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**A comparison of system ( $O_2$  and  $CO_2$ ) and C-14 measurements of metabolism in estuarine mesocosms**

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# A comparison of system ( $O_2$ and $CO_2$ ) and C-14 measurements of metabolism in estuarine mesocosms

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**ABSTRACT:** Metabolism in estuarine mesocosms was measured by total system oxygen and carbon dioxide and by C-14 bottle incubations to determine the effects of nutrient enrichment (6 levels) over a 9 mo period. These data provided an unprecedented opportunity for calculating metabolic ratios (photosynthetic quotient [P.Q.] and respiratory quotient [R.Q.]) based on the 3 measures of metabolism and determining the impact of other system processes. System metabolism ratios based on daily data varied from 0 to 5.0. System metabolism ratios of P.Q. and R.Q. based on integrated data were highly correlated ( $r = 0.95$  to  $0.96$ ) and similar to traditional ratios obtained in phytoplankton studies. A system photosynthetic quotient of 1.2 and a system respiratory quotient of 1.1 were calculated from the integrated data. These ratios were only slightly affected by carbon dioxide diffusion and 3 benthic processes: denitrification, sulfur metabolism and calcium carbonate dissolution. There was no trend for system metabolism ratios up the nutrient gradient. The C-14 estimations of productivity appeared nitrogen limited in the lower nutrient treatments and provided lower estimates than the 2 system measures of production.

## INTRODUCTION

Every measure of primary production has its own complexities. Metabolism measurements by oxygen changes in dark and light bottles began in the 1920's. In the 1950's this technique was largely replaced by more sensitive C-14 changes in bottles. However, uncertainties in the C-14 technique have led to the practice of measuring primary production by oxygen and converting to carbon using metabolic ratios to calculate carbon flow from primary producers to higher trophic levels. Similar conversions of oxygen to carbon have commonly been made for respiration estimates. These metabolic ratios, the photosynthetic quotient (P.Q.) and the respiratory quotient (R.Q.) need to be assessed for their variability over short and long term time scales.

Both oxygen and C-14 bottle incubations have long histories (Carpenter & Lively 1980, Peterson 1980, Harris 1978). Decisions must be made on trace metal clean techniques, incubation period, depths of incubation,

length of incubation (Ryther & Vaccaro 1954), size and composition of bottles for incubation (Gieskes et al. 1979), whether and how to filter at the end of incubation (O'Reilly & Thomas 1982), whether to use complex light models for calculations of integrated day and depth values (e.g. Fee 1973, 1980) or to use empirical values derived by others (e.g. Vollenweider 1966, Oviatt et al. 1981). After 30 yr it is still uncertain how the use of C-14 measurement compares to gross and net productivity as determined by changes in oxygen (Davies & Williams 1984).

Even less well understood is the relation between bottles techniques and total system measures of metabolism using oxygen and/or total  $CO_2$  (e.g. Odum & Hoskin 1958, Park et al. 1958, Nixon & Oviatt 1973, Johnson et al. 1981). Since total system measurements are usually made in a field situation, horizontal advection, turbulence of water masses and diffusion across the air-sea interface confuse the interpretation of data. Even though diffusion of gases is usually taken into account (Nixon & Oviatt 1973, Day 1983), these proces-

ses are complex and quantified only with considerable uncertainty (Bower & McCorkle 1980, Emerson 1975a, b). Several other processes may affect system concentrations of oxygen and carbon dioxide which do not affect bottle concentrations. These are usually benthic process, and include denitrification, sulfur metabolism and calcium carbonate precipitation or dissolution.

For these reasons it was useful to compare measures of metabolism in mesocosms which did not have the problem of an erratically advected water mass and in which separate estimates of benthic metabolism and other processes which impact oxygen and carbon dioxide concentrations could be made. From June 1981 to September 1983 a nutrient addition experiment was conducted in 9 mesocosms at the Marine Ecosystems Research Laboratory (MERL) (Nixon et al. 1984). During the last 9 m of the experiment, weekly total system metabolism was estimated by measuring dawn-dusk-dawn changes in oxygen and carbon dioxide and by biweekly, midday, bottle C-14 incubations. In this paper, system and C-14 bottle measures of metabolism will be compared at different levels of nutrients in both daily and integrated data sets and some of the processes affecting metabolism ratios will be examined.

### The experiment

For 28 m, from June 1981 to October 1983 inorganic nutrients in ratios similar to those of sewage were added daily to 6 mesocosms (Nixon et al. 1984). The sewage input to Narragansett Bay ( $1\times$ ) on an areal basis is  $2.88 \text{ mmol N m}^{-2} \text{ d}^{-1}$ ,  $0.22 \text{ mmol P m}^{-2} \text{ d}^{-1}$  and  $0.21 \text{ mmol Si m}^{-2} \text{ d}^{-1}$ . The 6 nutrient addition treatments were geometric multiples of  $1\times$ ,  $2\times$ ,  $4\times$ ,  $8\times$ ,  $16\times$  and  $32\times$ , spanning the known range of nutrient inputs to estuaries. Three other mesocosms with no nutrient additions served as controls for the gradient experiment.

### The mesocosms

The mesocosms ( $13 \text{ m}^3$ ) are scaled to the natural system in terms of sunlight, mixing, flushing, temperature, sediment resuspension and bottom communities. The tanks (1.83 m dia., 5.49 m height) are constructed of fiberglass-reinforced polyester resin and have white interior walls. The water column is 5 m deep to prevent sunlight from reaching the bottom, and the sediments, a soft bottom community obtained from central Narragansett Bay, are 37 cm deep. Sea water is fed in a pulsed period every 6 h providing a 27 d turnover time. Temperature control ( $\pm 2^\circ\text{C}$ ) is accomplished with glass heat exchangers which can both heat and cool.

Mixing is accomplished with a plunger, 50 cm in diameter. It moves in a vertical excursion of 60 cm at a rate of 5 cycles  $\text{min}^{-1}$  for one 2 h period each 6 h and resuspends bottom sediments to the same levels that are observed in Narragansett Bay.

### METHODS

*Total system oxygen.* Daily production and night respiration were estimated from consecutive dawn-dusk-dawn oxygen measurements (Odum & Hoskin 1958). Oxygen concentrations were determined from Winkler titrations as modified by Carritt & Carpenter (1966) with a precision of  $\pm 0.05 \text{ mg O}_2 \text{ l}^{-1}$ . The bottles (60 ml glass B.O.D.) were filled from the bottom with a siphon and allowed to overflow to eliminate air bubbles. Samples were fixed immediately and titrated within 24 h. The oxygen concentration ( $\text{mg l}^{-1}$ ) at dawn was subtracted from the dusk oxygen concentration to calculate daytime production. This value in  $\text{mg l}^{-1}$  was multiplied by the depth of the tank (5 m) to convert to  $\text{g m}^{-2}$ , then divided by the number of hours between the dawn dusk sampling times. The resulting value ( $\text{g O}_2 \text{ m}^{-2} \text{ h}^{-1}$ ) was corrected for oxygen diffusion from or to the atmosphere.

The diffusion flux was calculated from an empirical linear regression derived from measurements in the Marine Ecosystems Research Laboratory (MERL) tanks (Roques 1985). A dome floating at the tank surface was flushed with  $\text{N}_2$  and the increase in  $\text{O}_2$  was monitored. Diffusion was calculated using the equation:

$$\text{diffusion flux} = f(0.1) \cdot (\text{tank O}_2 - \text{O}_2 \text{ saturation})$$

where  $f$  = a temperature dependent gas exchange coefficient determined empirically. The diffusion flux (+ or -) was added to the uncorrected production values and multiplied by the number of daylight hours (sunrise to sunset) to estimate daily oxygen production. The nighttime respiration was calculated in a similar manner using dusk-dawn samples.

Trapezoidal integration was used to calculate tank production and respiration per week, per season and per year. In 3 control tanks over 2 annual cycles the coefficient of variation (c.v.) in production was 10 to 19%; the c.v. for night respiration was 5 to 10%.

*Total system carbon dioxide.* Dawn-dusk-dawn estimates of  $\text{TCO}_2$  concentration were derived from measurements of pH, alkalinity, salinity and temperature using the method of Strickland & Parsons (1972), but utilizing a more accurate determination of salinity effects (Table 1). Water samples were siphoned from the tanks, taking care not to trap air in the bottles, and transferred to a temperature control bath set for *in situ* tank temperature. The pH meter was standardized

Table 1. Procedure for calculating total carbon dioxide (TCO<sub>2</sub>) from pH, total alkalinity, temperature and salinity (M. Pilson, pers. comm.)

$$\text{TCO}_2 = \left[ \text{TA (equiv)} - \frac{K_w}{a_H} - \frac{K'_B * \text{salinity} * 1.243 \times 10^{-5}}{a_H + K'_B} \right] * \left[ \frac{a_H^2}{K'_1 (a_H + 2K'_2)} + \frac{a_H + K'_2}{a_H + 2K'_2} \right]$$

Derived from Culberson et al. (1970):

$$K_w^1 = a_H + c_{\text{OH}} = (K_w^{\text{sw}} \text{ of C \& P}) \gamma_{\text{H}^+}$$

$$Y = -0.80046393 + (0.08708525 * ^\circ\text{C}) \text{ for Sal} = 30\text{‰}$$

$$K_w = \exp(Y) * (10. ** (-14.1) \text{ molar})$$

where

$$a_H = 10^{-(\text{pH})}$$

$$K'_B = 10^{-(\text{p}K'_B)}$$

$$\text{p}K'_B = \frac{2291.9}{^\circ\text{K}} + (^\circ\text{K}) 0.01756 - 3.3850 - 0.26316 (\text{Salinity})^{1/3}$$

$$K'_1 = 10^{-(\text{p}K'_1)}$$

$$K'_2 = 10^{-(\text{p}K'_2)}$$

Mehrback constants (Mehrback et al. 1973):

$$\text{p}K'_1 = -13.7201 + 0.031334(^\circ\text{K}) + \frac{3235.76}{^\circ\text{K}} + 1.300 \times 10^{-5} (\text{Sal}) (^\circ\text{K}) - 0.1032 (\text{Sal})^{1/2}$$

$$\text{p}K'_2 = 5371.9645 + 1.671221 (^\circ\text{K}) + 0.22913 (\text{Sal}) + 18.3802 \log(\text{Sal}) - 128375.28/^\circ\text{K} - 2194.3055 \log(^\circ\text{K}) - 8.0944 \times 10^{-4} (\text{Sal}) (^\circ\text{K}) - 5617.11 \log (\text{Sal})/^\circ\text{K} + 2.136 (\text{Sal})/^\circ\text{K}$$

monthly with fresh buffers (pH 9, pH 7 and pH 4) and was rechecked with a pH 7 buffer solution prior to sample analysis. Samples were read within 1 h after collection. Precision was  $\pm 0.02$  pH units.

Total alkalinity was calculated by the method of Culberson et al. 1970. For alkalinity measurements 100 ml of sample were pipeted into a clean jar with 25.0 ml of 0.010M HCl. Samples were read within 2d at 25 °C with a pH electrode after calibration with a pH 4 buffer. Precision was  $\pm 0.006$  pH units. Salinity measurements were determined the same day by AgNO<sub>3</sub> titration. Day production and night respiration were calculated in a manner similar to oxygen except that no diffusion corrections were made. Precision of controls was  $\pm 4.2$  mmol C m<sup>-2</sup> per day or night or 1 mol C m<sup>-2</sup> over a 9 mo period.

**Production by C-14.** Primary production measured by the fixation of C-14 CO<sub>2</sub> was determined every 2 wk using the method of Strickland & Parsons (1972) with some modifications (Almquist 1983). Pooled samples were siphoned from 0.1, 2.5 and 4.5 m during the morning mixing cycle into 2 l amber polyethylene bottles and taken to a darkened laboratory. Polycarbonate centrifuge bottles (85 ml) with polypropylene screw closures were used for incubations to avoid metal contamination. The bottles had been initially cleaned by soaking in warm (50 °C) HCl (high purity) for at least 3 d. Between incubations these bottles were rinsed with

quartz-redistilled, deionized water with 3 drops Ultrex-N HCl added to prevent bacterial growth and to remove trace metals that may have accumulated during prior incubations. For each tank 5 light and 1 dark bottles were filled with 80 ml samples and inoculated with 1 µCi NaH<sup>14</sup>CO<sub>3</sub> solution (New England Nuclear) with an automatic pipet. Incubation bottles were transferred to the mesocosms in a dark box, and suspended cap down in their respective tanks at 0.1, 0.5, 1.0, 2.5 and 4.5 m. The dark bottle was suspended at 4.5 m. Bottles were incubated from 1000 h to 1400 h. After incubation, the bottles were transferred to the laboratory in a dark box and filtered immediately through 25 mm Gelman A/E glass fiber filters (retaining 1 µm size particles) at 125 mm Hg maximum vacuum. Filters were rinsed with 2 successive filtered sea water rinses of 20 ml each to remove any residual inorganic C-14. The filters were not allowed to dry. The edge of the filter was also rinsed 3 times. The filters were placed in scintillation vials with forceps and 10 ml or 3.5 ml of scintillation cocktail (Aquasol II, New England Nuclear) were added depending on the size of the vials. The samples were left uncapped for 5 min to allow degassing of any residual inorganic <sup>14</sup>C. The samples were shaken for 3 h to aid penetration of the filters by the cocktail and to degas inorganic <sup>14</sup>C. The samples were then placed in the scintillation counter and remained in the dark for at least 8 h prior to counting.

Counts per minute (cpm) were converted to disintegrations per minute (dpm) using the external standard channels ratio method of calibration against a quench curve. Primary production was calculated using the equations of Strickland & Parsons (1972) and depth integrated by trapezoidal integration. Reproducibility of replicate bottle values was  $\pm 10\%$ .

*Photosynthetic and respiration quotients.* Total system  $O_2$  changes and total system  $CO_2$  changes were used to calculate photosynthetic quotients:

$$P.Q. = \frac{+\Delta O_2}{-\Delta CO_2}$$

and respiratory quotients:

$$R.Q. = \frac{+\Delta CO_2}{-\Delta O_2}$$

For whole system P.Q. calculations, daytime apparent production by  $O_2$  was divided by daytime apparent system production by  $CO_2$ . No attempt was made to convert these values to gross production by adding night respiration.

The comparison of C-14 production with systems  $O_2$  and  $CO_2$  changes is less direct than the comparison of  $O_2$  with  $CO_2$ . The  $O_2$  and  $CO_2$  estimations include wall production and benthic respiration whereas C-14 measures water column production. Furthermore, the C-14 incubations, made for 4 h during midday must be extrapolated to a whole day.

Rates from diel system  $O_2$  measurements were manipulated to be comparable to water column midday bottle measurements. Benthic  $O_2$  consumption was added to system  $O_2$  production to estimate water column processes. Benthic respiration was measured using a chamber that covered the entire sediment surface by taking initial and final water samples over a period of several hours. The entire benthos was capped with a 1.76 m diameter, 13 cm high clear plastic chamber designed to fit over the sediment tray. Initial and final samples were withdrawn by siphon after mixing with a hand operated stirring bar. A control bottle was incubated on top of the chamber to correct for changes induced by the water within the chamber. Incubation time varied inversely with temperature and ranged from 9 to 1 h over the course of the experiment. Intercepts of individual treatment regressions of daily C-14 values versus systems  $O_2$  plus benthic respiration were interpreted as wall production. No manipulations were made for  $CO_2$  systems production since no measures of  $CO_2$  flux from the sediments were made.

Comparison of C-14 and  $O_2$  production was made using a functional regression (Ricker 1973) of hourly C-14 versus daily  $O_2$  system production plus benthic  $O_2$  consumption. The regression slopes of hourly C-14

production versus daily  $O_2$  and  $CO_2$  production were compared to the Vollenweider (1966) factor. Vollenweider (1966) has estimated that 55 to 60% of the production occurs during the midday period (the hourly rate times factors of 6.67 to 7.27).

## RESULTS

### Daily variability in P.Q. and R.Q.

The metabolic ratios for daily data, collected weekly from January through September 1983 in all 9 mesocosms, range from 0 to 5 and can occasionally be greater (Fig. 1). The central tendency, or median value, for P.Q. was 0.9, but there was also a peak at 1.2. The

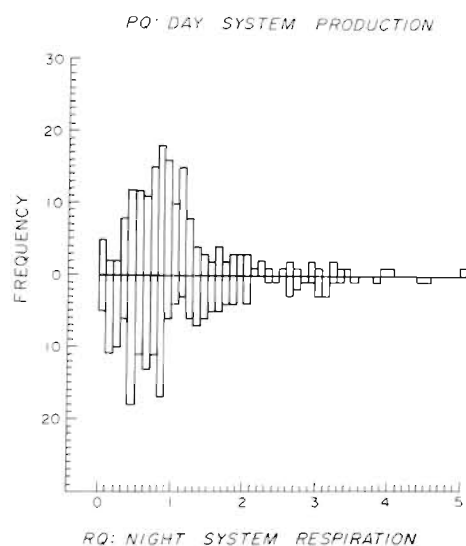


Fig. 1 Frequency of values for P.Q. and R.Q. from system  $O_2$  and  $TCO_2$  measures of production and respiration taken weekly from Jan to Sep 1983

central tendency for R.Q. was 0.5, and there was also a peak at 0.9.

A source of error could arise from uncertainties in the calculation of  $CO_2$  concentrations. Concentrations of  $CO_2$ , calculated based on pH, alkalinity, temperature and salinity, were compared with measurements using the coulometric titration of samples for the control,  $8\times$  and  $32\times$  treatment levels (K. M. Johnson et al. 1985) (Table 2). Differences ranged from  $+8.2$  to  $-36.3$   $\mu\text{mol}$ . Overall titrated  $CO_2$  values tended to predict higher production ( $\bar{X} = 5.0$   $\mu\text{mol}$ ) and slightly lower respiration ( $\bar{X} = -1.2$   $\mu\text{mol}$ ) (Fig. 2). If the worst case dawn-dusk control mesocosm is examined, the production from titrated  $CO_2$  was  $16.7$   $\mu\text{mol}$  and the production from calculated  $CO_2$  was  $6.2$   $\mu\text{mol}$  (Fig. 2). The

Table 2. A comparison of CO<sub>2</sub> concentrations by direct titration and calculated from pH, alkalinity and salinity. From samples taken July 5–6, 1983

Time	Treatment	CO <sub>2</sub> μmol	CO <sub>2</sub> μmol	Difference
Dawn	8×	1884.5	1875.0	- 9.5
	Control	1995.1	1858.8	-36.3
	32×	1530.8	1525.8	- 5.0
Dusk	8×	1862.3	1854.6	- 7.7
	Control	1878.4	1852.6	-25.8
	32×	1526.5	1523.8	- 2.7
Dawn	8×	1874.5	1865.6	- 8.9
	Control	1893.8	1861.8	-32.0
	32×	1561.8	1570.0	+ 8.2

<sup>1</sup> Coulometric titration (Johnson et al. 1985)  
<sup>2</sup> Calculated from pH, alkalinity (Culberson et al. 1970), temperature and salinity

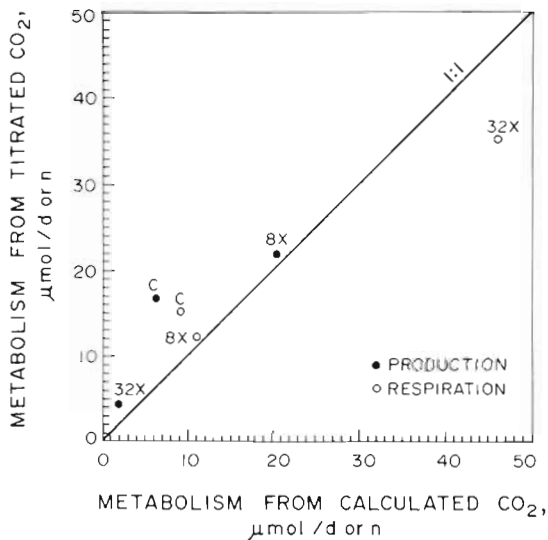


Fig. 2. The difference in production and respiration as determined by calculated TCO<sub>2</sub> compared with coulometric titration values of TCO<sub>2</sub>

other 2 treatments (8× and 32×) had productivity values that agreed within 2 μmol by the 2 methods of measurement. The reason for these differences is not known. In a small data set, the differences were large; more comparative measures are needed to evaluate a large data set.

#### P.Q. and R.Q. from integrated metabolism – Jan to Sep 1983

The integrated values for production and respiration from total system changes in O<sub>2</sub> and CO<sub>2</sub> up the nutrient gradient show a high correlation contrasting with

highly variable daily values. The ratios for P.Q. and R.Q., derived from functional regressions (Ricker 1973, 1975) on the integrated values, had correlations between 95 and 96 % (Table 3). Absolute values for production and respiration increased up the nutrient gradient but P.Q. and R.Q. showed no trend related to the gradient. For all treatments P.Q. was 1.24 and R.Q. was 1.16 (the slopes of the regression lines). The gain in correlation by using integrated data means a sacrifice in degrees of freedom. Thus 95 % confidence intervals on these ratios were large (Table 3).

#### Comparison with integrated C-14 production

The comparison of C-14 to O<sub>2</sub> + benthic respiration was in good agreement with Vollenweider's factors (Table 4). A slope of 6.70 was obtained for the comparison of C-14 with O<sub>2</sub> + benthic respiration. A lower slope of 4.92 was obtained for the comparison of C-14 with uncorrected CO<sub>2</sub> (Table 4). An intercept of 57 mmol was obtained for the oxygen regression which may be partially attributable to wall production. At first, this value appeared unacceptably high. However, individual treatment regressions of daily C-14 values versus O<sub>2</sub> + benthic respiration (in which the intercepts were interpreted as wall production), on all days when concurrent measurements were made, indicated that a mean of 10 % total production occurred on the walls (Table 5). A low of 2 % was found in the 16× treatment and a high of 20 % was found in the 32× treatment. Wall growth (mainly benthic diatoms) was noticeably greater in the 32× treatment and even twice-weekly wall cleanings did not totally eliminate its vigor.

Photosynthetic quotient calculations were made between C-14 production and both net and gross oxygen production in the water column (Table 5). Daily values for C-14 were calculated by multiplying by a rounded factor of 7 and integrating over the 9 mo period. Benthic respiration was added and wall production was subtracted from total system oxygen production to provide estimations of net water column production. Night respiration was used to calculate values of water column respiration and added to net water column production to estimate gross production although no estimate was available to make corrections for wall respiration (Table 5). The functional regressions using net and gross water column productions resulted in P.Q.s of 0.81 and 1.45 (Table 5). The mean of these (1.13) was slightly less than the system P.Q. (Table 3). The intercepts in these regressions cannot be interpreted as wall production and might reflect the irregular trend in the C-14 values up the nutrient gradient (Table 5). Control, 1× and 8× treat-



Table 3. Integrated values for production and respiration from dawn-dusk-dawn measurements of O<sub>2</sub> and CO<sub>2</sub> changes. Metabolism calculations for O<sub>2</sub> are diffusion corrected; those from CO<sub>2</sub> are not diffusion corrected. Period of measurement from Jan to Sep 1983. Values in mol m<sup>-2</sup> 9mo<sup>-1</sup>

Treatment	Production			Respiration					
	X CO <sub>2</sub>	Y O <sub>2</sub>	CO <sub>2</sub> /O <sub>2</sub>	X O <sub>2</sub>	Y CO <sub>2</sub>	P/R O <sub>2</sub>	P/R CO <sub>2</sub>	P-R O <sub>2</sub>	P-R CO <sub>2</sub>
Control	9	14	0.6	13	6	1.1	1.5	1	3
Control	8	14	0.6	16	8	0.9	1.0	-2	0
Control	6	11	0.5	15	6	0.7	1.0	-4	0
1×	13	16	0.8	18	12	0.9	1.1	-2	1
2×	24	30	0.8	27	18	1.1	1.3	3	6
4×	28	33	0.8	30	16	1.1	1.8	3	12
8×	27	25	1.1	21	15	1.2	1.8	4	12
16×	29	40	0.7	34	31	1.2	0.9	6	-2
32×	37	52	0.7	44	42	1.2	0.9	8	-5

P.Q. from a functional regression:  $Y = 1.24X + 1.02$ ;  $r = 0.95$   
P.Q. = 1.24 95% confidence interval: 0.31-4.87  
R.Q. from a functional regression:  $Y = 1.16X - 10.9$ ;  $r = 0.96$   
R.Q. = 1.16 95% confidence interval: 0.33-4.22

ments showed particularly poor agreement between corrected O<sub>2</sub> and C-14 which was not evident between O<sub>2</sub> and CO<sub>2</sub> (Table 3).

#### The nutrient gradient

No obvious trends in system P.Q. and R.Q. occurred up the nutrient gradient suggesting that the processes which affect P.Q. and R.Q. are independent of absolute

values of metabolic activity (Table 3). Production to respiration (P/R) ratios do show some irregular differences up the gradient with values ranging from 0.7 to 1.8 (Table 3). Despite similar proportionality in metabolic ratios, the magnitudes of O<sub>2</sub> metabolism and to a less regular extent CO<sub>2</sub> metabolism do increase up the treatment gradient. Thus net ecosystem production (P-R), based on O<sub>2</sub> was less than 1 mol O<sub>2</sub> m<sup>-2</sup> 9mo<sup>-1</sup> in control mesocosms, and 8 mol O<sub>2</sub> m<sup>-2</sup> 9mo<sup>-1</sup> in the 32× treatment.

Table 4. A comparison of total system apparent production by O<sub>2</sub> and CO<sub>2</sub> changes with midday hourly C-14 production in the water column from Jan to Sep 1983 (9 mo or 273 d)

Treatment	Benthic respiration	Production		Water column production
	O <sub>2</sub> mol m <sup>-2</sup> 9mo <sup>-1</sup>	Y <sub>1</sub> O <sub>2</sub> + benthic respiration mol m <sup>-2</sup> 9mo <sup>-1</sup>	Y <sub>2</sub> CO <sub>2</sub> mol m <sup>-2</sup> 9mo <sup>-1</sup>	X C-14 mol m <sup>-2</sup> h <sup>-1</sup> × 9mo
Control	5.0	19.0	9	0.89
Control	4.9	18.9	8	1.27
Control	5.3	16.3	6	1.05
1×	6.9	22.9	13	0.86
2×	4.3	34.3	24	3.41
4×	2.9	35.9	28	3.11
8×	8.0	33.0	27	1.24
16×	5.9	45.9	29	5.12
32×	11.2	63.2	37	7.34

Functional regressions:  
C-14 vs O<sub>2</sub> + benthic:  $\text{mmol m}^{-2} \text{d}^{-1} = 6.70 (\text{C-14}) + 57 \text{ mmol}$   
 $r = 0.95$ ; 95% confidence interval: 1.7-26.3  
C-14 vs CO<sub>2</sub>:  $\text{mmol m}^{-2} \text{d}^{-1} = 4.92 (\text{C-14}) + 82 \text{ mmol}$   
 $r = 0.83$ ; 95% confidence interval: 0.7-32.6



Table 5. A comparison of water column net and gross production from Jan through Sep 1983. Hourly C-14 values have been multiplied by a rounded factor of 7 and integrated (from Table 4)

Treatment	1 Net production (S + BR) - (Walls)		2 Day respiration (1.078 NR) - (BR)		1 + 2 Gross	C-14
	mol O <sub>2</sub> m <sup>-2</sup> 9mo <sup>-1</sup>				Y	mol C m <sup>-2</sup> 9mo <sup>-1</sup> X
Control	19.9	2.0	14.5	5.0	27	6.2
Control	18.9	3.0	17.2	4.9	28	8.9
Control	16.3	1.9	16.2	5.3	25	7.4
1×	22.9	1.5	19.4	6.9	34	6.0
2×	34.3	3.5	29.1	4.3	56	23.8
4×	35.9	2.7	32.3	2.9	63	21.8
8×	33.0	8.5	22.6	8.0	40	8.7
16×	45.9	1.0	36.7	5.9	76	35.9
32×	63.2	12.6	47.4	11.2	87	51.4

P.Q. from functional regressions:  
Based on net water column production  
 $Y = 0.81X + 14.3$ ;  $r = 0.96$   
P.Q. = 0.81  
Based on gross water column production  
 $Y = 1.45X + 20.9$ ;  $r = 0.96$   
P.Q. = 1.45

S = System daytime production  
BR = Benthic respiration  
Walls = Wall production from treatment intercepts  
NR = System night respiration; the factor 1.078 corrects for day length

Table 6. Metabolic ratios derived in other studies and processes potentially impacting these ratios

Location	Method	P.Q.	R.Q.	Influencing factors	Source
Texas coastal bays	System O <sub>2</sub> & CO <sub>2</sub>	0.3–1.0	0.5–3.0*	Microbial activity, water mass changes	Park et al. 1958
Aquatic microcosms	System O <sub>2</sub> & CO <sub>2</sub>	1.1–2.5*	0.5–3.3	Light	Beyers 1963
Estuarine & coastal	Bottle O <sub>2</sub> & C-14	1.1–2.3	—	Nitrate utilization	Williams et al 1979
Marine culture	Bottle O <sub>2</sub> & CO <sub>2</sub>	0.1–1.8	—	O <sub>2</sub> concentration	Burris 1981
Marine ecosystems	System O <sub>2</sub> & CO <sub>2</sub>	0.2–0.7	—	Microbial activity	Johnson et al. 1981
Enclosed ecosystems	O <sub>2</sub> & C-14	1.3–1.6	—	Nitrate utilization, DOC production	Davis & Williams 1983
Mesocosms: daily values	System O <sub>2</sub> & CO <sub>2</sub>	0–5.0	0–5.0	—	This study
Mesocosms: integrated values	System O <sub>2</sub> & CO <sub>2</sub>	1.2	1.2	—	This study
	System O <sub>2</sub> & C-14	0.8–1.5	—	—	

\* Inverse of reported values

## DISCUSSION

### System metabolism ratios

The system P.Q. value of 1.24 was within the range of traditional water column estimates of 1.1 to 1.3 (Ryther 1965); although the system R.Q. value of 1.16

was slightly high (Parsons et al. 1977). In the daily data set any P.Q. and R.Q. between 0 and 5 might occur (Fig. 1). Many processes in the water column are thought to affect metabolic ratios (Table 6). High P.Q. values may be caused by nitrate utilization (Burris 1981, Williams et al. 1979) and by low light (Anderson & Sand-Jensen 1980); low P.Q. values may be caused

by photorespiration (Burris 1981), photooxidation and microbial activities (Johnson et al. 1983). However, in the integrated data set (9 mesocosms measured weekly for 9 mo) these processes appear to cancel out and more traditional ratios were obtained (Table 3).

### Processes affecting metabolism ratios

A number of processes change P.Q. and R.Q. values (Table 6), including carbon dioxide diffusion, nitrification-denitrification, sulfate reduction-sulfide oxidation and calcium carbonate precipitation/dissolution. We calculated the effects of these processes on the integrated P.Q. and R.Q. values. These calculations were made only for the control mesocosms, but the net effects were assumed to be proportional up the nutrient gradient (Table 3). The lack of long term trends does not rule out large changes in some processes over the short term, particularly in the highly enriched treatments. For example, shell formation in bivalves in the 8× treatment may have affected CO<sub>2</sub> concentrations during the first year of the experiment (Donaghay unpubl.); nitrification and sulfur metabolism rates were high periodically and could have affected metabolic ratios (Berounsky & Nixon in press, Sampou unpubl.). While these short term rate changes apparently did not affect long term metabolic ratios, they probably contribute to variability observed in daily ratios (Fig. 1).

Corrections for oxygen exchange with the atmosphere were applied to oxygen metabolism values but carbon metabolism values were not corrected for the slower exchange of CO<sub>2</sub> with the atmosphere. Rough CO<sub>2</sub> diffusion corrections were calculated assuming a previously determined film thickness at the air-water interface of 0.07 cm (Bopp et al. 1981). (We have ignored potential chemical enhancement of CO<sub>2</sub> flux suggested by Broecker & Peng [1974] and wind effects calculated by Teal & Kanwisher [1966]). The changes calculated were generally in fractions of a mole for day or night corrections over a 9 mo period (Table 7). Skirrow (1975) noted that it is not possible to calculate the rate of transfer of CO<sub>2</sub> across the air-sea interface in either direction from first principles and these values were at best approximate. The main point, however, is that the values were small and would not change the metabolism estimate when rounded to the nearest mole (Table 3). The error caused by lack of CO<sub>2</sub> diffusion correction appears too small to have affected P.Q. and R.Q.

Nitrate is formed in the water column and the sediments from ammonia and oxygen (Fenchel & Blackburn 1979):

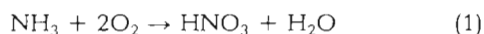
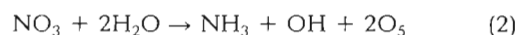


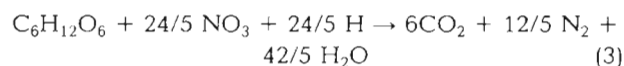
Table 7. Net CO<sub>2</sub> diffusion calculated assuming (1) a film thickness previously determined to be 0.07 cm, (2) P<sub>CO<sub>2</sub> sat</sub> equal to 330 μatm (3) diffusivity equal to 2 × 10<sup>-5</sup> cm<sup>2</sup> s<sup>-1</sup> and (4) equations from Skirrow (1975)

Treatment	Diffusion (mol C m <sup>-2</sup> 9mo <sup>-1</sup> )	
	Day	Night
Control	-0.4	-0.3
Control	-0.2	-0.1
Control	-0.4	-0.2
1×	-0.4	-0.3
2×	+0.1	+0.1
4×	+0.1	+0.1
8×	-0.9	-0.6
16×	-0.2	-0.1
32×	-0.5	-0.4

When water column nitrate is utilized by phytoplankton, the oxygen used in formation is returned. The formula is given by Williams et al. (1979):



While in short-term data sets the latter reaction may increase P.Q. (Williams et al. 1979), in a long-term data set where the principal nitrogen form is ammonia, the 2 reactions should be roughly equivalent and P.Q. should not be affected. However, most of the nitrate formed in the sediments appears to be denitrified (Seitzinger & Nixon in press). Denitrification proceeds in the sediment utilizing organic matter and nitrate (Fenchel & Blackburn 1979):



For each cycle of a N atom in the nitrification-denitrification reaction in sediments, 4 oxygen atoms are used in nitrification and only 2.5 atoms reappear as carbon dioxide in denitrification for a deficit of 1.5 oxygen atoms as H<sub>2</sub>O. These reactions thus result in the net consumption of 0.75 mol O<sub>2</sub>/mol N with no corresponding CO<sub>2</sub> reduction. Denitrification proceeded at a rate of 7.20 m mol N m<sup>-2</sup> 24 h or 1.86 mol N m<sup>-2</sup> 9 mo<sup>-1</sup> in control systems (Seitzinger & Nixon in press). If nitrification is assumed equal to denitrification, then 0.90 mol O<sub>2</sub> m<sup>-2</sup> 9 mo<sup>-1</sup> by day and 0.77 by night can be calculated as deficit amounts (Table 8).

Anaerobic sulfur metabolism in the sediments can contribute to higher metabolic ratios. Organic matter can be utilized by bacteria using sulphate as an oxygen source; the sulphide produced is then reoxygenated by molecular oxygen (Fenchel & Blackburn 1979):

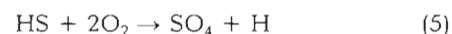


Table 8. Effect of 3 benthic processes on system P.Q. and system R.Q. in control mesocosms

		Source
A. Denitrification		
Rate: 1.86 mol N m <sup>-2</sup> 9mo <sup>-1</sup>		Seitzinger & Nixon in press
1.67 mol O <sub>2</sub> m <sup>-2</sup> 9mo <sup>-1</sup>		
O <sub>2</sub> : + Δ system Apparant daytime production 6.9% (.90 mol)		
- Δ system apparent nighttime respiration 5.1% (.77 mol)		
B. Sulfate reduction – sulfide oxidation		
Rate: Oxidation 5.8 mol O <sub>2</sub> m <sup>-2</sup> 9mo <sup>-1</sup>		Sampou unpubl.
Reduction 6.4 mol CO <sub>2</sub> m <sup>-2</sup> 9mo <sup>-1</sup>		
O <sub>2</sub> : + Δ system apparent daytime production 2.6 % (.34 mol)		
- Δ system apparent nighttime respiration 2.1 % (.31 mol)		
C. Calcium carbonate dissolution		
Rate: + 2.08 mol Ca + CO <sub>2</sub> m <sup>-2</sup> 9mo <sup>-1</sup> *		Smith & Key 1975
CO <sub>2</sub> : + Δ system apparent daytime production 14 % (1.1 mol)		
- Δ system apparent nighttime respiration 14 % (0.9 mol)		
D. Combined effect on system P.Q. and system R.Q. (Table 3)		
System P.Q.:	1.24 $\frac{\Delta O_2}{\Delta CO_2}$	$\left( \frac{\begin{array}{ccc} \text{N} & \text{S} & \text{CaCO}_3 \\ 1.069 & 1.026 & \\ & & 1.14 \end{array}}{\quad} \right) = 1.19$
System R.Q.:	1.16 $\frac{\Delta CO_2}{\Delta O_2}$	$\left( \frac{\quad}{\begin{array}{ccc} & & .86 \\ .949 & .979 & \end{array}} \right) = 1.08$
* Corrected for sulfide storage (0.64 equiv. m <sup>-2</sup> )		

These equations are balanced but Jorgensen (1977) found that 10 % of the sulfide produced remains in the sediment on a yearly basis. For each mole of stored S, 2 moles of CO<sub>2</sub> had been produced for which no O<sub>2</sub> had been consumed. Several measurements in control mesocosms integrated over the year indicated that 4.27 mol SO<sub>4</sub> were reduced m<sup>-2</sup> yr<sup>-1</sup> in control mesocosms to a depth of 20 cm (Sampou unpubl.). If the 10 % deficit is assumed, and the amount is made proportional to a 9 mo period, then 0.34 mol O<sub>2</sub> m<sup>-2</sup> 9 mo<sup>-1</sup> by day and 0.31 by night must be added to production and subtracted from respiration, respectively (Table 8).

Calcium carbonate precipitation or dissolution can affect CO<sub>2</sub> concentration and therefore P.Q. and R.Q. The processes can be detected by changes in alkalinity. Calcification lowers the total CO<sub>2</sub> content of sea water 1 mol for each mole of CaCO<sub>3</sub> precipitated and the total CO<sub>2</sub> content of seawater is, therefore, lowered by 0.5 mol for each equivalent of total alkalinity reduction or the reverse reaction for dissolution (Smith & Key 1975). Each mole of sulfide stored in the sediment yields 2 equivalents of alkalinity production for the water column. If 0.32 mol of sulfide were buried over 9 mo, 0.64 equivalents were produced. Thus the change in alkalinity was partially due to sulfide storage. The changes in alkalinity due to CaCO<sub>3</sub> dissolu-

tion and sulfide storage were corrected to yield the change due to CaCO<sub>3</sub> dissolution. The daytime average increase in 3 control mesocosms in alkalinity due to CaCO<sub>3</sub> in control mesocosms over the 9 mo period results in an increase of 1.1 mol CO<sub>2</sub> m<sup>-2</sup> by day or 0.9 mol CO<sub>2</sub> m<sup>-2</sup> by night (Table 8). This dissolution would have the effect of lowering both P.Q. and R.Q. slightly (Table 8).

The combined effect of these 3 benthic processes was to lower P.Q. from 1.24 to 1.19 and to lower R.Q. from 1.16 to 1.08 (Table 8). Given the uncertainty of these calculations, values have been rounded to a P.Q. of 1.2 and an R.Q. of 1.1. It takes a certain lack of caution to take the rates from several investigators and extrapolate them to a 9 mo period even when the rates are measured in the same mesocosms. The benthic processes examined show evidence of impacting P.Q. and R.Q. slightly; whether the exact impact has been correctly calculated is unknown.

### Water column production

Since the C-14 method measures primary production rates that are between gross and net production, P.Q.'s were calculated using both measures of water column

O<sub>2</sub> production. Neither calculation provided a value of 1.2 and the ratios were not consistent up the treatment gradient (Table 5). Treatments with lower phytoplankton biomass (controls, 1× and 8× (which had a high abundance of filter feeders)) had higher P.Q. values and treatments with high phytoplankton biomass had lower P.Q. values. Of the 3 methods of measurements, C-14 appears to be least consistent.

One reason for differences in controls and 1× treatment for production measured by C-14 appears to be nitrogen limitation in the C-14 bottles (Table 9). Nitrogen limitation was calculated by comparing the C-14

Table 9. Calculation of nitrogen limitation based on the calculated demand using the Redfield ratio (C:N of 106:16) from the C-14 production and comparing the demand to standing stock concentrations

	Ammonia limiting % time	Inorganic N limiting % time
Control	65	48
Control	71	59
Control	70	30
1× treatment	70	50
8× treatment	0	0

primary production demand using the Redfield ratio (C106:N16:P1) and comparing the demand over a 4 h incubation period to the standing stock from January to September 1983. These calculations indicate N limitation from 30 to 50 % of the time. System measures of production would likely experience more nitrogen availability because of movement through the water column and because of benthic nitrogen regeneration which the bottle incubations would not receive. This explanation does not explain the discrepancy for 8× treatment which experienced no nitrogen limitation (Table 9). The large number of filter feeders in the 8× may have reduced the phytoplankton biomass to a level which precluded initiation of a bloom during the incubation period. A lower production and respiration in the 8× treatment also was found using total system measures (Table 3).

### CONCLUSION

The measurements of metabolism by 3 methods in controlled ecosystems have provided a holistic evaluation of metabolic ratios and processes affecting them. Integrated long term metabolic values were highly correlated and only slightly affected by the processes examined. By contrast, daily ratios were variable and little information emerged that can explain this varia-

bility (Fig. 1). It is likely that benthic and water column processes may have a significant short term influence on metabolic ratios. In taking 3 benthic processes into account a P.Q. of 1.2 and a R.Q. of 1.1 was calculated for integrated system measures of production and respiration by oxygen and carbon dioxide. These ratios do not appear to be affected by a wide range of nutrient treatments suggesting the processes occur proportionally up the nutrient gradient. A comparison of C-14 production to net and gross oxygen production yielded P.Q.'s of 0.8 and 1.5, respectively. Despite the manipulations of total system oxygen to make these comparisons, the C-14 values appear less comparable than the 2 system methods of measurement. These results provide evidence supporting traditional corrections of oxygen to carbon for system measures of metabolism for long term integrated data sets, but not for short term data sets.

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