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Light attenuation in estuarine mangrove lakes

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ABSTRACT

Submerged aquatic vegetation (SAV) cover has declined in brackish lakes in the southern Everglades characterized by low water transparencies, emphasizing the need to evaluate the suitability of the aquatic medium for SAV growth and to identify the light attenuating components that contribute most to light attenuation. Underwater attenuation of downwards irradiance of photosynthetically active radiation (PAR) was determined over a three year period at 42 sites in shallow (<2 m depth) mangrove-surrounded lakes in two sub-estuaries in the coastal Everglades, Florida USA. Turbidity, chromophoric dissolved organic matter (CDOM), and phytoplankton chlorophyll *a* (chl *a*) were measured concurrently and their respective contributions to the light attenuation rate were estimated. Light transmission to the benthos relative to literature estimates of minimum requirements for SAV growth indicated that the underwater light environment was often unsuitable for SAV. Light attenuation rates (n = 417) corrected for solar elevation angles ranged from 0.16 m^{-1} to 9.83 m^{-1} with a mean of 1.73 m^{-1}. High concentrations of CDOM with high specific light absorption contributed the most to light attenuation followed by turbidity and chl *a*. CDOM alone sufficiently reduces light transmission beyond the estimated limits for SAV growth, making it difficult for ecosystem managers to increase SAV abundance by management activities. Light limitation of SAV in these areas may be a persistent feature because of their proximity to CDOM source materials from the surrounding mangrove swamp. Increasing freshwater flow into these areas may dilute CDOM concentrations and improve the salinity and light climate for SAV communities.

1. Introduction

Ecosystem managers have been seeking to restore freshwater flow to the Florida Everglades and increase submerged aquatic vegetation (SAV) coverage and associated fish and waterfowl densities in the coastal mangrove estuaries (USACE, 1999). SAV loss observed during the 20th century was associated with the encroachment of marine waters into the coastal Everglades as canals were constructed to drain the watershed. Increased salinities beyond the oligohaline to mesohaline preference range of the upstream *Chara hornemannii* algal communities were presumed to be the major factor causing SAV decline (Tabb et al., 1962; Craighead, 1971), but recent studies have identified low underwater light availability as a major contributor to continued low SAV cover (Frankovich et al., 2011, 2012) and in need of further study.

Quantifying the underwater availability of photosynthetically available radiation (PAR, 400–700 nm) is fundamental for determining the suitability of aquatic environments for SAV. SAV is often limited to water depths receiving >5–40% of surface PAR irradiance (Duarte, 1991; Kenworthy and Fonseca, 1996; Middelboe and Markager, 1997; Manuel et al., 2013). Spatial and temporal distributions of underwater light availability often correlate with SAV abundance and community composition with large declines in SAV abundance associated with reduced light availability (Orth and Moore, 1983; Cambridge and McComb, 1984). Ecosystem resource managers may seek to restore SAV communities by increasing underwater light availability, but their actions are limited to indirect methods because light transmission cannot be directly regulated. SAV growth has been increased in shallow lakes by temporarily lowering water levels to allow greater light transmission to the lake bottom (Wallsten and Forsgren, 1989; Havens et al., 2004). Another management strategy is to decrease light attenuation by decreasing the concentrations of light-scattering and light-absorbing

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constituents in the water column such as suspended sediment, phytoplankton or organic matter. Successful implementation of this strategy ideally includes determination of the light attenuation coefficient with adjustments made for solar elevation angle [K_t (adj)], and identification of the constituents that contribute most to the light attenuation rate. The downwelling light attenuation coefficient for PAR is judged to be the best single parameter by which light availability may be compared among different water bodies (Smith, 1968).

The light attenuation coefficient, K_0, is an apparent optical property that is affected by the solar elevation angle, the relative amounts of diffuse versus direct beam radiation (e.g., cloudiness), and the amounts and character of light-scattering and light-absorbing constituents in the water column (Kirk, 1994). Ideally, all of the factors influencing K_0 should be measured for the most complete and accurate determination of light attenuation specific to local water column characteristics. In practice, some of these factors are not often measured in the field and therefore these deficiencies must be considered when evaluating light attenuation rate determinations (McPherson and Miller, 1994). Inherent optical properties are affected only by light-scattering and light-absorbing constituents in the water column (Kirk, 1994); therefore, it is beneficial to adjust or make corrections to K_0 by subtracting the effects that contribute only to apparent light attenuation (e.g., solar elevation angle) so that the effects of water column parameters on light attenuation can be more accurately determined. A light attenuation component model can be used to express the adjusted light attenuation coefficient, K_t (adj), as the sum of partial light attenuation coefficients that correspond to a specific water column constituent (Kirk, 1994). The relative contributions of water column constituents can then be determined. Each partial coefficient is estimated by the product of the constituent concentration and a specific light attenuation coefficient for that constituent (Kirk, 1994). Specific light attenuation coefficients can be estimated either mechanistically through controlled laboratory experiments or statistically by regression of observed light attenuation coefficients versus the concentration of light attenuation constituents. The light attenuation component model has been successfully used to estimate the relative contributions of turbidity, chlorophyll *a* (chl *a*), chromophoric dissolved organic matter (CDOM), and water to light attenuation in estuarine waters (McPherson and Miller, 1987; 1994; Christian and Sheng, 2003; Kelble et al., 2005; Kostaglidis et al., 2005; Obrador and Pretus, 2008; Buzzelli et al., 2012).

The present study describes the underwater light climate in estuaries of the southern Everglades that are surrounded by extensive mangroves and characterized by persistent phytoplankton blooms and SAV decline (Frankovich et al., 2011). Measurements of underwater light availability are compared to estimates of SAV minimum light availability requirements. The light attenuation component model is used to estimate the contributions of water column light attenuation components to the downwelling light attenuation rate and to identify components of management concern. This study also compares results of the light attenuation component model using assumed regionally-relevant specific light attenuation coefficients obtained from the literature with that using coefficients determined from multiple regression of local field measurements of turbidity, chl *a*, and CDOM.

2. Materials and methods

2.1. Study area

This investigation was conducted at 42 sites in the estuarine mangrove-surrounded lakes and bays located along and adjacent to the north shore of Florida Bay inside Everglades National Park (Fig. 1). These sites are located in two sub-estuaries of Florida Bay defined by separate freshwater flow paths that drain the southern Everglades via Alligator Creek and McCormick Creek. The western Alligator sub-estuary is comprised of West, Long, and Cuthbert Lakes, The Lungs, and Garfield Bight. The eastern McCormick sub-estuary is comprised of Seven Palm, Middle, and Monroe Lakes, and Terrapin Bay. Henry and Little Henry Lakes (not sampled due to inaccessibility) are located between the two sub-estuaries but connections between these and the surrounding lakes were not found. Water depths are <2 m. Large differences in water quality exist between the two sub-estuaries, with higher phytoplankton abundances and lower underwater light availabilities in the Alligator sub-estuary (Frankovich et al., 2011). SAV communities consisting of the green alga *Chara hornemannii* in the upstream lakes and the seagrass *Halodule wrightii* in the McCormick sub-estuary and Garfield Bight are organized along salinity and light availability gradients (Frankovich et al., 2011, 2012).

2.2. Measured parameters

Downwards irradiance of photosynthetically active radiation (PAR) was measured just below the water surface and at 25 cm below the upper measurement in order to calculate the downwelling light attenuation coefficient (K_0) at 42 sites (Fig. 1) at varying temporal frequencies ranging from 0.6 to 7.6 yr^{-1} (mean = 3.0 yr^{-1}) during the period 2/9/2012 through 5/18/2015 (total K_0 estimates = 417). PAR measurements were made at both depths simultaneously using two Licor LI-192SA cosine-corrected sensors (flat irradiance collectors) and a Licor LI-1000 datalogger. Cosine-corrected sensors were used, as opposed to spherical scalar irradiance sensors, because inherent optical properties of the water column were compared. K_0 was calculated using the Lambert-Beer equation (Kirk, 1994):

$$I_z = I_0 \exp[-K_0(z)] \quad (1)$$

where I_z = PAR irradiance ($\mu E\ m^{-2}\ s^{-1}$) at depth, I_0 = PAR irradiance just below the water surface and z = distance (m) between light sensors. Because light attenuation calculations are affected by the solar elevation angle at the time and latitudinal location of light measurements (Moore and Goodman, 1983; Miller and McPherson, 1995) and because the primary focus of this study was relating properties of the aquatic medium to K_0, adjustments were made for the effects of solar elevation angle (β). The adjusted light attenuation coefficient, K_t (adj), was calculated using the equations of McPherson and Miller (1994) and Miller and McPherson (1995):

$$\psi = (d - 1)\,360/365.242 \quad (2)$$

$$\delta = 12 + 0.1236\sin(\psi) - 0.0043\cos(\psi) + 0.1538\sin(2\psi) + 0.0608\cos(2\psi) \quad (3)$$

$$Y = 15(\tau - \delta) - \lambda \quad (4)$$

$$\sigma = 279.9348 + \psi + 1.9148\sin(\psi) - 0.0795\cos(\psi) + 0.0199\sin(2\psi) - 0.0016\cos(2\psi) \quad (5)$$

$$\kappa = \arcsin[0.39785077\sin(\sigma)] \quad (6)$$

$$\sin(\beta) = \sin(\gamma)\sin(\kappa) + \cos(\gamma)\cos(\kappa)\cos(Y) \quad (7)$$