

## PHYSICAL MODELS OF INTEGRATED WASTE RECYCLING- MARINE POLY-CULTURE SYSTEMS

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Contribution No. 3411 from the Woods Hole Oceanographic Institution

(Received August 27th, 1974)

### ABSTRACT

Ryther, J.H., Goldman, J.C., Gifford, C.E., Huguenin, J.E., Wing, A.S., Clarner, J.P., Williams, L.D. and Lapointe, B.E., 1975. Physical models of integrated waste recycling-marine polyculture systems. *Aquaculture*, 5: 163-177.

A combined tertiary sewage treatment-marine aquaculture system has been developed, tested and evaluated using several different experimental sizes and configurations located both at Woods Hole, Mass. and Fort Pierce, Fla. Domestic wastewater effluent from secondary sewage treatment, mixed with sea water, is used as a source of nutrients for growing unicellular marine algae and the algae, in turn, are fed to oysters, clams, and other bivalve molluscs.

Solid wastes from the shellfish are fed upon by polychaete worms, amphipods, and other small invertebrates that serve as food for flounder, lobsters, and other commercially valuable secondary crops. Dissolved wastes excreted by the shellfish and other animals and any nutrients not initially removed by the unicellular algae are removed by various species of commercial red seaweeds (*Chondrus*, *Gracilaria*, *Agardhiella*, *Hypnea*) as a final 'polishing' step. The final effluent from the system is virtually free of inorganic nitrogen and is incapable of supporting further growth of marine life or of contributing to eutrophication of the receiving waters.

A description of experiments with the above food chains and preliminary results with some alternative approaches are discussed, including a detailed account of the nitrogen mass balance through all of the components of one of the experimental systems.

### INTRODUCTION

Demonstration that treated wastewater effluent diluted with sea water is a complete and adequate enrichment medium for the growth of marine phytoplankton (Dunstan and Menzel, 1971) led to the concept of an integrated tertiary wastewater treatment-marine aquaculture system. Unicellular algae, grown in diluted wastewater effluent, remove the inorganic nutrients from the waste water and provide food for oysters or other filter-feeding bivalve molluscs. Other marine plants and animals utilize the solid and dissolved

wastes from the shellfish culture and serve as a final "polishing" step before the nutrient-free effluent is discharged to the environment (Ryther et al., 1972). Various parts of this system have been tested and evaluated on a small scale, both in the laboratory under controlled conditions and outdoors under natural conditions of light and temperature (Dunstan and Tenore, 1972; Tenore and Dunstan, 1973; Tenore et al., 1973; Goldman et al., 1974). The net result of this experimental work has been to strengthen our optimism concerning the feasibility of the concept. Several problems in its application have been revealed; some of these have been satisfactorily answered, while others remain unresolved. A number of significant findings of basic scientific value have also resulted. But it was not possible, working with the various isolated elements of the system, to make any valid judgements concerning the practical applicability of the process as a whole.

By the spring of 1973, sufficient progress with the different parts had been made to design and construct a small but complete physical model of the entire system, which was then operated and monitored continuously from May through October of that year. From that experience, certain information concerning the performance and reliability of the integrated process could be evaluated which, though not in every case directly applicable to a full-scale operation, did serve to identify some of the potentials and the constraints of the system as originally conceived. Based on these findings, modifications and improvements were incorporated into the design and operation of a subsequent scaled-up "pilot plant", which went into operation in November 1973 at the new Woods Hole Oceanographic Institution's Environmental Systems Laboratory. In addition, experiments similar to those conducted in the 1973 Woods Hole study with the small physical model were started in January 1974 in southeastern Florida at the Harbor Branch Foundation Laboratory.

Reported here is an overview of our experiments with the integrated polycultures in Woods Hole and Florida which consist of growth systems for marine algae (mostly diatoms), oysters (*Crassostrea virginica*) and clams (*Mercenaria mercenaria*), detrital feeders such as polychaete worms (*Nereis virens* and *Capitella capitata*) and shrimp, and a variety of seaweeds in various food chain combinations.

#### 1973 WOODS HOLE STUDY

The physical model used in this study was a revised and expanded version of the previously reported system (Goldman et al., 1974). The system, as depicted in the schematic flow chart (Fig.1) and viewed in the photograph (Fig.2), consisted in part of two circular algal growth ponds (fiberglass-lined) each of 2.27 m diameter and 50 cm deep (2 020 l). Continuous mixing and aeration were accomplished with both motor-driven rotating arms and recirculation through pumping.

Secondarily treated effluent was collected daily from the trickling filter treatment plant at Otis Air Force Base located 15 km from the Woods Hole

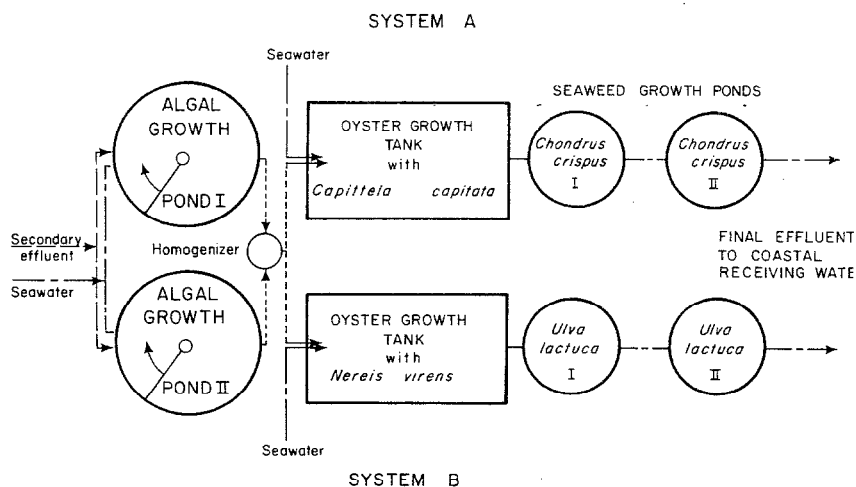


Fig.1. Schematic flow diagram of nitrogen stripping—aquaculture system.

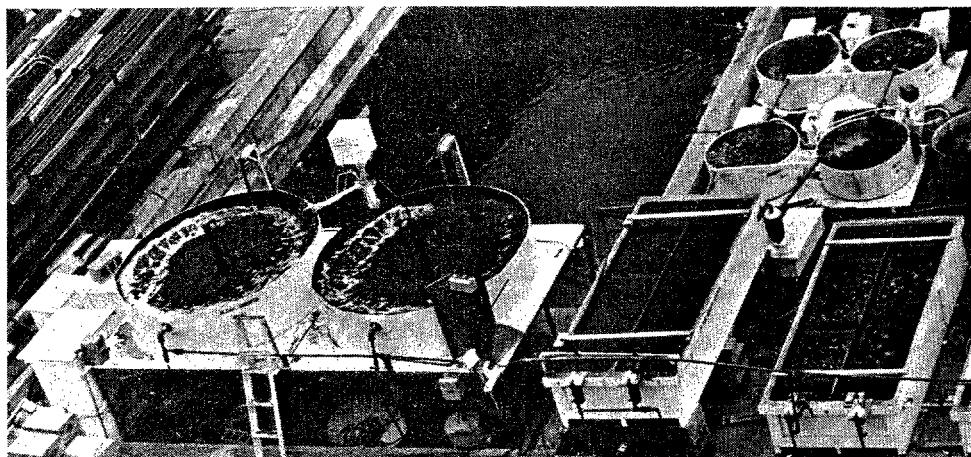


Fig.2. Photograph of nitrogen stripping—aquaculture system.

Oceanographic Institution dock where the experiment was performed. The nutrient characteristics of the treated effluent were previously described by Goldman et al. (1974), and were virtually the same during the current study. Inorganic nitrogen concentrations were typically about 10–20 mg/l.

The waste water was pumped from a 1 000-l polyethylene storage tank along with 1  $\mu$ -filtered sea water to headboxes above the ponds, and then blended into each pond at the desired flow rate and mixture. The algal ponds were elevated on steel frames so that the pond effluents flowed by gravity through the remainder of the system, discharging into Woods Hole Harbor.

The continuous effluents from both algal ponds were mixed in a common line and were considered as one flow for evaluating the performance of the remaining system (Fig.1). The combined pond effluent was then passed through a high-speed homogenizer (Tekmar Model SD-45) so that any clumped algal cells were separated intact to insure the availability of single-cell food to the oysters. Only a portion of the total effluent from the algal ponds was used as food for the oysters, with the excess culture used in concurrent but separate experiments.

The remaining portion of the process, consisting of the oysters, worms, and seaweeds, was divided into two parallel systems (Fig.1). System A consisted of oysters and worms (*C. capitata*) combined in a growth tank similar to the one used previously (Goldman et al., 1974). 1 000 small oysters — later increased to 2 000 — were used in each tank, representing a significant increase in oyster biomass as compared to the 500 oysters of similar size used in the previous study (Tenore et al., 1973; Goldman et al., 1974). The algal culture was added to the oyster tank at a constant rate of about 0.35 l/min, supplemented by 100 $\mu$ -filtered sea water pumped in at rates varying from 5 to 8 l/min. The entire overflow from this tank was then discharged to the first of two seaweed ponds in series, each containing *Chondrus crispus* previously collected in local coastal waters. The seaweed growth ponds were 355-l circular tanks (1.12 m diameter and 36 cm deep), constructed of fiberglass. Mixing was accomplished through recirculation.

A nominal standing crop of 5 000 g (wet weight) of *C. crispus* was maintained by removing the entire crop weekly, shaking free the excess water, and then weighing the biomass. Any biomass over 5 000 g was harvested.

System B was a duplicate of System A except that the polychaete worm was *N. virens* and the seaweed species was sea lettuce *Ulva lactuca* at a standing crop of 3 000 g (wet weight).

During the 6 months of continuous operation of the experimental model, considerable time and effort were expended in acquiring and stocking the animal and seaweed components and empirically achieving the proper balance in numbers and biomass between them. Insufficient time was left to obtain meaningful data on the growth and production of the shellfish, deposit feeders, and seaweeds. Primary attention was therefore focused upon the production of unicellular algae as a function of both wastewater concentration and exchange or dilution rate (reciprocal of retention time) and upon the mass balance of nutrients, especially nitrogen, through the entire system from wastewater input to final discharge. This information will be published elsewhere (Goldman and Ryther, in press), but is reviewed briefly as follows.

Chemical monitoring consisted of determinations for total inorganic nitrogen ( $\Sigma N = \text{NH}_4^+ \text{-N} + \text{NO}_2^- \text{-N} + \text{NO}_3^- \text{-N}$ ) (tri-weekly), and pH, particulate nitrogen (PN), and particulate carbon (PC) (twice daily). All techniques were as reported previously (Goldman et al., 1974).

In one of the algal growth ponds the mixture of waste water and sea water was varied from 30 to 67% waste water, representing an increase in the  $\Sigma N$

load from 5 to 10 mg/l, and a corresponding decrease in the salinity from 20 to 10‰. The dilution rate was held constant at 0.5 day<sup>-1</sup>. For each wastewater-seawater mixture, steady-state conditions were established by maintaining the desired flow for a minimum of 7 to 10 days. As seen in Fig.3, the production of PN and PC, representing algal biomass, increased with an

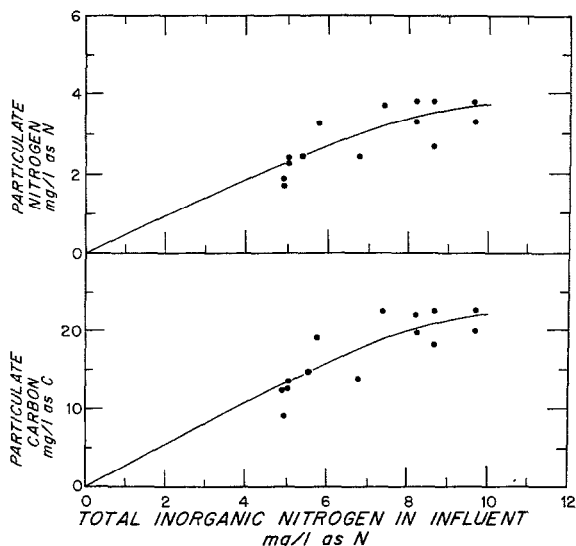


Fig.3. Effect of variations in wastewater-seawater mixture on algal particulate nitrogen and carbon production at a dilution rate of 0.5 day<sup>-1</sup>.

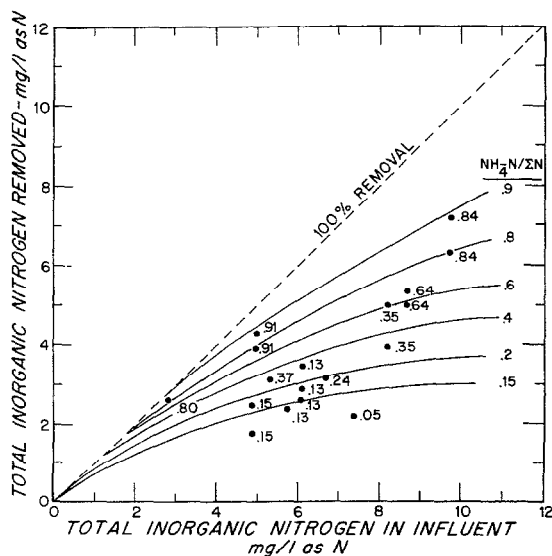


Fig.4. Effect of influent  $\text{NH}_4^+\text{-N}/\Sigma\text{N}$  ratio on total inorganic nitrogen at a dilution rate of 0.5 day<sup>-1</sup>.

increase in  $\Sigma N$  loading until a maximum PN value of about 3–4 mg/l was reached. The influent  $\Sigma N$  concentration of approximately 8 mg/l at this peak biomass level represented a wastewater fraction of about 40–50% of the total influent flow.

Only about 50% of the influent  $\Sigma N$  could be accounted for as PN. Removal of the remaining  $\Sigma N$  appeared to be highly dependent on whether  $\text{NH}_4^+\text{-N}$  or  $\text{NO}_3^-\text{-N}$  was the dominant form of  $\Sigma N$  in the waste water. During the experimental period the  $\Sigma N$  concentration in the waste water remained relatively constant at 10–20 mg/l. However, operations at the wastewater treatment plant varied during the test period, and as a result the  $\text{NH}_4^+\text{-N}/\Sigma N$  ratio changed considerably. Shown in Fig.4 are a series of contour curves illustrating the increasing removal of  $\Sigma N$  as the  $\text{NH}_4^+\text{-N}/\Sigma N$  fraction in the secondarily treated waste water increased. This effect was measured by differences in influent and effluent levels of  $\Sigma N$ , and was consistent at all concentrations of influent  $\Sigma N$ . For example when the  $\text{NH}_4^+\text{-N}/\Sigma N$  ratio was 0.8–0.9,  $\Sigma N$  removal efficiency decreased slightly from almost complete removal at low  $\Sigma N$  loadings of 2–3 mg/l to removals of about 7–8 mg/l at high  $\Sigma N$  loadings of 8–10 mg/l. At the same time a maximum of only 3–4 mg/l of PN was produced when the  $\Sigma N$  load was greater than 8 mg/l (Fig.3). When  $\text{NO}_3^-\text{-N}$  was the primary form of  $\Sigma N$  ( $\text{NH}_4^+\text{-N}/\Sigma N = 0.15$ ) and the  $\Sigma N$  loading was 8 mg/l only about 3 mg/l was removed (Fig.4). This removed  $\Sigma N$  could be virtually accounted for by the formation of PN (Fig.3).

It was surmised that when the  $\text{NH}_4^+\text{-N}/\Sigma N$  ratio was high the evolution of  $\text{NH}_3$  to the atmosphere was mainly responsible for the added removal of  $\Sigma N$ . Afternoon pH values typically rose from influent levels of 7.3–7.6 to 10.1–10.3 in the pond cultures as the aqueous buffer system was destroyed through inorganic carbon assimilation by the algae. At these high pH values un-ionized  $\text{NH}_3$  was the major form of  $\Sigma N$ , thus enhancing the evolution of  $\Sigma N$  to the atmosphere at the intense level of agitation employed. Therefore, it is apparent that for maximum nitrogen removal it will be necessary to prevent nitrification of the waste water at the biological treatment plant which serves the nitrogen stripping–aquaculture system.

Also, utilization of high wastewater fractions (up to at least 67%) appear to be technically feasible without any obvious deleterious effects on algal growth through salinity decreases. However, at least in the current experiments, it appeared that  $\Sigma N$  assimilation by the marine algae was not enhanced beyond a wastewater fraction of about 40–50%, although total  $\Sigma N$  removal was highly dependent on the  $\text{NH}_4^+\text{-N}/\Sigma N$  ratio. Whether this upper limit for assimilation was caused by light or other nutrient limitations was not established. Similarly, the effect on nitrogen removal of using different waste waters, at dilutions with sea water similar to those used in these experiments, remains to be determined.

The dilution rate in the second pond was maintained at four levels (0.25, 0.50, 0.75, and 1.00  $\text{day}^{-1}$ ), and the wastewater fraction was held constant at 50% of the total pond influent. As seen in Fig.5, under relatively steady

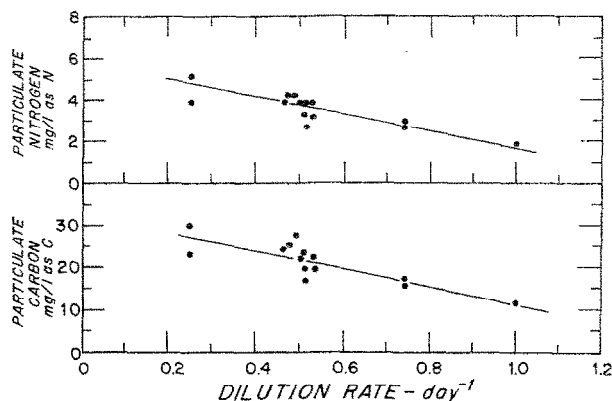


Fig. 5. Effect of dilution rate on algal particulate nitrogen and carbon production at a wastewater-seawater mixture of 1 : 1.

state conditions, pond PN and PC concentrations decreased almost linearly as the dilution rate increased in the range described with concomitant decreases in  $\Sigma N$  removal.

On the basis of these results, selection of the optimum dilution rate and wastewater-seawater mixture appears to depend on whether exploitation of the oyster or seaweed system is the desired end-result. In the current experiment the maximum yield of PN ( $1 \text{ g/m}^2/\text{day}$ ), occurred at a dilution rate of  $0.75 \text{ day}^{-1}$ . At this dilution rate and a wastewater fraction of 50% the maximum production of oysters would be obtained. Use of higher dilution rates and wastewater fractions would decrease the yield of PN, resulting in reduced oyster production, and increase the  $\Sigma N$  load to the seaweed system. The efficiency of the seaweed crop in removing  $\Sigma N$  and the desirability of promoting a seaweed crop in favor of oyster cultivation would obviously dictate how the algal system would be designed and operated.

No attempt was made initially to inoculate a particular algal species into the ponds. Rather, when the ponds were started up early in May 1973, natural populations were allowed to develop. During the entire experiment marine pennate diatoms were the exclusive algal species, although there was a succession of species among the pennate forms.

From May until mid-June *Phaeodactylum tricornerutum* was dominant, followed by an unidentified naviculoid diatom which prevailed until mid-August. *Amphora* sp., a small pennate form, then prevailed until mid-September when the naviculoid species returned as the main diatom. These results are very similar to the changes in diatom species that occurred in the previous study (Goldman et al., 1974), in which *P. tricornerutum* was dominant for most of the experiment, except during the period from late August to mid-September when *Chaetoceros* sp., a small centric diatom, prevailed.

The change from larger pennates to smaller diatoms appears strongly correlated with temperature, as the highest pond temperatures ( $25\text{--}28^\circ\text{C}$ )

were observed when the smaller species were dominant. This phenomenon typically occurs in natural marine waters (Ryther, 1969).

The total mass flow of  $\Sigma N$  through Systems A (oysters—*C. capitata*—*C. crispus*) and B (oysters—*N. virens*—*U. lactuca*) was compared by averaging all of the data collected during the 6-month test period (Table I). When considering only that fraction of the  $\Sigma N$  load in the algal pond cultures that flowed to Systems A and B, and excluding the fraction of  $\Sigma N$  in the sea water added to the oyster systems, there was approx. 90% removal of wastewater-borne  $\Sigma N$  in System A and 99% removal in System B.

TABLE I

Inorganic nitrogen transformations in an integrated food chain system. Average total inorganic nitrogen loads expressed in g/day

System	Oyster tanks input				Seaweed ponds input		Final effluent	
	Algal* ponds input	Algal* ponds output	Seawater fraction	Total input	I	II	Total	Less seawater fraction
A	3.06	1.43	0.55	1.98	2.46	1.61	0.85	0.30
B	3.09	1.34	0.53	1.87	2.56	1.25	0.56	0.03

\*based only on fraction of wastewater—seawater load treated through complete system.

In calculating  $\Sigma N$  regeneration in the oyster tank, no attempt was made to separate the contribution of the oysters from that of the worms. For System A, containing *C. capitata*,  $\Sigma N$  regeneration amounted to about 30% of the  $\Sigma N$  originally removed in the algal ponds; for System B containing *N. virens* it was about 40% (Table I). In contrast, the regeneration of  $\Sigma N$  in the previous experiment amounted only to about 16–18% of the  $\Sigma N$  removed in the algal system (Goldman et al., 1974). It would appear that the increase in regeneration levels was due to the fact that more oysters along with the worms, were present in the current study.

The removal of  $\Sigma N$  was practically identical in the phytoplankton and seaweed systems (Table I). However, the average  $\Sigma N$  removal in the phytoplankton system reflects the composite of many experiments in which the dilution rate and wastewater—seawater mixture were varied. Based on the mass flow of nitrogen introduced to the seaweed system, they appeared ideally sized to remove virtually all of the  $\Sigma N$  not removed in the algal ponds or regenerated by the oysters and worms. For further  $\Sigma N$  removal more seaweed biomass would have to be used.

It was apparent that more efficient removal of  $\Sigma N$  occurred in System B containing *U. lactuca* than in System A containing *C. crispus*. Over 60% of the  $\Sigma N$  removed in the seaweed ponds of System B occurred in Pond I as compared to 53% removal in Pond I of System A. In addition, the average

C/N ratio in the *U. lactuca* increased from 7.8 in Pond I to 10.0 in Pond II, indicating that the seaweed in Pond II was nitrogen-starved. On the other hand, the C/N ratios in the *C. crispus* were relatively constant at 8.6 in Pond I to 8.9 in Pond II. The lower C/N ratio in Pond I of System B would suggest that *U. lactuca* is more efficient in assimilating  $\Sigma N$  than *C. crispus* when nitrogen is in excess. However, a major problem developed with use of *U. lactuca* that made *C. crispus* a far more attractive species to use. On an infrequent but persistent basis *U. lactuca* would go into the reproductive stage with the result that much of the biomass would be lost through release of spores. New thallus growth would quickly occur, but compared to *C. crispus*, which never went into the reproductive stage, the *U. lactuca* ponds were highly unstable. The added attraction of using *C. crispus* is that it is already a commercially attractive crop because of its high content of carrageenin, a chemical used as a suspending agent in the food industry.

In general, the results of the 1973 experiment were most encouraging. The reliability of the integrated system was firmly established on the basis of 6 months of continuous operation. In addition, the very high removals of wastewater-borne nitrogen achieved suggest that the process is a promising alternative to more conventional tertiary treatment methods. Termination of the experiment in October 1973 was dictated solely by the readiness of the new Environmental Systems Laboratory with its significantly larger facilities for carrying out similar experiments on a pilot-plant scale over extended periods.

#### ENVIRONMENTAL SYSTEMS LABORATORY

In the fall of 1973, the Woods Hole Oceanographic Institution's Environmental Systems Laboratory was completed and occupied. This laboratory was designed and constructed to serve as a pilot plant for the W.H.O.I. Waste Recycling—Aquaculture Project as well as to provide space and facilities, including a relatively large-flow treated seawater system, for related studies in aquaculture and pollution assessment, control, and management (Figs 6 and 7) (Huguenin, 1975).

Because of temporary logistic and financial problems in obtaining daily shipments of the required large volumes of treated wastewater effluent from the nearest treatment plant (Otis Air Force Base or Wareham, Mass.) to the tank storage system, the algal farm was initially operated with "artificial wastewater effluent", a mixture of monobasic sodium phosphate and ammonium chloride. These salts, made up and delivered in concentrations comparable to secondary wastewater effluent, together with filtered sea water, have been added continuously to the 130 000-l algae ponds beginning in December 1973. Two of the algal ponds can be heated and circulated by heat exchangers in the mechanical space of the laboratory, and they were operated at 15°C throughout the winter. Following the initial heating and enrichment, a population of mixed diatoms rapidly developed in the ponds which, after a few weeks,

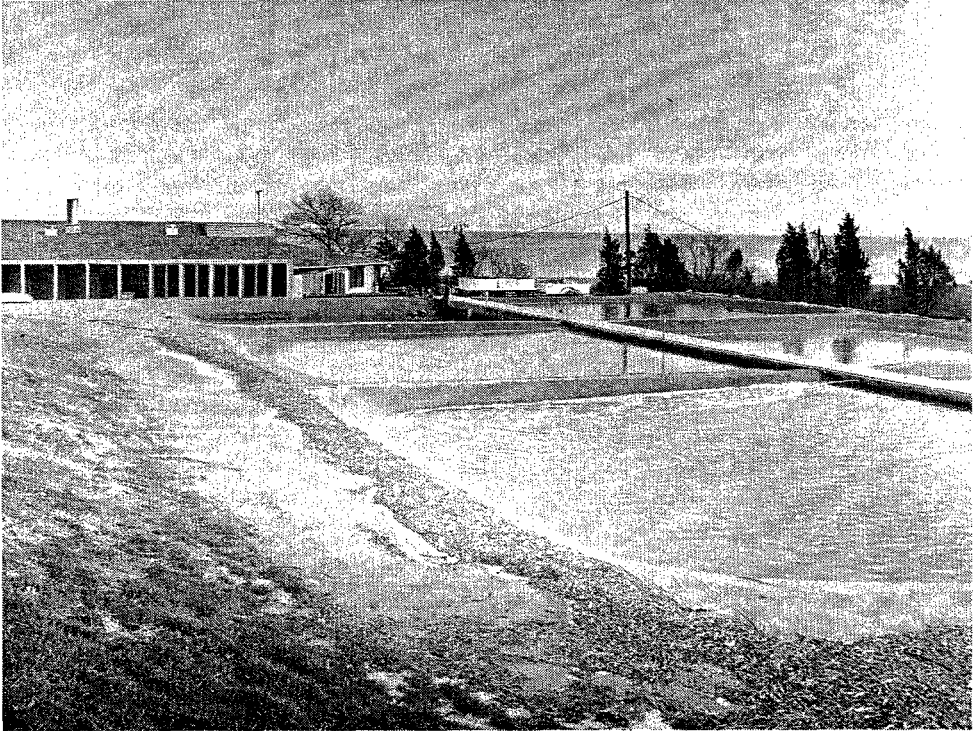


Fig. 6. Environmental Systems Laboratory. Laboratory with algae ponds in foreground.

evolved to virtually a pure culture of the diatom, *Phaeodactylum tricornerutum*. This culture, in each of the two ponds, has been maintained for 8 months at a concentration of approximately  $10^6$  cells/ml with a turnover rate of 30% of the pond volume per day and an input of sea water and nutrients comparable to 50% treated wastewater effluent. Little or no change in algal production has occurred in response to variations in solar radiation associated with storms or cloudy weather. Beginning in April 1974, the algal ponds were operated at ambient water temperature; all six ponds were put into operation, and algal production was comparable to that obtained earlier in the season with the heated ponds. At the time of writing final arrangements have been made for the daily delivery, beginning in July 1974, of 30 000 l of secondary effluent from a nearby treatment plant. At that time the two heated ponds will be switched to a 1 : 1 mixture of secondary effluent and sea water and operated in this mode throughout the year.

The output from each algal pond (ca. 45 000 l/day) is fed by gravity into one of the 12 m  $\times$  1.2 m  $\times$  1.5 m deep cement raceways which contain 150 000 seed oysters (*Crassostrea virginica*) approx. 2.5 cm long or 150 000 seed hard clams (*Mercenaria mercenaria*) approx. 1.25 cm in length (longest dimensions). The shellfish are held in stacked wooden trays, lined with plastic (Vexar) mesh, at approx. 3 000 animals per tray. A flow of sea water variously

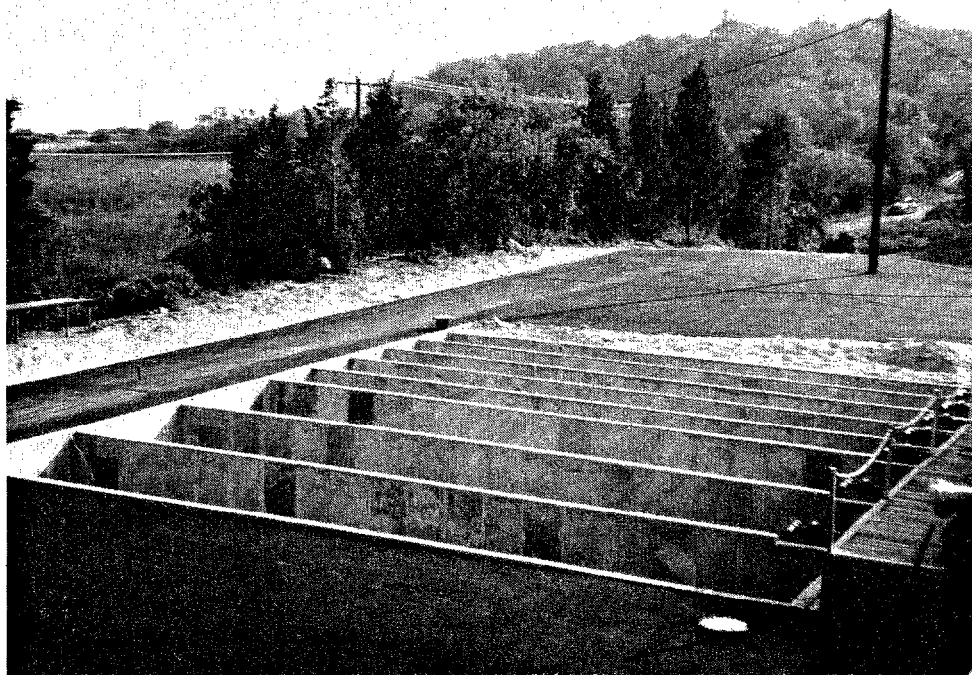


Fig. 7. Environmental Systems Laboratory. Animal raceways.

filtered and/or heated and at different flow rates is added to each of the shellfish raceways to dilute the food and provide additional flow for oxygen supply and waste removal. The raceways containing the shellfish are covered with plywood sheets to prevent fouling of the animals with filamentous algae and to reduce heat loss.

The small polychaete worm *C. capitata* has been inoculated in the bottom of one of the raceways containing the oysters, where it feeds upon the feces and pseudofeces produced by the molluscs. These organisms, inoculated in January 1974, have been observed to be multiplying but the population has not been assessed since it was stocked. 500 winter flounder (*Pseudopleuronectes americanus*) (length 3–6 cm) were subsequently stocked in this raceway to feed upon the capitellid worms.

The raceway containing the hard clams has been stocked with 1 400 juvenile “bait worms” (*Nereis virens*) approx. 2 cm in length. It is expected that these worms, which may reach lengths of 25 cm at maturity, will grow on the clam biodeposits, as occurred in our small-scale experiments during the summer of 1973. To provide the worms with shelter and to reduce cannibalism, the bottom of this raceway has been lined with beach stones to a depth of 5–10 cm (fine sand tends to become anoxic and unsuitable as a substrate).

The discharge from the raceways containing the molluscs flows into and through adjacent raceways stocked with seaweed (*Chondrus crispus*), which is kept in suspension by aeration along one edge of the bottom of the raceway (providing a circular rotation of the water). The purpose of the seaweed, as in the earlier experiments, is to provide the final "polishing" step to remove nutrients not initially assimilated by the diatoms in the algae ponds together with soluble nutrients added to the system by the shellfish, worms and fish.

In the 8 months since the Environmental Systems Laboratory was first occupied, the expanded, "pilot-plant" model of the waste recycling-marine polyculture system has gradually been put into full operation, the various components stocked with organisms, and the complete unit empirically balanced to achieve the dual objectives of advanced waste treatment and aquaculture. Performance data are now being taken and, after sufficient experience, will be reported separately.

An interesting new departure recently initiated at the Environmental Systems Laboratory has been the growth, in one of the 15-m diameter (130 000-l) ponds, of a mass continuous culture of brine shrimp (*Artemia salina*). The pond now contains a dense culture of adult *Artemia*, started from nauplii hatched from eggs in the laboratory, in which living young are actively being produced. The daily harvest from an algal pond (45 000 l/day of diatom *P. tricornutum* at approx.  $10^6$  cells/ml) is introduced into the *Artemia* pond from which the brine shrimp completely remove the algae. The corresponding harvest of 45 000 l/day from the *Artemia* pond contains both adult and larval brine shrimp which are fed into a raceway containing trout and other plankton-eating fishes.

Although the system is currently operated on an "artificial" wastewater food chain in which full sea water (salinity 30‰) is enriched with highly concentrated nutrients as described above, preliminary laboratory experiments indicate that the *Artemia* will continue to grow and reproduce at a salinity of 15‰, consistent with a 50% wastewater effluent enrichment of the algal ponds.

The wastewater-algae-brine shrimp-trout food chain, or modifications thereof, may represent an attractive alternative to shellfish production in cases where the concentration of pathogens from waste water by the molluscs cannot be satisfactorily corrected or resolved. It is recognized, however, that introduction of an additional link in the food chain will lead to reduction in the production of the final product (fin fish) by 80–90% from that which could be expected from the herbivores.

#### FLORIDA EXPERIMENTS

The systems described above appear to operate effectively and with a high degree of efficiency for nutrient removal, but only insofar as the inherent biological processes are working at or reasonably near their optimal conditions. In temperate climates, during the winter months, biological processes for many, if not most species come to a virtual standstill as water temperatures

fall below 10°C. In many locations, such as New England, water temperatures may approach 0°C.

The heating of seawater and wastewater effluent to permit biological activity to continue and the system to operate throughout the winter would be prohibitively expensive. A possible solution would be to use the heated effluent from the once-through cooling water system of a coastal power plant, but this would require side-by-side locations of the utility and waste-treatment plants and other constraints that would impose severe limitations to the application of the concept. The rationale can also be used that advanced wastewater treatment (nutrient removal) is most critically needed in summer, particularly in coastal resort communities where both population and coastal water use are at their peaks. But all things considered, the system we have developed and described above is clearly most practical for tropical and semi-tropical climates where the biological processes will operate continually throughout the year at ambient water temperatures. It is also obvious that both the physical—chemical environment and the biota, including the organisms that could be used in our system, are different at least to some extent in the tropics from those that occur in temperate latitudes, and that experience obtained in the latter (i.e., Woods Hole) is not necessarily easily translated to a more tropical climate.

For the above reasons, we have considered it advisable to initiate experiments in Florida, and we were able to transport the entire system used in the 1973 Woods Hole experiment, as described here, to the Harbor Branch Foundation Laboratory in Fort Pierce, Fla., under a grant from the Atlantic Foundation. The system was installed in January 1974 and is currently in full operation (Fig.8). Treated wastewater effluent from a small extended aeration plant serving the Harbor Branch Laboratory community and located adjacent to the aquaculture facilities is used in the various experiments. Not only does the location provide excellent year-round climatic conditions, but we are able to test the feasibility of utilizing a variety of native species in the system. For example, native seaweeds such as *Hypnea musciformis*, *Eucheuma isoforme*, *Gracilaria foliifera*, and *Agardhiella tenera* (all commercially valuable algae) are being tested in the seaweed growth systems, and juvenile white shrimp *Penaeus setiferons* have been stocked in the oyster system as a detrital feeder. Ancillary experiments dealing with the feasibility of operating a benthic marine algae—grey mullet (*Mugil cephalus*)—seaweed food chain as an alternative to our previous diatom—mollusc—seaweed system are under way. In addition, a one-step wastewater-fed seaweed system will be examined.

#### PROCESS APPLICABILITY

At present the process offers a rather Utopian solution to two important problems facing man: wastewater pollution and the shortage of proteinaceous foodstuffs. We are, however, fully aware of the many inherent problems associated with the recycling of waste products into edible food in closed-

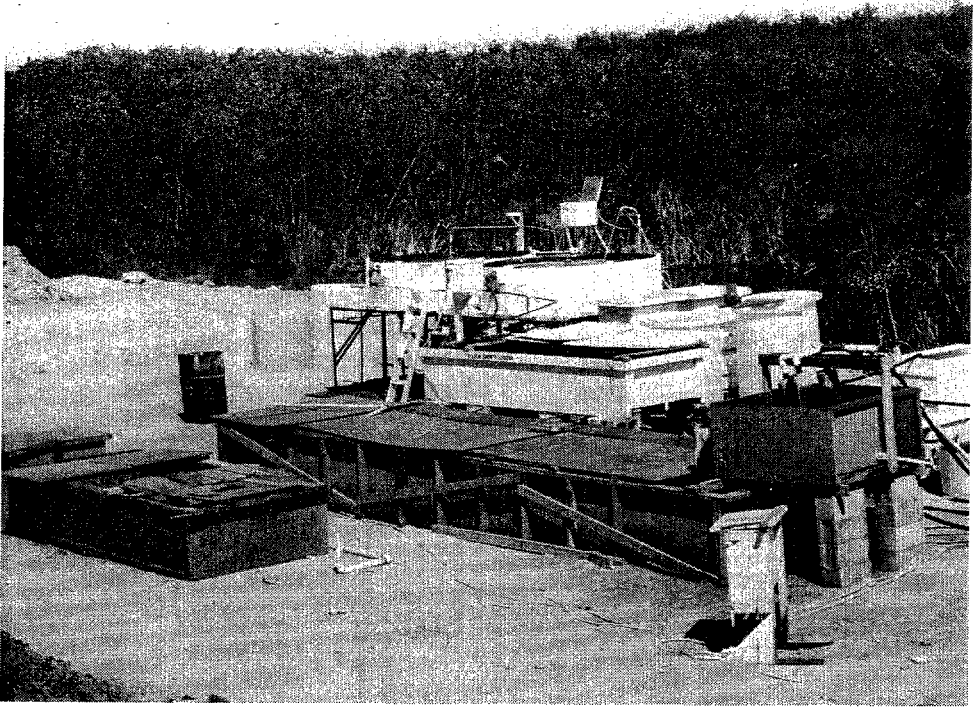


Fig.8. Harbor Branch Laboratory aquaculture facilities.

loop systems. The very fact that so little is known about both the survival, transport, and accumulation of wastewater-borne pathogens in the biological systems, especially viruses (Vaughn and Ryther, 1974), and the potential toxicity of other substances in waste water (Ongerth et al., 1973), both known and unidentified, is reason enough to raise questions regarding the use of marine organisms grown in a sewage-based food chain as human food.

We have shown, though, that technically the system is entirely feasible both from the standpoint of advanced wastewater treatment and the development of aquaculture. Considerable future research will be required for proper identification of, and solutions to, the problems associated with the transport and accumulation of pathogens and trace contaminants in the system. Successful resolution of these problems will depend upon our ability to treat or control the quality of waste water entering the aquaculture system and/or to deplete the organisms thereby produced in contaminant-free sea water to the point where they are unquestionably safe and acceptable for human consumption. Our research in these areas has just begun, but promising new approaches provide encouragement for their ultimate solution.

## ACKNOWLEDGEMENTS

This project was supported by National Science Foundation (RANN) Grant GI-32140, NOAA Sea Grant 04-4-158-5 and The Atlantic Foundation.

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