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Solar radiation and productivity in India — I : Potential productivity

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सार — पौधों की सौर ऊर्जा भण्डारण करने की क्षमता शुष्क पदार्थ उत्पादन की निर्भरता को बताने वाले सात कारकों के उत्पादन/परिणाम के रूप में निर्धारित व वर्णित की गई है। यह निर्भरता, वायुमण्डल के अक्षांश और ऋतु, मेघाच्छादितता, एयरोसोल जैसे तत्वों, विकिरण की मानावलीय संरचना, प्रकाश-रसायनी प्रक्रिया की प्रमात्रा की आवश्यकता पत्ता क्षेत्र सूचकांक तथा पत्र व्यवस्था, छतरी में कार्बनडाइआक्साइड की सांद्रता व पत्तों के विसरण प्रतिरोध और श्वसनक्रिया में प्रयुक्त स्वांगीकारको के एक भाग पर होती है।

भारत में 8° से 30° अक्षांश के मध्य बोई जाने वाली विभिन्न फसलों की विभव तथा कुल शुष्क पदार्थ उत्पादकता यह दर्शाती है कि विकिरण अपरोधन, विसरण तथा श्वसन की क्षमताएं पर्यावरणीय दबाव उपलब्ध कराती हैं। ये कार्यक्षमताएं पर्णसमूह घनत्व के वितरण तथा पर्णसमूह घनत्व के आनति सूचकांक के रूप में फसलों की छतरी संरचना से प्रभावित होती है।

ABSTRACT The efficiency with which the plants store solar energy was determined and expressed as the product of seven factors describing the dependence of dry matter production on latitude and season, cloudiness and aerosol contents of the atmosphere, on the spectral composition of the radiation, on the quantum need of the photochemical process, on leaf area index and leaf arrangement, on the concentration of carbondioxide in the canopy and diffusion resistance of leaves, and on the fraction of the assimilates used in respiration.

The potential and net dry matter productivity of different crops grown between 8 and 30° latitudes in India shows that the efficiencies of radiation interception, diffusion and respiration provide the environmental constraints. These efficiencies are also influenced by the canopy architecture of crops in terms of the distribution of foliage densities and inclination index of foliage densities.

1. Introduction

Conventional estimates of efficiency in terms of the amount of solar radiation incident at the earth's surface provide ecologists and agronomists with a method for comparing plant productivity under different systems of land use and management in different climates. Interaction of various components of efficiencies of dry matter production determines the growth rate which is influenced by the physical and biological factors. Therefore, it is very essential to estimate the potential dry matter productivity of crops under limited and unlimited supply of inputs to enlighten the constraints in growth rates. Monteith's (1972) concept of determining various components of efficiencies have been utilised in this paper.

2. Components of efficiency

Monteith (1972) defined efficiency (E) with which crops produce dry matter as the ratio of the net amount of solar energy stored by photosynthesis to the solar constant integrated over the same period. This efficiency was expressed as a product of following 7 factors as : $E=E_g\ E_a\ E_s\ E_q\ E_i\ E_d\ E_r$.

2.1. *The geometric factor* (E_g)

It was defined as the ratio of the radiant energy received outside the atmosphere on a plane parallel to earth surface to the solar constant integrated over the same period to account for the geometry of earth with respect to the sun. Variation in E_g values was quite high between 10° and 40°N latitudes throughout the year, however, the average value was 0.2726 ± 0.0079 having a small biannual oscillation (Fig. 1).

2.2. *Atmospheric transmission factor* (E_a)

This factor was calculated by the ratio of the solar energy received at the earth's surface on clear days and extra terrestrial radiation on a horizontal surface. Fig. 2 shows that attenuation caused by the atmospheric transmission with an average transmissivity over the region is 0.5949 ± 0.4099.

2.3. *The spectral factor* (E_s)

The fraction of solar spectrum absorbed by the green leaves will represent the spectral efficiency. The process

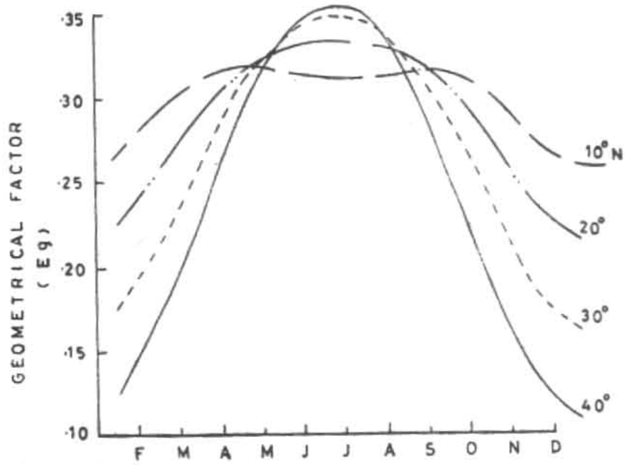

Fig. 1. Variation of geometrical factor with latitude

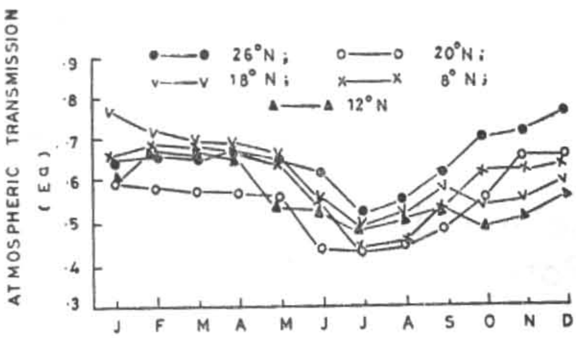

Fig. 2. Variation of atmospheric transmission with latitude

of photosynthesis in green leaves needs the absorbed radiant energy in the wave length from 0.4 to 0.7 μm (PAR). PAR can be estimated from the solar radiation data with the help of conversion factor which are reported to increase from 0.40 at 5° solar elevation to 0.59 at 70° solar elevation and further it also varies with cloudiness having values of 0.68 on clear days and decreases to 0.48 on cloudy days (Ross 1976). Ross (1976) recommended the conversion factor of 0.42 for direct solar radiation, 0.60 for diffuse solar radiation and 0.52 for total solar radiation for micrometeorological calculations. Szeicz (1970) found the average value of the conversion factor about 0.49 with a minimum of 0.48 in the spring to a maximum of 0.51 in winter for the total solar radiation. The absorption of PAR also varies from 50 to 90 per cent in different parts of visible spectrum due to chlorophyll and other pigments in green vegetations. On the average absorption in PAR is about 85 per cent.

The fraction of radiation spectrum absorbed by green leaves is, therefore, about $0.5 \times 0.85 = 0.425$.

2.4. *Photochemical efficiency* (E_q)

When PAR is absorbed by cells containing chloroplasts, the efficiency of photosynthesis is the ratio of energy stored in the formation of carbohydrates to the absorbed radiant energy. Monteith (1972) reported that only 20 per cent of the absorbed energy is stored in the final products of photochemical system and remaining is rejected in the form of heat or used in formation of higher compounds such as proteins and fats. Hill (1970) reported that the formation of one molecule of carbohydrate needs one molecule of CO_2 and the energy of nearly 10 light quanta. Therefore, the photochemical efficiency being the ratio of amount of heat stored in one molecule to the total energy content in 10 light quanta is about 0.215.

Dry matter production rate of 16.7 k J gm^{-1} for herbaceous species (Westlake 1963), 20 k J gm^{-1} for woody plants (Leith 1968) and 18-20 k J gm^{-1} for grasses (Wiegert & Evans 1964) have been reported. Therefore, adopting a figure of 16.7 k J gm^{-1}, the maximum rate or potential dry matter productivity rate (P) is $\frac{I\, E_s\, E_q}{16.7}$ gm per k J of solar radiation where I is solar radiation at the earth surface. Substituting the values of the parameters $P = 19.69\, I$ gm m^{-2} h^{-1}.

Table 1 presents the gross photosynthess rate with the assumption that there is no diffusion of CO_2 molecules in chloroplasts, radiation is fully intercepted by the vegetation and losses due to respiration are negligible. This maximum photosynthetic efficiency is a theortical limits achieved in principle only when the irradiance and the gross rate of photosynthesis are very small.

2.5. *Interception efficiency* (E_i)

The interception efficiency is the ratio of the actual rate of gross photosynthesis to the maximum rate estimated for a stand of identical plants with enough leaves to intercept all the incident light. Photosynthesis rate of a crop canopy cannot be strictly proportional to the fraction of intercepted radiation unless all the leaves are working at the same photochemical efficiency. This ideal situation cannot be achieved practically because of the variation of intensity of light and differences in photosynthetic rates of shaded and sunlit leaves. Monteith (1970) presented the linear relation between photosynthesis and intercepted radiation except when the geometrical factor of canopies is very large($\simeq$0.8)and use of intercellular concentration of CO_2 approaches zero at light saturation stage or the rate of photosynthesis is proportional to the concentration of CO_2 in the external atmosphere. To a good approximation valid for most crops and climates, the ratio of actual photosynthesis by a stand to the maximum rate achieved at full light interception can be calculated as per the Monteith's (1972) expression.

$E_i = 1 - \{S + (1-S)\tau\}^L$ Where S is sunfleck parameter, τ is PAR transmission coefficient and L is leaf are index. During clear days τ is about 0.07 in fully turgid leaves (Bishnoi 1983). E_i being a function of S and L for

TABLE 1

Gross photosynthesis rate (gm m^{-2} day^{-1})

Month	Tri-van-drum	Mad-ras	Pune	Cal-cutta	Jodh-pur	Delhi	Sri-nagar
Jan	113.4	99.8	97.4	81.6	95.3	94.9	40.0
Feb	124.8	124.8	117.8	95.3	109.0	96.5	56.3
Mar	130.3	136.1	127.0	108.7	124.8	115.7	92.1
Apr	124.8	136.1	136.1	115.7	136 1	129.4	97.2
May	107.8	131.5	138.2	118.1	140.6	138.2	139.8
Jun	102 2	113 5	113.5	.92.7	136.1	129.4	112.3
Jul	95.3	96.5	90.7	90.7	113.5	95.3	115.6
Aug	102.0	102.0	90.7	90.7	111.1	92.9	114.3
Sep	113.5	104.4	102.0	88.6	113.5	102.0	108.3
Oct	102.0	90.7	107.8	90.7	111.1	99.8	78.8
Nov	96.5	85.0	95.3	92.9	95.3	103.6	77.5
Dec	99.8	88.6	90.7	86.2	90.7	72.5	50.9
Average	109.3	109.1	108.9	96.0	114.8	104.2	90.3

TABLE 2

Interception and diffusion efficiencies during the growing season

Month	Interception efficiencies for the groups of vegetation					
	A		B		C	
	E_i	E_d	E_i	E_d	E_i	E_d
Jul	0.60	0.50	0.50	0.45	0.40	0.28
Aug	0.85	0.55	0.80	0.47	0.75	0.30
Sep	0.95	0.66	0.85	0.50	0.85	0.31
Oct	0.40	0.30	0.30	0.20	0.20	0.10
Nov	0.50	0.30	0.40	0.20	0.30	0.10
Dec	0.60	0.40	0.50	0.25	0.40	0.15
Jan	0.70	0.50	0.60	0.40	0.50	0.25
Feb	0.80	0.55	0.70	0.45	0.60	0.28
Mar	0.90	0.65	0.80	0.50	0.75	0.31
Apr	0.95	0.65	0.90	0.55	0.85	0.31
May	0.65	0.50	0.50	0.40	0.50	0.25
Jun	0.95	0.65	0.85	0.50	0.80	0.30
a	0.125		0.25		0.50	
S	0.55		0.65		0.55	

different crops, broadly falls in three groups, namely, (A) — the tropical grasses which are known to have relatively fast rates of photosynthesis in bright sunlight, for example, maize, millet, sugarcane etc, (B) — the cereals which has 20 to 25 per cent less dry matter production rates suitable for rice, wheat, barley, sorghum etc and (C) — this group contains beans, cotton, groundnut and many other tropical plants.

Table 2 presents the E_i values for these three groups curing the growing season determined with the data recorded on the PAR interception in the different crop canopies under Hissar conditions.

2.6. *Diffusion efficiency* (E_d)

The basic photosynthesis (*P*)-light (*I*) response equation $P=(a+b/I)^{-1}$ shows that as irridiance tends to zero, the gross rate of photosyntheis per unit incident radiation tends to a constant value of $1/b$ or in terms of carbohydrate of the order of 19.69 g $h^{-1}kw^{-1}$. But as the irridiance increases the photosynthesis rate falls further and further below the maximum rate of $1/b$ and approaches a limiting value of $1/a$ when intercellular concentration of CO_2 approaches zero. This value has been reported about 2 gm^{-2} h^{-1} for cotton, tobacco, sugarbeet to about 8 gm^{-2} h^{-1} in maize, sugarcane (D'Costa & Milburn, 1970). Monteith (1970) stated that the total resistance to the diffusion of CO_2 from external air to the chloroplasts is $14\,a\,S$ cm^{-1}. Monteith's (1965) expression has been used here to derive the diffusion efficiency of a stand by expressing the predicted rate of photosynthesis when the diffusion resistance of leaves is finite as a fraction of the rate when the resistance is zero. It was noted that the E_d values as a function of daily radiation was sensitive to the values of '*a*' than '*S*'. Therefore three sets of values of '*a*' and '*S*' appropriate for three groups of vegetation were evaluated (Table 2).

2.7. *Respiration efficiency* (E_r)

So far it has been assumed that the gross uptake of CO_2 by a leaf/vegetation can be measured as a function can be measured as a function of the irridiance and of the the external CO_2 concentration. In practice the laboratory measurement determines the net exchange, the true rate of the gross photosynthesis is determined by adding the dark respiration rate to the net photosynthesis rate in the light. The respiration factor $E_r = 1 - R/P$ where *R* is the weight of carbohydrate used for respiration per day, *P* is weight of carbohydrate produced by photosynthesis over the same period calculated by adding the dark respiration rate to the net uptake of photosynthesis during the day. The traditional figure for E_r is about 0.2 to 0.25, but Gaastra (1963) quoted a range from 0.25 to 0.50 consistent with growth room measurements on barley and Hamil grass and with field measurements of lucerne, barley (Monteith 1968, 1970), maize and wheat (Lemon 1970). An even higher value of 0.75 was reported for tropical rain and humid forest (Kira *et al.* 1967). McRee (1970) reported E_r values of 0.5 in the tropics after analysing the data on different vegetations available in the literature.

TABLE 3

Maximum dry matter productivity (gm^{-2} day^{-1})

Month	Trivandrum			Madras			Pune			Calcutta		
	A	B	C	A	B	C	A	B	C	A	B	C
Jul	14.3	10.7	5.3	14.5	11.2	5.6	13.6	10.2	5.0	13.6	10.2	5.2
Aug	24.0	19.2	11.5	23.9	19.2	11.5	21.2	17.0	10.2	21.2	17.1	10.2
Sep	35.6	25.6	15.0	32.7	23.5	13.8	32.0	23.0	13.5	27.8	20.0	11.7
Oct	6.2	3.0	1.0	0.5	3.2	1.0	6.5	3.3	1.0	5.5	2.7	0.9
Nov	8.7	3.9	1.5	7.7	3.4	1.3	7.2	3.8	1.4	7.0	3.7	1.4
Dec	12.0	6.3	3.0	10.7	5.6	2.6	10.9	5.7	2.7	10.4	5.4	2.6
Jan	19.9	13.6	7.1	17.5	12.0	6.3	19.6	11.7	6.1	14.3	9.8	5.1
Feb	27.5	19.6	10.5	27.5	19.7	10.5	25.9	18.6	7.4	22.0	15.0	8.0
Mar	31.5	26.0	10.2	39.8	27.2	15.8	37.2	25.4	14.8	31.8	21.8	12.6
Apr	38.5	30.9	16.5	42.0	33.7	18.0	42.0	33.7	18.0	35.7	28.7	15.3
May	17.5	10.7	6.7	21.4	13.2	8.2	22.5	13.6	8.5	19.2	11.8	7.4
Jun	31.5	21.6	12.3	35.0	24.1	13.6	35.0	24.1	13.6	28.7	19.8	11.2
Average	22.3	15.9	8.4	23.2	16.3	9.0	22.8	15.8	8.5	19.8	13.8	7.6

Month	Jodhpur			Delhi			Srinagar		
	A	B	C	A	B	C	A	B	C
Jul	17.0	12.8	6.4	14.3	10.7	5.4	17.4	13.0	6.5
Aug	26.0	20.9	12.5	21.7	17.5	10.5	26.7	21.4	12.8
Sep	35.6	25.6	15.0	31.9	23.0	13.5	33.9	24.3	15.0
Oct	6.7	3.4	1.1	6.0	3.0	1.0	4.8	2.4	0.8
Nov	7.2	3.8	1.5	7.8	4.2	1.6	5.8	3.1	1.2
Dec	10.9	5.6	4.6	8.7	4.6	2.2	6.1	3.2	1.6
Jan	16.7	11.5	9.1	13.1	9.0	4.6	7.0	4.8	2.5
Feb	24.0	17.2	14.7	21.3	15.2	8.1	12.4	8.9	4.7
Mar	36.5	25.0	14.5	33.9	23.2	13.5	26.9	18.4	10.7
Apr	42.0	33.7	17.9	40.0	32.0	17.2	30.0	24.0	12.8
May	22.8	14.1	8.8	22.5	13.8	8.7	22.7	14.0	8.7
Jun	42.0	28.1	16.4	40.0	27.5	15.5	34.6	23.9	13.5
Average	24.0	16.8	10.2	21.8	15.3	8.5	19.0	13.4	7.5

TABLE 4

Maximum rates of dry matter production efficiency of solar energy conversion and efficiency of incident surface radiation energy conversion

Month	Maximum dry matter production rates			Efficiency of solar energy conversion			Efficiency of incident surface radiation energy conversion		
	A	B	C	A	B $E_{g,r}$	C	A	B $E_{i,r}$	C
Jul	14.6	11.0	5.5	0.20	0.15	0.07	1.60	1.16	0.58
Aug	23.0	18.5	11.1	0.30	0.24	0.14	2.21	1.82	1.00
Sep	32.6	23.5	13.8	0.45	0.32	0.19	2.98	2.14	1.25
Oct	6.1	3.1	1.0	0.09	0.04	0.02	0.57	0.29	0.10
Nov	7.6	3.8	1.5	0.12	0.06	0.02	0.71	0.38	0.14
Dec	10.6	5.5	3.0	0.20	0.11	0.05	1.15	0.60	0.29
Jan	16.9	11.3	6.4	0.30	0.20	0.11	1.66	1.14	0.59
Feb	24.7	17.5	9.9	0.39	0.27	0.15	2.11	1.50	0.80
Mar	35.1	24.8	13.6	0.50	0.34	0.20	2.80	1.91	1.11
Apr	40.2	32.1	17.1	0.51	0.41	0.22	2.99	2.36	1.20
May	21.0	12.9	8.1	0.26	0.16	0.10	1.54	0.95	0.40
Jun	35.4	24.2	13.7	0.45	0.31	0.17	2.99	2.05	1.16
Average	22.3	15.4	8.7	0.31	0.22	0.12	1.94	1.36	0.72

3. Maximum dry matter production

The efficiency with which a stand of vegetation is expected to store solar energy by photosynthesis can now be derived as a product of the above discussed seven factors. In the tropics. however, larger amounts of radiation are received throughout the year but can be used only when the temprature and rainfall regime allow a canopy to develop. Growth of the subsistence crop is assumed to be limited by a serious shortage of nutrients and water. The main effect of these shortages is to restrict leaf development so that E_i and E_d are severely affected. Throughout the country solar radiation does not provide any constraints in the three groups of vegetations. But there is variation of 7.5 to 24.0 gm^{-1} day^{-1} dry matter productivity in different vegetations from short duration pulses to fast rates of photosynthesis in maize or sugarcane crops in bright sunlight when the inputs are not contraints (Table 3). The computation of different factors showed that estimates of crop growth rate were sensitive to differences in 'a' and 'S'. These values were consistent with the observed values upto 200-300 gm^{-2} $week^{-1}$ in the field studies (Bishnoi 1983). It was also observed that during the vegetative phase the differences in leaf area index between crops accounts for the differences in dry matter production rate. Table 4 presents the efficiency of the whole system $E_{g,r}$ — the maximum dry matter production rate and the efficiency $E_{i,r}$ — with which solar radiation incident on a crop canopy is converted into dry matter. Among all the components of efficiency factors E_i, E_r and E_d emerge as a major discriminants of dry matter production accounting for differences of crop producitivity under different conditions of climate and management. It may be noted that the efficiency of solar energy conversion is varying between 0.12 to 0.31 per cent only when the other input factors — like soil moisture, fertilizers are non-limiting.

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