

Predictors of Seasonal Oxygen Levels in Small Florida Lakes: The Importance of Color

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Received 28 May 1996; in revised form 20 January 1998; accepted 2 March 1998

Key words: Dissolved oxygen, color, Florida lakes, trophic state

Abstract

This study examines the relationship of profundal oxygen concentrations in 55 shallow Florida lakes to humic color, trophic state, and lake size during different seasons. The data set represented a broad range of color and trophic state. The percent saturation of dissolved oxygen remained relatively constant during the fall (mean 78.4%), winter (mean 81.3%), and spring (mean 82.5%), but declined markedly during summer (mean 65.2%). Chlorophyll *a* concentrations were highest during the winter (mean 2.52 mg m⁻³) and lowest during the fall (mean 1.17 mg m⁻³), while color peaked during the fall (mean 30.1 mg Pt l⁻¹) and was lowest during the summer (mean 12.7 mg Pt l⁻¹). The relative importance of lake size, chlorophyll *a*, and color in explaining variation in percent oxygen saturation was examined using multiple regression. Percent oxygen saturation was negatively correlated with color during the winter, spring, and summer, and positively correlated with lake size in the winter and spring. However, percent oxygen saturation showed no relationship with chlorophyll *a* during any season. These results suggest that colored Florida lakes are naturally oxygen depleted and that profundal oxygen values have little relationship to lake trophic state.

Introduction

Humically colored (dystrophic) lakes were classified early in this century as a subset of oligotrophic lakes, differing from the latter by their increased content of suspended allotrophic organic matter (Naumann, 1921 as cited by Ruttner, 1963). It took over four decades, however, to recognize that such lakes can span the entire range of trophic state and differ from comparable clear water systems in a number of respects (Jarnefelt, 1958).

Although planktonic primary productivity is often reduced in colored lakes relative to comparable clear water systems (Jackson & Hecky, 1980) as a result of increased thermal stratification of the water column (Bowling, 1990; Bowling & Salonen, 1990), compression of the photic zone, and complexation of

phosphorus and iron (Jones, 1992), a systematic impact of color on phytoplankton productivity across a broad trophic gradient is not readily apparent (Beaver & Crisman, 1991). Additionally, it appears that phytoplankton production is insufficient to support zooplankton populations in colored lakes (Stoneburner & Smock, 1980; Salonen et al., 1992) and that the microbial loop is of paramount importance in energy transfer from the predominately allochthonous carbon base to zooplankton (Crisman, 1992; Jones, 1992).

In addition to trophic state, Thienemann (1925) and Lundbeck (1926) suggested that the abundance and species composition of benthic invertebrate assemblages were also influenced by humic color via its role in hypolimnetic oxygen budgets. Rasmussen & Kalff (1987) demonstrated that although trophic state statistically explained more of the interlake differences

in benthic invertebrate biomass for a set of temperate systems, the relationship was improved through inclusion of humic color concentrations. It has been suggested that estimation of lake trophic state recognize confounding properties of colored lakes (Brezonik, 1978; Canfield & Hodgson, 1983) and the fact that such systems often exhibit severe hypolimnetic oxygen depletion regardless of trophic state (Belanger et al., 1985).

The relationship among trophic state, humic color, and profundal oxygen regimes has not been examined quantitatively. As most studies of colored lakes have been limited to small sheltered systems in the temperate zone, the roles of lake size and climate on profundal oxygen concentrations have also not been considered. The present paper examines the relative importance of trophic state, lake size, color, and climate in explaining variation in observed oxygen regimes from 55 Florida lakes representing a broad humic color gradient. These lakes were not stratified; most showed a top-bottom temperature differential of less than 1 °C, and no lake had a differential of more than 5 °C.

Methods

Data collection

Physical and chemical parameters were measured once quarterly (December 1982–January 1983, March–May 1983, July–August 1983, October–December 1983) from 55 lakes in the Ocala National Forest of central Florida. True color (mg Pt/L) and chlorophyll *a* (mg m⁻³) were determined by standard methods (USEPA, 1979) and were expressed as a mean from composited water column samples (top, middle, bottom) collected with a 2.2 l Kemmerer bottle from three midlake stations in each lake. Profiles of temperature and dissolved oxygen were based on one meter sampling of the water column at three midlake stations using a YSI model 54 temperature/oxygen meter on each sampling day. Finally, lake sizes were estimated from USGS 1:24 000 scale maps.

Statistical analyses

Data have been expressed as a three station mean for each sampling event. Dataset geometric means were then calculated for color and chlorophyll *a* for each of the four sampling periods. Dissolved oxygen (measured in mg l⁻¹) was converted to percent saturation

using standard tables (Wetzel & Likens, 1991). Seasonal changes in average values of profundal dissolved oxygen were presented as arithmetic means.

Simple linear regressions were used to quantify the relationships between dissolved oxygen (percent saturation at the bottom of the lake) and each of the three independent variables (color, chlorophyll *a*, and lake size, log₁₀ transformed). A Pearson product-moment correlation matrix was used to identify significant relationships among the independent variables (color, chlorophyll *a*, and lake size). As a means of determining the degree to which differences in dissolved oxygen (percent saturation) among lakes related to color, chlorophyll *a*, and lake size, all variables were entered into a multiple regression analysis, and partial correlation coefficients were examined. Stepwise multiple regressions were used to develop an empirical model to predict percent oxygen saturation based on the three independent variables. Although some correlations were significant ($P < 0.05$) between sets of independent variables, the relationships were weak. Both the condition index and the variance decomposition matrix were used to judge whether collinearities incurred by the correlated predictor variables seriously destabilized the regression coefficients (Belsley et al., 1980).

Results

The 55 lakes of the Ocala National Forest included in the current database ranged in surface area from 2 to 698 ha (mean 30.7 ha), with a maximum depth of 7 meters (mean 3.0 m). The lakes spanned a broad range of trophic state with greatest chlorophyll *a* concentrations during winter (0.9 to 9.1 mg m⁻³, mean 2.52 mg m⁻³) followed by spring (0.3 to 14.4 mg m⁻³, mean 1.45 mg m⁻³), summer (0.3 to 12.7 mg m⁻³, mean 1.19 mg m⁻³), and fall (0.3 to 18.5 mg m⁻³, mean 1.17 mg m⁻³), respectively (Figure 1). Color peaked during fall (1.8 to 648 mg Pt l⁻¹, mean 30.1 mg Pt l⁻¹) followed by spring (0.0 to 618 mg Pt l⁻¹, mean 27.0 mg Pt l⁻¹), winter (1.1 to 845.3 mg Pt l⁻¹, mean 24.8 mg Pt l⁻¹), and summer (0.0 to 748.2 mg Pt l⁻¹, mean 12.7 mg Pt l⁻¹, Figure 1).

Profundal dissolved oxygen concentrations were greatest during winter (4.7 to 10.8 mg l⁻¹, mean 7.9 mg l⁻¹), followed by spring (0.6 to 9.1 mg l⁻¹, mean 7.4 mg l⁻¹), fall (1.8 to 9.6 mg l⁻¹, mean 7.1 mg l⁻¹), and summer (0.7 to 7.7 mg l⁻¹, mean 5.0 mg l⁻¹). The percent saturation of profundal waters in the Ocala lakes with respect to dissolved oxy-

gen remained relatively constant during fall (21.4 to 101.5%, mean 78.4%,), winter (51.1 to 105.0%, mean 81.3%,), and spring (6.9 to 100.6%, mean 82.5%,), but declined markedly during summer (8.8 to 101.7%, mean 65.2%), the period of lowest color (Figure 1).

A correlation matrix was constructed for individual seasons with oxygen percent saturation, color, chlorophyll *a* and lake size as variables (Table 1). Although 54% of the resultant correlations were significant ($P < 0.05$), all were weak ($r < 0.6$). Color was negatively correlated with oxygen percent saturation in winter, spring, and summer, and was positively correlated with chlorophyll *a* in the spring, summer, and fall. With the exception of winter for chlorophyll *a*, lake size was consistently positively correlated with both color and chlorophyll *a*. Simple linear regression models were then developed for the database. The explained variance was relatively small (10% during spring to 19% during summer). Color was the only significant predictor of profundal percent oxygen saturation in the winter ($\text{pbsat} = -6.66 \log_{10}(\text{color}) + 90.55$, $r^2 = 0.16$, $P = 0.0069$), spring ($\text{pbsat} = -6.36 \log_{10}(\text{color}) + 91.57$, $r^2 = 0.10$, $P = 0.0199$), and summer ($\text{pbsat} = -8.88 \log_{10}(\text{color}) + 75.01$, $r^2 = 0.19$, $P = 0.0014$). There were no significant predictors of profundal percent oxygen saturation in the fall.

Multiple regression models were then developed to separate the importance of color, chlorophyll *a* and lake size as contributors to interlake and interseasonal variance in profundal oxygen percent saturation (Figure 2). Significant regressions were produced from this four parameter model for winter, spring, and summer. During winter and spring, percent oxygen saturation was negatively correlated with color (winter: partial $r = -0.52$, $P = 0.0004$; spring: partial $r = -0.36$, $P = 0.0098$) and positively correlated with lake size (winter: partial $r = 0.45$, $P = 0.0025$; spring: partial $r = 0.33$, $P = 0.0176$, Figure 2). Oxygen saturation was negatively correlated with color during the summer (partial $r = -0.41$, $P = 0.0023$) when both dissolved oxygen (absolute and percent saturation values) and color were at minimal values for the year, but did not correlate with lake size (Figure 2).

Equations produced by the stepwise multiple regressions using color, chlorophyll *a*, and lake size as variables explained 18% (summer) to 33% (winter) of the variance in percent oxygen saturation in the winter, spring, and summer (Table 2). In these three seasons, color was the most significant predictor. Lake size entered into the regression during winter and spring,

Table 1. The correlation matrix for % oxygen saturation, color (mg l^{-1}), chlorophyll *a* (mg m^{-3}), and lake size (ha) for 66 lakes in the Ocala National Forest, Florida (** $P < 0.01$, * $P < 0.05$). Correlation values are presented for winter (December–January), spring (March–May), summer (July–August), and fall (October–December) of 1982–1983. Color, chlorophyll *a*, and lake size were log-transformed.

	% Saturation	Color	Chlorophyll <i>a</i>	Lake size
Winter				
% Saturation	–	–0.402**	–0.174	0.229
Color		–	0.205	0.376*
Chlorophyll <i>a</i>			–	0.111
Lake size				–
Spring				
% Saturation	–	–316*	–0.194	0.096
Color		–	0.577**	0.510**
Chlorophyll <i>a</i>			–	0.457**
Lake size				–
Summer				
% Saturation	–	–421**	–0.176	–0.084
Color		–	0.433**	0.470**
Chlorophyll <i>a</i>			–	0.367**
Lake size				–
Fall				
% Saturation	–	–0.174	–0.028	0.140
Color		–	0.372**	0.503**
Chlorophyll <i>a</i>			–	0.275*
Lake size				–

but not in the summer. Collinearity diagnostics suggested that although weak relationships exist between the independent variables, the collinearities incurred do not seriously destabilize the regression coefficients. Belsley et al. (1980) suggested that condition indices for results of all stepwise multiple regressions must be less than 30 to eliminate models with excessively correlated predictor variables. All condition indices of our models were less than 10.

Discussion

Our Florida database spanned a broad range of color (0–845 mg Pt l^{-1}), lake size (2–698 ha), and trophic states from ultraoligotrophic (0.3 mg m^{-3} chlorophyll) to mildly eutrophic (18.5 mg m^{-3}). Although all lakes were shallow and did not exceed 7 meters depth (mean 3.0 m), the water columns of most lakes displayed dissolved oxygen depletion throughout the year.

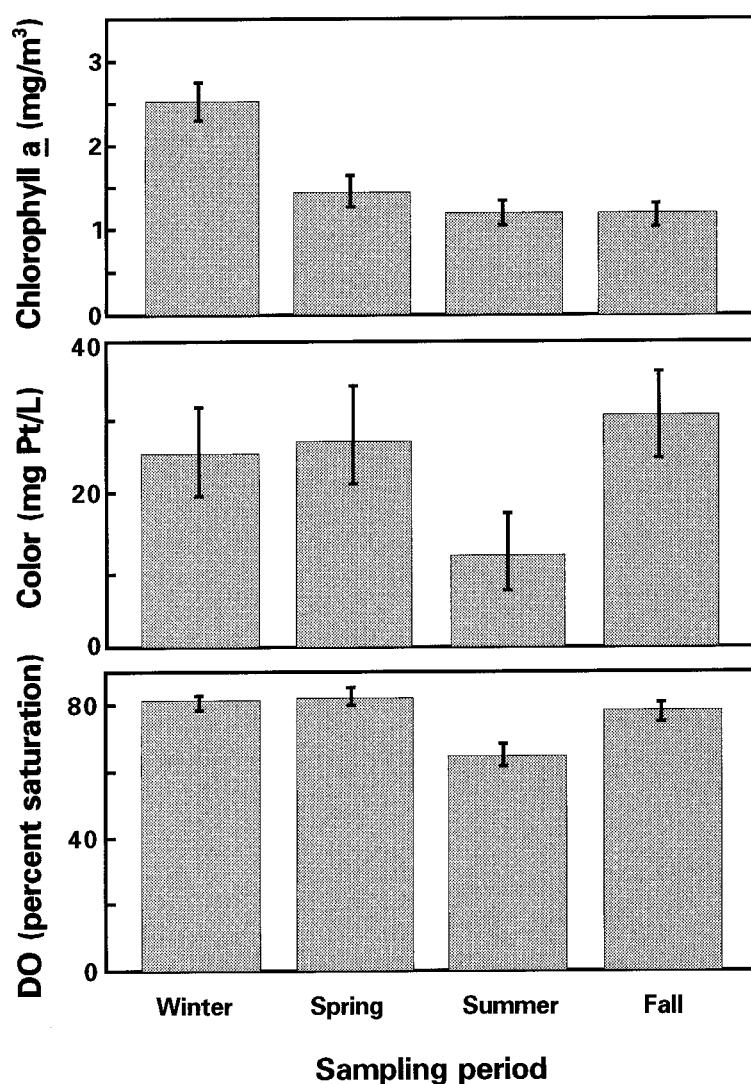


Figure 1. Mean values (\pm SE) of chlorophyll *a* (mg m^{-3}), color (mg Pt l^{-1}), and dissolved oxygen (percent saturation) for 55 Florida lakes during the winter (December–January), spring (March–May), summer (July–August), and fall (October–December) sampling periods of 1982–1983. Geometric means are presented for color and chlorophyll *a*.

Color levels in our lakes tended to be maximal during fall and minimal during summer and are likely under the control of input source and hydrology. Although colored lakes in the Ocala National Forest are fringed by pine flatwoods, marshes, and cypress swamps, the relative importance of each as color contributors is likely site specific. Cypress (*Taxodium*) sheds its needles in late fall and early winter (Nessel & Bayley, 1984), but its importance as a color contributor to the adjacent lake may be delayed until the end of the dry season in spring. By summer,

pronounced flushing during the rainy season will have reduced color input from ecotonal sources through dilution resulting in the lowest lake values for the year.

Solar radiation is rapidly attenuated with depth in colored waters (Jones & Arvola, 1984; Bowling et al., 1986) resulting in little heat storage deeper in the water column (Bowling, 1990). In temperate lakes, most daytime heat input to the system is quickly lost to the atmosphere at night. Small, sheltered, temperate forest lakes develop vertically restricted epilimnia often less than two meters thick (Salonen et al., 1984,

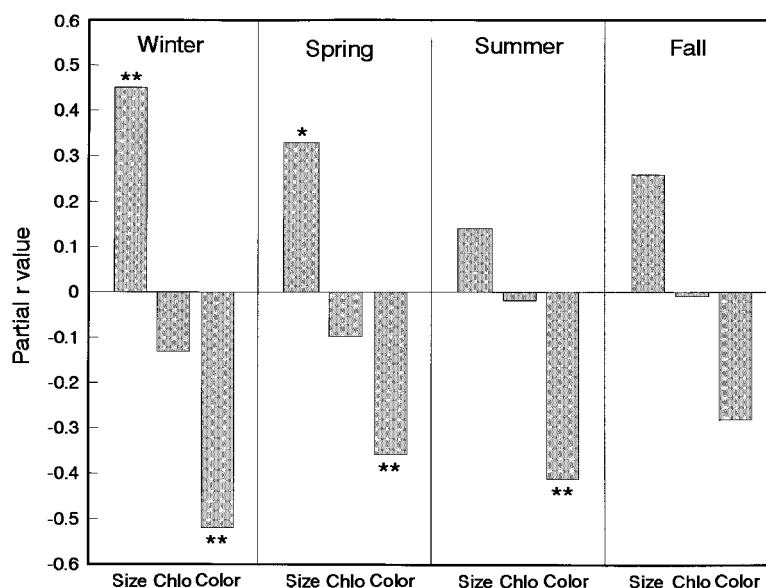


Figure 2. Partial correlation values from multiple regression models developed to separate the importance of color (mg Pt l^{-1}), chlorophyll *a* (mg m^{-3}), and lake size (ha) as contributors to interlake and interseasonal variance in profundal percent oxygen saturation. All independent variables were \log_{10} transformed. ** $P < 0.01$, * $P < 0.05$.

Table 2. Stepwise regression models depicting the relationship between profundal dissolved oxygen (percent saturation) in 66 lakes of the Ocala National Forest, Florida and three independent variables (color, chlorophyll *a*, and lake size) for winter (December–January), spring (March–May), and summer (July–August) sampling periods of 1982–1983. No significant regression model was found for the fall (October–December) sampling period. All independent variables were \log_{10} transformed.

Winter						
Step	r^2	<i>P</i> value	Variable	Partial correlation coefficient	<i>P</i> value	
1	0.161	0.0069	color	–	–	
2	0.330	0.0026	color	–0.541	0.0002	
			size	0.448	0.0026	
Spring						
1	0.100	0.0199	color	–	–	
2	0.190	0.0214	color	–0.427	0.0014	
			size	0.316	0.0214	
Summer						
1	0.177	0.0014	color	–	–	

Bowling & Tyler, 1988; Bowling & Salonen, 1990), with the thickness of the mixed zone being positively correlated with humic color (Jones & Arvola, 1984). Comparably small (<3 ha) and sheltered subtropical

colored lakes in Florida also display thin epilimnia usually less than 3 meters (Nordlie, 1972; Whitmore et al., 1991). The water columns of these temperate and subtropical lakes display pronounced oxygen depletion or total anoxia, and extremely low oxygen concentrations ($< 1 \text{ mg l}^{-1}$) have been noted in surface waters during the winter mixing period in northern Florida (Whitmore et al., 1991).

The present database allowed separation of the influence of color, trophic state, and lake size on profundal oxygen concentrations in shallow subtropical lakes. Regression models demonstrated that profundal oxygen concentrations in the Florida database consistently were most strongly related to color values with lake size being a secondary contributor. Oxygen values were not significantly correlated with trophic state (chlorophyll *a*) during any season. Oxygen consumption in colored waters is elevated because of the additional carbon source for oxidation provided by humic materials (Miles & Brezonik, 1981; Wetzel, 1983), and poor relationships between areal hypolimnetic oxygen depletion and primary productivity in small lakes have often been attributed to elevated inputs of allochthonous matter and humic color from the watershed (Charlton, 1980; Fulthorpe & Paloheimo, 1985).

The intensity of turbulence increases with lake size (Ward, 1977; Quay et al., 1980) as does the depth of the epilimnion (Sterner, 1990), thus minimizing the ability of color to promote differential water column heating and shallow stratification. Hakanson (1993) noted an extremely weak positive relationship between color and lake size for small and medium sized Swedish lakes, but no significant relationship was evident for lakes greater than 15 km². Rasmussen et al. (1989) found color to be negatively related to both lake area and mean depth for a large temperate lake database and concluded that colored lakes tend to be small shallow headwater basins with rapid turnover located in relatively large low sloped watersheds. Florida lakes are also shallow basins located in low sloped watersheds, but unlike the temperate lakes of Rasmussen et al. (1989), color in these subtropical systems displayed a significant positive relationship with lake size. For the Ocala lakes, ecotonal sources of color, especially fringing cypress swamps, should increase proportionately with increasing lake size. Summer was the only season that lake size did not enter significantly into the multiple regression model. Color values in most lakes were at their annual minimum during this period reflecting complete flushing of color source areas during the height of the rainy season.

Profundal dissolved oxygen was not correlated with trophic state (chlorophyll *a*) in the Ocala lakes. Colored Florida lakes rarely meet the regulatory minimum 5 mg l⁻¹ dissolved oxygen required for Class I (potable) and Class III (recreational) waters by the State (Belanger et al., 1985), and it now appears that the entire water column of small highly colored lakes can approach anoxia during mixis (Whitmore et al., 1991). Our study suggests both that colored Florida lakes are naturally oxygen depleted and that profundal oxygen values have little relationship to ecosystem trophic state. Thus, conventional water quality parameters including dissolved oxygen and benthic macroinvertebrates are likely to be of marginal value in either classifying such systems or denoting ecosystem response to human disturbances.

Acknowledgments

The authors wish to express their appreciation to Chandler Clarkson and Robert Garren for their assistance in field data collection and laboratory analyses for color. This project was funded in part by a grant to TLC from the U.S. Forest Service.

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