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Assessing Solar Energy and Water Use Efficiencies in Winter Wheat

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Abstract

Water-use and solar-energy-conversion efficiencies of two cultivars of winter wheat (Triticum aestivum L., vars. Centurk and Newton) planted at three densities, were examined during a growing season.

Water use, based on soil-moisture depletion, was the lowest under the light, and the highest under the heavy, planting densities of both cultivars. Water use efficiency of medium and heavy planting densities were greater than the light planting densities in both cultivars.

The canopy radiation extinction coefficients of both cultivars increased with increases in planting density. Efficiency of interception of photosynthetically active radiation by both cultivars improved from the time of jointing until anthesis, and then decreased during senescence. The efficiency of the conversion of intercepted radiation to dry matter (biochemical efficiency) decreased throughout the growing season in both cultivars. The interception, biochemical and photosynthetic efficiencies were improved as planting density increased.

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ATTACHMENT 2

Assessing Solar Energy and Water Use Efficiencies in Winter Wheat[1]

G. Asrar, L. E. Hipps, and E. T. Kanemasu[2]

ABSTRACT

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Introduction

Solar radiation and water are perhaps two of the most important resources in agriculture. To examine the role of these resources in optimum crop production, the inherent variability and efficiency of their use throughout the season by a given grop should be assessed.

Water use of a crop depends on the rate of its water uptake which in turn depends upon the evaporative demand of the atmosphere, and the status and mobility of soil water as well as plant root density and distribution (Gardner, 1964). A suitable root system also varies with the soil moisture regime, which is influenced by factors such as water storage capacity of the soil and frequency of profile recharge (Meyer and Alston, 1978). Solar radiation provides energy for the evaporation of water, and quantum for photosynthesis.

Water-use efficiency is generally defined as the ratio of dry matter (M) produced to the amount of water used as evapotranspiration (ET) or transpiration (T). Early investigation of water use by agricultural crops (Briggs and Shantz, 1914) indicated that measurement of water requirements (i.e. T-efficiency) should be considered in relative rather than absolute terms, since differences in transpiration depend upon atmospheric conditions. Gradmann (1928) and Van den Honert (1948) expressed such a relationship in terms of the vapor-pressure gradient from the leaf to the air. Bierhuizen and Slayter (1965), Tanner (1981), and Tanner and Sinclair (1982) proposed a linear relationship between M and T normalized with water vapor deficit (e^*-e),

$$\frac{M}{ET} = \frac{C}{(e^*-e)} \qquad [1]$$

where M is total dry matter or marketable yield, ET is evapotranspiration, C is crop coefficient, e*' is vapor pressure of the leaf, e is vapor pressure of the air. The crop factor (C) is used to evaluate water use efficiency of any specified crop. In this study, the vapor pressure term is assumed constant, since both cultivars were examined at the same location and season,

$$\frac{M}{ET} = C \qquad [2]$$

Equation [2] is a modified version of the simple model of DeWit (1958).

The efficiency of crop production could also be evaluated in thermodynamic terms as the ratio of the energy equivalent of dry matter produced to the photosynthetically active portion of solar energy (PAR) intercepted by the plant (i.e., photochemical efficiency). The amount of intercepted photosynthetically active radiation (0.4 - 0.7 μm) depends upon solar radiation and the seasonal distribution of leaf area, which in turn is primarily a function of temperature and soil water supply (Osman, 1971). Following Monteith (1970), photosynthetic efficiency (ε) could be expressed as the product of several factors,

$$\varepsilon = \varepsilon_s \, \varepsilon_i \, \varepsilon_c \qquad [3]$$

where ε_s is the ratio of photosynthetically active radiation (PAR) to incident solar radiation; ε_i is the fraction of photosynthetically active radiation intercepted by crop canopy; ε_c is defined as the ratio of chemical energy stored in dry matter to intercepted photosynthetically active radiation (photochemical efficiency). Analysis of theoretical calculations and experimental measurements by Szeicz (1974) showed that the photosynthetically useful fraction of the solar spectrum for the total (direct + diffuse) radiation is nearly independent of atmospheric conditions.

The interception efficiency, ε_i, is a major discriminant of dry matter production accounting for differences of productivity under different conditions of climate and management, as well as for differences between the mean and maximum rates of production in a given plant population (Monteith, 1970). Varlet-Grancher and Bonhomme (1982), and Bonhomme et al. (1982) have used this concept in studying photosynthetic efficiency of cowpea, lucern, and sugar beets, and different varieties of corn, respectively.

We propose that equal consideration should be given to both water-use and photosynthetic efficiencies for a better understanding of the problem of crop productivity and its optimization. Therefore, our objective in this study was to assess the water use and photosynthetic efficiencies of two cultivars of winter wheat planted at three different planting densities.

Materials and Methods

A field experiment was conducted during the 1980-1981 season on a Muir silty clay loam (fine-silty, mixed, mesic, Pachic Haplustoll) at Kansas State University research farm, 14 km southwest of Manhattan, Kansas. On October 3, 1980 two varieties of winter wheat (Triticum aestivum L., vars. Centurk and Newton) were planted at three different densities, 22.4, 44.8, and 67.2 kg ha^{-1}, and are referred to as light, medium, and heavy, respectively. Newton emerged on October 10 and Centurk on October 12. The development of Centurk was consistently delayed throughout the season. Plants were harvested on June 25, 1981.

Soil moisture was monitored at three locations in each planting density plot gravimetrically from 0-15 cm, and with a neutron moderation technique to a depth of 300 cm in 15 cm increments. Water extraction by the roots and evaporation was only considered in the top 200 cm, while changes in moisture content of the bottom 100 cm of the profile were used to account for drainage or upward movement of water. The largest change recorded for this layer did not exceed ± 1% by volume for each plot.

When the wheat resumed growth early in spring after winter dormancy, quantum light sensors (Li-Cor Model LI-190SB) were placed at one representative site in each plot. At each site, sensors were placed as follows: four sensors wired in parallel facing upward at the soil surface (PAR_i); one sensor inverted at about one centimeter above the soil surface (PAR_{rsfc}); and one sensor inverted at 50 cm above the crop (PAR_{ref}). One sensor was mounted above the Centurk heavy density plot to record the incoming radiation (PAR_o). The quantum sensors were connected into a data acquisition system (Hewlett-Packard 2012) and thei outputs were sampled at 10-minute intervals by an on-line (Hewlett-Packard 9820A) calculator and recorded by a teletypewriter during the daylight hours throughout the season. Sensors were kept level and clean throughout the season and their placement and maintenance were accomplished with minimal disturbance to the wheat. At approximately 10-15 day intervals the sensors were moved to new sites in each plot, and three 50 cm sections of rows were harvested from the previous sites for leaf area and dry matter determination.

The spectral factor (ε_s) was computed as the ratio of photosynthetically active radiation (PAR_o) to total incoming solar radiation (G_n) measured by a small weather station adjacent to the plots. The quantity of intercepted light (IPAR) by the canopy was calculated as,

$$IPAR = (PAR_o - PAR_i) + (PAR_{rsfc} - PAR_{ref}) \qquad [4]$$

Interception efficiencies (ε_i) were computed as the ratio of total intercepted radiation (IPAR) to total incident PAR for each day. The photochemical efficiency (ε_c) was computed from total dry matter produced and intercepted radiation,

$$\varepsilon_c = \frac{\sum_{i=1}^{n} \alpha\, m_i}{\sum_{i=1}^{n} IPAR_i} \qquad [5]$$

where m is the amount of dry matter produced; n number of days; α is an energy equivalent factor for conversion of dry matter, varying linearly between 13.41 J kg^{-1} during vegetative stages to 17.59 J Kg^{-1} for heading and the stages thereafter (Subcommittee on Feed Composition, 1969). Total dry matter values were adjusted by estimating respiration rates using a simulation model (Mohiuddin and Kanemasu, 1981). Canopy extinction coefficients (K) for the total (direct + diffuse) radiation were computed for a period of two hours around solar noon using,

$$\frac{PAR_i}{PAR_o} = \mathrm{Exp}\ (-K*LAI) \qquad [6]$$

where LAI is green leaf area index.

Statistical analysis of data was based on a split split plot design analysis of variance.

Results and Discussion

Water use of the two varieties of winter wheat planted at three densities varied throughout the growing season. Figures 1 and 2 depict changes in available soil moisture, and rainfall distribution throughout the season for all planting densities of Centurk and Newton, respectively. Soil moisture depletion (100 - % available) was lowest for the light planting density of both varieties during the entire season. In variety Centurk, both medium and heavy density treatments displayed a similar soil moisture depletion pattern, and extracted virtually the same quantity of water from the soil until the time of jointing (Julian date 92). From jointing until harvest, soil moisture extraction of three populations of Centurk were distinctly different, with the lowest and highest amount of water use being under light and heavy plant densities, respectively. In variety Newton, soil moisture depletion of three densities were different throughout the season. Similar to variety Centurk, water use was lowest for light, and highest for the heavy planting densities of Newton (Fig. 2). In general, the water use of both varieties increased prior to the time of heading. This is consistent with the finding of Meyer and Alston (1978). Differences in water use among the planting densities of two cultivars were statistically significant ($P = 0.05$).

Table 1 presents the water use efficiencies of all planting densities of both cultivars with computations based on their total dry matter production. The data show a general decrease in water use efficiencies of both varieties throughout the season. Medium and heavy density treatments were significantly ($P = 0.05$) more efficient than the light density in utilizing the soil moisture for production of total dry matter as well as production of grain yield (Table 2). Higher water use efficiencies observed for medium and heavy density plots likely resulted from full canopy cover, and an associated reduction in evaporation from the soil surface. When the two cultivars were compared Centurk, which is a semi-dwarf and late maturing variety, was more water-use-efficient based on total dry matter as well as grain yield production. Differences in cumulative dry matter production of three planting densities of Centurk and Newton were not statistically significant.

Tables 3 and 4 present the light extinction coefficients (K), as well as spectral (ε_s), interception (ε_i), biochemical (ε_c), and photosynthetic (ε) efficiency coefficients of Centurk and Newton during the growing season, respectively. There was a general increase in magnitude of extinction coefficients of both cultivars with increase in their planting density. These differences in K values were statistically significant ($P = 0.05$) and are consistent with the findings of Osman (1971). Saeki (1960) reported that the extinction coefficient for total (direct + diffuse) radiation is usually between 0.3 - 0.5 in stands with steeply inclined leaves and 0.7 - 1.0 in stands with less inclined leaves. The arrangement of leaves in a wheat canopy are less inclined, and our K values notably fall within the latter range. However, some of the K values, especially for heavy density treatments, were higher than the daily values reported by Monteith (1977). The magnitude of spectral parameter (ε_s) decreased slightly during the growing season. However, values are within the range of reported values by other researchers (Monteith, 1965; Szeicz, 1974; Varlet-Grancher et al., 1982). Efficiency of interception of photosynthetically active radiation (ε_i) increased from the time of jointing until anthesis

(Julian date 130), and then decreased until harvest. Both K and ε_i values are strongly dependent on green leaf area index. Therefore, the seasonal variation of K and ε_i likely resulted from the allocation of assimilates to reproductive organs and the associated senescence of green leaves during the latter part of the growing season. Biochemical (ε_c) and photosynthetic (ε) efficiencies of all planting densities of both varieties decreased during the growing season (Tables 3 and 4). These changes in ε_c and ε with time were statistically significant ($P = 0.05$). The ε_c values for the period of post-anthesis (Julian date 133-150) may be biased low, since some leaves were starting to senesce during that time, thus distorting the values of intercepted radiation too high. If the values of ε_c are combined, the average ε_c values for each variety are within the range of seasonal values reported by other researchers (Monteith, 1970 and 1977; Varlet-Grancher et al. 1982; Bonhomme et al., 1982). In general, variety Newton was more efficient in interception of light (ε_i), while Centurk was more efficient in converting the intercepted energy to dry matter (ε_c).

Conclusions

The results indicated variable water use in two varieties of winter wheat planted at three densities during a growing season. Depletion of soil moisture was the lowest under the light, and highest under the heavy, planting densities of both varieties. High water use efficiency in medium and heavy density plots likely resulted from full canopy cover and reduction of evaporation from soil. This is supported by large K values observed in those plots. Water use of both varieties increased before the time of heading. However, the water use efficiency of both varieties decreased throughout the season. The variety Centurk was more efficient than Newton in using soil moisture for total dry matter, as well as grain yield, production.

The extinction coefficients of both cultivars increased with increases in their planting density. This resulted in more efficient water use in medium and heavy planting densities of both cultivars. Efficiency on interception of photosynthetically active radiation by both varieties increased from the time of jointing until anthesis, and then decreased until late in the growing season. Efficiency of both varieties in converting intercepted radiation to dry matter decreased during the growing season. Variety Newton was more efficient in intercepting the solar energy, while variety Centurk was more efficient in converting the intercepted photosynthetically active portion of solar energy to biomass. The photosynthetic efficiency, based on incident solar radiation, was similar for each cultivar, but improved as planting density increased.

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Table 1. Seasonal distribution of water use efficiencies of Centurk and Newton computed based on total dry matter production of each variety.

		Water use efficiency (Kg m^{-2} m^{-1})					
		Centurk			Newton		
Julian Date	Growth Stage	Light	Medium	Heavy	Light	Medium	Heavy
93-96	Jointing	3.9	4.9	3.9	3.4	3.8	4.5
97-113		2.8	3.9	3.7	2.6	2.7	3.3
119-126	Booting	3.8	3.8	3.9	3.8	3.9	3.8
127-132	Anthesis	2.4	2.4	3.3	2.4	2.6	2.9
133-150	Soft Dough	2.8	2.3	1.6	1.3	1.2	1.3

Table 2. Total seasonal water use and water use efficiencies of Centurk and Newton computed based on final total dry matter and grain yields.

Planting Density	Centurk					Newton				
	Total Water Use (m)	Total Dry Matter (kg m^{-2})	TWUE † (Kgm^{-2}m^{-1})	Grain Yield (kg m^{-2})	GWUE †† (kg $m^{-2}m^{-1}$)	Total Water Use (m)	Total Dry Matter (kg m^{-2})	TWUE † (Kgm^{-2}m^{-1})	Grain Yield (kg m^{-2})	GWUE †† (kg $m^{-2}m^{-1}$)
Light	0.39	1.25	3.15	0.23	0.59	0.45	1.14	2.70	0.21	0.47
Medium	0.41	1.29	3.46	0.25	0.61	0.50	1.23	2.84	0.30	0.60
Heavy	0.47	1.32	3.28	0.30	0.64	0.54	1.31	3.16	0.30	0.56

† water use efficiency based on total dry matter

†† water use efficiency based on grain yield

Table 3. Values of extinction coefficient (K), spectral factor (ε_s), light interception (ε_i) biochemical (ε_c), and photosynthetic (ε) efficiencies of Centurk during different stages of crop development.

Julian Date	Growth Stage	ε_s	Planting Density											
			Light				Medium				Heavy			
			K	ε_i	ε_c	ε	K	ε_i	ε_c	ε	K	ε_i	ε_c	ε
93-96	Jointing	51.4	0.70	78.2	6.8	2.7	0.76	83.4	9.7	4.1	0.77	87.3	9.45	4.2
97-113		49.9	0.65	85.1	5.9	2.5	0.70	88.3	5.6	2.5	0.72	90.5	6.5	2.9
119-126	Booting	47.9	0.72	88.3	5.7	2.4	0.81	89.1	4.7	2.0	0.88	92.0	6.8	3.0
127-132	Anthesis	45.8	0.74	90.4	4.6	1.9	0.83	90.3	3.9	1.6	0.89	91.1	3.5	1.5
133-150	Soft Dough	43.7	----	84.3	3.1	1.1	----	87.2	3.5	1.3	----	90.1	3.6	1.4

Table 4. Values of extinction coefficient (K), spectral factor (ε_s), light interception (ε_i), biochemical (ε_c), and photosynthetic (ε) efficiencies of Newton during different stages of crop development.

			Planting Density											
			Light				Medium				Heavy			
Julian Date	Growth Stage	ε_s	K	ε_i	ε_c	ε	K	ε_i	ε_c	ε	K	ε_i	ε_c	ε
93-96	Jointing	0.51	0.70	90.0	6.9	3.2	0.78	92.2	7.3	3.4	0.89	95.0	9.5	4.6
97-113		0.50	0.70	91.2	4.7	2.1	0.70	94.3	5.1	2.4	0.84	94.2	5.3	2.5
119-126	Booting	0.48	0.71	93.0	4.3	1.9	0.77	95.1	5.0	2.3	0.78	96.3	5.3	2.4
127-132	Anthesis	0.46	0.73	93.1	4.3	1.8	0.78	94.0	8.2	3.6	0.79	94.0	7.8	3.4
133-150	Soft Dough	0.43	----	93.4	2.9	1.2	----	96.2	6.2	2.6	----	96.1	613	2.6

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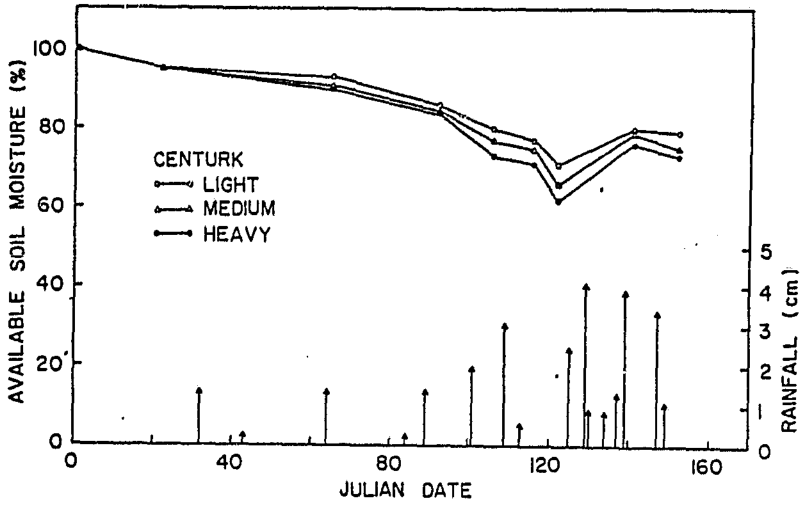

Figure 1. Seasonal distribution of available soil moisture and rainfall under three planting densities of Centurk.

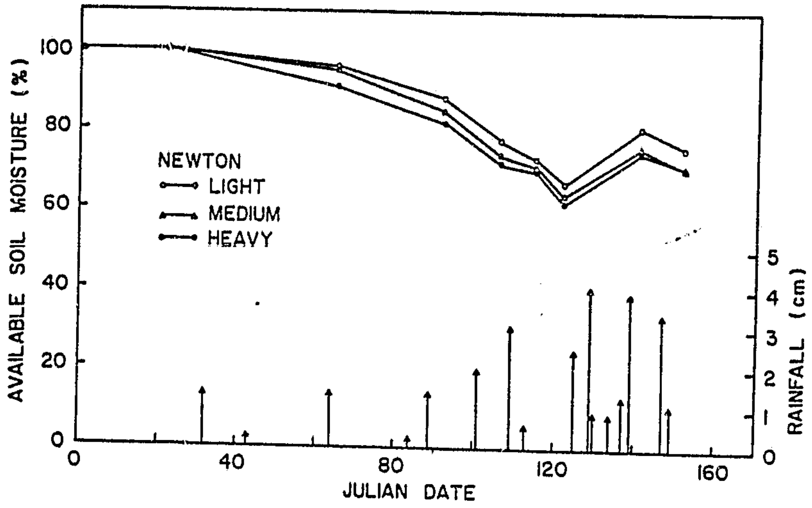

Figure 2. Seasonal distribution of available soil moisture and rainfall under three planting densities of Newton.