

Spectral estimates of the absorbed photosynthetically active radiation and light-use efficiency of a winter wheat crop subjected to nitrogen and water deficiencies†

S. STEINMETZ, M. GUERIF, R. DELECOLLE and F. BARET

Institut National de la Recherche Agronomique (INRA),
Station de Bioclimatologie, BP 91, 84140 Montfavet, France

Abstract. A linear regression equation is found relating the photosynthetically active radiation intercepted by the canopy (PAR_i), measured with hemispherical photographs, and both the normalized difference ND and the ratio NIR/R vegetation indices. On the basis of this equation, NIR/R is used to estimate PAR_i during the crop cycle. The efficiency with which the PAR absorbed by the crop is transformed into biomass (ϵ_c) is calculated for three phenological phases of the crop. Nitrogen fertilization is the main factor affecting light interception. At the booting stage, PAR_i is about 15 per cent greater for treatments with higher nitrogen levels. ϵ_c is influenced by both nitrogen and irrigation levels, and varies with the phenological phases of the crop. For the irrigated plots, ϵ_c is higher in the period going from anthesis to soft dough and not in the period from stem elongation to anthesis as most published results indicate. Water stress is the main factor affecting ϵ_c . The greatest reductions of ϵ_c are observed on plots with higher biomass levels when water shortage starts. The results suggest the need for a water stress index for biomass estimations of rain-fed crops in regions susceptible to drought. This would require knowledge of ϵ_c for the crop grown under non-limiting conditions.

1. Introduction

Estimation of cereal-crop production is considered as a priority in most research programmes. Solar radiation and water are two of the most important environmental factors affecting biomass production and final grain yield.

According to Monteith (1972), the mechanism by which the solar radiation intercepted by a crop is transformed into dry matter can be written as:

$$DM = \int_t \epsilon_s \epsilon_i \epsilon_c S dt \quad (1)$$

where DM is dry-matter production (in $g m^{-2}$); t is the time period, ϵ_s is the fraction of photosynthetically active radiation (PAR) of the solar radiation, ϵ_i is the fraction of the incident light intercepted by the canopy (interception efficiency), ϵ_c is the efficiency with which solar energy is converted into dry matter (light-use efficiency) (in $g MJ^{-1}$) and S is the global solar radiation (in $MJ m^{-2} day^{-1}$).

The PAR fraction of solar radiation ϵ_s has been found to be nearly constant and nearly independent of atmospheric conditions (Seicz 1974, Varlet-Grancher *et al.* 1982).

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Several studies have shown that the amount ϵ_i of solar radiation intercepted by a crop canopy can be estimated by vegetation indices based on the crop spectral reflectance in the red (R) and near-infrared (NIR) wavelengths, which can be obtained from remote sensing techniques (Kumar and Monteith 1981, Daughtry *et al.* 1983, Baret *et al.* 1989). A good estimate of ϵ_i from spectral data will depend on the crop parameters linked to light penetration into the canopy and on the capability of the spectral data to characterize the evolution of the crop structural and physiological changes during the season. Chlorophyll concentration, water content, senescence and environmental stresses such as nutrient deficiencies and toxicities are some of the factors affecting leaf reflectance (Gausman *et al.* 1978, Guyot 1989).

Spectral discrimination of nitrogen and/or irrigation treatments has been reported by Kleman and Fagerlund (1981, 1987) on barley, by Jackson *et al.* (1980) on sugarcane and by Stanhill *et al.* (1972) and Hinzman *et al.* (1986) on wheat. Wiegand *et al.* (1986) suggested that canopy reflectance may be a more accurate monitor of the crop photosynthetic capacity than leaf area index, mainly during crop senescence, since the spectral indices can respond to non-leaf photosynthetically active organs, such as heads and sheaths of cereals.

The efficiency of PAR absorbed that is converted to dry matter ϵ_c can also be affected by nitrogen fertilization and water stress. Gallagher and Biscoe (1978) found that, for a wheat crop, nitrogen increased the mean seasonal ϵ_c from 2.8 to 3.1 g MJ⁻¹. Similar results were reported by Green (1987). Monteith and Elston (1983) suggested that ϵ_c may be insensitive to temperature, water stress and nitrogen fertilization during the vegetative growth period. Contrasting results were found by other authors, indicating that responses of ϵ_c to the environmental stresses depend on the phenological stage of the crop (Asrar *et al.* 1984, Oliso 1987, Garcia *et al.* 1988).

Water deficit has been found to affect ϵ_i more than ϵ_c when plants were stressed from the beginning of the cycle (Legg *et al.* 1979). However, ϵ_c was more affected than ϵ_i when water deficit increased rapidly and, in particular, on well-developed canopies (Muchow 1985). Asrar *et al.* (1985) combined multispectral reflectance and a crop-temperature-based water-stress indicator to estimate above-ground dry-matter production and found good correlations between measured and estimated results.

Results presented in this paper are part of a two-year global study involving satellites images (SPOT), aircraft and micrometeorological measurements. Some data have already been published by Guerif *et al.* (1988). The main objectives of this study are to estimate the efficiency ϵ_i of PAR interception from spectral reflectance data and to evaluate the influence of nitrogen fertilization and irrigation treatments on ϵ_i and on the efficiency ϵ_c with which the intercepted PAR radiation is converted into dry matter.

2. Materials and methods

2.1. Site, experimental procedure and rainfall distribution

The experiment was carried out in a private farm, in the Crau region (Moulès), in south-east France, in the 1987/88 crop season. The soil is shallow and stony, having a hardened stony calcarious horizon at 50–55 cm depth. In the first 30 cm the soil texture is classified as sandy-clay-loam. The bright stones correspond to about 50 per cent of the total soil volume. The site was chosen to increase the probability of water stress.

The experimental procedure consisted of four treatments (two nitrogen fertilization and two irrigation levels) with two replicates (table 1). The eight plots of

Table 1. Nitrogen-fertilization and irrigation treatments

Growth period	Nitrogen (kg ha ⁻¹)				Irrigation			
	Date	S Temp (°C)‡	N1	N2	II			I2
					Date	S Temp (°C)‡	I2	
Sowing	10 November	0	30	30	27 March	1205	No irrigation	
Tilling	27 January	678	40	0	6 May	1729		
Stem elongation	7 March	975	100	70	29 May	2129		
Booting	28 April	1604	70†	70†	7 June	2292		

†N fertilization for improving grain quality.

‡S Temp = sum of temperature (>0°C) from sowing.

20 m × 20 m were located in the middle of a 3.5 ha wheat field. Because of the peculiarities of the experimental area, no particular statistical design was used. The experimental plots were disposed in order to facilitate irrigation and mechanical applications of nitrogen.

Flooding is the irrigation system used in the region, and water is scheduled to be available, systematically, every eight days, starting in March. Irrigations out of the schedule will depend on water availability.

A durum winter wheat (variety Arcour) was sown on 10 November, 1987 with a 18 cm space between rows. Plant density was about 360 plants m⁻². The fertilization at sowing was the same (30:100:70) for all treatments. Post-emergence herbicides were used to control weeds.

Total rainfall was 427 mm from sowing to harvest. Most of this rainfall (257 mm) occurred until the end of January and during April until mid-May. A low amount of rainfall occurred during February and March, causing a moderate but long water-deficit period for all treatments. A second and more severe water stress took place from anthesis until the end of the grain-filling period. The first period of water stress was defined according to rainfall distribution, visual evaluation of the plant response to water deficit and soil tensiometers. The second water-stress period was characterized by the Stress Degree Day (SDD), as proposed by Jackson *et al.* (1977), which is based on the difference between crop and air temperatures.

2.2. Measurements and data processing

2.2.1. Biological measurements

Five samples per plot of the above-ground biomass (0.5 m of three adjacent rows) were taken every 15 days before the beginning of stem elongation and once a week afterwards. Samples were oven-dried at 105°C during 24 h for determination of dry matter.

The evolution of the crop growth with time will be expressed as a function of the accumulated sum of temperature (base 0°C) from sowing (Russelle *et al.* 1984).

2.2.2. Spectral reflectance

The spectral reflectance in the red (610–680 nm) and near-infrared (790–890 nm) wavelengths was measured with a SPOT satellite simulation CIMEL radiometer (Guyot *et al.* 1984). The radiometer was mounted on a support 2.5 m high, vertically oriented, viewing a circle 0.52 m in diameter. The radiometer was calibrated using a reference panel painted with barium sulphate with known reflectance properties. Ten radiometric readings were taken in each plot for 16 different dates covering the entire cycle of the crop. Measurements were done around solar noon on clear or nearly clear sky conditions.

Based on the red (R) and near-infrared (NIR) spectral reflectance, the normalized difference (ND) and the ratio NIR/R vegetation indices were calculated. Despite their different uses, according to particular applications, these indices can be considered as equivalent (Wiegand and Richardson 1982, Perry and Lautenschlager 1984).

2.2.3. PAR interception

Estimates of intercepted radiation using hemispherical photographs have been done by several authors (Bonhomme and Chartier 1972, Ducrey 1975 a, b). Their studies used a 'fish-eye' lens placed under the crop and/or forest, viewing upwards. This procedure is not adequate for agricultural crops during early stages of develop-

ment. An adaptation of this method, in which hemispherical photographs are taken about 10 cm over the canopy, looking downwards, was proposed by Baret *et al.* (1989). Their method was used in this study to estimate the amount of PAR intercepted by a wheat canopy. Since details of the method are given by Baret *et al.*, only the most relevant aspects will be presented in this paper.

A Nikkor fish-eye lens (7.5 mm focal length) equipped with a filter to cut out wavelengths less than 600 nm and infrared colour film (Ektachrome 2236) were used. Twelve pictures (six in the rows and six between rows) for each treatment were taken on five dates from emergence to heading. In order to avoid shadows, which make it difficult to distinguish soil surface from shadows of plants (Oliosio 1987), pictures were taken on completely covered days or protected by a beach umbrella on clear days.

Photographs were digitized using a CCD camera equipped with filters that allowed both red and infrared images to be obtained. From these images, a threshold (visually estimated) is used to separate green vegetation from the other elements (soil and non-green vegetation). The output of the digitizing process is a matrix of 36×9 (36 azimuthal and 9 zenithal angle classes of 10° each) coefficients of directional interception. An average interception coefficient is obtained for each date from the 12 pictures taken for each treatment.

The directional interceptions measured by this method were transformed into a daily average $\bar{\epsilon}_i$, neglecting the diffuse radiation and assuring that incident solar radiation is proportional to the cosine of the zenithal solar angle:

$$\bar{\epsilon}_i = \frac{\sum_{\text{dawn}}^{\text{noon}} \epsilon_i(\theta_s) \cos \theta_s}{\sum_{\text{dawn}}^{\text{noon}} \cos \theta_s} \quad (2)$$

where $\bar{\epsilon}_i$ is the integrated daily value of ϵ_i , θ_s is the zenithal solar angle, 'dawn' is the onset of solar elevation, 'noon' is solar noon. Daily solar radiation S was taken from the meteorological station of INRA/Montfavet. The daily amount of PAR absorbed by the crop was calculated as

$$\text{PAR}_a = \bar{\epsilon}_i \epsilon_s S \quad (3)$$

A constant value of 0.50 was used for ϵ_s (Seicz 1974). According to Oliosio (1987) and Baret *et al.* (1989), the amount of PAR intercepted by the crop can be considered as PAR absorbed, since 94 per cent of the radiation intercepted was effectively absorbed by the green leaves of the canopy.

A ϵ_c coefficient was calculated for three phenological stages of the crop using the ratio between the above-ground biomass produced and the cumulative PAR absorbed by the crop in each phenological stage. A mean seasonal ϵ_c was calculated following the same principle but using both biomass produced and PAR absorbed for the entire cycle.

3. Results and discussion

3.1. Estimates of PAR interception $\bar{\epsilon}_i$ from spectral measurements

3.1.1. Evolution of the spectral reflectance during crop cycle

The spectral-reflectance NIR/R vegetation index clearly indicated the canopy changes caused by nitrogen fertilization and irrigation treatments (figure 1). Treatments with higher nitrogen levels showed a NIR/R greater than those with lower nitrogen fertilization during most of the cycle, agreeing with published results (Stanhill *et al.* 1972, Hinzman *et al.* 1986). However, when a severe water stress

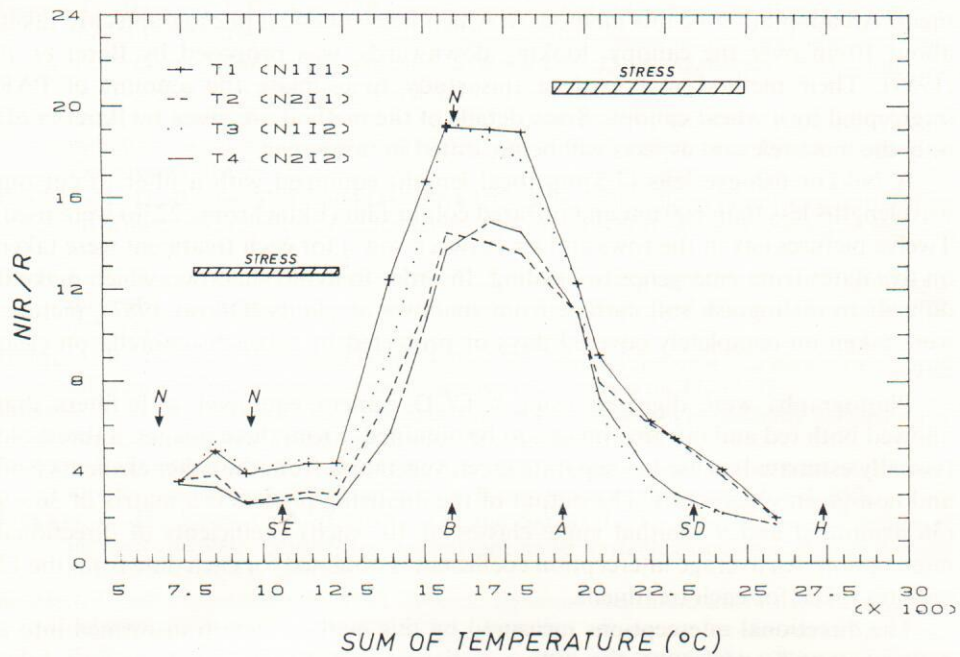


Fig. 1. Evolution of the NIR/R vegetation index during the crop cycle for the four treatments. N= nitrogen application; SE= stem elongation; B= booting; A= anthesis; SD= soft dough; H= harvesting; stress= period of water stress.

occurred, after anthesis, NIR/R decreased more dramatically for plots with higher fertilization levels. This behaviour can be attributed to a greater decrease in the green-leaf area index, observed for plots with higher biomass levels, probably because of their greater water demand. Changes in the canopy geometry, due to water stress, possibly also had some influence on the crop reflectance (Jackson and Ezra 1985).

3.1.2. Relationship between \bar{e}_i and NIR/R

A linear regression equation was found between the ratio NIR/R and the daily average of PAR interception \bar{e}_i estimated with hemispherical photographs (figure 2):

$$\bar{e}_i = (0.0294 \text{ NIR/R}) + 0.3669 \quad (R^2 = 0.90) \quad (4)$$

This equation considered only measurements done before heading. Linear interpolations were used to obtain daily values of \bar{e}_i during the crop cycle. A straight line was also obtained with the normalized difference ND, but the NIR/R ratio was chosen due to its better correlation with measurements of PAR intercepted. The straight-line relationship between NIR/R and PAR_i found in this study does not agree with the non-linear relationship for corn (Gallo *et al.* 1985) and for wheat (Ajai *et al.* 1984). The relatively small number of data points used for the regression equation and the relatively low maximum green LAI (between 3 and 4.5) for three of the four treatments are probably the main reasons for these contrasting results.

It seems that the low green LAI and the relatively dry stony-soil background at

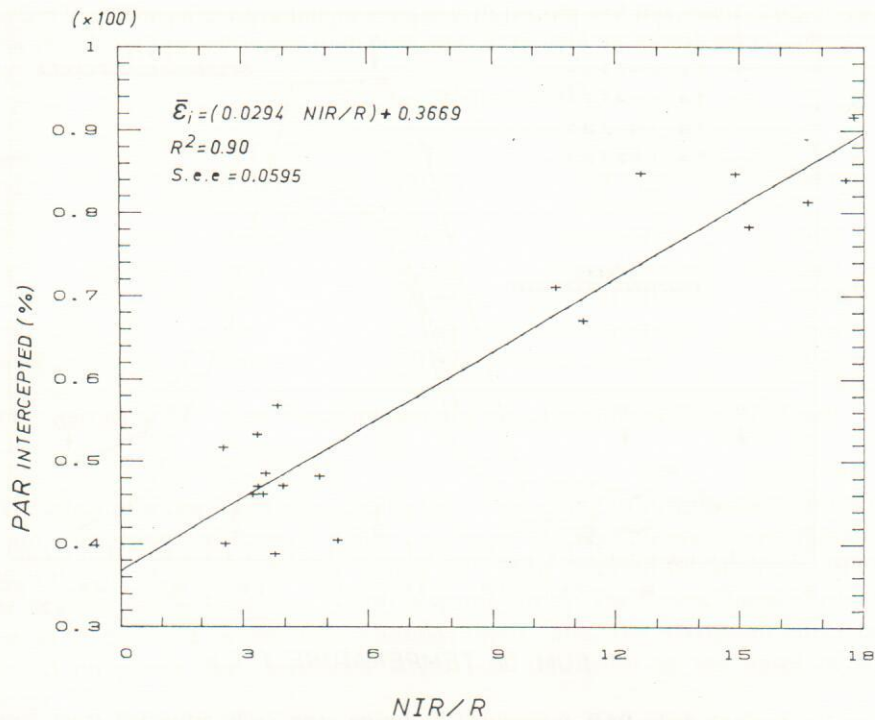


Figure 2. Regression line between average daily values of PAR intercepted $\bar{\epsilon}_i$ measured with hemispherical photographs, and the NIR/R vegetation index.

the beginning of the cycle contributed in keeping the NIR/R ratio at low levels (Huete *et al.* 1985), resulting in a relatively low slope of the regression equation.

It is assumed that no great error is incurred by not forcing the line between NIR/R and $\bar{\epsilon}_i$ to pass through the origin. The reason is that all NIR/R data used to estimate $\bar{\epsilon}_i$ are included in the range of the regression equation.

3.1.3. Estimates of $\bar{\epsilon}_i$ from spectral data

PAR interception during crop cycle (figure 3) was estimated as a function of the NIR/R vegetation index using equation (4). A coherent pattern of PAR intercepted radiation was obtained. Maximum $\bar{\epsilon}_i$ values were similar to those found by other authors (Hippis *et al.* 1983, Hatfield *et al.* 1984, Olioso 1987).

Although a moderate water stress occurred at the beginning of the cycle, nitrogen fertilization was the main factor to influence light interception. At booting stage about 15 per cent more light was intercepted by the two treatments having higher nitrogen levels.

It should be noted that at the soft-dough stage, when the green LAI was close to zero, around 40–50 per cent of PAR energy was estimated to be intercepted by the canopy. High values of $\bar{\epsilon}_i$ during the senescent period were reported by Hatfield *et al.* (1984) and Gallo *et al.* (1985), which is attributed to the interception of PAR radiation by non-green vegetation.

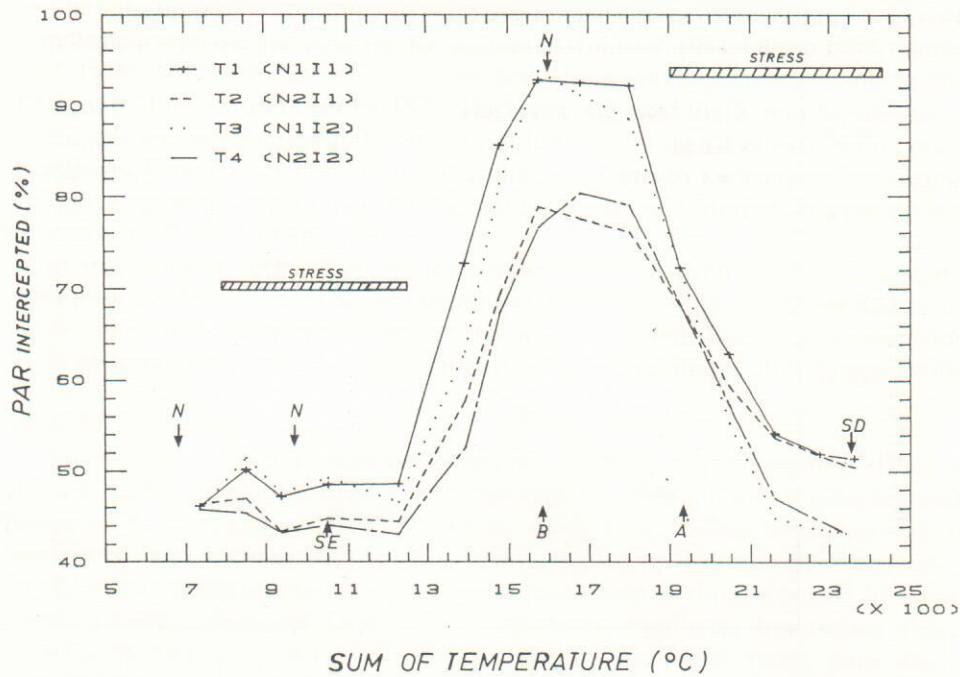


Figure 3. Average daily PAR intercepted $\bar{\epsilon}_i$ during crop cycle estimated from spectral reflectance NIR/R data. N=nitrogen application; SE=stem elongation; B=booting; A=anthesis; SD=soft dough; stress=period of water stress.

3.2. Efficiency ϵ_c of PAR conversion to dry matter

3.2.1. Estimates of ϵ_c during crop phenological phases

The data of table 2 and figure 4 show the clear effect of the crop growth period on ϵ_c . For all treatments, excluding treatment 3, higher values of ϵ_c were found during the growth period going from anthesis to soft dough. These data do not agree with those in most of the literature, which indicate that maximum ϵ_c values were obtained in the period before heading or anthesis (Gallagher and Biscoe 1978, Green 1987, Garcia *et al.* 1988). However, Green (1987) reported that in one experiment with winter wheat the mean seasonal ϵ_c was greater than ϵ_c during the vegetative growth period. He suggested that this behaviour was caused by a poor establishment and low vigour of the crop, causing a greater sink-induced promotion of photosynthesis during the post-anthesis growth period. A similar explanation seems to apply to results reported here. One of the reasons is probably related to the occurrence of a moderate water deficiency around the stem elongation period prior to the first irrigation on 27 March and 25 mm of rainfall on 30 March. It seems that a disease incidence (rust) that was controlled only after some delay could also have contributed to the decrease of ϵ_c from stem elongation to anthesis. A third possible reason could be related to errors in estimating ϵ_i during this period by using equation (4), which was established for the period prior to anthesis. The decrease of PAR interception during senescence is lower than the decrease of the green LAI, since part of the PAR radiation is absorbed by non-green vegetation (Hatfield *et al.* 1984). On this basis an underestimate of PAR absorbed, with a consequent overestimate of ϵ_c , would be expected.

Table 2. Evolution of ϵ_c according to crop-growth periods and treatments. Data in parentheses are relative to ϵ_c calculated from plant emergence until the growth period considered.

Growth period †	Slope ϵ_c (g MJ ⁻¹)			
	T1 (N1 I1)	T2 (N2 I1)	T3 (N1 I2)	T4 (N2 I2)
E-SE	0.68	0.49	0.60	0.52
SE-A	2.34 (1.81)	2.23 (1.64)	2.26 (1.71)	2.05 (1.53)
A-SD seasonal	2.81 (2.09)	2.83 (1.99)	1.63 (1.69)	2.49 (1.80)

† E=emergence; SE=stem elongation (ear at 1 cm); A=anthesis; SD=soft dough.

The effect of water stress on ϵ_c during the period going from anthesis to soft dough was more severe for treatment 3, which had higher levels of biomass than treatment 4 when water stress started. Similar results have been reported by Muchow (1985) in grain legumes and by Legg *et al.* (1979) in spring barley. The latter found a reduction of up to 11 per cent in the daily photosynthesis rates, the maximum effect being observed on plants that developed larger leaf area prior to the onset of water shortage.

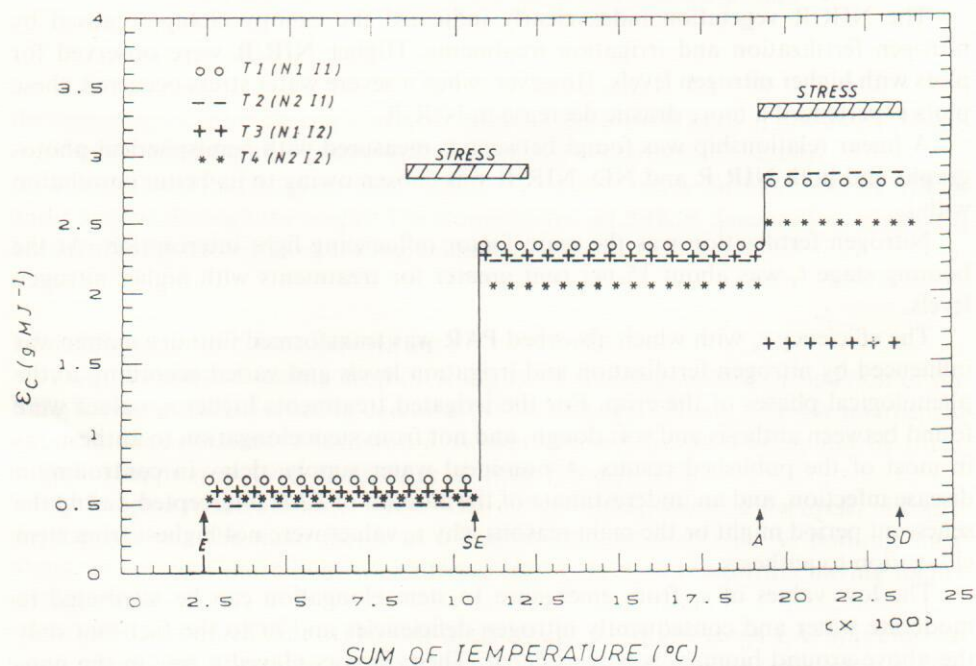


Figure 4. Evolution of ϵ_c for the four treatments during three phenological phases of the crop. E=emergence; SE=stem elongation; A=anthesis; SD=soft dough; stress=period of water stress.

The variations of ϵ_c according to plant phenological stages and with treatment are in agreement with the findings of other authors (Asrar *et al.* 1984, Olioso 1987, Garcia *et al.* 1988). However, they do not agree with the results of Gallagher and Biscoe (1978) and Monteith and Elston (1983). The latter suggested that ϵ_c may be insensitive to temperature, water stress and nitrogen fertilization during the growth period prior to anthesis. Garcia *et al.* (1988) suggested that variations in the temperature regime could be part of the explanation for the distinct values of ϵ_c during the crop phases prior to anthesis in the United States.

In this study it seems that the low values observed from emergence to stem elongation can be attributed to the limited water supply during this period and/or to the fact that only above-ground dry matter was considered. Roots can account for 30–35 per cent of the total plant dry matter (Gallagher and Biscoe 1978, Green 1987).

3.2.2. Mean seasonal estimates of ϵ_c

An analysis of the mean seasonal values of ϵ_c indicates that nitrogen fertilization affected ϵ_c , but to a lesser degree than reported by other authors (Gallagher and Biscoe 1978, Garcia *et al.* 1988). However, much lower values were obtained in treatments 3 and 4, indicating the water-deficit effect on ϵ_c . The seasonal values of ϵ_c for the irrigated treatments were of the same magnitude as those reported by Baret (1986), Olioso (1987) and Green (1987). However, they were lower than those reported by Garcia *et al.* (1988). The ϵ_c values under water stress, particularly specially that of treatment 3, were much lower than most of the data cited in the literature.

4. Summary and conclusions

The NIR/R vegetation index clearly indicated the canopy changes caused by nitrogen fertilization and irrigation treatments. Higher NIR/R were observed for plots with higher nitrogen levels. However, when a severe water stress occurred, these plots experienced a more drastic decrease in NIR/R.

A linear relationship was found between $\bar{\epsilon}_i$ measured with hemispherical photographs and both NIR/R and ND. NIR/R was chosen owing to its better correlation with $\bar{\epsilon}_i$.

Nitrogen fertilization was the main factor influencing light interception. At the booting stage $\bar{\epsilon}_i$ was about 15 per cent greater for treatments with higher nitrogen levels.

The efficiency ϵ_c with which absorbed PAR was transformed into dry matter was influenced by nitrogen-fertilization and irrigation levels and varied according to the phenological phases of the crop. For the irrigated treatments higher ϵ_c values were found between anthesis and soft dough, and not from stem elongation to anthesis, as in most of the published results. A non-ideal water supply, delay in controlling a disease infection, and an underestimate of the amount of PAR intercepted during the senescent period might be the main reasons why ϵ_c values were not highest from stem elongation to anthesis.

The low values of ϵ_c from emergence to stem elongation can be attributed to moderate water and consequently nitrogen deficiencies and/or to the fact that only the above-ground biomass was considered. These factors played a role in the non-constancy of ϵ_c from emergence to anthesis as found in some studies, particularly in the United Kingdom.

The mean seasonal ϵ_c was more affected by water stress than by nitrogen levels. A

much greater reduction of ε_c was observed for treatment 3, which had a higher biomass level prior to the onset of the water-stress period.

The strong effect of water stress on ε_c suggests the use of an index accounting for the negative effect of limiting water conditions on crop production. The use of such an index, which implies knowledge of ε_c for crops grown under non-limiting conditions, seems to be indispensable for estimating biomass production of rainfed crops in regions where water stress can seriously affect cereal-crop production.

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