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Application of underwater light measurements in nutrient and production studies in shallow rivers

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Summary

*Due to fluctuations in water turbidity, river depth and total reflection from one river section to another, plant production is poorly correlated to solar radiation incident on the water surface. A relationship was observed between daily relative photosynthesis and photosynthetically available radiation (PAR) at the plant depth for *Cladophora*, with a correlation coefficient (r) of 0.73. Therefore, the effect of low light levels can be compensated for when evaluating nutrient-growth relationships for *Cladophora* in the field.*

Introduction

The photosynthesis of aquatic plants depends on many factors and it is generally accepted that the quantity of available light is an important rate-determining factor (Ryther, 1956). The light energy received by attached plants in rivers may not relate to solar radiation incident at the water surface due to extreme variation in water turbidity and, to a lesser extent, plant depth and total reflection which includes surface effects. Therefore, the largest uncertainty in previous production studies was the relationship between the rate of photosynthetic oxygen production and solar radiation incident at the water surface (Owens, Knowles & Clark, 1969). Plotted on a log-log scale, oxygen production in the River Ivel, England, varied widely on days when low light energy was received at the water surface. The large variation in response of the plants to low light energy might be explained by changing turbidity levels and/or water depth. A very small

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change in water turbidity with low light energy at the water surface might greatly affect the light received at the plant depth, but with increasing light energy, light saturation levels are approached or surpassed and fluctuation in water turbidity would then have less effect. Thus, the importance of correlating photosynthetic production to the light energy received at the plant depth becomes apparent.

This report discusses the relationships between photosynthesis of *Cladophora*, solar radiation incident at the water surface and light energy at the plant depth, and describes the practical uses of underwater light measurements in stream productivity studies.

Methods

The study areas chosen from six rivers in southwestern Ontario, namely the Avon, Middle Maitland, Bayfield, Nith, Conestogo, and Thames have been previously described (Wong & Clark, 1976). *Cladophora glomerata* (L.) Keutzing was the dominant plant species appearing in the spring and remaining until the water temperature exceeded 25°C which occurred between late June and August depending on the river. *Cladophora glomerata* attaches itself to the substrate and grows in long filaments which are pressed against the bottom by the water current. Therefore, the depth at which the plants are growing is assumed to be the mean depth of the river. River sections were chosen with reasonably uniform depth so that the mean depth of the river would be an accurate plant depth for the sections studied. The mean depth of a section was calculated by dividing its volume by the surface area. Volume was determined by multiplying the flow rate by the time of travel. Flow rates were obtained from previously derived stage-discharge relationships.

Time of travel between stations was measured with a dye tracer (Rhodamine WT) for a range of

flows (Church & Kellerhals, 1970). The time of travel for any given day could then be established from its relationship to the flow. Surface area was calculated from direct physical measurements of stream length and width. Average width measurements were related to flow so that any variation in surface area as a result of changing flows could be accounted for.

Solar radiation above the water surface was measured in $\text{g cal/cm}^2 \cdot \text{min}$ with a Weather Measure R401 Pyranometer (Weather Measure Corp., Sacramento, California). The transmission of light through the water column was measured at each sampling station with an underwater quantum sensor (LI-COR model 185, Lambda Instruments, Lincoln, Nebraska). The light sensor, corrected for cosine response, measures photosynthetically available radiation (PAR) under the surface in the 400–700 nm range. The quantum sensor units in microeinsteins/ $\text{m}^2 \cdot \text{s}$ can be converted to gram calories assuming that 1 einstein/ $\text{m}^2 \cdot \text{day}$ of visible light (400–700 nm) corresponds to about $8.4 \times 10^{-3} \text{ g cal/cm}^2 \cdot \text{min}$. (Withrow & Withrow, 1956). This conversion to $\text{gcal/cm}^2 \cdot \text{min}$ permits comparison of the daily underwater PAR with the above surface pyranometer readings.

Triplicate light readings were taken at each station at 10-cm intervals to the bottom. The readings can be plotted on semi-log paper and the line of best fit calculated or the values can be averaged for each depth. The line is extrapolated back to zero depth to derive the light energy associated with 100% of the subsurface PAR. The vertical extinction coefficient (K_e) and the depth associated with 1% of the subsurface PAR (z_1) can be calculated from Lambert-Beer's Law using the average reading from two depths.

$$K_e = \frac{\ln I_1 - \ln I_2}{z_2 - z_1} \quad (1a)$$

where I_1 is the light intensity at depth z_1 and I_2 is the light intensity at depth z_2 .

For the special case that I_1 is the subsurface light intensity (100%) with a depth (z_1) of zero and I_2 is the light intensity at the unknown depth associated with 1% of the subsurface PAR $z_2 = z_1$, then equation (1a) can be rearranged to calculate this depth

$$z_1 \% = \frac{\ln 100}{K_e} = \frac{4.6}{K_e} \quad (1b)$$

The depth associated with 1% of the subsurface

PAR will be used as an expression of water turbidity (Chandler, 1942).

The light intensity was measured at intervals of 3 h at each sampling station. Every 3 h the available light energy at the plant depth for a river section was determined as an average of the upstream and downstream measurements. Thus, plants growing within the section are assumed to receive an amount of light energy equivalent to the average of the upstream and downstream measurements. The determination of PAR at the plant depth will be discussed in detail in the results.

The gross community production was estimated by the upstream-downstream diurnal curve method described by Odum (1956) and Armstrong, Gloyna & Copeland (1968). A continuous record of diurnal oxygen fluctuation at upstream and downstream stations was obtained using E.I.L. oxygen meters (Electronic Instruments Ltd, Richmond, Surrey, England) coupled with Rustrak recorders (Gulton Industries, Manchester, New Hampshire, U.S.A.). Production was measured for 3 consecutive days, every other week, and the average production during a 2-week period was used to evaluate the nutrient effect on production.

The method of collecting and analysing plant samples for nutrient content has been previously described (Wong & Clark, 1976). River sections were visited every 2 weeks and the average phosphorus content in the plant tissue was derived from the values measured on two visits.

Results and Discussion

Turbidity fluctuation in rivers

Uniform vertical mixing of suspended solids was verified as indicated by the linear plots of light intensity against depth on semi-log graph paper. Therefore, the flow rates of 0.8–8 m/s will maintain uniform vertical mixing of suspended solids. Horizontal transects also revealed adequate mixing of turbidity except for short distances from each shore. Thus, light extinction measurements from mid-stream will represent the water turbidity of almost the entire cross-section.

The water turbidity rarely remained constant during the day at individual stations or from one station to the next. Figure 1 illustrates the irregularity of water turbidity observed between sampling stations within a 1.5-km stretch of river. Although the river sections chosen were relatively free from the

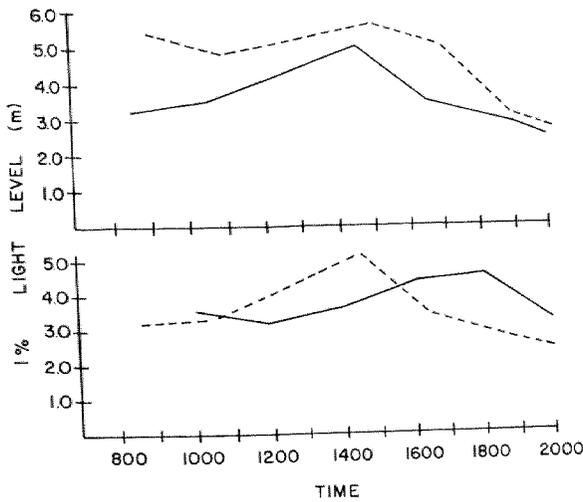


Fig. 1. Daily fluctuations in turbidity expressed as the 1% light level for upstream (—) and downstream (---) stations on the Thames River (Ontario) for two particular days.

effects of effluent inflows and tributaries, the fluctuation in turbidity at the downstream station was highly susceptible to factors such as the filtering mechanism of the aquatic vegetation, sedimentation of suspended particles, water depth and occasionally the scouring effect due to sudden changes in flow. Because of the upstream-downstream variations in turbidity and the daily fluctuation in turbidity, the solar radiation incident at the water surface is not proportional to the underwater light energy reaching the plant depth. Therefore, many measurements of extinction coefficients at both upstream and downstream stations during the day are necessary to accurately modify the solar radiation at the water surface. However, the measurement of extinction coefficients with the quantum sensor will mean that the underwater light energy has been directly measured and the PAR at the plant depth can be calculated as described in the following section.

Determination of PAR at the plant depth

The mean depth, or plant depth, of the reach may vary during the course of extended production studies. The mean depth (reach volume divided by surface area) is a function of volume and therefore flow. Until the relationship between flow and mean depth has been determined, the measurement of the light energy at the mean plant depth for the reach is

not possible. The following methods will allow both the determination of mean depth and the light energy associated with it after the field studies have been concluded.

The light data collected from six rivers were used to verify the relationships between vertical extinction coefficient, percentage subsurface light and depth as described by Vollenweider (1955). The theoretical relationships expressed in the nomograph (Fig. 2)

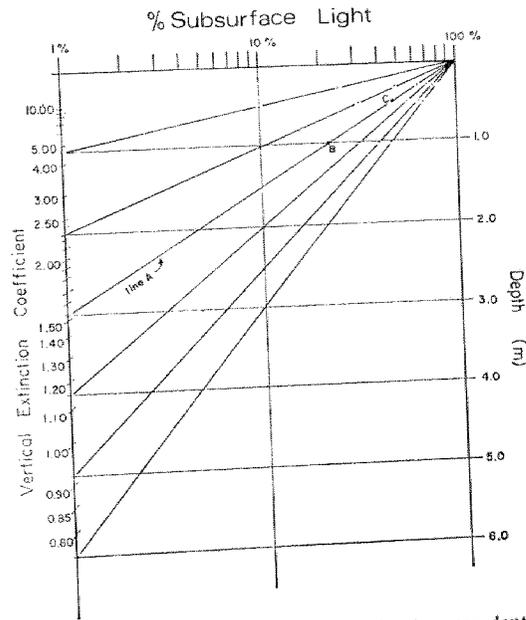


Fig. 2. Nomograph showing the relationship between depth, percent surface light and the vertical extinction coefficient.

can be applied in our rivers since uniform vertical mixing will be maintained by the flow. For any given extinction coefficient, the depth associated with 1% of the subsurface light and the percentage light transmission at various depths can be read from the nomograph. The percentage of subsurface light will be proportional to the actual quantity of light energy for different depths at any given time. Therefore, the light energy at the plant depth can be computed by determining the percentage of subsurface light received at that depth, and relating it to the actual quantity of light energy measured at any given depth.

Depending on the circumstances, there are various methods which may be used in working up the field data to determine the light energy at the plant depth. The light profiles at each station may include the actual measured light energy at the plant

depth if the light profile was done to sufficient depths. Often, however, the light profile does not include measurements at the plant depth. In this case the nomograph may be used to calculate the actual light intensity at the plant depth. The vertical extinction coefficient is calculated (i.e. 1.53) as described in the methods. The line joining the 100% subsurface light energy with the calculated vertical extinction coefficient is then used to calculate the percentage light at the plant depth (line A Fig. 2). For instance if the plant depth is 1 m, then using line A, the subsurface light energy at 1 m is 23% (Point B, Fig. 2). If the actual light energy at 0.5 m was 1.0 g cal/cm².min, using line A, we also know that that amount of light energy corresponds to 47% of the subsurface light energy (Point C, Fig. 2). Therefore the actual amount of light energy at 1.0 m is $23/47 \times 1.0 = 0.49$ g cal/cm².min. The actual amount of light energy at the plant depth should be calculated for each station every 2–3 h. The upstream and downstream light energy values are averaged and plotted against time. The daily light energy for the reach at the plant depth is the graphic integration of these values. For example, Fig. 3 compares the solar

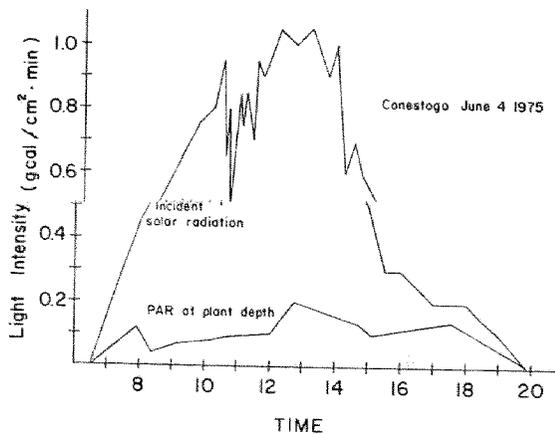


Fig. 3. Incident solar radiation and photosynthetically active radiation at the plant depth in g cal/cm².min plotted against time.

radiation at the water surface and the calculated light energy at the plant depth for a particular day on the Conestogo River. This again illustrates the point that PAR at the plant depth is not proportional to the solar radiation incident at the water surface due to changing turbidity levels.

Not only do varying water turbidity levels affect the transmission of light through the water column

but a percentage is lost at the surface due to total reflection. Previous studies have applied a constant to account for back reflection, i.e. 3.0–5.5% (Sauberer & Eckel (1938); 5%, Ryther (1956)); 6% (Patten (1961)); 10%, Westlake (1966) and Vollenweider (1969). However, the total loss of light energy at the water's surface depends on factors such as the composition and angle of the light reaching the surface, as well as the physical nature of the water's surface. These factors make it difficult to accurately predict the percentage loss due to total reflection. The present method would avoid possible errors in the use of such a constant because the actual underwater light energy is measured rather than correcting solar radiation incident on the water surface.

Rivers receiving the same solar radiation but with dissimilar mean depths, water turbidity and total reflection will exhibit different rates of gross production even though the quantitative and qualitative biomass may be identical. Estimates of available energy based on underwater light measurements, rather than on solar radiation above the water, will permit the comparison of different river systems and their corresponding production since the problems in dealing with surface effects, water turbidity and mean depth have been eliminated in the method.

Relationship between PAR at the plant depth and relative photosynthesis

The assimilation ratio at light saturation often referred to as the assimilation number, is defined as the ratio between the maximum gross photosynthetic rate (P_{max} , g/m².h) and the plant biomass in chlorophyll base. For measurements conducted in particular areas having similar ecological characteristics, this ratio may remain reasonably constant (Talling, 1965; Curl & Small, 1965) such that P_{max} will be proportional to the quantity of plants. In addition, the daily relative photosynthesis (P/P_{max}) which is derived by dividing the daily gross photosynthesis [P (g/m²).h daylight] by the maximum gross photosynthetic rate, would also be proportional to the daily assimilation per unit plant biomass. Thus, P/P_{max} will allow us to compare the daily photosynthetic rate of separate plant communities in different river sections without considering the actual quantity of plants.

The effect of limiting light intensity on hourly and daily P/P_{max} has been well documented in the literature (Rabinowitch, 1951, p. 964 *et seq*; Ryther, 1956; Ryther & Yentsch, 1957; Steele, 1962).

Nutrient deficiency which causes a reduction in P/P_{max} also causes a decline in assimilation ratio. This observation is supported by the work of Bongers, 1956; Caperon, Cateil & Krasnick, 1971; Coombs, Spanis & Volcani, 1967; Coombs *et al.*, 1967; Eppley, Strickland & Solorzano, 1970; Eyster *et al.*, 1958; Glooschenko & Curl, 1971; Ichimura, 1967; Healy, 1973; Firson, Tichy & Wilhelmi, 1952; Platt & Subba Rao, 1973a; Platt, Denman & Jassby, 1975; Thomas, 1970; Thomas & Dodson, 1972; and is based on the biochemical theory concerning enzyme activity and the enzymatic control of photosynthesis (Rabinowitch, 1951). Therefore, since the assimilation ratio is affected by light, temperature and nutrients, the effect of light energy must first be compensated for before a nutrient effect will become apparent.

To investigate the effect of varying light intensity on P/P_{max} , production measurements with nutrient levels of nitrogen and phosphorus below the critical tissue content of 13 g N/g dry wt and 1.3 g P/g dry wt respectively (Gerloff & Krombholz, 1966) were eliminated from the data so that the relationship between production and light presented in the following graphs (Figs. 4, 5) were presumably not including the effect of nutrient deficiency. The data from six rivers in southwestern Ontario, Canada (Fig. 4) illustrates the poor relationship between daily relative photosynthesis of *Cladophora* and solar radiation incident at the water surface. This

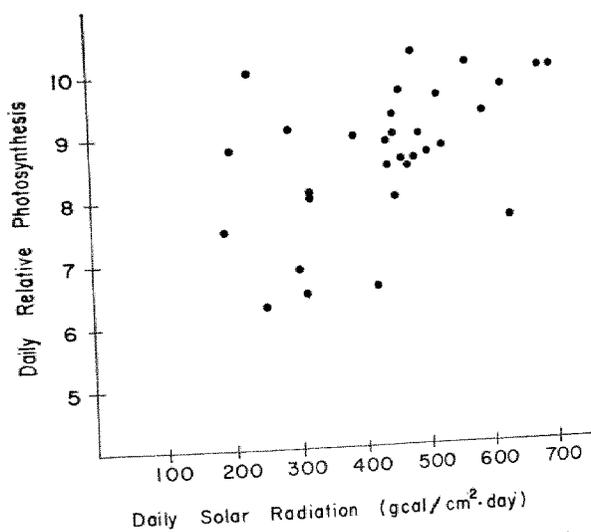


Fig. 4. Relationship between daily relative photosynthesis and total daily solar radiation above the water surface.

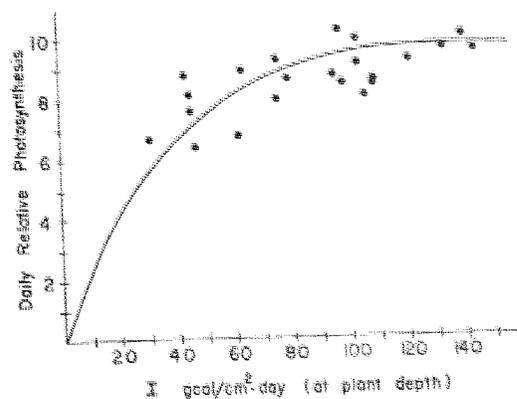


Fig. 5. Relationship between daily relative photosynthesis and PAR at the plant depth for *Cladophora*.

indicates that the use of available light energy above the water surface is oversimplified and unreliable. On the other hand, a plot of daily relative photosynthesis against PAR at the plant depth (Fig. 5), gives a statistically significant relationship. The regression line is $R = 0.59 + 4.26 \log I$, ($r = 0.73$, $P > 0.01$) where R is photosynthesis in relative units and I is the light energy at the plant depth. Although the data represents mostly the higher portion of light intensities (40–140 g cal/cm².day), the slope of the partial curve shown in Fig. 5 is similar to the complete curve described by Ryther & Yentsch (1957).

Variations in water temperature may at times affect the photosynthesis of aquatic plants. Since the average maximum water temperature recorded during the period of study was around 24–26°C, the effect of water temperature on growth has not been considered in this report. Furthermore, it is known that photosynthetic oxygen production is relatively independent of temperature when light is the limiting factor (Rabinowitch, 1945).

Nutrient-growth studies in streams

Luxury storage of nutrients in plants (Caines, 1965) will allow aquatic plants to grow independent of the external source of available nutrients. Therefore, the tissue contents which serve as the immediate source of food, were used as an index of the availability of phosphorus for plant growth (following Gerloff & Krombholz, 1966). Since growth response to nutrient supply is a long-term effect, our evaluation of the nutrient effect is based on a bi-weekly sampling period.

Plant growth measurements have been traditionally determined from the results of plant harvesting. The quantitative measurements of any heterogeneous plant community not only require a large number of samples (Edwards & Owens, 1970; Westlake, 1974) but also fail to account for the large amount of detached, drifting *Cladophora* filaments (Table 1). As suggested by Goldman (1972) the

Table 1. Drifting *Cladophora* collected on vertical 1 m² screens placed perpendicular to the flow at three stations on the Thames River (Ontario) in 1973. The quantity of plant material is based on a 6-h exposure and is expressed in Kg fresh wt

N. Thames River	Transect	Drifting <i>Cladophora</i> (kg fresh wt per m ² cross-sectional area per 6 h)
23 May	T ₁	8.10
	T ₂	8.76
	T ₃	6.06
25 May	T ₁	2.40
	T ₂	9.90
	T ₃	3.24
20 June	T ₁	1.14
	T ₂	3.84
	T ₃	7.92

metabolic activity of the algae could be measured in order to observe the response of the algae to various environmental conditions. Thus, the oxygen production was measured directly for each river section and the rate of gross production relative to the maximum production (P/P_{max}) averaged over a 2-week period was used to represent the daily relative photosynthesis of the plant community. Since daily production is governed by nutrient supply as well as the amount of light energy available, the effect of light energy (PAR) on growth cannot be disregarded and the compensation for its effect on growth response to available nutrient becomes necessary.

Allowance for the effect of light in nutrient studies

The average bi-weekly value for P/P_{max} , uncorrected for light energy, was compared with the average phosphorus content in plant tissue during the same period (Fig. 6a). Plant growth is poorly related to phosphorus when the effect of light energy is not considered. The regression equation derived from Fig. 5, relating daily relative photosynthesis and light energy at the plant depth ($R = 0.59 + 4.26 \log I$) can be used to correct all production

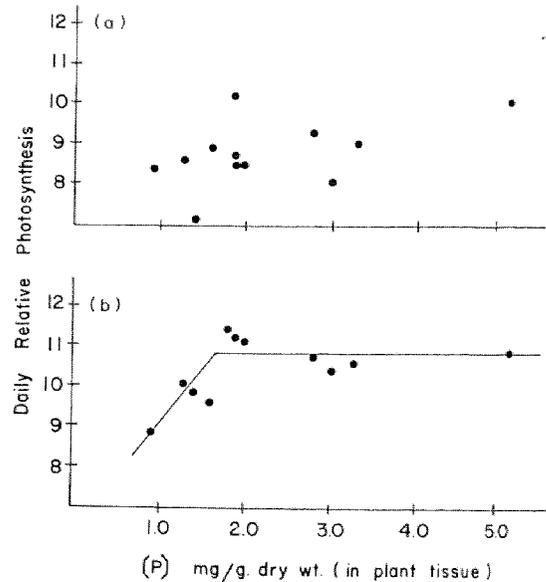


Fig. 6. Relationship between phosphorus content in the plant tissue and daily relative photosynthesis. (a) Before correction for light intensity; (b) after correction for light intensity.

measurements made by any particular light energy to a predicted daily relative photosynthesis at one common light intensity. The maximum light energy at the plant depth for the six rivers studied was observed to be 160 g cal/cm².day. Therefore, all production measurements at low light energy were corrected to give the predicted production occurring at 160 g cal/cm².day using equation (2)

$$\Delta R = 4.26 \log \frac{(I \text{ max})}{I} \quad (2)$$

Thus $\Delta R = 4.26 \log (160)/I$, and $R_{160} = R_I + \Delta R$, where R_{160} is daily relative photosynthesis at 160 g cal/cm².day, R_I is the actual measured daily relative photosynthesis at light energy at the plant depth I , and ΔR is the correction factor for R_I .

Figure 6b illustrates the relationship of total P in the plant tissue and the mean daily relative photosynthesis values corrected for light effect. After compensation for the light effect, the critical phosphorus concentration resulting in reduced daily relative photosynthesis can now be observed to be approximately 1.6–1.7 mg P/g dry wt which is in close agreement to Gerloff & Krombholz (1966) under controlled laboratory conditions. Therefore, daily relative photosynthesis of *Cladophora* is not affected by nutrients if the cellular phosphorus concentration is above 1.7 mg P/g dry wt. Below

this tissue phosphorus level, the daily relative photosynthesis is reduced. A relationship between phosphorus content in the tissue and phosphorus in the water has been reported previously (Wong & Clark, 1976) and can be used to predict the phosphorus concentration in the water which would result in a reduction of the daily relative photosynthesis. The determination of a critical phosphorus concentration in the water is helpful in making decisions concerning river management.

From the above analysis, it is apparent that although nutrient concentration is an important factor in plant growth, it is an over-simplification to ignore the effect of variations in PAR at the plant depth on photosynthetic oxygen production.

Conclusion

Water turbidity fluctuates daily at individual stations as well as with progression of the water body downstream. Differences in mean depth and total reflection also affect the amount of light energy received at the plant depth. Therefore, solar radiation incident at the water surface does not represent the light energy available to the plants and will not allow comparison of the effect of light on the photosynthesis of plant communities in different river sections.

The application of underwater light profiles constructed with data from individual stations not only provided an estimation of the mean water turbidity for the reach expressed at the depth associated with 1% of the subsurface light, but also allowed us to compute the actual PAR at the plant depth. This method would also eliminate the need to consider the errors resulting from various surface effects.

Daily relative photosynthesis of *Cladophora* is correlated with available underwater light energy ($r = 0.73$). This relationship enables us to adjust all the P/P_{\max} values to a maximum PAR at the plant depth such that all the adjusted values are independent of a light effect. These values can then be compared to the corresponding available nutrients in order to observe any nutrient effect. This empirical relationship, while only an approximation, will serve to compensate for the variations in underwater light energy at plant depths which are encountered during daily productivity measurements.

Since little can be done to reduce the input of light energy, suppression of nutrients has always

been emphasized as a possible measure for controlling the luxurious growth of *Cladophora*. In the past, enrichment studies have been based on observations of nutrient growth relationships without compensating for the effect of light and these have provided few reliable results. As suggested in the present study, empirical relationships between daily energy (PAR) and the daily relative growth will allow us to compensate for light effects and then evaluate the nutrient effect on growth.

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