OCEANOLOGICA ACTA 1986 - VOL. 9 - N° 3

Nutrient uptake and regeneration ratios in the Red Sea with reference to the nutrient budgets

Red Sea
Oxidative ratios
Plankton composition
Nutrient budgets
Nitrogen fixation

Mer Rouge
Rapports d'oxydation
Composition du plancton
Bilan de sels nutritifs
Fixation de l'azote

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Received 4/7/85, in revised form 6/1/86, accepted 6/2/86,

ABSTRACT

The relationships between apparent oxygen utilization and inorganic micronutrients have been studied on the basis of extensive observations in the Red Sea. The ratios obtained are $-\Delta AOU : \Delta SiO_4 : \Delta NO_3 : \Delta PO_4 = 230{:}17{:}21{:}1$ (by moles). The departures of the observed ratios from the corresponding open-ocean values are presumably caused by the prevailing low levels of nutrients and a relative deficiency in phosphate as compared to nitrate in the Red Sea. The composition of organic matter within the Red Sea, however, appears to be rather uniform, and the atomic ratios between carbon, nitrogen and phosphorus in the biomass are deduced to be 188:21:1. Increased input of nutrients associated with subsurface inflow of nutrient-rich waters from the Gulf of Aden to the Red Sea does not seem by itself to make up the apparent deficits in all nutrients, as suggested by earlier workers. Due to the high $\Delta NO_3 : \Delta PO_4$ ratio observed in the Red Sea, more nitrate relative to phosphate appears to escape the Red Sea with the outflowing high-salinity water than the quantity added by the inflowing current. Assuming that the conservation of phosphate is maintained by increased inputs from the Gulf of Aden in late summer, the excess flux of nitrate out of the Red Sea is estimated as 0.74×10^6 tons of nitrogen yr^{-1}. It is suggested that this excess of the combined nitrogen results from nitrogen fixation, presumably by *Trichodesmium* spp. It is estimated that nitrogen fixation may contribute up to 6% of the total primary production in the Red Sea.

Oceanol. Acta, 1986, **9**, 3, 271-275.

RÉSUMÉ

Taux d'absorption et de régénération des sels nutritifs dans la Mer Rouge en relation avec leurs bilans

A partir d'observations extensives en Mer Rouge, nous avons étudié les relations entre l'utilisation apparente d'oxygène (UAO) et les sels nutritifs inorganiques. Les rapports obtenus sont : $\Delta UAO : \Delta SiO_4 : \Delta NO_3 : \Delta PO_4 = 230{:}17{:}21{:}1$ (en moles).

Les écarts entre les taux observés et les valeurs correspondantes dans l'océan au large sont probablement dus aux faibles teneurs en sels minéraux et à un déficit relatif en phosphate par rapport au nitrate en Mer Rouge. La composition de la matière organique paraît cependant assez uniforme et les rapports atomiques entre le carbone, l'azote et le phosphore dans la biomasse sont 188:21:1. Un apport plus important de sels minéraux associé à un flux sous-jacent d'eaux riches en sels nutritifs dirigé du Golfe d'Aden vers la Mer Rouge ne semble pas suffisant pour combler les déficits apparents des teneurs de tous les sels minéraux, comme l'ont suggéré d'autres auteurs. Le rapport élevé $\Delta NO_3 : \Delta PO_4$ observé en Mer Rouge, indique que le flux des eaux salées sortant de la Mer Rouge est plus chargé en nitrate et, dans une moindre part, en phosphate que le flux des eaux entrantes. Si la conservation du phosphate est maintenue par les apports élevés en provenance du Golfe d'Aden à la fin de l'été, le flux de nitrate en excès qui sort de la Mer Rouge est de l'ordre de $0,74 \times 10^6$ tonnes

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d'azote par an. Nous suggérons que cet excès d'azote sous forme combinée est dû à une fixation de l'azote, probablement par *Trichodesmium* spp.; la fixation d'azote peut contribuer jusqu'à 6% de la production primaire totale de la Mer Rouge.

Oceanol. Acta, 1986, **9**, 3, 271-275.

INTRODUCTION

Balancing inputs and outputs of inorganic combined nitrogen, phosphorus and silicon to and from the Red Sea through the Strait of Bab-el-Mandeb has posed certain problems. The high-salinity water flowing out of the Red Sea is richer in nutrients than the inflowing current, and so the quantity of nutrient salts escaping the Red Sea appears to exceed that added to the region by the inflowing current (Grasshoff, 1969; Morcos, 1970). Since the Red Sea does not receive any river runoff, Grasshoff suggested that the deficits could be made up by intermittent flow of nutrient-rich water below the thermocline from the Gulf of Aden to the Red Sea. Poisson *et al.* (1984), however, pointed out that Grasshoff's results are based on observations during winter when the circulation in the Red Sea and the Strait of Bab-el-Mandeb is vastly different from that prevailing during the summer. During the latter period, the inflowing current, rich in nutrients, is located at mid-depth, embedded between the two outflowing currents at the surface and over the sill. As the positive component of water exchange through the Strait is also maximal in late summer, Poisson *et al.* suggested that the supply of nutrients to the Red Sea should be at maximum during late summer, and it may account for the apparent anomalies in the nutrient budgets.

However, these authors have ignored an important feature: Grasshoff's (1969) results indicate different nitrogen versus phosphorus relationships in the Red Sea and the Gulf of Aden. Hence an increase in input from the Gulf of Aden below the thermocline would not alone result in satisfactory mass balance of all nutrient salts. It is the purpose of the present study to establish the relationships between oxygen consumption and nutrient regeneration in the Red Sea and to examine the significance of the different uptake and regeneration ratios observed in the region on the nutrient budgets.

MATERIAL AND METHODS

The present study was undertaken during the 3rd trial cruise of R. V. *Sagar Kanya* in the Red Sea in May 1983. Data from some stations in the inner Gulf of Aden occupied by F. S. *Meteor* during the International Indian Ocean Expedition (IIOE) (Dietrich *et al.*, 1966) have also been utilized. Station locations are given in Figure 1.

Water samples from standard depths covering the entire water column were collected in the Red Sea with CTD rosettes and TPN water samplers fitted with reversing thermometers. These were analysed on board ship shortly after collection for phosphate-phosphorus, nitrate-nitrogen, silicate-silicon, dissolved oxygen and salinity. A Skalar 6-Channel analyser 5100/1 was used for the estimation of nutrients following standard procedures as described in the analytical manual provided by Skalar Analytical, the Netherlands. The analyser was initially operated in the "peak-detection mode" using the auto-sampler. While this mode gave excellent and highly reproducible results for nitrate and silicate, intermediate peaks, presumably arising because of differences in salinities of samples and wash water, disturbed the phosphate recorder graphs, making the phosphate data rather suspect. The system was, therefore, modified to work in the "steady-state mode" by manually feeding the samples for 4 minutes each, starting from station 52. The reproducibility of phosphate determinations improved considerably after this modification and the "steady-state mode" was followed during rest of the cruise.

Dissolved oxygen was estimated by the modified Winkler procedure (Carpenter, 1965) and salinity was measured with an Autosal model 8400 salinometer.

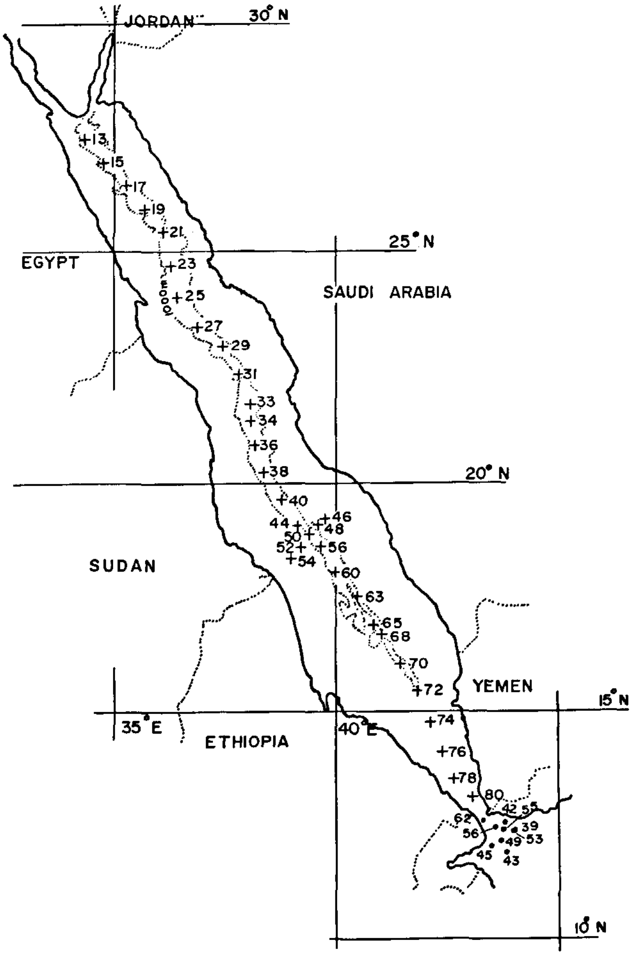

Figure 1

Location of stations (crosses for Sagar Kanya; *circles for* Meteor).

RESULTS AND DISCUSSION

The oxygen saturation values computed from the equation of Weiss (1970) have been combined with the observed data to obtain the apparent oxygen utilization (AOU). The relationships between AOU and nutrients (nitrate, phosphate and silicate) were determined by two-way linear regression analysis. As stated earlier, the "peak-detection mode" did not yield very reliable phosphate data, and although these results were subsequently corrected, they have not been considered here. Some surface values associated with negative values of AOU have also been excluded; all other values have been considered while determining the oxidative ratios. The ratios obtained are presented in the Table. Previously published results from the Arabian Sea, together with the values predicted by the Redfield-Ketchum-Richards (RKR) model, are also given for comparison. Scatter diagrams showing correlations between AOU and PO_4; AOU and NO_3; and AOU and SiO_4 are presented in Figures 2-4.

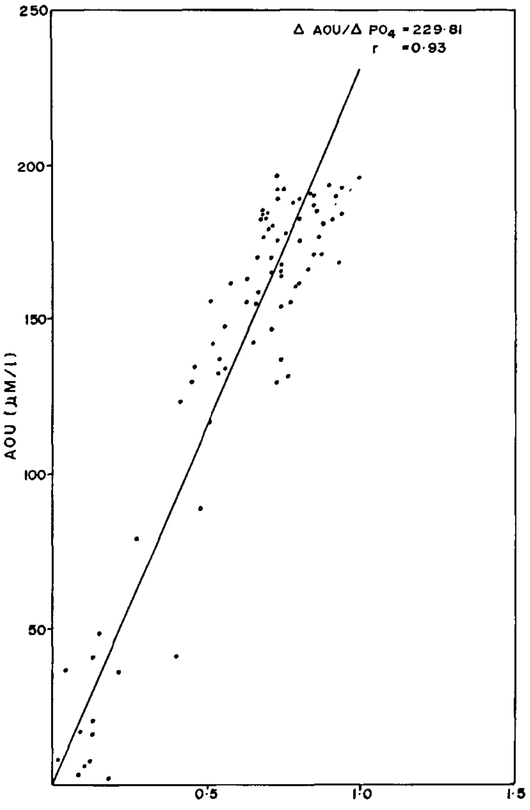

Figure 2

Correlation between apparent oxygen utilization (AOU) and phosphate-phosphorus for Sagar Kanya *stations* 52-80.

Table

Oxidative ratios (by moles) in the Red Sea (present study) and in the Arabian Sea (Sen Gupta, Naqvi, 1984) as compared to the theoretical values for the open ocean (Redfield et al., 1963).

Ratio	Red Sea	Arabian Sea	Theoretical value
$\Delta AOU/\Delta PO_4$	229.8	127-140	138
$\Delta AOU/\Delta NO_3$	10.85	7.95-8.75	8.62
$\Delta AOU/\Delta SiO_4$	13.52	3.5	–

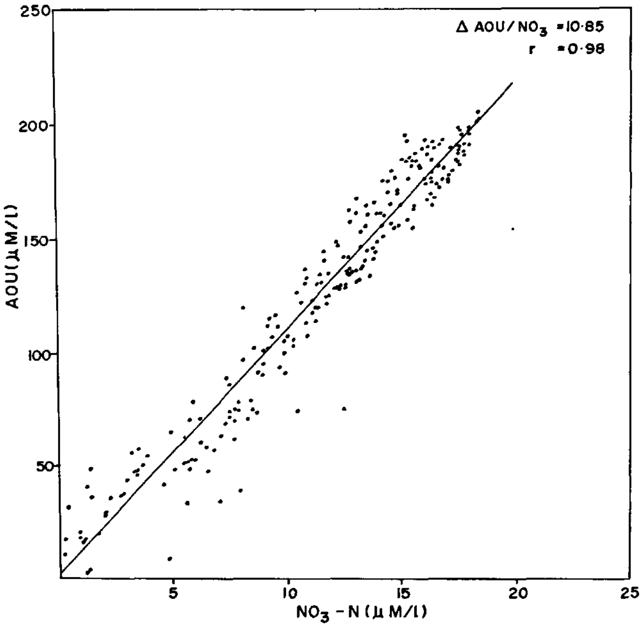

Figure 3

Correlation between AOU and nitrate-nitrogen for Sagar Kanya *stations* 13-80.

It may, however, be added here that the regression between AOU and total inorganic nutrient concentrations often does not yield correct oxidative ratios. As pointed out by Redfield *et al.* and Pytkowicz (1971), only the nutrients of "oxidative" origin *i.e.* those regenerated from the organic matter after the formation of the water mass, should vary linearly with AOU. Presence of appreciable and variable amounts of "preformed" nutrients will distort the relationships, resulting in departures of the slopes from true values. Corrections for preformed nutrients could be made using nutrient-potential temperature relationships for surface waters (Chen *et al.*, 1982), but such corrections may involve considerable uncertainties. However, if the preformed nutrients do not vary greatly with depth, their concentrations do not have to be accounted for; relatively uniform concentrations of preformed nutrients will only determine the intercepts of AOU-nutrients regression lines with little effect on the slopes. Fortunately, such appears to be the case in the Red Sea where waters below the thermocline have remarkably uniform thermohaline characteristics. These are largely of the same origin, having been formed in the northern Red Sea during winter, except the hot brines and limited inflow from the Gulf of Aden. Therefore, the error introduced by calculating the oxidative ratios from regression between AOU and total nutrient concentrations will probably be negligible. This is especially true for nitrate because surface nitrate concentrations are very often close to zero in both the Red Sea and the Gulf of Aden.

It is evident from the Table that while the oxidative ratios observed in the Arabian Sea are close to the values predicted from the RKR model, those observed in the Red Sea are widely different. Grasshoff (1969) also observed high oxidative ratios, but his results ($\Delta AOU/\Delta PO_4 = 196$ and $\Delta NO_3/\Delta PO_4 = 20$, giving $\Delta AOU/\Delta NO_3 = 9.8$, by moles) based on data from only

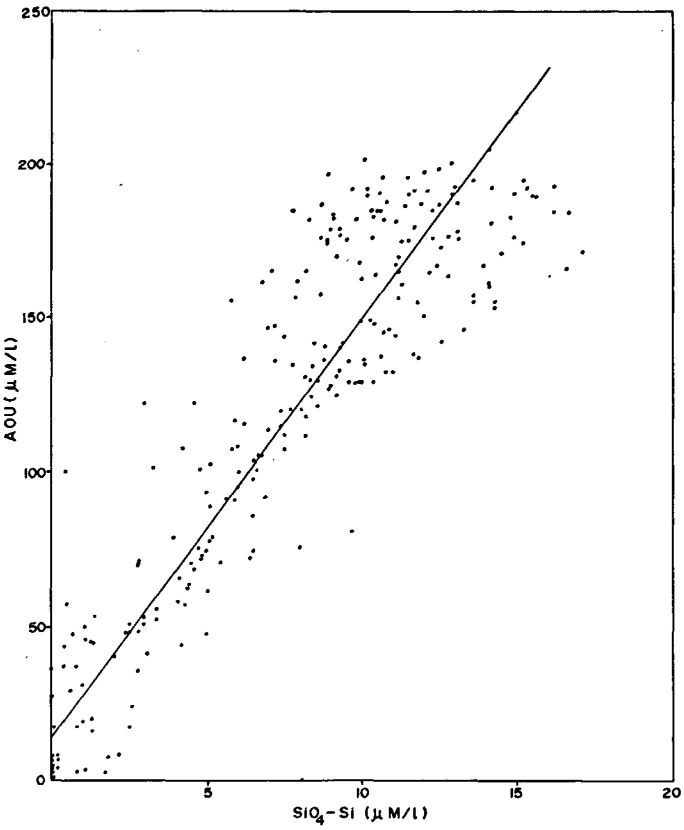

Figure 4

Correlation between AOU and silicate-silicon for Sagar Kanya *stations* 13-80.

five stations in the southern Red Sea, are lower than observed in the present study. Although the ratios observed in the Red Sea differ widely from the oceanic averages, they do not vary greatly within the Red Sea itself, as reflected by small scatters observed in Figures 2-4. This means that the concept of a statistical uniformity in the composition of biomass observed in the oceans (Redfield *et al.*, 1963) holds good within the Red Sea as well, enabling us to deduce the relative proportions of carbon, nitrogen and phosphorus in the biomass. Assuming that the $\Delta NO_3/\Delta PO_4$ ratio observed in the water (21, by atoms) reflects the N:P ratio in the plankton, and following the procedure of Sen Gupta and Koroleff (1973) the atomic ratios between carbon, nitrogen and phosphorus in the biomass have been deduced to be 188:21:1, as compared to the Redfield ratios C:N:P = 106:16:1 (Fleming, 1940). Thus the biomass in the Red Sea appears to be characterized by lower phosphorus to carbon, and nitrogen to carbon ratios than the "average" marine organic matter. Of the two elements phosphorus and nitrogen, the deficiency in phosphorus appears to be more pronounced in both the water and the biomass.

The $\Delta NO_3/\Delta PO_4$ ratio in seawater observed in the present study (21) is close to the value (20) reported by Grasshoff (1969). However, it is much higher than the corresponding value for the waters other than the Red Sea outflow in the inner Gulf of Aden; the relationship between nitrate and phosphate in the latter region, determined from the *Meteor* data (stations 39-62, Fig. 1) is represented by the equation:

$$NO_3 = 14.37\,PO_4 - 4.23. \qquad (1)$$

The excellent correlation (r = 0.99) indicates that the above relationship applies equally well to the surface and subsurface layers in the inner Gulf of Aden from which the inflowing current is derived. Also, the relationship is remarkably consistent with the results of Naqvi *et al.* (1982) based on summer observations in the Arabian Sea. Consequently, it seems reasonable to assume that the nitrate-phosphate relationship as given by equation (1) would undergo little seasonal changes.

Grasshoff (1969) estimated the phosphate concentration in the outflowing current at the Strait of Bab-el-Mandeb to be 0.8 µM dm^{-3}. Entering this value in equation (1) we get NO_3 as 7.23 as compared to 12.0, the nitrate concentration actually observed in the outflowing water (Grasshoff, 1969). If the apparent deficits in nutrients in the Red Sea are made up only by the subsurface inflow of nutrient-rich waters either intermittently, as suggested by Grasshoff, or largely in summer, as evident from the results of Poisson *et al.*, the relative proportions of nitrate and phosphate should be the same in both the inflowing and outflowing currents. However, such does not appear to be the case; when normalized to phosphate, more nitrate appears to escape the Red Sea than the quantity added by the inflowing current from the Gulf of Aden.

Although Grasshoff considered the re-solution of phosphate from phosphorite-phosphates in the sediments as a possible contributing factor for maintaining phosphorus budget, such solution, if at all, is probably small in magnitude. It is much more likely that the phosphate flux out of the Red Sea is more or less balanced by increased inputs from the Gulf of Aden in late summer. Assuming this to be the case, the excess nitrate transported out of the Red Sea with the high-salinity water mass could be estimated from equation (1), concentrations of nutrients reported by Grasshoff (1969) in the outflowing current, and Morcos' (1970) estimates for the volumes of inflowing and outflowing waters (0.358 and 0.33 × 10^6 m^3 s^{-1}, respectively). This works out to be 0.74 × 10^{12} gN yr^{-1}.

Additional sources of inorganic combined nitrogen must, therefore, exist in the Red Sea to account for the anomaly in the nitrate budget. The most obvious but hitherto ignored process that could supply the nitrogen required for the mass balance is the nitrogen fixation by organisms. There are numerous published reports on the occurrence of massive blooms of the blue green *Trichodesmium* spp. in the Red Sea both during the summer and winter (Carpenter, 1983 and the references cited therein). Indeed, it was from this region that *Trichodesmium* was first described by Ehrenberg (1830). Blooms of *T. erythraea* were abundant in this sea in the 1800s and were thought to be the origin of its red coloration (Carter, 1863 as cited by Carpenter, 1983). Significantly, it is believed that the Red Sea was so named by the ancient sailors because of this coloration (Brongersma-Sanders, 1957;

Wood, 1965; Devassy *et al.*, 1978). There are, however, no quantitative data on the distribution and density of this genus with the exception of the work of Kimor and Golandsky (1977) in the Gulf of Aqaba. The ability of *Trichodesmium* to fix molecular nitrogen is well established (*e.g.*, Dugdale *et al.*, 1964; Goering *et al.*, 1966). Field as well as experimental studies have demonstrated that large quantities of phosphate and nitrate are released by *Trichodesmium* blooms in the Arabian Sea (Qasim, 1970; Devassy *et al.*, 1978). We feel that this process may quantitatively supply the "excess" nitrogen to the Red Sea, resulting in high $\Delta NO_3/\Delta PO_4$ ratio in the water and high N:P ratio in the plankton. If this is true then the role of nitrogen fixation versus the overall primary production in the Red Sea could be assessed. Kondratieva and Finenko (1971, as cited by Romankevich, 1984) estimated the total production of photosynthetically derived carbon in the Red Sea as 90×10^6 tons yr^{-1}. This will correspond to the annual utilization of 11.7×10^6 tons of inorganic nitrogen, considering that the atomic ratio between carbon and nitrogen in the plankton is 188:21, as deduced earlier. If approximately 0.74×10^6 tons of molecular nitrogen is "fixed" annually in the Red Sea, it follows that the process may contribute as much as 6% to the total primary production in the region.

The rate of nitrogen fixation deduced above from the anomaly in nitrate budget in the Red Sea is about 3% of the global estimate for the rate of marine nitrogen fixation (25×10^{12} gN yr^{-1}; Codispoti, Christensen, 1985). Considering that the area of the Red Sea is only about 0.12% of the total area of the oceans including the adjacent seas (Sverdrup *et al.*, 1942), it appears that the rate of marine nitrogen fixation could be severely underestimated so far; this may in part be responsible for an imbalance in the budgets of marine combined nitrogen (*see* Codispoti, Christensen, 1985). It should, however, be conceded that our estimate is based on deductions. Elemental analysis of the plankton, quantitative studies on the distribution of *Trichodesmium* and direct measurements of the rates of nitrogen fixation are required to confirm the conclusions reached in the present study.

Acknowledgements

The authors express their gratitude to Drs. S. Z. Qasim, H. N. Siddiquie, T. S. S. Rao, R. Sen Gupta and the late C. V. G. Reddy for providing them with the opportunity of participating in the cruise. Critical reviews by the referee Dr. Selim Morcos and the two other referees selected by the journal helped considerably in enriching the contents of this paper.

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