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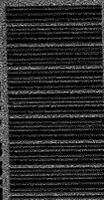
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THE DETERMINATION OF DESIRABLE AND NUISANCE PLANT LEVELS IN STREAMS

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Abstract

To cope with luxuriant plant growth in the streams of southern Ontario, an approach to determine the desirable and nuisance plant levels was proposed.

With a more intensive analysis of the assimilation efficiency of plant communities, which includes the fractionation of community respiration as well as compensation for the plant self-shading effect, the plant biomass of all species component expressed as chlorophyll *a* can be estimated from the modified growth equation,

$$B = \frac{P_{\max}}{A \cdot S}$$

where *B* is the biomass, P_{\max} is the photosynthetic growth rate at light saturation, *A* is the assimilation number and *S* is the plant shading coefficient. Once comparable biomass values are available, a desirable plant level relative to specified environmental standards can be determined.

For instance, to meet the minimum dissolved oxygen criteria of 5 ppm, the desirable and the nuisance crop levels in the North Thames River, Ontario, were found to be 0.15 and 0.75 g chl*a*/m² respectively.

Introduction

The depletion of dissolved oxygen content resulting from the over-population of submerged aquatic vegetation is recognized as a major factor contributing to the deterioration of water quality in many river systems (Edwards & Owens, 1965; Westlake, 1960). As yet the reduction of plant biomass necessary to achieve a desired water quality cannot be quantitatively determined; thus, there is no

method available for estimating the permissible standing crop of the plant material. Such information is also necessary to determine whether the excessive plant biomass will be sufficiently reduced by proposed nutrient removal programs. Therefore, the need to establish plant biomass-water quality relationships for a given river system is important to river management in Ontario.

Conventional techniques for the quantitative estimation of biomass e.g. plant cropping, optical methodologies, leaf indices (Wetzel & Westlake, 1974) are still in wide use even though they are, in most cases, impractical to perform and generally unreliable when heterogeneous plant communities are involved (Blum, 1957; Edwards & Owen, 1960; Owens, Knowles & Clark, 1969; Wetzel, 1964). Since no better methods are presently available, there have been few advances in the understanding of the effects of crop size on water quality in shallow rivers.

It is our intention in this study to explore other alternatives to this problem. According to the findings cumulated from past production studies (Ryther, 1956; Verduin, 1952; Talling, 1974; Lorenzen, 1963), the fluctuations in photosynthesis exhibited by a plant population are mainly due to variations in the population's assimilation efficiency and crop density. It has also been implied by many other authors (Wright, 1960; Ganf, 1974; Bindloss, 1974) that crop size, self-shading and assimilation efficiency are closely related. Once these relationships are considered, the total plant biomass of the community can be approximated using productivity measurements.

It is the purpose of this report to describe further research concerning productivity aspects of shallow streams and to specify the desirable level of plant biomass in two southern Ontario streams.

Methods

The location and physical morphometry of the river sections studied have been described previously (Wong & Clark, 1976; Painter *et al.*, 1976).

Primary production was measured using the two-station technique as described in Odum (1956a) and Armstrong, Gloyna & Copeland (1968). Diurnal fluctuations in dissolved oxygen and water temperature were measured for three days each week using E.I.L. oxygen meters (Electronic Instruments Limited, Richmond, Surrey, England) coupled with Rustrak continuous recorders (Gulton Industries, New Hampshire, Mass.). Sampling stations were situated approximately 1.8 km apart to keep the retention time between stations to less than four hours. Three to nine consecutive stations were situated on each river section depending on its physical characteristics and accessibility. Physical measurements such as discharge, time of travel, surface area and light transmission have been described previously (Wong *et al.*, 1976).

Quadrat cropping of the plant biomass and photographic techniques (Edwards & Owens, 1965; Westlake, 1974) were employed on many occasions. In each case, over 100 random quadrats and quadrat photographs were taken for both the dominant plant species, namely, *Cladophora glomerata* and *Potamogeton pectinactus*. Owing to the fact that the plant distribution was extremely heterogeneous and the area of our river sections was large, this technique did not give us a reliable estimation of plant biomass because of the large sample requirements. At the same time, no general relationship between percent leaf area as determined planimetrically from quadrat photographs and plant weight could be established for the mixed community of both *Cladophora* and *Potamogeton*. These methods for biomass determination were eventually abandoned. The shortcomings of these techniques have been reviewed frequently in the literature (Wetzel & Westlake, 1974; Edwards & Owens, 1960) and will not be discussed further.

Photosynthetic assimilation studies were performed with *Cladophora glomerata* under natural sunlight conditions in the laboratory. River water collected from sample stations was filtered through a 0.45 μ Millipore filter and stirred overnight to ensure 100% saturation at a temperature of approximately 20°C. The plant material was obtained in the morning and allowed to adjust to the experimental conditions for an hour. To avoid any effects of nutrient limitation, the plants were collected from an

area which would guarantee nutrient contents of greater than 1.6 mg/g dry wt. and 16 mg/g dry wt. for phosphorus and nitrogen respectively (Wong & Clark, 1976). The experimental chamber was an open 4-L beaker with a power stirrer inserted from above. The plants were suspended below a 3/4" mesh screen placed midway in the vessel and the change in oxygen concentration resulting from photosynthetic activity was continuously monitored under constant water temperature.

To correct for gas diffusion across the air-water interface, simultaneous experiments were performed following the procedure described by Verduin (1959a, 1959b, 1962). In brief, CO₂ was introduced to filtered river water to lower the pH. It was then allowed to come to equilibrium under constant surface turbulence and the rate of CO₂ exchange from water to air was measured using the pH-CC technique (Verduin, 1959a, 1951; Beyer & Odum, 1959). A stepwise differential titration was performed to establish the relationship between the change in pH and the change in CO₂ concentration. The pH values were recorded at 15 minute intervals and the transfer coefficient was computed using Fick's diffusion equation,

$$Q/at = D/L (C_w - C_f) \quad (1)$$

where Q/at is the transport per unit time and $C_w - C_f$ is the concentration difference between the water (w) and the surface film (f) assumed to be in equilibrium with the air. D/L is the transfer coefficient in cm/sec. The O₂ transfer coefficient across the air-water boundary was then computed according to O₂ and CO₂ molecular ratios.

By allowing gas evasion, the extreme supersaturation of dissolved oxygen which would significantly affect the rate of plant metabolism is avoided (Owens & Maris, 1964).

Fresh weight, dry weight and chlorophyll content of the plant materials were determined at the conclusion of the experiments. Chlorophyll pigments were extracted in 90% acetone and measured as described in UNESCO (1966). The pheopigments were determined according to the procedure described by Lorenzen (1967).

Results and discussion

The effect of self-shading on assimilation efficiency

The ratio of production to biomass is, by definition, equal to the instantaneous growth rate (g) (Mathews, 1970).

$$P/B = g \quad (2)$$

where P is plant production and B is the mean plant biomass. This is analogous to the assimilation ratio:

$$P_{\max}/B = A \quad (3)$$

measured at or near light saturation. This ratio is sometimes called the 'assimilation number' (Talling, 1974); where P_{\max} , in our case, refers to the gross photosynthetic assimilation at light saturation, B is the plant biomass expressed as chlorophyll *a* and A is the assimilation number.

Wide variations have been found in this assimilation number under different environmental conditions (Platt & Subba Rao, 1973; Rabinowitch, 1951). Nonetheless it is believed that the assimilation number should be reasonably uniform for a specific area or period of time (Curl & Small, 1965; Talling, 1965). For this reason, it is generally accepted that P_{\max} is proportional to the quantity of chlorophyll *a* present in plant tissue. Consequently, the value ' P_{\max} ' is frequently used in many studies to represent the plant biomass (Ryther & Yentsch, 1957; Ryther, 1956; Steele, 1962; Rabinowitch, 1951).

In laboratory studies with *C. glomerata*, the photosynthetic rate at light saturation as calculated from the oxygen change at hourly intervals was corrected for gas diffusion to provide an estimate of net P_{\max} . Figures 1a and 1b illustrate the relationship between biomass as chl *a* and dry weight, and net assimilation number. In well-stirred river water, with no nutrient limitation, the assimilation number fell in the range between 0.4 and 8.7 $\text{g O}_2/\text{gChl a}/\text{h}$. The fact that the rate of photosynthesis per unit chlorophyll *a* decreased as the biomass became greater would indicate the importance of self-shading by the overlying plants.

Wetzel (1964) observed that in productivity measurements, plant weight determinations and photosynthetic assimilation were non-related. This observation is supported by our data showing that photosynthetic rate appears as a smooth function of the plant chlorophyll *a* content (Fig. 1b) but is less well correlated with plant dry weight.

Experimentally, it is difficult to measure the maximum assimilation number occurring free from the influence of self-shading. The problems involved with measuring the photosynthetic response of a very small quantity of plants results in large variations in the experimentally determined assimilation number. Therefore, rather than use the highest value observed, the maximum value was derived by a regression analysis of the data obtained at low densities. Due to the effects of plant layering on the assimilation numbers so derived, data utilizing high plant densities with maximum plant surface cover were excluded. The linear regression provides the best fit

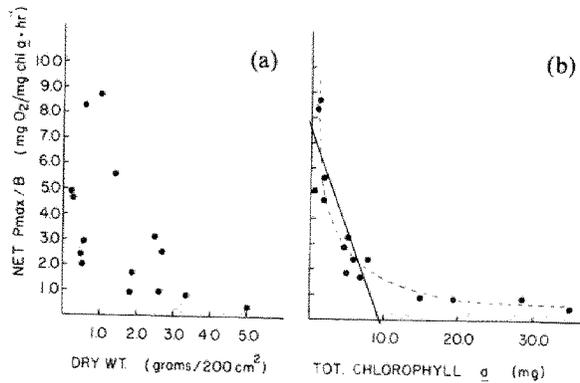


Fig. 1.

with correlation coefficient (r) of 0.84. If the maximum assimilation number is attained as the quantity of plant material approaches zero, this value is found to be 7.5 $\text{g O}_2/\text{gChl a}/\text{h}$ under laboratory conditions (Fig. 1b).

In order to permit comparison with gross community photosynthesis, the maximum net assimilation of 7.5 $\text{g O}_2/\text{gChl a}/\text{h}$ was converted to gross assimilation by assuming 5% plant respiration at the maximum photosynthetic rate, based on the range from 5 to 7% reported in the literature (Eppley & Sloan, 1965; Ryther, 1954; Bindloss, 1974; Steeman Nielsen & Jensen, 1957; Ryther & Guillard, 1962). Thus the gross assimilation number became $7.5 \times 105\%$ or 7.9 $\text{g O}_2/\text{gChl a}/\text{h}$ with no self-shading.

Efforts by Westlake (1964) to observe the plant shading effect using the optical density of the plant material were found to be unsuitable at the onset of the study because of the heterogeneity and uneven distribution of the plant community. But when the problem is approached from the primary production standpoint, the variations in the ratio of the maximum gross photosynthesis (P_{\max}) and the minimum respiration rate (R_{\min}) over a 24h period can be used to estimate the self-shading coefficient of the plant community. This assumes that the variations in the P_{\max}/R_{\min} ratio are mainly influenced by the change of assimilation number and the chlorophyll content.

The P_{\max}/R_{\min} ratio

The maximum rate of photosynthesis (P_{\max}) at light saturation is essentially a measure of the photosynthetically active portion of the plant community that is responsible for the photochemical reactions from direct light sources. Community respiration, on the other hand,

reflects the total plant biomass including both the photosynthetically active and inactive portions.

Although the daily mean respiration is generally used to evaluate lotic plant communities, it rarely shows good correlation with plant biomass, because it is subject to the influence of many changing environmental conditions during the course of the day (Owens & Maris, 1964). The minimum respiration rate (R_{min}) which often occurs in the morning hours between 1200 and 0300 appears to have a comparatively better capacity in this respect.

For a retention time of 2 to 4 hours between stations, R_{min} observed at these hours will not encompass the light effects of either dawn or dusk. Therefore, it is least affected by the broad range in daily fluctuation of water temperature and dissolved oxygen concentration than R mean. During the summer months, the mean water temperature observed at 1200-0300 hours in the North Thames River was $21.0^\circ \pm 3.0^\circ\text{C}$ and the mean percent saturation of dissolved oxygen was $67.3\% \pm 9.8\%$. These mean values represent minimal fluctuation when compared to the possible daily range in water temperature of between 15°C and $> 30^\circ\text{C}$ and percent saturation of dissolved oxygen of between $< 10\%$ and $> 250\%$. Secondly, R_{min} does not account for photorespiration during daylight hours. Finally, if P_{max} and R_{min} ratios can describe changes in the exposed plant surface area and plant volume, these ratios can be used to estimate the degree of self-shading of the plant community.

Figures 2a and 2b show the relationships of P_{max} and R_{min} observed from the North Thames and the Upper Grand River where the essential growth elements (phosphorus and nitrogen) showed no limitation from plant tissue analysis in either of these areas (Wong & Clark, 1976; Painter *et al.*, 1976). The positive correlations between P_{max} and R_{min} (solid lines) indicate that community respiration is due mainly to the plant population. If the oxygen demand by bacteria and microorganisms had been substantial, the relationship would be more diverse as shown in Figure 3a. A linear relationship of P_{max} and R_{min} indicates the dominance of the plant biota in community respiration with the condition of minimum plant shading (Fig. 3b) (Kowakzewski & Lack, 1971). However, when dealing with plant communities dominated by higher aquatic plants instead of phytoplankton, the steady increase of plant population size would result in self shading among the plants as demonstrated earlier in the assimilation study on the *Cladophora* sp. As a result of the compounding effects of shading due to silt deposition, compilation of plant layers

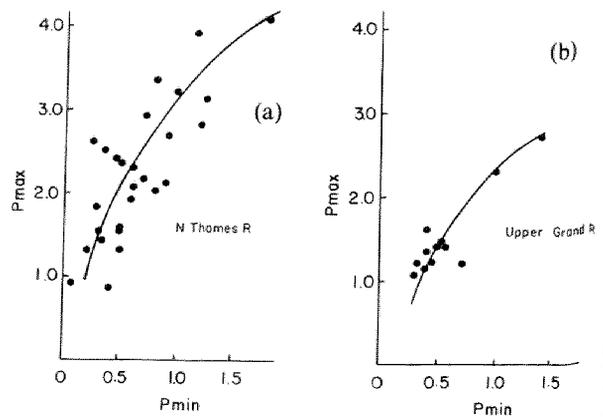


Fig. 2.

and the filtering of suspended particles particularly with *Cladophora* sp., the typical hyperbolic curve as described in Figure 1b, would be distorted to some extent. These are the reasons why only a coarse P_{max} - R_{min} relationship could be measured (Fig. 2). Similarly, Verduin derived an inconsistent slope when the relationship between photosynthetic assimilation and plant biomass under natural conditions was attempted (see Fig. 2, Odum, 1956b).

If our estimation of plant biomass is based on the relatively stable relationship between plant respiration and its density, then the correction for the uptake of oxygen content due to non-plant sources must be made regardless of how trivial the amount of oxygen metabolized by the suspended organisms and bacteria is comparative to the community respiration. That is,

$$R_c = R_p + R_b \quad (4)$$

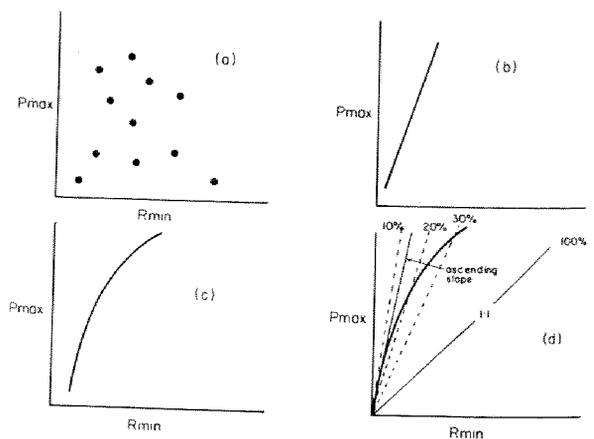


Fig. 3.

where $R_b = \text{BOD} + \text{sludge}$, and R_c is the community respiration composed of both plant and background sources. For uneven substrate beds, the use of respirometers and BOD tests on direct estimation of background respiration is difficult. To arrive at the same objective, a hypothetical evaluation of the significance of these background components can be attained by combining the concepts in Figures 3b and 3c. A non-shading condition can be reproduced by constructing an ascending slope on the hyperbolic $P_{\max}\text{-}R_{\min}$ curve as illustrated in Figure 3d. The respiration values illustrated by this ascending slope, provide an approximation of the background sources which will correspond to the maturity of the plant community.

Considering that a $P_{\max}\text{-}R_{\min}$ ratio of 1.0 can serve as the baseline arbitrarily representing a condition of 100% self-shading, in which the amount of oxygen produced by the active chlorophyll portion is equal to the amount of oxygen consumption of the total biomass, a comparative evaluation on the background sources can be made by constructing the scale of percent respiration relative to the 1 : 1, $P_{\max}\text{-}R_{\min}$ line as shown in Figure 3d.

The determination of a plant shading coefficient

If plant shading and population size are the direct causes of variations in assimilation efficiency, then the percent plant shading departing from 100 is proportional to the efficiency at a constant plant population. When the assimilation efficiency is approximated by the ratio of P_{\max} and R_{\min} , the phenomenon can be expressed as:

$$100\% - s\% \propto P_{\max}/B - P_{\max}/R_{\min} \quad (6)$$

where $s\%$ is the percent plant shading. To simplify the relationship describing the effect of plant shading on the assimilation efficiency, a nomograph (Fig. 4) describing this relationship at the maximum crop level was constructed using the following equation:

$$\frac{R_{\max}}{R_{\min}} = \frac{\text{Opt } R_{\min} - \text{arb } R_{\min}}{\text{Opt } R_{\min} - R} \times 100 \quad (7)$$

$$= \frac{\% \text{ shading away from its max}}{\text{max shading of 100\%}} \quad (8)$$

where $\text{Opt } R_{\min} = \text{Opt } P_{\max}$ at the maximum crop level and is assumed to be 10 units as suggested by the literature i.e. the P_{\max} - respiration ratio will likely vary less than tenfold (Lorenzen, 1963; Verduin, 1956; Ed-

wards, 1962; McConnell & Sigler, 1959; Ryther, 1954; Ganf, 1974), and that the community respiration would exceed 10% of P_{\max} , arb. R_{\min} is the arbitrary value within the range of 1-10 units, R is the background respiration in which 1 unit represents 10% of the Opt R_{\min} , and $R_{P_{\max}/R_{\min}}$ is the ratio.

For example, the observed P_{\max}/R_{\min} ratios of

$$\frac{10}{10} = 1, \quad \frac{10}{5} = 2, \dots, \quad \frac{10}{1} = 10$$

will have the percent self-shading departing from 100 of 0%, 56%..... 100%

respectively at the known background respiration of 10% according to the formula, the percent increases in plant shading will be equivalent to the fractional increase of the plant shading coefficient (the relative assimilation number) in the order of

$$0\%, \quad 0.56, \dots, \quad 1.0$$

Once the plant shading coefficient is derived, the biomass for any river reach can be estimated by modifying equation (3) into

$$B = \frac{P_{\max}}{A S} \quad (9)$$

(where P_{\max} is the observed maximum gross photosynthetic rate at light saturation, A is the experimental assimilation number being $7.9 \text{ gO}_2/\text{gchl}a/\text{h}$ at zero shading and S is the plant shading coefficient from the nomograph). The community plant biomass within

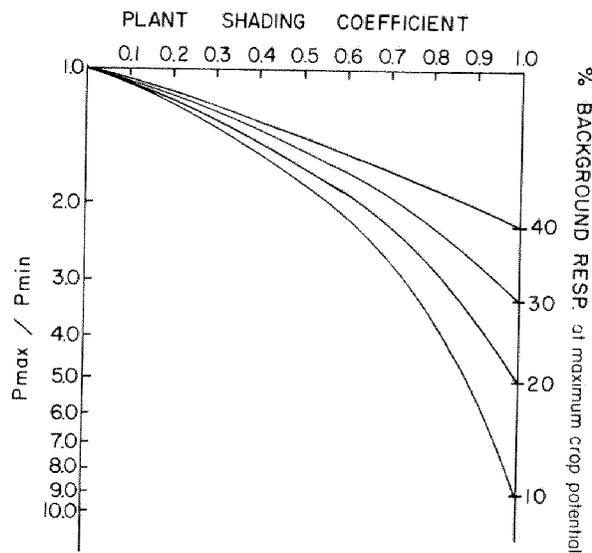


Fig. 4.

the area between two sampling stations was computed in chlorophyll units to represent total photosynthetic pigment including both the active and temporarily inactive chlorophyll resulting from silt cover and self-shading.

The biomass-oxygen relationship

Generally a large plant community would correspond to an increase in the respiratory demand on the dissolved oxygen content of shallow streams. Criteria referring to such a phenomenon are often based on the minimum oxygen concentration observed from a diurnal curve. Figure 5 shows the relationship between the biomass calculated within the reach and the minimum oxygen concentration recorded at the downstream stations of the North Thames River. Being highly complicated by other environmental factors such as aeration, community respiration and the initial oxygen concentration of upstream waters, it is comprehensible that the variations of the minimum dissolved oxygen content do not reveal positive correlation with the change of plant densities. Therefore, without the existence of a proper relationship between the minimum dissolved oxygen content and the plant densities, the possibility of predicting the dissolved oxygen content from the perspective of nutrient removal process is very unlikely.

The desirable biomass and its upper limit

If our definition of 'desirable plant biomass' refers to the quantity of plant materials which will meet the established dissolved oxygen criteria of no less than 5 mg/l at all times (O.W.R.C., 1970) and given that at the same time a daily oxygen balance ($P/R = 1.0$) in the community should be maintained, then a simple approach based on the relationship between biomass and daily net production (Fig. 6) can be used to define the desirable crop level.

By denoting the data points having a minimum oxygen concentration of less than 5 mg/l with an x, it is observed that the plant biomass over the experimental range can violate the dissolved oxygen criteria at any one time. Being extremely sensitive to climatic changes and to in-stream conditions, such as reaeration and oxygen contents in upstream waters, plant biomass only at very low densities would achieve the oxygen balance through a natural reaeration process. Therefore, our desirable crop level at zero net production where the $P : R$ ratio is one should have a biomass of less than $0.15 \text{ g chl}a/\text{m}^2$.

At high plant densities of greater than $0.75 \text{ g chl}a/\text{m}^2$, the violation of dissolved oxygen is immanent even under

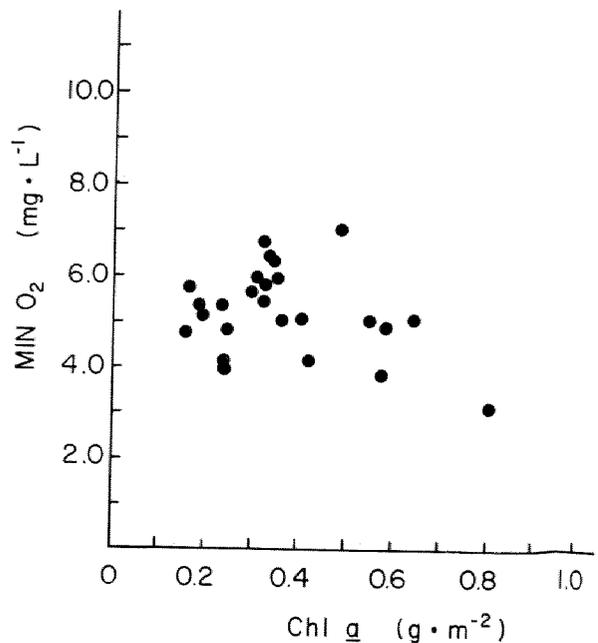


Fig. 5.

favourable conditions as indicated by its high productivity. Thus, the upper limit of plant density in our area is $0.75 \text{ g chl}a/\text{m}^2$, beyond which unwanted plant materials are present. This crop level is equivalent to approximately 160 g dry weight of plant materials in July when the average chl a concentration was found to be $4.5 \text{ mg chl}a/\text{g dry wt}$ in the North Thames. For areas that have plant biomass above this quantity, we can do little to maintain the water quality if plant removal is not somehow instigated.

Conclusion

When plant biomass is expressed as chlorophyll a as described in our study, the entire photosynthetic component of a stream reach is represented. This avoids the problems resulting from the heterogeneous nature of the community.

At times, when biomass in terms of plant weight is desired, a conversion of chlorophyll content to fresh plant weight can be determined from the chlorophyll concentration of plant materials from midstream areas. Since chlorophyll concentration varies with season and location due to plant succession and species variation, it is important to note that the conversion from chlorophyll con-

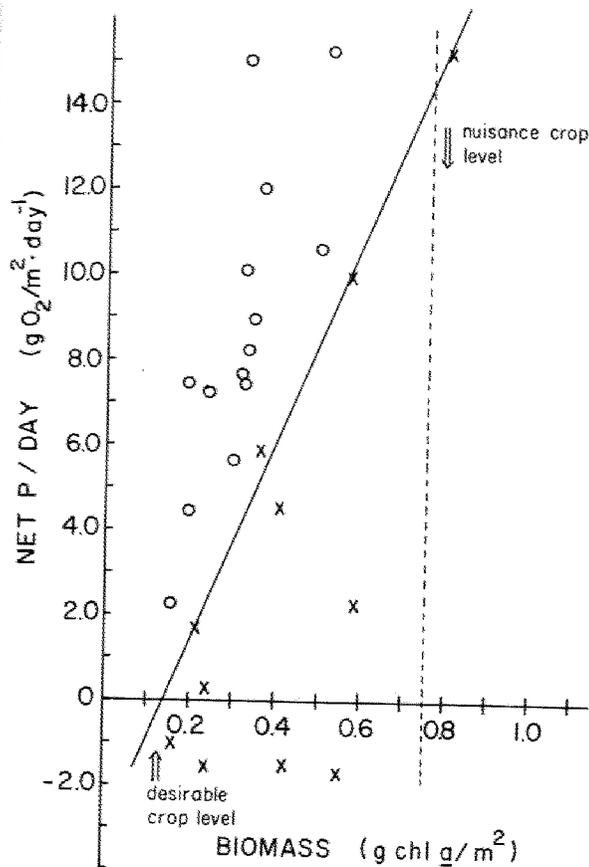


Fig. 6.

centration to dry weight must be derived from field measurements conducted at the time of interest. Chlorophyll content provides a comparative quantitative measure of the plant population.

The major problems involved with using assimilation numbers and respiration coefficients in past production studies in plant communities have been,

1. Assimilation numbers have never been adjusted to allow for the effect of crop size which has a major influence on its fluctuation even when other external factors are negligible.
2. The inability to fractionate community respiration by direct measurements allows little value to the application of respiration coefficients to a natural community.

Therefore, it is important to compensate for both the effects of plant shading and background respiration whenever assimilation efficiency of the plant community is employed.

Dealing with certain external factors such as tempera-

ture and velocity in the mixed plant community of running waters undoubtedly requires in depth studies before their effects can be properly incorporated in production studies. Our approach is therefore handicapped to some degree by not considering these effects. Nonetheless an estimation of the biomass quantity compared to its desirable level allows some quantification for management decisions.

Due to the diverse specifications among river systems with regard to their structure and function, it is unlikely that our assimilation number and desired crop level can be applied to all river systems. However, it is hoped that our approach will have some use in future pollution studies in streams.

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