

COMMENT

***In situ* eutrophication caused by fish farms in the northern Gulf of Eilat (Aqaba) is beneficial for its coral reefs: a critique**

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In their recent paper, Bongiorni et al. (2003a) claim that nutrients released from fish farms (Fig. 1A) at Eilat (Red Sea) 'may not necessarily lead to the demise of coral reefs as is commonly presumed' (p. 137). Their study, aimed at assessing the 'impacts of a commercial fish farm near Eilat, Israel, on some life-history parameters of selected coral species' (p. 138), showed that 7 mo after experimentally suspending branches of *Acropora eurystoma* corals at the fish farm site, there was an accelerated growth rate and weight increase in these branches compared with corals at a reference site across from the Interuniversity Institute (IUI). They further showed that in colonies of the coral *Stylophora pistillata* growing on artificial substrata at depths of 10 to 17 m close to the fish farm, there were significantly more polyps with developing testes and oocytes at the fish farm site, compared with the reference site. It is important to critically examine this work since the authors conclude that their results 'challenge the prevailing notion ... that nutrient effluents released from intensive net-pen fish-farms in the Gulf of Eilat is the major detrimental factor contributing to the degradation of the coral reefs along the Israeli coast' (Bongiorni et al. 2003a, p. 143). We contend that the methodology and experimental design used in that study are unsuitable for obtaining a correct assessment of the impact of commercial fish farms. Moreover, we claim that their results actually attest to the opposite, i.e. to the detrimental effect that eutrophication has on the coral species examined.

Experimental design and methodology. In their study, Bongiorni et al. (2003a) transplanted coral fragments of the branching coral *Acropora eurystoma* onto PVC plates suspended at a depth of 6 m in the vicinity of the fish farm. The seafloor at that site is approximately 22 m deep. The reasoning behind mooring the

plates at such a shallow depth in the water column was to exclude 'possible impacts from resuspended bottom sediments' (p. 139). But by doing so they also prevented the coral fragments from 'experiencing' the true concentrations of both particulate and dissolved matter that naturally growing colonies on the sea floor experience. Much of the nutrients released from the fish farms is in the form of particulate materials that accumulate on the sediment. Unfortunately, Bongiorni et al. (2003a) failed to provide an accurate description of the benthic environment under the fish cages; fish feces and sinking food particles have an adverse effect on natural communities, making the benthic habitat anaerobic and supporting the growth of bacterial mats (Fig. 1A,B), protozoans and of a sulfide-resistant community. Sinking particulate matter can be resuspended by water motion, where it can be colonized by mucopolysaccharide-producing diatoms and microbes (Fabricius & Wolanski 2000, Wolanski et al. 2003). By settling on the coral colonies this particulate matter may cause polyp suffocation and disease (Fabricius & Wolanski 2000). In addition, resuspension of this particulate matter increases the nutrient levels that natural colonies encounter at both sites, compared to the nutrient levels experienced by the colonies grown by Bongiorni et al. at 6 m depth. The experimental design presented in their paper is thus inadequate for assessing nutrification effects on natural coral communities.

The authors state that 'During the experiment, algae and encrusting invertebrates were removed from the PVC plates on a monthly basis' (Bongiorni et al. 2003a, p. 139; emphasis added). In doing so, they artificially eliminated one of the most important environmental effects of fish farms on corals: stimulating growth of benthic algae (Fig. 1C) that may smother the corals (Fig. 1D) (Laws 1992, Genin et al. 1995, McCook 1999).

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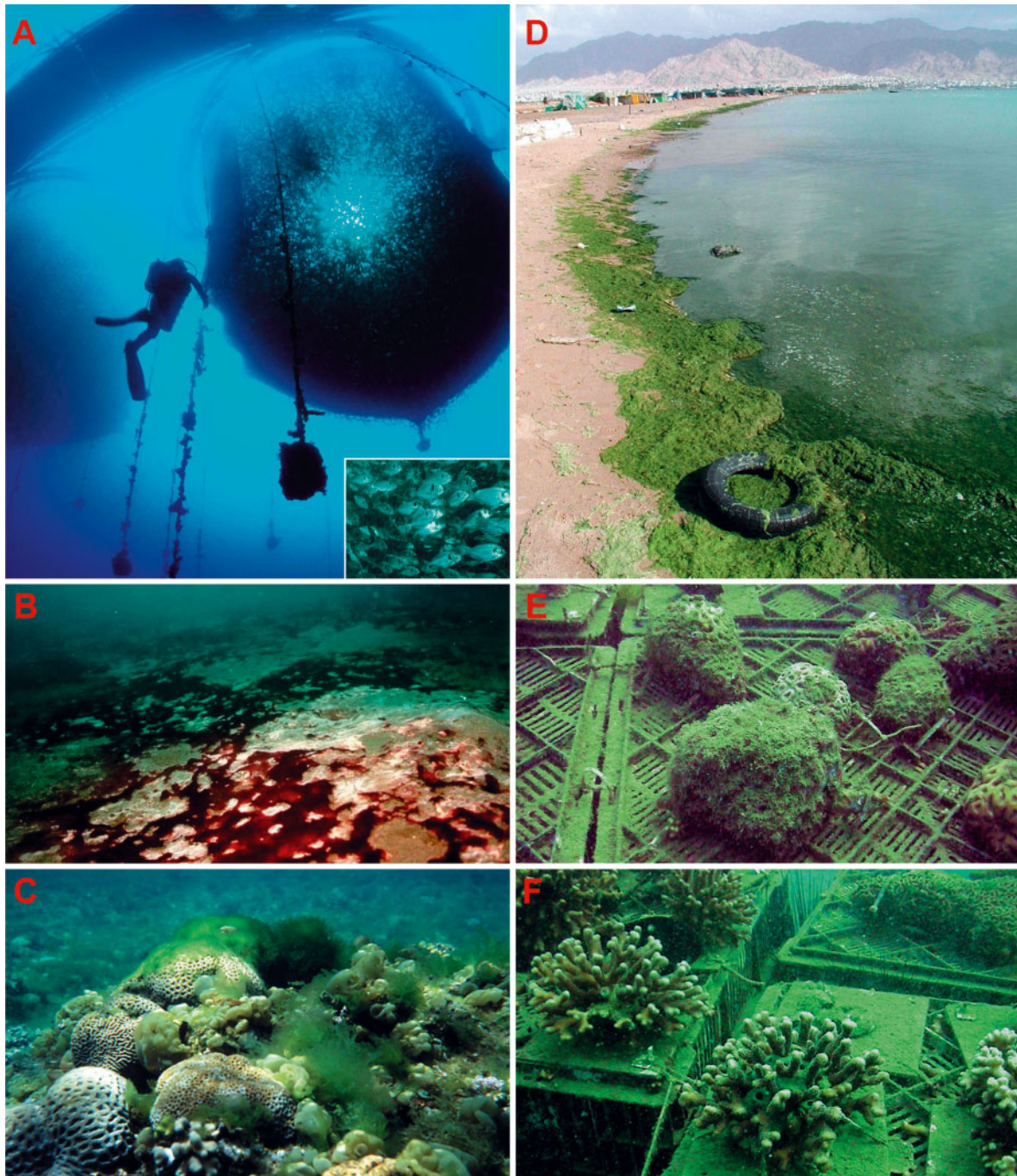


Fig. 1. (A) The intensive net-pen fish farms situated in the northernmost section of the Gulf of Eilat (Aqaba) utilize cages 12 m in diameter and 10 m in length, each stocked with ca. 70 000 fish. Annual production is >2200 t, mostly of seabream *Sparus aurata* (inset). The farms release ca. 18×10^6 mol N yr⁻¹ and are the largest source of N and P to the northern Gulf (Atkinson et al. 2001). (B) The seafloor near the fish cages resembles a 'biological desert'. This anaerobic benthic habitat supports bacterial mats and sulfide-resistant populations. (C) During winter, the cold surface waters of the Gulf sink, creating vertical mixing and pumping the deep nutrient-rich waters to the surface. This results in competitive exclusion of stony corals by algal blooms (Genin et al. 1995). In 1999–2000, surplus nitrate accumulated at >500 m depth was 200 t. During this period the farms released 500 t of nitrate into the water column (i.e. N accumulated in deep water was ca. 40% of N originating from the fish farms; Lazar et al. 2000). (D) A storm detached vast amounts of macroalgae from the vicinity of the fish farm onto the shoreline. (E) For studies on coral survivorship and reproductive effort we transplanted massive *Favia fava* colonies and (F) encrusting *Coscinarea monile* colonies (top right), as well as branching mature *Stylophora pistillata* and *Acropora* (not shown) colonies. They were placed on inverted plastic boxes near the cages and at the reference site, Interuniversity Institute (IUI) at 19 m depth, 50 cm above the substrate. Reproductive effort (reproductive fitness) of experimental *S. pistillata* colonies was ca. 3 times higher at the IUI than at the farm site, indicating the harmful effects of nutrient release. Most branching colonies at both sites survived and continue to grow well 3 yr after transplantation. Most massive and encrusting colonies at the farm site were overgrown by algae and died within a year, while those at the IUI are still growing well today. Photographs: A by I. Grinberg (2001); A (inset) by D. Zakai (2002); B by Z. Livnat (August 2000); C by Y. Loya (March 2000); D by A. Diamant (February 2001); E–F by R. Shem-Tov (December 2001)

Consequently, their experiments can not be perceived as a true gauge of the environmental conditions. Monthly removal of algae and encrusting invertebrates permitted uninterrupted and better coral growth at the fish farm site than would have been observed under natural conditions. If the plates had not been repeatedly cleaned, it is very likely that the experimental corals would have become overgrown by macroalgae and encrusting organisms, causing their death within a short time. This could have been illustrated, had the authors presented an underwater photograph of the corals growing on the plates *in situ* prior to the monthly cleaning, rather than only providing a photograph illustrating a 'representative subset of branches' (Bongiorno et al. 2003a, Fig. 2A, p. 141) following treatment with chlorine bleach. Indeed, in a set of experiments using *Stylophora pistillata* nubbins (not cleaned monthly), the authors reported that when compared to growth of nubbins in the reference site, branches of the fragments from the fish farms showed accelerated growth on the one hand, but a reduction of lateral growth on the other (see also Bongiorno et al. 2003b). This illustrates the problematic choice of growth parameters and species. The coral species selected for the experiments, *Acropora eurystoma* and *S. pistillata*, occur naturally and are more abundant than other coral species in the vicinity of the fish farms. However, both *A. eurystoma* (Y. Loya pers. obs.) and especially *S. pistillata* (Loya 1976) are typical r strategists or 'weedy' coral species. They are the first to settle where new space becomes available, grow quickly and mature sexually at a small size. Although these species are also abundant on reefs further south, they are almost the only coral species in the vicinity of the fish farms. Other coral species are scarce in the vicinity of the fish farms (Y. Loya unpubl. data), while ca. 100 coral species exist at the coral nature reserve only 7 km further south. Hence, the authors pre-selected coral species that have the highest chances of surviving and growing in the vicinity of the fish farms. It is unfortunate, but not surprising, that the authors did not select for their experiments a representative massive coral species (such as *Favia fava*, which is one of the most abundant corals on the reefs further south, but absent in the vicinity of the fish farms (Y. Loya pers. obs.). In our own experiments conducted in the vicinity of the fish farms (see also below), we found that 7 mo after transplantation of *F. fava* colonies in this site, all colonies were overgrown by algae and consequently died (Fig. 1E), while similarly transplanted colonies at a reference site (IUI) are all still growing well 3 yr after transplantation. Moreover, both *Acropora* species and *S. pistillata* colonies transplanted at the same time in both sites are still growing well (Fig. 1F; Loya & Kramarsky-Winter unpubl.).

Another question is the annual estimated discharge of nitrogen and phosphorus (both particulate and dissolved) by the fish farms. It is unclear why the authors chose to calculate these parameters from Lupatsch & Kissil (1998): i.e. 92 t of nitrogen and 16 t of phosphorus, released from the central and western pontoons. This is most likely an underestimate, in view of the more recent and comprehensive account provided by Gordin (2000), who estimated that the annual discharge of the fish farms is ca. 242 t of nitrogen and 40 t of phosphorus, an estimate closer to the annual discharge occurring during the 2001 experiments of Bongiorno et al. (2003a),

Coral growth and skeletal density. High nutrient concentration results in quick linear growth of corals (Hoegh-Guldberg et al. 1997). The rapid extension (growth) of the coral branches transferred to the fish farm station is therefore not surprising. The question that arises is whether there was a difference in skeletal density between the experimental corals at the 2 sites. It is unfortunate that this important parameter was not examined. We suspect that the quick vertical extension of the branches grown in the vicinity of the fish farms may have resulted in lower skeletal density compared with the experimental corals at the reference site. This is important since higher skeletal density helps the coral to withstand breakage and often decreases the infestation by boring organisms that may weaken its skeleton. At Eilat, the skeletons of live coral colonies near the fish farms have significantly higher levels of infestation by boring organisms than is the case further south (Wielgus 2003). Furthermore, the fact that the growth experiments were short (7 and 13 mo for *Acropora eurystoma* and *Stylophora pistillata*, respectively) resulted in a failure to assess longer-term cumulative impacts of eutrophication on coral growth, as pointed out by the authors themselves, and, as we suspect, on coral skeletal strength.

Coral reproductive effort and lipid content. Bongiorno et al. (2003a) examined the reproductive state in *Stylophora pistillata*. They removed individual branches from 14 similarly sized colonies growing naturally at a depth range of 10 to 17 m on artificial substrates near the fish farms and at the IUI. Their results showed that there were a higher number of colonies with female gonads at the fish farm than at the IUI, and that the average sizes of the 'oocytes in *S. pistillata* colonies growing near the fish farm were twice as large as their counterparts at IUI, ... although the difference was not statistically significant' (p. 141). Rinkevich & Loya (1989) found that normal hermaphroditic colonies undergoing stress lose their female function and 'revert to maleness'. Bongiorno et al. (2003a) do not mention how many of the polyps were hermaphroditic, how many were male and how many were sterile.

They simply noted that the average number of oocytes polyp⁻¹ was significantly higher at the fish farm site than at the IUI. Unfortunately, they did not discuss the reproductive patterns in their results that show that the average number of oocytes per polyp varied significantly between sampling dates and sites, *increasing* between January and May in the fish farm site, and *decreasing* at the IUI site (their Fig. 3). *S. pistillata* releases planulae during the winter until early summer (Rinkevich & Loya 1979b). The fact that there were fewer oocytes at the IUI site during the May sampling, may be an indication that in *S. pistillata* colonies at that site, fertilization and consequent release of planulae had already taken place. This would have resulted in fewer oocytes remaining in each colony. It is also possible that at the fish farm site, fewer oocytes are fertilized and thus are not 'lost', resulting in higher numbers. This is not surprising, since in areas of high eutrophication corals may develop a higher number of male gonads and oocytes (Ward & Harrison 2000, Harrison & Ward 2001). The question remains, however, as to whether in the *S. pistillata* colonies from the fish farm site, the oocytes developed normally, reached maturity, were fertilized and developed into healthy planulae.

An additional indication of the reproductive state of *Stylophora pistillata* is the lipid content in their tissues during the reproductive season. The authors found that the colonies at the fish farm had lower levels of lipid. Contrary to their interpretation, we believe that this is a strong indication that the fish farm colonies are not as reproductively mature as the reference site colonies, since the lipid content increases during maturation of the oocytes and their development into planulae. Thus, the corals may have been vertically elongating faster, but at the expense of their reproductive output (i.e. a trade-off between coral growth and reproductive effort). This is in contrast with the authors' claim that '... not only growth but also the reproductive activities of *S. pistillata* were higher at the fish farm than at IUI' (Bongiorni et al. 2003a, p. 142).

The authors did not actually study 'reproductive effort' (p. 142) in *Stylophora pistillata* as they claimed in their discussion. The most important parameter in assessing reproductive effort is the number of planulae produced by this brooding coral. Reproductive effort is a much more accurate measure of reproduction in corals than numbers of testes and oocytes per polyp, since it takes into account the number of offspring actually produced. Indeed, to do so properly, the authors would have had to study changes in oocyte size frequencies occurring with time, as well as the production of planula larvae. During oogenesis in *S. pistillata*, usually only one oocyte per polyp reaches maturity at a time. The oocytes reach a size of ca.

200 µm, just prior to fertilization (Rinkevich & Loya 1979a). Successful fertilization results in the development of one planula per polyp, and the other oocytes, which are believed to act as 'nurse cells', may be resorbed (Rinkevich & Loya 1979a,b). Thus, the questions that arise from the results presented in Bongiorni et al. (2003a) are: Do the oocytes found in *S. pistillata* colonies under the fish cages reach maturity, and are they fertilized? Indeed, in contrast to what was cited in the Discussion by Bongiorni et al. (2003a), Koop et al. (2001), summarizing the ENCORE project, reported that gametes of the broadcasting corals *Acropora longicyathus* and *Goniastrea aspera* exhibited low fertilization rates and increasing numbers of irregular embryos following exposure to elevated levels of nitrogen. In addition, settlement trials using larvae of *A. longicyathus* and some brooding species showed a reduction in settlement of planulae at high levels of nitrogen and phosphorus (Ward & Harrison 1997, Koop et al. 2001).

Our own research at the same sites during the last 3 years (Loya & Kramarsky-Winter unpubl.) has yielded different conclusions to those of Bongiorni et al. (2003a). We collected 40 mature *Stylophora pistillata* colonies (larger than 20 cm in diameter) from a site midway between the fish farm site and the IUI site and transplanted 20 colonies to each of the 2 sites: (a) 200 m west of the fish farm cages at a depth of 19 m (Fig. 1E), and (b) at the IUI reef at the same depth. Over the next 2 consecutive years, histological studies of the reproductive effort of the experimental corals showed that there were indeed more oocytes per polyp in colonies sampled from the fish farm site than at the IUI reference site, but they remained significantly smaller at the fish farm site throughout the reproductive season. Monitoring changes in oocyte size frequency distribution in the colonies throughout the reproductive cycle, we found that polyps from the IUI colonies contained significantly more oocytes that had reached the mature size of over 200 µm than those from the colonies beneath the cages. Moreover, the percentage of polyps with planulae was significantly higher in colonies from the IUI site than from those under the cages. This leads to the conclusion that in Bongiorni et al. (2003a) the fish-farm corals indeed produced a higher number of oocytes, but that most of them did not reach maturity and most probably were not fertilized. Thus, in contrast to their interpretations and conclusions, we suggest that the results presented in their paper, together with our own results, actually attest to a severe reduction in the reproductive effort of the coral colonies near the fish farms. This leads to the inference that the conditions at this site are harmful to these corals. Since much of the nutrients released from the fish farms were found to reach the reefs further south (see Abelson et al. 1999, Lazar et al. 2000) it is likely that these

reefs are affected as well. Indeed, when comparing the reproductive effort of *S. pistillata* in 1975 (after Rinkevich & Loya 1979b) and 2000 at the IUI site, there was a marked reduction in planulae release per coral head in the year 2000 (Glassom (2002), and an even further reduction in 2003 (D. Zakai & N. Chadwick-Furman, pers. comm.). It is thus most likely that the continuous eutrophication of the Gulf of Eilat (Aqaba) has marked deleterious effects on coral reproductive effort even in areas that are distant from the fish farm site.

Conclusions. We therefore conclude that nutrients released from the fish farms are the most probable and direct cause of harmful effects on this coral's reproduction, and most likely other coral species as well, as reported for other reefs around the world (Tomascik & Sander 1987, Ward & Harrison 2000, Harrison & Ward 2001). The continuation of the present eutrophication rate originating from the fish farms constitutes one of the major causes of continued deterioration of the unique coral reefs of Eilat and comprises a serious threat to their very existence.

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