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Experiments With Engineering of Marine Ecosystems[1]

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Abstract

Moderate sized ecosystem cultures were attempted in concrete ponds simulating some principal bay types found on the Texas Coast: (a) the reef-plankton brackish bay, (b) the grassy bottom, and (c) the blue-green algal flats. Processes and successional changes within the engineered systems were monitored with diurnal curve methods. Some general aspects of photosynthesis, community respiration, and organismal dominance were similar to those of the bay prototypes.

The relative role of respiration and reaeration was delimited in several experiments. In a sequence of extreme salinity shocks, one oyster reef-bay system exhibited rapid metabolic recovery and successive diatom blooms like that in San Antonio Bay.

Some experimental means for partial replication of artificial ecosystems were tested with concrete reef ponds in triplicate. High alkalinity regimes at controlled salinity were developed with evaporation and freshwater inflow sequences like that in some Texas river estuaries. pH control was also demonstrated with carbon dioxide gas injections from tanks. Over a six-month period a semi-anaerobic system replaced an aerobic system. It was shown that a pollution-resembling syndrome could gradually emerge from a more normal aerobic system where there was initial inorganic nutrient fertilization. The graphs resembled some based on data from upper Galveston and Nueces Bays. The low nighttime oxygen regime was a climax for the summer weather regime. Pyrheliometer data were used to compute efficiencies of gross photosynthesis (0.8 — 3%), in utilizing the visible wave lengths somewhat less than in the bay prototypes.

In a large concrete pond, a grassy bottom system without stratification provided populations of diatoms, zooplankton, and foraminifera with diurnal variations, trace element concentrations, and metabolic quotients like those in Redfish Bay and Aransas Bay.

In very shallow ponds, heavy blue-green algal mats once transplanted, were maintained with large diurnal oxidation and reduction changes and high metabolic quotients like those in parts of the Laguna Madre.

Some similarity of processes and concentration levels maintained in these artificial ecosystems may justify their use for controlled experimental study of the bays.

Introduction

In previous papers measurements of gross photosynthesis and system respiration were reported for various bays along the Texas coast (Odum and Hoskin, 1958; Odum and Wilson, 1962; Odum, 1963; and Odum, Cuzon, Beyers, and Allbaugh, 1963). The metabolic measurements indicated the functional state of these ecosystems under influences of seasonal change, pollution, dredging, and other experimental changes. In such large bays, the investigations were restricted to the natural experimental situations fortuitously provided. For further study of these bays, some smaller models were needed in which controlled experimental manipulations might be feasible.

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In 1960 and 1961, to meet the need for experimental ecosystems, plastic and concrete ponds were built. Attempts were made to develop formulae for culturing ecosystems with ecological engineering methods. By selection of depth, salinity, and mechanism of circulation, conditions in several bays were simulated and these ponds were heavily seeded with water, muds, and organisms from the several bay prototypes. This is a report of the metabolic patterns which resulted in 4 types of ecosystem cultures in these ponds.

Conditions in the pond systems were devised to simulate three important bay ecosystem types. The first type was the low salinity, turbid bay containing oyster bars in which a biogeochemical cycle was maintained that included the phytoplankton-producing water circulating over the concentrations of sessile reef consumers, filter-feeding and releasing nutrients from the reefs. Copano, San Antonio, and Matagorda Bays were examples. A plastic system (Fig. 1A) in 1960 was continued with concrete systems in 1962 (Fig. 1B). The second type was the shallow grassy bottom bay at about 30‰ with much of the photosynthesis by benthic plants such as parts of Redfish and Aransas Bays. The large pond (Fig. 1C) was used. The third type was the system of blue-green algal mats carpeting the thin-water flats of part of the Laguna Madre often under hypersaline conditions. Shallower, smaller ponds were used for these (Fig. 1D).

ECOSYSTEM CULTURING, ECOLOGICAL ENGINEERING

Experiments with small microcosms have been useful in showing some of the abstract general patterns of succession, climax, population structure, and biogeochemical cycling that are observed in larger natural ecosystems. Because of their small size they could be replicated and manipulated in controlled experiments at the ecosystem level of study (Odum and Hoskin, 1957; Beyers 1962, 1963a, 1963b).

A logical continuation was the culture of somewhat larger experimental ecosystems in concrete tanks so that some of the larger-scale processes might be included such as larger animals, larger genetic reservoirs, water current systems, natural lighting fields, larger geochemical reservoirs, and sea-air exchanges. Such larger microcosms may serve as simulators of the expansive natural systems where enough of the dominant organisms and controlling processes can become established. The culture of ecosystems thus may provide means for study and eventual management of larger ecosystems. For example, can species of commercial interest be most simply managed by culturing the ecosystem in which they are dominant?

In a previous commentary (Odum, 1962), ecological engineering was defined as environmental manipulations by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources. Formulae for ecological engineering may begin with natural ecosystems as a point of departure, but the new ecosystems which develop may differ somewhat since boundary conditions established in the engineering process are different.

Thus attempts to culture some marine ecosystems in ponds are also experiments in ecological engineering of new systems because of such special conditions as pumped circulation, tank walls, constant salinity, and diminished imigration from larger population reservoirs.

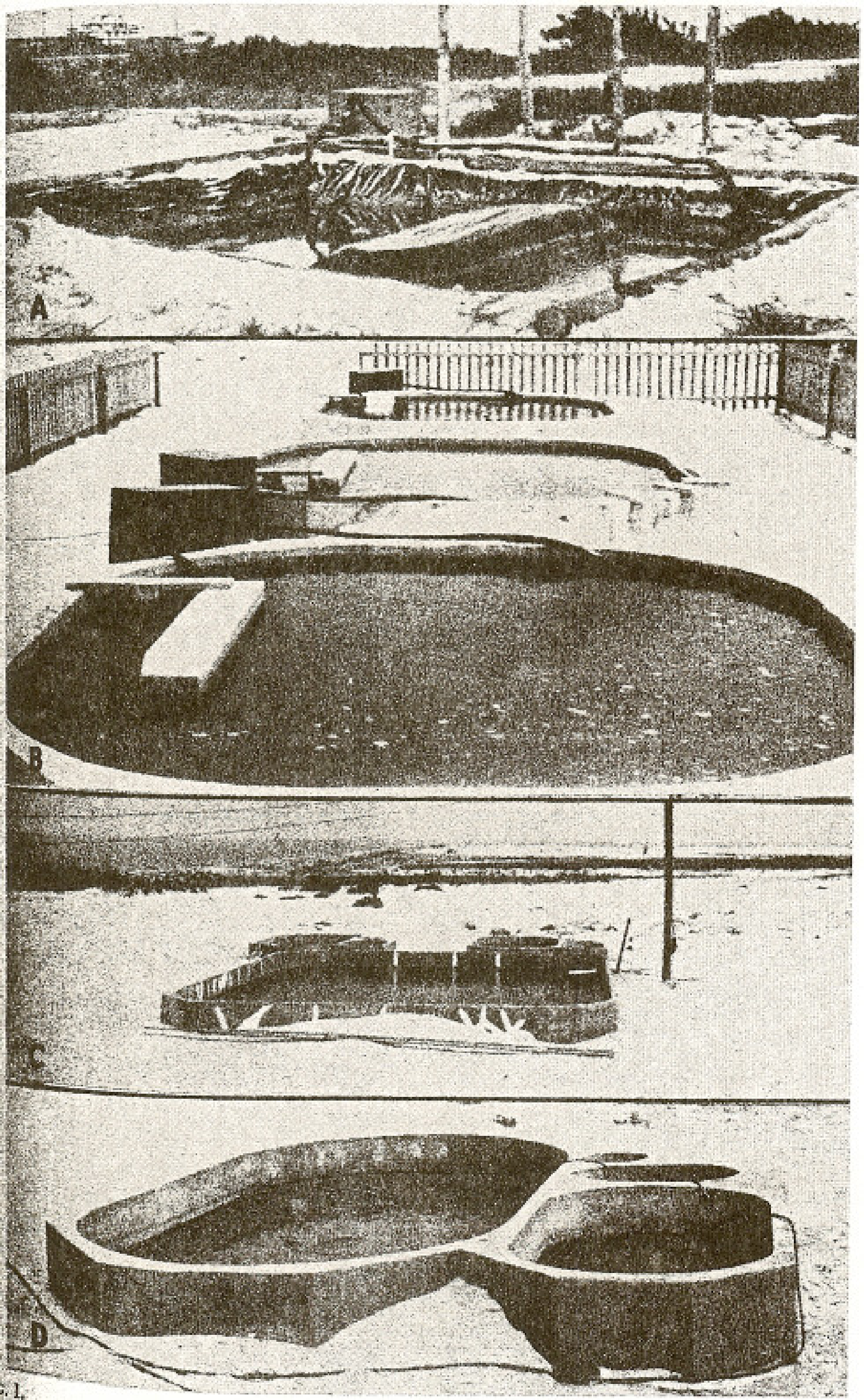


FIG. 1.
A. Plastic oyster reef pond system with island and circulatory pump.
B. Triplicate reef ponds in concrete.
C. Grass Pond.
D. Blue-green mat ponds.

Methods

MEASUREMENTS

Diurnal curve methods for study of photosynthesis and respiration were followed as described in other papers on oxygen (Odum and Hoskin, 1958; Odum and Wilson, 1962); on pH-CO_2 (Beyers and Odum, 1959; Beyers, *et al.*, 1963). Diurnal curves were very uniform and regular without the complication of diurnally varying current velocities found so often in field measurements. However, reaeration constants in the reef ponds were a function of the stirring rates in the ponds with pumps.

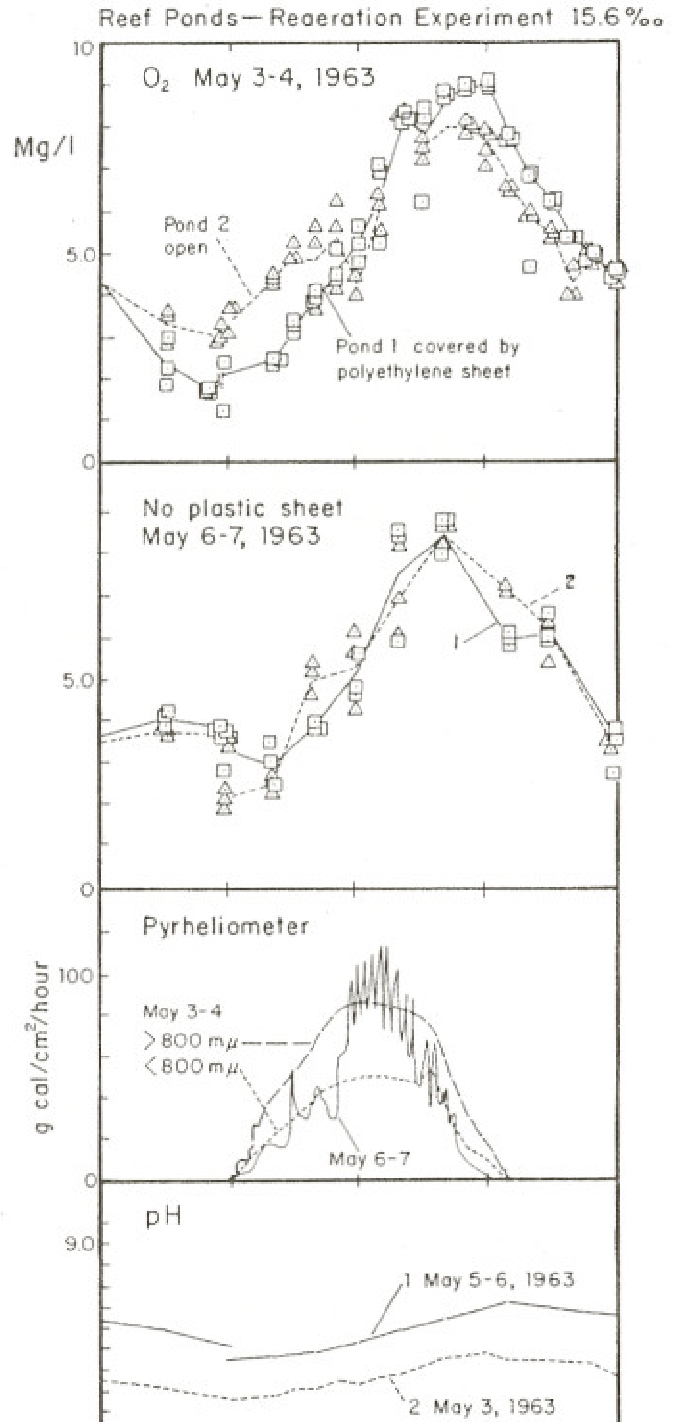
Reaeration constants for the plastic pond and the grass pond were estimated from the graphs on the limiting premise of constant nighttime respiration. This older procedure overestimates the diffusion constant because it includes any change in nighttime respiration rates as part of changes in reaeration rate.

In the triplicate reef ponds an experiment was conducted to infer the reaeration constant comparing a plastic covered pond with one not covered as reported in Fig. 2. Following a winter shut-down period, new oysters and other reef components were added and the ponds interpumped for two days. After ponds were again isolated on May 3–4, a heavy polyethylene transluscent sheet was placed on top of the surface of pond number 1 with less than 1% of the water surface exposed to air. Pond 2 was left uncovered. Evidence that the oxygen patterns of the ponds were similar was obtained May 6–7 with both ponds uncovered. Since insolation was less that day as indicated by the pyrheliometer the May 6–7 data are not a perfect control on the plastic experiment May 3–4.

The two May 3–4 diurnal oxygen curves (covered and uncovered) were plotted together for comparison (Fig. 2). The rates of oxygen decrease at night were greater in the covered pond. The difference between the rates of night decline in the two ponds divided by the saturation deficits provided a reaeration coefficient that was used for computing oxygen metabolism values in these ponds (0.5g $O_2/m^3/hr$ at 100% deficit). That this coefficient led to oxygen data in agreement with pH-CO_2 method with a nighttime RQ of 0.7 to 1.1 was a check on the approximate accuracy of the reaeration constant used. Rate of change graphs corrected with this constant show a decline of respiration between sunset and sunrise as already studied extensively by Beyers (1963a, 1963b) in other systems. When the constant respiration assumption is made in the old procedure, a reaeration constant between 1 and 2 g oxygen per m^3 results. As discussed elsewhere (Odum, Beyers and Armstrong, 1963) the respiration decline at night is expected to be maximal in a system like that of the reef ponds in which nanoplankton are important and less important in systems with more plant storage capacity for labile new photosynthetic products like the benthic systems including the grass pond and the blue-green mats.

For the shallow blue-green mat ponds, a reaeration constant of 1 $g/m^3/hr$ at 100% deficit was used based on studies of other shallow environments with benthic communities (Odum and Wilson, 1962).

Application of the Ohle (1953) test for Winkler interference was made in the ponds with results similar to findings in the bays. Winkler results were not more than a few tenths of a mg/1 off in aerobic conditions, but larger errors 1 mg/1 or more developed during the low oxygen periods late at night. Thus, as indicated in Table 1, Ohle correc-



2. Comparison of diurnal oxygen graphs in interpumped triplicate ponds with and without sheets resticting reaeration, May 3–6, 1963. pH records are for uncovered ponds. The diurnal ls of total insolation were made by an Eppley pyrheliometer and the visible fraction computed by cting the values when covered by an RG-8 Schott filter which transmits in the infra-red.

Tarle 1

Ohle Analyses

			1 Winkler	2 Winkler Plus Ohle	3 Ohle only	4 Corrected (2-3)	5 Anomaly (1-4)
Reef Pond, Sept. 12, 1962	Pond 1	0600	0	2.72	1.99		
			0	2.60	1.44		
			0	2.65	1.98		
			0	2.66	1.80	.86	—.86
	Pond 2	1830	11.37	14.21	2.55		
			11.37	14.11	2.52		
			11.47	14.06	2.55		
			11.40	14.13	2.54	11.59	—0.19
Mat Pond, July 3, 1962	Pond 1	1500	14.14	13.92	0.17		
			13.49	14.95	0.28		
			13.81	14.44	0.22	14.22	—0.41
Mat Pond, Sept. 4, 1962	Pond 1	1845	7.38	9.02	0.08		
			7.33	8.82	0.14		
			7.35	8.92	0.11	8.81	—1.46
	Pond 2	0540	0.0	0.28	0.0		
			0.0	0.59	0.0		
			0.0	0.44	0.0	—	—
Mat Pond, Sept. 3, 1962	Pond 1	1900	6.93	3.42	1.35		
			2.88	4.24	1.13		
			4.90	3.83	1.24	2.59	—2.31
Blue-green Mat Transplanted to Laboratory Cylinder, Sept. 5, 1962		0600	12.4	14.4	1.03		
			10.6	12.2	1.80		
			11.50	13.3	1.41	11.89	—0.39
Sept. 5, 1962		1800	9.20	11.10	0.0		
			14.70	18.10	1.35		
			12.40	15.40	2.39		
			12.1	14.9	1.25	13.65	—1.55

tions are required in the night periods. That this occurs in fertile marine systems without pollution is of considerable interest. Since metabolic rates are computed as changes, the effect on computations of rates becomes significant mainly in the computation which corrects for reaeration. In this paper the original Winkler analyses are shown and the Ohle correction also indicated where known, but the metabolic rates are made with an Ohle correction. Further evidence for a diurnal change in Winkler interference is provided in a paper on abnormal bays (Odum, *et al.*, 1963).

Since the pH-CO_2 method involves neither reaeration correction nor interference correction, comparison of the metabolic results of the two methods concurrently are important. Metabolic quotients are computed where data are available (Table 2).

Gross photosynthesis and 24 hour respiration rates are related on a molar basis (CO_2/O_2). As indicated in the several examples in the figures, a slanted straight line is drawn from pre-dawn respiration to post-sunset respiration for this purpose.

The Mancy-Okun lead-silver membrane electrode for oxygen was used in the systems with near-anaerobic conditions to show the presence of some oxygen and confirm the interference with the Winkler analyses indicating zero at that time. Phosphorus measure-

TABLE 2

Metabolism, Metabolic Quotients, and Efficiencies of Gross Production based on 50% of pyrheliometer records.

	Pond number	Oxygen g/m²/day		Carbon g/m²/day		Metabolic quotient CO^2/O_2		Efficiency $O_2 \times 4.5$
		P	R	P	R	AQ	RQ	% of visible
Reef Ponds (See also Fig. 6)								
March 23–25, 1962	1	9.3	11.5	2.8	3.1	0.80	0.72	2.1
	2	12.5	11.4	....	....	....	....	2.3
	3	16.7	14.6	....	.	....	....	3.3
March 25–26, 1962	1	....	....	1.9	2.8	....	....	....
March 26, 1962	1	....	....	1.6	1.7	....	....	....
April 18–19, 1962	1	5.8	11.6	....	....	....	....	0.9
June 7–8, 1962	11	6.9	6.8	....	....	....	....	1.0
	2	0.4	10.8	....	....	....	....	1.6
	3	6.7	7.3	....	....	....	....	1.0
July 19–20, 1962	1	7.7	12.2	....	. .		....	1.4
	2	5.8	8.7	2.6	2.5	1.22	0.78	1.0
	3	6.6	9.6	....	....	....	....	1.2
August 8–8, 1962	1	7.8	9.5	....			. .	0.8
	2	8.9	10.7	3.8	3.5	1.1	0.88	0.9
	3	5.8	10.0	....	....	....	....	0.6
Sept. 11-12, 1962	1	13.7	13.7	....	....	....	....	2.2
	2	15.2	19.2	....	....	....	....	2.4
	3	4.7	9.5	....	....	....	....	0.7
Sept. 12–13, 1962								
½ covered with plastic	1	14.0	17.0	....	....	....	....	2.2
Uncovered	2	13.2	14.1	....	....	....	....	2.3
May 3–4, 1963								
With plastic cover	1	6.6	7.4	....	....	....	. .	0.7
Uncovered	2	5.1	5.8	2.2	2.0	1.2	0.7	0.6
May 6–7, 1963	1	5.1	7.1	2.5	2.4	1.7	1.1	1.05
	2	5.1	4.8	....	....	....	....	1.05
Grass Pond (Also see Fig. 11)								
June 8, 1961		3.3	4.8	1.7	1.9	1.3	1.06	0.5
June 15–16, 1961		2.8	3.8	1.2	0.72	1.1	0.5	0.7
July 12–13, 1961		4.8	3.8	4.0	1.5	2.2	1.0	0.6
Blue-green Mat Pond								
July 3–4, 1962		5.2	5.4	5.2	5.2	2.7	2.5	0.5
July 22–23, 1962		....	....	1.3	1.3	....	....	....
Aug. 6–7, 1962		....	....	12.3	12.0	....	....	....
Plastic Pond (See also Fig. 4)								
Nov. 6, 1960		1.5	0.1	1.2	0.7	2.1	1.9	....

ments were made with perchloric acid digestions following Zwicker and Robinson (1944). Iron analyses were made by Miss Lorna McGough and Dr. Patrick Parker using the phenanthroline method of Lewis and Goldberg (1954). Alkalinites were titrated with dilute HCl to an end point of pH 5.0 indicated with a glass electrode.

Except during August, 1961, and August, 1962, continuous recordings with a 50 junction Eppley pyrheliometer were taken using an amperometric recorder of Yellow Springs Instrument Co. Calibration was made using the electrical voltage equivalent of radiant energy supplied by the Eppley Co. and by means of amperage measurements with a Weston-calibrated microammeter. To obtain the fraction available to photosynthesis, the pyrheliometer was covered with a box made of RG-8 Schott filters which excluded the visible rays available for photosynthesis but transmitted the infra-red rays not usable in photosynthesis. The difference between the two was taken as available energy for primary production. See the example in Fig. 2. To compute efficiency where the filter was not used, visible light was taken as 50% of total pyrheliometer record. In much of the field work reported in previous papers, a hand light meter with an approximate foot-candle scale provided by the manufacturer was used (General Electric Golden Crown Exposure Meter, Type PR3, with an incident light attachment). The ease of use, sensitivity, portability, and low cost made the meter useful in the field. Whereas it is not possible to convert approximate foot-candle data to energetic data without detailed analysis of the spectral composition, in practice where there are some similarities in spectral composition of incident insolation it may be possible to obtain some empirical relations between the foot-candle data and the pyrheliometer data for some representative sunny conditions such as clear sky and broken cumulus. Foot-candle and pyrheliometer graphs were plotted as overlays in several diurnal graphs in this paper. A graph of foot-candle estimates with the GE meter is plotted as a function of pyrheliometer readings in Fig. 3. This graph provides a rough method for converting one type of data to the other where only one was available in similar circumstances in the south Texas area. The abscissa is 50% of total insolation so that foot-candle estimates can be converted to available energy for photosynthesis. The dashed line is extremely

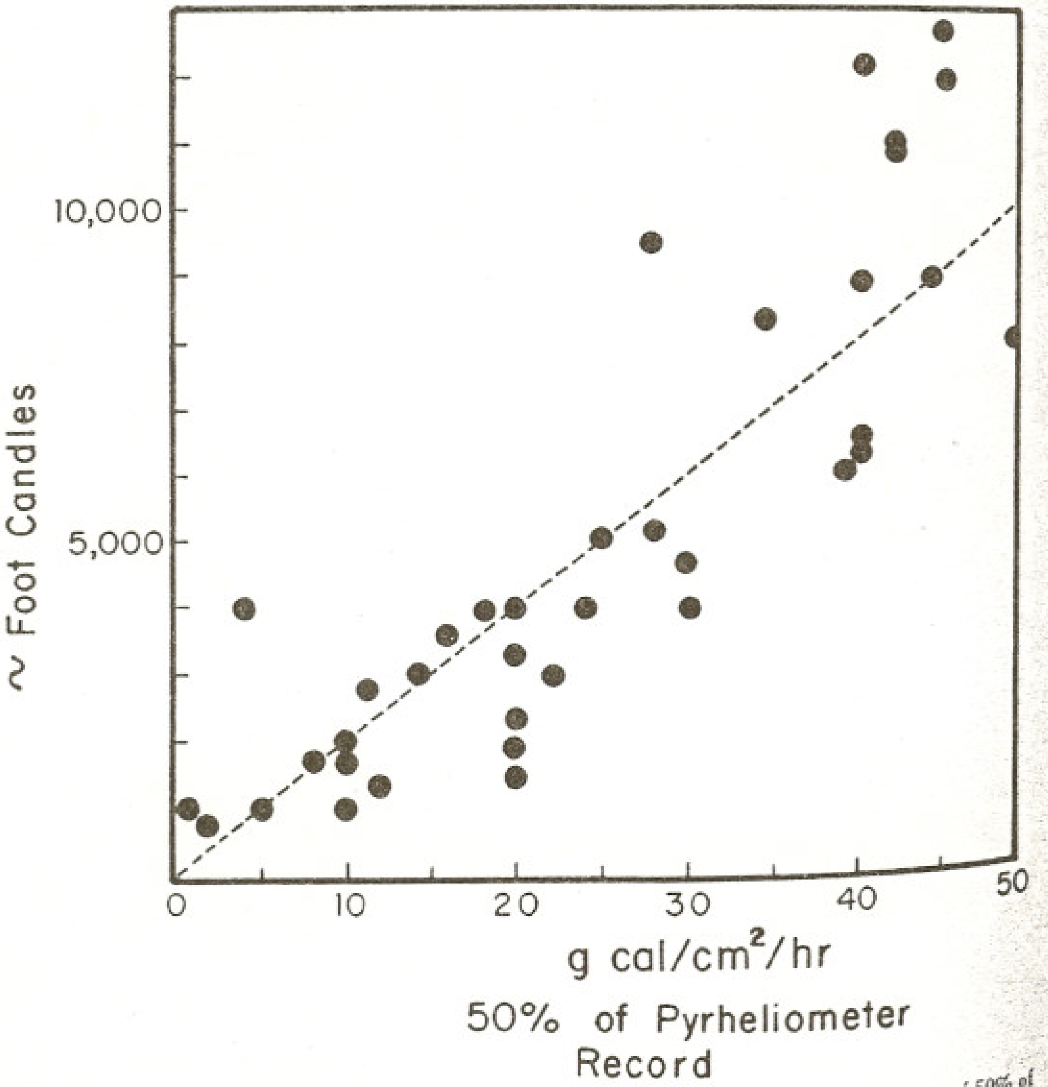


Fig. 3. Graph of foot candles from a General Electric hand exposure meter as a function of 50% of the total radiation from an Eppley Pyrheliometer.

approximate. Use of the Schott filter indicated that percentages of total insolation in the visible were from 45 to 80% depending on clouds.

Total organic matter in water samples, and the organic matter in millipore filtrates were analyzed according to the persulfate digestion and infra-red CO_2 method of Wilson (1962).

After the experience with cracking of the large pond in Hurricane Carla, later ponds were constructed with enough reinforced steel and basic foundations on creosote pilings jetted 12 feet into the sand to prevent damage from undermining of the sand by hurricane waves and currents.

DIURNAL SAMPLING BUOY

With the help of Dr. Marcel Gres and Tracor, Inc., of Austin, Texas, a floating fiberglass buoy was developed for filling 125 cc glass stoppered bottles over a 24 hour period. A timing motor operating from a storage battery operated a solenoid valve and a selector switch allowed the bottles to fill every three hours by gravity fill. Originally, the buoy was designed to take samples for later measurement of oxygen and pH, but no satisfactory method was found for preservation since all of the preservatives and poisons yet tested either changed oxygen contents or interfered with the Winkler method. Curves which duplicated those in the outside water were obtained only in turtle grass beds in which the plankton was negligible and the waters entering the buoy were thus effectively removed from the metabolism of the community. Although designed with a chamber for ice, tests of the buoy operating with ice indicated inadequate preservation. The mechanical system of the buoy was found to work adequately in the experimental ponds, and the buoy may become useful with diurnal sampling studies involving sampling for radiotracers and other chemical entities not subject to metabolic change while in the bottles. Tracor Corp. manufactured the buoy for $800.

PONDS AND SEEDING SEQUENCES

With the reasoning applied in the microcosm studies, organic biomass and essential inorganic constituents were transferred from the environmental prototype to the tank so that the release of chemicals from respiration and decomposition would provide the inorganic ratios most suitable for the plants of that system and inversely so that the plant species thus competing with that inorganic composition would have the proper nutritive ratio for the consumers normally in that system. Then the dominant boundary conditions of the prototype were set with respect to water depth, circulation rate, and sediment type. Finally species from the prototype environment were added in quantity and diversity including micro-organisms, plankton, benthic animals, and small fishes. Where replications were desired, ponds were intermixed with inter-pond pumping. The ecosystems which emerged in a few days were the result of organizational influences such as natural selection and behavioral responses of species within the system. A moderately large metabolic rate resulted in each of the experimental sequences.

Plastic Reef Pond. In July, 1960, a pond ecosystem simulating a low salinity bay was improvised by laying a black sheet of polyethylene in an excavation in the sand 9 by 5.1 m as shown in Fig. 1A. A small island was arranged at one end, and a live oyster reef from San Antonio Bay was introduced into the narrow channel 0.6 m wide made by the island. A pump was arranged to draw water from the broad part of the pond discharging across the reef at about 0.2 m/sec. Thus the pond water was being moved from bay area to reef simulating bay-reef relations of the oligohaline Texas bays. In several diurnal curves, oxygen sampling was done just above and below the rapid current zone of the reef and the values reported separately (Fig. 5). Fresh water was added to balance evaporation. The area of reef to total photosynthetic surface was 1 to 20 like that in a diagram for the Copano Bay area given by Hedgpeth (1954). Twenty-eight grams of nitrogen and phosphorus fertilizer were added. There were immediate blooms of diatoms with a rich brown color. Then the patterns were followed through the summer and during the fall. In this period, there were interruptions due to heavy rain-floods which overran the pond decreasing the salinity and covering the pond bottom with sand and sediments from outside. In this pattern of events, conditions in the upper bays were simulated.

After one such flooding all the oysters were killed and replaced. It was obvious during the fall experiments that the plastic had been punctured, and the pond was in exchange with the ground water. At the end of the experiment, the system was allowed to become entirely fresh.

Triplicate Reef Ponds in Concrete. In the fall of 1961, the arrangement for the reef-

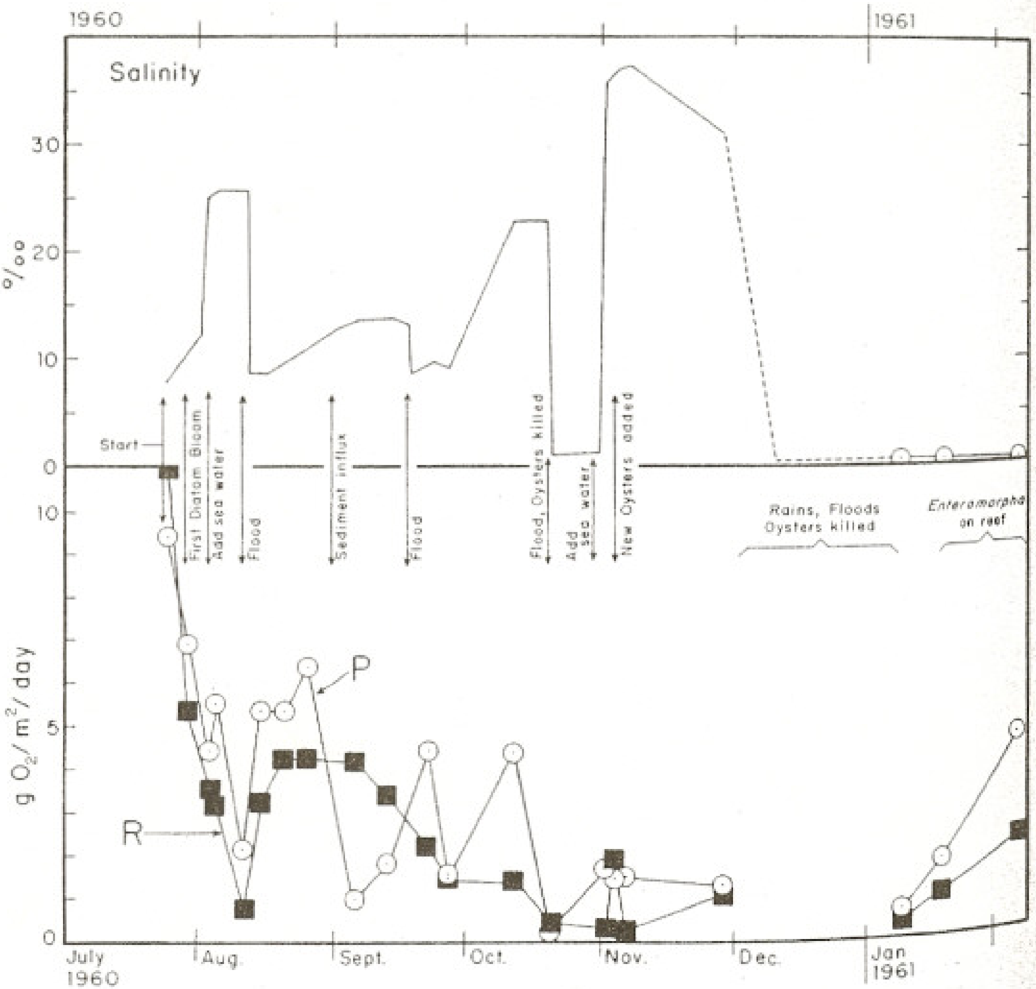


FIG. 4. Seasonal graph of salinity, metabolism, and the sequence of events in the plastic oyster-reef pond system (Fig. 1A).

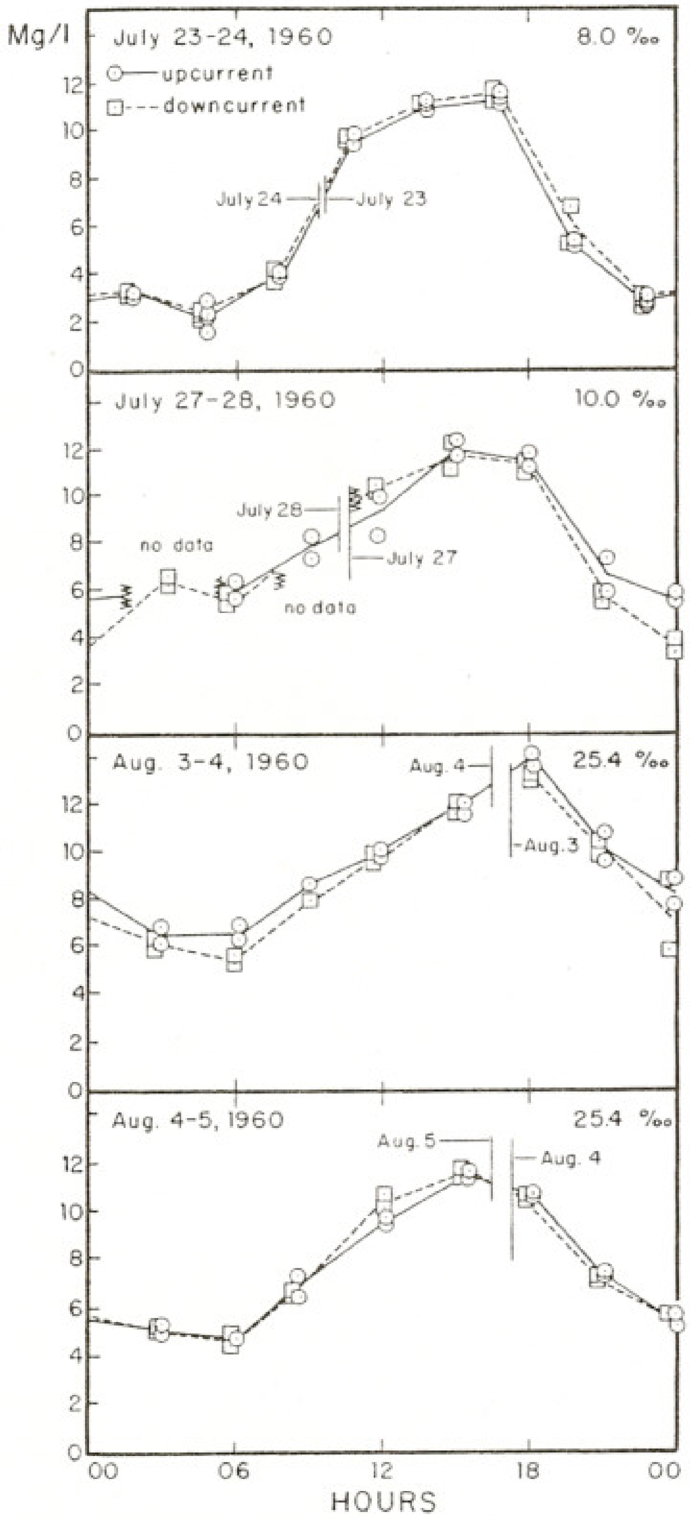


FIG. 5. Four diurnal curves of oxygen in the plastic oyster reef systems. Measurements were made upstream and downstream from the reef assemblage.

island-bay plankton system in the plastic pond was constructed in triplicate in concrete as shown in Fig. 1B. Sea water, sediment, and reef materials were introduced and seeded as before. Depth was adjusted to 0.52 m and salinity to about 16 ‰. The area of water in each pond was 11.4 m^2 and the volume was 5.87 m^3. The three ponds were homogenized by interconnecting intake and discharge hoses of the 3 pumps. Then the pumps were returned to their single pond function of circulating water from the broad area to the reef. Metabolic patterns were compared between the three ponds. In setting up the three ponds the first time 5 pounds of nitrogen and phosphorous fertilizer was added on March 19, 1962, (6% N, 12% P_2O_5, 6% K, Wonder Gro Fertilizer Co., San Antonio, Texas). Very heavy nanoplankton blooms were sustained and anemones, gammarids, mud crabs, barnacles, and other animals on the reef became very numerous. Few oysters survived, however; rotifers dominated the zooplankton. After a period of 6 weeks without intermixing, differences became noticeable in the ponds. Interpumping was continued every few weeks. Later in the summer when the pumps became fouled so that circulation stopped, some stratification and the excess of respiration over photosynthesis produced an almost anaerobic nighttime condition. Then when the pumps were returned to adequate function, the ecosystems continued to maintain a near anaerobic nighttime phase. With declining light in the fall, metabolism in the pond and densities of animals on the reef declined also.

Salinities were adjusted by adding tap water to balance evaporation to a mark previously established on the wall. The alkalinity of the tap water used was 2.1 milliequivalents per liter on May 5, 1962, this water being derived from Corpus Christi water mains and ultimately the dam on the Nueces River. A study of alkalinities was made in these ponds under the arrangement of adding high alkalinity fresh water to balance evaporation.

Twice in May after sediments were added, carbon dioxide gas from a tank was injected for several hours into the pump intake lowering the pH. The carbon dioxide bubbles entering the pump were completely dissolved in passing through the pump system.

A diurnal study of total and filtered organic matter was made by Ronald Wilson on March 24, 1962.

For economy reasons, the interchangeable pump units in these experiments were ⅓ horsepower "Mitey Mites" with the disadvantage of a bronze impeller which undoubtedly contributed copper to the systems. Dicharge rates were 62.5, 63.4, and 60.9 liters per minute on May 7, 1963.

Grass Pond. In the spring of 1961, a concrete pond 13 m by 11 m and 1.3 m deep was constructed with rounded corners as shown in Fig. 1C. In early June turf of turtle grass bottom and associated animals and sediments were brought from Redfish Bay covering the bottom with grass beds in many places and with a layer of sediment throughout. Water to a depth of 0.4 meters was pumped from the inlet nearby. Thereafter, tap water was added as needed to balance evaporation to a mark thus simulating a similar process in the bays where addition of river water tends to balance evaporation. Plankton seeding was continued from many bays during the month. The pond was seined during the month and components of the nekton smaller than about 4 inches were allowed to remain. Diurnal curves of metabolism were taken with oxygen and pH-CO_2 methods. Class projects were done on the ecosystem, including a study of foraminifera by Warren Horton and attached diatoms by Alice E. Sharp. Diurnal measurements of a number of variables were made. The effectiveness of mixing under wind stress was studied with duplicate oxygen and temperature measurements. Studies were terminated by Hurricane Carla which flooded and broke the tank September 9, 1961. The cracks have since been repaired and the system is again in use.

Blue-Green Algal Mat Ponds. In spring, 1962, additional small concrete ponds were built as shown in Fig. 1D. The bottom was covered with a layer of sand. Then on June 28, 1962, partially dry, leathery blue-green algal mats from heavy beds near a bleed-water outfall in the Laguna Madre 3 miles south of the Flour Bluff Causeway Toll Station were collected, stacked, and transported in a station wagon like sheets of burlap. The mats had *Microcoleus*, *Lyngbya* and other genera as interwoven filaments.

These mats were placed over 90% of the bottom sands of the ponds. Sea water was added to a depth of about 10 cm simulating the conditions on the blue-green flats. Thereafter the water levels were allowed to rise and fall with rain and evaporation. Diurnal measurements were made for comparison with similar measurements in the blue-green mat systems of the bays such as reported by Odum, Cuzon, Beyers, and Allbaugh (1963).

Results

Metabolic rates for all pond experiments are given either in the tables or in the seasonal graphs.

REEF POND SYSTEMS

The sequences of salinities, metabolism, and events are given for the plastic pond experiment in Figs. 4 and 5, and for the triplicate concrete ponds in Figs. 6–10.

Plastic Reef Pond. The system was exposed to an alternating sequence of sharp salinity changes like that in the bay prototype. The graph (Fig. 4) shows a rapid recovery of community metabolism following salinity shocks even when the salinity changes caused death of the oysters and other dominant populations as on August 11 and October 20. The ability of the system to substitute new populations with little interruption of photosynthesis or respiration was also noted in field measurements in Nueces Bay (Odum *et al.*, 1963). The decline of metabolism during the latter part of the season accompanied decline in insolation and resembled the decline in metabolism in the bays. The slight metabolism on August 11–12 was associated with heavy rain clouds during the day. The evaporation rate was 8 to 12 cm per week. Daily temperature sequences ranged from 28°C at dawn to 39°C before sunset.

With the pump then being used, there was some injection of bubbles. The reaeration coefficients as determined from the diurnal curves (subject to the assumption of constant nighttime respiration) were variable, in part due to the variable effectiveness of the pump, and ranged from 0.8 to 3.0 gm oxygen per m^2 per 100% deficit. The diurnal curves were all without anaerobic nighttime phases. P and R were out of phase more than in some experimental ecosystems in which irregular boundary fluctuations were eliminated (Beyers, 1963a).

A slightly different oxygen concentration was sometimes found below the reef stream compared with that above (Fig. 5) the difference representing the metabolic and reaeration roles of the reef under the adapted conditions. Possibly significant differences (paired points not overlapping) were present in two of the four graphs, (July 27–28 and August 3–4).

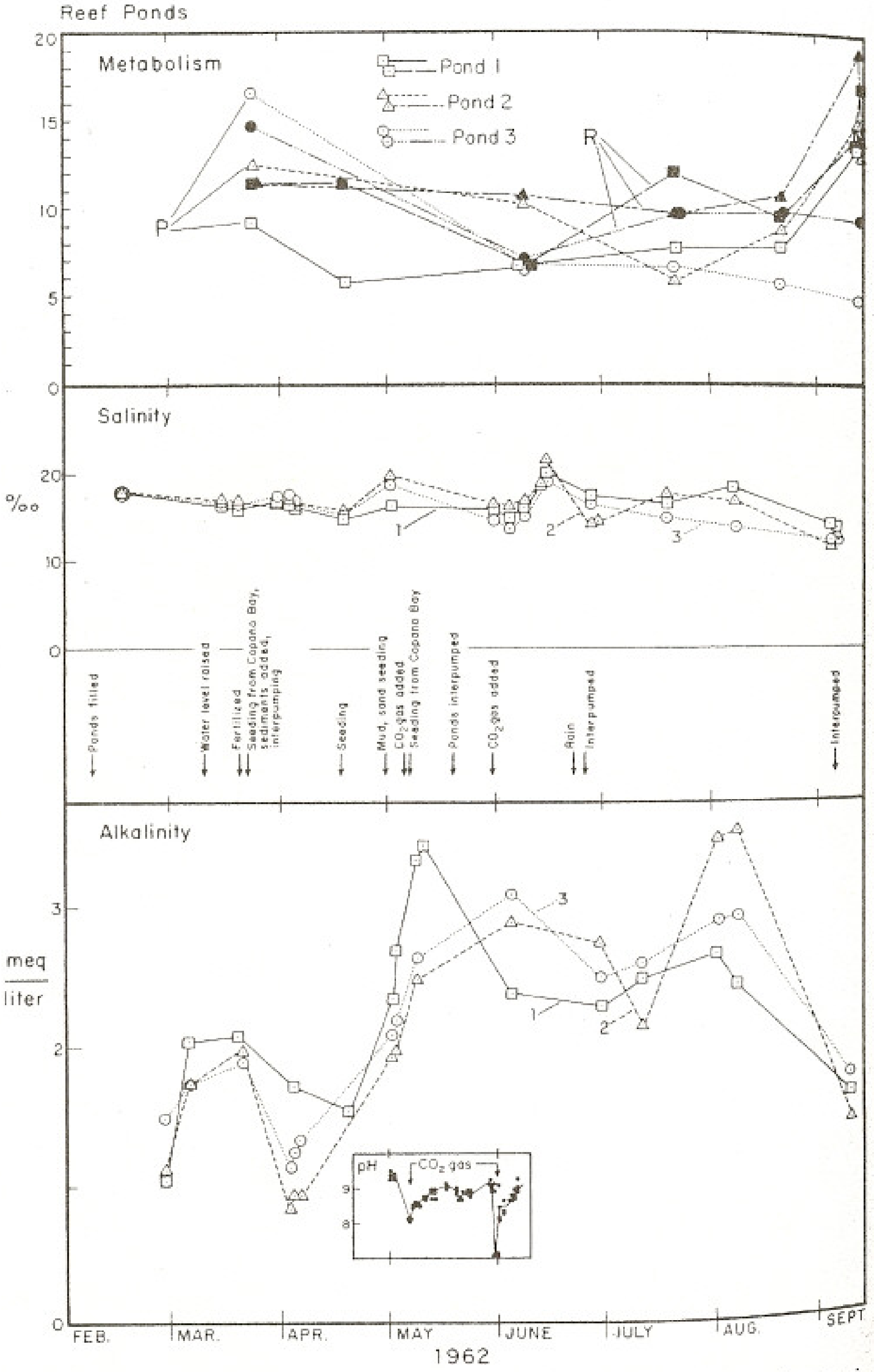


Fig. 6. Seasonal record of metabolism, salinities, alkalinities, and the sequence of events in the triplicate reef ponds in 1962. The pH record during the carbon-dioxide gas injection experiments is given as an inset.

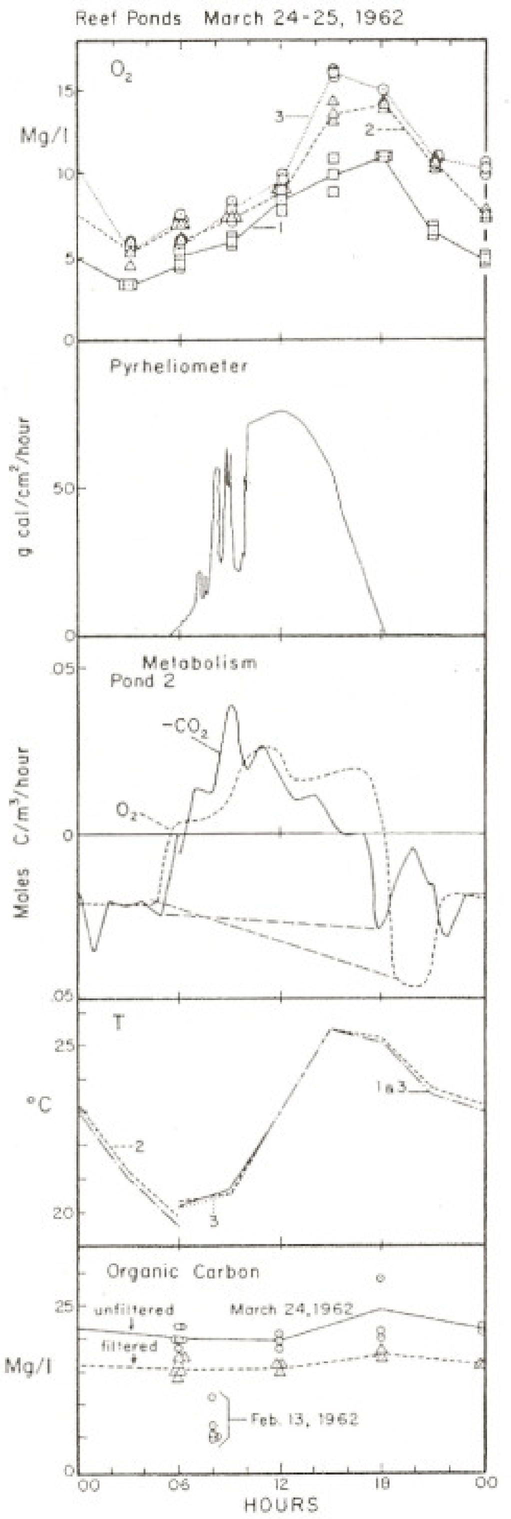


FIG. 7. Diurnal record of oxygen content, total insolation, carbon and oxygen metabolic rate, temperature, and organic carbon concentration in the triplicate reef ponds March 24–25, 1962.

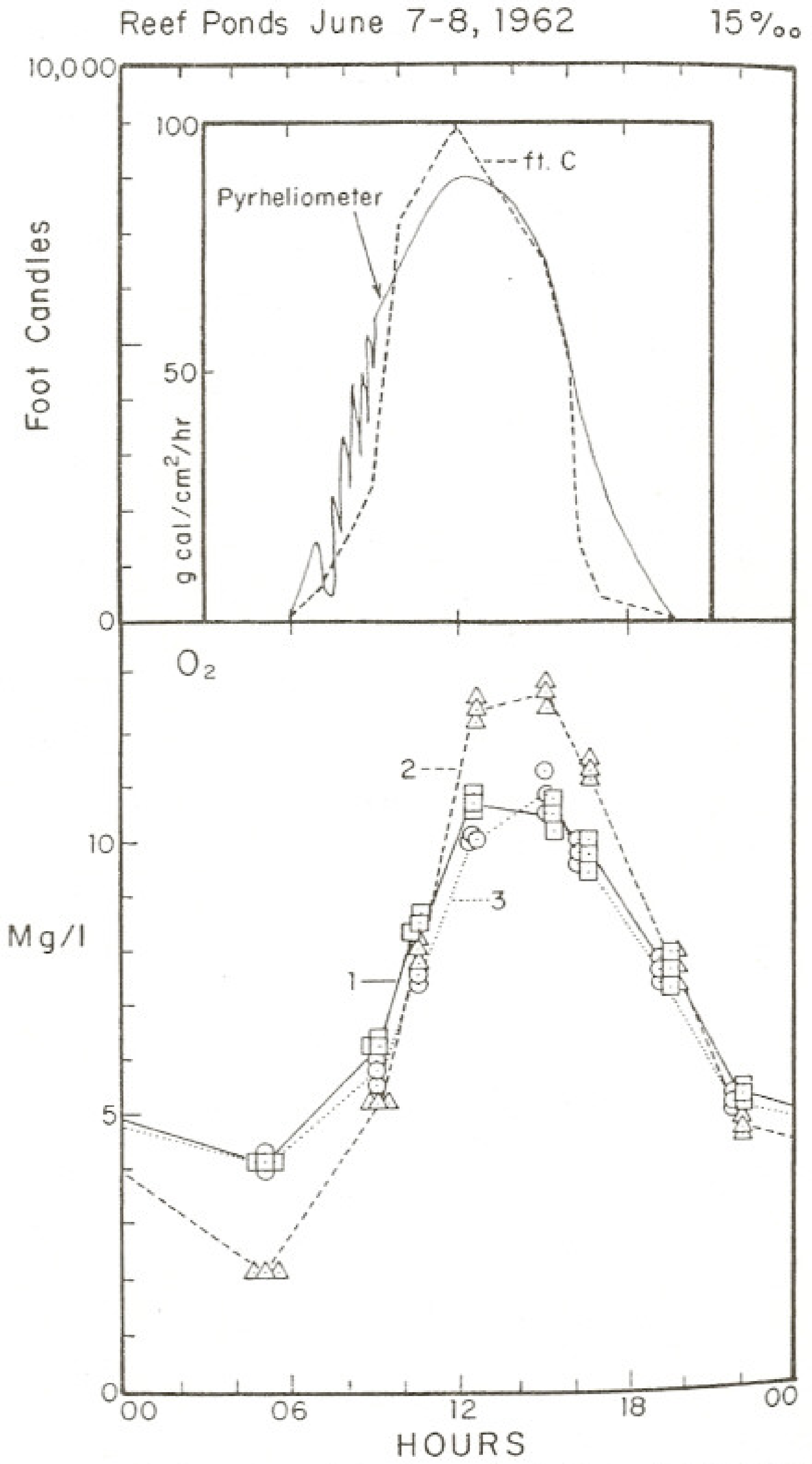


FIG. 8. Diurnal record of incoming insolation, foot candles incident, and oxygen concentrations in the three reef ponds June 7–8, 1962.

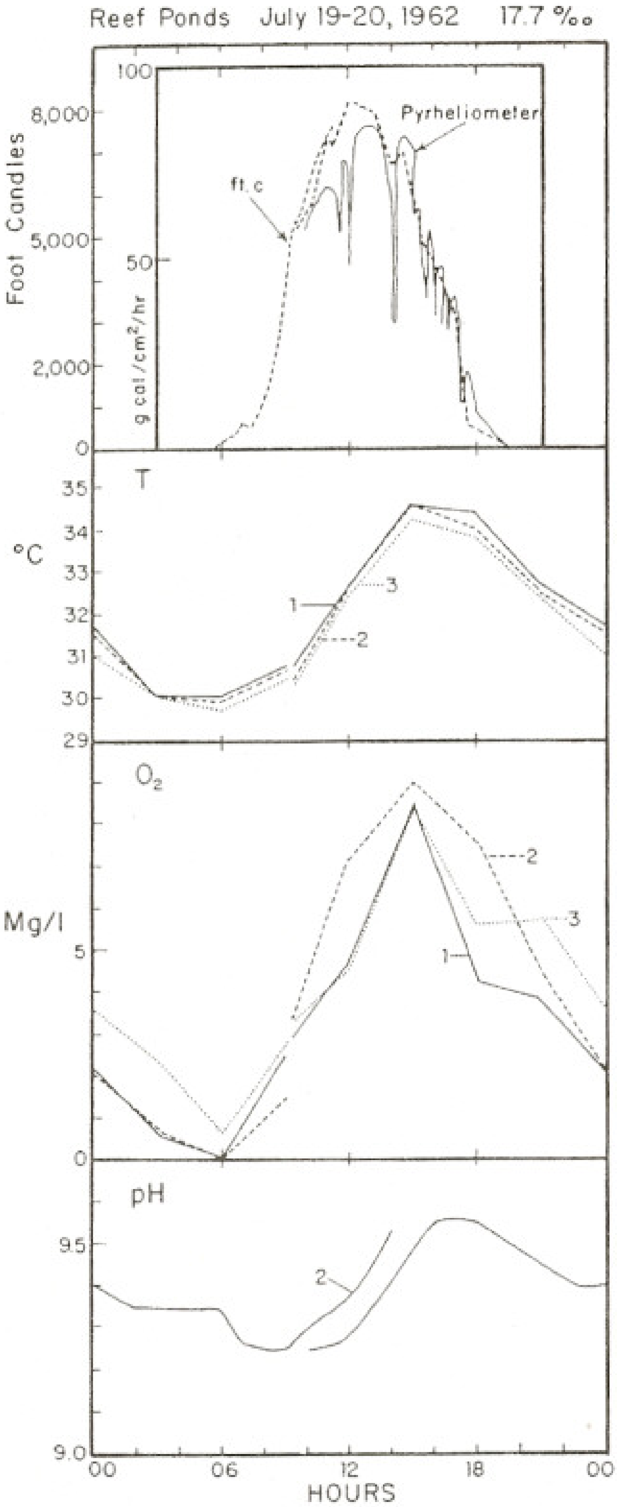


FIG. 9. Diurnal record of incoming insolation, incident foot candles, temperature, oxygen content, and pH in the triplicate reef ponds July 19–20, 1962.

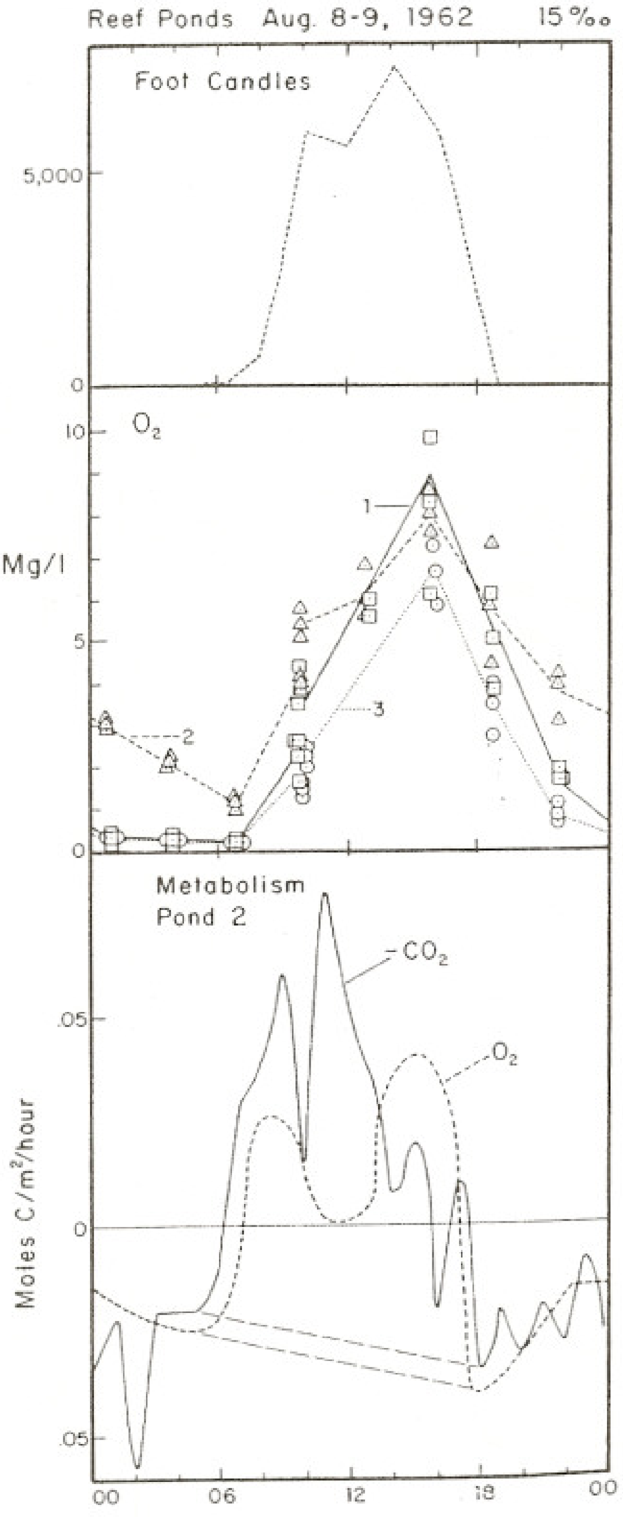


Fig. 10. Diurnal record of incident foot candles, oxygen concentration and rate of carbon and oxygen metabolism in the triplicate reef ponds August 8–9, 1962.

In the upstream and downstream data in Fig. 4, the changes in oxygen concentration range from values too small to be significant to changes of 1.0 mg/1. With a flow of 0.2 m/sec. through a reef cross sectional prism of 0.6 by 0.1 m or less, the reef metabolism ranges from 0 to 2 g/m^2 per hr as prorated over the 22m^2 of the total bay-reef system. Thus the reef at times may have had a metabolic rate dominating the total metabolism, but at other times the metabolic contribution of the reef was minor. Some photosynthetic contribution from reef algae to the system may be detectable in these upstream-downstream curves as indicated by oxygen increases in daytime July 27–28 and August 4–5. The changes on July 23–24 suggest aeration. Large variations in the respiration of an oyster reef may be consistent with the findings of Collier (1959) that oysters pump at widely varying rates in relation to the food concentration.

On November 1, 1960, after the reef had been removed, diurnal metabolic measurements were taken in which the oxygen ranged from 90 to 150 per cent of saturation. Then, on November 2, a new reef of oysters and barnacles was placed in the island channel and another diurnal oxygen curve was taken on November 3 in which the oxygen ranged from 70 to 125 per cent. Whereas photosynthetic rates were similar (November 1, 1.4 g/m^2/day; Nov. 3, 1.6 g/m^2/day) the respiration rates increased from 0.3 g/m^2/day on Nov. 1 to 1.9 g/m^2/day on Nov. 3. However, a low respiration rate of 0.3 g/m^2/day was obtained again on Nov. 6.

At peak population the reef held 123 *Crassostrea virginica*, 410 *Brachiodontes exusta*, 36 small mud crabs, and many *Balanus eburneus* and bryozoa. The spectacular diatom bloom contained numbers up to 1300 *Pleurosigma sp.* and *Amphora sp.* per square millimeter of bottom ooze. The same species were present in six oyster stomachs in concentrations 9 to 10 times greater than outside. Although the water remained relatively clear, diatoms were being transported from their prevalent position on the bottom ooze of the system to the stomachs of the reef organisms via the current system. Increases in the brown blooms were observed after each influx of fresh or salt water.

On the evening of August 10 a large number of the heteronereis form of *Nereis dumerlii* was found swarming on the water surface of the tank, the congregation lasting 2 hours.

Triplicate Reef Ponds. The results of the salinity, alkalinity, and circulation manipulations are graphed in Figs. 6–10. Whereas the plastic pond experiment simulated oyster-diatom populations of the moderately fertile low salinity reef containing bay, different populations developed in the triplicate ponds resembling most the heavily enriched systems of upper Galveston Bay and Nueces Bay. Most of the oysters did not survive, but there was a very heavy reef growth of other consumers, *Balanus eburneus*, gammarids, mud crabs, and sea anemones. The extremely productive plankton was dominated by small green nanoplankters and rotifers. The swarm of small animals on the reef was very much like that observed on reefs between Corpus Christi and Nueces Bays in the same season.

In the spring and early summer the diurnal range of oxygen was within the aerobic range suitable for most larger animals (Figs. 7–8), but by the end of the summer the amplitude of oxygen range had increased so that oxygen values near zero were reached at night (Figs. 9–10). Temporary pump failures caused temporary stratifications and anaerobic nighttime bottom conditions during several days in July. When pump functions were restored, the system continued to develop near-anaerobic nighttime conditions even with sustained mixing. This sequence demonstrated that an enriched bay could follow a succession towards an anaerobic nighttime oxygen condition where radiation and mixing conditions were sustained. Such oxygen regimes provided limits to the number and type of participating animal and plant populations. This experiment indicated that a wide oxygen range pattern once stimulated by some enrichment such as from pollution influx could be self maintaining. Recovery of ecosystems to normal patterns from bay enrichment may not be possible without flushout.

The three ponds set up in a similar manner, seeded, and then interpumped did produce rough replicates with similar dominant plankton, animal populations, salinities and alkalinities. Replication of metabolic rates was not as good since conditions in the ponds gradually drifted apart over a several-week period. As indicated in Fig. 6, interpumping was arranged several times during the 6-month sequence. The degree to which the replications were maintained can be observed from the graphs of ponds 1, 2, and 3. Whereas interpumping momentarily makes the fluid uniform, the nekton, benthos, and reef components are sufficiently different to keep metabolic patterns somewhat apart.

A study was made of the alkalinity changes that accompanied the high rates of pond metabolism. In March when metabolism did not get an effective start in the bare tanks, fertilizer and a sediment floor was added, followed by tremendous blooms in which the alkalinity was lowered as pH levels became very high. What contribution alkali from new concrete was making at this time is not known. Later, as in all the concrete experiments, the walls became heavily coated with a biological encrusting layer thus making the walls similar to the bottom sediments as living biogeochemical exchange surfaces.

Then, in April, more seeding with organic matter containing muds contributed to respiration lowering pH levels somewhat. To control the alkalinity range upward and the pH range downward, an experiment was twice made with injecting carbon dioxide into the ecosystem as an ecological engineering technique. As indicated by the graph in Fig. 6, pH was immediately lowered, rising again in several days with increased alkalinity as the free carbon-dioxide added was neutralized by carbonate solution from the sediments.

During much of the summer, salinities were held fairly constant by adding the hard tap water to maintain a constant water level of 0.5 m. That little further rise in alkalinity developed indicates an equivalent deposition of calcium carbonate in the ecosystem as in the rapid growth observed in barnacles and mussels on the reef.

The increase of alkalinities over that of sea water due to the use of high alkalinity fresh water to balance evaporation apparently duplicates the situation in some Texas bays. Park, *et al.* (1958) showed the increase in alkalinity to chlorinity ratio in the bays. A series of 22 alkalinities from the Aransas Pass inlet into Baffin Bay via the Corpus Christi and Laguna Madre ranged from 2.9 milliequivalents/1 at Port Aransas through values above 3.0 in the upper Laguna Madre to 4.0 in Baffin Bay (Park *et al.*, 1958). This system of high alkalinities is favorable for a regime of calcareous depositions in biological components reefs and sediments so that a steady state can develop between evaporation-inflow and losses from deposition and Gulf exchange. Thus the general carbonate geochemical patterns of the pond sequences were similar to the bay prototypes.

Wilson (1963) was able to demonstrate direct changes in organic matter in dark and light bottles containing plankton with direct organic matter determinations. The diurnal measurement sequence on March 24, 1962 (Fig. 7) suggests the diurnal pattern to be expected although the method was not sensitive in this situation. Organic matter levels in the water on February 12, 1962, just after the ponds were started, were 5–11 mg/1, not much above that of the Gulf water used to start the ponds. By March, however, the ecosystem was maintaining levels of 19 to 30 mg/1 like those in some of the isolated bays like the Laguna Madre and Baffin Bay. It may be postulated that with restricted diversities among the consumer networks, the organic levels in the pond must rise, thus stimulating micro-organism metabolism adequate to balance photosynthesis just as in the bays.

It may be suggested that there is a general inverse relation between dissolved organic matter and diversity of consumer circuits among higher organisms. The low nighttime oxygen regime favors restriction of species and increase of organic matter. In this sequence the organic matter is entirely self-generated and is not controlled by import or pollution.

The energetic input to the triplicate ponds during the summer was from two sources, the sunlight and the circulatory energy supplement supplied from man's civilization as a power supplement. In the absence of this circulatory energy, the processes of photosynthesis and respiration, each dependent on recirculation of products of one to the other, would have been limited to those circulatory mechanisms paid for from the systems own energy as with fishes, diurnally moving zooplankton, migrating dinoflagellates or pumping of reef animals. The pumping rate of 62.2 liters per minute from electrical power supplement contributed 4.2K Calories kinetic energy per square meter per day to the system as compared to 4200K Calories per m^2 of visible light received. If, in the absence of such circulation, the ecosystem were circulating nutrients by supporting large nekton at the herbivore and carnivore levels, the transfer of visible light energy through the trophic levels, thus concentrating power enough to provide movement independent of the medium, would result in the same order of magnitude of power for nutrient circulation. In the Laguna Madre, Hellier (1962) found a conversion of gross plant production to fish production of 0.074%.

In a number of graphs replicate Winkler analyses showed irregularities in the diurnal curve of oxygen at a time when the pump-driven reaeration was unchanging and the light fields were unchanging. These variations appeared, for example, in Figs. 2, 9, and 10. These changes observed in field work have often been attributed to wind variations affecting reaeration and differences in local trajectory, fish schools, etc. In the tanks they apparently represent large changes in the system metabolism such as might be provided by components of the reef pumping or not pumping. The rise in oxygen about midnight or before dawn observed in several curves may represent cessation or decline of some respiratory functions such as pumping.

GRASS POND

The records of metabolism and events in the grass pond are given in Figs. 11–13. Shortly after transplanting and seeding of the large pond a moderately high photosynthesis and respiration developed which was similar to that in parts of Aransas and Redfish Bays (Odum and Wilson, 1962; Odum, 1963). During the summer, animal and plant populations developed like those in the bay prototype. *Thalassia testudinum*, *Diplanthera wrightii*, and *Ruppia maritima* continued to maintain new growths. Benthic

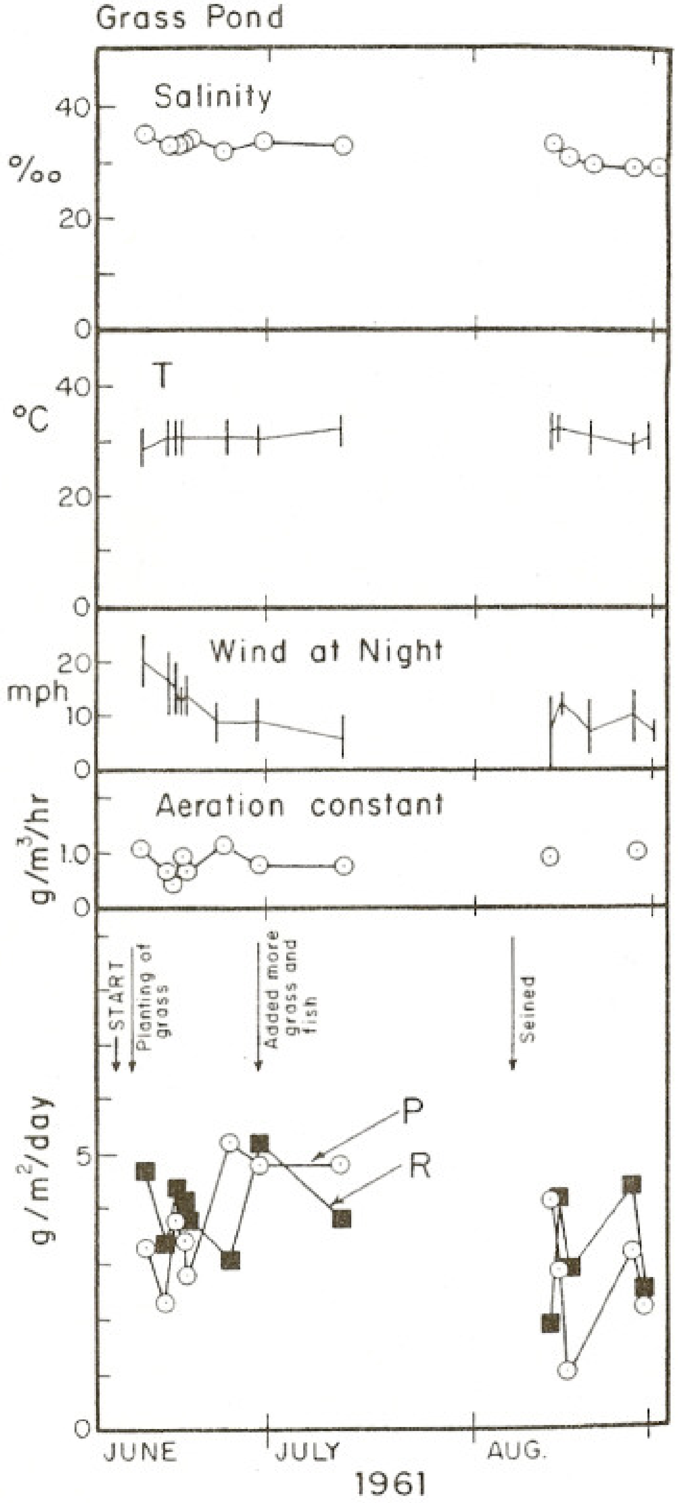


Fig. 11. Seasonal record of salinity, temperature, wind at night, reaeration constant for 100% oxygen deficit, system metabolism and the sequence of events in the grass pond.

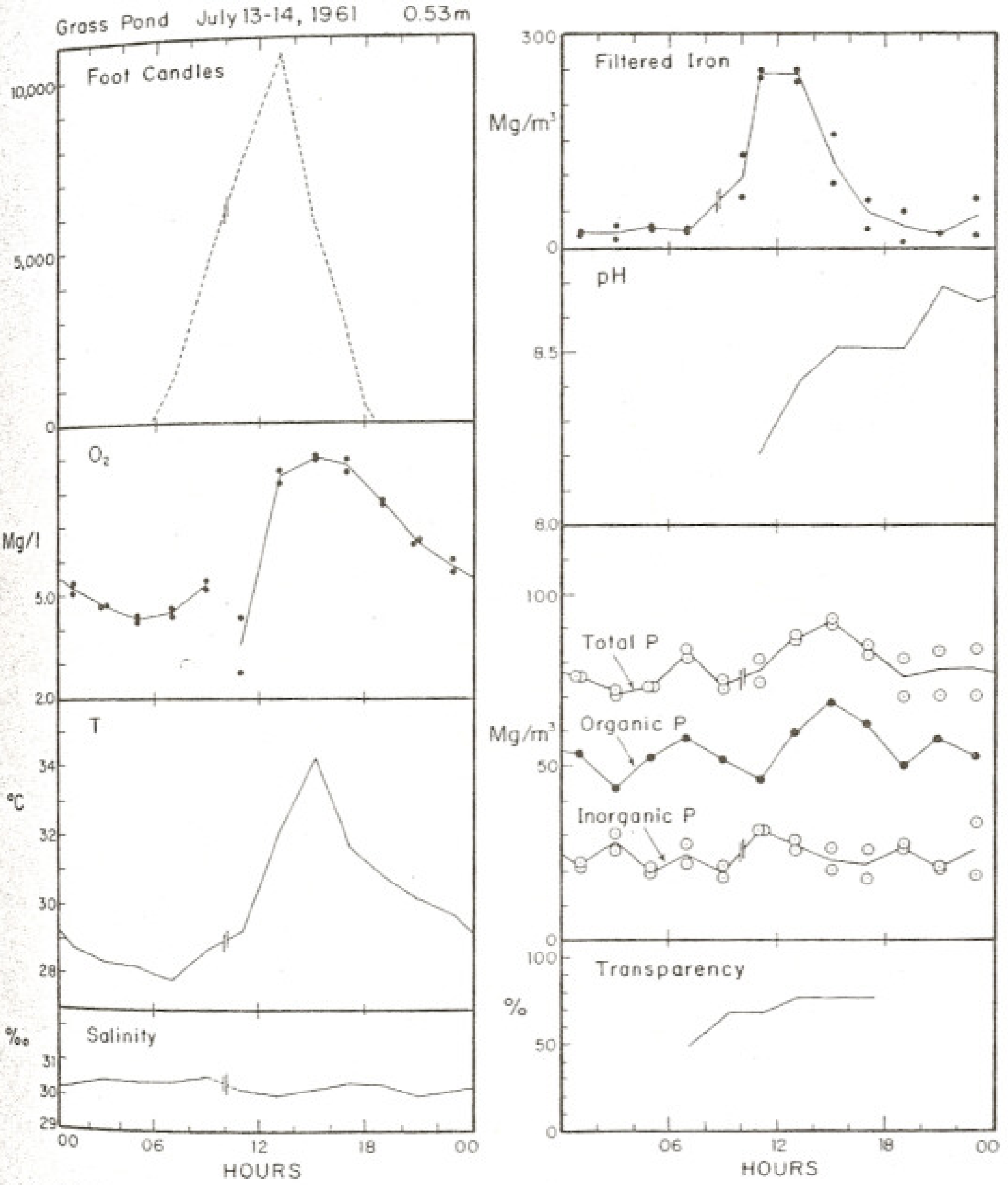


FIG. 12. Diurnal record of incident foot candles, oxygen concentration, temperature, salinity, iron in millipore-filtrates, pH, phosphorus, and bottom transparency in the grass pond, July 13–14, 1961.

diatom populations were observed in sediments and water, especially *Nitschia closterium* and *Navicula grenville* (identified by E. J. Ferguson Wood). The dominant vertical migration of *Acartia* was verified on August 23, 1961, (Fig. 13). Brown shrimp, *Bairdiella, Cyprinodon variegatus, Fundulus similis,* and *Menidia beryllinia* were common. When the pond was examined after draining on September 9, 5-inch oysters and heavy barnacle growths were observed on the walls just as on the solid substrates of the prototype bays. A dense population of bottom foraminifera was observed and studied by Wayne Horton. From his measurements of metabolism per individual with the pH-CO_2 method in vials, and from 10 bottom counts, he estimated that 5% of the total metabolism (0.030g O_2/

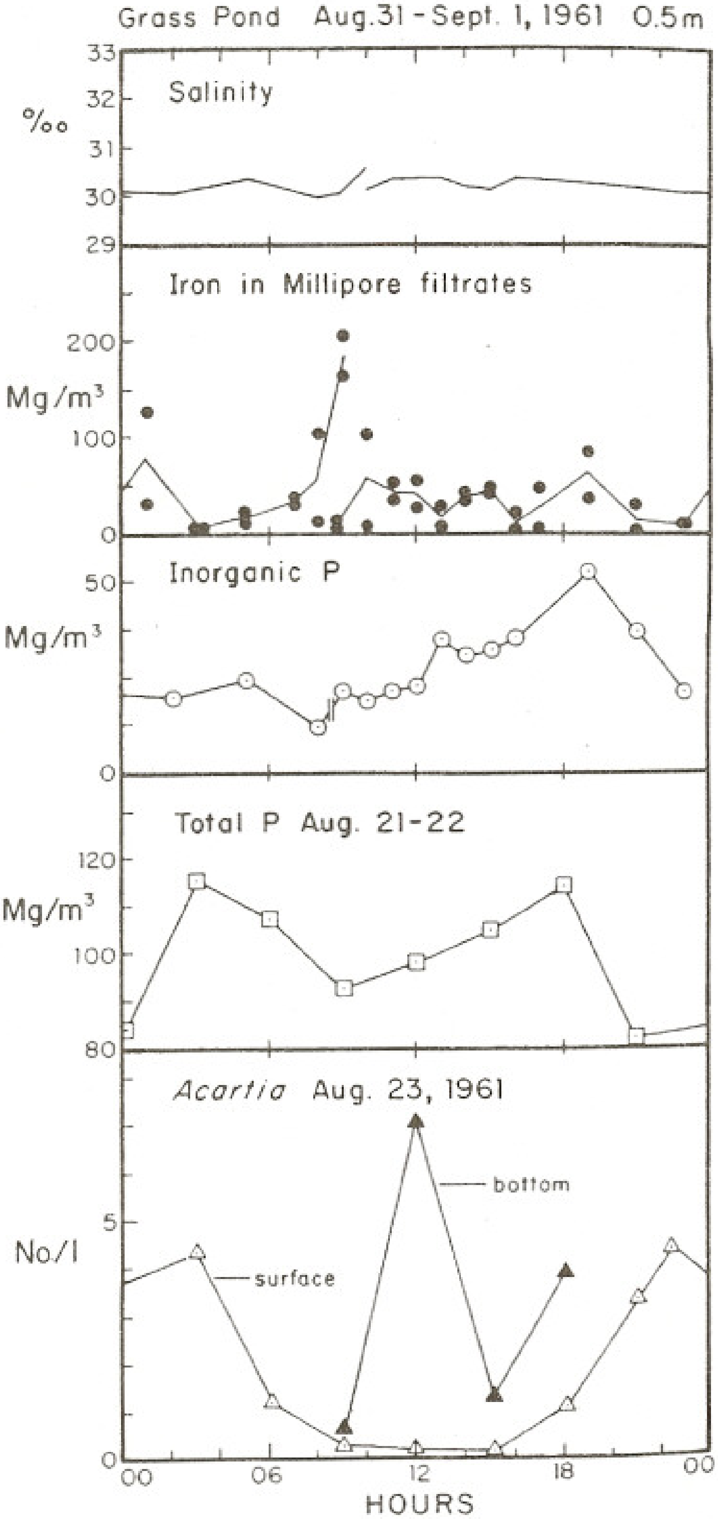


FIG. 13. Diurnal record of salinity, iron in millipore-filtrates, and inorganic phosphorus in the grass pond, August 31–September 1, 1961. Total phosphorus is given for August 21–22, 1961, and concentrations of the copepod *Acartia tonsa* are given for August 23, 1961.

m^2/hr) was attributable to the dominant benthic foraminifera: *Ouinqueloculina poeyana* and *Streblus becarii.*

The diurnal variations of many properties were explored as reported in Figs. 12–13. The level of phosphorus maintained by the cycles of the ecosystem was 50 to 115 mg/m^3, similar to that in the bays (Odum and Wilson, 1962). There was a curious diurnal change in water transparency conspicuous to people in the pond area even without instrumental measurements (Fig. 12). The per cent transmission to the bottom with a selenium photometer in daylight was 50% in the early morning improving to 66% by afternoon. Salinities were successfully maintained between 28 ‰ and 34 ‰ by balancing tap water against evaporation which was about 8 to 12 cm per week. The pH remained between 7.2 and 9, the temperature between 28 and 35°C, and efficiencies of gross photosynthesis between 0.5 and 1.5 per cent of visible light incident on the pyrheliometer.

Not all of the diurnal patterns were as expected from bay studies. Although the pH rose during the day, the iron concentration of millipore filtrates increased during the day (Fig. 12), a reverse effect from that expected from considerations of pH effect on iron solubility. Phosphorus in the graphs for July 13–14 (Fig. 12) showed variation with little trend. The graphs for August 21–22 have day and night minima. The August 31 series (Fig. 13) had inorganic phosphate increasing during the day, in reverse from that expected from studies of Bruce and Hood (1959) for the bays.

One finding of considerable significance for future pond work was the demonstration of continuous mixing without stratification in the larger pond under ordinary wind stresses of the Texas coast. By having straight walls and rounded corners, no consistent vertical temperature or oxygen differences developed. The water was observed to drift and roil slowly as it does in the bays when there is little wave action. The reaeration constant as computed from the graphs ranged from 0.4 to 1.1 g oxygen/m^3/ hr for 100% deficit, a value less than that of strongly mixed open bays but more than in stratified ponds. Light penetration and bottom heating helped maintain daytime turnover. The General Marine Science class found constant vertical temperature patterns in a diurnal study July 6–7, 1961, measuring temperatures at 1, 5, 10, 20, and 30 cm depth.

Dr. Reid Bryson and Dr. Robert Ragotzkie pointed out verbally that the diurnal measurements of temperature and salinity in the pond could be used as a net radiometer. As a sample, they computed from the temperature curve of the water on a clear day for July 7, 1961, an increase of heat content in the water from dawn to dusk of 300 calories per cm^2, a heat loss due to evaporation of 128 cal/cm^2, and a heat loss through conduction of 13 cal/cm^2 for a total of 441 cal/cm^2/day net radiation input. The total insolation received from pyrheliometer readings was 765 cal/cm^2.

The hundreds of diurnal temperature curves taken in the bays in the past 5 years as part of diurnal oxygen studies are presumably usable for similar analysis.

pH-CO_2 graphs were made along with oxygen on two days in the summer. Metabolic molar quotients were computed as the ratio of carbon to oxygen in Table 1. These values mainly show some confirmation of the oxygen method and carbon methods. These quotients fall within the ranges found in the prototype environments. Thus in many indices with which bay processes are measured, similar values were maintained by the grass pond system during the summer period.

BLUE-GREEN ALGAL MAT PONDS

In a week after seeding, the blue-green algae developed fresh green new mats over the bare sand between the transplanted mats so that there was a continuous carpet. A heavy population of corixid water bugs developed. Metabolic curves with an anaerobic nighttime phase with low redox potentials were observed just as in the environmental prototype. A vertical structure of filaments and black organic ooze was maintained like that analyzed by Sorensen and Conover (1962). In November, 1962, with the onset of cold weather, the blue-green algae disappeared and the heavy black ooze below the mats declined. Microscopic examination during the winter showed only diatoms. Then in late March, 1963, the ponds turned bright yellow as the blue-green algae again bloomed as a bottom carpet. Although salinities ranged from oligohaline to hypersaline, the water bugs were abundant in the water over the bottom throughout the summer, winter, and spring.

In Figs. 14–16 are the diurnal properties observed in the blue-green algal mat pond which may be compared with those in the environmental prototype (Odum *et al.*, 1963). The low level of the water allowed the heat and metabolic reception of the sun's energy to be concentrated so that very wide daily ranges of temperature, oxygen, redox potential, and pH were observed (Fig. 14) as in the prototype. Salinity was initially 15‰ but increased to 20–30‰ by evaporation when the metabolic pattern was recorded in Fig. 14. Alkalinity ranged between 2.1 and 2.6 milliequivalents per liter. By July 22 when metabolism was again measured (Fig. 15) the salinity had reached 74.4‰. These wide ranges precluded the development of many kinds of organisms. The persistence of these mats and metabolic patterns in these ponds through the summer confirmed the role of the shallow depth as a mechanism controlling biota. The role of the anaerobic nighttime phase in restricting consumers and thus favoring the deposition of organic matter suitable for oil petrogenesis was proposed earlier (see abstract, Odum and Vick, 1962).

The feasibility of culturing the blue-green mat system in ponds and smaller microcosms has implications for experimental study of sedimentary diagenesis. The diurnal variations in potential and the significance of electrochemical power take off from this ecosystem is explored in a manuscript by Armstrong and Odum (1963).

The comparison of metabolic rates computed for carbon are compared with those for oxygen in Fig. 14. As in the blue-green mat ecosystems in the bay prototypes, a very large molar metabolic quotient (CO_2/O_2) developed. The discrepancy exists even after over-corrections are made for Winkler interference and reaeration. The discrepancies between carbon and oxygen were particularly large after dawn when it may be postulated that oxygen deficits accumulated in the mat during the low oxygen periods of the night were oxidized thus masking the gross photosynthesis. The metabolic patterns of carbon in Figs. 14 and 15 were not greatly asymmetrical and were similar to those in aerobic systems.

The record on August 5–7 in Fig. 16 indicates the rising salinity with evaporation during a two day period as well as the normal metabolic rise and fall of pH. With high pH values and carbonate equilibria shifted mainly toward the carbonate state, photosynthesis in this system is apparently operating directly on carbonate fractions as indicated by the variation in alkalinity.

The steady rise in salinity charted in Fig. 16 reflects the evaporation rate.

DISCUSSION

In these examples, control and morphometry, circulation, and seeding in ponds allowed

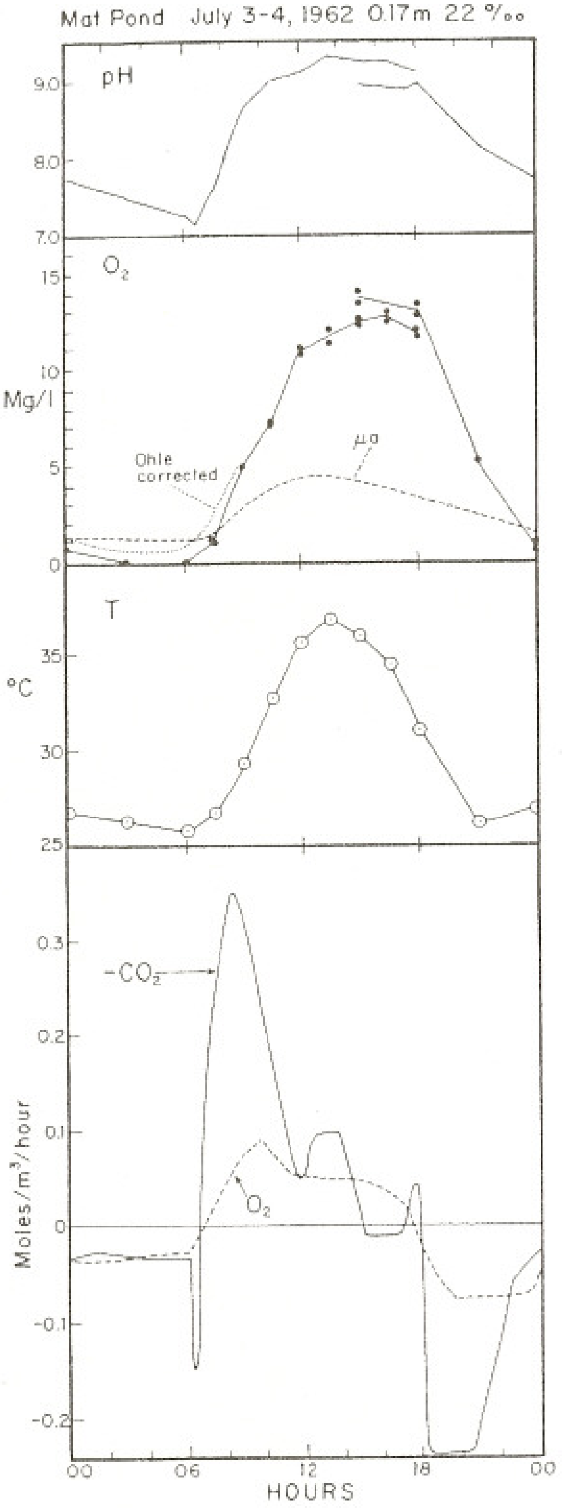


FIG. 14. Diurnal record of pH, oxygen concentration, temperature, and carbon and oxygen metabolic rates, July 3–4, 1962, in the blue-green mat pond. Oxygen rate was overcorrected for reaeration by using K_G 1.5.

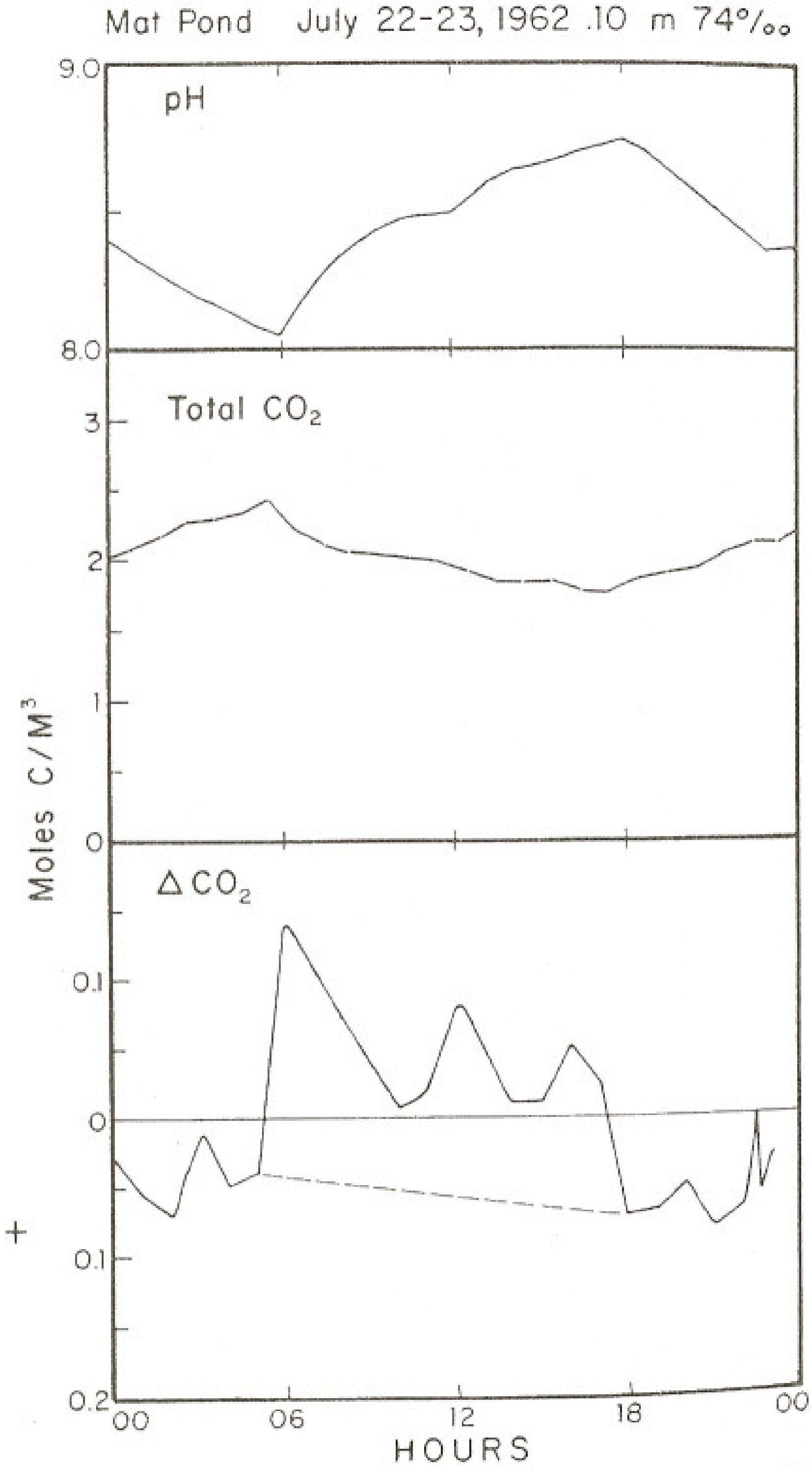


FIG. 15. Diurnal record of pH, total carbon dioxide, and rate of carbon metabolism, July 22-23, in the blue-green mat pond. Alkalinity was 2.1 meq/l.

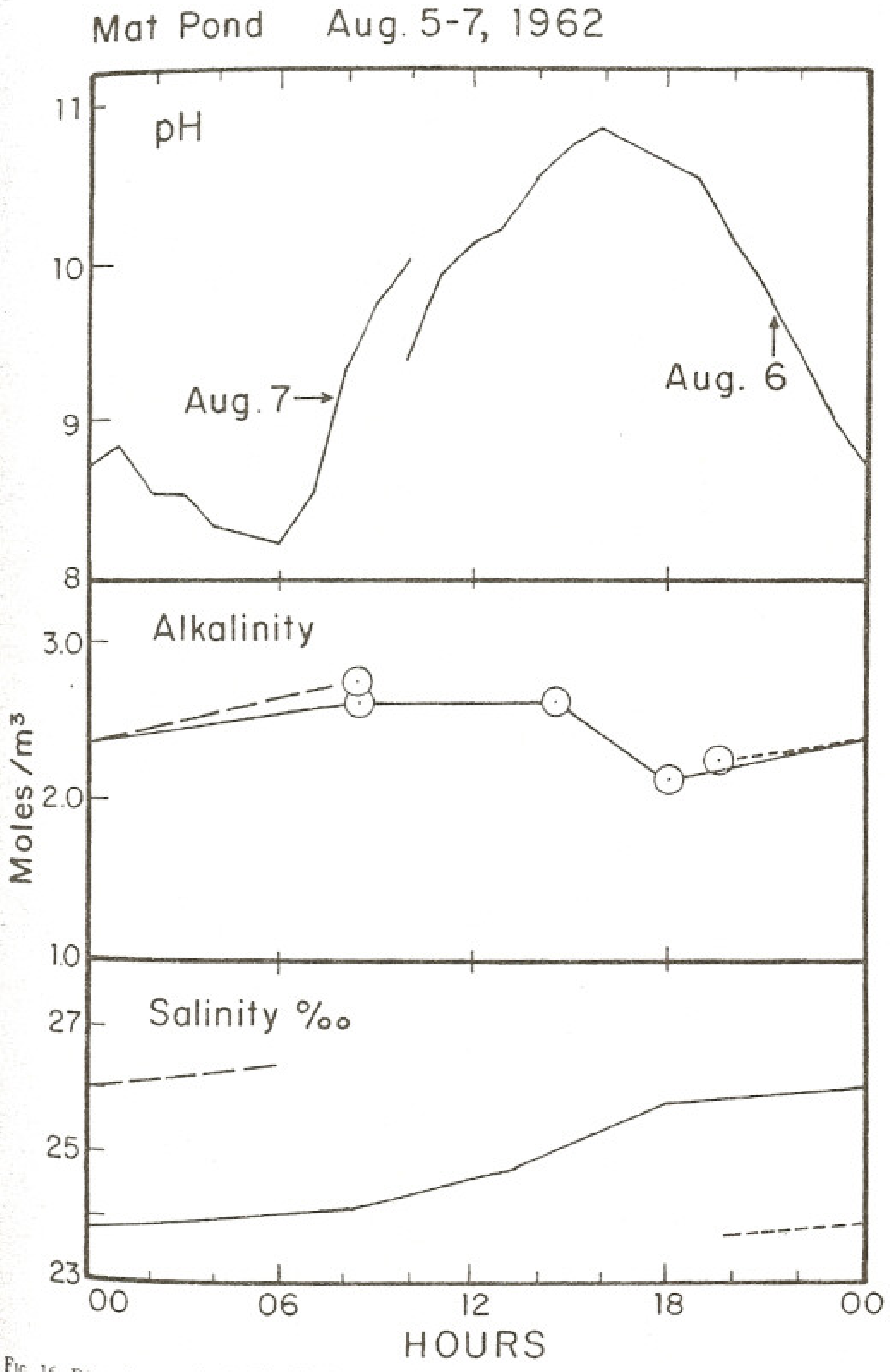


FIG. 16. Diurnal record of pH, alkalinity, and salinity, August 5–7, 1962, in the blue-green mat pond.

productive ecosystems to develop with many properties like those of the bay prototypes being simulated. Not all the properties and components were like the bays, however, as in the instances of rotifers in the reef ponds or the water-bugs in the blue-green mat ponds. The systems cultured were similar but not the same as the prototypes.

Nighttime low oxygen conditions were developed according to the water depth and nutrient concentrations without contributions or organic pollution, especially when respiration exceeded photosynthesis following periods of high productivity. In very shallow waters, low nighttime oxygen tension was apparently a necessary consequence of appreciable productivity.

Discrepancies between carbon and oxygen rates by these methods apparently exist even when potential artifacts such as Winkler interference and inadequate reaeration corrections are eliminated. In the shallow blue-green mat system photosynthetic oxidants apparently go for oxidation of system substances without appearing as dissolved oxygen so that the diurnal oxygen underestimates the metabolism as measured by carbon. A similar process may have been involved in the sequence in the triplicate ponds in which respiration seemed to be exceeding photosynthesis through much of the summer. Diversion of some plus charge "holes" in photosynthetic receptors into some processes other than release of oxygen causes the P/R ratio to be too low and the assimilatory quotient to be too high. Whereas P/R and AQ are objective parameters of the ecosystem, regardless of the diversions of electrons or holes to other processes, the P/R and AQ under these conditions are representing only part of the basic oxidation and reduction processes driven by light. The circumstances resemble those in the Black Sea as studied by Kriss (1963).

Considering all the pond experiments, metabolic rates were mostly less than 6 g oxygen per m^2 per day without outside pumping energy and somewhat higher in the triplicate reef ponds with auxiliary power supplement through the pump. These values involve photosynthetic efficiencies 0.5 to 3% of visible energy received and were generally somewhat less than the best developed prototype bays.

Considering the cost of marine field work, the pond method for experimental and replicated study of the bay prototypes is attractive for intensive controlled study of metabolism and marine biogeochemistry. For example, radiotracer experiments in ecosystems of known metabolism and populations can be safely followed in the pond systems and used to interpret bay phenomena with some justification.

The pond systems were less diversified than the bay prototypes as expected due to their isolation from large population reservoirs. Total metabolism was also less than in some prototypes. Formulae for ecological engineering such as those tested in this study may be useful in channeling energies into particular food chains in ecosystem culture.

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iron analyses and Mr. Ron Wilson organic matter determinations. Illustrations were done by Mrs. Pauline West.

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