

Original Research Article

N:P RATIOS IN ESTIMATING NUTRIENT LIMITATION OF A COASTAL BAY IN SOUTHERN ADRIATIC SEA

ABSTRACT

The optimal DIN:DIP ratio (N/P ratio) for phytoplankton growth is 16:1 (bases on molar concentration) and is called the Redfield ratio. Significant deviations from 14 at low N/P ratios might indicate potential nitrogen limitation, ratio between 14 and 16 both nitrogen and phosphorus co-limitation and from 16 at high N/P ratios potential phosphorus limitation of phytoplankton primary production. This might affect to biological state of the ecosystem, in particular the phytoplankton biomass, species composition and eventually food web dynamics. NO_3^- & PO_4^{3-} concentrations of surface waters in six station samples were measured with spectrophotometer UV-VIS monthly from May - October 2011 & from June - October 2012. The data are converted on molar concentration ($\text{NO}_3\text{-N}$ & $\text{PO}_4\text{-P}$) to calculate N/P ratios. In 2011 there was both N & P co-limitation of phytoplankton growth, whereas in 2012 N/P ratios in all stations resulted N limitation. Comparing N:P ratios of year 2011 to 2012 in Durres Bay, results that in 2011 both N & P have been identified as the growth limiting nutrient, whereas in 2012 N. Comparing N:P ratio of both 2011 & 2012 years in Durres Bay to Southern Adriatic Sea, it resulted that in Durres Bay had N limitation, whereas in open waters both N & P co-limitation of primary production. But we have to emphasize that in Durres Bay the concentration of $\text{NO}_3\text{-N}$ & $\text{PO}_4\text{-P}$ are higher than permitted standards for surface waters. This distribution pattern is attributed to anthropogenic influence of the surface waters in high N & P loads, which makes the N/P ratio values differ easily passing from P to N limitation or N & P co-limitation in marine coastal waters of Southern Adriatic Sea, like Durres Bay.

KEYWORDS: N/P ratio, horizontal distribution, Southern Adriatic Sea, coastal waters.

INTRODUCTION

Since the observation of Redfield (Redfield, 1934, 1958) that marine phytoplankton contains a molecular C:N:P ratio of 106:16:1 (50:7:1 by weight), the use of elemental ratios has become widespread in marine and freshwater phytoplankton studies.

Ratio N/P (called "Redfield ratio") is an important indicator which nutrient restricts eutrophication. If the ratio N: P > 16, phosphorus (P) is a limiting factor for the growth of algae (Redfield *et al.*, 1963; Hodgkiss & Lu, 2004).

If N: P is between 14 and 16, are both N & P limiting factors (Koerselman & Meuleman, 1996) and if the ratio N: P < 14 indicates that nitrogen (N) is the limiting factor for the growth of algae (Redfield *et al.*, 1963; Hodgkiss & Lu, 2004).

The dominant nutrient limitation (of primary production) paradigms applied to this continuum for more than one-half a century, were that phosphorus (P) availability controlled primary production in freshwaters, while nitrogen (N) was the dominant limiting nutrient in the more saline downstream estuarine and coastal waters (Ryther & Dunstan 1971; Schindler 1975; Nixon 1995; Boesch *et al.*, 2001; Smith & Schindler 2009). Recent analyses of diverse nutrient limitation studies in both freshwater and marine ecosystems indicate that these paradigms may be "eroding" (Elser *et al.*, 2007; Lewis & Wurtsbaugh 2008; Sterner 2008; Conley *et al.*, 2009; Lewis *et al.*, 2011). Increasingly, incidences of N & P "co-limitation", i.e., the stimulation of primary production by the addition of N and P in combination, where N or P alone stimulate production far less, have been reported (Elser *et al.*, 2007; Lewis *et al.*, 2011). Concurrently, recent estuarine and coastal studies indicated that N&P and / or P limitation are

geographically widespread (Peeters & Peperzak 1990; Elmgren & Larsson 2001; Sylvan *et al.*, 2006; Paerl & Justić 2011; Laurent *et al.*, 2012; Paerl *et al.*, 2014).

The first aim of this study was to estimate limiting nutrient of phytoplankton primary production basing on N/P ratios in surface waters of Durres Bay. The second aim of this study was to understand the difference between coastal waters and surface open waters of Southern Adriatic Sea basing on previous study (Manca *et al.*, 2004). An another aim was to understand how are presented coastal waters and open waters according the recommended standard of NO₃-N & PO₄-P for surface waters in natural conditions (Chapman, 1996), as water eutrophication is mainly caused by excessive loading of nutrients into water bodies like N and P (Yang *et al.*, 2008).

MATERIALS AND METHODS

Nitrate NO₃⁻ & PO₄³⁻ concentrations of surface waters in six station samples were measured with spectrophotometer UV-VIS according APHA *et al.* (2005) and Grasshoff *et al.* (1999), monthly from May - October 2011 & from June - October 2012. Samples were monthly collected in the following stations: Golemi Beach (GB), Plepa Channel (PCh), Hekurudha Beach (HB), Ex-Fuel Quay in Marine Durrës Harbour (EFQ), Water Channel of Durrës City (WChDC) and Currila Beach (CB), at 1 meter depth from the water surface. Sea water (~ 2 l) was collected for NO₃⁻ & PO₄³⁻ and other investigation purposes. The plastic container was filled up, and preserved in an ice chest. Thereafter, the samples were taken to the laboratory for analyses.



Figure 1: Locations of sampling stations at Durrës Bay (from right to left Golemi Beach (GB), Plepa Channel (PCh), Hekurudha Beach (HB), Ex-Fuel Quay in Marine Durrës Harbour (EFQ), Water Channel of Durrës City (WChDC) and Currila Beach (CB). (Google Earth, 2014).

The data are converted not only on mg/L but also on molar concentration of NO₃-N & PO₄-P to calculate N/P ratios according ICES (International Council for the Exploration of the Sea; <http://ocean.ices.dk/Tools/UnitConversion.aspx>).

RESULTS AND DISCUSSIONS

3.1 Concentration of nitrogen as NO₃-N in all water sample stations

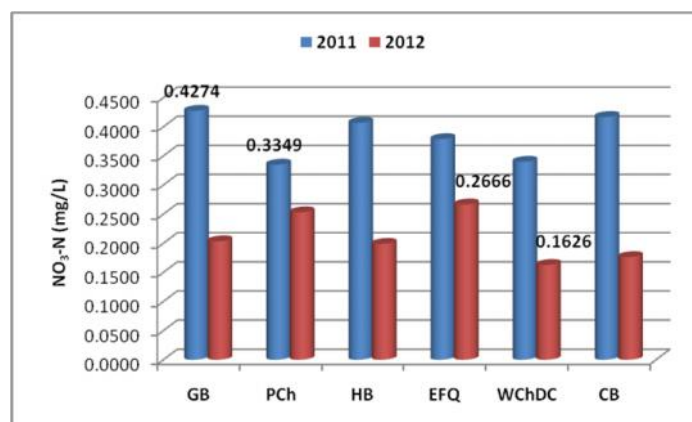
Surface water of nitrate (NO₃⁻) concentration for all stations for period May - October 2011 & from June - October 2012 range between 0.3 - 5.8 mg/L (Gjyli & Bacu, 2014; Gjyli *et al.*, 2013a, b; Gjyli & Kolutari, 2011).

In 2011 GB had the highest NO₃-N concentration (0.4274 mg/L) (Tab. 1, Fig. 2). Then there were ranked CB, HB, EFQ, WChDC, whereas the lowest concentration was in PCh (0.3349 mg/L).

Nitrogen values of 2011 are considered higher than the recommended standard of NO₃-N (0.1 mg/L) for surface waters in natural conditions (Chapman, 1996; Gjyli *et al.*, 2013b; Gjyli & Bacu, 2014).

Referring 2012, EFQ had the highest NO₃-N concentration (0.2666 mg/L). Then there were ranked PCh, GB, HB, CB whereas the lowest concentration was in WChDC (0.1626 mg/L).

82 Nitrogen values of 2012 are considered higher than the recommended standard of $\text{NO}_3\text{-N}$ (≤ 0.1 mg/L) for
 83 surface waters in natural conditions (Chapman, 1996; Gjyli *et al.*, 2013b; Gjyli & Bacu, 2014).
 84 $\text{NO}_3\text{-N}$ concentration of 2012 was 1.8 times smaller than 2011, informing that nitrogen loads of these
 85 coastal water bodies were reduced, improving situation of coastal waters.



86
 87 **Figure 2:** Nitrogen concentrations as $\text{NO}_3\text{-N}$ (mg/L) according sample stations: GB, ChP, HB, EFQ,
 88 WChDC and CB.

89 To study better the variability of nitrogen of coastal waters bodies, there are taken also references about
 90 surface open waters of Southern Adriatic Sea as Durres Bay is part of this sea.
 91 If we compare total average of $\text{NO}_3\text{-N}$ (0.305 mg/L) concentration for years 2011 & 2012 of Durres Bay
 92 to $\text{NO}_3\text{-N}$ (0.008 mg/L) of surface open waters in Southern Adriatic Sea ($\text{NO}_3^- = 0.57$ mmol/m³) (Manca
 93 *et al.*, 2004) converted according ICES (International Council for the Exploration of the Sea;
 94 <http://ocean.ices.dk/Tools/UnitConversion.aspx>), it resulted that the concentration of nitrogen in Durres
 95 Bay was 38 times higher than in Southern Adriatic Sea and 3 times higher than the recommended standard
 96 of nitrogen for surface waters in natural conditions. Unlike coastal waters, the surface open waters of
 97 Southern Adriatic Sea are approximately 13 times better than the recommended standard of nitrogen for
 98 surface waters in natural conditions (Tab. 1) (Chapman, 1996; Manca *et al.*, 2004).

99 3.2 Concentration of phosphorus as $\text{PO}_4\text{-P}$ in all water sample stations

100 Surface water phosphate (PO_4^{3-}) concentration for all stations for period May - October 2011 & from June
 101 - October 2012 range between 0.019 - 0.41 mg/L (Gjyli & Bacu, 2014; Gjyli *et al.*, 2013a, b; Gjyli &
 102 Kolitari, 2011).
 103 In 2011 PCh had the highest $\text{PO}_4\text{-P}$ concentration (0.0653 mg/L). Then there were ranked WChDC, EFQ,
 104 HB, CB, whereas the lowest concentration was in GB (0.0456 mg/L) (Tab. 1; Fig. 3).
 105 Phosphorus values of 2011 are considered higher than the recommended standard of $\text{PO}_4\text{-P}$ (0.005 - 0.020
 106 mg/l) for surface waters in natural conditions (Chapman, 1996; Gjyli *et al.*, 2013b; Gjyli & Bacu, 2014).
 107 Referring 2012, ChP had the highest $\text{PO}_4\text{-P}$ concentration (0.0913 mg/L). Then there were ranked
 108 WChDC, EFQ, GB, HB whereas the lowest concentration is CB (0.0724 mg/L).
 109 Phosphorus values of 2012 are considered higher than the recommended standard of $\text{PO}_4\text{-P}$ (0.005 - 0.020
 110 mg/L) for surface waters in natural conditions (Chapman, 1996; Gjyli *et al.*, 2013b; Gjyli & Bacu, 2014).
 111 $\text{PO}_4\text{-P}$ concentration of 2012 was nearly 1.5 times higher than 2011, reporting an increase in phosphorus
 112 loads of coastal water bodies. It is evident that wastewater discharges like sewage especially from PCh &
 113 WChDC channels may be increased the amount of phosphorus loads in coastal waters bodies.

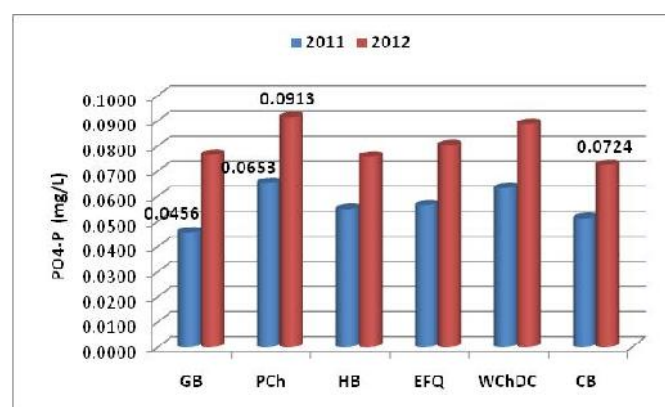


Figure 3: Phosphorus concentrations as $\text{PO}_4\text{-P}$ (mg/L) according sample stations: GB, ChP, HB, EFQ, WChDC and CB.

To study better the variability of phosphorus in coastal waters bodies, there are taken also references about surface open waters of Southern Adriatic Sea as Durres Bay is part of this sea.

If we compare total average of $\text{PO}_4\text{-P}$ (0.0673 mg/L) concentration for years 2011 & 2012 of Durres Bay to $\text{PO}_4\text{-P}$ (0.00124 mg/L) of surface open waters in Southern Adriatic Sea ($\text{PO}_4^{3-} = 0.04 \text{ mmol/m}^3$) (Manca *et al.*, 2004) converted according ICES (International Council for the Exploration of the Sea; <http://ocean.ices.dk/Tools/UnitConversion.aspx>), it resulted that the concentration of phosphorus in Durres Bay was 54 times higher than in Southern Adriatic Sea and 3.5 times higher than the highest level recommended standard of phosphorus for surface waters in natural conditions. Unlike coastal waters, the surface open waters of Southern Adriatic Sea are approximately 4 times better than the lowest level recommended standard of phosphorus for surface waters in natural conditions (Tab. 1) (Chapman, 1996; Manca *et al.*, 2004).

3.3. N/P ratio in estimating nutrient limitation in all water sample stations of Durres Bay

In 2011, if we compare the ratios of N/P (basing on molar concentration) according stations, it resulted that WChDC & PCh had lowest N/P ratios respectively 11.9 and 11.34 (Tab. 1, Fig. 4). So there was N limitation of primary production growth in WChDC & PCh. GB & CB had highest ratios N/P respectively 20.75 and 18. So there was P limitation of phytoplankton growth in these coastal water bodies, especially in GB. Whereas HB and EFQ have ratios N/P respectively 16.41 and 14.68, showing for co-limitation of N & P of primary production. So in 2011 the stations are divided in all three types of nutrient limitation of phytoplankton primary production.

As it resulted only in WChDC & PCh, nitrogen (N) was the dominant limiting nutrient as in the more saline downstream estuarine and coastal waters according results reported from Ryther & Dunstan (1971), Schindler (1975), Nixon (1995), Boesch *et al.* (2001), Smith & Schindler (2009). As the sewage waters were discharged permanently in WChDC & PCh, here there was brought a good quantity of nutrients loads in these stations. May be this the reason of lowest ratios N/P, favoring N limitation in WChDC & PCh.

The results in GB & CB and in HB & EFQ, respectively P limitation and co-limitation of N & P of primary production are in line with recent estuarine and coastal studies (Peeters & Peperzak, 1990; Elmgren & Larsson, 2001; Sylvan *et al.*, 2006; Paerl & Justić, 2011; Laurent *et al.*, 2012; Paerl *et al.*, 2014).

In 2011, the mean N/P for all stations was 15.32. So there was a N & P co-limitation of algae bloom referring hypertrophic level according *Chl a* (Håkanson *et al.*, 2007; Gjyli *et al.*, 2013a, b; Gjyli & Bacu, 2014).

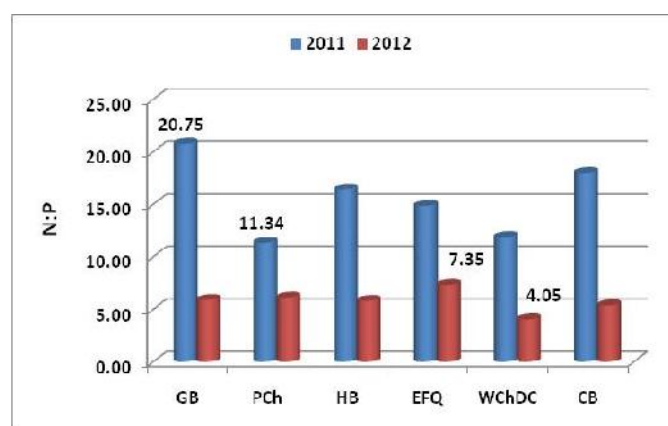


Figure 4: N: P ratio basing on molar concentration (mmol/L) according sample stations: GB, ChP, HB, EFQ, WChDC and CB.

Table 1: NO₃-N & PO₄-P (mg/L), converted in mmol/L and N:P ratios (mmol/L / mmol/L) according sample stations: GB, ChP, HB, EFQ, WChDC and CB in years 2011, 2012, 2011 & 2012, and the Southern Adriatic Sea (Manca *et al.*, 2004).

Stations		NO ₃ -N (mg/L)	NO ₃ -N (mmol/L or mM)	PO ₄ -P (mg/L)	PO ₄ -P (mmol/L or mM)	N:P (mM/mM)	Limiting Factor
2011	GB	0.4274	0.0305	0.0456	0.0015	20.75	P
	PCh	0.3349	0.0239	0.0653	0.0021	11.34	N
	HB	0.4067	0.0290	0.0548	0.0018	16.41	N & P
	EFQ	0.3787	0.0270	0.0564	0.0018	14.86	N & P
	WChDC	0.3398	0.0243	0.0632	0.0020	11.90	N
	CB	0.4168	0.0298	0.0512	0.0017	18.00	P
	Average	0.3840	0.0274	0.0554	0.0018	15.32	N & P
2012	GB	0.2033	0.0145	0.0763	0.0025	5.89	N
	PCh	0.2530	0.0181	0.0913	0.0029	6.13	N
	HB	0.1988	0.0142	0.0757	0.0024	5.81	N
	EFQ	0.2666	0.0190	0.0802	0.0026	7.35	N
	WChDC	0.1626	0.0116	0.0887	0.0029	4.05	N
	CB	0.1762	0.0126	0.0724	0.0023	5.38	N
	Average	0.2101	0.0150	0.0808	0.0026	5.75	N
2011 & 2012	Tot. Average	0.3050	0.0218	0.0673	0.0022	10.02	N
	South. Ad. Sea	0.0080	0.0006	0.0012	0.00004	14.23	N & P

Legend: Tot. Mean = Total mean, South. Ad. Sea = Southern Adriatic Sea

In 2012 ratios N/P in all stations resulted N limitation, as in the more saline downstream estuarine and coastal waters according results reported from Ryther & Dunstan (1971), Schindler (1975), Nixon (1995), Boesch *et al.* (2001), Smith & Schindler (2009). The highest N/P ratio value was in EFQ (7.35). Then there were ranked ChP, GB, HB, CB, whereas the lowest N/P ratio was WChDC (4.05).

This result is in line with the result reported from Billen *et al.* (1991), which report the N/P ratio in nutrient loads from urban areas tends to be quite low, further favoring N limitation in the coastal systems that receive such loads, especially it is evident in WChDC, where there is permanent discharge of wastewater including sewage.

If we compare the total mean N/P of 2011 to 2012, it is reported that this ratio is decreased significantly (from 15.32 to 5.75), passing from co-limitation of N & P of primary production, to limitation of N for algal growth. This may be as a result of reducing of NO₃-N concentration during 2012 and increasing of PO₄-P concentration.

To study better the variability of nutrient limitation in coastal waters bodies, there are taken also reference about surface open waters of Southern Adriatic Sea as Durres Bay is part of this sea.

Comparing total mean of N/P ratio (10.02) of 2011 & 2012 years in Durres Bay to N/P ratio (14.23) of surface open waters in Southern Adriatic Sea (Manca *et al.*, 2004), it is resulted that N had been identified

the limiting nutrient in Durres Bay. This result is in line with the result reported from Billen *et al.* (1991), where N/P ratio in nutrient loads from urban areas tends to favoring N limitation in the coastal systems that receive such loads.

Whereas in surface waters of the Southern Adriatic Sea there is co-limitation of N & P (Manca *et al.*, 2004). The offshore central and southern Adriatic, however, show clearly oligotrophic characteristics (Vilicic *et al.*, 1989) and the primary production cycle is regulated by the nutrient supply to the euphotic zone from the deep part of the water column by different upwelling and mixing processes (Zavatarelli *et al.*, 2000). In oligotrophic environments where ambient nutrient concentrations are extremely low, the paradigm of a single nutrient limiting phytoplankton may not always be valid, and the autotrophic community can be co-limited by multiple nutrients (Arrigo, 2005). Similarly results like Southern Adriatic Sea, there are reported in the Eastern Mediterranean (Thingstad *et al.*, 2005) and the oligotrophic Central North Atlantic (Mills *et al.*, 2008), where phytoplankton community was shown to be N & P co-limited.

CONCLUSIONS

GB had the highest NO₃-N concentration in 2011, whereas the lowest concentration was in WChDC in 2012. PCh had the highest PO₄-P concentration in 2012, whereas the lowest concentration was GB in 2011. In 2011 there was both N & P co-limitation of phytoplankton growth. In 2012 N/P ratios in all stations resulted N limitation, where the lowest N/P ratio it was in WChDC, as wastewaters like sewage were discharged frequently. These discharges favor a quite low N/P ratio and N limitation in coastal systems that receive such loads.

Comparing N:P ratio of both 2011 & 2012 years in Durres Bay to Southern Adriatic Sea, it resulted that in Durres Bay had N limitation, whereas in open waters both N & P co-limitation of primary production. But we have to emphasize that in Durres Bay the concentration of NO₃-N & PO₄-P were higher than permitted standards for surface waters, showing also from *Chl a* levels hypertrophic characteristics, while in the Southern Adriatic Sea these concentrations had been presented within standards, show clearly oligotrophic characteristics. This distribution pattern is attributed to anthropogenic influence of the surface waters in high N & P loads, which makes the N/P ratio values differ easily passing from N limitation to P limitation or both N & P co-limitation in marine coastal waters of Southern Adriatic Sea, like Durres Bay.

REFERENCES

- APHA., AWWA., WEF. 2005: Standard Methods for the Examination of Water and Wastewater, 21st ed. American Public Health Association, Washington D.C.
- Arrigo, K. R. 2005: Marine microorganisms and global nutrient cycles. *Nature* 437: 349–355.
- Billen, G.; Lancelot C.; Meybeck, M. 1991: N, P, and Si retention along the aquatic continuum from land to ocean, p. 19–44. In R. F. C. Mantoura, J. M. Martin, and R. Wollast [eds.], *Ocean margin process in global change*, Wiley.
- Boesch, D. F.; Burreson, E.; Dennison, W.; Houde, E.; Kemp, M.; Kennedy, V.; Newell, R.; Paynter, K.; Orth, R.; Ulanowicz, W. 2001: Factors in the decline of coastal ecosystems. *Science* 293: 629–638.
- Chapman, D. 1996: *Water Quality Assessments - A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring*, Second Edition, Published on behalf of UNESCO, WHO, and UNEP. Chapman and Hall, London.
- Conley, D. J.; Paerl, H. W.; Howarth, R. W.; Boesch, D. F.; Seitzinger, S. P.; Havens, K. E.; Lancelot, C.; Likens, G. E. 2009: Controlling eutrophication: nitrogen and phosphorus. *Science* 323: 1014–1015.
- Elmgren, R. & Larsson, U. 2001: Nitrogen and the Baltic Sea: managing nitrogen in relation to phosphorus. *The Scientific World, Special Edition (S2)*: 371–377. Balkema Publishers.
- Elser, J. J., Bracken, M. E. S.; Cleland, E. E.; Gruner, D. S.; Harpole, W. S.; Hillebrand, H.; Bgai, J. T.; Seabloom, E. W.; Shurin, J. B.; Smith, J. E. 2007: Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecology Letters* 10: 1124–1134.

- 219 Gjyli, L. & Bacu, A. (2014). Possible correlation between the diversity of 16-23S rDNA-ITS diversity of
220 *Synechococcus* populations and quality of the waters at Durres Bay. *Journal of Natural and Technical*
221 *Sciences, (JNTS)*, Vol. XIX (1): 77-90, ISSN: 2074-0867.
- 222 Gjyli, L. & Kolutari, J. 2011: Variation of Phytoplankton Biomass as Chlorophyll a in coastal waters of
223 Durrës. Proceedings of International Conference Biotechnological Development, 20-21 November 2011,
224 Tirana, Albanian. BSHN (UT), 2011, Special: 247-255. ISSN: 224-1779.
- 225 Gjyli, L.; Bacu, A.; Kolutari, J.; Gjyli, S. 2013a: Primarily results of phytoplankton and variation to
226 environmental factors in Durrës's Bay coastal waters (Albania). *Journal of Microbiology, Biotechnology*
227 *and Food Sciences, (JMBFS)*, 3 (2), 132-136. ISSN: 1338-5178.
- 228 Gjyli, L.; Bacu, A.; Kolutari, J.; Gjyli, S. 2013b: Dynamics of picophytoplankton and presence of
229 cyanobacteria *Synechococcus* in coastal waters of Durrës Bay (Albania). *Albanian Journal of Agriculture*
230 *Sciences (AJAS)*.12(4),585-592.ISSN: 2218-2020.
- 231 Grasshoff, K.; Kremling, M.; Ehrhardt, M. 1999: *Methods of Seawater Analysis*. Third Completely
232 Revised and Extended Edition, Verlag Chemie, Weinheim, Germany.
- 233 Håkanson, L.; Bryhn, A. C.; Blenckner T. 2007: Operational Effect Variables and Functional Ecosystem
234 Classifications - a Review on Empirical Models for Aquatic Systems along a Salinity Gradient.
235 *International Review of Hydrobiology*, 92: 326-357.
- 236 Hodgkiss, I. J. & Lu S. H. 2004: The effects of nutrients and their ratios on phytoplankton abundance in
237 Junk Bay, Hong Kong. *Hydrobiologia*, 512 (1-3): 215-229.
- 238 International Council for the Exploration of the Sea; <http://ocean.ices.dk/Tools/UnitConversion.aspx>)
- 239 Koerselman, W. & Meuleman, A. F. M. 1996: The vegetation N:P ratio: a new tool to detect the nature of
240 nutrient limitation. *Journal of applied Ecology*, 33: 1441-1450.
- 241 Laurent, A.; Fennel, K.; Hu, J.; Hetland, R. 2012: Simulating the effects of phosphorus limitation in the
242 Mississippi and Atchafalaya River plumes. *Biogeosciences Discussion*9: 5625–5657.
- 243 Lewis, Jr. W.M. & Wurtsbaugh. W.A. 2008: Control of lacustrine phytoplankton by nutrients: erosion of
244 the phosphorus paradigm. *Internationale Revue gesamten Hydrobiologie*93: 446–465.
- 245 Lewis, W.M.; Wurtsbaugh, W.A.; Paerl, H.W. 2011: Rationale for control of anthropogenic nitrogen and
246 phosphorus in inland waters. *Environmental Science & Technology*45: 10030–10035.
- 247 Manca, B.; Burca, M.; Giorgetti, A.; Coatanoan, C.; Garcia, M. J.; Iona A. 2004: Physical andbiochemical
248 averaged vertical profiles in the Mediterranean regions: an important tool to trace the climatology of water
249 masses and to validate incoming data from operational oceanography. *Journal of Marine Systems*, 48: 83–
250 116.
- 251 Mills, M. M.; Moore, C. M.; Langlois, R.; Milne, A.; Achterberg, E.; Nachtigall, K.; Lochte, K.; Geider,
252 R. J.; La Roche J. 2008: Nitrogen and phosphorus co-limitation of bacterial productivity and growth in the
253 oligotrophic subtropical North Atlantic. *Limnol. Oceanogr.*,53(2) , 824–834.
- 254 Nixon, S. W. 1995: Coastal marine eutrophication: a definition, social causes, and future
255 concerns. *Ophelia*41: 199–219.
- 256 Paerl, H. W. & Justić, D. 2011: Primary producers: phytoplankton ecology and trophic dynamics in
257 coastal waters. In *Treatise on estuarine and coastal science*, vol. 6, ed. E. Wolanski and D.S. McLusky, 23–
258 42. Waltham: Academic.
- 259 Paerl, H.W.; Hall, N. S; Peierls, B. L.; Rossignol, K. L. 2014: Evolving Paradigms and Challenges in
260 Estuarine and Coastal Eutrophication Dynamics in a Culturally and Climatically Stressed World. *Estuaries*
261 *and Coasts* 37:243–258. Coastal and Estuarine Research Federation; DOI 10.1007/s12237-014-9773-x
- 262 Peeters, J. C. H. & Peperzak, L. 1990: Nutrient limitation in the North Sea: a bioassay
263 approach. *Netherlands Journal of Sea Research* 26: 61–73.
- 264 Redfield, A. C. 1934: On the proportions of organic derivatives in sea water and their relation to the
265 composition of plankton. *Liverpool University Press, Liverpool*, p. 176–192.
- 266 Redfield, A. C. 1958: The biological control of chemical factors in the environment. *Am Sci* 46:205–221.
- 267 Redfield, A. C.; Ketchum, B. H.; Richards, F. A. 1963: The Influence of Organisms on the Composition
268 of Seawater. In: Hill, M.N. (Ed.), *The Sea*. Volume 2. Wiley-Interscience, New York, p. 26-77.

- 269 Ryther, J., and W. Dunstan. 1971. Nitrogen, phosphorus, and eutrophication in the coastal marine
270 environment. *Science* 171: 1008–1013.
- 271 Schindler, D. W. 1975: Whole-lake eutrophication experiments with phosphorus, nitrogen and
272 carbon. *Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie* 19:
273 3221–3231.
- 274 Smith, V.H.& Schindler, D.W. 2009: Eutrophication science: where do we go from here? *Trends in*
275 *Ecology and Evolution* 24(4): 201–207.
- 276 Sterner, R. 2008: On the phosphorus limitation paradigm for lakes. *International Review of*
277 *Hydrobiology* 93: 433–445.
- 278 Sylvan, J. B., Dortch, Q.; Nelson, D. M.; MaierBrown, A.F.; Morrison, W.; Ammerman, J.W. 2006:
279 Phosphorus limits phytoplankton growth on the Louisiana shelf during the period of hypoxia
280 formation. *Environmental Science & Technology* 40: 7548–7553.
- 281 Thingstad, T. F.; Hangroström, Á.; Rassoulzadegan, F. 2005: Nature of phosphorus limitation in the
282 ultraoligotrophic eastern Mediterranean. *Science* 309: 1068–1071.
- 283 Vilicic, D.; Vucak, Z.; Skrivanic, A.; Grzetic, Z. 1989: Phytoplankton blooms in the oligotrophic open
284 south Adriatic waters, *Mar. Chem.*, 28, 89–107.
- 285 Yang, X.; Wu, X.; Hao, H.; He, Z. 2008: Mechanisms and assessment of water eutrophication (review). *J.*
286 *Zhejiang Univ. Sci.* 9(3):197-209.
- 287 Zavatarelli, M.; Baretta, J. W.; Baretta-Bekker, J. G.; Pinardi, N. 2000: The dynamics of the Adriatic Sea
288 ecosystem: An idealized model study, *Deep Sea Res., Part I*, 47, 937–970.