# Anthropogenic enhancement of Egypt's Mediterranean fishery

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**The highly productive coastal Mediterranean fishery off the Nile River delta collapsed after the completion of the Aswan High Dam in 1965. But the fishery has been recovering dramatically since the mid-1980s, coincident with large increases in fertilizer application and sewage discharge in Egypt. We use stable isotopes of nitrogen ($\delta^{15}N$) to demonstrate that 60%–100% of the current fishery production may be from primary production stimulated by nutrients from fertilizer and sewage runoff. Although the establishment of the dam put Egypt in an ideal position to observe the impact of rapid increases in nutrient loading on coastal productivity in an extremely oligotrophic sea, the Egyptian situation is not unique. Such anthropogenically enhanced fisheries also may occur along the northern rim of the Mediterranean and offshore of some rapidly developing tropical countries, where nutrient concentrations in the coastal waters were previously very low.**

fisheries | Nile delta | nutrient enrichment | stable isotope

In contrast to many of the world's fisheries, which are in serious decline (1, 2), Egypt's Mediterranean fishery offshore of the Nile River delta has been expanding dramatically in recent decades and at rates higher than can be explained by fishing effort alone (3, 4). Although the dependence of the Egyptian culture on the Nile has been noted for thousands of years, the importance of the river for the offshore fishery is less well known.

More than 95% of Egypt's population and all of its agriculture are concentrated in <5% of Egypt's land, along the banks of the Nile and throughout the 25,000-km$^2$ Nile delta (Fig. 1). For more than 5,000 years, Egyptians depended on the annual fall flooding of the Nile, which irrigated and fertilized the floodplain and eventually discharged to the Mediterranean Sea. Nutrients in the floodwater thus supported a large diatom bloom and a productive fishery, particularly for sardines (5, 6). As early as the 19th century, Egypt's population began to outpace its resources, and talk of damming the Nile began (7). When the Aswan High Dam was completed in 1965, the fall flood decreased by about 90%, and the water held in the Lake Nassar reservoir behind the dam was used to irrigate 3 crops a year instead of 1 crop (8). But an unintended and widely reported consequence of the dam was that the coastal fish landings dropped dramatically without the fertile (and buoyant) floodwaters (Fig. 2) (4, 5, 9, 10).

But in the late 1980s, the coastal fishery began to exhibit a surprising recovery. Today, landings are more than 3 times the predam levels (Fig. 2) (4, 11). Although improvements in fishing technology and increasing effort must have played some role in the recovery, neither catch per trip data for 1966–1986 nor catch per boat data for 1995–2007 show any clear trends (13, 14). A recent assessment of potential anthropogenic nutrient sources in Egypt also suggested that these sources may have more than replaced the fertility carried by the historical floodwaters (4). Since the completion of the dam, Egypt's population has more than doubled, and per capita calorie and meat consumption have increased by 33% and 45%, respectively, which translates to more people excreting more nitrogen (N) and phosphorus (P).

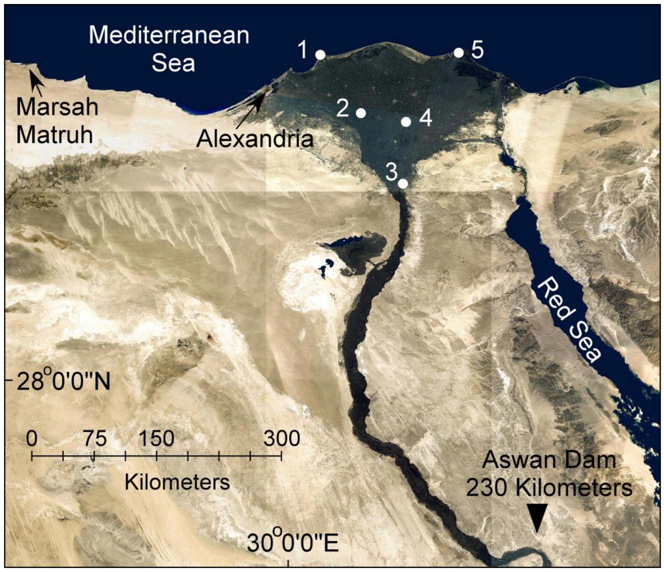


**Fig. 1.** The lower Nile valley and delta from LandSat images (http://gaialab.asu.edu/home/LandSat14.php). Point 1 is the mouth of the Rosetta Branch, point 2 is a sampling location on the Rosetta, point 3 is Cairo, point 4 is a sampling location on the Damietta Branch, and point 5 is the mouth of the Damietta. For additional specific sampling locations, see Fig. S1.

Public water and sewer systems have expanded greatly (4), and annual fertilizer consumption has increased almost 4-fold, from $3.4 \times 10^5$ tons to $13 \times 10^5$ tons (11). Before 1965, the Nile flood delivered about $7 \times 10^3$ tons year$^{-1}$ of N and 7–11 $\times 10^3$ tons year$^{-1}$of P to the Mediterranean coast (4). Today, the Rosetta Branch of the Nile alone discharges almost 3 times more inorganic N (DIN) per year ($2 \times 10^4$ tons) and about half as much bioavailable P ($4 \times 10^3$ tons) into this oligotrophic region, and there are 7 other major and countless minor drainage points along the coast (15, 16). Improved sewerage infrastructure now allows effluent to efficiently reach the coast (4), and tile-drained fields release water into more than 13,000 km of drainage canals, which eventually discharge offshore (17). Like the cities and towns on the delta, most of Cairo's human waste (from almost 20 million people) is released directly into these drainage canals. Alexandria's wastewater (from about 4 million people) receives primary treatment without nutrient removal and is discharged

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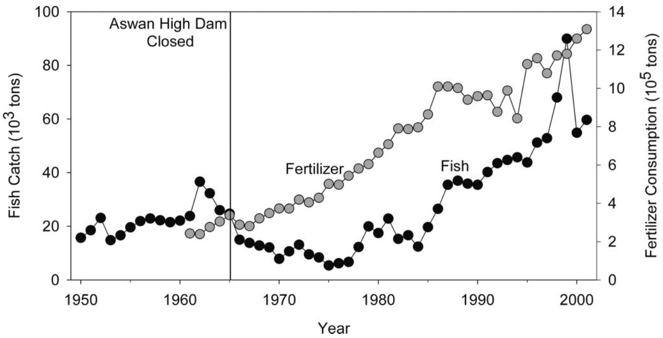


**Fig. 2.** Egypt's Mediterranean fish landings (closed circles) and fertilizer consumption (gray circles) (11, 12).

into the Maryut Lagoon, just inshore of the city. The lagoon water is eventually pumped out to sea.

The morphology of the Egyptian coast and the west-to-east Mediterranean Sea water circulation (18) provide a unique opportunity to directly test the hypothesis that the recent rise in fish landings off the delta is due to increasing N (and associated P) loads from fertilizer and sewage runoff. Although we hypothesized that anthropogenic loads of both N and P are largely supporting the coastal fishery, we were able to measure only the contributions of N, using stable isotopes ($\delta^{15}N$). The primary sources of N (i.e., fertilizers, sewage) also contain significant amounts of P; thus, we use $\delta^{15}N$ as a proxy for both N and P loads. For example, the Rosetta Branch of the Nile discharges fertilizer and sewage-enriched water that has a N:P molar ratio of 11:1, which is close to the Redfield ratio of 16:1 (15, 16). Although some evidence exists that the open Mediterranean Sea is P-limited (19), whether this is also true for coastal regions is unclear. In fact, a review of nutrient data from the Nile delta lagoons (which have open exchange with coastal Mediterranean waters) suggests that they are N-limited (20). Because the Mediterranean system is characterized by extremely low concentrations of both N and P, loadings of both are likely very important to this coastal system. Thus, N loading would result in coastal P limitation if P loading did not increase in parallel with N loading. Although the focus of this paper is necessarily on N loads and associated $\delta^{15}N$ values in fish, the importance of bioavailable anthropogenic P is directly linked to these results.

## Results and Discussion

We measured stable isotopes of N ($\delta^{15}N$) in the muscle tissue of fish collected offshore of the western desert near the Egyptian border with Libya (Marsa Matruh), "downstream" of this site at the western edge of the agricultural delta (which is "upstream" of most of the drainage associated with Alexandria), and from 4 regions receiving delta runoff. We compared these samples with one another and with fish from agricultural drains in the delta, from 4 large coastal lagoons on the delta, and from the Nile River itself [supporting information (SI) Fig. S1]. To assess the potential contribution of organic matter outwelled from the delta, we measured stable carbon isotopes ($\delta^{13}C$) in the samples. More than 600 fish, from 110 sources (fishermen and vendors), were collected in August 2006 (summer) and November 2007 (winter). More than 45 different genera were represented, spanning all trophic levels, although inshore fish were generally omnivorous, and most offshore fish were carnivorous (Table S1) (12, 21). No significant differences in $\delta^{15}N$ values were found between trips for the whole data set and at particular locations. Offshore of the delta, $\delta^{13}C$ values were 1% heavier in August than in November ($P = .0188$).

Fish from both Marsa Matruh and Alexandria (about 250 km apart) reflect unimpacted Mediterranean $\delta^{15}N$ values (Fig. 3).

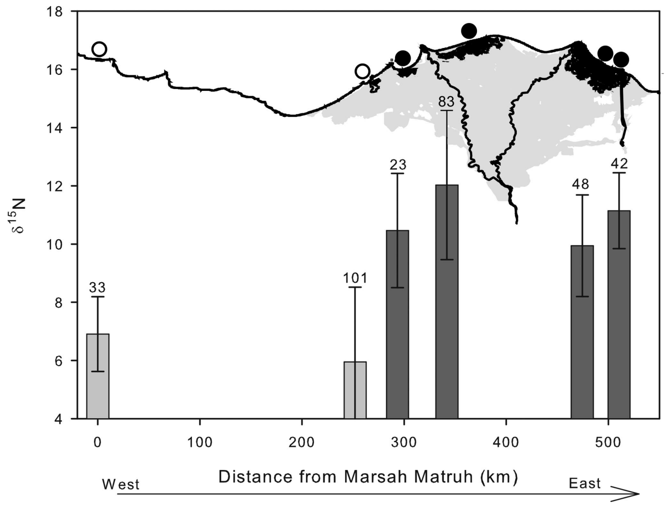


**Fig. 3.** Mean $\delta^{15}N$ values of fish sampled offshore of the Nile delta. Error bars represent standard deviations; the number of fish collected at each location is above the bar. Fish from Marsa Matruh and Alexandria (light bars) were significantly lighter than those from the delta (dark bars) ($P < .0001$).

Surface particulate organic matter ($\geq$ 0.1 $\mu$m) and nitrate ($NO_3^-$) in this area have $\delta^{15}N$ values of approximately −0.2% and 2.5%, respectively (22). Considering a trophic fractionation of approximately 3.5% (23) and the mixed trophic levels of these fish, the values for the fish off Marsa Matruh and Alexandria ($\approx$ 6%) are consistent with Mediterranean particulate organic matter and $NO_3^-$ values (Table S1). These values also are similar to those reported for fish from Linosa Island, Italy (5%–7%), in the center of the Mediterranean, west of Marsa Matruh (24). Fish sampled at 4 locations offshore of the delta (i.e., in the deltaic plume) and across more than 220 km of coastline had $\delta^{15}N$ values 5% heavier than those from the west ($P < .0001$; Fig. 3), but differences at the 4 locations were not statistically significant. Mean $\delta^{13}C$ values were indistinguishable among all offshore fish from all locations and were within the range seen elsewhere in the Mediterranean (−12% to −19%). Although $\delta^{15}N$ values increase with trophic level, the differences among locations for $\delta^{15}N$ likely cannot be explained by the variation in trophic levels present. For example, sardines (*Sardinella sardinella*), the only widespread primary consumers (herbivores, the lowest consumer trophic level) in the offshore data set, were heavier off the delta (10.0% ± 1.4%; $n = 51$) than virtually all of the fish from the west, or "upstream" of the Nile delta ($P < .0001$), which are largely carnivorous. Furthermore, the sardines were more than twice as heavy as the planktivorous *Siganus luridus* from Alexandria and the largely planktivorous *Chromis chromis* (Table S1; Fig. 4). The phytoplankton's N isotope composition and N source must contribute to the elevated $\delta^{15}N$ values in these sardines.

$\delta^{13}C$ values were much lighter in the fish from the lagoons, drains, and the river than in the Mediterranean fish and resembled those in $C_3$ plants and freshwater phytoplankton ($\approx$−28%) (Table S1). These values suggest that although terrestrial and freshwater carbon sources are significant inshore on the delta, they have little influence on the offshore fishery, which is supported by marine phytoplankton. Fish from lagoons, the Nile River, and agricultural drains along the northern edge of the delta had $\delta^{15}N$ values similar to those offshore of the delta, suggesting that the primary N sources for these fish are the same (Fig. 4). The $\delta^{15}N$ values ranged widely for the inshore fish, from −1% to 23%. Synthetic fertilizers initially applied to fields have $\delta^{15}N$ values between −2% and 2% (25), and the lightest inshore fish (< 5%) were taken from agricultural drains (Fig. S1;

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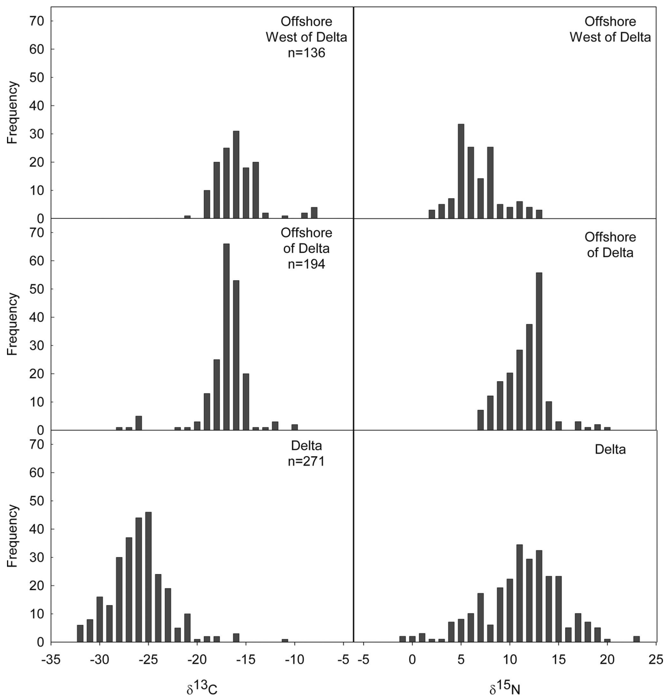


**Fig. 4.** Frequency of observed mean $\delta^{15}N$ and $\delta^{13}C$ values in muscle tissue of Mediterranean fish west of the delta (Marsa Matruh and Alexandria; $\delta^{13}C = -16.8\% \pm 3.0\%$; $\delta^{15}N = 6.2\% \pm 2.4\%$), immediately offshore of the delta ($\delta^{13}C = -17.5\% \pm 2.3\%$; $\delta^{15}N = 11.2\% \pm 2.2\%$), and from inshore coastal lagoons, drainage canals, and the Rosetta and Damietta Branches in the Nile delta ($\delta^{13}C = -26.4\% \pm 3.0\%$; $\delta^{15}N = 10.8\% \pm 4.1\%$).

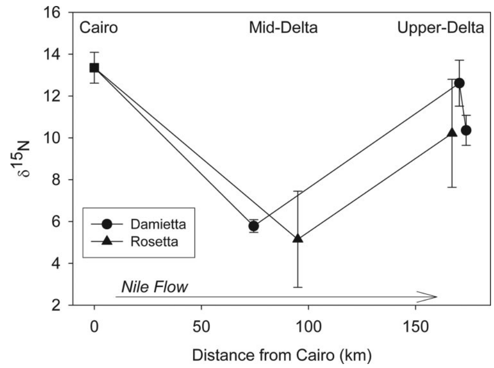


**Fig. 5.** Mean $\delta^{15}N$ values of fish from Cairo, the mid-delta, and upper delta, with distance from Cairo. Just north of Cairo, the Nile splits into the Damietta and Rosetta Branches.

Table S1). These fish also had $\delta^{13}C$ values similar to those in $C_3$ vegetation (the primary vegetation on the delta and in the drains) and freshwater phytoplankton (≈-28%) (23, 26). But the fish at the northernmost edge of the delta generally had much heavier $\delta^{15}N$ values (> 10%), suggesting that uptake, processing, and recycling of nutrients from drainage water (which contains both sewage and fertilizer runoff) are important processes. Isotope fractionations shift the $\delta^{15}N$ values so that the lagoon and offshore fish do not directly reflect their terrestrial N sources, even though these sources supply the bulk of their assimilated N. The fish with the heaviest $\delta^{15}N$ values (> 15%) were from 2 of the coastal lagoons, where there is minimal exchange with the sea and residence time is about 45 days, allowing ample time for denitrification and other fractionating processes (27). The $\delta^{15}N$ values of fish collected from the Nile River in August 2006 support this interpretation. Values for fish from the Nile at Cairo were 13.4% ± 0.7% ($n = 10$); those for fish in the agricultural mid-delta were significantly lighter, at 5.4% ± 1.7% [$P < .0001$, 74 km north (Damietta) and 95 km north (Rosetta), $n = 15$]; and those for fish from the area where the Damietta and Rosetta discharge to the sea were 10.7% ± 2.2% ($P < .0001$, 170 km north of Cairo, $n = 24$) (Fig. 5). The lighter $\delta^{15}N$ values observed mid-delta almost certainly reflect the inflow of fertilizer-rich agricultural drainage, but water reuse and in-stream processing during transport make the $\delta^{15}N$ values heavier at the mouth.

Assuming that fish from west of the delta and Linosa Island (24) represent the unimpacted Mediterranean (the area has no agricultural or urban areas, and only one agricultural drain west of Alexandria), and that fish on the northern edge of the delta represent anthropogenic signatures, a simple 2 end-member mixing model using $\delta^{15}N$, $f_1 = [(\delta_{sample} - \delta_{source2})/(\delta_{source1} - \delta_{source2})]$, where $\delta_{sample}$ is the mean deltaic offshore $\delta^{15}N$ value (11%), $\delta_{source2}$ is the mean inshore value from the coastal lagoons and the mouths of the Damietta and Rosetta (12%), and $\delta_{source1}$ is the offshore value west of the delta (6%), suggests that 80% of the nitrogen in the fish captured offshore of the Nile delta is from land drainage (or, considering the range in standard deviations associated with the estimated values, between 60% and 100%). This is consistent with the magnitude of the rise in fish landings since the completion of the Aswan High Dam. The depressed landings after the dam's completion (1966–1975; 12,300 tons year$^{-1}$) were only 20% of the most recent landings (1991–2000; 63,400 tons year$^{-1}$) (12). Assuming that the earlier landings represent a fishery that was unenhanced by anthropogenic enrichment, ≈80% of the current landings may be artificially supported by anthropogenic N (and associated P) and, to a lesser extent, improved fishing practices (3, 4). This rough estimate is consistent with the mixing model results. Such artificial enhancements are not unique to this region, because fish landings along the northern rim of the Mediterranean also have been increasing at a rate that cannot be accounted for by increases in fishing efforts alone (3). Fertilizer consumption is rising rapidly in many developing countries that are adjacent to formerly oligotrophic tropical waters (28), and these also may experience at least initial stimulation of fish production. It remains to be seen how sustainable these "artificial fisheries" will be over the long term, but some preliminary evidence indicates that increasing nutrient loads may stimulate landings only up to a point, beyond which the fisheries decline due to poor water quality or overfishing (20, 29).

## Materials and Methods

Fish were purchased either directly from fishermen or from outdoor markets adjacent to fishing ports. The sources of the fish were determined through interviews, and aquaculture fish were excluded from this data set. Specimens were numbered and photographed for later identification. Samples (a portion of the tail muscle) were removed from the fish, dried at 65 °C for 48 h, and placed in individual plastic bags filled with noniodized salt for transport to the University of Rhode Island. The samples were redried in the laboratory, and all fin, skin, and bone were carefully removed. The remaining tissues were ground to a fine powder and stored in acid-washed scintillation vials in a desiccator until analysis.

Carbon and nitrogen stable isotopes were measured using a Carlo-Erba NA 1500 Series II elemental analyzer interfaced with a Micromass Optima mass spectrometer at the Environmental Protection Agency in Narragansett, Rhode Island, with a precision of more than ± 0.3% for both C and N and expressed as a part per thousand (per mil, %) deviation from the reference standard PDB ($\delta^{13}C$), and from the composition of $N_2$ in air ($\delta^{15}N$) as follows:

$$\delta X = [(R_{sample}/R_{standard}) - 1] \times 10^3$$

where $x$ is $\delta^{13}C$ or $\delta^{15}N$ and $R$ is the ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$. Samples were analyzed randomly and in duplicate, in batches of ≈25. Laboratory standards were used to check for instrument drift in each run; no drift was observed when analyzing



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these samples. One-way ANOVA and the paired Student *t*-test were used to determine significant differences among stations, groups, and lagoons.

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