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WATER USE EFFICIENCY REGULATED BY AUTOMATIC DRIP IRRIGATION CONTROL

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ABSTRACT

An automatic irrigation system that allowed either high yields or high water use efficiency to be chosen would be a useful farming tool. We tested a system that uses crop canopy temperature to automatically schedule and apply irrigations. Corn (*Zea mays* L., hybrid Pioneer 3162) was grown in 1997 and 1999; and soybean (*Glycine Max* (L.), var. Pioneer 9481) was grown in 1996, 1998, and 2000, all with surface and subsurface drip irrigation. Each year, the four automatic treatments were compared with a manual weekly irrigation regime that was 100% replenishment of water to field capacity as measured by neutron probe. Treatments of 67% and 33% of the 100% amount were also applied manually to provide data for curves of yield vs. water use. Treatments were triply replicated. Most or all of the automatic treatments out yielded the 100% treatment in each year. Corn yield, total water use (mm) and water use efficiency, WUE, were stable for the automatic irrigation treatments. Corn water use and WUE varied widely over the two years for the manual treatments. The automatic system was able to respond to low stress levels resulting from good rainfall, and thus delivered larger irrigation WUE values when rainfall was more plentiful. For soybean, yields and WUE were not more stable for all automatic treatments. It appears that manipulation of irrigation control parameters will allow a choice between larger yields and larger water use efficiencies to be achieved for corn, but not for soybean.

An automated irrigation scheduling and control system that could be set up to control irrigation to arrive at a given level of water use efficiency would have obvious advantages. This paper describes the water use efficiency results from an automatic irrigation scheduling and control system tested at Bushland, Texas from 1996 through 2001. The system evaluates crop canopy temperature at every minute of the day, and makes irrigation decisions every night based on the number of minutes in the day that the canopy temperature was above a threshold value. Burke (1993) and Burke and Oliver (1993) showed that plant enzymes operate most productively in a narrow temperature range called the thermal kinetic window. Wanjura et al. (1992 and 1993) described systems for using a threshold canopy temperature, based on the thermal kinetic window, as an index for automatic control of irrigation on a near real-time basis. A temperature-time threshold concept was introduced by Wanjura et al. (1995a,b) to see if irrigation intervals could be extended to once a day or longer. The studies, conducted with cotton (*Gossypium hirsutum*, L.), were not replicated but did prove the workability of an automated system and appeared to confirm that the 28°C threshold for cotton resulted in the largest yields. Upchurch et al. (1996) received patent no. 08/261,510 for an irrigation management system based on optimal leaf temperature for enzyme activity.

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In a precursor to the study reported here, we used 28 and 30°C thresholds and 15-min and 3-d decision intervals to automatically drip irrigate corn in 1995 (Evett et al., 1996). We found that the automatic method was more responsive to plant stress and produced yields equal to or greater than those from treatments irrigated to replenish soil water to field capacity weekly. We also concluded that a 15-min decision interval was too frequent and a 3-d interval probably too infrequent for best production and water use. Thus, in the present study we used a decision interval of one day for the automatic system. Our objectives were to compare yields and water use efficiencies (WUE) obtained using weekly replenishment of soil water to field capacity, and obtained using 33 and 67% of that amount, with yields and WUE obtained with the temperature-time threshold method; and to evaluate the feasibility of using the temperature-time threshold method to control WUE of corn and soybean production.

MATERIALS and METHODS

The study was done from 1996 through 2000 on a Pullman clay loam, fine, mixed, thermic Torrertic Paleustoll at Bushland, TX in the southern High Plains. Each of the 21 plots was 10.7 by 27.4-m and contained 12 rows with 0.76-m row spacing. Half of each plot was irrigated with drip lines buried at 0.3-m depth in every other interrow (1.52-m line spacing). The other half plot was surface irrigated with three drip lines (model T25-0.6-18, Netafim Irrigation Inc., Fresno, CA[**]) in every other interrow. Integral pressure compensating emitters, rated at 2.7 L/h at the 69 kPa design pressure, were spaced at 0.45-m intervals along the tubing. Flow to each plot submain was controlled at 908 L/h by a Dole Flow Control valve (Eaton Corp., Carol Stream, IL). Flow to each IRT plot was recorded from totalizing flow meters (Master Meter 1 inch) on a weekly basis. Phosphoric acid was injected at 5.3 mg/L as a P source and to prevent root plugging.

Plots were leveled and bermed to prevent runoff and runon. Weekly measurement of soil water content was in one access tube in each plot by neutron moisture meter at depths of 0.1 through 2.3 m in 0.2-m increments (model 503DR, Campbell Pacific Nuclear Int., Inc., Martinez, CA)(32-s counts at each depth). A depth control stand*** was used to ensure accurate depth positioning of the neutron probe. The meter was previously field calibrated for the A, B and calcic B horizons with coefficients of determination of 0.90, 0.96, and 0.97, respectively, and RMSE < 0.01 $m^3\ m^{-3}$ for all horizons, using methods described by Evett and Steiner (1995). The change in stored soil water to 2.4-m depth was calculated between the first measurement date and harvest. Seasonal crop water use was calculated from totals of irrigation, rainfall, and change in stored soil moisture.

Corn (*Zea mays* L., hybrid Pioneer 3162) was planted in 1997 after 186 kg N ha^{-1} was applied, and in 1999 after 230 kg N ha^{-1}. Atrazine was applied at 2.24 kg ha^{-1} in 1997 and 1999. For corn, liquid urea was injected into the irrigation water at 75 mg L^{-1}. Soybean (*Glycine Max* (L.), var. Pioneer 9481, late maturity group 4) was planted in 1996, 1998, and 2000, after Treflan was applied and incorporated. Analysis of variance of the results and Student-Newman-Keuls multiple range tests on the means were done using the SAS (SAS Institute, Inc., Cary, NC) and COSTAT statistical analysis packages (COHORT, Inc., Minneapolis, MN).

[**] The mention of trade or manufacturer names is for information only and does not imply an endorsement, recommendation or exclusion by USDA-Agricultural Research Service.

***Description available at http://www.cprl.ars.usda.gov/programs/

Seven irrigation treatments were randomized within blocks in a split plot (surface and subsurface drip) design with three replications. Treatments were randomized each year. For drip-irrigated field corn at Bushland, Howell et al. (1997) showed no significant difference in yield between once-a-day and once-a-week irrigation treatments that replenished soil water to field capacity. Thus, a check treatment, designated 100%, consisted of weekly irrigations to replace 100% of crop water use as measured by neutron scattering (average of three replicates). Crop water use was calculated as the difference between soil water storage in the top 1.5 m of soil and field capacity in that layer (0.333 m^3 m^{-3} average water content). Two other treatments, designated 67% and 33%, were irrigated weekly to provide 67% and 33% of the amount provided to the 100% treatment.

Four other treatments were implemented with two threshold canopy temperatures, each of which was implemented with two threshold times to create four automatic irrigation treatments. The threshold temperatures were determined by the ARS Plant Stress and Water Conservation Laboratory, Lubbock, TX, on the basis of temperature kinetics of soybean and corn photosynthetic enzymes. The 28°C threshold is the center of the thermal kinetic window for corn (Burke, 1996) and represents peak photosynthetic enzyme activity. It should be the optimum. Similarly, the optimum temperature threshold for soybean was determined to be 27°C. For corn, a 30°C threshold treatment was established to see if a 2°C increase would substantially change water use, WUE, and yields. Similarly, for soybean, a 29°C threshold was used.

For corn, the time threshold was determined to be 240 min for a 28°C threshold temperature using the crop energy balance method proposed by Wanjura et al. (1995b) with weather data from Bushland. The aim of this method is to calculate, over the irrigation season, the average time period over a day for which the canopy temperature of a well-watered crop, with a particular canopy resistance, exceeds the threshold temperature. For a 30°C threshold temperature, the time threshold was 160 min. To study the effects of using a shorter or longer threshold time, the threshold time for 28°C was used with the 30°C threshold, and the threshold time for 30°C was used with the 28°C threshold. The resulting four treatments, collectively called the corn IRT treatments, were designated 28-240, 28-160, 30-160, and 30-240. For soybeans grown under sprinkler irrigation at Bushland in 1995, the threshold times were 256 min and 171 min for threshold temperatures of 27 and 29°C, respectively. The four soybean IRT treatments were designated 27-256, 27-171, 29-171, and 29-256.

For irrigation system control, the time threshold is compared to a daily accumulation of measured time that the canopy is above the threshold temperature. During our experiment, the canopy temperature was measured every second and the mean calculated every minute. If the mean temperature was above the threshold temperature, and if the relative humidity (RH) was below a limiting RH, then one minute was added to the sum of time for which canopy temperature exceeded the threshold. The limiting RH was that equivalent to a wet bulb temperature of 2°C below the threshold temperature. This limitation is introduced to avoid counting times when the canopy cannot physically cool below the threshold temperature due to high humidity. Irrigations were applied on any day when the time threshold was exceeded. The irrigation amount was set equal to the crop's peak daily ET. From historical data, this was chosen as 10 mm for both soybean and corn at Bushland. The 28-240 and 30-160 corn treatments and the 27-256 and 29-171 soybean treatments can be called the theory-based treatments because they used time thresholds that were determined for their respective temperature thresholds. For each species, the other two IRT treatments, 28-160 and 30-240 for corn and 27-171 and 29-256 for soybean, were used to explore whether lowering or raising, respectively, the time threshold for a given temperature threshold would cause changes in irrigation amount, yield, and/or water use efficiency.

Canopy temperature was measured with thermocouple infrared thermometers (IRT) (model IRt/c.2-T-80, Exergen Corp., Newton, MA) digitized with a data logger (model 21x, Campbell Sci. Inc., Logan, UT) that also served to control flow to the 12 plots irrigated by canopy temperature control. There was one IRT per plot, mounted on an adjustable mast one third of the distance from the south end of the plot, and adjusted to point down 45° from the horizontal and to point across the rows at 45° from north. Flow to each IRT plot was turned on and off by a solenoid valve actuated by the data logger via a control module (model SDM-CD16AC, Campbell Sci. Inc., Logan UT). Irrigation decisions were programmed to take place after sunset; and all irrigations were done at night.

RESULTS and DISCUSSION

Rainfall during the soybean irrigation season varied from 411 mm in 1996 to 85 mm in 1998 and 126 mm in 2000 (Table 1). In the relatively wet year 1996, soil water storage increased for most automatic irrigation treatments, whereas in 1998 and 2000, soil water was depleted for all treatments. Total water use varied widely, and was largest in 1996 when yields were also the largest. Yields under 100% irrigation declined in the more stressful years 1998 and 2000. Yields for the theory-based automatic treatments were about the same in 1996 and 1998, only declining in 2000. The year 2000 was the most stressful due to the fact that most of the rainfall came in May, leaving the rest of the summer almost devoid of rain and unusually hot during flowering and pod filling. There were few significant differences in WUE or IWUE among treatments (Table 1, Fig. 1); and there was no clear difference between automatic and manual irrigation treatments across years. A regression of IWUE vs. total irrigation was not significant at $P = 0.05$. There were no clear yield differences between the automatic treatments and the 100% manual treatment. The 67% manual treatment always resulted in lower yields, often significantly so, while IWUE and WUE values for this treatment were sometimes significantly larger than those for some of the automatic treatments. However, this was not consistent across years. The theory-based automatic treatments resulted in yields as large as or larger than those from the 100% treatment except for the 29-171 treatment in 2000 for which there was a slightly but not significantly smaller yield. While the automatic irrigation system can be relied upon to produce soybean yields as large as those obtained with manual irrigation, while reducing management decisions and time, there does not appear to be a way to control WUE or IWUE with it. This seems to be largely due to the fact that WUE for soybean is not strongly tied to the availability of water. A plot of total water use efficiency vs. total water use is very similar to Fig. 1 in that WUE is not significantly related to total water use (data not shown). Values of WUE reported by Eck et al. (1987) for border irrigated soybean (Douglas, maturity group IV) were in the same range as those reported here, although yields were lower. Values of WUE efficiency for the three years were 0.40, 0.45, and 0.50 kg m^{-3}; and irrigations were applied so as not to induce stress. When irrigation was reduced to stress the crop, Eck et al. (1987) found that WUE was not increased. This agrees with our results, showing little relationship between stress level (irrigation amount) and WUE.

Results for corn are much different. The automatic treatments applied significantly more water to corn in six of eight cases than did the 100% treatment in 1997 and 1999 (Table 2). Yields in the drier year 1997 (189 mm irrigation season rainfall) were significantly larger for the automatic treatments vs. the manual ones. In the wetter year 1999 (323 mm irrigation season rainfall), yields from three of the automatic treatments were not significantly different from that of the 100% treatment. Yield from the more stressful 30-240 treatment was significantly smaller. Irrigation WUE for the 30-160 and 30-240 automatic treatments was larger in both years than that from the 100% treatment (only significant for the

30-240 treatment in 1999). While IWUE values were larger than those for automatic treatments in 1999 for the 33% (significant) and 67% (not significant) treatments, they were significantly smaller in the more stressful year 1997. For the automatic irrigation treatments, there was a significant ($P = 0.0004$) and strong ($r^2 = 0.94$) relationship between irrigation water applied and IWUE. No such consistent relationship existed for the manual treatments (Fig. 1). For all three manual treatments, both WUE and IWUE varied widely from year to year, even though the amount of irrigation applied did not. The larger IWUE values from automatic treatments in the less stressful 1999 year, compared with those from 1997, indicate the ability of the automatic system to respond to less stressful conditions by applying less water (Table 1). The larger yield values from automatic treatments in 1997, compared with those from the manual treatments, indicate the ability of the system to relieve stress in a timely fashion. This is particularly important during silking in corn.

The differences between corn and soybean results may be due both to differences in photosynthetic mechanisms (corn is a C_4 crop and soybean a C_3) and to differences in plant development. Corn is able to efficiently use higher levels of radiation than is soybean (Loomis, 1983) and probably would benefit more from the high levels of solar radiation available at Bushland (due to clear skies and the high elevation of 1170 m MSL). Also, it is well established that corn yield potential is sensitive to water stress level, particularly during silking.

In conclusion, for both corn and soybean, the automatic, canopy temperature based irrigation system was consistently able to produce yields as large as or larger than those from a more traditional weekly irrigation scheduling system that employed soil water measurements to determine the amount of water needed to bring the soil profile back to field capacity. However, only for corn was the automatic system clearly more capable of maintaining high yields while using rainfall efficiently and delivering large IWUE values in years with good rainfall.

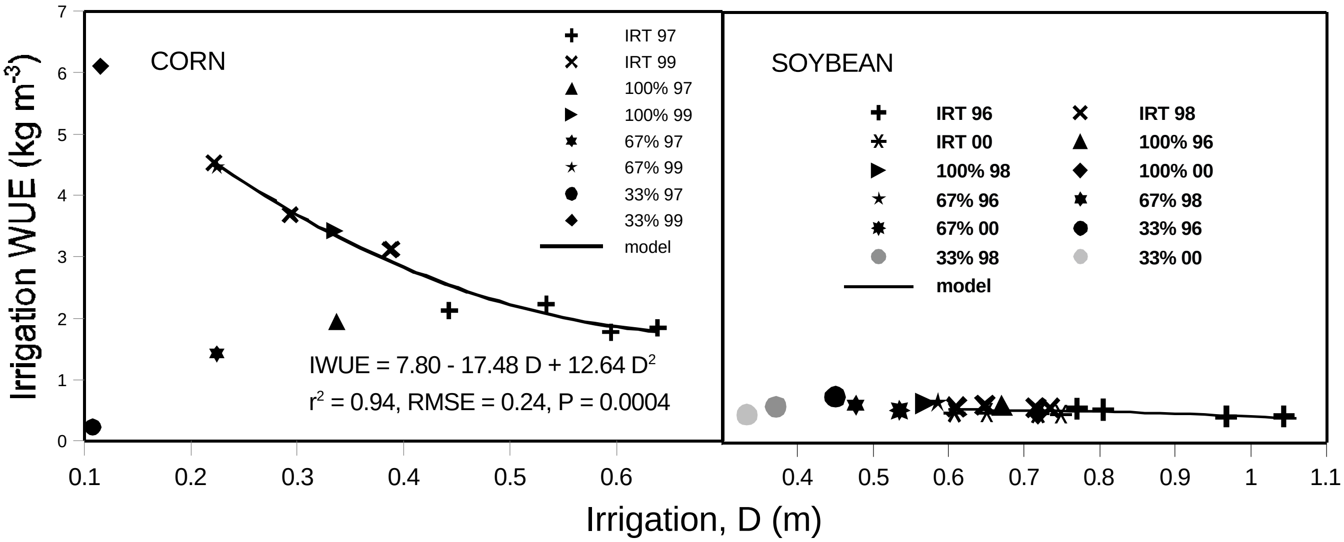

Figure 1. Soybean (right) and corn (left) irrigation water use efficiencies (WUE, kg m^{-3}) vs. irrigation depth (D, m) for automatic and manual drip irrigation treatments.

REFERENCES

Burke, J.J. 1993. Thermal kinetic windows of plant enzymes. *In* Biotechnology for arid plants. pp. 73-82.

Burke, J.J. 1996. Personal communication from USDA-ARS Crop Stress Research Laboratory, Lubbock TX.

Burke, J.J., and M.J. Oliver. 1993. Optimal thermal environments for plant metabolic processes (*Cucumis sativus L.*): Light-harvesting chlorophyll a/b pigment-protein cmplex of photosystem II and seedling establishment in cucumber. Plant Phys. 102:295-302.

Eck, H.V., A.C. Mathers, and J.T. Musick. 1987. Plant water stress at various growth stages and growth and yield of soybeans. Field Crops Res. 17:1-16.

Evett, S.R., and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type moisture gages based on field calibration. Soil Sci. Soc. Amer. J. 59:961-968.

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 1996. Canopy temperature based automatic irrigation control. Pp. 207-213 *In* C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.) Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling. Nov. 3-6, 1996, San Antonio, Texas, U.S.A. 1166 pp.

Howell, T.A., A.D. Schneider, and S.R. Evett. 1997. Subsurface and surface microirrigation of corn - Southern High Plains. Trans. ASAE 40(3):635-641

Loomis, R.S. 1983. Crop manipulation for efficient use of water: An overview. Pp. 345-374 *In* H.M. Taylor, et al. (eds.) Limitations to efficient water use in crop production. Amer. Soc. Agron., Crop Sci. Soc. Amer., Soil Sci. Soc. Amer., Madison, WI.

Upchurch, D.R., Wanjura, D.F., Burke, J.J., and Mahan, J.R. 1996. Biologically-Identified optimal temperature interactive console (BIOTIC) for managing irrigation. United States Patent 5,539,637, July 23, 1996.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1992. Automated irrigation based on threshold canopy temperature. Trans. ASAE 35:153-159.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1993. Canopy temperature controlled irrigation scheduling. Acta Horticulturae 335:477-490.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1995a. Control of irrigation scheduling using temperature-time thresholds. Trans. of the ASAE 38(2):403-409.

Wanjura, D.F., D.R. Upchurch, G. Sassenrath-Cole, and W.R. DeTar. 1995b. Calculating time-thresholds for irrigation scheduling. *In* Proceedings of the 1995 Beltwide Cotton Conferences, Jan. 4-7, 1995, San Antonio, TX.

Table 1. Soybean irrigation, soil water used, total water use[a], dry yield, irrigation water use efficiency (IWUE) and total water use efficiency (WUE).

	Irrigation (mm)			Soil Water Used (mm)			Total Water Use (mm)		
Treatment	1996	1998	2000	1996	1998	2000	1996	1998	2000
27-256[b]	770 bc[c]	715 a	719 b	-14 ab	66 ab	122 a	1167 bc	866 b	966 a
27-171	968 ab	734 a	749 a	-43 a	90 abc	76 b	1335 ab	910 a	952 ab
29-171	1044 a	648 b	651 c	-21 ab	95 abc	117 ab	1433 a	828 bc	894 dc
29-256	805 bc	610 c	608 d	29 dc	101 bcd	114 ab	1245 abc	797 c	849 d
100%	671 dc	570 d	718 b	10 bc	63 a	64 b	1092 dc	718 d	908 bc
67%	586 dc	477 e	535 e	28 dc	124 dc	101 ab	1024 dc	686 d	762 e
33%	450 d	371 f	333 f	50 d	133 d	126 a	910 d	589 e	586 f
	Dry Yield (kg/m^2)			IWUE (kg/m^3)			WUE (kg/m^3)		
27-256	0.407 ab‡	0.403 a	0.341 a	0.554 ab	0.565 ab	0.475 ab	0.354 a	0.466 ab	0.354 a
27-171	0.402 ab	0.410 a	0.340 a	0.416 b	0.559 b	0.454 b	0.302 a	0.451 b	0.356 a
29-171	0.432 a	0.392 ab	0.315 ab	0.421 b	0.604 ab	0.485 ab	0.305 a	0.474 ab	0.353 a
29-256	0.423 a	0.348 c	0.295 bc	0.528 ab	0.571 ab	0.485 ab	0.341 a	0.437 b	0.347 a
100%	0.401 ab	0.364 ab	0.334 a	0.600 ab	0.639 a	0.465 ab	0.368 a	0.509 a	0.368 a
67%	0.368 bc	0.289 d	0.276 c	0.647 a	0.605 ab	0.517 a	0.363 a	0.421 b	0.363 a
33%	0.328 c	0.216 e	0.149 d	0.738 a	0.583 ab	0.447 b	0.362 a	0.367 c	0.254 b

[a] Rainfall during the irrigation season was 411 mm in 1996, 85 mm in 1998, and 126 mm in 2000. Total water use was the sum of irrigation, rainfall, and change in stored soil water to 2.4-m depth.

[b] Hyphenated treatment names include the threshold temperature (°C) as the first number, and the threshold time (min) as the second number. Treatment names with percent signs are based on weekly replenishment of soil water in the top 1.5 m of the profile to field capacity.

[c] Numbers in a column followed by the same letter are not significantly different at the 0.05 probability level.

Table 2. Corn irrigation, soil water used, total water use[a], dry yield, irrigation water use efficiency (IWUE) and total water use efficiency (WUE).

Treatment	Irrigation (mm)		Soil Water Used (mm)		Total Water Use (mm)	
	1997	1999	1997	1999	1997	1999
28-240[b]	639 a[c]	387 a	15 c	96 ab	843 a	806 a
28-160	595 a	389 a	5 c	96 ab	789 b	808 a
30-160	534 b	293 c	28 c	118 ab	751 b	735 b
30-240	443 c	222 d	29 c	79 b	661 c	624 d
100%	337 d	336 b	42 bc	97 ab	569 d	756 b
67%	224 e	224 d	81 ab	118 ab	494 e	666 c
33%	108 f	115 e	116 a	139 a	412 f	577 e
	Dry Yield (kg/m^2)		IWUE (kg/m^3)		WUE (kg/m^3)	
28-240[a]	1.18 a[b]	1.20 ab	1.84 abc	3.11 d	1.40 abc	1.49 a
28-160	1.04 b	1.21 a	1.77 bc	3.13 d	1.32 bc	1.50 a
30-160	1.19 a	1.07 bc	2.23 a	3.69 c	1.59 a	1.46 a
30-240	0.94 b	1.00 c	2.12 ab	4.54 b	1.42 ab	1.62 a
100%	0.65 c	1.15 ab	1.96 ab	3.42 dc	1.16 c	1.52 a
67%	0.32 d	1.00 c	1.43 c	4.47 b	0.65 d	1.50 a
33%	0.02 e	0.70 d	0.23 d	6.10 a	0.06 e	1.21 b

[a] Rainfall during the irrigation season was 189 mm in 1997, and 323 mm in 1999. For soybean, rainfall during the irrigation season was 411 mm in 1996, and 85 mm in 1998. Total water use was the sum of irrigation, rainfall, and change in stored soil water to 2.4-m depth.

[b] Hyphenated treatment names include the threshold temperature (°C) as the first number, and the threshold time (min) as the second number. Treatment names with percent signs are based on weekly replenishment of soil water in the top 1.5 m of the profile to field capacity.

[c] Numbers in a column followed by the same letter are not significantly different at the 0.05 probability level.