Long term changes of nutrients in the Northern Gulf of Aqaba (Elat), Red Sea

The consequences of mariculture on the ecosystem of the Northern Gulf of Eilat

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DCPE (ISF), REEFLUX (BSF), RSP (BMBF), RSMPP (US-AID), FAST TRACK (US-AID)
\[ \tau \approx 2 \text{ y} \]

\[ \tau \approx 50 \text{ y} \]
Depth of the mixed layer in station A1. The 1975-1977 data was estimated only from the Nansen bottles hydrocasts, therefore their accuracy is not more than ±50 m. The blue ellipses with the downward pointing arrows represent bottle hydrocasts and/or CTD profiles where the thermocline was not encountered, indicating that the mixed layer was deeper than the maximum depth for that particular profile.
The Nature Reserve Reef, Elat
Two profiles cross NRR
24 Feb., 1998

Chlorophyll $\alpha$ ($\mu g l^{-1}$)

Temperature

Reef Slope - Open
Reef
Fore
Lagoon

Distance from shore (m)

Temperature (°C)
Phytoplankton

Dissolved Nutrients

Zooplankton
Summer Gradient Productivity

Iluz, 1999
Figure 21: Nitrogen and phosphorus budgets of the fish farms for the last decade (data provided by Dr. Yuval Cohen, IOLR). The total emitted N and P are indicated in the graphs assuming that the present values are equal to the 2002 values. The integrated total N (assumed to be available for oxidation in the marine environment) and dissolved P are indicated above the graphs. a- Nitrogen emission rates. b- Phosphorus emission rates. c- The $\frac{N_{\text{emitted}}}{N_{\text{total fish feed}}}$ (nitrogen emitted to nitrogen in the fish feed) and $\frac{P_{\text{emitted}}}{P_{\text{total fish feed}}}$ (phosphate emitted to phosphate in the fish feed) ratios that are the solid + dissolved fractions of N and P emitted into the marine environment by the fish farms.

Equals to 2% - 5% of the annual N flux through the Straits of Tiran
Location map of hydrographic stations. **a-** DCPE project stations; **b-** Meteor stations (1999); **c-** Northern stations (1988-present) and coastal sampling stations.
Nitrate concentrations in the northern Gulf of Aqaba. a- East-west and north-south contour profile during 16.5.2000 (adopted from David, 2002). b- Vertical profiles measured at stations along a north-south line on 10.8.2003 (see Fig. 1 for station location). c- Vertical profiles measured at stations along a north-south line (FF, OS, A1, B) and east-west line (E1, W1) on 22.2.2004. Note that during the last four years (represent by the data in this figure) no nutrient gradients were observed from the northern tip to station B1, some 20 km southward of the North Beach along the main axis of the Gulf. This indicates homogenous horizontal distribution within the northern gyre of the Gulf of Aqaba.
Nitrate ($\mu\text{mol L}^{-1}$)

Phosphate ($\mu\text{mol L}^{-1}$)

$N:P \approx 12$

$N:P \approx 18$

Change in plankton community?
\[ y = 18.11x - 0.06 \], \( R^2 = 0.99 \)

\[ y = 21.37x - 0.68 \], \( R^2 = 0.95 \)

Sigma (\( \mu \text{mol L}^{-1} \)) vs. P (\( \mu \text{mol L}^{-1} \))

- 06/02/2000
- 13/03/2000
- Linear (06/02/2000)
Concentrations
Dissolved Oxygen (µmol·L⁻¹) AOU (µmol·L⁻¹)

Depth (m) 0 700 1975 1980 1990 2000 2005

Oxygen

ΔO₂ ≈ -10 µmol·L⁻¹
Redfield ratios=
\[ \Delta O_2: \Delta N: \Delta P = -138: 16: 1 \]

If \( \Delta O_2 \approx -10 \, \mu \text{mol} \cdot \text{L}^{-1} \) then:

\[ \Delta N = -10 \cdot 16 / (-138) = 1.2 \, \mu \text{mol} \cdot \text{L}^{-1} \]
\[ \Delta P = -10 \cdot 1 / (-138) = 0.07 \, \mu \text{mol} \cdot \text{L}^{-1} \]
Nitrate concentrations at station A versus time. Data presented are those that comply with overall consistency of the water column profile, and not contradicting with the data of cruises from close dates. 

- **a** – water sampled below 500 m. 
- **b** – water sampled between 500 m and 600 m. 
- **c** – water sampled between 450 m and 550 m. 

Note that low nitrate values occur when mixing depth were close or passed the limits of the plotted depths inducing phytoplankton growth that lowered water column nitrate below the conservative mixing value (the deepest and most documented was the deep mixing event of 2000, circled in blue in **a**). Hence, these low values are irrelevant for estimating long-term changes in deep water organic load. 

The plot shows that the nitrate concentration in deep water increased since the early 90’s by ca. 1.5 µmol·L⁻¹. The increase is seen also from Feb. 1999, even though nitrate concentration decreased to about 1.5 µmol·L⁻¹ during the deep mixing event of 2000.
**Figure 6:** Deep water concentrations of phosphate at station A versus time. Data presented are those that comply with overall consistency of the water column profile, and not contradicting with the data of cruises from close dates. Hence, there are considerably less data points in the phosphate plot than in the nitrate plot (Fig. 5). a – water sampled below 500 m; b – water sampled between 500 m and 600 m; c – water sampled between 450 m and 550 m. Note that low phosphate values occur when the mixing depth passed the limits of the plotted depths inducing phytoplankton growth that lowered water column phosphate below the conservative mixing value (deep mixing zone). Therefore, these low values are irrelevant for estimating long term changes in deep water organic load. The plot suggests that the maximum phosphate concentration may have increased slightly, by ca. 0.05 µmol·L⁻¹, since the late 90’s. Such an increase is in agreement with the measured nitrate increase during that period (Fig. 5).
Long Term
Oxygen decreased
Nitrate increased

Water column inventories
Oxygen

\[ \Delta O_2 \approx -10 \text{ mol}\cdot\text{m}^{-2} \]
Figure 9: Long-term variations of the water column nitrate inventory (integral) at station A1. The relatively high values during observed during 1991-1993 suggest that an increase in the nitrate inventory occurred during late 80’s and early 90’s. The decrease during the mid 90’s (dashed arrows) may be due to the deep mixing of 1992. The best vertical resolution and analytical data set starting in Feb. 1999 (see also Figs. 18, 22) shows that annual maximum nitrate inventories increased by ca. 0.5 mol·m⁻², from their values before the deep mixing event of 2000, even though the deep mixing event significantly depleted the water column nitrate. The nitrate data of 1997-1998 and 1991-1992 of Gordon et al. 1994 (see methods for clarification) are circled with blue.
Nitrate (mol·m⁻²)

1999-2004
1997-1998
1988-1992
1975-1977

\[ \frac{\Delta DO}{\Delta N} = -8.6 \]

\[ \frac{\Delta DO}{\Delta N} = -15 \]

Maximum limit of DO inventory

DO (mol·m⁻²)
Figure 11: Long-term variations of the water column phosphate inventory (integral) at station A1. Phosphate integrals are noisy and show features that resemble the nitrate inventories since the end of the 90’s. Due its relatively large sampling and analytical error, phosphate is particularly sensitive to integration (errors are additive) compared to nitrate whose concentrations are ca. 20 time higher. P inventory estimates for the end of the 90’s are reliable due to high vertical resolution of measurements and the use of MAGIC pre-concentration method. Despite the noise, it seems that the P inventory increased since the end of the 90’s by ca. 0.02 mol·m$^{-2}$. 

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Phosphate
Long Term
Oxygen decreased
Nitrate increased

Spatial distribution
Nitrate

Fig. D.28. Averaged isolinths of NO$_3$-N (µg at 1$^{-1}$) summer 1974. Shaded area see Fig. D.27 (Klinker et al. 1978)

Klinker et al., 1978
The northern basin: 2000’s nutrient levels > 1970’s nutrient levels

The mixing event of 2000
Depth of the mixed layer in station A1. The 1975-1977 data was estimated only from the Nansen bottles hydrocasts, therefore their accuracy is not more than ±50 m. The blue ellipses with the downward pointing arrows represent bottle hydrocasts and/or CTD profiles where the thermocline was not encountered, indicating that the mixed layer was deeper than the maximum depth for that particular profile.
The DO in the deep water of northern Gulf of Aqaba

Winter mixing

$\Delta DO/\Delta t = 10$ $(\mu mol L^{-1} y^{-1})$

Time

DO $(\mu mol L^{-1})$
It takes more than 4 years to laterally mix the deep water as indicated by the time to reach a new steady state following the deep mixing event of 2000.
Figure 22: a- Variations of water column nitrate inventory (integral) in station A1 since February 1999 (a blowup of Fig. 9), the best vertical resolution and analytical data set (see also Fig. 18). The arrows indicate fluxes of nitrate (indicated close to the arrow), arrow direction indicates input (positive) or output (negative) and arrow length represents the duration of the flux (see text). The red line represents the present day minimum nitrate inventory “leftover” after a complete mixing of the water column (see Fig.12a); b- One box model of the nitrate inventory (mol·m⁻²) and net N fluxes (mol·m⁻²·y⁻¹) in the northern Gulf of Aqaba after the deep mixing of 2000, the number in parenthesis is the annual average nitrate increase in mol·m⁻²·y⁻¹ (arrow 1 in the graph above). The calculation are explained in the text.
Fish Farms N emission is 2-5 % of flux through the Straits of Tiran

Fish Farms N emission (for the northern 25 km):

$$0.1 \text{ mol N}\cdot \text{m}^{-2}\cdot \text{y}^{-1}$$

Summer “New Production”:

$$0.0005 \text{ mol N}\cdot \text{m}^{-2}\cdot \text{d}^{-1} \text{ (David, 2002)} = 0.2 \text{ mol N}\cdot \text{m}^{-2}\cdot \text{y}^{-1}$$

Fish Farms N emission is 50% of new production
$O_2$ decreased and $N$ increased over 4 years following the mixing of Fish Farms. $N$ emissions is 50% of the summer “new productio”.

Lesson from Silica
Nitrite: PO4
Nitrate: Si

Deep:Surface ≈ 100
Deep:Surface ≈ 4
Silicates

Si(OH)$_4$

“New Nutrients”

Weathering

Diatom Productivity

Opal

Photic

Fast Dissolution

Opal

Sinking

Dark

"New Nutrients"
0.065 mol Si m\(^{-2}\) d\(^{-1}\) = 0.14 mol N m\(^{-2}\) d\(^{-1}\)
/continued from previous page

Nitrate versus silica water column concentrations in station A1 during the years 1989-1992 (left) and after the deep mixing of the year 2000 (right). Data for shallow water (< 250 m) are plotted in blue and deep water (>250 m) are in red. It is clear that during early 90’s the slope of N versus Si was 4.5 for shallow and deep water, and for the current period the shallow water data follow a line with N:Si ratio of 4.5 while the deep water data follow a line with N:Si ratio of 2. The high N:Si ratio of surface water is a sum of silica and nitrogen uptake by the phytoplankton community and their regeneration in the photic zone or mixed layer. The small N:Si ratio (N:Si=2) of deep water suggests that at present diatoms that dominate the surface phytoplankton population sink below the thermocline as “empty” opal shells (after their organic matter was regenerated at the surface) and dissolve in the deep water. Thus, increasing the deep water silica concentration and decreasing the N:Si ratio. It is well known that diatoms thrive under high nitrate conditions, therefore, the low Si:N ratio may be indicative of a “new” nitrogen source.
Increase in deep water silica suggests population shift to diatoms and increase in N and P input “Short Range” trap More Evidence for Eutrophication
Primary production Gulf of Eilat
Station A1

Year

Productivity (gC m⁻² yr⁻¹)

1976-7

Levanon et al. (1979)
"Millepora zone" (1-3 m depth) Eilat Coral Nature Reserve: 1969 vs. 2004 (Loya et al., unpublished)

Loya, 2005
Eilat Coral Nature Reserve – (ECNR): “Japanese Gardens” 3-7m depth:
Long-term monitoring of the coral community structure (3-7 m depth). Averages (± SD) computed from 10m line transects. Data for 1969 after Loya (1972); for 1986 after Abelson (Loya et al., 1983). Significant difference.

Smaller coral colonies?

% Cover
# Colonies

0 10 20 30 40 50 60 70
0 20 40 60 80

Loya, 2005
Figure 7. An example of *Acropora* partial coral mortality (ECNR, Dec. 2004).

Loya, 2005
Eutrophication!

End
Conclusions

Water column inventory of dissolved oxygen (DO) in the northern Gulf of Aqaba decreased by ca. 13 mol·m⁻² since 1991. The DO depletion rate increased considerably since the deep mixing event of 2000, it is not clear whether it reached steady state.

Nitrate inventory of the northern Gulf of Aqaba increased from the 1990's to present: The increase in nitrate deep water concentration since the 1990's was ca. 1.5 mmol·L⁻¹ and the increase in water column nitrate inventory from mid 1999 (before the deep mixing event of 2000) to 2003 was about 0.5 mol·m⁻².

Nitrate inventories in the southern basin of the Gulf of Aqaba during the 70's and 80's were larger than in the northern basin, while the opposite was observed during 1999. This suggests that at present "new" nitrogen originates in the northern Gulf, while in the past the nitrogen was supplied from the Red Sea through the straits of Tiran.

The N:P ratio have increased during the end of the 90's from about 12 to 18, suggesting addition of nutrient source with relatively high N:P ratio. The fish farms release to the environment ammonia and dissolved P at a ratio of 28.

In the last 7-8 years, the NGA is going through a significant eutrophication process that had decreased the deep water inventory of oxygen and had increased the inventories of nitrogen and silica. In parallel, an increase in the N:P ratio and a decrease in the N:Si ratio suggest major shifts in the nutrient sources and in the phytoplankton composition (diatom dominated community).
Station A; depth > 500m

Oxygen (µmol L⁻¹)

Station A; 500m < depth < 600m

Oxygen (µmol L⁻¹)

Station A; 450m < depth < 550m

-10 µmol·L⁻¹

Station A; depth 600±25 m

Deep mixing zone

Line of minimum O₂

Oxygen "gained" in samples above this line (see caption)

Deep mixing zone

Line of minimum O₂

Oxygen

ΔSi ≈ 0.42 mol m\(^{-2}\)

Abrupt decrease due to high productivity induced by deep mixing

Nov. 1992
Figure 10: Seasonal variations of nitrate (solid circles) and nitrate+nitrite (DIN; open circles) water column inventory (integral) in station A1. Note that during an annual cycle, DIN changes by a factor of 2 and the net yearly change is very small. Therefore, multi-annual observations are needed in order to establish net change in water column DIN inventory. Nitrate is the main DIN species, while even during active mixing, nitrite comprises less than ca. 7% of the water column DIN.
\[ \tau_{\text{gulf}} = \frac{V_{\text{gulf}}}{V_{\text{in}}} = \frac{S_{\text{gulf}}}{\Delta S} \cdot \frac{V_{\text{gulf}}}{V_{E}} \approx 2y \]
Figure 21: Nitrogen and phosphorus budgets of the fish farms for the last decade (data provided by Dr. Yuval Cohen, IOLR). The total emitted N and P are indicated in the graphs assuming that the present values are equal to the 2002 values. The integrated total N (assumed to be available for oxidation in the marine environment) and dissolved P are indicated above the graphs. a- Nitrogen emission rates. b- Phosphorus emission rates. c- The $\frac{N_{\text{emitted}}}{N_{\text{total fish feed}}}$ (nitrogen emitted to nitrogen in the fish feed) and $\frac{P_{\text{emitted}}}{P_{\text{total fish feed}}}$ (phosphate emitted to phosphate in the fish feed) ratios that are the solid + dissolved fractions of N and P emitted into the marine environment by the fish farms.

Equals to 2% - 5% of the annual N flux through the Straits of Tiran
Date

1/5 1/7 1/9 1/11 1/13 1/15 1/17 1/19 1/21

New Production (mol C m⁻² d⁻¹)

0.0 0.3 0.6 2.5 2.6 2.7

Light Limited New production
Nitrate versus silica water column concentrations in station A1. a- plot of all data (1975 to 2004). The average slope (eyeballed) for surface and deep water before 1999 was about 4.5. The data collected after 1999 is plotted along two distinct trend lines; one for surface and intermediate water with slope of 4.5 and the second for deep water with much lower N:Si ratio of 2. This phenomena become clearer on separate plots (see Fig. 19b on the next page).
The graph shows a linear relationship between $G$ (mmol C m$^{-2}$ day$^{-1}$) and $\Omega_{\text{arag-24-reef}}$, with two equations:

1. $y = 92.06x - 300.93$ with $R^2 = 0.98$
2. $y = 38.40x - 105.95$ with $R^2 = 0.87$
The DO and N cycle in the deep water of NGA
And the reconstruction of the DO/N ratio of -15
17/01/05

20 21 22 23

0 100 200 300 400 500 600 700

Temp. (°C)

Flu

17/01/05

14/02/05

20 21 22 23

0 100 200 300 400 500 600 700

Temp. (°C)

Flu

14/02/05

20/03/05

20 21 22 23

0 100 200 300 400 500 600 700

Temp. (°C)

Flu

20/03/05
Figure 12: Property/property plots of water column inventories in station A1 during the period 1975 - 2004, plotting data from the same time intervals as Fig. 7. a - Nitrate versus DO; b - nitrate versus phosphate. The average slopes (ΔDO:ΔN and ΔN:ΔP) have near Redfield values (slopes indicated on the lines). Plot (a) shows that the ΔDO:ΔN ratio of the present decade (1999-2004, open squares, ΔDO:ΔN ≈ -15) is higher than that of the last decade (1988-1992), which was closer to Redfield (ΔDO:ΔN ≈ -8.6). The intercept of the 1999-2004 trend line with the maximum limit of DO inventory (MDO) is higher than the intersection of the 1988-1992 trend line (dashed line with Redfield slope) with the MDO. Where, MDO was calculated for a 700 m water column in atmospheric equilibrium with average salinity and deep water temperature that could be the result of a long deep mixing event such as the one that occurred in 1992. This clearly indicates that after a deep mixing event, the present day water column will contain about twice more nitrate than after deep mixing during the early 90’s. Deep mixing shifts the phytoplankton community (PTC) from nutrient limitation regime to light limitation regime, hence even a large PTC cannot assimilate all the water column nutrients. According to this rationale, the larger the DIN water column inventory, the larger the “leftover” nitrate that PTC cannot assimilate during a complete mixing event. It should be noted that even if we draw a line with a ΔDO:ΔN = -15 that passes through the center of the 1975-1992 data, its intercept with the MDO will still be below the intercept of the 1999-2004 line.

Plot (b) is rather noisy but seems to follow the temporal behavior of the P vs. N concentrations plot (Fig. 7a). It appears that before 1999 the ΔN:ΔP ratio of water column inventories was lower than the period following 1999 with the exception of the inventories calculated from Gordon et al. (1994) data for 1991-1992 that clearly deviates from all data collected before 1999. The lines were drawn manually to emphasize trends.
Examples of the two criteria for data screening: 1. Compliance with the overall consistency of the water column profile (a, b), the data points excluded are circled with red for phosphate and blue for nitrate, note the good correlation of the N vs. P plot after the exclusion; 2. Compliance with data from preceding and following cruises (c), the nitrate profile of station A1 during 12.2.91 (red squares) looks coherent, but its concentrations are ca. 1.5 times higher (at deep and shallow water) than the nitrate profiles before and after this cruise that show the same deep water concentration. This is most probably a calibration (standard factorization) problem and the whole profile was discarded even though dividing the data by 1.5 would produce a good profile.
Station A1

MBL: stored chilled in triplicate 20 ml autosampler tubes; for SRP (soluble reactive phosphorous) MGIC analyses, NaOH was added on board to 200 ml centrifuge tubes; analyzed on 23.3.2004.
Stanford: filtered through 0.2 μm; shipped frozen; analyzed on 24.5.2004.

Princess Hotel

MBL: stored chilled in triplicate 20 ml autosampler tubes; for SRP (soluble reactive phosphorous) MGIC analyses, NaOH was added on board to 200 ml centrifuge tubes; analyzed on 23.3.2004.
Stanford: filtered through 0.2 μm; shipped frozen; analyzed on 24.5.2004.
Figure 14: Dissolved oxygen profiles along the Gulf of Aqaba during project DCPE, which was conducted during the mid 70’s (upper row) and the Israeli-Egyptian joint cruise, which was conducted at the beginning of the 90’s (lower row). Station locations are presented in Fig. 1a. Note the distinct mid water oxygen minimum in all stations inside the Gulf of Aqaba during the mid 70’s. The Gulf of Aqaba minimum was much smaller than in the northern Red Sea (station H). The mid water oxygen minimum during the beginning of the 90’s was not as distinct as it was during the mid 70’s.
**Figure 15:** Dissolved oxygen profiles along the Gulf of Aqaba during the Meteor cruise 1999. Station locations are presented in Fig. 1b, **upper row**- the Gulf of Aqaba; **lower row**- northern Red Sea. Note that compared to the marked mid water oxygen minimum in the northern Red Sea, it was quite small in the southern Gulf of Aqaba and was not present in the northern Gulf of Aqaba.
Figure 16: a- Nitrate profiles along the Gulf of Aqaba during project DCPE, which was conducted during the mid 70’s (upper row), and the Israeli-Egyptian joint cruise, which was conducted at the beginning of the 90’s (lower row). Station locations are presented in Fig. 1a. Note the distinct mid water nitrate maximum in all stations inside the Gulf of Aqaba during the mid 70’s even though it was much smaller than in the northern Red Sea (station H). The mid water nitrate maximum during the beginning of the 90’s was not as distinct as it was during the mid 70’s. continued next page/
Figure 17: Nitrate profiles along the Gulf of Aqaba during the Meteor cruise 1999. Station locations are presented in Fig. 1b, upper row- the Gulf of Aqaba; lower row- northern Red Sea. Note that compared to the marked mid water nitrate maximum in the northern Red Sea, it was quite small in the southern Gulf of Aqaba and very small in the northern Gulf of Aqaba.
A1, 2004