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Amsterdam university
limnological laboratory

algal respiration

a literature review

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Preface

This report deals with the results of an extensive literature research to algal respiration.
It is the third report of a literature research performed by Mrs. M. Lingeman-Kosmerchock of the Limnological Laboratory of the University of Amsterdam, in cooperation with Mr. F.J. Los of the Delft Hydraulics Laboratory.
The first report deals with the contents of nitrogen phosphorus, silicon and chlorophyll in phytoplankton cells, the mineralization rates of nutrients from phytoplankton cells and the sinking rates of phytoplankton cells.
The second report considers the relationship between light and photo-synthesis and carbon-chlorophyll ratios in phytoplankton cells.
This research project is part of an extensive assignment by the Environmental Divison of the Delta Department to Delft Hydraulics Laboratory in order to develop ecological models, which can serve as tools in providing adequate guide-lines for environmental management in the (future) water basins in the Delta area.
This multi disciplinary project, called Water Basin Model (WABASIM) is carried out in close co-operation between the Environmental division of the Delta Department and the Environmental Hydraulics Branch of the Delft Hydraulics Laboratory.

CONTENTS

1. Algal respiration

Cellular respiration can be defined as the oxidation of organic compounds to carbon dioxide and water with molecular oxygen as the ultimate electron acceptor. The empirical formula for this reaction is:

$$O_2 + (CH_2O) \longrightarrow H_2O + CO_2$$

In this process a transfer of electrons is accomplished through a series of organic catalysts (enzymes and coenzymes) which release energy for the cell from the breakdown of the organic compounds.

It is generally thought that algal respiration most likely follows metabolic pathways similar to those of higher plants. The EMP (Embden-Myerhof-Parnas) pathway is a biological cycle which functions in higher plants to reduce glucose to pyruvic acid. The occurrance in algae of protease, lyasis, and glucose-1-phosphate indicates that the breakdown of reserves such as proteins, amino acids, peptides and polysaccharides by phosphorylation to yeild the initial substrates for the EMP pathway is possible. Much research has been done in an attempt to detect the presence in algae of intermediates and enzymes of the EMP pathway. The results continue to provide more knowledge to the mechanisms involved in algal respiration. The studies of Brown and Weis (1959), Reid et al. (1973), Webster and Hackett (1965), Weigel et al. (1951), and the reviews of Gibbs (1962), Danforth (1968), and Goddard & Bonner (1960) can provide detailed information on the biochemical pathways known to be involved in algal respiration.

Very little detail is known about the respiratory pathway of blue-green algae. Evidence has been found (Webster & Hackett, 1965) that the respiratory chain of the blue-green algae is quite unlike that of the other algae and higher plants. This subject has been reviewed in considerable detail by Holm-Hansen (1968), Biggins (1969), and Fogg et al. (1973).

The rate of respiration is measured by following the uptake of oxygen per unit of time. This value is often referred to as the oxygen quotient (Q_{O_2}) and is given in microliters of oxygen consumed per milligram dry weight per hour. Some deviations from this unit include the use of packed cell volume and fresh weight. In some cases the evolution of carbon dioxide has been followed rather

than the uptake of oxygen and in such cases the respiration rate is given in terms of volume of carbon dioxide per milligram dry weight per hour. Respiration rates which have been found by various investigators are given in Table 1 for individual algal species and in Table 2 for algal communities.

Another aspect of algal respiration is expressed in terms of the respiratory quotient (RQ). This value is the ratio of the carbon dioxide produced to the oxygen consumed ($+CO_2/-O_2$).Through experimentation many workers have concluded that the endogenous respiratory quotient of healthy autotrophically grown algal cells should be near 1.0 (Gibbs, 1962). The respiration of many algal species such as Chlorella, Scenedesmus, Anabaena, and Nostoc have been shown to be stimulated by the addition of glucose to their medium. Gaffron (1939A) was one of the first to observe this phenomenon. He found cultures of Chlorella pyrenoidosa, Chlorella variegata, and Scenedesmus sp. grown in a 1.5% solution of glucose had RQs of 1.2-2.0 in contrast to a RQ of 1.0 for autotrophically grown cells. This was also observed by Kandler (1954) who concluded that in many algae glucose and other sugar substrates stimulate oxygen consumption, however, the substrate isn't completly broken down to carbon dioxide and this is then reflected in a high RQ. This effect of stimulation is not found in all algae. Flagellates such as Euglena gracilis (Heinrich & Cook. 1967) exhibit little or no stimulation of oxygen consumption above the endogenous level with the addition of glucose to the substrate.

1.1 Effect of pH

Research which has been conducted on the effect of pH on algal respiration indicates that the effect is extremly variable from species to species. In one of the earliest studies Emerson and Green (1938) found that respiration in Chlorella increased 30% when the pH was lowered from 7.0-4.6. The effect of pH on Chlorella pyrenoidosa was later studied in detail by Steemann-Nielsen (1955A). He observed that the effect of pH was independant of method of buffering the media, the pH at which the algae were cultured, as well as whether aerobic or anaerobic conditions existed before experimentation. The highest respiration rate was between pH 6 & 7. At all pH levels the reaction was time dependant; initially pH had an effect on respiration but after 1-2 hours the algal respiration was independant of pH. The explaination Steemann-Nielsen suggested is that the lowered respiration rate observed at the start of the exposure to high or low pH might be caused by a decrease in some

enzymatic process of respiration which adapts with time. Frequently a very high respiration rate is observed at very high pH values (10.0 and above). It is possible that this is close to the limit of survival and emergency mechanisms begin to work within the cell.

The pH of maximum respiration as reported in the literature is species specific. Myriophyllum has a 20% lower respiration rate at pH 4.5 than at pH 9.3 (Steemann-Nielsen, 1947). Ochromonas malhamensis has its maximum respiration rate at pH 5 (Weis & Brown, 1959). Many blue-green algae have m much higher optimum respiration rates at around pH 8, although Anabaena variabilis showed no change in respiration rate between pH 4.5-9.3 (Holton, 1962, Gibbs, 1962).

The effect of pH on cell growth and respiration in Euglena has been studied by Wilson and co-workers (1959) to see if changes in respiration rates induced by pH can be reflected by changes in the rate of growth. They concluded that no simple relationship existed. The effect of pH depended upon the substrates and was varied, sometimes inhibiting respiration and not growth, and sometimes effecting both in the same manner.

1.2 Effect of temperature

The effect of temperature on algal respiration is more consistant than that of pH. A decrease in temperature decreases the respiration rate of the algae. The decrease in the respiration rate is generally much greater than the decrease in photosynthesis thus resulting in a higher photosynthesis to respiration ratio at lower temperatures.

Gibbs (1962) groups algae into two catagories with regards to temperature. One group contains common freshwater species such as Chlorella and Scenedesmus which have optimum respiration rates at around 27°C. The second group includes the thermophilic and many of the blue-green algae such as Oscillatoria subbrevis (Moyse et al., 1957), Anacystis nidulans (Kratz & Myers, 1955), and Hapalosiphon laminosus (Prat & Kubin, 1956) which have a much higher temperature optimum of around 40°C.

The response in respiration rate of several species of algae to changes in the temperature were found to be species specific and non-consistant in laboratory studies of Rhyther & Guillard (1962). Most of the studies relating to the effect of temperature on respiration deal with field studies of natural phyto-

plankton communities (Hargrave, 1969, Pamatmat, 1968, Yokohama, 1973, Smith, 1967, Hartwig, 1978, Robertson & Lewin, 1976 and others). All found a significant correlation between temperature and oxygen consumption. Hargrave found seventy percent of the variation in the benthic algae community respiration could be accounted for by temperature and the effect was interrelated to other factors such as the oxygen tension.

A relation between temperature and respiration rate in natural populations of Chaetoceros was found to be dependant on the oxygen content of the water in the field study of Robertson & Lewin (1976). Experiments in the coldest temperature (4.6^{o}C) yeilded the lowest respiration at the highest temperature (13.6^{o}C) was not the highest measured. Within 6-8^{o}C temperature had little effect and the respiration rate was a function of the oxygen tension. Above 8^{o}C the respiration rate increased with temperature to a maximum of 12-12.5^{o}C above which the respiration rate decreased.

The interrelations of temperature, current velocity and oxygen saturation on the respiration of natural communities of algae were studied by McIntire (1966) in laboratory streams. Temperature had the greatest influence between 8-13^{o}C regardless of the current velocity. Very little work has been done to study the effects of freezing and extremely low temperatures on the respiration of algae. This effect was studied by Kanwisher (1957) on macroscopic algae and by Scholander and co-workers (1953) on arctic microalgae. Both consider the extremely low respiration rates when frozen or near frozen are a value to survival in times of stress. Since a supply of nutrients is not readily available during periods of ice cover the slow down of respiration rate represents a less serious drain on food supplies.

1.3 Effect of water current

Water currents have also been found to be a factor which influence algal respiration rates. There are many species (lotic) that can survive only in a current. This is particularily the case when water temperatures are high. It has been suggested (Whitford, 1960) that a current produces a steep diffusion gradient which increases oxygen exchange between algae and water. Species which are characteristic of habitats with a current include; Lemanea, Batrachospermum, Hydrurus, Cladophora, Oedogonium and Spriogyra. The effect of

current on several species of algae was studied in the laboratory by Whitford and Schumacher (1961 & 1964). All species had a higher respiration rate in a current than in still water although the response of the lentic species was much less than that of the lotic species.

1.4 Effect of algal size

Banse (1976) has postulated that under similar conditions larger species have a lower specific rate of respiration than the smaller species. A size dependant model for phytoplankton respiration has been developed by him. This model is based on data obtained from Eppley and Sloan (1965). In actual experiments with represenative diatoms, green algae and dinoflagellates Falkowski & Owens (1978) obtained results which suggest that respiration rates are not a function of cell size. Their data did not fit within acceptable statistical limits the exponential model of Banse for respiration rate as a function of cell size.

1.5 Effect of oxygen concentration

Gessner and Pannier (1958) working with a naturally occurring population of Anabaena, found the rate of respiration increased as the percent of oxygen saturation in the water increased. They felt that the diffusion rate of the different oxygen concentrations is a possible factor for this phenomenon. A linear increase in respiration in the light with an increase in oxygen tension up to a limiting point was also observed in Anabaena by Lex and co-workers (1972). However, they found respiration in the dark to be saturated at a much lower level. They concluded that the respiratory process in the light is quite distinct from that in the dark with respect to the response to oxygen tension.

Many studies of algal respiration have made use of the respirometer technique. In respirometers, where vessels are shaken 100 times or more per minute, diffusion rates cease to be a factor and respiration proceeds at a maximum rate which is independant of the oxygen concentration. Thus, with the use of the respirometer it is difficult to make any definate observations on the relation between oxygen tension and respiration (Kanwisher, 1957, McIntire, 1966, and Gessner & Pannier, 1958).

Dokulil (1971) working with various green and blue-green algae after a period of oxygen deficency, concluded that most algae are able to adapt their respiration rate to sudden changes in oxygen concentration. After a prolonged

anaerobic period he found as much as 500% increase in the respiration rate when the algae were placed in aerobic conditions. He calls this increase "recovery to respiration". However, if the anaerobic period is very long the algae are irreversibly damaged. In response to oxygen deficiency the blue-green algae are significantly different from all other algae as they can live without irreversible damage for as long as ten days without oxygen. The resistance to such anaerobic periods decreases when the temperature increases.

Robertson and Lewin (1976) working with a naturally occurring population of the diatom Chaetoceros armatum in a range of 6-8 ml 0_2 per liter in the water found the oxygen level in the water always had an effect on the respiration rate. When the oxygen concentration was increased the respiration rate also increased, and when the oxygen concentration was decreased the respiration rate was lowered. The extent it was lowered, however, depended on the recent history of the cells. They also found that the effect of oxygen concentration had a relationship to the temperature. At a given temperature a higher oxygen content resulted in a higher respiration rate. Below $8^{o}C$ respiration was a function of the oxygen concentration, whereas, above $8^{o}C$ the respiration was affected by both temperature and oxygen. This positive correlation between concentration of dissolved oxygen and algal respiration rate, and the increase in respiration rate with temperature up to a limiting point above which temperature produced a detrimental effect on the respiration was also observed by McIntire (1966).

1.6 Photorespiration

There is extensive literature concerning the influence of light on photosynthesis in plants. The effect of light still remains a complicated and controversial field with the problems concerning photorespiration remaining unsolved. The term photorespiration is used to define all respiratory activity in the light regardless of the pathways by which carbon dioxide is released and oxygen consumed. Detailed biochemical explainations of the pathways involved in photorespiration are given by Jackson and Volk (1970) and Goldsworthy (1970).

One of the earliest published attempts to determine the effect of light on respiration was that of Bonner and Mangin (1886). For information on the results of the early studies of respiration in algae the reviews of Rabinowitch

(1945), and Weintraub (1944) should be consulted. These early studies employed diverse methods to determine the photo-influence. Gaffron (1937, 1939A & B) prevented photosynthesis with various poisons and then looked for photo-effects on the residual respiration which was not effected by these inhibitors. Warburg and co-workers (1949) deprived green cells of carbon dioxide as a device for elimination of the complications of photosynthesis and sought light effects on the remaining respiration. Working with Chlorealla they showed that red light doesn't inhibit respiration per se when the light intensity employed was one that gave a high photoefficiency. Variation of these methods were also used by Davis (1950 & 1952) on Chlorella. It was concluded by these investigators that the difference in respiration rate in the dark and the light were negligable. It is unfortunate that experimental material used in the tests were not capable of normal photosynthesis and thus interpretation of results can be questionable.

Another experimental method avoids this objection of abnormal cells by measuring gas exchange in the dark and at several low intensities. The assumption that photosynthetic rate is directly proportional to the light intensity and thus departure from linearity of the relation between gas exchange and intensity may be interpreted as evidence of altered respiration rate under the influence of light. Kok (1949) reported such effect and others have confirmed it. This has come to be known as the "Kok effect". However, this effect is not always reproducable and when demonstrated it can be interpreted as either respiratory or photosynthetic anomality.

Until recently the usual way to measure respiration in the light was to measure the rate immediatly after turning out the light. It has been found, however, that many algae exhibit a short enhancement of oxygen uptake immediatly after the light is turned off. This enhancement is followed by a rapid short lived decay and then a slow decline to a stable endogenous rate (Yentsch & Reichert, 1963, Kok, 1952, Reid, 1968, Brackett et al., 1953). This has been interpreted as a delayed respiratory response to illumination.

A complete valid explaination of the influence of light can only be achieved when respiratory and photosynthetic process are both functioning. Both processes involve exchange of the same gases and therefore conventional (manometric) methods are inadequate. With the use of appropriate isotopes a tracer experiment may be designed whereby each of the concurrent processes may be

measured seperatly. Some of the first applications of this method were done by Brown (1953) and Brown and Webster (1953).

Most of the studies already mentioned as well as the work of Brown and Weis (1959) with Ankistrodesmus support the view that light has little or no influence on the normal algal respiration rate and there is a temptation to generalize. The matter is complicated by reports of light indiced anomalities in respiration. Some investigators have found evidence of photostimulation of respiration (Gessner, 1938, Emerson & Lewis, 1943, Bunt & Heeb, 1971, Padan et al., 1971, & Lex et al., (1972). Others attribute the response of algae to light to be due to photoinhibition of respiration (Weigel et al., 1951, Kok, 1952, Bunt, 1965, Falkowski & Owens, 1978, Brown, 1953, & Cook, 1963). Some species of algae, such as Anacystis, Scenedesmus, and Anabaena exhibit inhibition of respiration at low light intensities (Hoch et al., 1963). The pattern of response to an increase in illumination for individual species of freshwater algae was found to be related to the oxygen concentration with photoinhibition occuring at low oxygen concentrations (less than 0.5%) and photostimulation at high oxygen tensions (Brown & Webster 1953). This was also observed by Lex and co-workers (1972) who found a linear increase in the respiration rate up to an oxygen tension of 0.23 atmospheres in the light but the effect was not observed in the dark where respiration was saturated at near 0.05 atmospheres.

In Ochromonas malhamensis the effect of illumination was found to be related to the conditions within the cell; normal unstarved cells were relatively intensive to illumination, whereas, at light saturation the oxygen consumption in the starved cells was doubled (Weis & Brown, 1959).

Current experimental evidence suggest that there are significant changes in respiration processes which occur upon radiation and under certain conditions the light respiration rate maybe a significant portion of the photosynthesis. It has been suggested that there are two mechanisms of oxygen uptake in the light; first a mechanism which is the same as endogenous dark respiration and inhibited by light, and a second mechanism of oxygen uptake which is light dependant and presumably proceeds without carbon dioxyde release. The second mechanism is quite distinct from endogenous dark respiration in response to oxygen tension, carbon dioxide levels, and the response to metabolic inhibitors. If continued research substantiates these results

this will have direct consequences on the interpretation of experimental results from field "light/dark bottle" productivity experiments.

1.7 Effect of added substrates

When some substances are added to cells the rate of oxygen uptake increases. In some cases this may be for chemical reasons due to catalyzed oxidation of the additive, in other cases this is a non-specific stimulation of respiration which may occur after the addition of small amounts of inhibitors (arsenic, cyanide). These effects must be taken into account if one is to distinguish metabolic substrates by their effect on respiration.

A list of organic compounds which stimulate respiration is given by Bach and Felling (1960). These compounds consist of metabolic inhibitors such as hydrogencyanide and 2-4-dinitrophenol, as well as simple nitrogen compounds which are known to act on nitrogen starved cells. The results of their experiments revealed that the stimulation of respiration by organic nitrogen compounds (purines) is at least ten times greater than the stimulation from inorganic compounds of nitrogen. They conclude that the added organic compounds result in a completely different mode of action.

Two carbon compounds such as ethanol and acetate can stimulate oxygen consumption as much as four times in Euglena (Heinrich and Cook, 1967) but many other organic compounds (succinate, malate, fumarate) cause little or no stimulation. The literature relating to inhibitors of respiration in algae has been reviewed by Webster and Hackett (1965).

Algae are known to react to exogenous glucose by increased respiration rate (Litwinenko 1960, Genevois, 1927 & Kandler, 1955). The amount of stimulation has been found to be related to such factors as whether previous culture conditions of the cell were aerobic or anaerobic (Dvorakova-Hladka, 1967), the amount of endogenous reserves (Kandler, 1958), the age of the organism (Oaks, 1962 A&B), as well as the amount of the substance which has been added (Kandler, 1958, Litwinenko, 1960).

The effects on respiration rate of the addition of other organic compound as well as metal ions have been studied to some extent. However, the results show considerable variation in reaction from one species to another and no

definite conclusion can be drawn. Yuan and Daniels (1956) studied the responses of respiration in Chlorella to substrates with cyanide, sodium azide, hydroxylamine and DNP. They concluded that all inhibitors have their characteristic means of inhibition. Hochacka and Teal (1964) also examined this factor but with a dinoflagellate, Gymnodinium nelsoni. They found that the intermediates of the Krebs Cycle can be either inhibitory or stimulatory to respiration. Amino acids; with the exception of glumatate, alanine and cysteine which had a slight stimulatory effect, seemed to have no effect on respiration rate.

In Ankistrodesmus braunii arsenate was found to stimulate respiration as much as 250% (Kessler & Buckner 1960). Fluoride, cyanide and copper have no effect on the respiratory rate in Chlorella other than a temporary increase in endogenous rate directly after the addition (Hassell, 1962). The effect of copper has been found to be dependent on the environmental conditions during treatment (Hassell 1962, McBrian & Hassell, 1967); under anaerobic conditions copper is highly toxic, whereas, in aerobic conditions respiration continues at normal levels. If copper is absorbed in aerobic conditions and then placed in anaerobic conditions respiration is inhibited but the cells can recover.

The simultaneous addition of two substances known to be individually unhibitory (copper and fluorine) have been shown to have an extremely inhibiting effect on respiration (Hassell 1967, 1969).A complete discussion of the biochemical pathways of the various inhibitors of Chlorella pyrenoidosa is given in the paper of Krause and Bassham (1969).

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species

species	Method of respiration measurement ☆	P/R	respiratory quotient	respiration rate	remarks	reference
CHLOROPHYTA						
Chaetomorpha linum	2	5.6 6.16 5.7		9.5 μmole O_2.mg Chl^{-1}.hr^{-1} 12.5 14.0 23.0	15.5°C 24.5°C 23.0°C 40.0°C	Raven & Smith, 1977.
Chlamydomonas moewusii	1			1.19–2.33 μl O_2.mg total N^{-1}.hr^{-1} 0.79–2.06	motile form, 23°C, $2.65x10^{-1}$ mg N.$cell^{-1}$ non-motile form 23°C, $2.65x10^{-1}$ mg N.$Cell^{-1}$	Ronkin, 1959.
Chlamydomonas reinhardtii	4			0.18 m moles $x10^4$ O_2.μg Chl^{-1} .hr^{-1}	dark, 0.03% CO_2	Bunt & Heeb, 1971.
			0.8	1.20	light, 0.03% CO_2	
				0.18	dark, 5% CO_2	
			1.5	0.36	light, 5% CO_2	
Chlamydomonas sp.	3	0.98–12.1		0.238–0.558 ml O_2.10^3 $cells^{-1}$.hr^{-1}	nutrient deficient culture daily for 30 days	Rhyter, 1954.
Chlorella ellipsoidea	3	5.7 –18.0 1.3 –18.0 1.1 –11.5		0.5–2.0 mg O_2.mg Chl^{-1}.hr^{-1} 0.5–3.0 1.0–4.0	media with 50–150 mg N/L & 1 –15 mg P/L, 25°C media with 1–1.5 mg N/L & 0.1–0.15 mg P/L, 25°C media with 0.1–0.15 mg N/L &0.01–0.015 mg P/L, 25°C	Nakanishi & Monsi, 1976.
Chlorella fusca	1			2.85 μl O_2.mg dry wt^{-1}.hr^{-1}	maximum rate, 25°C	Dokulil, 1971.
Chlorella pyrenoidosa	7			350–1500 μl O_2. g dry wt^{-1}.hr^{-1} 20,000	endogenous rate, 25°C rate with glucose substrate	Goddard & Bonner, 1960.
Chlorella pyrenoidosa	1			23 mm^3 O_2. 2ml $suspension^{-1}$.hr^{-1} 30 mm^3 O_2.2 ml $suspension^{-1}$.hr^{-1}	endogenous with 1/30 M phosphate buffer endogenous with no buffer	Kandler, 1958.
Chlorella pyrenoidosa	1			29.8–36 μl O_2.10^6 $cells^{-1}$.hr^{-1}	in $1.05x10^{-4}$ – $1.05x10^{-2}$ M fluoride	McNutly & Lords, 1960.
Chlorella pyrenoidosa	4			0.2 mmole x $10^{-4}CO_2$.3μg Chl a^{-1} 0.04 0.008 0.0085	5% V/V O_2, 20°C 20% V/V O_2, 20°C 60% V/V O_2, 20°C 78% V/V O_2, 20°C	Bunt, 1970.
Chlorella pyrenoidosa	5	1–3.06		6.66–14.28 μmoles CO_2.hr^{-1} 6.18–14.64	endogenous in presence KCN, low concentration, slight stimulation of respiration, high concentration inhibition	Yuan & Daniels, 1956.
		0.62–1.75		12.0–22.44 μmoles CO_2.hr^{-1}	in presence NaN_2– stimulation of respiration at low concentrations, 20% inhibition at higher concentration	
		0.97–2.65		8.4–18.72 μmoles CO_2.hr^{-1}	in presence of Na_2OH – no stimulation or inhibition observed	
		0.66–1.62		21.36–59.34 μmoles CO_2.hr^{-1}	in presence of DNP, no inhibition, stimulation only at very low concentrations	
Chlorella pyrenoidosa	2			0.2–1.7 μl O_2.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1})	0–10 ft Cd x 10^{-2}	Brown & Richardson, 1968.
Chlorella pyrenoidosa (log phase)	4			0.06 mmole x 10^4O_2.μg Chl a^{-1}.hr^{-1}	dark, 0.03% CO_2	Bunt & Heeb, 1971.

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 1)

species	method of respiration measurement ☆	P/R	respiratory quotient	respiration rate	remarks	reference
Chlorella pyrenoidosa (log phase)		1.25		0.24 mmole x 10^4 O_2. μg Chl.a^{-1}.hr^{-1}	light, 0.03% CO_2	Bunt & Heeb, 1971.
				0.06	dark , 0.05% CO_2	
		1.0		0.36	light, 5% CO_2	
Chlorella pyrenoidosa (stationary phase)	4			0.06 mmole x 10^4 O_2. μg Chl.a^{-4}.hr^{-1}	dark, 0.03% CO_2	Bunt & Heeb, 1971.
		0.7		0.24	light, 0.03% CO_2	
				0.06	dark , 0.03% CO_2	
		1.0		0.36	light, 0.03% CO_2	
Chlorella pyrenoidosa	1		1.03	3.4 mm^3 O_2.mm^3 cells^{-1}.hr^{-1}	sun adapted cells	Sargent, 1940.
			1.17			
			1.02			
			1.54	0.9	shade adapted cells	
			1.30	1.2		
			1.85	1.5		
Chlorella pyrenoidosa	2			4.6–13.8 μl O_2. mg cells^{-1}.hr^{-1}	values obtained with cell densities of 1.6–3 μl cells. ml^{-1} [dry wt. varied from 0–179–0.256 g. ml^{-1}]	Myers & Grahm, 1971.
Chlorella pyrenoidosa	1	9.0			steady state, dark	Burris, 1977.
Chlorella pyrenoidosa	3	12.0				Steemann-Nielsen, 1955A.
Chlorella pyrenoidosa	3			1.0–1.4 ml O_2.μg dry wt^{-1}.hr^{-1}	25°C normal cells	Genevois, 1927.
				5.0	25°C normal cells, glucose substrate	
				3.2	25°C normal cells, acetaldehyde substrate	
				3.4	25°C normal cells, butyrate substrate	
				2.8	20°C normal cells, grown in dark, glucose substrate	
Chlorella pyrenoidosa	1			2.3 ml O_2.μg dry wt^{-1}.hr^{-1}	27°C starved cells	Kandler, 1954.
				17.1	27°C starved cells, glucose substrate	
Chlorella vulgaris	5	15.1		1.32 mg CO_2. gm fresh wt^{-1}.hr^{-1}	dark	Brown & Tregunna, 1967.
Chlorella vulgaris	1			2.7 μl O_2. 3 x 10^8 cells^{-1}.hr^{-1}	anaerobic	McBrian & Hassell, 1967.
				2.7	aerobic	
Chlorella vulgaris	1			2.4 μl O_2. 3 x 10^8 cells^{-1}.hr^{-1}	endogenous	Hassell, 1962.
				0	2.6×10^{-2} mole $CuSO_4$, unshaken	
				12.0	8.3×10^{-3} mole $CuSO_4$, unshaken	
				22.0	3.3×10^{-3} mole $CuSO_4$, unshaken	
				20.0	1.7×10^{-3} mole $CuSO_4$, unshaken	
				22.0	8.3×10^{-4} mole $CuSO_4$, unshaken	
				49.0	2.0×10^{-4} mole $CuSO_4$, unshaken	
Chlorella vulgaris	1			88 μl O_2.3 x 10^8 cells^{-1}.hr^{-1}	unshaken 2 hrs, shaken 1 hr	Hassell, 1962.
				7	7×10^{-4} mole $CuSO_4$ unshaken 2 hrs, shaken 1 hr	
				88	7×10^{-4} mole $CuSO_4$ shaken	
				100	3×10^{-3} mole $CuSO_4$ shaken	
				112	2×10^{-2} mole $CuSO_4$ shaken	
Chlorella sp.	1	0.95		1 μl O_2. mg dry wt^{-1}.hr^{-1}	endogenous, dark rate	Kok, 1952.
Chlorococcum wimmeri	2			3.8–7.9 μl O_2.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1}	0–10 ft cd. x 10^{-2}	Brown & Richardson, 1968.
Cladophora crispata	1			0.99 μl O_2.mg dry wt^{-1}.hr^{-1}	15°C	Dokulil, 1971.

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 2)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
Cladophora fracta	1			0.98 µl O_2.mg dry wt^{-1}.hr^{-1}	15°C	Dokulil, 1971.
Cladophora glomerata	1			2.80 µl O_2.mg dry wt^{-1}.hr^{-1}	15°C	Dokulil, 1971.
Cladophora glomerata				2.70 mg O_2. mg dry wt^{-1}.hr^{-1}		Gessner, 1959.
Cosmarium sp.	3	4–15 4–15 2–10		0.1–0.5 mg O_2.mg Chl.a^{-1}.hr^{-1} 0.1–0.5 0.1–0.5	media with 10–15 mg N/L & 1–1.5 mg P/L, 25°C media with 1–1.15 mg N/L & 0.1–0.15 mg P/L, 25°C media with 0.1–0.15 mg N/L & 0.01–0.015 mg P/L, 25°C	Nakanishi & Monsi, 1976.
Cyanidium caldarum	2			1.5–1.8 µl.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1}	0–10 f/ od x 10^{-2} slight increase respiration with increase in intensity	Brown & Richardson, 1968.
Dunaliella euchlora	3	12.0 4.5 2.0		0.03 ml O_2 2.1 x 10^6 $cells^{-1}$.hr^{-1} 0.02 0.015	20°C – 3 day old culture 20°C – 6 day old culture 20°C –15 day old culture	Rhyther, 1956.
Dunaliella euchlora	3	1–12.0				Rhyther, 1954.
Dunaliella tertiolecta	2			1.89x10^{-7} µg-at O_2.pg C^{-1}.hr^{-1}		Falkowski & Owens, 1978.
Dunaliella tertiolecta	2	9.1		1.35 µg O_2.10^6 $cells^{-1}$.hr^{-1}	endogenous dark rate	Humphrey, 1975.
Enteromorpha intestinalis	2	13.0 15.2 13.75		5.0 µmole O_2.mg $Chl.^{-1}$.hr^{-1} 6.5 8.0 10.0	15.5°C 24.5°C 23.0°C 40.0°C	Raven & Smith, 1977.
Gonium pectorale	5	9.5		1.1 mg CO_2.g fresh wt^{-1}.hr^{-1}	dark – endogenous rate	Brown & Tregunna, 1967.
Haematococcus lacustris	3	1.8–3.6 0.3–1.8 1.8		1.4–1.8 mg O_2.mg Chl.a^{-1}.hr^{-1} 1.8–3.0 1.8	media with 10–15 mg N/L & 1–1.5 mg P/L, 25°C media with 1–1.5 mg N/L & 0.1–0.15 mg P/L, 25°C media with 0.1–0.15 mg N/L & 0.01–0.015 mg P/L, 25°C	Nakanishi & Monsi, 1976.
Hydrodictyon africanum	2	5.25 6.0 5.2		4.0 µmole O_2.mg Chl.a^{-1}.hr^{-1} 5.0 6.5	15.5° 24.5° 23.0°	Raven & Smith, 1977.
Hydrodictyon africanum	2	4.07 7.6		2.8 µmole O_2.mg Chl.a^{-1}.hr^{-1} 2.0	young cell (1.97 µg Chl.a.mg dry wt^{-1}) old cell (11.2 µg Chl.a.mg dry wt^{-1})	Raven & Glidewell, 1975.
Oedogonium kurzii	1			0.923 ml O_2.g dry wt^{-1}.hr^{-1} 1.624	no current, 22°C current 18 cm.sec^{-1}, 22°C	Schumacher & Whitford, 1965.
Oedogonium kurzii	1			20–22 µl CO_2. g dry wt^{-1}.hr^{-1} 11–12	current of 15 cm.sec^{-1} 24.5°C no current, 24.5°C	Whitford & Schumacher, 1961.
Oedogonium kurzii	1			15.0 µl CO_2. g dry wt^{-1}.hr^{-1} 25.3	no current 25°C, lotic species current 15 cm.sec^{-1}, 25°C, lotic species	Whitford & Schumacher, 1961.

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 3)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
Oedogonium sp.	1			17,5 µl CO_2.g dry $wt^{-1}.hr^{-1}$	No current, 25°C, lentic species	Whitford & Schumacher, 1964.
				24.0	current 15 cm.sec^{-1}, 25°C, lentic species	
Oedogonium sp.				0.95 mg O_2. g dry $wt.hr^{-1}$		Gessner, 1959.
Porphyridium aerugineum	2			0.5–0.6 µl O_2.(ml packed cell vol x $10^{-3})^{-1}.hr^{-1}$	0.5–0.6 ft cd. change in intensity had no visible effect on respiration	Brown & Richardson, 1968.
Porphyridium cruentum	2			1.1–2.1 µl O_2.(ml packed cell vol x $10^{-3})^{-1}.hr^{-1}$	1.1–2.1 ft. cd. Slight increase in respiration with increase in intensity	Brown & Richardson, 1968.
Protheca zopfii	1			2–6 µl O_2. mg dry $wt^{-1}.hr^{-1}$	endogenous rate	Webster & Hackett, 1966.
				28–30	glucose substrate, 20% cell suspension by wt	
				20.0	10^{-5} M HCN, 33% inhibition of respiration	
				17.0	10^{-4} M HCN, 45% inhibition of respiration	
				30.0	19:1 N_2:O_2, no inhibition	
				20.0	19:1 CO:O_2, 20% inhibition of respiration	
Pteromonas protracta	3	2–7		0.8–1.0 mg O_2. mg Chl.$a^{-1}.hr^{-1}$	media with 50–150 mg N/L & 10–15 mg P/L, 25°C	Nakanishi & Monsi, 1976.
		2–6.5		1.0–1.5	media with 10–15 mg N/L & 1–1.5 mg P/L, 25°C	
		1–2		1.0–3.5	media with 1–1.5 mg N/L & 0.1–0.15 mg P/L, 25°C	
		2.5		1.0–2.9	media with 0.1–0.15 mg N/L & 0.01–0.015 mg P/L, 25°C	
Scenedesmus obliquus	2	1.2		0.09 cell vol.hr^{-1}	mean dark value	Horwitz & Allen, 1957.
				0.15	mean light value	
				0.6–0.8	20.5°C	
Scenedesmus quadricauda	1			13.00 µl O_2. mg dry $wt^{-1}.hr^{-1}$	25°C	Dokulil, 1971.
Scenedesmus quadricauda	5	17.7		7.3 µg CO_2. g fresh $wt^{-1}.hr^{-1}$	endogenous dark rate	Brown & Tregunna, 1967.
Scenedesmus spp.	3	4–11		0.5–1.0 mg CO_2. mg Chl.$a^{-1}.hr^{-1}$	media with 50–150 mg N/L & 10–15 mg P/L, 25°C	Nakanishi & Monsi, 1976.
		0.8–2.5		0.8–5.0	media with 1–1.5 mg N/L & 0.1–0.15 mg P/L, 25°C	
		0.75–2.5		0.0–4.0	media with 0.1–0.15 mg N/L & 0.01–0.015 mg P/L, 25°C	
Scenedesmus sp.	6			3.4 cell vol.hr^{-1}	control dark	Hoch et al., 1963.
		0.8		4.2	control low light intensity	
		2.2		31.5	control high light intensity	
				5.8	glucose substrate, dark	
		0.66		5.2	glucose substrate low light intensity	
		8.4		9.2	glucose substrate high light intensity	
				2.5	starved cell dark	
				2.4	starved cell high light intensity	
		2.0		12.3	starved cell high light intensity	
		0.3		1.2	+DCMU in dark	
				0.8	+DCMU in light	
Scenedesmus sp.	3			1.8 ml O_2. g dry $wt^{-1}.hr^{-1}$	20°C	Gaffron, 1937.
				3.8	20°C glucose substrate	
Sphacelaria sp.	2			8.0–12.0 µl O_2.(ml packed cell vol x $10^{-3})^{-1}.hr^{-1}$	0–12 ft cd. No effect of increased intensity	Brown & Richardson, 1968.

Table 1: The photosynthesis to respiration ratio, resp ratory quotient and respiration rate of some phytoplankton species (continuation 4)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
Spirogyra sp. 1	1			38 µl CO_2. g dry $wt^{-1}.hr^{-1}$ 50.2	no current, 25° lotic species	Whitford & Schumacher, 1964.
Spirogyra sp. 2	1			35.9 µl CO_2.g dry $wt^{-1}.hr^{-1}$ 36.1	no current, 25° lentic species current 15 cm.sec^{-1}, 25°C, lentic species	Whitford & Schumacher, 1964.
Spirogyra sp. 3	1			76.3 µl CO_2. g dry $wt^{-1}.hr^{-1}$ 82.8	no current, 25°C lentic species current 15 cm.sec^{-1}, 25°C, lentic species	Whitford & Schumacher, 1964.
Spirogyra sp. 4	1			39.9 µl CO_2. g dry $wt^{-1}.hr^{-1}$ 40.5	no current, 25°C lentic species current 15 cm. sec^{-1}, 25°C, lentic sp.	Whitford & Schumacher, 1964.
Spirogyra sp. 1	1			1.88 µl O_2. mg dry $wt^{-1}.hr^{-1}$	15°C	Dokulil, 1971.
Spirogyra sp. 2	1			1.26 µl O_2.mg dry $wt^{-1}.hr^{-1}$	15°C	Dokulil, 1971.
Spirogyra sp. 3	1			1.70 µl O_2.mg dry $wt^{-1}.hr^{-1}$	15°C	Dokulil, 1971.
Zygnema pectinatum	1			1.35 µl O_2. mg dry $wt^{-1}.hr^{-1}$	15°C	Dokulil, 1971.
CYANOPHYTA						
Anabaena cylindrica	1			6.48 µl O_2. mg dry $wt^{-1}.hr^{-1}$	25°C	Dokulil, 1971.
Anabaena cylindrica	4			16 µl $O_2.hr^{-1}.ml^{-1}$ 308	dark endogenous photorespiration	Lex et al, 1972.
Anabaena cylindrica	4			48 µl O_2.25 $ml^{-1}.hr^{-1}$ 15.6 3.4	photorespiration pCO_2/Atm 0.002 photorespiration pCO_2/Atm 0.010 photorespiration pCO_2/Atm 0.020	Lex et al, 1972.
Anabaena cylindrica	4			485 µl O_2. 25 $ml^{-1}.hr^{-1}$ 466 322 214 70	photorespiration control photorespiration 0.1 mmole $NaHCO_3$ photorespiration 0.5 mmole $NaHCO_3$ photorespiration 1.0 mmole $NaHCO_3$ photorespiration 2.0 mmole $NaHCO_3$	Lex et al, 1972.
Anabaena cylindrica	4			338 µl O_2. 25 $ml^{-1}.hr^{-1}$ 16 268 0 20 0	light control, photorespiration light + DCMU, photorespiration light + 10^{-4} mole KCN, photorespiration dark control dark + DCMU dark + KCN	Lex et al, 1972.
Anabaena variabilis				1.7-8.4 µl O_2. mg dry $wt^{-1}.hr^{-1}$	endogenous, 25°C	Goddard & Bonner, 1960.
Anabaena variabilis	1		1.10 1.0	8.4 µl O_2. mg dry $wt^{-1}.hr^{-1}$ 1.7	Growing cells, 25°C dry wt. 0.206 mg.cm $cells^{-1}$ starved, 25°C	Kratz & Myers, 1955.
Anabaena sp.	1	3.2-4.5		4.5 cm O_2. mg dry $wt^{-1}.hr^{-1}$ 4.6	culture solution, endogenous at pH 9.3 0.05 mole bicarbonate-carbonate buffer pH 9.1	Webster & Frenkel, 1953.
			0.9 0.9	4.7 4.2	0.05 mole phosphate buffer pH 7.9 0.05 mole phosphate buffer pH 7.1	

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 5)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
Anabaena sp.	1		0.9 0.95	4.6 cm O_2.mg dry $wt^{-1}.hr^{-1}$ 4.8	0.05 mole phosphate buffer pH 6.0 0.05 mole pho phate buffer pH 5.3	Webster & Frenkel, 1953.
Anabaena sp.	3			2.584 mg $O_2.L^{-1}$ 3.560 5.088	100% O_2 saturation 230% O_2 saturation 373% O_2 saturation	Gessner & Pannier, 1958.
Anacystis nidulans	3		1.0 0.93	1.6 µl O_2. mg dry $wt^{-1}.hr^{-1}$ 0.3	growing cells, 25°C dry wt = 0.271 mg.cm $cells^{-1}$ starved cells, 25°C dry wt = 0.271 mg.cm $cells^{-1}$	Kratz & Myers, 1955.
Anacystis nidulans	3			0.03–0.19 mg O_2. $cell^{-1}.hr^{-1}$ 0.02–0.18 0.22–0.55 0.02–0.2	4 Klux with gas exchange 4 Klux without gas exchange 2 Klux with gas exchange 2 Klux without gas exchange	Gnuskin et al, 1971.
Anacystis nidulans	3		1.10 1.10 1.05	4.7 µl O_2. mg dry $wt^{-1}.hr^{-1}$ 1.9 7.5 2.9	growing cells 39°C starved cells 39°C growing cells, 39°C starved cells 39°C	Kratz & Myers, 1955.
Anacystis nidulans	2			4–6 µl O_2. mg dry $wt^{-1}.hr^{-1}$	endogenous, dark rate	Biggins, 1969.
Gleocapsa alpicola	2			1.5–2.1 µl O_2.(ml packed cell vol $_{x10-3})^{-1}.hr^{-1}$	0–12 ft cd x 10^{-2} slight increase in respiration with increase in temperature	Brown & Richards, 1968.
Hapalosiphon liminosus	3			0.8 µl O_2. mg dry $wt^{-1}.hr^{-1}$ 2.8 4.4 3.2 5.9 7.7 8.6 8.4 4.2	endogenous rate with optimum conditions starved cells, 18 hrs in dark pH 4.5 pH 5.2 pH 5.8 pH 6.95 pH 7.8 pH 8.5 pH 9.5	Holton, 1962.
Nostoc muscorum	3			3.17 µl O_2. mg dry $wt^{-1}.hr^{-1}$	25°C	Dokulil, 1971.
Nostoc muscorum	3			4.4 µl O_2. mg dry $wt^{-1}.hr^{-1}$ 1.1	growing, 25°C dry wt = 1.94 mg.cm $cells^{-1}$ starved 25°C	Kratz & Myers, 1955.
Phormidium lucidum	2			4–6 µl O_2. mg dry $wt^{-1}.hr^{-1}$	endogenous dark rate	Biggins, 1969.
Phormidium lucidum	2			0.5–0.9 µl O_2.(ml packed cell vol $_{x\ 10^{-3}})^{-1}.hr^{-1}$	0–14 ft cd x 10^{-2} a decrease in respiration with an increase in intensity	Brown & Richardson, 1968.
Phormidium persicinum	2			1.5–3.8 µl O_2.(ml packed cell vol $_{x\ 10^{-3}})^{-1}.hr^{-1}$	1.5–3.8 ft cd x 10^{-2}, an increase in respiration rate with an increase in intensity	Brown & Richardson, 1968.
Plectonema boryanum	2			.9–1.2 µmoles O_2. mg $protein^{-1}.hr^{-1}$ .3 2.7–3.3	endogenous, dark rate log phase cells cells incubated in dark cells incubated at optimum conditions for photo-assimilation	Padan et al., 1971.

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 6)

species	method of respiration measurement	P/R	respiratory quotient	respiration rate	remarks	reference
BRACILLARIOPHYTA (diatoms)						
Biddulphia aurita	2	7.3		5.10 μl $O_2 . 10^6$ cells^{-1}.hr^{-1}	dark endogenous	Humphrey, 1975.
Chaetoceros armatum	3			0.005–0.122 ml $O_2 . 10^4$ cells^{-1}.hr^{-1}	natural population	Robertson & Lewin, 1976.
				0.122	11.8°C, 6.96% ml $O_2 . L^{-1}$ natural population	
				0.03	8°C, 7.5 ml O_2. L^{-1} natural population	
				0.03	11.0°C, 6.5 ml O_2. L^{-1} natural population	
				0.49	10.4°C, 11.8 ml $O_2 . L^{-1}$ natural population	
Chaetoceros didymum	2	3.3		6.37 μl $O_2 . 10^6$ cells^{-1}.hr^{-1}	endogenous dark	Humphrey, 1975.
Cyclotella nana	3			5.6×10^{-12} ml O_2.cell^{-1}.hr^{-1}	15°	Rhyther & Guillard, 1962.
				7.1×10^{-12}	20°	
				9.6×10^{-12}	25°	
Cyclotella nana	3			6.7×10^{-11} ml O_2.cell^{-1}.hr^{-1}	5°	Rhyther & Guillard, 1962.
				1.8×10^{-10}	10°	
				3.6×10^{-10}	15°	
				3.5×10^{-10}	20°	
				5.0×10^{-10}	25°	
Cyclotella nana	2			1.36×10^{-7} μg-at.O_2.pgC^{-1}.hr^{-1}		Falkowski & Owens, 1978.
Cylindrotheca closterium	2	7.0		0.95 μl $O_2 . 10^6$ cells^{-1}.hr^{-1}	dark endogenous	Humphrey, 1975.
Detonula confervacia	3			1.3×10^{-8} ml O_2.cell^{-1}.hr^{-1}	5°C	Rhyther & Guillard, 1962.
				1.5×10^{-8}	10°C	
Ditylum brightwellii	2			8.97×10^{-7} μg-at O_2.pgC^{-1}.hr^{-1}		Falkowski & Owens, 1978.
Eunotia pectinalis	1			1.126 ml $O_2 . \mu$g dry wt^{-1}.hr^{-1}	no current, 22°C	Schumacher & Whitford, 1965.
				3.454	current 18 cm.sec^{-1}, 22°C	
Fragilaria sublinearis	4	0.9–4.7			3°C	Bunt, 1965.
		2.1–4.9			10°C	
		0.9–1.0			20°C	
Melosira sp 1	3	5.5–13.5		0.2–1.0 mg O_2.mg Chl.a^{-1}.hr^{-1}	media with 10–15 mg N/L & 1–1.5 mg P/L, 25°C	Nakanishi & Monsi, 1976.
		3.0–13.5		0.1–0.5	media with 1–1.5 mg N/L & 0.1–0.15 mg P/L, 25°C	
		4.0–13.5		0.1–0.2	media with 0.1–0.15 mg N/L & 0.01–0.015 mg P/L, 25°C	
Melosira sp 2	3	5.5–10.0		0.3–0.8 mg O_2.mg Chl.a^{-1}.hr^{-1}	media with 10–15 mg N/L & 1–1.5 mg P/L, 25°C	Nakanishi & Monsi, 1976.
		2.8–11		0.1–0.5	media with 0.1–0.15 mg N/L & 0.01–0.015 mg P/L, 25°C	
Nitzschia closterium	2	9.0		0.59 μl $O_2 . 10^6$ cells^{-1}.hr^{-1}		Humphrey, 1975.
Nitzschia closterium	1			15 cm O_2. 10 cm cells^{-1}.hr^{-1}	35°C	Barker, 1935.

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 7)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
Nitzschia closterium	1	0.94 0.93 1.01 0.89 0.93 0.87 0.92			12.35°C 15.8 °C 18°C 21.25°C 24.65°C 27.65°C 30.65°C	Barker, 1935.
Nitzschia closterium	2			0.9-2.5 µl O_2.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1}	0-12 ft cd. slight increase in respiration rate with light intensity	Brown & Richardson, 1968.
Nitzschia palea	1			1.5 cm O_2. 10 cm $cells^{-1}$.hr^{-1}	6°C	Barker, 1935.
Nitzschia palea	1		0.81 0.74 0.76 0.80 0.78 0.85 0.88		24.6°C 24.6°C 24.6°C 26.25°C 28°C 28.0°C 30.5°C	Barker, 1935.
Nitzschia sp.	2	5.7		0.52 µl O_2.10^6 $cells^{-1}$.hr^{-1}	endogenous dark	Humphrey, 1975.
Phaeodactylum tricornutum	2	4.0		0.21 µl O_2. 10^6 $cells^{-1}$.hr^{-1}		Humphrey, 1975.
Rhizosolenia setigera	3			1.8 x 10^{-8} ml O_2. $cell^{-1}$.hr^{-1} 3.7 x 10^{-8} 1.2 x 10^{-8} 1.4 x 10^{-7}	5°C 10°C 15°C 20°C	Rhyther & Guillard, 1962.
Skeletonema costatum	2			1.01 x 10^{-8} µg-at O_2.pgC^{-1}.hr^{-1}		Falkowski & Owens, 1978.
Synedra sp.	3	3.8-8.0 3.0-7.0 5.6-12.0		0.05-0.09 mg O_2. mg $Chl.a^{-1}$.hr^{-1} 0.5 0.1-0.5	media with 10-15 mg N/L & 1-1.5 mg P/L, 25°C media with 1-1.5 mg N/L & 0.1-0.15 mg P/L, 25°C media with 0.1-0.15 mg N/L & 0.01-0.015 mg P/L, 15°C	
Thalassiosira fluviatilis	3			3.2x10^{-9} ml O_2. $cell^{-1}$.hr^{-1} 6.2x10^{-9} 2.5x10^{-9} 1.8x10^{-9}	10°C 15°C 20°C 25°C	Rhyther & Guillard, 1962.
Thalassiosira pseudonana	1	8.3			steady state, dark	Burris, 1977.
RHODOPHYTA (RED ALGAE)						
Audouinella violacea	1			0.98 ml O_2. g dry wt^{-1}.hr^{-1} 6.604	no current, 22°C current 18 cm. sec^{-1}, 22°C	Schumacher & Whitford, 1965.
Batrachospermum macrosporum	1			12.74 ml O_2. g dry wt^{-1}.hr^{-1} 20.84	no current, 22°C current 18 cm. sec-1, 22°C	Schumacher & Whitford, 1965.

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 8)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
Batrachospermum moniliforme	1			1.41 µl O_2. mg dry $wt^{-1}.hr^{-1}$	15°C	Dokulil, 1971.
Batrachospermum moniliforme				2.86 mg O_2. g dry $wt^{-1}.hr^{-1}$		Gessner, 1938
EUGLENOPHYTA						
Astasia klebsii			1.0			Danforth, 1968.
Astasia longa	2			12-14 µl O_2.(ml packed cell vol x 10^{-3})$^{-1}.hr^{-1}$	0-12 ft cd x 10^{-2} slight decrease in respiration rate with an increase in intensity	Brown & Richardson, 1968.
Astasia longa				6-8.4 µl O_2. 10^6 $cells^{-1}.hr^{-1}$	15 - 28°C	Wilson & James, 1963.
Astasia sp	7			10 µl O_2. 10^6 $cells^{-1}.hr^{-1}$	25 - 28°C	Danforth, 1968.
Euglena gracilis	2		1.0	20 - 25 µl. 10^6 $cells^{-1}.hr^{-1}$	30°C	Cook & Heinrich, 1965.
Euglena gracilis	2			3.8-3.9 µl O_2.(ml packed cell vol x 10^{-3})$^{-1}.hr^{-1}$	0 - 10 ft cd x 10^{-2}	Brown & Richardson, 1968.
Euglena gracilis	2		1.0	20-58 µl O_2. 10^6 $cells^{-1}.hr^{-1}$	acetate substrate	Heinrich & Cook, 1967.
Euglena gracilis	1			75 µl O_2. g dry $wt^{-1}.hr^{-1}$	dark endogenous rate, 5°C	Wolkin, 1961.
		39.7		6 µl O_2. g dry $wt^{-1}.hr^{-1}$	grown in light, 25°C	
		0.71		8.9	"heat" treated, 25°C	
		0.09		49.2	dark grown, 25°C	
		0.12		39.9	dark grown 1 hr light	
		4.0		7.8	dark grown 1 day light	
		13.1		4.95	dark grown 2 days light	
		42.5		1.6	dark grown 3 days light	
Euglena gracilis	1			142.9-147.7 µl O_2.mg protein $N^{-1}.hr^{-1}$	pH 3.5, stationary stage, zinc sufficient cells	Price & Millar, 1962.
				75.8	pH 3.5, stationary stage, zinc deficient cells	
				39.6-151.7	pH 6 , stationary stage, zinc sufficient cells	
				76.7-51.0	pH 6 , stationary stage, zinc deficient cells	
				336.1-423.9	pH 3.5, stationary stage, zinc sufficient, acetate substrate	
				116.3	pH 3.5, stationary stage, zinc deficient, acetate substrate	
				460.7-466.7	pH 3.5, stationary stage, zinc sufficient, ETOH substrate	
				157 - 160	pH 3.5, stationary stage, zinc deficient, ETOH substrate	
				307 - 369	pH 6 , stationary stage, zinc sufficient, octanate substrate	
				15.5 - 155	pH 6 , stationary stage, zinc deficient, octanate substrate	

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 9)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
Euglena sp.	7			10 µl O_2. 10^6 cells^{-1}.hr^{-1}	25-28°C	Danforth, 1968.
PYRROPHYTA (dinoflagellates)						
Amphidinium carterae	2	2.7		7.49 µl O_2. 10^6 cells^{-1}.hr^{-1}	dark endogenous	Humphrey, 1975.
Amphidinium sp.	2			1.9-5.0 µl O_2.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1}	0-12 ft cd x 10^{-2} slight increase in respiration rate with intensity	Brown & Richardson, 1968.
Glenodinium	2	1.3			steady state, dark	Burris, 1977.
Gonyaulax tamarensis	2			1.62x10^{-7} µg at O_2 pgC^{-1}.hr^{-1}		Falkowski & Owens, 1978.
Gymnodinium nelsonii	2			4.4 mm^3 O_2. mg dry wt^{-1}.hr^{-1} 1.5	exponential stage cells, light exponential stage cells, dark	Hochachka & Teal, 1964.
Gymnodinium splendens	2	4.0		14.7 µl O_2.10^6 cells^{-1}.hr^{-1}		Humphrey, 1975.
CHRYSOPHYTA						
Isochrysis galbana	2			1.53 x 10^{-7} µat O_2. pgC^{-1}.hr^{-1}		Falkowski & Owens, 1978.
Monochrysis lutheri	2	8.3		0.17 µl O_2. 10^6 cells^{-1}.hr^{-1}		Humphrey, 1975.
Ochromonas malhamensis	4			34-35 µl O_2. mg dry wt^{-1}.hr^{-1} 15-17 33 28	normal cells , dark starved cells, dark normal cells , light starved cells, light	Weis & Brown, 1959.
Ochromonas malhamensis	1 ,			28 ml O_2. g dry wt^{-1}.hr^{-1} 19	26°C growing 26°C starved for 20 hr	Reazin, 1954.
Ochromonas danica	2			8.0-12.0 µl O_2.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1}	0-14 ft cd x 10^{-2} increase in respiration rate with increase in temperature	Brown & Richardson, 1968.
CRYPTOPHYTA						
Chroomonas	2	5.3		0.55 µl O_2. 10^6 cells^{-1}.hr^{-1}		Humphrey, 1975.
Cryptomonas ovata	2			0.2-0.5 µl O_2.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1}	0-12 ft cd x 10^{-2} slight decrease in respiration with increase in intensity	

Table 1: The photosynthesis to respiration ratio, respiratory quotient and respiration rate of some phytoplankton species (continuation 10)

species	method of respiration measurement ★	P/R	respiratory quotient	respiration rate	remarks	reference
XANTHOPHYTA						
Tribonema aequale	2			2.0–4.0 μl O_2.(ml packed cell vol x 10^{-3})$^{-1}$.hr^{-1}	0–12 ft Cd x 10^{-2}, slight increase in respiration with increase in intensity	Brown & Richardson, 1968.
Tribonema monochlorum	1			2.88 ml O_2. g dry wt^{-1}.hr^{-1}	no current 22°C	Schumacher & Whitford, 1965.
				5.55	current 18 cm sec^{-1}, 22°C	
Vaucheria ornithocephala	1			3.99 ml O_2. g dry wt^{-1}.hr^{-1}	no current 22°C	Schumacher & Whitford, 1965.
				5.57	current 18 cm sec^{-1}, 22°C	

★ - method of measurement

1 - Warburg manometric methods
2 - O_2 electrode
3 - Winkler method
4 - mass spectrophotometric method
5 - infarred spectrophotometric method
6 - radio active tracer (O^{18}) method
7 - not given in reference

Table 2: The respiration rate and photosynthesis/respiration ratio of some natural phytoplankton communities

location	dominant species	P/R	respiration rate	comments	reference
Sandusky Bay, Lake Erie	mixed	3.3			McQuate, 1956
Canyon Ferry Reservoir, Montana USA	Aphanizomenon, Stephanodiscus Fragilaria, Melosira, Asterionella		0.26–1.56 μmole $O_2 . L^{-1} . hr^{-1}$	September & October experiments	Wright, 1958
Canyon Ferry Reservoir, Montana USA	Aphanizomenon, Stephanodiscus Fragilaria, Melosira, Asterionella		0.004–0.118 μmole $O_2 . \mu g$ $Chla^{-1} . hr^{-1}$ 0.033 μmole $O_2 . \mu g$ $Chla^{-1} . hr^{-1}$	Period of low zooplankton Mean value, period of low zooplankton	Wright, 1959
Lake Washington, USA	Mixed	2.2–46.2			Devol & Packard, 1978
Lake Marion, Canada	Mixed		1.3×10^{-6} μl $O_2 .$ $alga^{-1} . hr^{-1}$	Mean annual value	Hargrave, 1969
Laboratory Stream	Synedra & Ulna dominant, also Melosira, Achnathes, Oedogonium & Anabaena		0.83 μl $O_2 .$ mg dry $wt^{-1} . hr^{-1}$ 1.13 1.59 1.84 2.04	$3^{\circ}C$ current velocity 38 $cm . sec^{-1}$ $8^{\circ}C$ $13^{\circ}C$ $18^{\circ}C$ $23^{\circ}C$	McIntire, 1966
Laboratory Stream	Phormidium & Anabaena dominant		0.29 μl $O_2 .$ mg dry $wt^{-1} . hr^{-1}$ 0.40 0.93 1.18 1.09	$3^{\circ}C$ current velocity 9 $cm . sec^{-1}$ $8^{\circ}C$ $13^{\circ}C$ $23^{\circ}C$	McIntire, 1966
Laboratory Stream	Synedra & Ulna dominant, also Melosira, Achnathes, Oedogonium & Anabaena		2.10 μl $O_2 .$ mg dry $wt^{-1} . hr^{-1}$ 1.81 1.12 0.94 1.29	$13^{\circ}C$, current 38 cm sec^{-1}, shaken, 100% Air Sat. $13^{\circ}C$, current 38 $cm . sec^{-1}$, shaken 75% Air Sat. 50% Air Sat. 25% Air Sat. 10% Air Sat.	McIntire, 1966
			1.44 μl $O_2 .$ mg dry $wt^{-1} . hr^{-1}$ 1.39 1.05 0.84 0.67	$13^{\circ}C$, current 38 $cm . sec^{-1}$, not shaken 100% Air Sat. 75% Air Sat. 50% Air Sat. 25% Air Sat. 10% Air Sat.	McIntire, 1966

Table 2: (Continuation)

location	dominant species	P/R	respiration rate	comments	reference
Laboratory Stream	Synedra & Ulna dominant, also Melosira, Achnathes, Oedogonium & Anabaena		0.86 µl O_2.mg dry wt^{-1}.hr^{-1}	5°C, current 38 cm.sec^{-1}, shaken, 100% Air Sat.	McIntire, 1966
			0.76	75% Air Sat.	
			0.70	50% Air Sat.	
			0.63	25% Air Sat.	
			0.55	10% Air Sat.	
			0.60 µl O_2.mg dry wt^{-1}.hr^{-1}	5°C, current 38 cm.sec^{-1}, not shaken 100% Air Sat.	McIntire, 1966
			0.66	75% Air Sat.	
			0.50	50% Air Sat.	
			0.36	25% Air Sat.	
			0.26	10% Air Sat.	
Laboratory Stream	Phormidium & Anabaena dominant		1.44 µl O_2.mg dry wt^{-1}.hr^{-1}	13°C, current 9 cm.sec^{-1}, shaken 100% Air Sat.	McIntire, 1966
			1.42	75% Air Sat	
			1.12	50% Air Sat.	
			0.94	25% Air Sat.	
			0.81	10% Air Sat.	
Laboratory Stream	Phormidium & Anabaena dominant		1.57 µl O_2.mg dry wt^{-1}.hr^{-1}	13°C, current 9 cm.sec^{-1}, not shaken 100% Air Sat.	McIntire, 1966
			1.71	95% Air.Sat.	
			1.38	50% Air Sat.	
			1.09	25% Air Sat.	
			0.52	10% Air Sat.	
			0.76 µl O_2.mg dry wt^{-1}.hr^{-1}	5°C, current 9 cm.sec^{-1}, shaken 100% Air Sat.	McIntire, 1966
			0.88	75% Air Sat.	
			0.74	50% Air Sat.	
			0.65	25% Air Sat.	
			0.47	10% Air Sat.	
			0.88 µl O_2.mg dry wt^{-1}.hr^{-1}	5°C, current 9 cm.sec^{-1}, not shaken 100% Air Sat.	McIntire, 1966
			0.84	75% Air Sat.	
			0.63	50% Air Sat.	
			0.48	25% Air Sat.	
			0.35	10% Air Sat.	

Table 2: (Continuation)

Location	dominant species	P/R	respiration rate	comments	reference
Laboratory Stream	Melosira & Synedra dominant	1.1 -1.9	1.6-3.2 g $O_2.M^{-2}.day^{-1}$	August	McIntire et al., 1964
		1.1 -2.6		September	
		1.0 -1.5		October	
River Thames, England	Mixed		4.59 $gO_2.M^{-2}.day^{-1}$	Spring	Kowalczewski & Lack, 1974
			0.09	November	
River Kinnet, England	Mixed		1.05 $gO_2.M^{-2}.day^{-1}$	Spring	Kowalczewski & Lack, 1971
			0.34	September	
San Marcos River, USA	Stigeclonium, Oscillatoria, Anabaena, Spirogyra, Cladophora dominant	0.59-1.38	12.1-19.9 $gO_2.M^{-2}.day^{-1}$	Mean annual value	Hannon & Dorris, 1970
Mississippi River, USA	Mixed	2.17	0.54 $mg.L^{-1}.day^{-1}$	Main River - mean annual value	Dorris et al., 1963
		2.4		Upper reaches - mean annual value	
		2.47		Lower reaches - mean annual value	
Forge River, USA	Mixed	0.53-1.55	3.2-14.6 mg $O_2.L^{-1}.day^{-1}$		Barlow et al., 1963
Blue River, USA	Mixed	0.61	11.0 $gO_2.M^{-2}.day^{-1}$	Limestone bottom	Duffer & Dorris, 1966
		1.70	12.6	Granite bottom	
		0.39	7.7	Sand bottom	
Neuse River, USA	Mixed		0.7-21.5 $gO_2.M^{-2}.day^{-1}$		Hoskin, 1959
Silver Springs, USA		7.0	5.0 $gO_2.M^{-2}.day^{-1}$	Spring	Odum, 1956
		2.9	2.8	Winter	
River Ivel, England	Mixed	1.13	6.7-15.4 $gO_2.M^{-2}.day^{-1}$		Edwards & Owens, 1960
River Itchen, England	Mixed	0.1-1.1	4.2-23.2 $gO_2.M^{-2}.day$		Odum, 1956
Marine coastal waters ,	Mixed	0.2-9.5			Platt & Subba Rao, 1970
Oslo Fijord	Mixed		0.03- .07 $ml.O_2.L^{-1}.day^{-1}$		Gaardner & Gran, 1925
Narragansett Bay, USA	Asterionella, Chaetoceros Nitzschia, Skeletonema Thalassiosira, Rhizosolena		0.268- .412 $ml.O_2.L^{-1}.day^{-1}$		Smayda, 1957

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