BALANCE SHEET FOR PRODUCTION AND CONSUMPTION OF ORGANIC CARBON IN THE WHOLE WATER COLUMN IN THE CELEBES SEA

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By

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Introduction

Total ultraplankton respiration was directly measured in the surface water (50 m) and in the deep water (500 m and 1,000 m) in the sea in the Southeast Asia. As the prime foundation of this discussion, the author assumes a steady state of organic materials averaged over one year, that is, total photosynthetic production in a year is expected to be counter balanced within the same year by the total respiration of various organisms living in the whole water column.

Materials and Methods

The sea water samples were collected from the seas around Southeast Asia (the

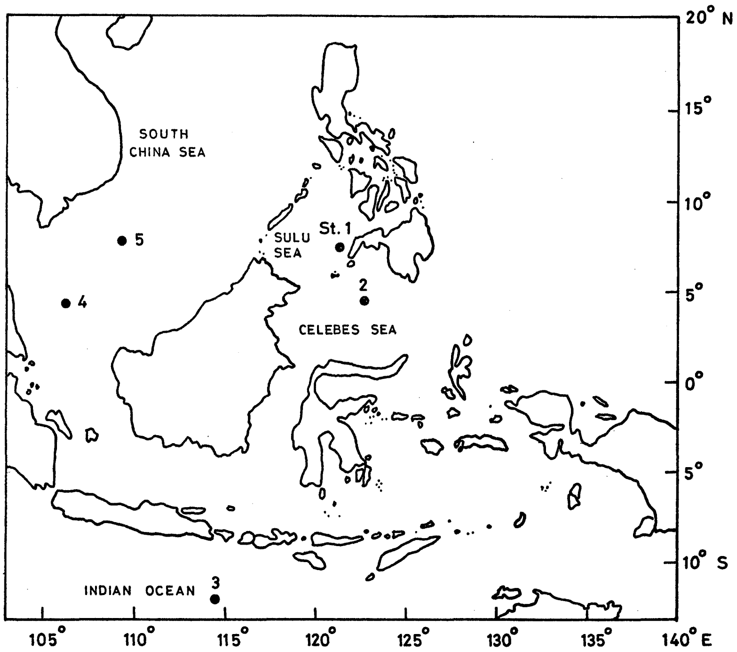

Fig. 1. Locations of sampling stations occupied during the KH-72-1 cruise of R.V. Hakuho-Maru.

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Celebes Sea, the Indian Ocean, and the South China Sea) during the KH–72–1 cruise of R.V. Hakuho-Maru, Tokyo University, in 1972 (Fig. 1). The method was originally described by Dodson and Thomas (1964) for concentration of plankton in a gentle fashion. The floating gentle concentrator used in these measurements was developed by Nishizawa (unpublished). By using several large type concentrators at the same time, it is possible to concentrate 240 l of sample water to about 5 l within several hours. The sample water was further concentrated with a small type concentrator to a final volume less than 1 l. The sample was incubated in oxygen bottles for 24 hours at 12°C in the shipboard laboratory. Oxygen consumption by concentrated organisms was directly measured by Winkler's method.

Results and Discussion

The results are shown in Table 1. The Celebes Sea was selected for constructing balance sheet of production and consumption of organic material (Table 2). The depth of the euphotic layer is assumed to be 100 m. Total primary production in the euphotic layer is assumed to be 800 mgC/m²/day (Sorokin, 1973). In his calculation, the extracellular production was estimated to be 185 mgC/m²/day. If we assume that these values represent a reasonable average level of daily primary productivity for this area, the total mean daily requirement of organic carbon in the whole water column should be compensated by this total production.

Table 1. Respiration at stations in the western tropical Pacific Ocean in μl O_2/l/day.

Sample / Depth (m)	St. 32	St. 36	St. 38	St. 39	St. 40	Average
50	2.45	2.22	1.89	8.05	4.00	3.72
500			1.38		1.42	1.40
1000	0.964	1.29	0.20	1.78		1.05

Assuming that the average sinking rate of phytoplankton is 1 m/day, the carbon input by this slow sinking into the layers below the euphotic layer is 6 mgC/m²/day. Additional input to the deep layers by mixing process is calculated to be about 1.5 mgC/m²/day using a mixing coefficient at the base of the euphotic layer of 0.002 in the tropical area (Riley, 1965). Summing these up, the total input of organic carbon to the deep water by settling and mixing processes alone would be 7.5 mgC/m²/day. This is an amount less than 1% of the total primary production and would have to be the only source of energy for the deep water organisms if we have to assume that these slow transports are the sole mechanism of material transfer.

On the other hand, Riley (1957) calculated the total deep water (below 500 m depth) consumption as 53 mgC/m²/day in the Sargasso Sea from a consideration of the large scale material budget due to physical dissipation and biological production. Recently, Packard et al. (1971) developed a sophisticated method using enzyme analyses

Table 2. Balance sheet for production and consumption of organic carbon in the whole water column in the Celebes Sea.

Production	
Particulate primary production	615 mgC/m²/day
Extracellular production	185
Total	800
Downward Transport to Deep Water	
Sinking	6
Mixing	1
Total	7
Deep Water Consumption	
(1) Riley (1957)	53
(2) Packard et al. (1971)	24
(3) Pomeroy and Johannes (1968)	585
(4) Present study	417
(5) zooplankton	47
Total	71–632
Surface Water Consumption	
(6) Vaccaro and Jannasch (1966)	120
(7) Packard et al. (1971)	43
(8) Pomeroy and Johannes (1968)	229
(9) Present study	199
(10) Zooplankton	63
Total	106–292
Total Consumption in the Whole Water Column	
199+63+417+47=726 mgC/m²/day	
(9) (10) (4) (5)	

in studying biological activity. They estimated oxygen consumption in the deep water and surface water of the eastern tropical Pacific Ocean by this method. According to their results, only 3% of the amount of primary production was consumed in the deep water below 100 m depth. If we adopt this value, the daily consumption in the Celebes Sea below 100 m depth would be 24 mgC/m²/day. Pomeroy and Johannes (1968) first attempted to measure ultraplankton respiration for the waters "gently" concentrated from large volume sample waters. They obtained ultraplankton respiration rates in the upper 800 m depth in the western North Atlantic and off Peru. If their minimum value at 800 m depth is applied, the equivalent carbon consumption in the deep water would be 585 mgC/m²/day (assumed RQ = 1). This estimate is an order of magnitude higher than those of Riley and of Packard et al., and seems to be more realistic as the average carbon consumption in the deep water. This is primarily because the Pomeroy and Johannes' estimate was based on large volume water samples (200 l) compared to the routine small volume samples used by Riley and by Packard et al. These large volume waters have a good chance of including a number of "organic aggregates" which are considered to be discrete centers of biological activity in the aphotic zone. These aggregates are usually missed from small volume samples from, say, a Nansen bottle. The oxygen consumption rates for the deep water (500 m and 1,000 m) obtained in the present study in five locations in the East Asian Sea areas in 1972 were scattered in a wide range of 0.20–1.78 μl/l/day (Table 1). Probably, some of these values are erroneously high because of possible contamination of zooplankton animals that were occasionally trapped in the 240 1 samples. In this discussion, the minimum values is adopted as the rate of deep water oxygen consumption in the Celebes Sea. Thus, the assumed deep water carbon consumption in the Celebes Sea is 417 $mgC/m^2/day$ (assumed $RQ=1$). The respiration thus obtained by the direct method is considered to represent the consumption by small organisms that escape from usual net sampling. Therefore, the consumption due to net sampled zooplankton should be added to ultraplankton biomass below 100 m depth in this area was estimated from the data obtained by Vinogradov (1968) in the tropical Pacific area in 1961. Assuming that one tenth of wet weight corresponds to dry weight, the daily carbon requirement for the deep water zooplankton was calculated to be 103 $mgC/m^2/day$ if we use the mean respiration rates per unit mass of mixed zooplankton animals obtained by Menzel and Ryther (1966) for the samples from the Sargasso Sea. This rate was corrected for temperature difference between the surface water of the Sargasso Sea and the deep water of the Celebes Sea, using the correction data of Marshall and Orr (1972). The final result of zooplankton respiration thus calculated was 47 mgC/day in the water column below 100 m depth down to the sea bottom. Thus, the total consumption in the water column below 100 m depth was 464 $mgC/m^2/day$, an estimate more than 50% of the surface production.

As to the consumption in the surface water, there are several sources of information available. All of these, however, are not yet considered precise enough to give a reliable estimate of natural rate of consumption. For instance, Vaccaro and Jannasch (1966) observed the rate of glucose uptake in the surface water of the tropical Atlantic Ocean, and gave values ranging from 0.01 to 0.18 $\mu gC/1/hr$ with a mean of 0.05 $\mu gC/1/hr$. This is equivalent to a daily rate of about 120 mgC/m^2. The enzymatic method of Packard et al. gave a low value of 43 $mgC/m^2/day$ for the surface water of the eastern tropical Pacific. The concentration method of Pomeroy and Johannes mentioned above gave a high rate of 0.382 mg-at $O_2/m^3/day$ for the upper 50 m depth in the western North Atlantic. If this value is assumed to be applicable to the surface water of the Celebes Sea, the carbon consumption in the upper 100 m depth is 229 $mgC/m^2/day$. The mean surface consumption obtained by gentle filtration method in the present study in the Celebes Sea was 0.332 mg-at $O_2/m^3/day$ which is equivalent to 199 $mgC/m^2/day$ in the upper 100 m depth. The zooplankton respiration in the surface layer calculated by the similar treatment described above, was 63 $mgC/m^2/day$. Thus, the total carbon consumption in the surface water column was estimated to be 262 $mgC/m^2/day$.

These calculations lead to a rough estimation of the total carbon consumption in the entire water column, i.e., 726 $mgC/m^2/day$. The value is roughly comparable to the daily organic production in this area. Considering many simplicistic assumptions involved in the calculation, the agreement between the two estimates would probably be fortuitous, and any estimates consisting the balance sheet should be considered tentative in nature and be open to criticism. In this paper, the author would not like to get involved in critical discussions of each calculation in the sheet, but would be satisfied to get a rough bird's-eye view of the relative proportion of the consumption in the water columns above and below 100 m depth in relation to the total photosynthetic production in the upper column.

Although there are many uncertainties concerning the precision of each calculation, present a consistent general picture that most of the products of the photosynthesis produced in the upper euphotic layer are not utilized in the euphotic layer itself, and that more than 50% of the production is consumed by the organisms living in the deep aphotic layer. The consumption in the deep layer is 1–2 orders of magnitude larger than the material input transfered by sinking particles with a mean velocity usually ascribed to planktonic microflora or their detritus. For instance in the Celebes Sea, the total flux into deep water by mixing and phytoplankton "sinking" is only 7.5 mgC/m^2/day, while the estimated consumption in the deep water is 464 mgC/m^2/day. There is no doubt that some rapid process or processes exist, which can supply material into the deep layer quickly enough to support the biological activity there. Most probably, fecal materials in conjunction with the daily migration activity of zooplankton are playing this role of rapid messengers between the surface water and the deep water.

These rapid messengers would carry organic matter mostly in the form of large particles. However, these particles may be utilized easily by filter feeding organisms and attached bacteria, and some of the organic matter will be released in the water as dissolved organic matter. The concentration of dissolved organic matter in the open ocean is not usually sufficiently high for direct utilization by bacteria. However, if the dissolved fraction is concentrated onto particles by adsorption processes, it can be utilized by bacteria and filter feeding organisms.

Recently, Fournier (1970, 1971, and 1973) found many pigmented procaryotic cells from deep waters in all of the main oceans. These cells look like green algae and could not be found in the illuminated surface layer. These apparently autochthonous heterotrophs in the deep layer of the ocean are considered to have the capacity to use directly dissolved organic matter. However, Fournier reported that the seasonal phase of bursting and declining of these bathypelagic flora closely coincides with the seasonal phase of the surface phytoplankton in each of the main oceans. This surprising phenomenon might be explained only if we consider again a rapid transport of organic matter for these pigmented cells living in deep layers.

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