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Relationship between Secchi disk visibility and chlorophyll *a* in aquaculture ponds

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Abstract

The potential of using Bannister's linear equation ($k_t = k_w + k_c c$) (where k_t is the overall light extinction coefficient, k_w represents the non-phytoplankton light extinction, k_c is the specific light extinction coefficient due to chlorophyll *a* (chla), *c* is the chla concentration, and $k_c c$ represents the light extinction due to chla) to partition sources of turbidity in Secchi disk visibility (SDV) measurements in aquaculture ponds was evaluated. Eight data sets from five sites around the world were used in the study. Chlorophyll *a* data were regressed against the overall light extinction coefficient determined from SDV measurements. The relationship between chla and overall light extinction coefficient was linear for seven of the eight data sets. The contribution of non-phytoplankton turbidity to SDV measurements was estimated by the intercept of the linear regression line (equivalent to k_w). The values obtained (range = 3.61–8.91 m^{-1}) were variable and unpredictable between replicate ponds at all sites, but did not vary significantly over time ($P < 0.05$). Because chla concentration serves as an indicator of phytoplankton concentration, the contribution of phytoplankton turbidity to SDV measurements was estimated by the slope of the linear regression line (equivalent to k_c) multiplied by the chla concentration. The slope of the regression line (0.014 ± 0.006 m^{-1} $(mg\ m^{-3})^{-1}$) was similar to values reported for natural freshwater systems. The partitioned light extinction coefficients and chla concentrations were also used to determine the threshold chla concentration above which SDV measurements are determined primarily by chla. The threshold chla concentrations (177–980 mg m^{-3}) above which phytoplankton biomass becomes the primary determinant of SDV were higher than observed chla concentrations. The results indicate that Bannister's linear equation can generally be used to partition and quantify the sources of turbidity in aquaculture ponds. The results also suggest that

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the contribution of non-phytoplankton turbidity to SDV measurements in fertilized and fed aquaculture ponds can be more important than phytoplankton turbidity.

Keywords: Secchi disk; Turbidity; Phytoplankton; Light extinction

1. Introduction

Secchi disk visibility (SDV) is commonly used by aquaculture pond managers as an indicator of phytoplankton concentration. Pond managers often have a range of SDV values within which they try to maintain their ponds, and they may alter fertilization, water exchange rates, or take other management actions to meet their SDV goals. In addition, SDV measurements may be used in modeling phytoplankton productivity when more direct phytoplankton concentration measurements are not available. Therefore, it is desirable that a quantitative treatment of the relationship between SDV measurements and chlorophyll *a* (chla) concentrations be carried out. Almazan and Boyd (1978) produced one such relationship for aquaculture ponds where phytoplankton was the major source of turbidity. However, in aquaculture ponds, organic matter, color of humic substances and inorganic materials like suspended clay may also be significant sources of turbidity. A majority of aquaculture ponds receive high inputs of organic matter in the form of food or organic fertilizers (Edwards, 1987; Schroeder et al., 1991; Chien, 1992). In such systems, non-phytoplankton sources of turbidity can be significant such that the Almazan and Boyd (1978) relationship may be inappropriate. This was recognized by Almazan and Boyd (1978) who cautioned against the use of SDV as an indicator of phytoplankton concentration unless plankton are the primary cause of turbidity.

Nath (1996) modified the Almazan and Boyd (1978) relationship to allow its application in waters with high non-algal turbidity, by including a non-algal turbidity parameter. Although the Almazan and Boyd (1978) relationship may have predictive power when applied to conditions under which the model was developed, it provides little opportunity for analyzing the functional relationship between turbidity and chla concentrations. Therefore, there is a need in aquaculture for methods that could be used to (a) estimate chla turbidity and (b) partition SDV measurements based on the source of turbidity. Such methods could be particularly useful in the interpretation of SDV data by aquacultural scientists and aquaculture pond managers. One such method for estimating chla from SDV and partitioning SDV has been proposed for natural freshwater systems:

$$k_t = k_w + k_c c, \tag{1}$$

where k_t is the overall light extinction coefficient (m^{-1}), k_w represents the non-phytoplankton light extinction (m^{-1}), k_c is the specific light extinction coefficient due to chla (m^{-1} (mg m^{-3}) $^{-1}$), c is the chla concentration (mg m^{-3}), and $k_c c$ represents the light extinction due to chla (Bannister, 1974; Lorenzen, 1980; Megard et al., 1980). Despite the need for a model to estimate chla from SDV measurements in aquaculture ponds with high non-phytoplankton turbidity (e.g., Burford, 1997), the general applicability of this method to aquaculture has not been evaluated. The aim of this study was to evaluate the applicability of the approach of Bannister (1974) to aquaculture ponds by partitioning sources of turbidity and determining the relative importance of phytoplankton and non-phytoplankton turbidity.

2. Materials and methods

Data for uncorrected chla and SDV measurements from the Pond Dynamics Aquaculture Collaborative Research Support Program database were used in this study (Table 1) (Berkman, 1995). The data were selected to encompass a wide range of pond input types, rates and chla concentrations. The data were collected during experiments designed to study the dynamics of aquaculture ponds. Standardized experimental protocols and data collection methods were used at all the research sites. Data included in this evaluation were collected at sites in Thailand (Ayutthaya and Asian Institute of Technology, AIT), Rwanda (Butare), Honduras (Comayagua), and Panama (Gualaca) (Table 1). The data used for the analysis consisted of simultaneous measurements of chla and SDV collected at various times during the conduct of pond experiments lasting approximately 5 months. Data were available from three replicate ponds receiving the same fertilization and feeding treatment at each site (Table 1); several treatments were available at each site.

Table 1
Description of Pond Dynamics Aquaculture Collaborative Research Support Program (PD/A CRSP) data sets and treatments used in the study

Site	Workplan	Database reference	Treatments
Ayutthaya, Thailand	Workplan 4, Experiment 1	C401[a]	Chicken manure @ 500 kg ha^{-1} $week^{-1}$
Ayutthaya, Thailand	Workplan 4, Experiment 4	C404[a]	Chicken manure × urea @ 35 × 250 kg ha^{-1} $week^{-1}$
Ayutthaya, Thailand	Workplan 5, Experiment 8	C508[b]	Artificial feed × urea × TSP[c] (satiation feeding × 2 kg ha^{-1} $week^{-1}$ × 1 kg ha^{-1} $week^{-1}$)
AIT, Thailand	Workplan 4, Experiment 5	I405[a]	Chicken manure × urea @ 250 × 50 kg ha^{-1} $week^{-1}$
Butare, Rwanda	Workplan 3, Experiment 5	H303 D[d]	Chicken manure @ 500 kg ha^{-1} $week^{-1}$
Butare, Rwanda	Workplan 4, Experiment 3	H403[a]	Chicken manure × green grass × urea @ 175–250 × 1142–1600 × 28.57–34 kg ha^{-1} $week^{-1}$[e]
Comayagua, Honduras	Workplan 3, Experiment 3	F303[d]	Chicken manure @ 500 kg ha^{-1} $week^{-1}$
Gualaca, Panama	Workplan 3, Experiment 3	B303 D[d]	Chicken manure @ 500 kg ha^{-1} $week^{-1}$

[a] PD/A CRSP, fourth experimental cycle (PD/A CRSP, 1989a).
[b] PD/A CRSP, fifth workplan (PD/A CRSP, 1989b).
[c] Triple superphosphate.
[d] PD/A CRSP, third experimental cycle (PD/A CRSP, 1985).
[e] Single treatment with input application rates varying overtime.

The overall light extinction coefficient (k_t) was estimated from SDV measurements using the Poole and Atkins (1929) equation:

$$k_t = \frac{1.7}{\text{SDV}}. \tag{2}$$

In order to calculate the non-phytoplankton and chla light extinction coefficients (k_w, k_c), individual values for the estimated overall light extinction coefficients (k_t) were plotted against the corresponding chla concentrations. All data from a given experiment at a site (Table 1) were used in the chla concentration vs. overall light extinction plot. A linear regression analysis on the light extinction coefficient vs. chla data was then performed using the TableCurve™ curve fitting software (Jandel Scientific, 1992). Preliminary linear regression equations were obtained for each experiment corresponding to a partitioning of the light extinction coefficient as proposed by Bannister (1974) (Eq. (1)). The final linear regression equations were obtained after confirming the appropriateness of the linear regression fit for each data set using the locally weighted regression smoothing (LOWESS) procedure in TableCurve™ and removing outliers identified by the analysis of residuals in the data set (Affifi and Clark, 1990; Jandel Scientific, 1992). Only outliers with standardized residuals greater than three were removed from the final regression analysis (Affifi and Clark, 1990). This general rule is very conservative and the chance of getting standardized residuals with a magnitude greater than three when this rule is used is very small (Affifi and Clark, 1990). Therefore, this procedure ensures that the extreme outliers removed do not significantly alter the regression line. Data points identified by the residual analysis were removed and treated as missing values in the regression analysis. The number of outliers removed from the data sets (shown in parenthesis) were as follows: C401 (7); C404 (3); I405 (1); H303 (2); H403 (2); B303_D (2) and F303 (2). The largest number of outliers (7) removed from data set C401 constituted 6.1% of the total data ($n = 87$) used in the preliminary regression analysis.

The light extinction coefficients (k_w and k_c) were estimated from the intercept (k_w) and the slope (k_c) of the linear regression of chla (c) and k_t. The use of Eq. (1) in partitioning the sources of turbidity requires that k_w and k_c are approximately constant for a particular data set (Megard et al., 1980). Single factor ANOVA showed that there were no significant differences ($P > 0.05$) in the k_c value between the different data sets, therefore k_c could be taken as a constant for all the data sets. Therefore, the mean k_c value for all the data sets was used in Eq. (1) to recalculate k_w for each set of SDV and chla measurements for a given input treatment at a given site (Table 1) using a reorganized form of Eq. (1):

$$k_w = k_t - k_c c. \tag{3}$$

The relative constancy of k_w over time for each treatment (three replicates per treatment) in Table 1 was then evaluated by testing for significant differences ($P < 0.05$) in k_w over time using single factor ANOVA.

In order to determine the relative importance of non-phytoplankton and phytoplankton turbidity in SDV measurements, two indices were calculated based on Eq. (1) as suggested by Bannister (1974). The first index, k_w/k_c, determines the threshold chla concentration (c_t) above which the contribution of non-phytoplankton sources to turbidity becomes negligible when compared to the contribution of phytoplankton. The value of c_t is defined as the value of c for which non-phytoplankton and phytoplankton contributions to light extinction are equal. This occurs when the two terms on the right hand of Eq. (1) are equal indicating that k_w and $k_c c$ equally contribute to k_t:

$$k_w = k_c c_t. \tag{4}$$

Eq. (4) can be rearranged to obtain a definition of c_t as follows:

$$c_t = \frac{k_w}{k_c}. \tag{5}$$

The second index proposed by Bannister (1974) representing the proportion (F) of subsurface light attenuated by phytoplankton can be calculated from Eq. (1) as the ratio between light extinction due to phytoplankton ($k_c c$) and the overall light extinction ($k_w + k_c c$) which can be simplified to (Bannister, 1974):

$$F = \frac{c}{\frac{k_w}{k_c} + c}. \tag{6}$$

The mean value of F was determined for each of the experiments by letting c in Eq. (6) equal the mean chla concentration (mg m^{-3}) during the growing season. The value of

Table 2
Specific light extinction due to chlorophyll *a* (chla) (k_c, m^{-1} (mg m^{-3})$^{-1}$) and non-phytoplankton light extinction coefficient (k_w, regression, m^{-1}) estimates obtained from the linear regression coefficients for chla (c) vs. overall light extinction coefficients (k_t). Mean ($n = 3$) non-phytoplankton light extinction coefficient (k_w, calculated) calculated using Eq. (3) ($k_w = k_t - k_c c$), the mean proportion of light attenuated by chla (F) and the threshold chla concentration (c_t, mg m^{-3}). All the data used for the calculations were from data sets in the PD/A CRSP database as described in Table 1

Site	Database reference	k_c	k_w (regression)	k_w (calculated)	Light attenuation index (F)	r^2	n	c_t (mg m^{-3})
Ayutthaya, Thailand	C401	0.017	7.15	7.27 ± 1.21	0.13	0.34**	80	421
Ayutthaya, Thailand	C404	0.011	6.45	6.11 ± 2.18	0.21	0.18**	33	586
Ayutthaya, Thailand	C508	0.009	8.82	7.99 ± 2.79	0.28	0.03[a]	29	980
AIT, Thailand	I405	0.028	4.96	5.26 ± 1.74	0.12	0.44**	30	177
Butare, Rwanda	H303 D	0.013	5.73	6.23 ± 1.29	0.26	0.35**	61	441
Butare, Rwanda	H403	0.012	4.07	4.06 ± 1.17	0.34	0.82**	24	339
Comayagua, Honduras	F3O3	0.014	8.91	11.28 ± 2.76	0.16	0.40**	36	636
Gualaca, Panama	B303 D	0.010	3.37	3.37 ± 1.13	0.19	0.63**	42	337

**Regression is significant ($P < 0.05$).
[a]Regression is not significant ($P > 0.05$).

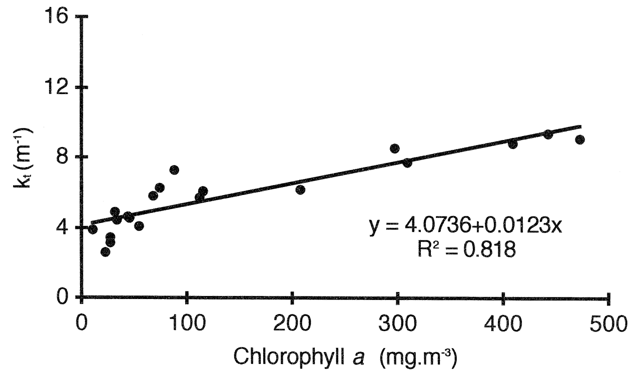

Fig. 1. Linear regression plot for chlorophyll *a* vs. overall light extinction coefficient for Rwanda Workplan 4, Experiment 3 (H403). The intercept and the slope of the regression line represent the estimates for the non-phytoplankton and the phytoplankton light extinction coefficients, respectively.

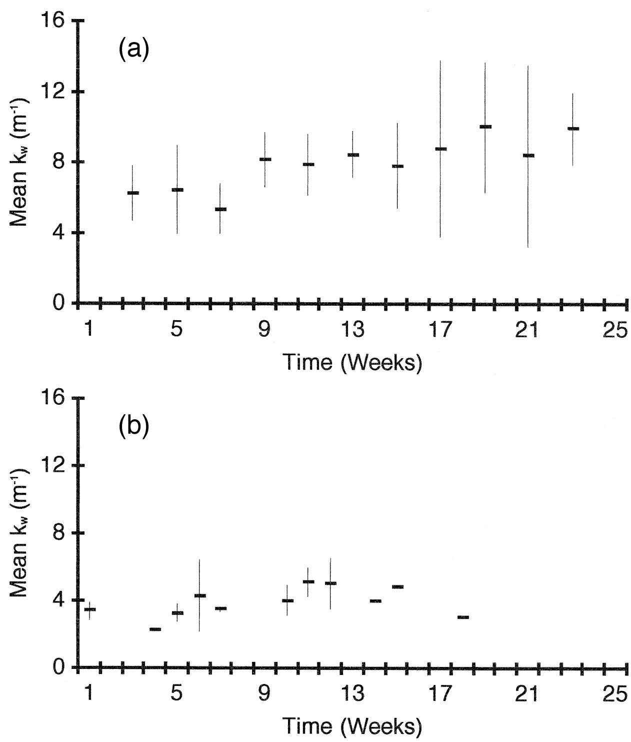

Fig. 2. Mean (± 1 s.d.) calculated non-phytoplankton light extinction (k_w) over time for (a) Ayutthaya Workplan 5, Experiment 8 (C508), and (b) Butare Workplan 4, Experiment 3 (H403). Pond treatments are as described in Table 1. The error bars correspond to the standard deviations for measurements collected in replicate ponds ($n = 3$).

k_w/k_c was obtained from the regression analysis described above. Based on Eq. (6), phytoplankton is determined to be the major source of turbidity in SDV measurements if $F > 0.5$ which corresponds to $c > k_w/k_c$ (Megard et al., 1980).

3. Results

The estimates of k_c and k_w from linear regression analyses of the data for each of the experiments, and the calculated k_w using mean k_c and chla concentrations for each treatment are shown in Table 2. An example of the linear regression plot between chla concentration and k_t is shown in Fig. 1, and the time histories of k_w for some representative data sets are shown in Fig. 2a and b. There was a significant ($P < 0.05$) linear relationship between chla and k_t for seven of the eight data sets evaluated (Table 2). Despite fitting Bannister's linear model, data for Ayutthaya, Thailand (C401, C404) and Butare, Rwanda (H303 D) had low r^2 values (Table 2). The low r^2 for the linear model for the above data sets may be due to the high variability of k_w (e.g., Fig. 2a and b). The Ayutthaya, Thailand (C508) data did not fit the linear model and this also may be attributed to the wide variability of k_w with time (Fig. 2a). In addition, this data set

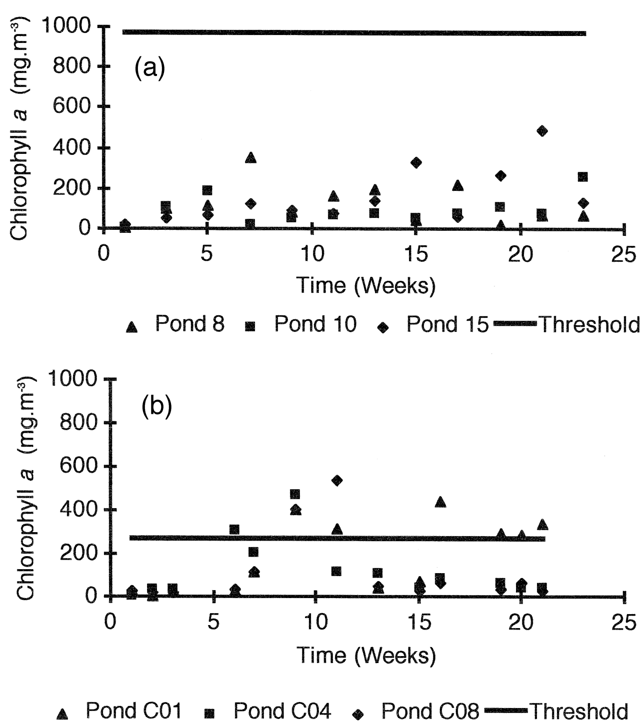

Fig. 3. Comparison between observed chlorophyll *a* (chla) and the threshold chla concentration above which chla becomes the primary source of turbidity for Secchi disk visibility measurements for (a) Ayutthaya Experiment C508, and (b) Butare Experiment H403. Pond treatments are as described in Table 1.

was different from the rest of the data sets in that the ponds were not fertilized with chicken manure (Table 1).

Estimates of k_c and k_w by the linear regression method ranged between 0.009–0.028 m^{-1} $(mg\ m^{-3})^{-1}$ and 3.61–8.91 m^{-1}, respectively, for the data sets corresponding to each of the experiments analyzed (Table 2). The k_c values showed little variability (0.014 ± 0.006 m^{-1} $(mg\ m^{-3})^{-1}$) and were not significantly different ($P > 0.05$) between sites.

The non-phytoplankton light extinction coefficients (k_w) calculated using Eq. (3) were highly variable between sites and between replicates (Table 2;Fig. 2a and b), however, k_w was not significantly different over time ($P > 0.05$) for any of the sites. The k_w values estimated using the linear regression method fell within the range of k_w values calculated using Eq. (3) (Table 2).

Fig. 3a and b show examples of typical plots of the measured chla concentrations in relation to the calculated threshold chla concentration above which the non-phytoplankton turbidity is considered to make a negligible contribution to SDV measurements (c_t from Eq. (5), and Bannister, 1974). For the examples shown in Fig. 3, calculated threshold chla concentrations (c_t) were greater than most observed chla concentrations, and the mean proportion of light attenuated by chla (F value defined in Eq. (6)) was less than 0.5 for all data sets (Table 2). These results suggest that, on average, phytoplankton was not the major source of turbidity for SDV measurements for the data sets evaluated.

4. Discussion

The range and mean of k_c values reported in this study are similar to the range (0.009–0.020 m^{-1} $(mg\ m^{-3})^{-1}$) and mean k_c (0.016 m^{-1} $(mg\ m^{-3})^{-1}$) for several temperate and tropical freshwater lakes (Megard, 1972; Bannister, 1974; Bindloss, 1974). Roose and Riise-Eriksen (1994) reported a k_c value of 0.0069 m^{-1} $(mg\ m^{-3})^{-1}$ for polyculture ponds in North-East Thailand. The small discrepancy in the aquaculture pond k_c values between the results reported in this study and that of Roose and Riise-Eriksen (1994) may be attributed to the different methods used to determine k_t. In this study, k_t was calculated from pond Secchi disk measurements while Roose and Riise-Eriksen (1994) measured k_t of pond water in an 8.5 cm deep transparent container. It is possible that the characteristics of the container used by Roose and Riise-Eriksen (1994) might have affected the measured incident light in the container. Bannister (1974) argued that k_c can be considered as a constant, therefore making it possible to calculate k_w when k_t and chla concentration are known. Since there were no significant differences in k_c between the different sites, k_c can be considered as a constant and Eq. (3) can be used to calculate k_w.

The two methods used to determine k_w in this study (linear regression and the use of Eq. (3) assuming that k_c is a constant) resulted in k_w values that were similar to the value (6.8 m^{-1}) reported by Roose and Riise-Eriksen (1994) for aquaculture ponds in North-East Thailand. However, these k_w values are different from values (range = 0.3–2.5 m^{-1}) reported for natural freshwater lakes (Talling, 1960; Bindloss, 1974; Ganf, 1974). The variability in k_w reported in this study may be explained in part by differences in the rates of application and the type of allochthonous organic matter used in the ponds (Table 1), and also by differences in the characteristics of the water supplies. For example, the high k_w reported for ponds in Honduras might be attributed to the high mud/inorganic turbidity reported for these ponds (Teichert-Coddington et al., 1992). Other factors which show wide variability in aquaculture ponds like inorganic minerals, amount of silt and dissolved pigments could also have contributed to the variability in k_w (Koenings and Edmundson, 1991; Teichert-Coddington et al., 1992; Burford, 1997).

This study has shown that the Bannister linear equation (Eq. (1)), can be applied to partition the overall light extinction coefficient into non-phytoplankton and phytoplankton components in aquaculture ponds. In addition, the results indicate that non-phytoplankton turbidity is the major determinant of SDV measurements in the tropical aquaculture ponds studied. These findings agree with those reported for various natural waters. For example, Koenings and Edmundson (1991) evaluated the effects of specific mixtures of color, turbidity and chla on submarine photometer and Secchi disk conversion factors among 58 Alaskan lakes. They showed that the use of SDV measurements to assess changes in chla or linkages to trophic state could only be made when non-algal turbidity had been shown to be either unchanged or unimportant. Their results confirmed the theoretical observations made by Lorenzen (1980) and Megard et al. (1980) on the need for establishing the relative importance of nonalgal turbidity in SDV measurements. In pond aquaculture, SDV measurements and/or water color are often used to determine success of fertilization regimes or as an index of phytoplankton production (e.g., Almazan and Boyd, 1978). As suggested by Almazan and Boyd (1978) and Koenings and Edmundson (1991), this application of SDV may be appropriate only when the non-algal turbidity remains constant or when it constitutes a relatively small contribution to the overall turbidity of the water. Under those conditions, SDV changes can be attributed to changes in chla and SDV measurements can be used reliably as indicators of chla (and phytoplankton) concentration in a pond. Given that, as has been shown here, non-phytoplankton turbidity may be the primary source of turbidity in some aquaculture ponds, the continued and generalized use of non-partitioned SDV measurements as indicators of phytoplankton concentration and for the management of algal populations may be questionable. It is proposed that, where appropriate, the use and reporting of partitioned SDV measurements in aquaculture should be encouraged to make the application and interpretation of SDV measurements for pond management and research more meaningful. The accurate interpretation, and quality of SDV measurements could also be improved if the effect of other exogenous factors on SDV measurements, such as time of day and operator differences, were minimized through the use of experienced personnel and standardized measurement techniques (Almazan and Boyd, 1978).

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