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Evaluation of irrigation scheduling program and spring wheat yield response in southwestern Colorado

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Abstract

Effective irrigation scheduling to manage water for spring wheat (*Triticum aestivum* L.) in southwestern Colorado was investigated under variable water applications. This study was conducted (1) to determine the effects of varying rates of water replacement (0ET, 0.33ET, 0.67ET, 1.0ET, and 1.33ET) on spring wheat grain yield, dry matter yield, root water uptake, and water use efficiency, (2) to develop local crop coefficients, and (3) to evaluate the irrigation scheduling program called 'SCHED' that had been used in the area. Daily weather data was used to calculate reference ET using the Penman equation. Crop ET was predicted by using the irrigation scheduling program, 'SCHED'. Both grain yield and dry matter increased significantly with the increase in water application rates, up to 1.0ET application rate. Crop coefficients estimated at various water application rates were greater than the values used in the irrigation scheduling program. Total water use efficiency (TWUE) and irrigation water use efficiency (IWUE) for grain yield were considerably greater at 0.33ET than for other rates, whereas TWUE and IWUE for dry matter yield followed the order 0.33ET > 1.0ET > 0.67ET > 1.33ET > 0ET. © 1997 Elsevier Science B.V.

Keywords: Evapotranspiration (ET); Crop coefficient; Irrigation scheduling; Drip irrigation

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1. Introduction

In many areas, irrigation provides the means to optimize plant water use and to increase crop production. Implementing sound irrigation water management practices is necessary to overcome excessive irrigation and eliminate many associated problems. This concept is critically important in areas such as southwestern Colorado, where deep percolation associated with over-irrigation combines with a saline geological formation (Mancos Shale), which contributes heavily to the salinity problem in the Colorado River. Therefore, irrigation scheduling becomes a crucial element in reducing deep percolation and improving water quality downstream.

The relationship between yield and crop water use has been investigated by many researchers. Information on the optimum time to apply limited amounts of water to obtain the maximum yield of high quality crops is essential for efficient use of irrigation water (Matsunaka et al., 1992). Studies show that proper irrigation management is critical to spring wheat yield quantity and quality. Sharma et al. (1990) found that when the same amount of water was applied at different growth stages, there was a significant difference in productive tillers. Chaudhary and Kumar (1980) reported that maximum reduction of productive tillers was obtained when moisture stress occurred at the tillering stage. Grain yield of wheat was significantly increased with increasing irrigation frequency.

Soil moisture conditions affect nutrient availability to the crops. Optimum irrigation increases N absorption by the crop, leading to a greater number of wheat tillers and a greater yield (Matsunaka et al., 1992).

Water applied directly to the root zone minimizes water loss through runoff and deep percolation. Precise and controlled water applications are necessary to achieve the desired yield and water use efficiency. The objectives of this study were to determine the effect of five irrigation rates on spring wheat grain and dry matter yields, root water uptake, water use efficiency and to develop regional crop coefficients that will be used in the irrigation scheduling program rather than using ones developed somewhere else; and to modify the irrigation scheduling program (SCHED) that had been used in the area by using the locally developed polynomials for crop coefficients.

2. Materials and methods

The study was conducted during the growing seasons of 1993 and 1994 at the Southwestern Colorado Research Center at Yellow Jacket, Colorado. The soil on the site is Wittco silty clay loam (fine-silty, mixed, mesic, Aridic Paleustalf). The experiment consisted of five irrigation rates which were replicated four times in a randomized complete block design. The treatments were 0%, 33%, 67%, 100%, and 133% of evapotranspiration (ET). Each treatment's plot had dimensions of 4.6 × 6.1 m. Plots in each replication were separated by a buffer zone 3.1 m wide and diked to contain the irrigation water and eliminate runoff. Replications were separated by a buffer zone 4.5 m wide. A 1.5 m galvanized (EMT) access tube 3.75 cm I.D. was installed in the center of each plot. Soil moisture content was measured twice a week by using a neutron probe (model CPN 503) [1] at depths of 15, 45, 75, 105 and 135 cm.

Irrigation water was applied by using a drip system. The irrigation system consisted of a 5 cm I.D. polyethylene tube connected to the main irrigation line. A filter was installed in the main line to prevent sediment from blocking the emitters. Five 1 cm I.D., 60 m long, lateral tubes were connected perpendicular to the main line. The drip irrigation system was designed to deliver four different rates of water: 0.33, 0.65, 0.95 and 1.28 cm h^{-1} at 10.4×10^4 Pa, which correspond to the irrigation treatments. The irrigation scheduling was conducted by using the 'SCHED' program (Buchleiter et al., 1988). The program estimates crop water use (ET) using the modified Penman equation (Jensen et al., 1971), along with polynomial functions to generate crop coefficients based on the fraction of time from planting to full cover and days after full cover (Duke, 1987).

Two varieties of hard red spring wheat (*Triticum aestivum* L.) were planted. The 'Oslo' variety was planted on April 20, 1993. The experimental line 'ID367' was planted on April 22, 1994 due to unavailability of the Oslo variety at the time of planting. Both varieties were tested in southwestern Colorado at the same research station in Yellow Jacket, Colorado. Variety trial results showed that 'ID367' heading date was 7 days earlier than 'Oslo'. Grain yield results show no significant differences between the two varieties (Stack et al., 1995). Planting was done at a row spacing of 20 cm and at a rate of 87 kg ha^{-1}. The P was applied at 25 and 30 kg ha^{-1} in 1993 and 1994 according to soil test recommendations, respectively. The N rates of 135 and 157 kg ha^{-1} were applied in 1993 and 1994, according to soil test recommendations, respectively. Plant samples for dry matter were taken at different growth stages by cutting plant shoots at the ground level. One half of each plot was harvested for dry matter yield determination. An area 1.20×6.1 m from each plot was harvested for grain yield assessment.

The following water balance relationship was used in estimating ET from soil moisture and irrigation data:

$$I + P - R = \mathrm{ET} + D + \mathrm{SW},$$

where the terms on the left hand side of the above equation represent the applied irrigation water (I), precipitation (P) and surface runoff (R). The sum of these three terms represents the net addition of water to the soil profile over a time period of interest. On the right hand side of the equation are evapotranspiration (ET), drainage or deep percolation (D), and the water storage change (SW) of the soil profile. Each of the terms in the above equation represents water flows or storage changes over some arbitrary time interval. All of the terms in the equation are positive except for D and SW, which may be either positive or negative depending on the direction of the water flow (upward or downward flow) (Jury et al., 1991).

[1] Trade name is included for the benefit of the reader and does not imply any endorsement or preferential treatment of the product by the authors or CSU.

Table 1
Regression equation coefficients for spring wheat estimated ET using water balance approach, crop coefficients (K_c), grain yield, and total dry matter (TDM) yield under variable water application rates

Treatments	Variables	Parameters					
		a	*b*(*x*)	$c(x^2)$	$d(x^3)$	R^2	std. err. of est.
Regression equation coefficients of estimated ET (Figs. 1 and 2)							
0ET	ET	7.098E−02	5.638E−03	−8.3E−05	3.1E−07	0.50	0.079
0.33ET	ET	1.169E−01	4.269E−03	−7.3E−05	3.1E−07	0.50	0.073
0.67ET	ET	2.360E−02	1.368E−02	−2.6E−04	1.3E−06	0.85	0.035
1.0ET	ET	8.288E−02	1.252E−02	−1.8E−04	5.6E−07	0.67	0.058
1.33ET	ET	2.015E−01	6.098E−03	−2.5E−06	−6.9E−07	0.74	0.056
Regression equation coefficients of crop coefficients (K_c) (Figs. 3 and 4)							
0ET	K_c	2.805E−01	6.414E−02	−3.97E−03	6.3E−05	0.73	0.060
0.33ET	K_c	3.709E−01	4.895E−02	−3.41E−03	5.8E−05	0.70	0.059
0.67ET	K_c	1.915E−01	1.410E−02	−1.09E−02	2.2E−04	0.87	0.081
1.0ET	K_c	3.349E01	1.509E−01	−9.83E−03	1.6E−04	0.88	0.101
1.33ET	K_c	5.792E01	1.001E−01	−4.78E−03	2.1E−05	0.91	0.100
Regression equation coefficients of grain and total dry matter yields as related to variable irrigation rates (Figs. 5 and 6)							
Yield-93	grain (Mg/ha)	1.015	6.98E−02	3.8E−04	−9.1E−06	0.99	0.044
Yield-94	grain (Mg/ha)	1.086	3.29E−02	2.3E−03	−2.8E−05	0.99	0.054
TDM-93	TDM (Mg/ha)	2.524	−6.02E−02	−7.2E−03	−7.7E−05	0.90	1.648
TDM-94	TDM (Mg/ha)	2.333	2.22E−02	3.3E−03	−3.4E−05	0.92	1.547

	Variables	Source	DF	Anova SS	Mean square	*F* value	Pr > F
Analysis of variance of 1993 and 1994 dry matter, ET, and crop coefficients at 0.05 level of significance							
	TDM (Mg/ha)	year	1	0.0176	0.0176	0.04	0.8491
	ET (cm/day)	year	1	0.0002	0.0002	0.02	0.8935
	K_c	year	1	0.0004	0.0004	0.01	0.9249

Surface runoff (R) was negligible due to control of the water application on each plot. Irrigation scheduling was based on estimated weekly crop water use (ET) from local weather. Deep percolation (D) did not occur, based on soil moisture readings at 130 and 160 cm depths, where no increase in soil moisture was found.

2.1. Data preparation

Data of estimated crop ET, crop coefficient, and dry matter yield are presented as averages of both 1993 and 1994 growing seasons. The combined statistical analysis of variance of 1993 and 1994 (Table 1) using the above mentioned parameters, showed differences between the two years for the same treatments were not significant. Therefore, for the reason of simplicity and clarity in presenting these data, we decided to use the average values to interpret the relationships in figures and tables in results and discussion sections. Data presented in Figs. 1–4 and 7 represent the predicted values

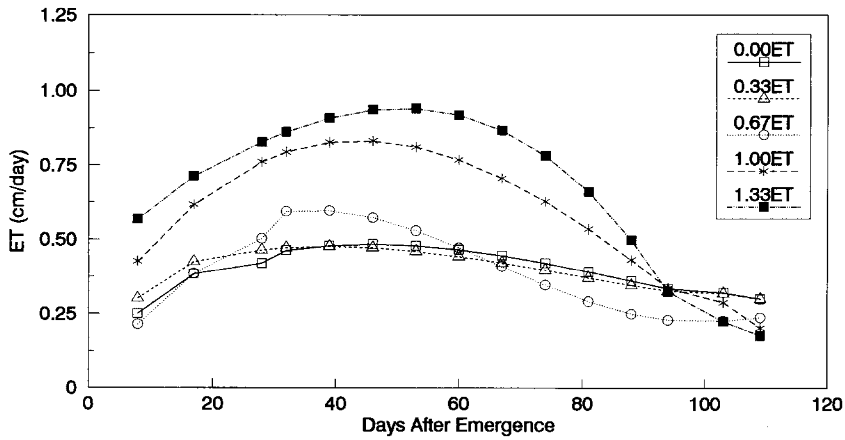

Fig. 1. Estimated ET average of 1993 and 1994 growing seasons of spring wheat.

generated by regression models from the two years' average data. The grain and dry matter yields as a function of applied water are presented for both years in Figs. 5 and 6.

Daily crop ET was calculated by using the USDA-ARS irrigation scheduling program, 'SCHED', developed by Buchleiter et al. (1988). The crop coefficients (K_c) used in this program were determined by polynomial equations (Duke, 1987) at different growth stages. Thus, crop ET is expressed as a function (both time and water content-dependent) of the reference ET (ET_r)

$$ET = K_{cb} * K_s * ET_r, \tag{1}$$

where ET is the estimated crop water use, K_{cb} is the basal crop coefficient, and K_s is

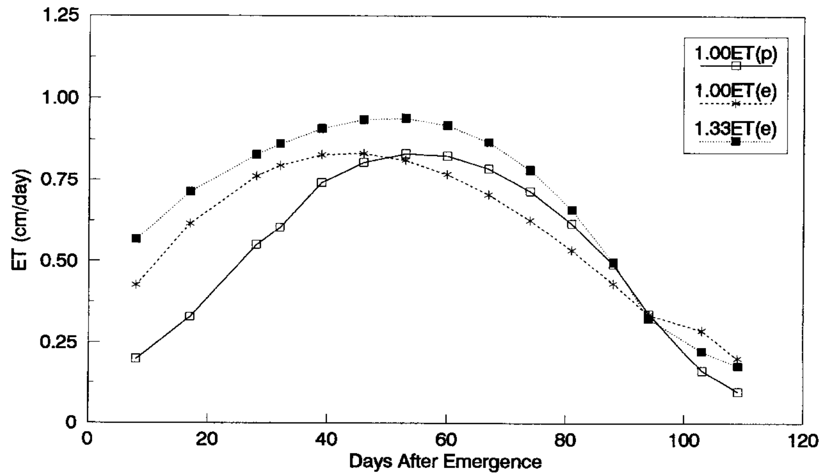

Fig. 2. Estimated (e) and predicted (p) ET averages of 1993 and 1994 spring wheat growing seasons.

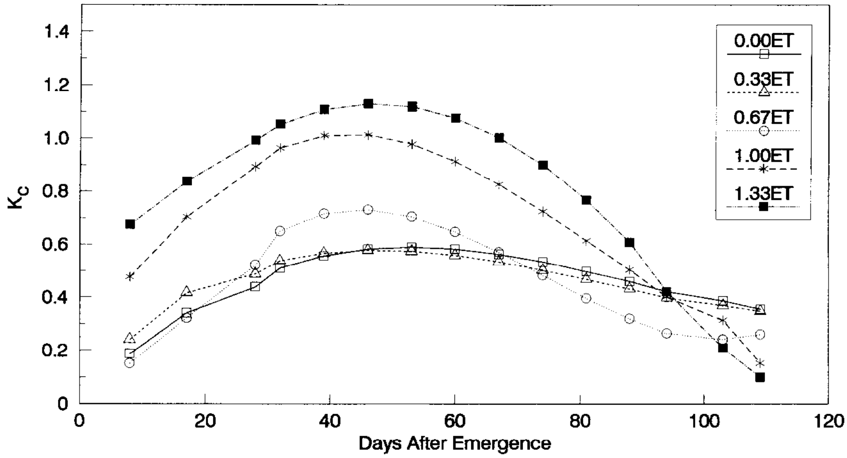

Fig. 3. Spring wheat crop coefficients using estimated ET (water balance approach) and Penman ET_r averages of 1993 and 1994 growing seasons.

the moisture stress coefficient. The crop coefficient was calculated by using the following polynomial function:

$$K_{cb} = aX^3 + bX^2 + cX + d, \tag{2}$$

where a, b, c and d are empirically determined coefficients and x is number of days since emergence from Duke (1987).

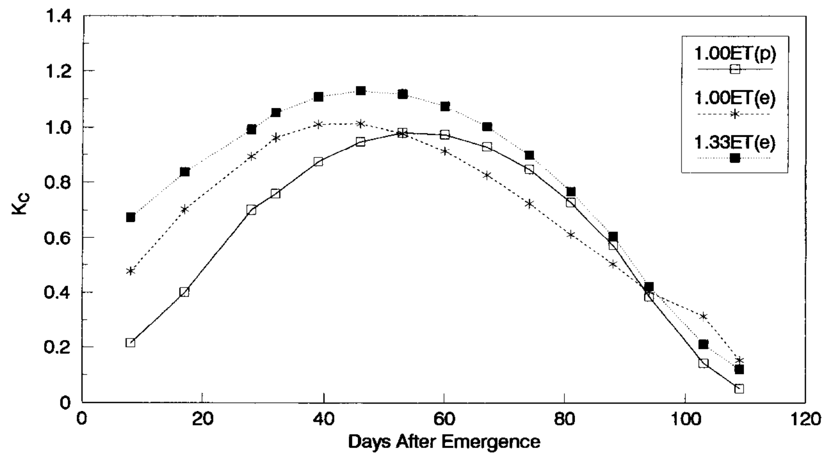

Fig. 4. Estimated (e) and predicted (p) crop coefficients averages of 1993 and 1994 spring wheat growing seasons.

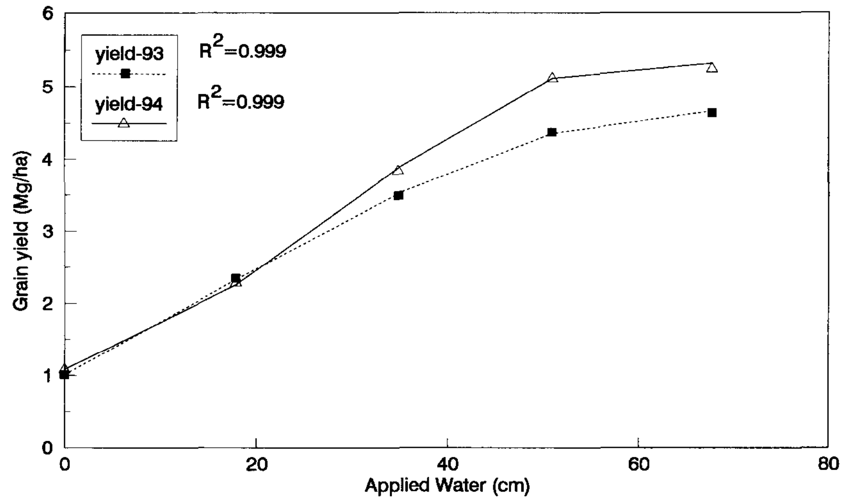

Fig. 5. Spring wheat grain yield as a function of applied water during 1993 and 1994 growing seasons.

The moisture stress coefficient, K_s, accounts for reduction in crop water use resulting from decrease soil water availability. This stress factor is computed by

$$K_s = \log\left(1 + 100 * \left(1 - D_p/D_t\right)\right)/\log(101), \tag{3}$$

where D_p is actual depletion in the root zone and D_t is the maximum available water (Buchleiter et al., 1988). Crop water use calculated by Eq. (1), assumes a dry soil surface. For wet soil surface following rain or irrigation, particularly while the crop is

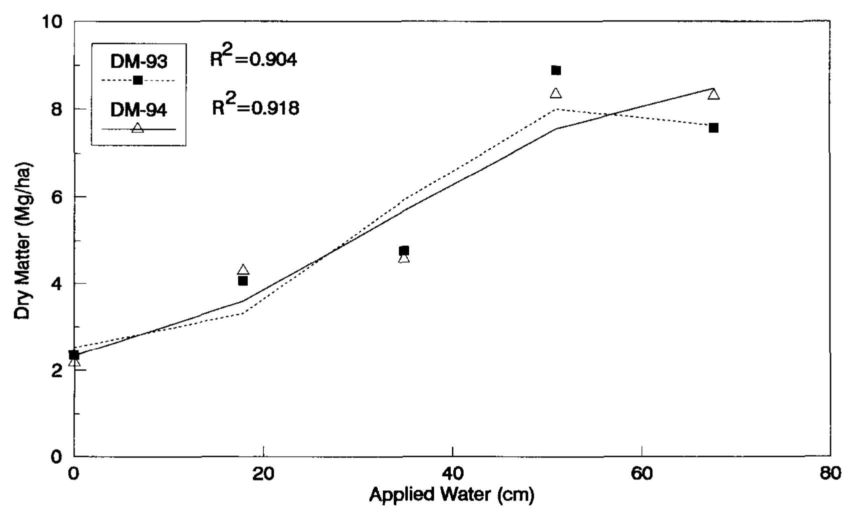

Fig. 6. Spring wheat dry matter (DM) yield as a function of applied water of 1993 and 1994 growing seasons.

small, additional soil surface evaporation, E_s, should be considered (Buchleiter et al., 1988)

$$E_s = K_r * (0.9 - K_c) * ET_r, \tag{4}$$

where

$$K_c = K_{cb} * K_s \tag{5}$$

$$K_r = 1/(4.05 - 15 * \mathrm{WHC})^{x_d - 1} \tag{6}$$

WHC is the soil water holding capacity and x_d is the number of days since the precipitation or irrigation event. $K_r = 0.8$ when $x_d = 1$. Eq. (6) is an empirical relationship which approximates field observations about the duration of a wet soil surface following a precipitation or irrigation event. Drying periods for sandy soils are 1 to 2 days and 3 to 4 days for clay soils. When the crop is sufficiently developed, (K_c greater than or equal to 0.9), then E_s is set to zero.

3. Results and discussion

3.1. Crop ET estimates

Fig. 1 summarizes the daily averages of 1993 and 1994 ET estimated by using the water balance approach. Regression coefficients for the third degree polynomials fitted through the original data are given in Table 1. Results of the *t*-test at the 0.05 level show that water use by spring wheat was significantly different between 0.67ET, 1.0ET, and 1.33ET irrigation treatments. The highest value of water use was obtained at 30, 40, and 50 days after emergence for 0.67ET, 1.0ET, and 1.33ET, respectively. There were no significant differences (*t*-test at alpha = 0.05) in water use throughout the growing season at the 0ET and 0.33ET treatments (Fig. 1 and Table 2).

ET values estimated by the water balance approach were greater than those generated by the irrigation scheduling program SCHED for 1.0ET and 1.33ET irrigation treatments (Fig. 2). Third degree polynomials were fitted through the averaged ET values over the 1993 and 1994 growing seasons. The results show that ET values of 1.0ET and 1.33ET irrigation treatments were significantly different early in the season. As the full canopy developed, the differences became very small. The 1.33ET irrigation treatment showed an increase in water use over both measured and predicted values of 1.0ET.

3.2. Crop coefficient calculations

Estimated K_c values in Fig. 3 were generated by fitting third degree polynomials through original data averages of the 1993 and 1994 growing seasons (Table 1). These values were significantly different among the irrigation rates. Crop coefficient is a function of crop growth stage, soil water content and climatological factors. Therefore, the limited soil water supply under low irrigation rates limits soil evaporation (Ritchie, 1971) and transpiration (Ritchie and Burnett, 1971). The high irrigation application rate

Table 2
Spring wheat yields and water use efficiency averages of 1993 and 1994 growing seasons

Treatment	Irrigation [a] (cm)	Total ET (cm)	Grain yield [b] ($Mg\ ha^{-1}$)	Dry matter ($Mg\ ha^{-1}$)	Grain [c] ($Mg\ ha^{-1}\ cm^{-1}$)		Dry matter ($Mg\ ha^{-1}\ cm^{-1}$)	
					IWUE	TWUE	IWUE	TWUE
0.00ET	0	22	1.04a	2.26a	—	0.05	—	0.10
0.33ET	18	24	2.14b	4.18b	0.12	0.09	0.23	0.17
0.67ET	35	34	3.66c	4.67c	0.11	0.11	0.13	0.14
1.00ET	52	62	4.74d	8.62d	0.09	0.08	0.17	0.14
1.33ET	69	75	4.94d	7.94e	0.07	0.07	0.12	0.11

[a] Irrigation amounts include precipitation.
[b] Means with the same letter are not significant at alpha = 0.05 (Duncan *t*-test).
[c] IWUE and TWUE are irrigation and total ET water use efficiencies, respectively.

provided a well-watered condition, where the rate of ET was significantly higher compared to the lower application rates. The minimum values of crop coefficients for all treatments were very close, except for the 1.33ET irrigation treatment. On the other hand, the maximum values of K_c were significantly different (t-test at alpha = 0.05), except for the 0ET and 0.33ET irrigation treatments. As the crop canopy developed, there were striking differences in plant height under different water application rates (visual observations).

Crop coefficient values (minimum and maximum) estimated by both methods (water balance and SCHED program) are summarized in Fig. 4. The values of crop coefficients were generated as a ratio of actual water use and potential ET by the Penman equation. The minimum and maximum values of estimated crop coefficients (K_{ce}) were 0.40 and 1.01 for the 1.0ET treatment and 0.60 and 1.1 for the 1.33ET treatment as compared to predicted (K_{cp}) minimum and maximum values of 0.18 and 0.98 for the 1.0ET treatment.

3.3. Yield function measurements

The effects of different rates of irrigation on grain yield, dry matter yield, and water use efficiency were evaluated. The results are summarized in Table 2. Irrigation amounts include seasonal precipitation, which amounted to 2.54 and 3.38 cm during the 1993 and 1994 growing seasons, respectively. The data represent the average values of both seasons. Grain yields under 0ET, 0.33ET, and 0.67ET irrigation treatments were significantly different, where 1.0ET and 1.33ET irrigation treatments show no significant differences (Table 2). Dry matter production increased significantly as irrigation rates increased. The irrigation water use efficiency (IWUE) and total water use efficiency (TWUE) were higher for dry matter than for grain yield.

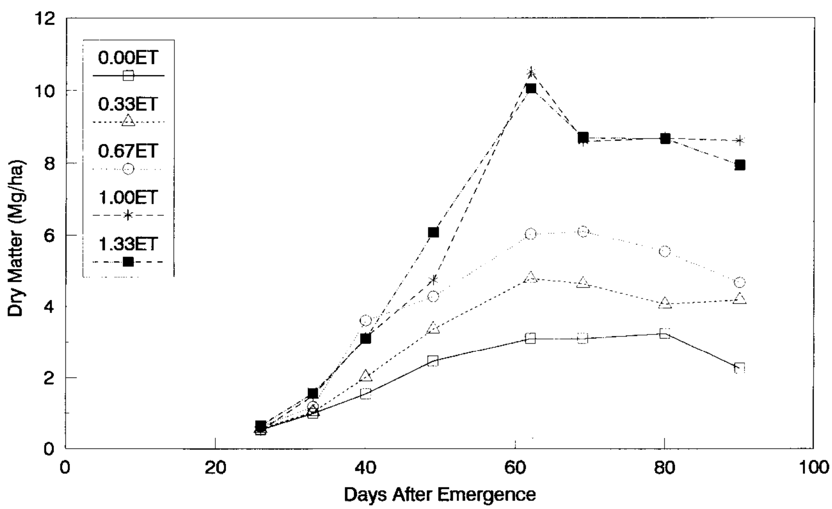

Fig. 7. Spring wheat dry matter yield of 1993 and 1994 growing seasons under variable water application rates.

Generally, both IWUE and TWUE increased as the rates of irrigation decreased. Moreover, the increase in the water application rate above 1.0ET did not produce a significant increase in grain yield. In similar studies on corn, Spurgeon and Makens (1991), using a LEPA irrigation system, and Weis et al. (1991) using drip irrigation, found no significant differences in corn yield between the 1.0ET and 1.33ET treatments.

Figs. 5 and 6 summarize the spring wheat response to various rates of irrigation. Both grain and dry matter yields of the wheat during 1993 and 1994 were represented as a function of irrigation amounts. Regression analysis suggests a nonlinear relationship between yields and water applications. However, the mean comparison in Table 2 shows no significant increase in grain and dry matter yields as the irrigation rate exceeds 1.0ET.

Dry matter response during the growing season as a function of time for different irrigation treatments shows a nonlinear relationship (Fig. 7). Mean comparison (*t*-test at alpha = 0.05) shows significant differences between all treatments (40–80 days after emergence) except between the 1.0ET and 1.33ET treatments. Dry matter reached its maximum at 60 days after emergence.

4. Conclusions

Water use by spring wheat under variable irrigation rates was affected by water application rate. Wheat water use was underestimated using the irrigation scheduling program ‘SCHED’, compared to the water balance approach. The 0.33ET application rate had the highest IWUE and TWUE for both grain and dry matter yields. Crop coefficients calculated from the water balance data were greater than those generated by the polynomial functions used in the irrigation scheduling program (SCHED) in southwestern Colorado. Grain yield and dry matter were nonlinearly related to irrigation applications.

The crop coefficients polynomial developed by this study will be a major contribution in modifying irrigation scheduling programs used in southwestern Colorado. It is important that local environment be considered in any adaptation or transfer of water management programs to achieve the objectives of such programs in improving water use efficiency. Water use improvement is an important concept, especially in southwestern Colorado where water quality, salinity, and yield are major concerns.

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