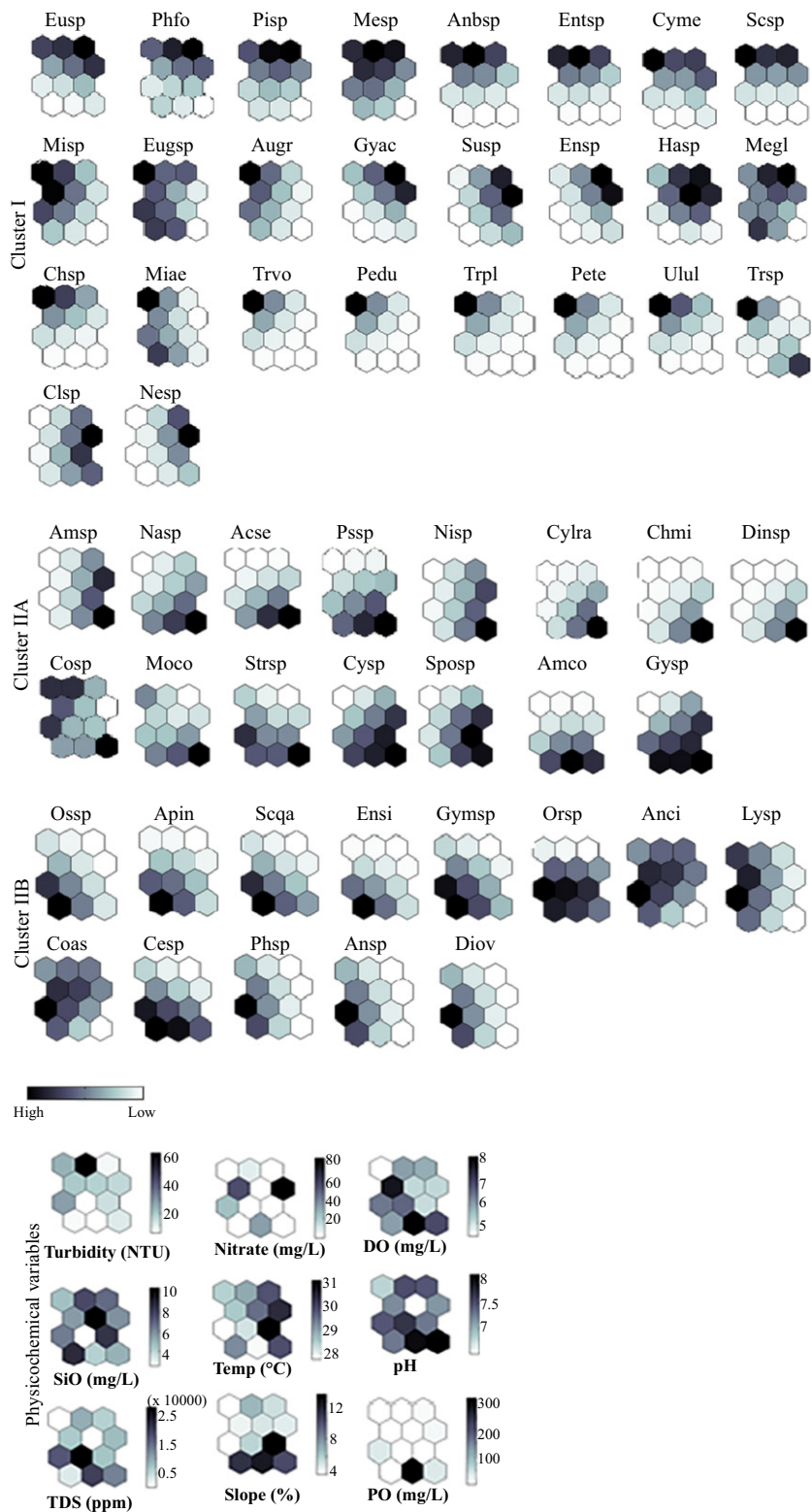


Fig 4 Species abundance (top) and environmental factors (each component plane is scaled independently) over the SOM. Darker shades represent higher values and vice versa. (DO: dissolved oxygen, PO: phosphate, SiO: silicate, Temp: temperature and TDS: total dissolved solids). List of taxa and acronyms is given in Table 1

Table 1 List of taxa and their acronyms as displayed on the SOM map

| Taxonomic classes | Code |
|---|-------|
| Bacillariophyceae | |
| <i>Actinocyclus senarius</i> Ehrenberg | Acse |
| <i>Amphora commutata</i> Grunow | Amco |
| <i>Amphora</i> sp. | Amsp |
| <i>Aulacoseira granulata</i> (Ehrenberg) Simonsen | Augr |
| <i>Cocconeis</i> sp. | Cosp |
| <i>Coscinodiscus asteromphalus</i> Ehrenberg | Coas |
| <i>Cyclotella meneghiniana</i> Kützing | Cyme |
| <i>Cyclotella</i> sp. | Cysp |
| <i>Diploneis ovalis</i> (Hilse) Cleve | Diov |
| <i>Encyonema silesiacum</i> (Bleisch) D.G. Mann | Ensi |
| <i>Encyonema</i> sp. | Ensp |
| <i>Entomoneis</i> sp. | Entsp |
| <i>Eunotia</i> sp. | Eusp |
| <i>Gyrosigma acuminatwn</i> Kützing | Gyac |
| <i>Gyrosigma</i> sp. | Gysp |
| <i>Hantzschia</i> sp. | Hasp |
| <i>Melosira</i> sp. | Mesp |
| <i>Naricida</i> sp. | Nasp |
| <i>Nitzschia palea</i> (Kützing) W. Smith | Nisp |
| <i>Orrhoseira</i> sp. | Orsp |
| <i>Pinnularia</i> sp. | Pisp |
| <i>Surirella</i> sp. | Susp |
| <i>Ulnaria ulna</i> (Nitzsch) Compere | Ulul |
| Euglenophyceae | |
| <i>Euglena</i> sp. | Eugsp |
| <i>Phacus</i> sp. | Phsp |
| <i>Strombomonas</i> sp. | Strsp |
| <i>Trachelomonas planctonica</i> Svirenko | Trpl |
| <i>Trachelomonas</i> sp. | Trsp |
| <i>Trachelomonas volrocina</i> Ehrenbera | Trvo |
| Cyanophyceae | |
| <i>Anabaena circinalis</i> Rabenhorst | Anci |
| <i>Anabaena</i> sp. | Ansp |
| <i>Anabaenopsis</i> sp. | Anbsp |
| <i>Aphanocapsa Incerta</i> (Lemmermann) Cronberg | Apin |
| <i>Chroococcus minutus</i> (Kützing) Nägeli | Chmi |
| <i>Chroococcus</i> sp. | Chsp |
| <i>Cylindrospermopsis racoborskii</i> (Woloszynska) | Cylra |
| <i>Lyngbya</i> sp. | Lysp |
| <i>Merismopedia glauca</i> (Ehrenberg) Kützing | Megl |
| <i>Microcystis aeruginosa</i> (Kützing) | Miae |
| <i>Microcystis</i> sp. | Misp |
| <i>Oscillatoria</i> sp. | Ossp |
| <i>Phormidiumfoveolarum</i> Gomont | Phfo |
| <i>Pseudanabaena</i> sp. | Pssp |
| Chlorophyceae | |
| <i>Closterium</i> sp. | Clsp |

(continued)

Table 1 (continued)

| Taxonomic classes | Code |
|---|-------|
| <i>Monoraphidium convolutum</i> Komárková-Legnerová | Moco |
| <i>Netrium</i> sp. | Nesp |
| <i>Pediastrum duplex</i> Meyen | Pedu |
| <i>Pediastrum tetras</i> (Ehrenberg) Ralfs | Pete |
| <i>Scenedesmus quadricauda</i> (Turpin) Brebisson | Scqa |
| <i>Scenedesmus</i> sp. | Scsp |
| <i>Spondylosum</i> sp. | Sposp |
| Dinophyceae | |
| <i>Ceratium</i> sp. | Cesp |
| <i>Gyrodinium</i> sp. | Gymsp |
| Chrysophyceae | |
| <i>Dinobryon</i> sp. | Dinsp |

and *Aphanocapsa incerta* (Lemmermann) Cronberg and Komárek and *Oscillatoria* sp. (cluster IIB). Species diversity is generally low in these coastal areas with mean Shannon diversity values of 0.95, 0.88 and 0.74 for clusters I, IIA and IIB, respectively. These low values of Shannon diversity are indicative of environments under stress. As regards indicator species, the freshwater diatom, *Eunotia* sp., best represents cluster 1. Cluster IIA is best represented by the diatom genus *Navicula* sp., while cluster IIB is best represented by the green algae genus *Scenedesmus quadricauda* (Turpin) Brébisson, which can stay buoyant because of its spines.

Relationship between taxa and environmental abiotic variables

Mean values of measured abiotic parameters are recorded in Table 2. pH, dissolved oxygen, silicate and temperature values were widely spread over the SOM map (Fig. 4). This signifies that they have fairly regular distribution and their values do not differ much between clusters. For instance, pH did not vary by more than two units between clusters and also surface water temperature did not vary by more than 3°C between clusters. Conversely, phosphate, nitrate, turbidity, total dissolved solids (TDS) and topographic high areas showed strong spatiotemporal patterns and were restricted to specific sites on the SOM map. Turbidity and nitrate are highly significantly associated with cluster I (upper parts of the map), representing upland tidal areas along the lagoon–land continuum with high freshwater influx. These parameters have direct relation to precipitation and river discharges (Morlière, 1970). Regions of cluster I are topographic low areas characterized by low

Table 2 Summary of the seasonal changes of the physicochemical parameters of the coastal environment in the different clusters

| Variables | Units | I | | IIA | | IIB | |
|-------------------------------|--------------------|-----------------|------------------|-----------------|-----------------|-----------------|-----------------|
| | | January (n = 6) | October (n = 12) | January (n = 6) | October (n = 3) | January (n = 8) | October (n = 5) |
| pH | Units | 6.5–7.8 | 6.4–8.6 | 7.4–8.8 | 7.8–8.1 | 7.1–8 | 6.9–8.2 |
| DO | mg L ⁻¹ | 4.1–12 | 1.7–7.1 | 4.7–9.2 | 6.2–9.4 | 4.3–7.9 | 5.2–7.2 |
| NO ₃ ⁻ | mg L ⁻¹ | 0.01–109 | 0.01–332.34 | 0.2–0.68 | 0.01–64.01 | 0.01–0.9 | 0.05–87.46 |
| PO ₄ ³⁻ | mg L ⁻¹ | 0.01–1.35 | 0.01–44.44 | 0.04–5.81 | 1.11–642.54 | 0.06–0.1 | 0.01–96.76 |
| SiO ₃ | mg L ⁻¹ | 0.01–13.3 | 0.01–12.56 | 3.29–9.32 | 0.21–7.94 | 0.01–11.32 | 1.9–12.75 |
| Temp | °C | 27.3–31.4 | 27.5–30.3 | 30.1–31.5 | 26.5–29.2 | 26.9–30.6 | 26–29.9 |
| TDS(*10 ³) | mg L ⁻¹ | 0.31–33.8 | 0.04–11.7 | 2.47–25.35 | 3.47–35.48 | 2.87–37.87 | 0.08–30.72 |
| Turbidity | NTU | 2.72–24.9 | 1.62–236 | 8.2–18.77 | 2.12–6.98 | 2.3–6.67 | 0.67–76.8 |
| Slope | % | 3.0–10.0 | 3.0–9.0 | 3.0–23.0 | 4.0–20.0 | 2.0–9.0 | 2.0–23.0 |

TDS, low phosphate, low pH and temperature. Adjoining land areas are under permanent agriculture. Phosphate and topographic high areas (slope %) are strongly and significantly associated with IIA, areas with high marine influence during the low-water season. Maximum temperature was recorded in this region. However, TDS is strongly associated with cluster IIB that pooled together areas along the lagoon–sea continuum during the high-water period. Correlations between measured environmental variables were deduced from the SOM map based on their positions on the component planes. These relationships were, however, quantified using nonparametric Spearman criterion at a significant level of 0.05. For instance, silicate and TDS with opposing distribution patterns imply negative correlation (Spearman rank correlation, $r = -0.6$). These are abiotic variable influxes from opposing sources, viz. landward and seaward sides, respectively. Silicate is also negatively correlated with pH ($r = -0.4$). TDS showed an inverse relationship with turbidity ($r = -0.6$) and a positive correlation with pH ($r = 0.7$). Although correspondence analyses (CCA) performed on the data set could not clearly define clusters, it clearly highlights silicate ($p: 0.008$) and total dissolved solids ($p: 0.038$) as predominant abiotic factors controlling phytoplankton dynamics in these coastal systems.

Discussions

Seasonal fluctuations in the quality of these shallow coastal waters are largely controlled by changing hydrologic regimes (Dandonneau, 1971; Dufour, 1994). Before the onset of annual rainfall events, during the low-water period (December–April), marine processes exert the strongest controls on the system's biogeochemical processes. Surface

water temperature and salinity are at their threshold values of 32°C and 32 ‰, respectively, during this period (Pagès, Lemasson & Dufour, 1979). However, after the rainfall events (June–July) and peak discharge seasons of the draining rivers (September–October), continental (fluvial and precipitation) processes dominate, resulting in the dilution of the coastal waters. Surface water temperature is cooler, and salinity approaches zero value (Pagès, Lemasson & Dufour, 1979). The changing hydrologic regime in turn influences phytoplankton dynamics. Algal floristic changes due to environmental fluctuations in this environment are well documented (Morlière, 1970; Iltis, 1982; Seu-Anoï *et al.*, 2013). Although diatoms are the most species rich, cyanobacteria are the most abundant in all biogeographical zones. They constitute up to 90% of phytoplankton biomass in some areas especially during the high-water period. Their dominance is favoured by phytoplankton blooms (Eea, 2008), a phenomenon triggered by eutrophication. It should, however, be noted that the dominance of cyanobacteria once established is difficult to reverse (Ekholm, 2008). Low taxonomic diversity of phytoplankton in this tropical environment is comparable to observations made along the nearby Lagos lagoon (Nkwoji, Onyema & Igbo, 2010). Conversely, phytoplankton abundance exceeds the bloom-forming thresholds of 20,000 cells mL⁻¹ for recreational purposes (WHO, 2003) in all sampled sites. The dominance and proliferation of the dinoflagellate genus, *Gymnodinium*, and bloom-forming cyanobacteria genera such as *Phormidium*, *Anabaena*, *Microcystis*, *Cylindrospermopsis* and *Oscillatoria* in some areas of this coast represent viable threats to the ecological status of these systems (Eea, 2008). Once established, their formation of bloom causes high turbidity, suppressing the growth of other phytoplankton species (Visser, 1990). Although not established in this study, these

potentially toxic genera have been implicated in fish kill events: *Gymnodinium* in Kuwait Bay, Arabian Sea (Heil *et al.*, 2001); *Anabaena circinalis* in Barwon–Darling River in New South Wales, Australia (Bowling & Baker, 1996); *Phormidium* in some lakes in New Zealand (Chorus & Bartram, 1999); and *Microcystis aeruginosa*, notorious for its production of hepatotoxin in Lake Erie in the United States of America (Brittain *et al.*, 2000) and in Krüger National Park, South Africa (Oberholster *et al.*, 2009). They are, however, not always toxic (Suthers & Rissik, 2009) as a recent study showed that fluctuations in environmental variables such as pH could act as a stimulant to toxin production in some potentially toxic species (Prosser *et al.*, 2012). The filamentous form of cyanobacteria that is dominant in this environment is not the preferred diet for majority of higher order aquatic species, and this could be a likely explanation for dwindling fish productivity. Nevertheless, there is also a strong argument for the key role played by overfishing (increase in demand), which cannot be underestimated. This fact is buttressed by data from Côte d'Ivoire's *Ministère de la Production Animale et des Ressources Halieutiques*, MIPARH, stating that the artisanal maritime and lagoonal fish catches actually increased from 8,139 tonnes in 2002 to 18,975 tonnes in 2012. Fish biomass should therefore be expected to diminish with the continued increase in fishing efforts (Laë, 1997). Fisheries decline in this environment has also been attributed to coastal habitat degradation (Kouassi & Biney, 1999). Nutrient influx into the Ébrié lagoon from land-based sources was estimated at 33 kilotonnes and 2.5 kilotonnes for nitrate and phosphate, respectively (Scheren *et al.*, 2004).

In regions of cluster IIA, high nitrate import during the high-water period is to be expected as adjacent land areas are permanently under agriculture. High nutrient levels, viz. nitrates and phosphates in this tropical environment, are decades-old problem (Dufour, Lemasson & Crémoux, 1981), similar to what is obtainable in Lake Victoria in East Africa (Zhou *et al.*, 2014) and some other coastal zones of the world (Diaz, Selman & Chique, 2011). Nutrient enrichment (eutrophication) is believed to be a key stressor in coastal ecosystems and the lead cause of hypoxia (low dissolved oxygen) in coastal waters (Diaz, Selman & Chique, 2011). Hypoxia, a more direct trigger of fish kills, is a serious environmental challenge in fisheries managerial strategies. Higher availability of nitrate and phosphate as observed in these environments causes phytoplankton to use more silicate (Wulff & Rahm, 1988). Different authors have put forward

theories to support the influx of nutrients into these systems. Proposed sources include urban and agricultural run-offs (Scheren *et al.*, 2004) and vertical upwelling currents that result in the upward movement of the horizontal nitracline from depths into the euphotic zone (Herbland & le Loeuff, 1993). This is because from observations, periods of high nutrient availability coincide with the major ocean upwelling events of the south Atlantic coastlines (Herbland & le Loeuff, 1993). Similar observations have also been made for the Senegal and Mauritania coastlines. Supporting details from the works of Morlière, 1970; Roy, 1991; Pezennec & Koranteng, 1998; Aman *et al.*, 2007; Djagoua *et al.*, 2011 have confirmed the Ivorian coastlines as a strong upwelling front.

In conclusion, SOM technique displayed the biogeographical patterns of phytoplankton distribution in these environments and effectively relates environmental variables to the different clusters. In case of a planned biological conservations, geographical areas within clusters I and IIA with the lowest Jaccard similarity index (0.25) should be the top priority for conservation as together they support relatively higher taxonomic diversity. Suffice to say some regions of cluster IIA border the Azagny National Park, a biological reserve since 1981. The present result is only a snapshot of the environment during this biannual investigation period, and continuous monitoring is required to establish trends.

Acknowledgements

This work was carried out under the framework of the West African Science Service Centre on Climate Change and Adapted Land Use, WASCAL, a Bundesministerium für Bildung und Forschung (BMBF), Germany-sponsored programme. The authors wish to also thank Mrs. Camilla Kurth and Mrs. Bettina Schultes-Van-Berkum of the hydrochemistry laboratory of the Steinmann-Institut, University of Bonn, Germany, for technical support. Also, special thanks to the anonymous reviewers for their comments and suggestions.

References

- AMAN, A., TESTUT, L., WOODWORTH, P.L., AARUP, A. & DIXON, D.J. (2007) Seasonal sea level variability in the Gulf of Guinea from altimetry and tide gauge. *Revue Ivoirienne des Sciences et Technologie*, **9**, 105–118.

- ASTEL, A., TSAKOVSKI, S., BARBIERI, P. & SIMEONOV, V. (2007) Comparison of self-organizing maps classification approach with cluster and principal components analysis for large environmental data sets. *Water Res.* **41**, 4566–4578.
- ASTEL, A.M., GIORGINI, L., MISTARO, A., PELLEGRINI, I., COZZUTTO, S. & BARBIERI, P. (2013) Urban BTEX spatiotemporal exposure assessment by chemometric expertise. *Water Air Soil Poll.* **224**, 1–17.
- BANDEJ, V., SOCIAL, G., PARK, Y.S., LEK, S., COPPOLA, J., CAMATTI, E., CAPUZZO, E., MILANI, L. & SOLIDORO, C. (2008) Analysis of multiprotrophic plankton assemblages in the Lagoon of Venice. *Mar. Ecol. Prog. Ser.* **368**, 23–40.
- BARAN, E. (2000) Biodiversity of estuarine fish faunas in West Africa. *Naga, The ICLARM Quarterly*, **23**, 4–9.
- BOWLING, L.C. & BAKER, P.D. (1996) Major cyanobacterial bloom in the Barwon-Darling River, Australia, in 1991, and underlying limnological conditions. *Mar Freshwater Res.* **47**, 643–657.
- BRITTAIN, S.M., WANG, J., BABCOCK-JACKSON, L., CARMICHAEL, W.W., RINEHART, K.L. & CULVER, D.A. (2000) Isolation and characterization of microcystins, cyclic heptapeptide hepatotoxins from a Lake Erie strain of *Microcystis aeruginosa*. *J. Great Lakes Res.* **26**, 241–249.
- BROGUEIRA, M.J., DO ROSÁRIO OLIVEIRA, M. & CABEÇADAS, G. (2007) Phytoplankton community structure defined by key environmental variables in Tagus estuary, Portugal. *Mar. Environ. Res.* **64**, 616–628.
- BULLINARIA, J.A. (2004) *Self-Organizing Maps: Algorithms and Applications*. Lectures. University of Birmingham, UK.
- CASTEL, J., CAUMETTE, P. & HERBERT, R. (1996) Eutrophication gradients in coastal lagoons as exemplified by the Bassin d'Arcachon and the Etang du Prévost. In: *Coastal Lagoon Eutrophication and Anaerobic Processes*. (Eds P. CAUMETTE, J. CASTEL and R. HERBERT). Kluwer academic publishers, Berlin.
- CHATTOPADHYAY, M., DAN, P.K. & MAZUMDAR, S. (2012) Application of visual clustering properties of self-organizing map in machine-part cell formation. *Appl Soft Comput.* **12**, 600–610.
- CHORUS, I. & BARTRAM, J. (1999) *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring and Management*. E and FN Spon, London.
- COCQUYT, C., LANGE-BERTALOT, H. & KOCIOLEK, J.P. (1998) *Diatoms from the Northern Basin of Lake Tanganyika*. (Ed. J. CRAMER). Bibliotheca Diatomologica 39: 276 pp, 56 plates. Schweizerbart Science Publishers, Stuttgart, Germany.
- COMPÈRE, P. (1991) Contribution à l'étude des algues de Sénégal. I. Algues du lac de Guiers et du Bas-Sénégal. *Bulletin du Jardin Botanique National Belgique* **61**, 171–267.
- DANDONNEAU, Y. (1971) Etude du phytoplancton sur le plateau continental de Côte d'Ivoire. 1. Groupe d'espèces associées. *O.R.S.T.O.M., Sér. Oceanogr.* **9**, 247–265.
- DE-CÁCERES, M. & LEGENDRE, P. (2009) Associations between species and groups of sites: indices and statistical inference. *Ecology* **90**, 3566–3574.
- DIAZ, R., SELMAN, M. & CHIQUÉ, C. (2011) *Global Eutrophic and Hypoxic Coastal Systems*. World Resources Institute.
- Eutrophication and hypoxia: Nutrient pollution in Coastal Waters map. Available at http://www.docs.wri.org/wri_eutrophic_hypoxic_data-sets_2011-03.xls (Accessed on 17 June 2015).
- DJAGOUE, E.V., AFFIAN, K., LAROCHE, P. & SALEY, M.B. (2006) Variabilité saisonnière et Interannuelle de la Chlorophylle en Surface de la Mer sur le plateau Continental de la Côte d'Ivoire à l'aide des images de SeaWiFS, de 1997 à 2004. *Télétection* **6**, 143–151.
- DJAGOUE, V.E., KASSI, J.B., MOBIO, B., KOUADIO, J.M., DRO, C., AFFIAN, K. & SALEY, B. (2011) Ivorian and Ghanaian upwelling comparison: intensity and impact on phytoplankton biomass. *Am. J. Sci. and Ind. Res.* **2**, 740–747.
- DUFOUR, P., LEMASSON, L. & CRÉMOUX, J.L. (1981) Contrôle nutritif de la biomasse du seston dans une lagune tropicale de Côte d'Ivoire. II. Variations géographiques et saisonnières. *J. Exp. Mar. Biol. Ecol.* **51**, 269–284.
- DUFOUR, P., ALBARET, J., DURAND, J. & GUIRAL, D. (1994) Fonctionnement de l'écosystème Ebrié. In: *Environnement et ressources aquatiques en Côte d'Ivoire: 2. Les milieux lagunaires* (Eds J. DURAND, P. DUFOUR, D. GUIRAL DANIEL and S.G.F. ZABI). ORSTOM, Paris.
- DUPRÊNE, M. & LEGENDRE, P. (1997) Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecol. Monogr.* **67**, 345–366.
- DURAND, J.R. & CHANTRAINE, J.M. (1982) L'environnement climatique des lagunes Ivoiriennes. *Revue de Hydrobiologie Tropical*, **15**, 85–113.
- EEA, J.R.C. & WHO (2008) *Impacts of Europe's Changing Climate – 2008 Indicator Based Assessment*. European Environment Agency, Copenhagen.
- EKHOLM, P. (2008) *N:P Ratio in Estimating Nutrient Limitation in Aquatic Systems*. Finnish Environment Institute, Helsinki, Finland.
- EVANS, M.I. & FISHPOOL, L.D.C. (2001) *Important Bird Areas in Africa and Associated Islands: Priority Sites for Conservation*. Bird life International, Cambridge, U.K.
- FOGED, N. (1966) Freshwater diatoms from Ghana. Collection Biologiske Skrifter Kongelige Danske Videnskabernes Selskab. Bd. 15 n°1, Kommissonaer, Munksgaard, 169 pp.
- HEIL, C.A., GLIBERT, P.M., AL-SARAWL, M.A., FARAJ, M., BEHBEHANI, M. & HUSAIN, M. (2001) First record of a fish-killing *Gymnodinium* sp. bloom in Kuwait Bay, Arabian Sea: chronology and potential causes. *Mar. Ecol. Prog. Ser.* **214**, 1–15.
- HERBLAND, A. & LOEUFF, P. (1993) Les sels nutritifs au large de la Côte d'Ivoire. In *Environnement et ressources Aquatiques de la Côte d'Ivoire. I - Le milieu marine*. ORSTOM, Paris. **1**, 123–148.
- ILTIS, A. (1982) Peuplements algaux des rivières de Côte d'Ivoire. 2. Variations saisonnières des biomasses, de la composition et de la diversité spécifique des peuplements. *Revue Hydrobiol. trop.* **15**, 241–251.
- JACCARD, P. (1912) The distribution of the flora in the alpine zone. *New Phytol.* **11**, 37–50.

- KASKI, S. & LAGUS, K. (1996) Comparing self-organizing maps. In: *Proceedings of ICANN96, International Conference on Artificial Neural Networks* (Eds VON DER MALSBERG C., VON SEELEN W., J. C. VORBRUGGEN and B. SENDHO). Lecture Notes in Computer Science, vol. 1112 Springer, Berlin.
- KOHONEN, T. (1995) *Self-organizing maps*. Springer, Berlin.
- KOHONEN, T. (2001) *Self-Organizing maps*. Springer, Berlin.
- KOHONEN, T., OJA, E., SIMULA, O., VISA, A. & KANGAS, J. (1996) Engineering applications of the self-organizing map. *Proc. IEEE* **84**, 1358–1384.
- KOMÁREK, J. & ANAGNOSTIDIS, K. (2005) Cyanoprokaryota 2. Teil/ 2nd Part: Oscillatoriales (Eds. B. BÜDEL, L. KRIENTZ, G. GÄRTNER and M. SCHAGERL). *Süßwasserflora von Mitteleuropa 19/2*. Elsevier/ Spektrum, Heidelberg.
- KONÉ, Y.J.M., ABRIL, G., KOUADIO, K.N., DELILLE, B. & BORGES, A.V. (2009) Seasonal Variability of Carbon Dioxide in the Rivers and Lagoons of Ivory Coast (West Africa). *Estuar. Coast.* **32**, 246–260.
- KOUASSI, A.M. & BINEY, C. (1999) Overview of the marine environmental problems of the West and Central African region. *Ocean Coast. Manag.* **42**, 71–76.
- KRAMMER, K. & LANGE-BERTALOT, H. (1991) Bacillariophyceae: Centrales. *Fragilariaceae, Eunotiaceae*. (Eds. H. ETTI, J. GERLOFF, H. HEYING and D. MOLLENHAUER) *Süßwasserflora von Mitteleuropa*, Stuttgart.
- KRASZNAI, E., BORICS, G., VARBIRO, G., ABONYI, A., PADISÁK, J., DEÁK, C. & TÓTHMÉRÉSZ, B. (2010) Characteristics of the pelagic phytoplankton in shallow oxbows. *Hydrobiologia* **639**, 173–184.
- KREBS, C.J. (1994) *Ecology: The Experimental Analysis of Distribution and Abundance*. 4th edn, Harper Collins, New York.
- LAË, R. (1997) Does overfishing lead to a decrease in catches and yields? An example in two West African coastal lagoons. *Fish. Manage. Ecol.* **3**, 101–116.
- LAMPINEN, J. & OJA, E. (1992) Clustering properties of hierarchical self-organizing maps. *J. Math. Imaging Vis.* **2**, 261–272.
- LEK, S., GIRADEL, J.L. & GUÉGAN, J.F. (2000) Neuronal networks: algorithms and architectures for ecologists and evolutionary ecologists. In: *Artificial Neuronal Networks* (Eds. S. LEK and J. F. GUEGAN). Springer, Berlin Heidelberg.
- LEK, S., SCARDI, M., VERDONSCHOT, P.F.M., DESCY, J.P. & PARK, Y.S. (eds.) (2005) *Modelling Community Structure in Freshwater Ecosystems*. Springer, Berlin.
- MIKKULAINEN, R. (1990) Script recognition with hierarchical feature maps. *Connection Science*.
- MORLIÈRE, A. (1970) Les saisons marines devant Abidjan. *Documents Scientifiques, Centre de Recherches Océanographiques, Abidjan* **1**, 1–15.
- NIAMIEN-EBROTTIE, J.E., KONAN, F.K., OUATTARA, A. & GOURENE, G. (2013) Spatio-temporal distribution of phytoplankton in four coastal rivers of southeastern of Ivory Coast (Soumié, Eholié, Ehania and Noé). *Afr. J. Ecol.* **52**, 395–403.
- NKWOJI, J.A., ONYEMA, I.C. & IGBO, J.K. (2010) Wet season spatial occurrence of phytoplankton and zooplankton in Lagos Lagoon, Nigeria. *Sci. World J.* **5**, 7–14.
- OBERHOLSTER, P.J., MYBURGH, J.G., GOVENDER, D., BENGIS, R. & BOTHA, A.M. (2009) Identification of toxigenic *Microcystis* strains after incidents of wild animal mortalities in the Kruger National Park, South Africa. *Ecotox Environ Safe.* **72**, 1177–1182.
- OH, H.M., AHN, C.Y., LEE, J.W., CHON, T.S., CHOI, K.H. & PARK, Y. (2007) Community patterning and identification of predominant factors in algal bloom in Daechung Reservoir (Korea) using artificial neural networks. *Ecol. Model.* **203**, 109–118.
- OKOGWU, I.O. & UGWUMBA, A.O. (2013) Seasonal dynamics of phytoplankton in two tropical rivers of varying size and human impact in Southeast Nigeria. *Revista de Biología Tropical.* **61**, 1827–1840.
- OUATTARA, A. (2000) *Premières données systématiques et écologiques du phytoplankton du lac d'Ayamé (Côte d'Ivoire)*. Thèse de l'Université Catholique Leuven, Belgique, 200p.
- PAGÈS, J., LEMASSON, L. & DUFOUR, P. (1979) Éléments nutritifs et production primaire dans les lagunes de Côte d'Ivoire. Cycle annuel. *Arch. Sci. Centre Rech. océanogr. Abidjan* **5**, 1–60.
- PARK, Y.S., CÉRÉGHINO, R., COMPIN, A. & LEK, S. (2003) Applications of artificial neural networks for patterning and predicting aquatic insect species richness in running waters. *Ecol. Model.* **160**, 265–280.
- PARK, Y.S., SONG, M.Y., PARK, Y.C., OH, K.H., CHO, E. & CHON, T.S. (2007) Community patterns of benthic macroinvertebrates collected on the national scale in Korea. *Ecol. Model.* **203**, 26–33.
- PEZENNEC, O. & KORANTENG, K.A. (1998) Changes in the dynamics and biology of small pelagic fisheries off Côte d'Ivoire and Ghana: an ecological puzzle. *Global versus Local Changes in Upwelling Systems* (Eds DURAND, M. H., MENDELSSOHN, R., CURY, P., ROY, C. and PAULY, D.). ORSTOM, Paris.
- PÖZLBAUER, G. (2004) *Survey and Comparison of Quality Measures for Self-Organizing Maps*. University of Technology, Vienna, Austria.
- PRICE, A.R. (2001) The marine food chain in relation to biodiversity. *The Scientific World Journal.* **1**, 579–587.
- PROSSER, K.N., VALENTI, T.W., HAYDEN, N.J., NEISCH, M.T., HEWITT, N.C., UMPHRES, G.D., GABLE, G.M., GROVER, J.P., ROELKE, D.L. & BROOKS, B.W. (2012) Low pH preempts bloom development of a toxic haptophyte. *Harmful Algae.* **20**, 156–164.
- ROY, C. (1991) Les upwellings: le cadre physique des pêcheries côtières ouest-africaines. *Pêcheries Ouest-Africaines*. (Eds. P. CURY and C. Roy). Orstom, Paris
- SAHU, G., K.K., SATPATHY, MOHANTY, A.K. & SARKA, S.K. (2012) Variations in community structure of phytoplankton in relation to physicochemical properties of coastal waters, southeast coast of India. *India Journal of Geo-marine sciences.* **41**, 223–241.
- SCHEREN, P.A.G.M., KROEZE, C., JANSSEN, F.J.J.G., HORDIJK, L. & PTASINSKI, K.J. (2004) Integrated water pollution assessment of the Ebrié Lagoon, Ivory Coast, West Africa. *J. Marine Syst.* **44**, 1–17.

- SCHOEN, S. (1988) Cell counting. In: *Experimental Phycology: A Laboratory Manual* (Eds C. S. LOBBAN, D. J. CHAPMAN and B. P. KREMER). Cambridge University Press, NY.
- SERRANO-CINCA, C. (1996) Self organizing neural networks for financial diagnosis. *Decis. Support Syst.* **17**, 227–238.
- SEU-ANOÏ, N.M., KONÉ, Y.J.M., KOUADIO, K.N., OUATTARA, A. & GOURÈNE, G. (2013) Phytoplankton distribution and its relationship to environmental factors in the Ebrié Lagoon, Ivory Coast, West Africa. *Vie Milieu*. **63**, 18–92.
- SHANNON, C.E. & WEAVER, W. (1949) *The Mathematical Theory of Communication*. University of Illinois press, Urbana.
- SUTHERS, I. & RISSIK, D.(Eds.). (2009) *Plankton: A Guide to their Ecology and Monitoring for Water Quality*. Csiro Publishing, Collingwood, Australia.
- VARLET, F. (1978) *Le régime de la lagune Ebrié*. Côte d'Ivoire. Traits physiques essentiels. Trav. Doc. ORSTOM, Paris.
- VESANTO, J. & ALHONIEMI, E. (2000) Clustering of the self-organizing map. *IEEE T neural networ.* **11**, 586–600.
- VISSER, P.M. (1990) *De primaire Productie van het Markermeer*. Microbiology Laboratory, University of Amsterdam, Amsterdam, Netherlands.
- WESTERLUND, L.M. (2005) *Classifying with Kohonen Self-Organizing Map*. Soft Computing, Haskoli Islands.
- World Health Organisation. (2003) *Guidelines for Safe Recreational Waters*. Volume 1. – Coastal and fresh waters. World Health Organization, Geneva.
- WULFF, F. & RAHM, L. (1988) Long-term, seasonal and spatial variations of nitrogen, phosphorus and silicate in the Baltic: an overview. *Mar. Environ. Res.* **26**, 19–37.
- YU, S., VAN VOOREN, S., COESSENS, B. & DE MOOR, B. (2006) Interpreting gene profiles from biomedical literature mining with self-organizing maps. In: *Proceedings of the Third International Conference on Advances in Neural Networks-Volume Part III* (Eds. W. JUN, Y. ZHANG, M. Z. JACEK, L. BAO-LIANG and Y. HUJUN). Springer, Berlin Heidelberg.
- ZHOU, M., BRANDT, P., PELSTER, D., RUFINO, M.C., ROBINSON, T. & BUTTERBACH-BAHL, K. (2014) Regional nitrogen budget of the Lake Victoria Basin, East Africa: syntheses, uncertainties and perspectives. *Environ. Res. Lett.* **9**, 1–10.

(Manuscript accepted 12 September 2016)

doi: 10.1111/aje.12379