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SIMULATION OF DIURNAL PROCESSES IN LAGUNA JOYUDA

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ABSTRACT

A microcomputer program in BASIC simulates the diurnal variations of oxygen observed in Laguna Joyuda in southwestern Puerto Rico. The model includes processes of production and consumption; nutrient inflows, outflows, and recycle; organic matter inflow, outflow and accumulation; and oxygenation, consumption, and exchange with the atmosphere. Reaeration coefficient was varied diurnally with the observed wind. By varying light input simulation, reproduced the general pattern of diurnal oxygen observed on sunny days and on cloudy days. Using the calibrated model, gross photosynthesis and total system respiration were calculated as graphical output. When simulation was begun with low phosphorus levels, the system increased the nutrients contained in the closed cycle until phosphorus was not limiting. Low oxygen periods had been observed after floods in 1986 that added organic-loaded freshwater on top of the saltwater. Nearly zero oxygen was simulated by reducing reaeration and adding organic inflow. Substantial nutrient filtration capacity was found by adding ten times more phosphorus, which caused increased organic deposition that absorbed most of the excess phosphorus. As an interface between estuaries and human economic activity, the shallow tropical lagoon is a stabilizing filter with good biological productivity.

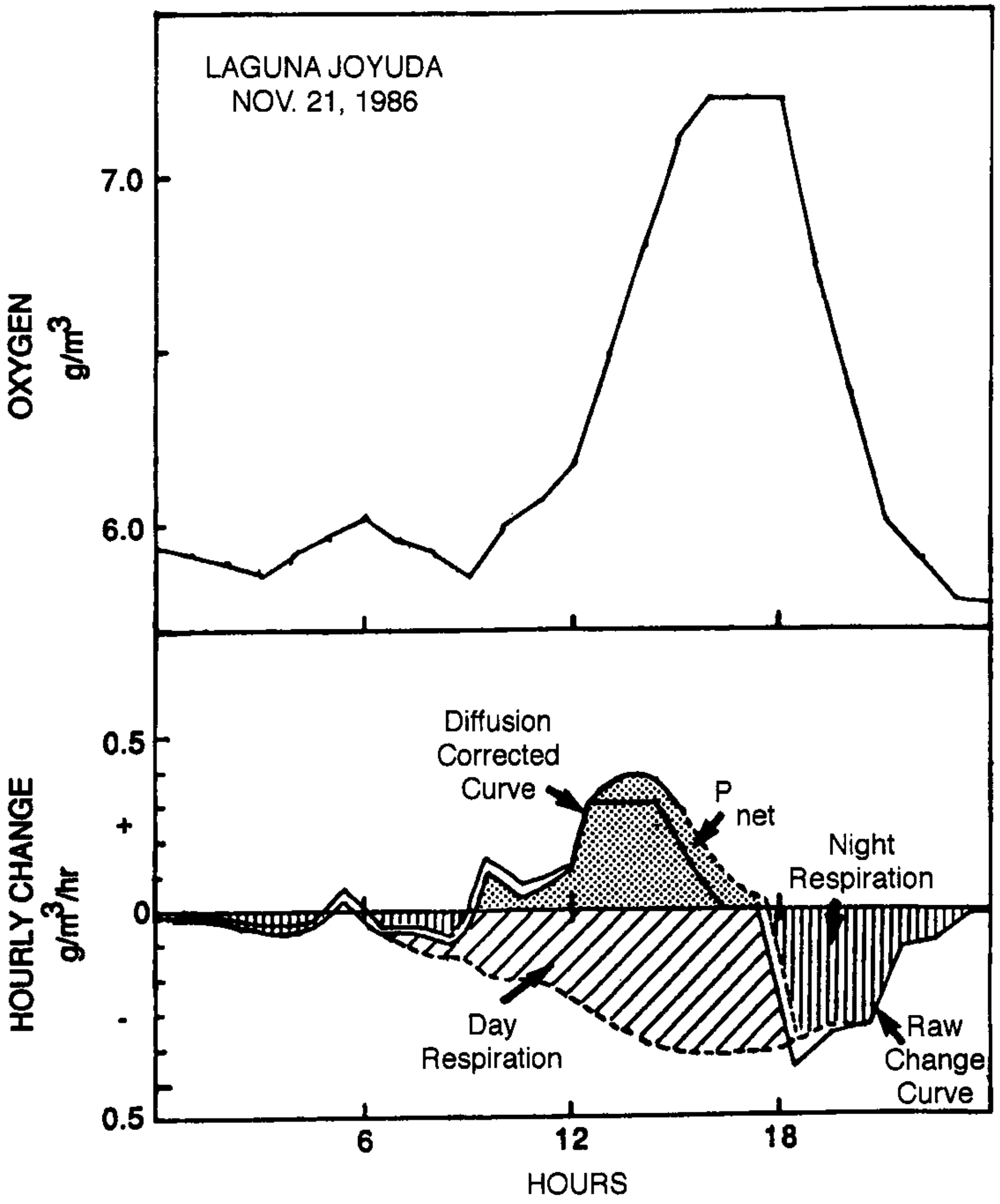
INTRODUCTION

Laguna Joyuda, on the west coast of Puerto Rico, is representative of tropical estuaries. It is small in area, fringed with mangroves, and has a small canal connecting it to the sea. The lagoon has been intensively studied by many investigators so that general features of the ecosystem are known (Carvajal *et al.* 1980, Stoner 1986, García and López 1989). The overall metabolic activity of the lagoon can be measured by diurnal analyses of dissolved oxygen. The day and night alternation of excess photosynthesis in daytime and respiration at night causes oxygen to rise and fall diurnally. An example of diurnal oxygen pattern is given in Figure 1 from a 1986 yearly series taken as part of the EPSCOR project by Figueroa. A microcomputer simulation model was prepared and calibrated to generate diurnal changes as a quantitative hypothesis relating the metabolism of the lagoon to oxygen, organic matter, nutrients, and physical stirring by the wind.

A MODEL OF DIURNAL METABOLISM

The ecosystem diagram (Fig. 2), drawn with energy language symbols, summarizes the metabo-

Figure 1. Observed data on diurnal oxygen variation for November 21, 1986. Compare these variations with those in Figure 3 generated by the model in Figure 2.

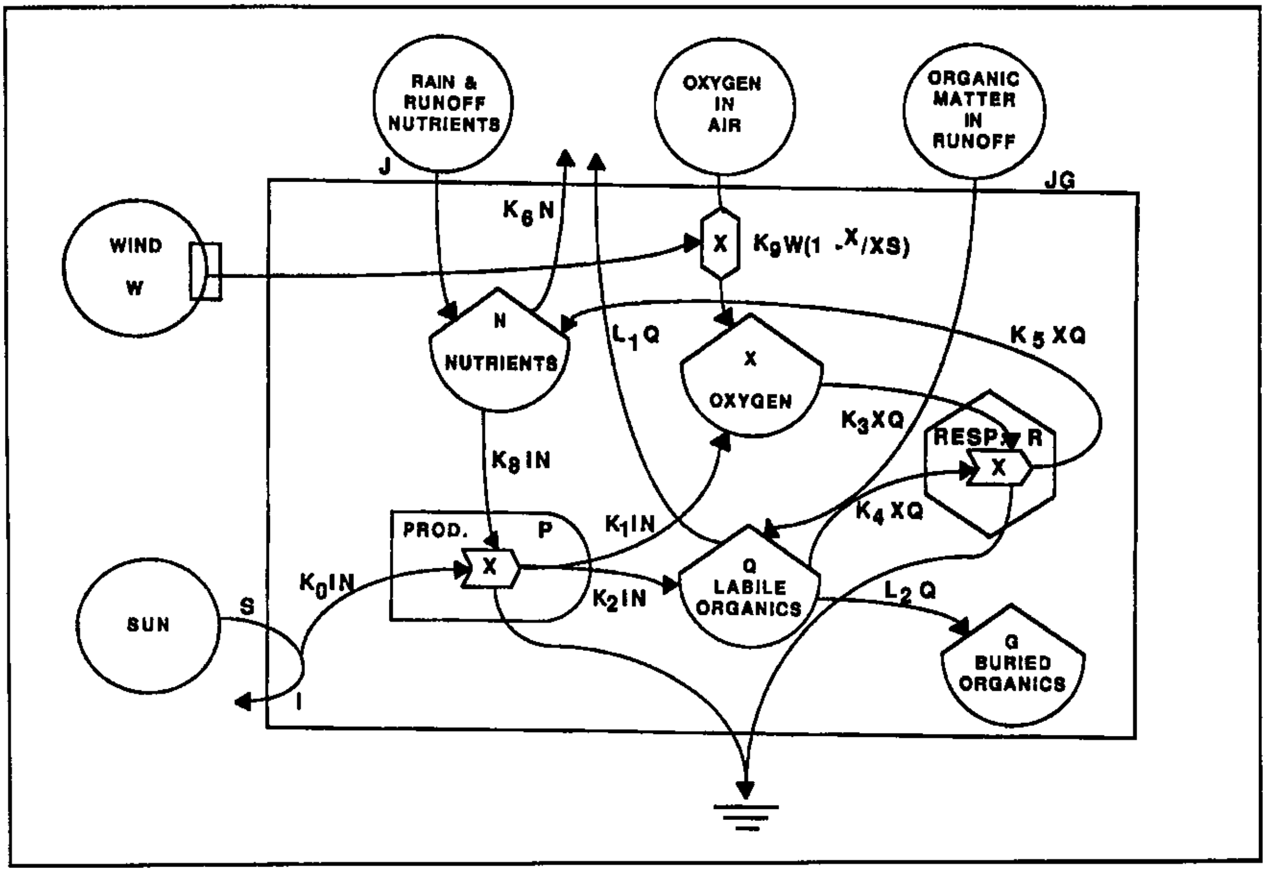


Diurnal Oxygen Curve calculation.

$P_{net} = 2.02$ g/m^2/day; $R_{day} = 3.9$ g/m^2/day

$P_{gross} = 5.92$ g/m^2/day; $R_{24hr} = 6.11$ g/m^2/day; P/R = 0.97

Figure 2. Energy systems diagram of the simulation model of diurnal phenomena in the Joyuda Lagoon. Mathematical terms are on the pathways. See equations in Table 1 and BASIC program in Appendix Table 1.



lism of the lagoon system. To read the diagram, start with outside energy sources, indicated as circles outside the system's boundary. These include the sun, wind, nutrients in the rain and runoff, oxygen in the air, and organic matter in runoff. The energy which comes into the system from these sources, flows through it, stimulating the flow of materials such as nutrients, oxygen, and organic matter. After being used, this energy flow out the heat sink (at the bottom of the diagram) as waste heat. The model includes some organic matter passing from the labile tank to a tank without outflow. This represents the organic matter that is buried in the sediments, unavailable for further metabolism.

The amount of sun used in the lagoon is proportional to that which is available (I). Oxygen diffuses in and out of the lagoon in proportion to a combination of the wind (W) and the oxygen deficit or surplus. Whether there is an oxygen deficit or surplus depends on whether the dissolved oxygen in the pond is less or greater than the saturation level (XS). Nutrients are added (J) to the lagoon water from direct rain and in the runoff, which is especially heavy after unusual rains. Nutrients flow out through the canal to the ocean. Organic matter also inflows (JG) in the runoff and flows out through the canal.

In the model phosphorus was used as an indicator of all inorganic nutrients, in the lagoon, storages of nutrients (N), interact with sunlight in the process of photosynthesis (P). This produces oxygen (X), which dissolves in the water, and organic matter (Q), in the cells of benthic algae and phytoplankton. All the photosynthesis in the water of the lagoon is included in the production. The oxygen and labile organic matter interact in total lagoon respiration (R); this includes respiration of producers as well as that of all the consumers, from bacteria to an occasional barracuda.

METHODS OF CALIBRATION AND SIMULATION

An ecosystem model was drawn as an energy diagram (Fig. 1) and a simulation computer program written in BASIC (Appendix Table 1). Drawing the diagram with energy systems symbols indicates the equations to put in the simulation program (Table 1). There is an equation for each storage tank in the diagram, and a positive mathematical term for each pathway of flow into that storage and a negative term for each pathway out. The term for the oxygen diffusion shifts from positive to negative as the dissolved oxygen goes from an undersaturated to oversaturated condition relative to the oxygen pressure in the air. The temperature range is small diurnally and seasonally, and omitting its effect was not a large error for these conditions.

Estimates of storages and flows used were obtained from previous measurements for calibration. These values are given in Table 2. Inputs are the changing hourly sunlight and wind, nutrient inflow, and organic matter inflow. Solar energy data from López and Soderstrom (1983) were entered as an array with the same values repeated each day. Initial calibration of production rates used a relatively low metabolic rate based on earlier measurements of oxygen in free water by Figueroa (Fig. 1). For calibration purposes, unknown flows were adjusted to fit the known flows so as to make a steady state.

A good estimate of reaeration (oxygen diffusion into and out of the surface) is important to the model. A large rate of diffusion reduces the range of diurnal oxygen. If this diffusion rate is overestimated, it may cause metabolism to be underestimated. Or vice versa, if the reaeration rate is too small, the metabolism estimates may be too large. Two field measurements of reaeration coefficient (k9) were made using a plastic floating dome initially filled with nitrogen to measure the rate of diffusion of oxygen from the water into the dome. The results were 1.016 on Aug. 27, and 1.02 on Oct. 10, 1987 (grams oxygen diffusing/m^2/hr/0.2 atmosphere gradient). For details on this method see Copeland and Duffer (1964). Reaeration coefficient was programmed to vary with wind-stirring of the lagoon waters. There is usually a diurnal variation of wind due to sea breeze circulation. For the simulation

Table 1. Equations for the Simulation Model in Figure 2.

Unused sunlight	$I = S/(1 + k_0)*I*N)$
Production rate	$P = kI*I*N$ $g/m^2/hr$
Respiration rate	$R = k3*I*N$ $g/m^2/hr$
Dissolved oxygen	$Dx = k1*I*N - k3*X*Q + k9*W*(1-X/XS)$ $X = Q + DQ*DT/Z$ where Z is average depth
Nutrient	$DN = N + J - k6*N + k5*X*Q - k8*I*N$ $N = N + DN*DT/Z$
Labile organics	$DQ = JG + k2*I*N - L1*Q - k4*X*Q - L2*Q$
Buried organics	$DG = L2*Q$

Table 2. Values used to calibrate the simulation model in Figure 1.

Item	Expression	Value and units
Nutrient inflow	J	0.002 micromoles/hr
Organic inflow	JG	0.02 $g/m^2/hr$
Reaeration rate	k9*W*(1-X/Xs)	1.0 $g/m^2/hr$ when x = 0 & W = 7 mph
Wind	W	7.0 mph, daytime high
Sun	S	2.2 $megajoules/m^2/hr$, daytime high
Unused sunlight	I	0.2 $megajoules/m^2/hr$
Nutrient concentration	N	1 micromole phosphorus
Oxygen concentration	X	7 milligrams per liter
Oxygen saturation	XS	6.4 milligrams per liter
Labile organic matter	Q	300 g/m^2
Buried organic matter	Q2	0 g/m^2 initially
Nutrient outflow	k6*N	0.002 micromoles/hr
Organic matter outflow	L1*Q	0.01 $g/m^2/hr$
Organic matter buried	L2*Q	0.01 $g/m^2/hr$
Gross production, oxygen	K1*I*N	0.11 $g/m^2/hr$
Gross production, organic	K2*I*N	0.11 $g/m^2/hr$
Respiration, oxygen	K3*X*Q	0.11 $g/m^2/hr$
Respiration, organic	K4*X*Q	0.11 $g/m^2/hr$
Nutrient recycle	K5*X*Q	0.017 micromoles/hr
Nutrient used, prod.	K8*I*N	0.017 micromoles/hr

wind data were applied with different value for each hour (Figs. 3 to 6) from measurements taken in July by Rice (1983).

A short program in BASIC was written to facilitate recalibrating the model for other simulations (AQUATIC CALIBRATE in Appendix Table 2). It has input statements that call for the user to enter the various values stepwise. Then the program prints out the coefficients on the screen, which can be typed into the simulation program.

SIMULATION RESULTS

Like controlled experiments, the model was simulated for different conditions, different coefficients, and different starting conditions. The first simulation reported in Figure 3 is for the initial calibration conditions as given in Table 2. When this program is run, the result a graph of the important daily changes in metabolism of the lagoon system during the day and night (Figs. 3 to 6). The changing and wind are plotted at the top, then the nutrients, with oxygen next. In the bottom section are plotted the rate of change of photosysthesis and respiration. Above that the difference between the rate of production (P) and the rate of respiration (R) is plotted on either side of a zero line, with P greater than R above the line and R greater than P below the line. Gross production and respiration are nearly balanced over a 24 hour period. A low level of nutrient is maintained and with diurnal fluctuations small. Organic matter in the buried compartment (Q_2) grows gradually. Simulation runs with the initial calibration were very close to the diurnal curves found in measurements.

Figure 4 is a simulation that starts with no stored nutrient but with gradual nutrient accumulation from inflowing waters and the recycle from organic

Figure 3. Simulation graphs resulting from the initial calibration with numbers in Table 2.

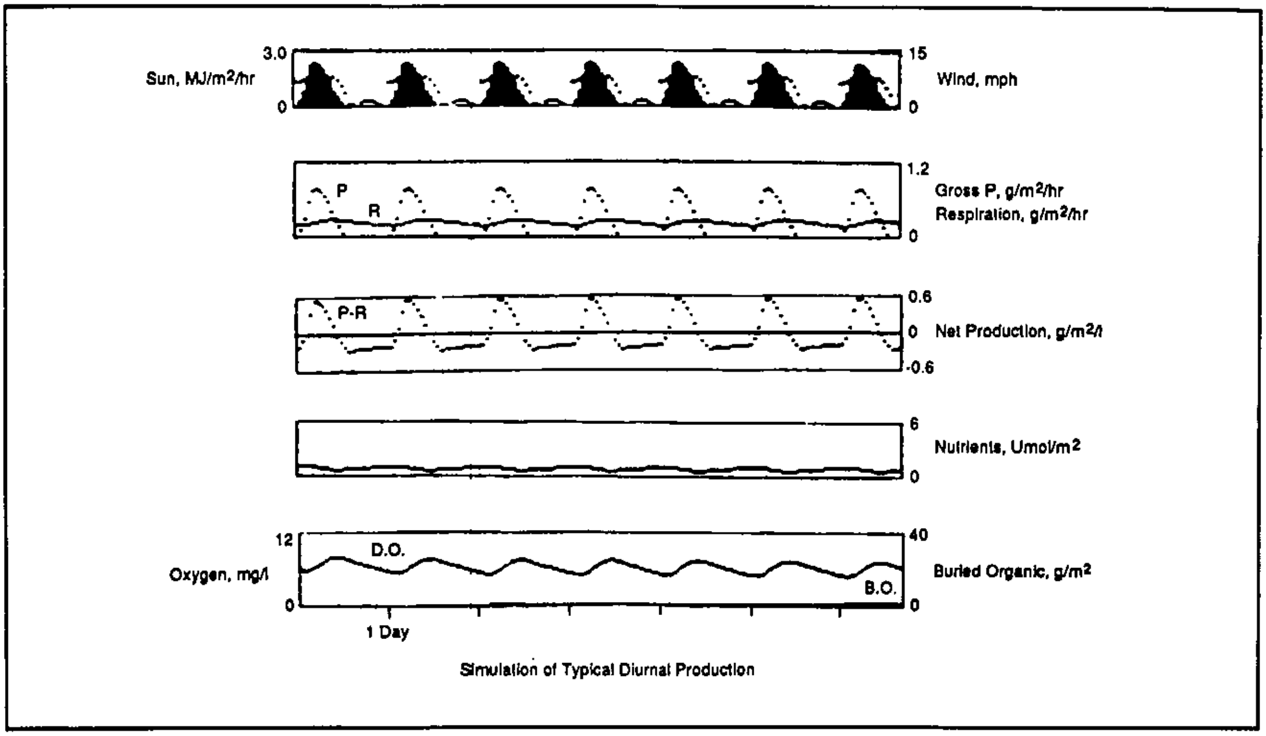
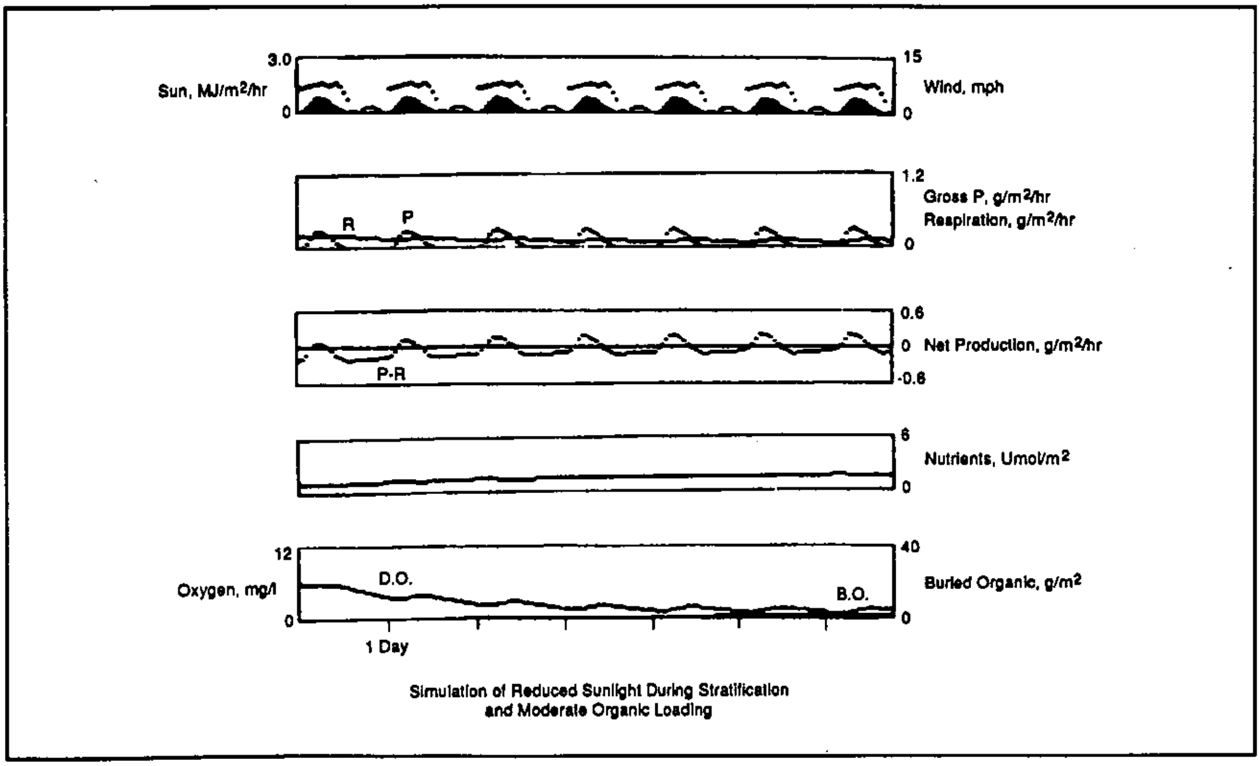


Figure 4. Simulation of effect of reduced sunlight, S = A(HR)/3, one third the intensity of sunlight used in simulation of Figure 3.



storages. Initially, respiration exceeds gross photosynthesis. Photosynthesis is clearly limited relative to the available sunlight. However, as nutrients are captured and recycled, gross photosynthesis gradually rises. Although it takes longer than the several days shown the Figure 4, the nutrients captured and recycled reach a level where they are no more limiting than the sunlight. In other words, the design of this model, like that of the more complex nature, has the property of self organizing to eliminate limiting factors and increase performance.

Figure 5 simulates a flood in which a heavy inflow of freshwater brings in large organic matter contribution and at the same time stops reaeration exchange of oxygen with the atmosphere because of the freshwater layering over the surface of the salt waters. Respiration is increased and exceeds photosynthesis. Oxygen goes down, reaching nearly zero in four days. Nutrients rise. As oxygen goes down respiration declines again so that photosynthesis exceeds respiration again. This set of events seems to reproduce the observed pattern of oxygen change after floods in 1986.

Figure 6 has the first few days of simulation of the effect of increasing the inflow of nutrients, which is relevant to the increasing nutrient from agriculture, populations, and urban development. Nutrient levels build up until a new steady state is reached. A 10-fold increase in nutrient inflow rate is readily absorbed, most of it going through the system and into the buried organic matter. With 100 times increase in nutrient inflow, it taken nine months to get

Figure 5. Simulation of high organic loading with stratification; simulates the effect of freshwater overlayering by elimination of reaeration and the effect of flooding by inflowing 100 times the typical organic matter input (JG = 20 g/m^2/hr).

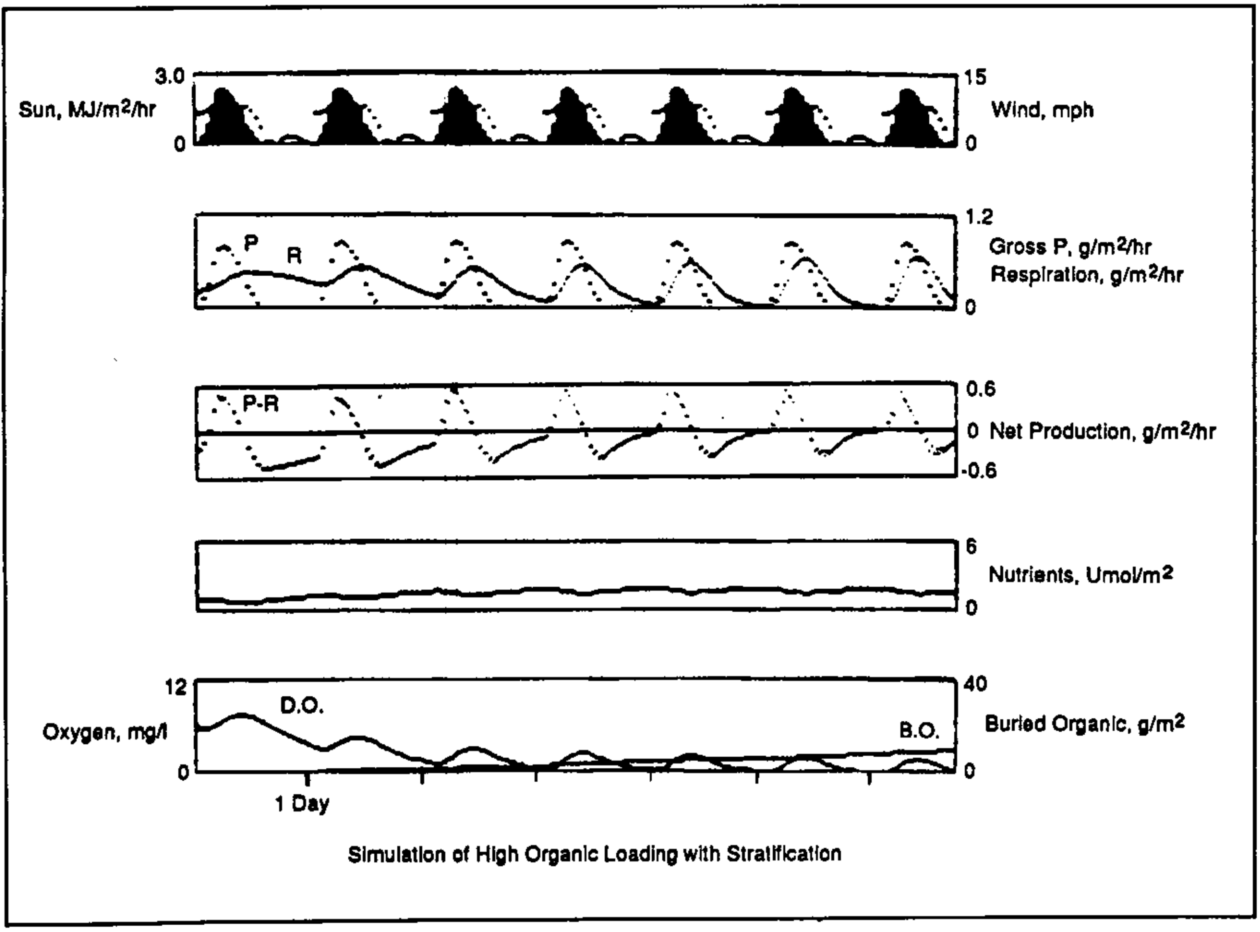
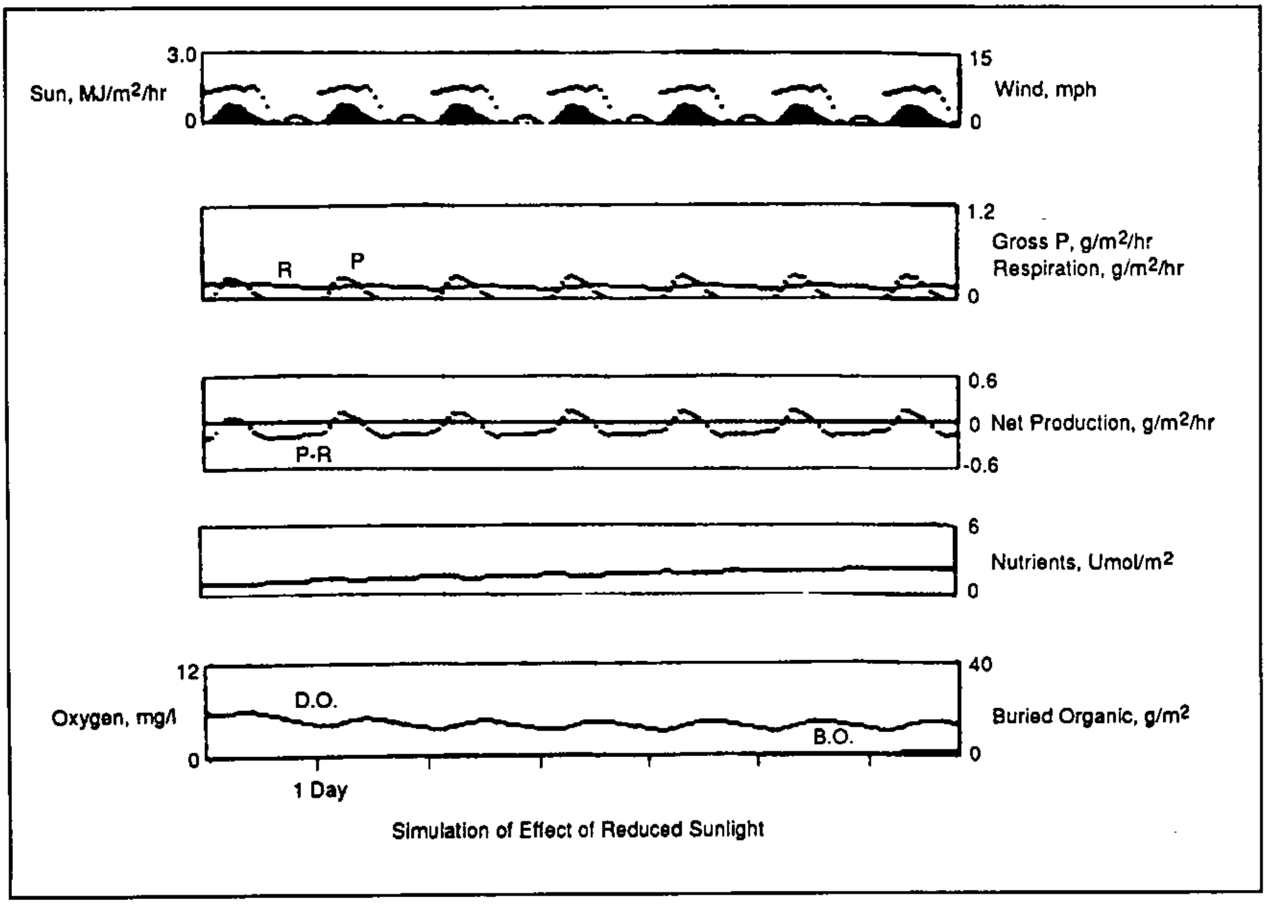


Figure 6. Simulation of reduced sunlight during stratification and moderate organic loading. Simulates cloudiness, S = A(HR)/3, and flooding with moderate (10 times the typical; J = 2 g/m^2/hr), and elimination of reaeration.



a steady state, and much of it then passes out the pass to the Caribbean Sea.

In other simulation, not shown here, results were as follows. With slightly higher nutrient conditions, some diurnal nutrient oscillation was observed and night respiration decreased during the night. With 1/3 the sunlight representing cloudy days, all the diurnal variations were reduced and respiration exceeded photosynthesis with somewhat lower average dissolved oxygen (below saturation). The simulations for various special conditions indicate the consideration potentials for shallow tropical lagoons to accept increasing land runoffs before developing conditions unfavorable for normal faunas.

ACKNOWLEDGEMENTS

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Appendix Table 1. Simulation Program DIELJOYU.BAS in BASIC.

```
3 REM Macintosh version
5 REM DIELJOYU E.C. and H.T. Odum
6 REM JOYUDA LAGOON, PUERTO RICO, MARCH, 1987
7 CLS
8 REM GRAPHICS:
15 LINE (0,0)-(320,180),3,B
18 LINE (0,30)-(320,30),3
20 LINE (0,60)-(320,60),3
25 LINE (0,100)-(320,100),3
27 LINE (0,120)-(320,120),3
30 LINE (0,140)-320,140),3
100 REM INSOLATION ARRAY AT 1 HR INTERVALS, MEGAJOULES PER SQUARE METER
110 DIM A (24)
120 (DATA 0, 0.3, 0.8, 1.6, 2.2, 2.3, 2.2, 2.0, 1.7, 1.3, 0.8, 0.5, 0.2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0
130 FOR HR = 1 TO 24
140 READ (A(HR)
150 NEXT
160 REM WIND ARRAY AT 1 HOUR TIME INTERVALS IN MILES PER HOUR
165 DIM B(24)
167 DATA 6.5, 6.7, 7.0, 7.1, 7.3, 7.6, 8.1, 7.6, 7.2, 7.5, 7.8, 7.0, 5.5, 3.5, 0.6, 0.3, 0, 1.0, 1.6, 1.4, 1.5, 1.2,
  0.7, 0.2
170 FOR HR = 1 TO 24
175 READ B(HR)
180 NEXT
200 REM SCALING FACTORS
205 DT = .5
208 TO = .5
240 NO = .2
250 GO = 1
260 SO = .1
270 XO = .3
280 PO = 0.15
290 RO = .015
295 WO = .5
297 HR= 1
300 REM STARTING VALUES:
305 Z = 1.3
310 J = .0002
315 JG = .02
320 XS = 6.4
330 X = 6
340 N = 1
350 Q = 300
355 P = .2
360 R = .2
365 REM COEFFICIENTS
370 KO = 6
380 K1 = 1.1
390 K2 = 1.1
400 K3 = .000052
```

Appendix Table 1. (continued).

```
410 K4 = .000052
420 K5 = .0000081
430 K6 = .0002
450 K8 = .17
460 K9 = .15
470 L1 = .00003
475 L2 = .000066
500 REM PLOTTING TIME CURVES:
510 REM SUN IN RED:
520 LINE (T/T0-30)-(T/T0,(30-S/S0)),3
522 REM WIND IN WHITE
525 PSET (T/T0, 30-W/W0),3
530 REM NUTRIENTS IN WHITE:
540 PSET (T/T0, 60-N/N0),3
550 REM OXYGEN IN BLUE:
560 PSET (T/T0, 100-X/X0),3
652 REM PERMANENT ORGANIC DEPOSITION IN RED
563 PSET (T/T0, 100-G/G0),3
570 REM NET PRODUCTION RATE IN RED:
580 PSET (T/T0,120-(P-R)/P0),3
590 REM GROSS PRODUCTION RATE IN RED:
600 PSET (T/T0,180-P/P0),3
610 REM TOTAL RESPIRATION RATE IN BLUE:
620 PSET (T/T0),180 - R/R0),3
700 REM EQUATIONS
710 S = A(HR)
712 W = (B(HR)
715 K7 = K9*W
720 IF S<0 THEN S = 0
730 I = S/(1 + K0*N)
740 DN = J - K8*I*N - K6*N +K5*X*Q
750 DQ = K2 *I*N - K4*X*Q +JG -L1*Q-L2*Q
760 DX = K1 *I*N - K3*X*Q +K7*(1-X/XS)
765 DG = L2*Q
770 REM NEXT VALUES
775 N = N +DN*DT/Z
780 Q = Q+DQ*DT
790 X = X +DX*DT/Z
795 G = G +DG*DT
800 P = K1*I*N
810 R = K3*X*Q
820 T = T+DT
825 HR = 1+INT(T-24*D)
827 IF HR>24 THEN HR=1:D=D+1
830 REM GO BACK AND REPEAT:
840 IF T/T0 < 320 GOTO) 500
850 END
```

Appendix Table 2. Simulation program AQUATIC CALIBRATE in BASIC.

```
10 REM AQUATIC CALIBRATE
20 PRINT ‘CALIBRATION OF AQUATIC?”
30 PRINT
40 PRINT “WHEN PROMPTED, TYPE IN OUTSIDE SOURCES AND STORAGES FROM THE
  DIAGRAM.”
50 PRINT
60 INPUT “OXYGEN IN MG/L (PPM), X =”;X
70 PRINT
80 INPUT “NUTRIENTS IN MICRO-MOLAR (MICRO-GRAM ATOMIC WEIGHT PER CUBIC
  METER), N =”; N
85 PRINT
90 INPUT “LABILE ORGANIC MATTER IN G/M2,Q=”;Q
100 PRINT
110 INPUT “SUNLIGHT HOURLY IN MJ/MZ, S =”;S
120 PRINT
130 INPUT “UNUSED SUNLIGHT, I =”;I
140 PRINT
150 INPUT “WIND IN MPH, W =”;W
160 PRINT
165 INPUT “ORGANIC MATTER INFLOW IN G/M2/H, JG =”;JG
166 PRINT
170 PRINT “WHEN PROMPTED, TYPE IN FLOWS FROM DIAGRAM.”
180 PRINT
190 INPUT “CALIBRATE SUNLIGHT USED = KO*I*N = “;CU
200 PRINT
210 KO = CU/(I*N)
220 PRINT
230 INPUT “PRODUCTION OF OXYGEN = K1*1*I*N =”;PO
240 PRINT
250 K1 = PO/(I*N)
260 PRINT
270 INPUT “PRODUCTION OF ORGANIC MATTER = K2*I*N =”;PQ
280 PRINT
290 K2 = PQ/(I*N)
300 INPUT “OXYGEN USED IN RESPIRATION + K3*X*Q =”;XR
310 PRINT
320 K3 = XR/(X*Q)
330 PRINT
340 INPUT “ORGANIC MATTER USED IN RESPIRATION = K48X8Q =”;MR
350 PRINT
360 K4 = MR/(X*Q)
370 PRINT
380 INPUT “RECYCLE NUTRIENTS FROM RESPIRATION = K5*X*Q =”;RN
390 PRINT
400 K5 = RN/(X*Q)
401 PRINT
402 INPUT “OUTFLOW OF NUTRIENTS IN RUNOFF = K68N =”;OU
403 KS = OU/N
```

Appendix Table 2 (continued).

```
404 PRINT
405 INPUT "NUTRIENTS USED IN PRODUCTION = K8*N*I=";OU
406 PRINT
407 K8 = NP/(N*I)
409 PRINT
410 INPUT "REAERATION RATE IN G/M2/HR=K9*W*(1-X/XS)=";RA
415 PRINT
425 PRINT
430 INPUT "SATURATION OXYGEN, MG/L (PPM), XS =";XS
435 PRINT
437 IF X/XS = 1 THEN SO=0:GOTO 444
440 SO = RA/(W*(1-X/XS)
444 K9 = ABS (SO)
450 INPUT "OUTFLOW OF ORGANIC MATTER, G/MZ/HR=L1*Q=";FQ
460 L1 = FQ/Q
470 PRINT
500 PRINT "THE COEFFICIENTS TO BE ENTERED IN THE PROGRAM ARE:"
505 PRINT
510 PRINT "K0="K0
520 PRINT "K1="K1
530 PRINT "K2="K2
540 PRINT "K3="K3
550 PRINT "K4="K4
560 PRINT "K5="K5
570 PRINT "K6="K6
590 PRINT "K8="K8
600 PRINT "K9="K9
603 PRINT "L1="L1
605 PRINT
606 IF SW = 1 GOTO 700
610 PRINT "ALSO TYPE INTO THE PROGRAM THE INITIAL STORAGE CONDITIONS WHICH
  MAY BE DIFFERENT FROM THE STORAGES USED TO CALIBRATE."
620 PRINT; PRINT
630 PRINT "TO SEND COEFFICIENTS TO THE PRINTER, TYPE: CONT.:
700 END
720 PR#1
730 SW=1
740 GOTO 505
```

oping new hypotheses with models, and training tropical marine scientists in systems ecology.

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