Concerning the photosynthetic solar constant

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Abstract

The photosynthetic solar constant is revised by considering experimental determinations of the wavelength-dependence of photosynthetic quantum efficiency and absorbance. Using the efficiency of the light-independent metabolic phase of photosynthesis, a new estimate of 17.5 W m^{-2} is obtained for the photosynthetic solar constant.

Keywords: Photosynthetic efficiency, solar constant.

Resumen

La constante solar fotosintética es revisada considerando las determinaciones experimentales de la dependencia de la longitud de onda de la eficiencia y la absorbencia cuántica fotosintética. Usando la eficiencia de la fase metabólica de la de luz-independiente de la fotosíntesis, se obtiene una nueva estimación de 17,5 W m-2 para la constante solar fotosintética.

Palabras clave: Eficiencia fotosintética, constante solar.

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I. INTRODUCTION

A series of interesting papers concerning photosynthetic energy transduction and CO_2 assimilation has appeared recently in this journal [1, 2, 3]. These have prompted me to consider the significance of the wavelength-dependence of photosynthetic efficiency in this context. In case they might be useful anyone contemplating using the photosynthetic solar constant [3] and the underlying analysis in their teaching I briefly outline my conclusions here.

II. SOME OBSERVATIONS

Photosynthetic efficiency (η) can be thought of as being the product of several component efficiencies corresponding to the phases of the process [4]. Combining some of these, η can be written as the product of the quantum efficiency (η_q), which is the CO_2 assimilated per photon absorbed, and the metabolic efficiency (η_m), which is the proportion of the CO_2 incorporated into biomass. The former depends on the wavelength of light (λ) [5, 6] whereas the latter does not. Consequently the absorbance factor ($\alpha(\lambda)$) used in calculating the input solar energy (Q_P) should be replaced with $\eta_q(\lambda)\alpha(\lambda)$, and η_m rather than η should be used in calculating the output power (P_P).

Three issues arise from the $\alpha(\lambda)$ data given in [2, 3]. First, the data are not simply the proportion of incident light of a given wavelength (I_0) that is absorbed (I_a), but are actually $\ln(I_0/(I_0 - I_a - I_r))$, where I_r is the light reflected from the sample. Even if this were not the case, the second issue is the assumption that there is a significant rate of photosynthesis at $\lambda > 700$ nm [2, 3]. Emerson and Lewis [5] observed a steep decline in η_q at $\lambda > 685$ nm despite light absorbance at these wavelengths (see Figure 1). This ‘red drop’ reflects the connection in series of two light-driven reaction centres, one of which requires energy equivalent to that of 680 nm photons. While it might be expected that the wavelength-dependence of the rate of photosynthesis should be related to $\alpha(\lambda)$, this need not be the case [5, 6]. Third, $\alpha(\lambda)$ depends on the amounts of the various pigments present in the tissue. While chlorophylls and carotenoids are present in higher plants, the phycocyanin incorporated in $\alpha(\lambda)$ in [2, 3] and other pigments are not, although they are present in some algae and some photosynthetic bacteria. Consequently, $\alpha(\lambda)$ varies between species and with environmental conditions [6, 7].

The theoretical upper limit of η_q is 0.125, although a more usual experimental estimate is 0.092 [8] and Gebhardt [4] suggested that $\eta_m = 0.46$. Taking these two values, η should be less than 0.06, which is consistent with experimental determinations of the efficiency of higher plant growth in full sunlight [9, 10], but is about a third of the value used in [2, 3].

III. THE CONSEQUENCES

The consequence of the wavelength-dependence of η is that the approximations of $\alpha(\lambda)$ [2, 3] should be replaced with approximations of $\eta_q(\lambda)\alpha(\lambda)$. Figure 1 shows $\alpha(\lambda)$ (= I_a/I_0) taken from [7], $\eta_q(\lambda)$ taken from [11] and $\eta_q(\lambda)\alpha(\lambda)$. It is clear that the $\alpha(\lambda)$ shown in [2, 3] and that shown in Figure 1 are quite different. The approximations of $\eta_q(\lambda)\alpha(\lambda)$ obtained in the style employed in [2, 3] are

$$\eta_q a = \begin{cases} -0.1765 + 0.0006356\lambda' & 400 \le \lambda' < 435 \\ 0.2872 - 0.00044\lambda' & 435 \le \lambda' < 541 \\ -0.1975 + 0.000456\lambda' & 541 \le \lambda' < 674 \\ 2.2410 - 0.00316\lambda' & 674 \le \lambda' \le 700 \end{cases}, \qquad (1)$$

where $\lambda' = 10^9 \times \lambda$, which are also shown in Figure 1.

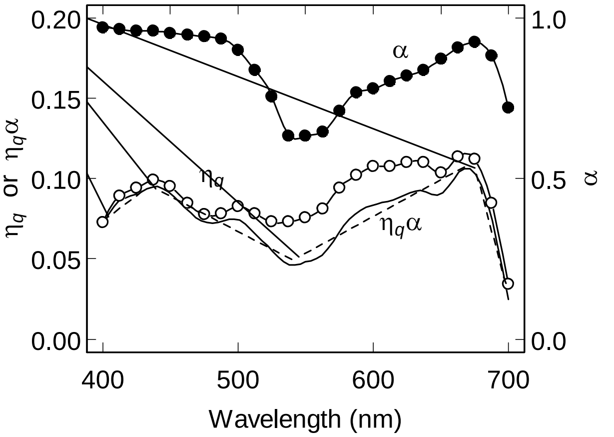

FIGURE 1. The absorbance factor (α, ●) [7] and quantum efficiency (η_q, ○) [11] for *Phaseolus vulgaris* L., and the product ($\eta_q\alpha$, ——) as a function of wavelength. Also shown (– – – –) are the approximations to $\eta_q\alpha$ given in Eq. (1).

The calculations specified in [2, 3] were carried out, replacing $\alpha(\lambda)$ with $\eta_q(\lambda)\alpha(\lambda)$ (Figure 1) in the estimate of input solar energy

$$Q_P = 2\pi hc^2 \int_{\lambda_i}^{\lambda_f} \frac{\eta_q(\lambda)\alpha(\lambda) f \, d\lambda}{\{\exp(hc/\lambda kT) - 1\}\lambda^5}, \qquad (2)$$

where $h = 6.63 \times 10^{-34}$ J s, $c = 3 \times 10^8$ m s^{-1}, $T = 5776$ K, $k = 1.38 \times 10^{-23}$ J K^{-1} and $f = (R_s/d)^2 = (6.96 \times 10^8 \text{ m})^2/(1.5 \times 10^{11} \text{ m})^2 \approx 2.15 \times 10^{-5}$. This necessitated the replacement of η with η_m in the estimate of the output power

$$P_P = \eta_m Q_P, \qquad (3)$$

but the rate of biomass accumulation (M_P) was left unchanged from [3]

$$M_P = 6.45 \times 10^{-8} P_P, \qquad (4)$$

where the constant has units of kg of biomass J^{-1}.

Revised estimates of Q_P, P_P and M_P obtained from (2-4) are given in Table I. Clearly, Q_P is about 10% of that calculated in [3], because $<\eta_q(\lambda)\alpha(\lambda)>$ is small compared with the $<\alpha(\lambda)>$ used in [3]. However, P_P and M_P are about 25% of the corresponding values because $\eta_m/\eta \approx 2.5$.

While the values calculated here are smaller than those in [3], they still represent biologically plausible upper limits on the parameters. For example, the productivity of wetlands can reach 0.19×10^{-6} kg m^{-2} s^{-1} and that of some forests may be as much as 0.26×10^{-6} kg m^{-2} s^{-1} [12].

Comparison of the $\alpha(\lambda)$ and of the $\eta_q(\lambda)$ given in [5, 6, 7, 11] indicates that there is considerable variation between species. From this one might infer that a small number of photosynthetic solar constants might be derived for particular classes of plants, algae and photosynthetic bacteria rather than assuming a single value.

TABLE I. Comparison of the values calculated by Agrawal [3] and the revised values obtained by considering the wavelength-dependence of η_q (Figure 1). In calculating P_P Agrawal [3] assumed that $\eta = 0.2$, but it was assumed that $\eta_m = 0.46$ [4] for the revised values.

Parameter	*Agrawal* [3]	*This work (2-4)*
Q_P (W m^{-2})	350	38
P_P (W m^{-2})	70	17.5
M_P (kg m^{-2} s^{-1})	4.5×10^{-6}	1.1×10^{-6}

IV. CONCLUSIONS

The analysis presented here yields a revised estimate of the photosynthetic solar constant of 17.5 W m^{-2} and a corresponding value for the rate of biomass accumulation. Underlying this revision is a consideration of the physical basis of photosynthesis and the data employed in the calculation.

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