*The following supplement accompanies the article*

# Long-term variations in primary production in a eutrophic sub-estuary. I. Seasonal and spatial patterns

**Charles L. Gallegos**

**Smithsonian Environmental Research Center, PO Box 28, Edgewater, Maryland 21037, USA**

Corresponding author: gallegosc@si.edu

*Marine Ecology Progress Series 502:53–67 (2014)*

---

**Supplement.** This supplement presents the development of an empirical factor to correct calculations of primary production for the spectral selectivity of absorption of scalar irradiance by phytoplankton in coastal water.

## Correction for spectral absorption and scalar irradiance

Phytoplankton production in estuaries is typically measured by incubating phytoplankton samples in light gradient created by different thicknesses of neutral density screening, with either natural sunlight (Harding et al. 2002, Kimmerer et al. 2012) or an artificial lamp for a light source (Lorhenz et al. 1994, Bouman et al. 2010). With some exceptions (see e.g. Lorhenz et al. 1992), no attempt has been made to match the spectrum of the light source to that *in situ*. The efficiency of light absorption by phytoplankton, however, depends on the pigment composition and the spectral composition of the *in situ* light field (Morel 1978). The mismatch between the spectral composition of the light source used to measure photosynthesis and the *in situ* spectrum can cause bias in calculated rates of photosynthesis (Schofield et al. 1991). Additionally, phytoplankton absorb light from all directions (Kirk 2011). A correction procedure was derived to account for the spectral selectivity of light absorption by phytoplankton and the geometry of the underwater light field. Due to the high concentrations of terrigenous suspended sediment in the Rhode River (Gallegos et al. 1990), previously derived solutions to account for the angular and spectral effects in oceanic waters (Sathyendranath & Platt 1989) were not attempted in this system and an empirical approach was adopted instead. Absorption and scattering spectra were measured at approximately weekly intervals at 3 stations on the Rhode River (0.0, 3.8, and 4.3 km, Fig. 1 in main paper) from August 1999 through December 2000 (Gallegos & Neale 2002). Eight measurements from each station that were made within 3 d of photosynthesis-irradiance (*P*-*E*) measurements were used to parameterize the radiative transfer program Hydrolight (Mobley 1994). Average backscattering ratios determined less frequently for the 3 stations were 0.017, 0.015, and 0.013 for stations 0.0, 3.8, and 4.3, respectively. Hydrolight 5.0 was used to simulate *in situ* quantum scalar irradiance spectra at 5 nm intervals and 10 depth intervals through the water column at 1-h intervals from sunrise to noon. A symmetric decrease was assumed for the afternoon hours.

The measured value of the initial slope of the *P-E* curve, $\alpha^B$, was corrected for the absorption by phytoplankton of the incubation light source relative to the *in situ* spectrum by a factor calculated as:

$$\alpha_A^B = \alpha_L^B \frac{\sum_{\lambda=400}^{700} a_\phi^*(\lambda) Q_A(\lambda)}{\sum_{\lambda=400}^{700} a_\phi^*(\lambda) Q_L(\lambda)} \tag{S1}$$

where $\lambda$= wavelength of light, the *A* and *L* subscripts on $\alpha^B$ denote *in situ* corrected and laboratory, respectively, $a_\phi^*(\lambda)$ = the chlorophyll-specific light absorption spectrum of phytoplankton (Gallegos & Neale 2002), $Q_L(\lambda)$ = the relative spectrum of the laboratory incubation light source in quantum units (normalized to a maximum of 1), and $Q_A(\lambda)$ = the relative *in situ* spectral quantum scalar flux calculated by Hydrolight, and normalized to have the same integral over wavelength as $Q_L(\lambda)$. For calculation of $\alpha_A^B$ in Eq. (S1), the $Q_A(\lambda)$ spectrum determined for 0800 h at the deepest depth for the station was used to ensure that the irradiance was low enough to be in the linear range. The spectrum of the light source was measured using an Ocean Optics USB-2000 spectrometer calibrated against the LS-1Cal light source, and converted to quantum units by applying Planck's equation (Atlas & Bannister 1980).

The spectrally averaged realized *in situ* light utilization efficiency $\phi_m$, was then calculated as (Sathyendranath & Platt 1989):

$$\phi_m = \frac{\alpha_A^B}{\langle a_\phi^*(\lambda) \rangle} \tag{S2}$$

where the angle brackets denote average over wavelength. The depth profile of production, $P(z,t)$, in terms of quanta absorbed for each hour of the day was then calculated:

$$P(z,t) = BP_{\max}^B \tanh\left( \frac{\sum_\lambda \phi_m a_\phi^*(\lambda) Q_A(\lambda, z, t)}{P_{\max}^B} \right) \tag{S3}$$

Eq. (S3) was numerically integrated by the trapezoidal rule over wavelength ($\Delta\lambda$= 5 nm), depth (15 intervals) and time ($\Delta t$ = 1 h) to calculate spectrally resolved daily production for comparison with and correction of the non-spectral calculation given by Eq. (7) in the main paper. From comparison of spectral with non-spectral calculations, a multiplicative correction factor, $S(Z_{OD})$, was derived that was a function of optical depth ($Z_{OD} = K_d \times H$). This factor, which was generally <1 (see below), was applied to the right hand side of Eq. (7, main paper) to give the final estimate of daily production. Six additional Hydrolight simulations and spectral photosynthesis calculations were used for used to independently evaluate the $S(Z_{OD})$ correction factor.

## RESULTS

The non-spectral calculation of daily production, $P_{H,T}$, according to Eq. (7, main paper) consistently overestimated the spectral calculation by about 28% (Fig. S1A, squares). The exact fraction, calculated as (Non-spectral—Spectral)/Spectral, varied significantly ($R^2 = 0.59$, $p < 10^{-4}$, n = 22) with optical depth of the water column (Fig. S1B), leading to a spectral correction factor given by:

$$S\left(Z_{\mathrm{OD}}\right) = \frac{1}{1 + \left(0.0647 Z_{\mathrm{OD}} - 0.0307\right)} \qquad \text{(S4)}$$

Application of the spectral correction factor effectively removed the bias in the non-spectral calculation (Fig. S1A, solid circles). The 6 simulations not used in the development of $S(Z_{\mathrm{OD}})$ exhibited similar distribution about the reference line as those used in the development (Fig. S1A, open circles).

## DISCUSSION

Calculation of photosynthesis profiles by non-spectral procedures potentially underestimates light absorption by phytoplankton due to the use of 2π downwelling irradiance in place of 4π scalar irradiance, and overestimates absorption due to the use of PAR in an energy field with predominately green wavelengths in the underwater irradiance spectrum. In the Rhode River, the spectral effects always dominated over geometric effects, as seen by the tendency of non-spectral calculations to always overestimate the spectral calculations (Fig. S1). In oceanic waters, the corrections for the geometry and spectrum of the light field tend to be in the same direction. That is, use of 2π irradiance and non-spectral calculations both underestimate *in situ* photosynthesis in oceanic waters, due to the spectral peak in irradiance at about 490 nm coinciding more closely with the chlorophyll absorption peak at 435 nm (Sathyendranath & Platt 1989, Schofield et al. 1991). The empirical correction factor derived here, which depended on optical depth, effectively corrected for the bias (Fig. S1A), but accounted for relatively little of the variance in $P_{HT}$ (Fig. 9A in main paper). A consistent overestimation averaging 28% is, however, noteworthy and worth eliminating from the estimates. The result may be typical for shallow, turbid, green waters, but the extent of such bias in estimates from other systems is unknown. The particular correction derived here should not be applied indiscriminately elsewhere due to its empirical derivation. The empirical approach may be used in any waters optically too complex for an analytical approach such as that by Sathyendranath & Platt (1989).

### LITERATURE CITED

Atlas D, Bannister TT (1980) Dependence of mean spectral extinction coefficient of phytoplankton on depth, water color, and species. Limnol Oceanogr 25:157–159

Bouman HA, Nakane T, Oka K, Nakata K, Kurita K, Sathyendranath S, Platt T (2010) Environmental controls on phytoplankton production in coastal ecosystems: a case study from Tokyo Bay. Estuar Coast Shelf Sci 87:63–72

Gallegos CL, Neale PJ (2002) Partitioning spectral absorption in case 2 waters: discrimination of dissolved and particulate components. Appl Opt 41:4220–4233

Gallegos CL, Correll DL, Pierce JW (1990) Modeling spectral diffuse attenuation, absorption, and scattering coefficients in a turbid estuary. Limnol Oceanogr 35:1486–1502

Harding LWJ, Mallonee ME, Perry ES (2002) Toward a predictive understanding of primary productivity in a temperate, partially stratified estuary. Estuar Coast Shelf Sci 55:437–463

Kimmerer W, Parker A, Lidström U, Carpenter E (2012) Short-term and interannual variability in primary production in the low-salinity zone of the San Francisco Estuary. Estuaries Coasts 35:913–929

Kirk JTO (2011) Light and photosynthesis in aquatic ecosystems, 3rd edn. Cambridge University Press, Cambridge

Lohrenz SE, Wiesenburg DA, Rein CR, Arnone RA, Taylor CD, Knauer GA, Knap AH (1992) A comparison of in situ and simulated in situ methods for estimating oceanic primary production. J Plankton Res 14:201–221

Lohrenz SE, Fahnenstiel GL, Redalje DG (1994) Spatial and temporal variations of photosynthetic parameters in relation to environmental conditions in coastal waters of the northern Gulf of Mexico. Estuaries 17:779–795

Mobley CD (1994) Light and water. Radiative transfer in natural waters. Academic Press, New York, NY

Morel A (1978) Available, usable, and stored radiant energy in relation to marine photosynthesis. Deep-Sea Res 25: 673–688

Sathyendranath S, Platt T (1989) Computation of aquatic primary production: extended formalism to include effect of angular and spectral distribution of light. Limnol Oceanogr 34:188–198

Schofield O, Prézelin BB, Smith RC, Stegmann PM, Nelson NB, Lewis MR, Baker KS (1991) Variability in spectral and nonspectral measurements of photosynthetic light utilization efficiencies. Mar Ecol Prog Ser 78: 253–271

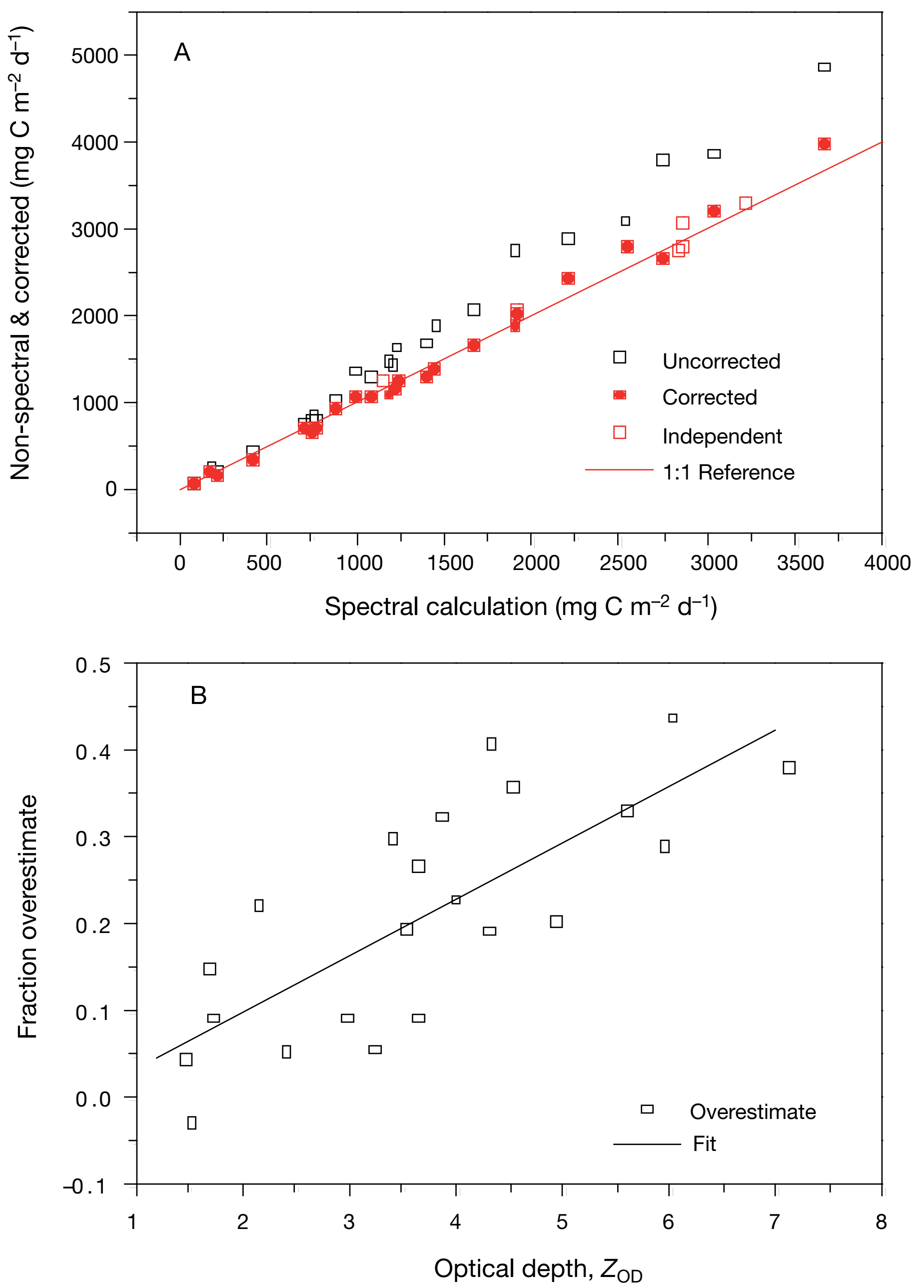


Fig. S1. (A) Daily primary production calculated from measurements of phytoplankton biomass and photosynthetic parameters using downwelling photosynthetically active radiation (PAR, 400–700 nm) against that calculated by absorption of scalar spectral photon flux density (open squares), and values corrected by empirical correction factor derived from linear fit in (B) (filled circles); corrected values applied to 6 additional measurements not used in derivation of the correction factor (open circles). Profiles of spectral scalar photon flux densities were simulated by the Hydrolight 5.0 radiative transfer program. (B) Fractional overestimate of daily production in (A) as a function of the dimensionless optical depth of the water column, $Z_{OD} = K_d \times H$, $K_d$ = diffuse attenuation coefficient, $H$ = water column depth (open squares). Line is least squares linear fit, $y = 0.0647x - 0.0307$. Fractional overestimate calculated as (Non-spectral—spectral)/spectral