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ELECTRON TRANSPORT SYSTEM ACTIVITY MEASUREMENTS IN THE APEX OF THE NEW YORK BIGHT

C. Garside

Bigelow Laboratory for Ocean Sciences
McKown Point, West Boothbay Harbor
Maine 04575

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ABSTRACT

Electron transport system (ETS) activity as a measure of respiration was determined along with respiration measured by direct respirometry on the Synoptic Investigation of Nutrient Cycles (SINC) cruises conducted as part of the Marine EcoSystems Analysis (MESA) program in the Apex of the New York Bight. The purpose was to evaluate ETS activity measurements for the monitoring of the potential for the development of anoxic conditions, such as those that caused the fish kill of the summer of 1976.

ETS activity grossly underestimated respiration on the first (spring) cruise although the two were correlated. On the second cruise (summer) ETS and respiration were correlated and of the same magnitude, but the relationship was not good enough that ETS was a satisfactory predictor of respiration. On the third and fourth (fall and winter) cruises, ETS and respiration were not correlated.

Attempts were made to assign quantitative estimates to the size of the components of the respiring community on a carbon basis, and to use these estimates in multiple linear regression analyses to evaluate ETS to respiration relationships which might be obscured within the data as a consequence of variability in the composition of the community. This was difficult task that was not satisfactorily resolved, but the best analysis possible with the data did not resolve any significant ETS to respiration relationships.

Finally, an analysis of variance of all of the data from each cruise showed that ETS was only related to temperature on the winter cruise, and on the other cruises was related as well or better to any of the biomass indicators (Chlorophyll *a*, ATP, or Carbon) as it was to respiration. It is concluded that ETS activity measurements are not a satisfactory estimator of water column respiration in the Apex of the New York Bight.

INTRODUCTION

The anoxic event of the summer of 1976 which resulted in an extensive fish kill and mortality of large areas of commercially important shellfish beds pointed clearly to the importance of an adequate concentration of dissolved oxygen in the bottom waters of the Apex of the New York Bight. The processes leading to the anoxic conditions are respiration and chemical oxidation within the water column and the sediments. There have been numerous measurements of the respiration rates both in the water column and the sediments of the Apex (e.g. Thomas *et al.*, 1976), but the major drawbacks of these determinations are that they are time consuming, and the incubation technique used does not lend itself to either rapid or extensive measurements.

The electron transport system (ETS) is an enzyme system common to all aerobic organisms and is responsible for electron transfer associated with cellular respiration. The determination of ETS activity has been developed in marine bacteria (Christensen *et al.*, 1980), marine phytoplankton (Packard, 1971) and in marine zooplankton (Owens and King, 1975), and factors relating the activity to respiration have been obtained. The method has been widely applied to whole water samples (e.g. King *et al.*, 1978) as a means of estimating the plankton metabolic activity. The method is attractive because the determination of activity can be made in the laboratory on samples refrigerated in liquid nitrogen and no incubation period is required.

Consequently, it is possible to undertake much more intensive sampling both in time and space, than is possible with the respirometry incubation methods.

Direct respirometry and the measurement of ETS activity were undertaken routinely as part of the field program of the Synoptic Investigation of Nutrient Cycles (SINC), which was a part of the Marine Ecosystems Analysis (MESA) Program in the Apex of the New York Bight. The purpose of these measurements was, in part, to evaluate the ETS assay as a monitoring tool to be used to estimate respiration rates in a routine way in the Apex, so that a rapid determination of the potential for development of anoxic conditions might be possible. This report evaluates the results of this comparison, and attempts to relate the ETS activity and respirometry measurements using various estimators of the biomass present in the samples.

METHODS

The methods and sampling rationale of the SINC program are fully described in the SINC Compendium Report (Malone, 1980) and the relevant parts are abstracted here.

SINC cruises (12 days each) were conducted on the following dates: SINC I, 9-19 May 1977; SINC II, 18-28 July 1977; SINC III, 7-20 November 1977; SINC IV, 5-16 March 1978. Estuarine water was tagged as it moved into the apex by deploying drogues (sail at 5m) near the mouth of the Hudson-Raritan estuarine complex. Once deployed, measurements were made at 3-6 hour intervals while following the drogue until the time-series was terminated (usually because the drogue went aground, remained nearly stationary for more than 12 hours, drifted out of the study area, or we ran out of time).

Raydist was the primary means of navigation with Loran-C and visual fixes as backup. Fixes were taken at the beginning and end of each sampling operation and at 30 minute intervals while following the drogue between sample times. Once a drogue was launched, a 24-hour sampling program was initiated and continued throughout the period of each drogue study. Sampling routines were started about 1 hour before sunrise (SR), mid-morning (MM), noon (N), sunset (SS) and midnight (MN). Water for direct respirometry, ETS activity measurements and associated biomass measurements was collected from 3 to 6 depths in the water column using Niskin sample bottles of either 6 or 30 ℓ capacity.

Vertical profiles of temperature and conductivity were obtained with an Interocean model 660 CSTD on SINC I and II and with a Plessy model 9040 CTD on SINC III and IV. Data were recorded by hand from a digital display on SINC I. A depth-driven, dual pen, strip-chart recorder was used to obtain continuous profiles on the remaining SINC cruises.

Dissolved oxygen was measured using the azide modification of the iodometric method (Am. Public Health Assoc. 1965) except that 0.0375 N phenylarsine oxide was used in place of sodium thiosulfate (Kroner, 1964; U.S. EPA 1974). All samples were collected in duplicate.

Photosynthetically active radiation (PAR, 400-700 nm) was measured with a Lambda quantum sensor (LI-190S) and recorded with a digital integrator (Li-500). Downwelling PAR was measured with a submersible quantum sensor (Li-192S) and a Lambda Li-185 photometer equipped with a strip-chart recorder. Secchi disc measurements were made in conjunction with downwelling PAR profiles.

Vertical (submersible pump) distributions of *in vivo* chlorophyll were determined by continous fluorometry standardized by *in vitro* chlorophyll *a* measurements on discrete samples from near the surface and bottom. All particulate measurements on discrete samples were made after filtration through Gelman Type A-E glass fiber filters.

Extracted (90% acetone) chlorophyll *a* (precision $\pm$ 0.1 µg l^{-1}) was measured by fluorometry (Holm-Hansen *et al.*, 1965). Particulate organic carbon ($\pm$ 0.04 mg l^{-1}) was determined with an HP-185 CHN analyzer (Strickland and Parsons, 1972) and ATP with a JRB model 300 ATP photometer (Holm-Hansen and Booth, 1966).

To determine plankton respiration, ten acid washed and baked (232°C for 1 hour) 300 ml BOD bottles were filled with water from each depth sampled. Half were fixed immediately and dissolved oxygen measured as described above. The remaining five bottles for a given depth were incubated in the dark at $\pm$ 1°C of *in situ* temperature for 12 (July) or 24 hours (May, November, March). The rate of oxygen consumption was calculated from the difference between the concentration of dissolved oxygen before and after the incubation period. Rates of respiration (precision $\pm$ 1.3 µg C l^{-1} hr^{-1}) were calculated from the disappearance of oxygen.

Potential rates of microbial respiration were estimated from measurements of ETS activity (Packard, 1971). Samples of 1 to 2 liters were filtered onto type A/E Gelman glass fiber filters, transferred to a 7 ml scintillation vial and stored in liquid nitrogen. ETS activity was measured as described by Kenner and Ahmed (1975a). Oxygen consumption rates were calculated using a respiration/ETS ratio of 0.15 (Kenner and Ahmed, 1975b).

Replicate zooplankton samples were obtained with paired half meter, 202 μm mesh nets equipped with inner and outer TSK flowmeters. Nets were towed obliquely over the entire water column for five to thirty minutes depending on the density of organisms. Half of each catch was preserved in 4% buffered formalin for enumeration and identification. The remaining half was briefly rinsed with distilled water and frozen for dry weight analysis. Samples for dry weight analysis were thawed, dried to constant weight at 60°C and weighed on a semi-micro balance after cooling in a desiccator.

All data are contained in the SINC Data Report (Garside, 1980) and have been archived with the NODC (Accession Number 79-0287).

RESULTS AND DISCUSSION

An initial comparison of the respiration and ETS data was made by plotting one aginst the other and computing the regression line for each set:

$$ETS = a + b\ R$$

where R is respiration, and the correlation coefficients (r^2) were obtained. The results are presented in Table 1.

The SINC I data gave an extremely small gradient, mainly because the ETS respiration numbers were about 5% of the respiration values, and the two were significantly correlated. This would suggest that the ETS samples were spoiled or degraded in some way, but in fact they were handled identically with the later cruise samples, and those all gave ETS and respiration values that were of comparable magnitude. The cause of the anomalously low ETS values on SINC I has not been identified. The SINC II data set was highly correlated although there was a very large intercept (ETS went to zero before respiration was zero). In fact the regression was strongly influenced by six data points with very high respiration and when these were eliminated the line passed through the origin although the regression coefficient of the ETS *vs* R relationship was changed markedly. The data on SINC III and IV were uncorrelated.

The ETS data had been converted to respiration using the factor of 0.15 (Kenner and Ahmed, 1976b), which if valid for these samples, should have resulted in the regression coefficient having a value of 1.0. The regression coefficient was always

less than 1.0 suggesting that a higher number would be more appropriate. Since zooplankton and bacteria are believed to have a higher R:ETS ratio (1.64 and 0.43 respectively - King *et al.*, 1978) it might be assumed that a significant portion of the measured respiration was contributed by these organisms and that a higher R:ETS ratio would be justified and representative of the Apex. Such an assumption would not be unrealistic, but the use of a single value for this ratio would only result in the regression coefficient becoming unity and would not reduce the scatter in the data. However, if phytoplankton, zooplankton and bacteria contributed variably to the total respiring community, then, since each would be expected to have a different R:ETS relationship, some of the scatter in the data might be accounted for.

Unfortunately, the separate contributing biomasses were not measured, and in fact there is no way of effecting such a physical separation. Nevertheless, for any given sample it is possible to write equations relating the zooplankton plus bacterial carbon (C_z), the phytoplankton carbon (C_p) and the detrital carbon (C_d) to respiration (R) through appropriate factors (R_z, R_p, and R_d respectively) and to ETS through similar factors (E_z, E_p, and E_d respectively):

$$C_zR_z + C_pR_p + C_dR_d = R \qquad 1$$

and

$$C_zE_z + C_pE_p + C_dE_d = ETS \qquad 2$$

For each sample where these various C values can be determined a separate equation can be written and the simultaneous equations could then be solved to obtain the separate R:ETS ratios for the individual components of the respiring community. What was required was a way of estimating the various C components of the community.

Carbon was chosen as the biomass basis on which to proceed because the total particulate organic carbon was measured on all samples and adenosine triphosphate (ATP) as an estimator of total living biomass and chlorophyll *a* (Chla) as an estimator of phytoplankton biomass were also measured.

The partitioning of the carbon between zooplankton and bacteria, phytoplankton and detritus was undertaken by writing a series of equations for all samples within a cruise:

$$C_z + C_p + C_d = POC \qquad 3$$

$$C_z + C_p = ATP.f_a \qquad 4$$

$$C_p = Chla.f_c \qquad 5$$

Then if the factors f_a and f_c can be obtained, equation 5 gives C_p directly, and rearranging equation 4 and substituting for C_p from equation 5 gives:

$$C_z = ATP.f_a - Chla.f_c \qquad 6$$

and a similar rearrangement of equation 3 and substitution from equation 4 gives:

$$C_d = POC - ATP.f_a \qquad 7$$

C_d was retained in these equations as an estimator of chemical oxidation although this would not be measured by the ETS assay.

f_a is 250 according to the literature (Holm-Hansen and Booth, 1966). The value of f_c can theoretically be obtained from a regression of Chla on POC.

The complete data files were extracted to obtain files containing only samples for which POC, Chla, ATP, ETS and R data were all available for each cruise. f_c was then computed from a linear regression of Chla on POC using all data available from this subset of the data, and it was found that the data were not linear, but that a linear relationship was approached at higher Chla values. This result was expected and has been explained as resulting from a higher proportion of the POC being detrital at low Chla concentrations so that the POC:Chla ratio is artificially increased if these samples are included in the analysis. To avoid this possibility, the data set was reduced to data pairs in which the Chla was greater than 4 $\mu g\ l^{-1}$, and a second data set in which only samples from above the 10 m depth, which would presumably contain more phytoplankton and less detritus, were included. Both these last two approaches gave similar values for f_c (Table 2).

It was decided to use the lower of these two factors for each cruise which resulted in the criterion of the f_c value obtained from the chlorophyll values greater than 4 $\mu g\ l^{-1}$ being used except for SINC III. The small number of samples greater than 4 $\mu g\ l^{-1}$ on SINC III and the very high values obtained

for f_c suggested that the major component of the POC pool was detrital and this data set was dropped from the rest of this analysis. C_z, C_p, and C_d were then calculated for all samples on SINC I, II and IV. The results were not satisfactory as the carbon computed from ATP was less than the carbon computed from chlorophyll in about 90% of the samples and resulted in negative values for the zooplankton carbon, C_z. No attempt could be made to set up the simultaneous equations 1 and 2 with negative zooplankton carbon, so it was decided to make a separate evaluation of the POC:ATP relationship to obtain a value for f_a that would better reflect the appropriate values for each cruise.

An initial approach to this was made using all data and then stations for which the Chla values were greater than 4 $\mu g\ l^{-1}$ and the POC *vs* ATP regressions were run to obtain values of f_a and the results are presented in Table 3.

The values for Chla greater than 4 $\mu g\ l^{-1}$ clearly biased the f_a values towards a ratio typical of phytoplankton, while the values using all the data were perhaps more representative of the populations as a whole but were influenced by detritus in a variable way. In any case, the SINC III f_a was so improbable that this value was discarded and the data dropped from the working file as before. When these values for f_a and values obtained above for f_c (Chla > 4 $\mu g\ \ell^{-1}$) were used to calculate C_z, C_p and C_d the values for C_z were, almost without exception,

negative, as would be expected since the values for f_a were all less than the 250 assumed before. Only the SINC II, all data value for f_a was not changed and remained 250.

In view of this generally unsatisfactory analysis of C_z an attempt to obtain C_z directly from zooplankton dry weight data was made, but quickly discarded, as the only zooplankton data available were from net tows which were therefore some form of water column integration, and cannot be correlated with any of the other data which came from samples at discrete depths.

Attempts to partition the total carbon between fractions based on the ratio of ATP and Chla to carbon using various criteria for selecting subsets of the total data clearly did not work. The problem lies in the tendency for total living carbon to be underestimated using ATP or for the phytoplankton carbon to be overestimated using Chla. The Chla:C_p ratios obtained from the data are consistent with those previously reported in the literature, and the ATP:C_z ratio is less than that reported by Holm-Hansen and Booth, (1966). To avoid using the ratios suggested by the data and at the same time to obtain positive C_z values three further approaches were used.

In the first of these f_a was set at 250 and the ATP.f_a values were computed to give total living carbon. f_c was then computed from a regression of ATP.f_a on Chla for all data and

for a subset using only the top 20% of the Chla values as the criterion for its selection. This latter approach makes the assumption that f_a is 250 for all cells and that at the highest Chla concentrations only C_p is present in the samples. It was further assumed that the f_c so obtained was applicable to all Chla values to obtain C_p. The results are presented in Table 4.

When C_z, C_p, and C_d were computed the resulting values were generally positive with only about 10% of the C_z values negative and some C_d values were negative when the ATP values were high. However, the values of f_c were unrealistic on SINC II and IV.

The next attempt was to repeat this analysis using the top 20% of the ATP data and this was even less satisfactory as even lower and unrealistic values of f_c were obtained for SINC I and II and this approach was not pursued further.

Finally, an extreme approach which was expected to give very low values for f_c was made as follows. f_a was set at 250 and ATP.f_a computed for all data, after which f_c was evaluated such that C_z was never negative. This ensured that a set of values for C_z, C_p, and C_d could be obtained for further evaluation of the simultaneous equations 1 and 2. At this stage it was felt that the unrealistic values of f_c would be a minor problem as they would affect the equations 1 and 2 similarly and would not greatly influence the E:R ratios that were the main objective of the analysis in the first place. The values of f_c obtained were 25 for SINC I and II and 16 for SINC III

and IV. These values were then used to set up the simultaneous equations 1 and 2 for each cruise, and multiple linear regression analysis was used to obtain the values for E_z, E_p, and E_d, and R_z, R_p, and R_d. The results are presented in table 5.

This approach was, of those tested, the one which gave the least number of negative R and E values, only two of which, E_z on SINC II and R_z on SINC III were significant. The negative E_d on SINC III is not considered important as E_d has no meaning since detrital non-living carbon should not be related to ETS and the relatively low values of E_d compared to E_z and E_c tend to confirm this. The relatively higher R_d values tend to suggest that C_d contributes to measured respiration which implies that at least some component of the carbon is chemically oxidized. It may well be that to attempt to attribute any significance to the relative values of E or R or their seasonal variability is futile given the unsatisfactory negative values that were obtained and a comparison of the ratios (E:R) is probably all that the results warrant. Table 6 presents these ratios.

Even with this method of partitioning the carbon such that there were fewest negative E and R values the E:R ratios on SINC I were necessarily low which was dictated by the original data. On the other cruises the individual E:R ratios were no nearer to unity than the average values of the ratio (b) in Table 1. Thus, it was concluded that there was no way of partitioning the carbon between the various functional pools

that permitted an analysis of the individual E:R ratios that gave more satisfactory relationships than could be obtained from the original data set. Thus, given the (extensive) data suite available for analysis, no functional relationship between the ETS activity and respiration of the original water samples or of the individual relationships for components of the respiration and ETS activity could be established. As a result this phase of the analysis was terminated.

To try and understand what ETS activity and respiration were related to, if not to each other directly in any elucidatable way, an analysis of variance was run using Chla, Phaeopigments (Phaeo), ATP, temperature (T), POC, R and ETS for each cruise with ETS or R as the independent variable. Rather than present each correlation matrix and Anovar the correlation matrices are summarized in Table 7, where only those relationships to R and ETS which were not significantly correlated at the 95% confidence level are identified.

Probably the most significant point here is that on two of the four cruises (III & IV) ETS was not significantly correlated with direct respirometry, and in fact on SINC IV was only correlated with temperature. Other than on SINC IV ETS was as well correlated with any of the biomass indicators as it was with respiration, and so was respiration except with ATP on SINC III.

CONCLUSIONS

On SINC I there was clearly a problem with the magnitude of the ETS activities, and it seems reasonable to conclude that these samples were in some way degraded. The cause of this problem cannot be identified as being related to the way in which the samples were taken or stored because the samples on subsequent cruises were treated in an identical manner and these samples gave ETS activities which translated into respiration values comparable to those obtained by direct respirometry. The most likely explanation is that at some stage the samples thawed and reached temperatures at which activity could be lost.

On only two of the four cruises were ETS activity and respiration correlated, and on two they were not (SINC III and IV). Even on the first two cruises, when ETS and respiration were correlated, the relation between them was insufficiently good to allow the prediction of one from the other with satisfactory precision. It may be that this scatter in the relationship between ETS and respiration, and the lack of correlation on two of the cruises, could be accounted for by the composition of the samples. That is, the difference in the relationship of ETS to respiration for zooplankton, phytoplankton and bacteria, and their relatively variable contribution to the respiring biomass may give rise to some of the scatter of the data.

This possibility was examined using multiple linear regression of respiration and ETS partitioned between the various identifiable respiring carbon pools. This analysis could have

been done using POC, ATP and Chla directly, but for the purposes of this analysis the separate biomass indicators were translated to carbon concentrations as these were easier to evaluate realistically. It was not possible to set up the simultaneous equations using reasonable ATP or Chla to carbon ratios even though a number of reasonable approaches to these numbers were made using literature values and values obtained from the data or subsets of them. Eventually, to try to obtain values which were not negative for one or another of the carbon pools, empirical values of the required ratios were obtained so as to preclude the possibility of negative carbon pools, and the multiple linear regressions obtained.

The multiple linear regression analysis suggested that chemical oxidation of the detrital pool could contribute to respiration but not to ETS (as would be expected). However, the results were not satisfactory as the fraction of the ETS associated with zooplankton was negatively correlated with total ETS on SINC II, and the same problem was encountered with the zooplankton respiration and total respiration on SINC III. The ratios of ETS to respiration were no more satisfactory as a result of this analysis and the ETS respiration relationship could not be improved over that obtained from simple linear regression. Consequently, it is concluded that ETS is only poorly related to respiration in the Apex of the New York Bight and that respiration cannot be satisfactorily predicted from ETS.

In an attempt to find what ETS was related to, an analysis of variance was run for all data on each cruise, and based on this it can be stated that on SINC IV ETS was correlated with temperature only, but that otherwise ETS was as well or better correlated with biomass indicators as it was with respiration. The use of ETS activity as a substitute for respirometry in the Apex of the New York Bight cannot be recommended.

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SINC Cruise	a	b	r^2	n
I	-0.122	0.047	0.62	43
II	-5.918	1.543	0.95	46
II*	-0.007	0.642	0.72	40
III	1.524	0.108	0.24	42
IV	1.012	0.033	0.09	50

Table 1. Regression coefficients of ETS *vs* Respiration for SINC Cruises. * denotes a subset of SINC II data excluding six data points for which the respiration exceeded 20 $\mu l\ l^{-1}\ h^{-1}$. n is the number of data pairs.

SINC Cruise	f_c	
	above 10 m	over 4 μg l^{-1}
I	0.057	0.048
II	0.083	0.073
III	0.209	0.809*
IV	0.060	0.049

Table 2. Values for f_c on SINC I - IV. * generally over 100 data pairs were used but in this case only 10 were greater than 4 μg l^{-1}.

SINC Cruise	f_a	
	all data	over 4 μg l^{-1}
I	206	164
II	250	151
III	1069	*
IV	120	*

Table 3. Values for f_a on SINC I - IV. * not computed.

SINC Cruise	f_c		
	all data	top 20% Chla	Chla $\mu g\ l^{-1}$
I	61	62	> 10
II	47	99	> 10
III	30	*	> *
IV	11	13	6

Table 4. Values of f_c for SINC I - IV. * top 20% of values not significantly different from all data.

SINC Cruise	R_z	R_c	R_d	E_z	E_c	E_d
I	14.9	38.2	12.6	0.6	1.0	0.6
II	29.5	78.1	12.0	-15.9	171.2	3.2
III	-14.3	132.0	6.2	20.2	69.9	-0.6
IV	12.1	35.8	8.8	3.0	11.1	0.5

Table 5. Computed factors relating the C values to respiration and ETS.

SINC Cruise	$E_z:R_z$	$E_c:R_c$	$E_d:R_d$
I	0.04	0.03	0.05
II	-0.54	2.19	0.27
III	-1.41	0.53	-0.10
IV	0.25	0.31	0.06

Table 6. E:R ratios obtained on SINC I - IV.

	Chla	Phaeo	ATP	POC	Temp	R
R			III & IV	IV	II & IV	-
ETS	IV	IV	IV	IV	II & III	III & IV

Table 7. SINC cruises on which the correlation between Respiration and ETS activity was not significant at the 95% confidence level.