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RESEARCH ARTICLE

A checklist of phytoplankton species in the Faafu atoll (Republic of Maldives)

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Abstract

1 - Phytoplankton is considered as a natural bioindicator of water quality because of its sensitivity and its complex and rapid response to change of environmental conditions.

2 - The aim of this study was to investigate and provide important new information about the checklist of phytoplankton species in different lagoons of the Faafu atoll in Maldivian archipelago.

3 - A total of 140 phytoplankton taxa were identified. In terms of species richness, dinoflagellates were the largest group with 55 identified taxa belonging to 22 genera. Coscinodiscophyceae recorded 38 taxa belonging to 14 genera; Bacillariophyceae represented by 18 taxa belonging to 10 genera and Fragilariophyceae recorded 11 taxa belonging to 8 genera. Most of the other classes were poorly represented with only one or , at most, two taxa for each genus.

Keywords: phytoplankton; taxonomic structure; diatoms; dinoflagellates; Maldivian Atoll; Indian Ocean.

Introduction

Phytoplankton account for ~1 % of the photosynthetic biomass on Earth, nevertheless they are responsible for between 40 and 50% of the total primary production (Longhurst *et al.*, 1995; Field *et al.*, 1998; Falkowski *et al.*, 2004). These photosynthetic protists, ubiquitous in earth's water environments, are also of global significance for climate regulation and biogeochemical cycling (Winder and Sommer, 2012).

Phytoplankton composition and size structure are considered as a natural bioindicator of water quality variations because of its sensitivity, and its complex and rapid responses to changes of environmental conditions (Livingston, 2001; Padisák *et al.,* 2006). Particularly, phytoplankton size spectra seem to have a high information content for assessing changing environmental conditions (Sabetta *et al.*, 2008; Lugoli *et al.*, 2012; Vadrucci *et al.*, 2013). According to the frequency and intensity of these changes, qualitative and quantitative aspects of the biota can be modified, selecting species by means of competition mechanisms allowing the survival of species favoured by their adaptive strategies (Margalef, 1983; Reynolds, 1988). Patterns of seasonal phytoplankton succession have been extensively investigated around the world. Long term monitoring programs allowed a comprehensive knowledge of phytoplankton dynamics in selected areas (e.g. Cloern, 1996; Ribera d'Alcalà *et al.*, 2004; Silva *et al.*, 2009).

Much work is still needed to unravel phytoplankton composition and patterns in many remote areas that remain largely unexplored, such as Maldivian atoll lagoons. Atoll lagoons and coral reef and are productive ecosystems, compared to surrounding ocean (Hatcher, 1997). Atolls have different morphologies; their general saucer-shape lagoon morphology is bounded by a rim, which can be completely closed by a continuous emerged rim, or very open to the ocean with continuous submerged reef flats. Open atolls have wide reef flats along most of their perimeter, draining waters from the ocean towards the lagoon when waves break along the rim crest (Dumas *et al.*, 2012). Proposed atoll typology (Andrefouet *et al.*, 2001) has some similarity with Mediterranean lagoon typology (Basset *et al.*, 2006) both considering lagoon surface as a main driver of lagoon biodiversity.

Maldivian archipelago, a small island nation in the tropical Indian Ocean (Southwest of India) shows some of the most characteristic and size able worldwide atoll systems (Risk and Sluka, 2000), with numerous coral-reef islands made up exclusively of accumulations of carbonate sand and gravel (Semprucci *et al.*, 2011).

With its 22 atolls rising from a submerged plateau or separated by deep ocean tracts, the Maldivian archipelago represents an excellent natural laboratory and opens many possibilities for research, since it is devoid of any consistent terrigenous influx (Ciarapica and Passeri, 1993).

Purely taxonomic papers about meiofauna (Gerlach, 1961, 1962, 1963a,b, 1964; Gallo *et al.*, 2007) and a fairly extensive literature available on biological and ecological topics concern Maldives (Anderson *et al.,* 2011; Bianchi *et al.*, 1997, 2006; Kitchen-Wheeler *et al.*, 2012; Lasagna *et al.*, 2008, 2010).

Information about phytoplankton biomass, in terms of chlorophyll-a concentrations, for a little part of these atoll lagoons is knows (Anderson *et al.*, 2011) however studies, in terms of taxonomic composition of phytoplankton, are lacking for this area.

The aim of this study was to provide new information about the phytoplankton taxonomic structure in different lagoons of the Faafu atoll in the Maldivian archipelago. This study was focused to the general description of phytoplankton species composition in 10 different atoll's lagoons.

Study area

The Maldivian archipelago extends between 7°10' N (Ihavandiffulu Atoll) and 0°43' S (Addu Atoll) for over 800 km and is 130 km wide. Its central sector consists of a double chain of atolls rising from a submerged plateau, whose depth varies from over 500 m in the North to 300-400 m in the South. The archipelago is made up of 22 atolls of circular or elongated shape, the sizes varying from some kilometers to many tens of kilometers, and contains more than 1000 islands which cover a surface of 298 km^2. Every atoll is formed by a marginal rim surrounding a lagoon commonly less than 50-60 m deep, though some reach depths of more than 80 m (Suvadiva Atoll, Kolumadulu Atoll). This marginal rim is interrupted by deep channels (passes; "kandu" in Maldivian language) which lead to strong water circulation inside the lagoon, favouring the development of many patch reefs. The atoll lagoon is dish-shaped but, in detail, the floor is very irregular with many patchy reefs.

The atoll lagoons are characterized mainly by sandy sediments; a large amount of the sand (more than 50%) derives from mechanical erosion and from bioerosion of the reef. A minor amount is due to benthonic organisms living in the sand with fewer contributions from planktonic foraminifers (Ciarapica and Passeri, 1993).

This study was conducted at Faafu Atoll, Republic of Maldives, a small nation of coral atolls off the south-west coast of the Indian Ocean (Fig. 1).

Material and methods

Field sampling and sample processing

The study was processed on different atoll lagoons selected according to a morphological parameter: lagoon area. This parameter has a clear influence on the degree of water exchange between lagoons and the surrounding ocean, a hydrodynamic factor which was proved to play a decisive role on nutrient budget in lagoons (Smith, 1984; Dufoura and Berland,1999).

In order to determine composition of phytoplankton in a pristine area, 10 lagoonal sites were sampled: BileydhooSWa, BileydhooSWb, BileydhooSWc, Ebulufushi, Ebulufushi AR, Filitheyo Maavaru, Maagaa, Medhugaa, Magoodhoo and Magoodhoo E.

Sampling has followed a hierarchical design according to the criteria adopted for a large scale survey, which is currently in progress in various worldwide eco-regions (POR Strategic Project) (see, Durante *et al.*, 2013; Souza *et al.*, 2013; Roselli *et al.*, 2013; Stanca *et al.*, 2013 for other world eco-regions) (for further information see the web site: http://phytobioimaging.unisalento.it/en-us/studysites/samplingdesign.aspx.).

This study was carried out in May 2012. Three sampling stations were set up for each site inside in each lagoon. At each station, three samples for the phytoplankton study were collected using a 6µm net.

The water samples were fixed with Lugol's solution. Phytoplankton analysis was carried out on preserved subsamples. Taxonomic identification was performed on a sub-sample of 400 cells at 400× magnification under an inverted microscope (Nikon Eclipse T*i*-S) connected to a video interactive image

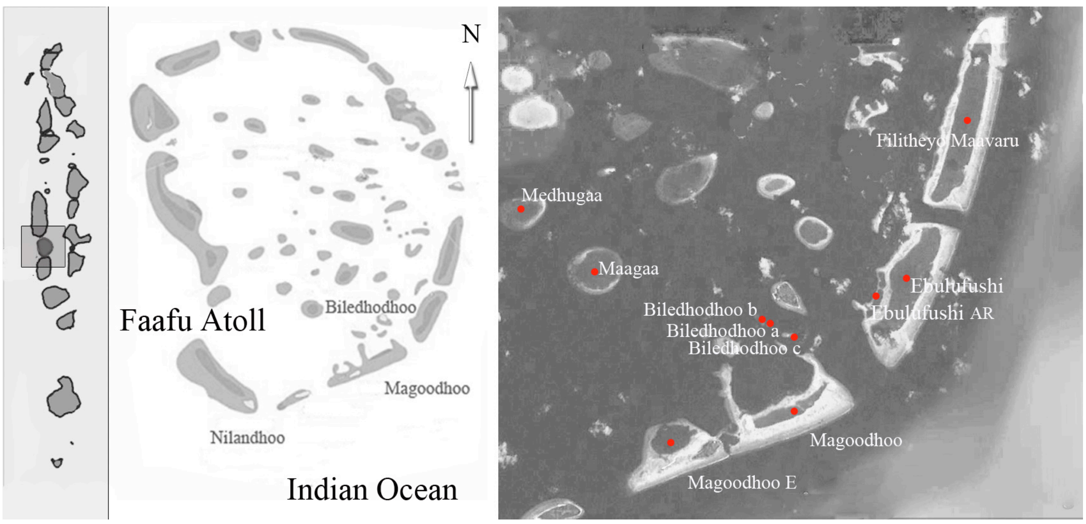

Figure 1. Localization of the 10 atoll's lagoons, in Faafu atoll.

analysis system (L.U.C.I.A, Version 4.8, Laboratory Imaging Ltd., Prague) with a lower detection limit of 5 µm following Utermöhl's method (Utermöhl, 1958). For a more detailed identification an inverted microscope Nikon Eclipse Ti-E coupled with an image analysis system (NIS–Elements AR Nikon Instruments software, version 3.06) was used.

Taxonomic identification of nano-microphytoplankton was carried out using specific manuals and appropriate monographs: Van Heurck, 1880-1885; Kofoid, 1907; Boyer, 1926; Cupp, 1943; Graham and Bronikovsky, 1944; Crosby and Wood, 1958, 1959; Wood *et al.*, 1959; Wood, 1963; Subrahmanyan, 1968; Subrahmanyan, 1971; Gopinathan, 1975; Rampi and Bernhard, 1978, 1980, 1981; Dodge, 1982; Ricard, 1987; Sournia, 1986, 1987; Chrétiennot-Dinet, 1990; Round *et al.*, 1990; Tomas, 1997; Bérard-Therriault *et al.*, 1999; Faust and Gulledge, 2002; Cortés-Altamirano and Sierra-Beltrán 2003; Pavel Škaloud and Řezáčová 2004; Gómez, 2007; Gul and Saifullah, 2007; Okolodkov, 2008; Hernández-Becerrila *et al.*, 2008; Saifullah *et al.*, 2008; Al-Kandari *et al.*, 2009; Al-Yamani and Saburova, 2010; Haraguchi and Odebrecht, 2010; Lee and Lee, 2011.

The "cf." qualifier was used to indicate specimens that were similar to (or many actually be) the nominated species. Taxa which contain the "undet." (undetermined) identifier were likely to be algal entities, but could not be identified as any identified genus. In some cases, species were broken up into separate taxa based on size (e.g., Dinophyceae undet. > 20 µm).

During phytoplankton identification, sometimes is not possible to identify the organism to the species level, though recognizing common characteristics within a group of cells belonging to the same genus. In this case, to identify that organism in the phytoplankton list is reported the name of the genus followed by numbered "sp." (e.g. *Pseudo-nitzschia* sp. 2, *Pseudo-nitzschia* sp. 3, *Pseudo-nitzschia* sp. 4, etc). The complete list, including all numbered species, is available on the website www.phytobioimaging.unisalento.it.

Results and Discussion

Phytoplankton composition in Maldivian atoll lagoons

The phytoplankton found in the Faafu atoll lagoons are listed below. The list is ordered by phylogenetic hierarchical taxonomic order. The study records the presence of eleven classes: Bacillariophyceae, Chlorophyceae, Coccolitophyceae, Coscinod iscophyceae,Cyanophyceae, Cryptophyceae, Dictiophyceae,Dinophyceae, Ebriophyceae, Fragilariophyceae and unidentified phytoflagellates.

A total of 140 phytoplankton taxa were identified, among which at least 75 to the species level and 54 to the genus level (Appendix 1). For 11 taxa identification to the genus level was not achieved.

Majority of the phytoplankton were Dinophyceae, making up 55 taxa belonging to 22 genera. The most representative dinoflagellates genera were *Ceratium* Schrank and *Prorocentrum* Ehrenberg with 8 taxa for both, *Oxytoxum* Stein and *Protoperidinium* Bergh with 6 and 4 taxa, respectively. 15 genera belonging to Dinophyceae were represented by only one taxon. The unidentified dinophyceae taxa were reported according to their different morphological characteristics (e.g., > or < 20 µm). Coscinodiscophyceae emerged as second dominant class, recording 38 taxa from 14 genera. Within these, most representative genera were *Chaetoceros* Ehrenberg with 13 taxa and *Rhizosolenia* Brightwell with 6 taxa, respectively. Bacillariophyceae were represented by 18 taxa belonging to 10 genera. Genus *Pseudo-nitzschia* H. Peragallo presented the higher number of taxa (6) Fragilariophyceae recorded 11 taxa belonging to 8 genera and *Licmophora* C.Agardh was the most important genus, with 3 taxa.

For the other classes, Chlorophyceae was represented by 5 taxa belonging to 3 genera, Cyanophyceae by 4 taxa belonging to 3 genera, followed by Coccolitophyceae with 2 taxa belonging to 2 genera. Only one taxon was recorded for both Dictiophyceae and Ebriophyceae, respectively. Cryptophyceae and phytoflagellates identification was not achieved to the genus level.

The results from the present study revealed floristically diverse phytoplankton composition in Faafu atoll lagoons with predominantly dinoflagellates and diatoms (Coscinodiscophyceae, Bacillariophyceae and Fragilariophyceae). Some taxa live singly, whereas others form colonies and they may assume a diverse range of shapes.

Dinoflagellates exhibit a wide divergence in morphology and size that are essential features used to identify species, as well as surface ornamentation (pores, areolae, spines, ridges, etc.). Armored or thecate species, those that possess a multi-layered cell wall, can be distinguished from unarmored or athecate species, those that lack a cell wall (Faust and Gulledge, 2002). On the other hand, the presence of association of centric and pennate diatoms, and their living conditions reflect the physical and chemical parameters of the lagoon (e.g. shallow water column; salinity) (Sylvestre *et al.*, 2001). Other phytoplankton groups, even though poorly represented in taxonomic terms, are an important component. of photosynthetic organisms and of the base in the aquatic food chain.

Analyzing species composition of phytoplankton community is, on one hand, high time consuming and requires detailed taxonomic knowledge, on the other hand, leads to important information about the changes occurring in species composition with environmental change.

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Appendix 1 - List of taxa identified during sampling period in the Maldivian atoll's lagoons.

Bacillariophyta
Bacillariophyceae
Amphora spp.
Bacillaria paxillifera (O.F.Müller) T.Marsson 1901
Bacillaria spp.
Cocconeis spp.
Diploneis spp.
Entomoneis alata (Ehrenberg) Ehrenberg 1845
Meuniera membranacea (Cleve) P.C.Silva in Hasle & Syvertsen 1996
Navicula spp.
Navicula transitans Cleve 1883
Nitzschia spp.
Pleurosigma spp.
Pseudo-nitzschia cf. *heimii*
Pseudo-nitzschia pungens (Grunow ex Cleve) G.R.Hasle 1993
Pseudo-nitzschia sp. 2
Pseudo-nitzschia sp. 3
Pseudo-nitzschia sp. 4
Pseudo-nitzschia spp.
Bacillariophyceae pennales undet.
Coscinodiscophyceae
Asteromphalus flabellatus (Brébisson) Greville 1859
Asteromphalus hepctactis cf. *flabellatus*
Bacteriastrum elongatum Cleve 1897
Bacteriastrum spp.
Bellerochea horologicalis Stosch 1980
Cerataulina pelagica (Cleve) Hendey 1937
Chaetoceros cf. *tetrastichon*
Chaetoceros cf. *tortissimus*
Chaetoceros coarctatus Lauder 1864
Chaetoceros constrictus Gran 1897
Chaetoceros curvisetus Cleve 1889
Chaetoceros decipiens Cleve 1873
Chaetoceros laciniosus F.Schütt 1895
Chaetoceros lorenzianus Grunow 1863
Chaetoceros messanensis Castracane 1875
Chaetoceros pelagicus cf. *laciniosus*
Chaetoceros sp. 9
Chaetoceros sp. 10
Chaetoceros spp.
Climacodium frauenfeldianum Grunow 1868
Dactyliosolen fragilissimus (Bergon) Hasle in Hasle & Syvertsen 1996
Guinardia delicatula (Cleve) Hasle in Hasle & Syvertsen 1997
Guinardia flaccida (Castracane) H.Peragallo 1892

Appendix 1 - Continued.

Bacillariophyta
Coscinodiscophyceae
Guinardia striata (Stolterfoth) Hasle in Hasle & Syvertsen 1996
Hemiaulus membranaceus Cleve
Hemiaulus sinensis Greville 1865
Hemiaulus spp.
Leptocylindrus danicus Cleve 1889
Proboscia alata (Brightwell) Sundström 1986
Proboscia indica (H.Peragallo) Hernández-Becerril 1995
Pseudosolenia calcar-avis (Schultze) B.G.Sundström 1986
Rhizosolenia bergonii H.Peragallo 1892
Rhizosolenia decipiens B.G.Sundström 1986
Rhizosolenia fallax cf. *decipiens*
Rhizosolenia imbricata Brightwell 1858
Rhizosolenia setigera Brightwell 1858
Rhizosolenia spp.
Stephanopyxis palmeriana (Greville) Grunow 1884
Fragilariophyceae
Bleakeleya notata (Grunow) Round in F.E. Round, R.M. Crawford & D.G. Mann 1990
Ceratoneis closterium Ehrenberg 1839
cf. *Fragilaria* spp.
Licmophora flabellata (Grev.)C.Agardh 1831
Licmophora sp. 2
Licmophora spp.
Podocystis spp.
Striatella unipunctata (Lyngbye) C.Agardh 1832
Thalassionema nitzschioides (Grunow) Mereschkowsky 1902
Thalassionema spp
Toxarium undulatum J.W.Bailey 1854
Chlorophyta
Chlorophyceae
cf. *Astasia* sp.
Pediastrum boryanum (Turpin) Meneghini 1840
Scenedesmus sp. 3
Scenedesmus sp. 8
Chlorophyceae undet. 2
Cryptophyta
Cryptophyceae
Cryptophyceae undet. 2
Cryptophyceae undet.

Appendix 1 - Continued.

Cyanobacteria
Cyanophyceae
Anabaena spp.
Lyngbya cf. *aestuarii*
Spirulina meneghiniana cf. major
Spirulina subsalsa Oerstedt ex Gomont 1892
Cyanophyceae undet. 3
Dinophyta
Dinophyceae
Akashiwo sanguinea (K.Hirasaka) G.Hansen & Ø.Moestrup 2000
Amphisolenia bidentata Schröder 1900
Biceratium furca (Ehrenberg) Vanhoeffen 1897
Ceratium breve (Ostenfeld & Schmidt) Schroder 1906
Ceratium cf. *gibberum*
Ceratium declinatum Karsten 1907
Ceratium dens Ostenfeld & J.Schmidt 1901
Ceratium fusus (Ehrenberg) Dujardin 1841
Ceratium minutum E.G.Jørgensen in Schmidt 1920
Ceratium setaceum E.G.Jørgensen 1911
Ceratium vultur var. *sumatranum* Karsten 1907
Ceratocorys horrida Stein 1883
Dinophysis hastata Stein 1883
Gonyaulax spp.
Gymnodinium spp.
Gyrodinium spp.
Heterocapsa spp.
Histioneis costata Kofoid & Michener 1911
Histioneis elongata Kofoid & Michener 1911
Ornithocercus cf. *hetoroporus*
Ornithocercus cf. *magnificus*
Ornithocercus thumii cf. *steinii*
Ostreopsis cf. *ovata*
Ostreopsis spp.
Oxytoxum cf. *tesselatum*
Oxytoxum laticeps Schiller 1937
Oxytoxum longiceps Schiller
Oxytoxum scolopax Stein 1883
Oxytoxum tesselatum (Stein) F.Schütt 1895
Oxytoxum spp.
Peridinium quinquecorne Abé 1927
Phalacroma doryphorum Stein 1883
Podolampas bipes Stein 1883
Podolampas palmipes Stein 1883

Appendix 1 - Continued.

Dinophyta
Dinophyceae
Podolampas spp.
Prorocentrum cordatum (Ostenfeld) Dodge 1975
Prorocentrum lima (Ehrenberg) F.Stein 1878
Prorocentrum micans Ehrenberg 1834
Prorocentrum rhathymum
Prorocentrum scutellum Schröder 1900
Prorocentrum sp.1
Prorocentrum sp. 2
Prorocentrum spp.
Protoperidinium bipes (Paulsen) Balech 1974
Protoperidinium cf. *divergens*
Protoperidinium steinii (Jorgensen) Balech 1974
Protoperidinium spp.
Pyrocystis hamulus Cleve 1900
Pyrocystis obtusa Pavillard 1931
Scrippsiella trochoidea (Stein) Balech ex Loeblich III 1965
Scrippsiella sp.1
Dinophyceae athecate undet. 1 (>20µm)
Dinophyceae athecate undet. 2 (<20µm)
Dinophyceae thecate undet. 1 (>20µm)
Dinophyceae thecate undet. 2 (<20µm)
Haptophyta
Coccolithophyceae
Lhomannosphaera cf. *tolica*
Syracosphaera pulchra Lohmann 1902
Ochrophyta
Dictyochophyceae
Dictyocha fibula Ehrenberg 1839
Protozoa incertae sedis
Ebriophyceae
Hermesinum adriaticum O.Zacharias 1906
Other Phytoplankton
Phytoplankton undet. 12
Phytoflagellates undet.

