Is Canopy Light Extinction Coefficient a Species – Specific Constant ?

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ABSTRACT. *The validity of the generally accepted and widely used contention that the canopy light extinction coefficient (k) of a given crop species is a constant irrespective of the growing conditions, canopy size or age of the crop was tested for a series of faba bean (Vicia faba L.) crops. The crops were grown under contrasting soil moisture supply regimes (imposed by combinations of differential irrigation and rain – shelters) in order to obtain a wide range of canopy sizes (as measured by Leaf Area Index – LAI –). Continuous measurements of incident solar radiation and its transmission through these canopies throughout the season showed that k did not remain constant either between crops growing under different water regimes or within individual crops during the course of the season. Canopy LAI was identified as a factor related to this variation of k and a significant negative linear relationship between k and LAI was found. It is proposed that this variation of k is of adaptive significance in view of the different light interception requirements of canopies of varying sizes.*

INTRODUCTION

Biomass accumulation of a crop has been shown to be directly proportional to the cumulative intercepted solar radiation (Monteith, 1977; Gallagher and Biscoe, 1978). The amount of incident solar radiation intercepted by a crop stand is determined by the size and the architecture of its foliage canopy. Canopy size can be specified by the Leaf Area Index (LAI). Canopy architecture, which is the spatial arrangement of its foliage elements, can be described quantitatively using two parameters (Campbell and Norman, 1989): the leaf area density distribution function (*i.e.* variation of leaf area per unit canopy volume with canopy height); and the canopy light extinction coefficient.

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Canopy light extinction coefficient (k) is a parameter that describes canopy architecture in terms of light penetration into the canopy.

The penetration of incident solar radiation into a crop canopy of infinitely thin layers of randomly distributed leaves was first quantified by Monsi and Saeki (1953) using a variant of the Beer's Law as;

$$I = I_o e^{-kL} \underline{\hspace{3cm}} (1)$$

where;

I_o = Solar radiation incident at the top of the canopy (MJ m^{-2})

I = Solar radiation transmitted to the soil surface beneath the canopy (MJ m^{-2})

L = Canopy leaf area index

The above relationship implies that the amount of radiation transmitted into the canopy decreases exponentially as it passes through each layer of foliage in the canopy. The extinction coefficient is a quantitative index of this exponential decrease.

The value of k for a given canopy is determined by the following factors (Monteith, 1969):

1.   Leaf angle, *i.e.* the angle at which a foliage element is oriented with respect to the vertical;

2.   Direction of incident solar radiation with respect to the foliage element as determined by the solar elevation and azimuth;

3.   Leaf transmission coefficient which determines the fraction of incident light that passes through the leaf.

Szeicz (1974a) showed that, for average skies and real crops, the effect of solar elevation on the value of k is negligible during the central 6–8 hours of the day when most of the solar radiation is intercepted. The leaf transmission coefficient is determined by the optical properties

of the foliage and is constant for a canopy of uniform colour (Monteith, 1969). Therefore, leaf angle is the major determinant of the value of k of a given crop. Since leaf angle is considered a genetically determined constant, it has been routine to consider k as species – specific constant (Monteith and Unsworth, 1990). It has been used extensively to estimate the amount of solar radiation intercepted under a variety of conditions when LAI and incident solar radiation is known (Gallagher and Biscoe, 1978; Kasim and Dennett, 1986). Even the detailed simulation models of crop photosynthesis (Penning de Vries and van Laar, 1982) do not make allowance for possible changes in canopy structure under different growing conditions or with age.

The objective of the present study is to investigate whether the generally accepted species – specific constancy of k really holds true either throughout the lifespan of a single crop or within the crop growing under contrasting water regimes.

MATERIALS AND METHODS

A field experiment was carried out at the Sonning Experimental Farm of the University of Reading, U.K. (51° 27'N, 0° 57'W) in the summer of 1990 using an indeterminate cultivar (*gobo*) of faba bean (*Vicia faba* L.). The crops were sown on 31 March, 1990 using a tractor – driven seed drill at a seed rate of 100 m^{-2} in 8 m x 6 m field plots. The inter – row spacing was 19 cm and the average intra – row spacing was 6 – 8 cm. The mean density after crop establishment was 58 plants m^{-2}.

Experimental treatments and design

Four contrasting water regimes were imposed on the crops.

W_1 (Wet) treatment

Crops were grown under a non – limiting supply of water. This was achieved by irrigating throughout the duration of the crops at 7 – 10 day intervals through a trickle irrigation system. The irrigations were scheduled to replace periodically the amount of water lost from the crop – soil system through evapo – transpiration.

W_2 (Intermediate) treatment

Crops were irrigated once just after flowering on the 63rd day after sowing (*i.e.* 63 DAS) and sheltered thereafter from rainfall using rain-shelters. The rain-shelters consisted of a metal structure and a transparent white polytene (600 gauge) `roof' which was at a height of 3.3 m. The open sides and the height of the rain-shelter allowed free unhindered circulation of air above the crops. Therefore, except for an 18% quantitative reduction of the incident solar radiation, the presence of the rain-shelter did not modify the microclimate of the sheltered crops.

W_3 (Dry) treatment

Crops were sheltered as early as practically possible and grown unirrigated, thus allowing them to grow on a gradually diminishing storage of soil moisture.

Rain-shelters of the W_2 and W_3 treatments were completed on 62 and 61 DAS respectively. Only 32 mm of rain occurred in 11 small rainfalls between sowing and 61 DAS and (as shown later) this did not cause an appreciable improvement in the soil moisture status of the plots.

W_4 (Open) treatment

Crops were grown unsheltered and without supplementary irrigation, *i.e.* rainfed.

These four water treatments which formed part of a larger series of treatments were laid out in a Randomized Complete Block Design with two replicates.

Except for the differential irrigation and sheltering treatments, all crops were managed identically with recommended practices of fertilization, weed and pest control.

Soil moisture content

Total profile moisture content of all the plots (down to a depth of 1 m) was measured throughout the season at 5 – 8 day intervals using a neutron soil moisture probe (Type 2H3, Didcot Instruments Co. Ltd., U.K.). A quantitative index of the soil moisture status of the different water treatments was defined as:

$$\text{Soil Moisture Deficit (SMD)} = SMC_F - SMC \underline{\hspace{3em}} (2)$$

where,

SMC_F = Soil moisture content at *in situ* field capacity (mm)
SMC = Soil moisture content at a given time (mm)

This was done to counter the substantial inter – plot variation in water holding capacities which was reflected as variation in in situ profile soil moisture contents at saturation.

Leaf area index (LAI)

LAI was measured at 10 – day intervals through sequential growth harvests of ten randomly selected plants. Leaf area was measured by an automatic area measurement system (Mk2, Delta – T Instruments Co. Ltd., U.K.).

Incident and transmitted solar radiation (I_o and I)

Incident solar radiation I_o was measured by a single Kipp Solarimeter installed in the middle of the field above the crops at a height of 3.3 m. Transmitted solar radiation (I) of each individual crop canopy was measured by tube solarimeters (80 cm long) installed in each plot at the ground level beneath the canopies. All solarimeters, which were installed just after emergence of the crops at 20 DAS, were oriented at an angle of 90° and traversed five crop rows. Prior to installation, each tube solarimeter was calibrated against the Kipp Solarimeter during a 7 – day period of clear, sunny weather. All solarimeters were cleaned periodically to prevent the accumulation of dust and dirt.

The electrical output signals from the Kipp and tube solarimeters were recorded and stored in multi-channelled data logger (Campbell CR7, Campbell Scientific Co. Ltd.). The signals were averaged and recorded every 10 seconds and integrated over a period of 30 minutes. The data stored in the logger were down-loaded periodically through a microcomputer.

The daily values of I_o and I were calculated by integrating the respective half-hourly values of Kipp and tube solarimeters over the day length of each day which was calculated by a set of standard meteorological equations.

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Canopy light extinction coefficient (k)

Light extinction coefficients of the two replicated crops under each water treatment were calculated using eq. 1 in two ways:

1) Linear regression

A common k value for each crop was calculated by regressing ln (I/I_o) against LAI. To avoid errors originating from the LAI values, only the respective ln (I/I_o) values on the days when LAI was actually measured were used in the regression. The constancy of the estimated k value of each crop over the season was tested by performing this regression for different lengths of periods. The slopes of the regressions were compared statistically using the method of Snedecor and Cochran (1976). To avoid errors originating from ln (I/I_o) values, measurements at the very early (*i.e.* 20-42 DAS) and late (*i.e.* 111-122 DAS) periods of the crops were omitted.

2) Direct calculation

Daily LAI values were estimated for each crop by fitting polynomial curves to measured LAI data. These were used along with the (I/I_o) values to calculate daily values of k for each crop.

RESULTS

Soil moisture deficit (SMD)

Seasonal variation of total profile soil moisture deficits in one replicate of the different water treatments are shown in Figure 1.

All treatments except W_1 experienced high levels of SMD which reached up to or above 120 mm. Crops under W_3 and W_4 treatments grew under continuously increasing levels of SMD (because of rain-shelters and very little rainfall) whereas the initial increase of SMD in the W_2 crops were reduced once to around 20 mm by the single irrigation on 63 DAS after which the SMD reached high levels similar to W_3 and W_4. In contrast, the maximum SMD reached by the W_1 crops ranged between 45–65 mm which lasted only for a brief period until the next irrigation.

Leaf area index

Crops growing under contrasting levels of SMD as described above developed canopies of varying sizes (Figure 2).

The W_1 treatment showed a faster canopy growth from the outset and achieved a very high maximum LAI of 10 while the W_3 and W_4 crops could achieve a maximum of only 2. The favourable soil moisture conditions following the mid-season irrigation and the indeterminate nature of the W_2 crops enabled them to achieve an intermediate maximum LAI of 5.

Canopy light extinction coefficient (k)

If the generally accepted contention that k remains constant for a given species irrespective of its growing conditions (and hence LAI) is true (Monteith and Unsworth, 1990), the canopies of all the present crops should show a seasonally constant and similar value of k.

Table 1 shows the mean k values for periods of different length for each individual crop estimated through linear regression.
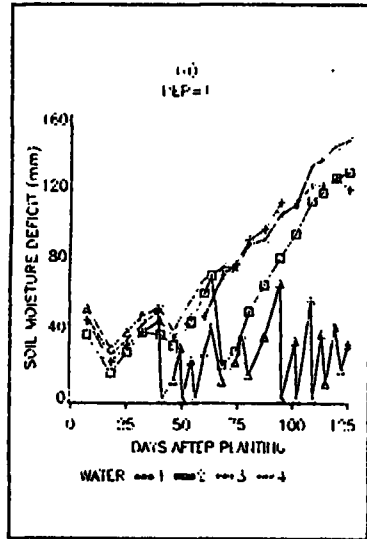
Figure 1.   Seasonal variation of total profile soil moisture deficits in the crops growing under different water treatments (see text for further explanations).
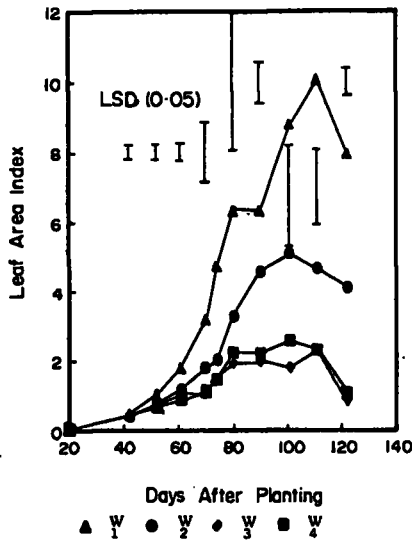

Figure 2.   Seasonal variation of leaf area index in the crops under different water treatments. Each point is the mean of two replicate plots.

Table 1.   Light extinction coefficients crops under different water regimes (estimated over varying durations by regression).

Treatment	Estimated extinction coefficients (k) over different durations from the emergence up to the times indicated below (DAS) (Adjusted R^2)			
	111	90	80	70
$W_1 R_1$	0.24 (0.92)	0.52 (0.97)	0.59 (0.97)	0.71 (0.98)
$W_1 R_2$	0.21 (0.91)	0.40 (0.94)	0.41 (0.92)	0.53 (0.98)
$W_2 R_1$	0.46 (0.92)	0.59 (0.98)	0.63 (0.98)	0.69 (0.99)
$W_2 R_2$	0.42 (0.96)	0.47 (0.97)	0.65 (0.99)	0.56 (0.99)
$W_3 R_1$	0.54 (0.83)	0.72 (0.96)	0.77 (0.95)	0.86 (0.93)
$W_3 R_2$	0.57 (0.96)	0.65 (0.98)	0.66 (0.97)	0.67 (0.95)
$W_4 R_1$	0.75 (0.98)	0.74 (0.98)	0.72 (0.90)	0.73 (0.96)
$W_4 R_2$	0.62 (0.92)	0.75 (0.97)	0.87 (0.99)	0.73 (0.96)

N.B. R_1 = Replicate 1; R_2 = Replicate 2.
All regressions were forced through the origin.

It can be observed clearly that k varied not only between crops under different water treatments but also within each crop when regressions were performed for different durations. These variations were of the order of 0.2 – 0.3 which represented substantial differences in canopy structure.

The variation of estimated daily values of k [Figure 3 (a – d)] again shows the lack of constancy of the k value during the lifespan of a crop.

It should be noted that the estimated k values up to around 45 DAS were prone to substantial error due to several reasons: poor fit of the polynomial LAI curve at this end where LAI < 1; unrepresentative measurements of transmitted radiation because of the low LAI present.

Relationship between k and LAI

One factor which could be related to the above variation of k between crops growing under different water regimes and within crops during the course of the season was the respective LAI. It was observed that the crops which had the lower k values had higher LAI and *vice versa*. A highly significant (p < 0.001) negative linear relationship was found between k and LAI for the present crops (Figure 4).

DISCUSSION

The results of the present study show that the notion that the canopy light extinction coefficient is dependent mainly on leaf angle and thus is a constant for a given species irrespective of LAI is not true for real crops growing in the field. The differential irrigation treatments produced canopies of different LAI mainly through the effects of moisture availability on leaf expansion. If the canopy structure remained constant irrespective of the amount of leaf layers present, a constant value of k would have resulted, both between and within crops under different water regimes.

The negative linear relationship between k and LAI meant that the crops became more `open' with increasing LAI by having leaves at steeper angles (*i.e.* more vertical) thus allowing light penetration into deeper leaf layers. On the other hand, crops growing under increasing
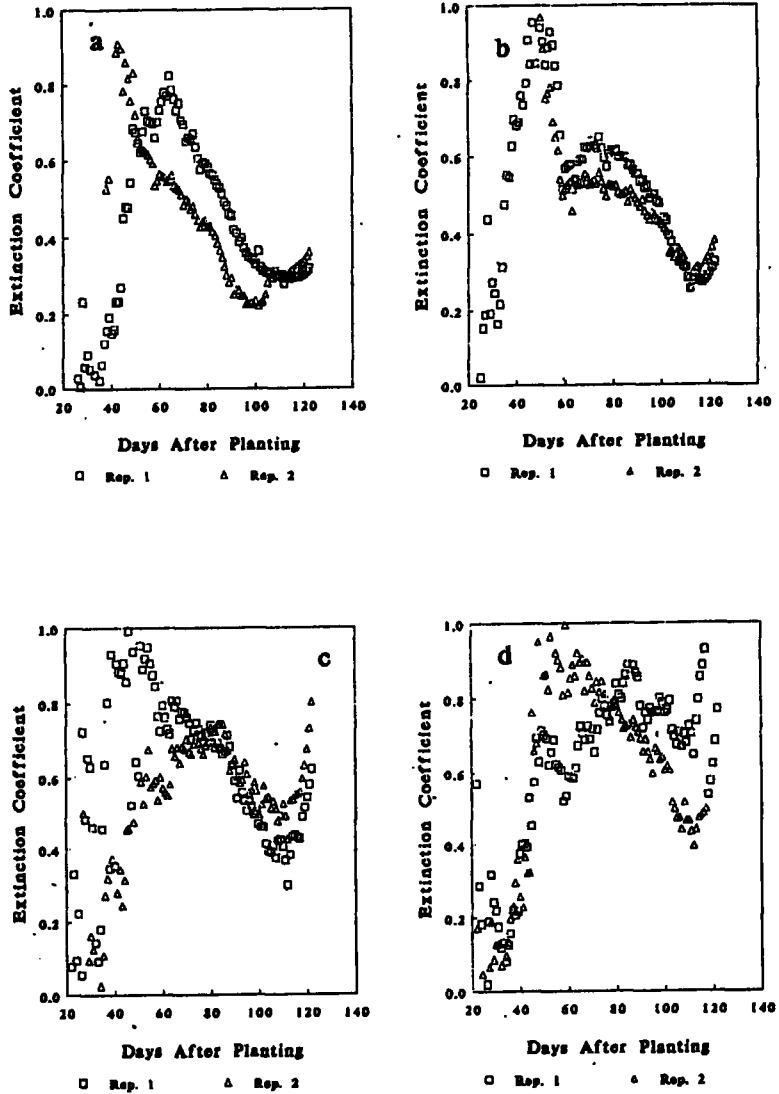
Figure 3. Variation of the canopy light extinction coefficient during the season in crops under different water treatments. (a) 'W1; (b) 'W2; (c) 'W3; (d) 'W4. The extinction coefficient values were calculated using measured values of daily radiation transmission and daily canopy area indices estimated by fitting polynomials to the measured seasonal patterns of LAI.
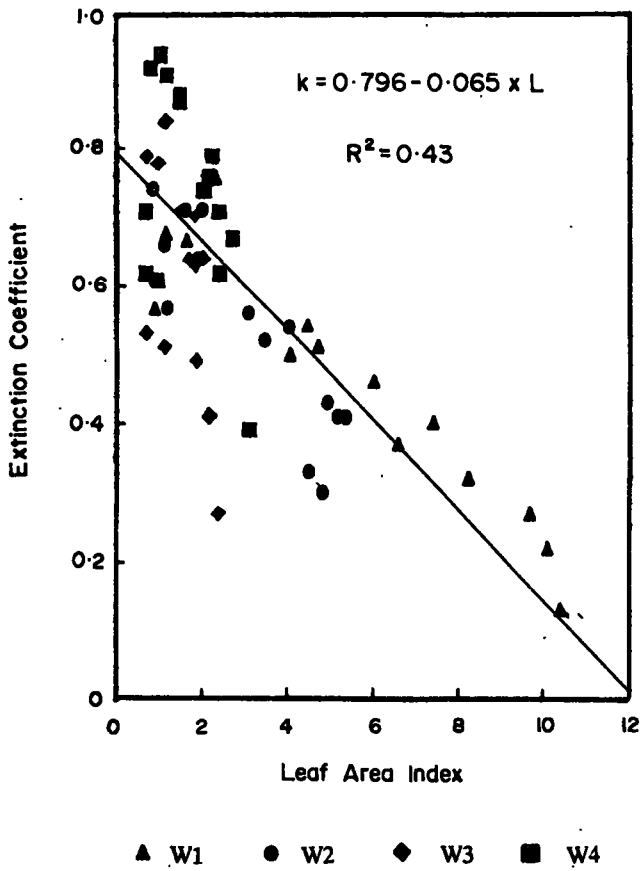
Figure 4. Relationship between the canopy light extinction coefficient
(k) and canopy leaf area index (L) in the different water
tratments.   Each point of k is based on daily totals of
incident and transmitted total solar radiation measured by
tube solarimters and LAI values measured from sequential
growth harvests.

moisture stress could achieve only a limited leaf area which was oriented more horizontally in order to maximize the amount of light intercepted. Both these phenomena are of adaptive significance in the respective conditions under which the crops were growing. Monteith and Elston (1983) postulated that a certain amount of light above a minimum threshold has to penetrate the lower leaf layers of a large canopy for these leaves to be productive and survive senescence. This purpose is achieved by having a more vertical leaf orientation (*i.e.* lower k). More importantly, a lower k at high LAI allows a more uniform distribution of light within the large canopy thus reducing the possibility of leaves being light saturated. On the other hand, for a water stressed crop having a smaller canopy, maximum interception of incident light would be a greater priority and this is achieved by a higher k through more horizontal leaves. This difference in leaf orientation could be observed visually in the field.

The same principle applies within a single crop during the course of the season [Figure 3 (a–d)], with k decreasing from a high value during the period of LAI increase and then increasing during LAI decrease due to senescence.

Results showing similar trends have been obtained by Hayashi and Ito (1962) for a series of rice varieties and by Monteith and Elston (1983) for a range of crops including *Vicia faba*. In both the above works, a negative linear relationship was shown between maximum LAI achieved and mean seasonal k estimated through regression. Evidence available from density experiments on non–water stressed *Vicia faba* crops (Stutzel and Aufhammer, 1991) in which lower k values were observed under higher densities (*i.e.* at higher LAI) also supports the argument proposed in the present paper. Moreover, both Szeicz (1974b) and Fasheun and Dennett (1982) showed, for well–irrigated crops of *Vicia faba*, that k decreased during the season as LAI increased.

CONCLUSION

The results of the present experiment and the supporting evidence given above in the discussion show strong evidence that taking the canopy light extinction coefficient as a species–specific constant under all conditions (*i.e.* different agronomic treatments, different times of the

season *etc.*) could introduce significant errors into calculations of light interception and, consequently, of biomass production.

ACKNOWLEDGEMENTS

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