Crop coefficients for drip-irrigated xeriscapes and urban vegetable gardens

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Abstract. *The decrease in water supply/demand ratios in the western U.S. is stimulating the region's municipalities to implement water conservation incentives. In response, many homeowners and businesses are replacing high water-using landscapes with drip-irrigated xeriscapes. Concurrently, due to concerns over food quality and safety, more home and community drip-irrigated vegetable gardens are being established in many of these municipalities. Unfortunately, due to a lack of adequate water-requirement information, these landscapes and gardens may receive inappropriate irrigation volumes required for acceptable plant quality and/or yield. This paper briefly describes research-demonstration projects that are developing climate-based (Penman-Monteith reference ET), canopy area-adjusted landscape or crop coefficients (K_L or K_C) for scheduling microirrigations in drought–tolerant landscapes and small vegetable gardens in northwestern New Mexico. Results indicated that an overall K_L of 0.3 would be appropriate for water management planning on xeric landscapes while canopy area-adjusted K_Cs ranging from 0.6 to 0.9 provided maximum yields of tomatoes, chile peppers, and sweet corn.*

Keywords. crop coefficients, xeriscape, chile, tomato, sweet corn, irrigation, reference evapotranspiration

Introduction

The population of the southwestern U.S. and the concurrent demand for the limited water supplies of the region has increased dramatically over the past 50 years. As a result, many municipalities in the region have implemented incentives to insure that adequate fresh water be available to satisfy this rising demand. Incentives have included increasing-block water rate structures, water-use restrictions, penalties for water waste, or cash rewards for removal of high water-use landscape plants such as turfgrass. In response, urban landscapes in the west are increasingly being converted from sprinkler-irrigated, imported turfgrass lawns to drip-irrigated xeriscapes consisting of native plants or plants more suitable to the arid or semi-arid environments typical of the region. While this measure has the potential to conserve water, savings may not be realized if irrigation management strategies are not developed that match irrigation volumes to the water required by each plant to exhibit acceptable growth and quality in the xeriscape.

Water conservation in landscaping is not the only concern of southwestern U.S. municipalities and citizens. There has also been an increasing interest recently in local food production and food safety and quality. *Salmonella* spp. and *E.coli* outbreaks, along with inferior quality and taste of imported produce have instigated a resurgence of home vegetable gardens for household consumption and for sale at increasing numbers of local farmers markets. If expensive domestic water is used to irrigate these vegetable gardens, water conserving techniques such as drip irrigation and efficient irrigation scheduling must be implemented to minimize water-use while sustaining optimum yields and/or economic returns.

It's possible that in both of the 'non-standard' situations above, climate-based irrigation techniques may be used to effectively manage irrigations. In climate-based irrigation scheduling, a crop's water requirement or evapotranspiration (ET_C) is estimated by the product of a reference ET (ET_{REF}), calculated from weather data, and an experimentally derived crop coefficient (K_C). Typically, ET estimates and accurate K_Cs are formulated under standard conditions where the crop is grown in large monocultures that are disease-free, well fertilized, grown under optimum soil water conditions, and which achieve full production under the given climatic conditions (Allen et al., 1998). Landscape plants are usually isolated or separated from neighboring plants by greater distances than that of row crops and acceptable quality, rather than full production, is the primary goal. Small garden plots represent somewhat isolated, heterogeneous plant communities that, like mixed-species xeriscapes, do not exhibit 'standard conditions' since the aerodynamic characteristics of these small plots may be quite different than those of a large cropped monoculture.

Additionally, most published K_Cs have been derived from cropped fields in which the entire soil surface is wetted by sprinkler or flood irrigation. Early in the growing season of plants, ET_C is limited by each plant's small, live-leaf canopy area. Consequently, the K_C or ratio of ET_C to the climate driven ET_{REF} (ET_C/ET_{REF}) is small but then increases gradually as the crop's live-leaf canopy area as a percentage of total ground area, increases. If the entire soil surface is wetted during this establishment period, soil evaporation exceeds plant transpiration in ET_C until the soil surface dries. In drip irrigation, the evaporation component of ET_C is much less, since only a small area of soil around the base of each plant is wetted. Because of this, using recorded K_C values (or curves) to estimate the water requirement of individual plants of a given species when the plant is drip irrigated and is not a component of a large monoculture becomes difficult. A problem with using a programmed K_C curve over a canopy-adjusted K_C was pointed out by Hartz (1993) who concluded that over-irrigation of tomatoes can potentially result if using a programmed K_C over a canopy-adjusted K_C when crop development is slower than expected. In this case, crop ET might be better estimated by using a constant K_L or K_C and a variable per plant, live leaf canopy area. The use of a variable per-plant canopy area with a formulated constant K_C may help compensate for non-standard conditions such as variability in plant spacing, varietal differences, plant vigor and other factors that can affect canopy area.

Specific objective of these studies were to evaluate the effects of drip irrigation on the growth and quality of various drought tolerant landscape plants and on the yield of chile peppers, tomatoes, and sweet corn grown in small plots in an effort to formulate K_C constants under variable, single-plant crop canopy area estimates for scheduling irrigations on these plants when drip irrigated.

Materials and Methods

Studies were conducted from 2004 thru 2009 at New Mexico State University’s Agricultural Science Center at Farmington, NM (ASCF). The ASCF is located on a high mesa (5,640 feet above mean sea level) overlooking the San Juan River in the northwest corner of the state. The site is semiarid, receiving an average annual precipitation of 8.2 inches. The soil classification at the study sites is a Kinnear very fine sandy loam soil (Typic Camborthid, fine loamy, mixed, calcareous, mesic family).

Daily Penman-Monteith reference ET for tall canopies (ET_{rs}) was calculated from daily maximum and minimum air temperature (^{o}C), daily minimum and maximum relative humidity (%), daily solar radiation (MJ $m^{-2}d^{-1}$), and average 24-hour wind speed (m s^{-1}) recorded at an automated weather station (Campbell Scientific, Inc. Model CR10) located less than 300 feet east of the plots using the ASCE-EWRI standardization procedures documented by Snyder and Eching (2004). ET_{rs} was then converted to English units for this paper.

Landscape Plants

A xeriscape demonstration garden consisting of more than 90 drought tolerant perennials having potential for use in urban landscapes was planted in 2002. The garden was split into four quadrants and at least one individual of each species was planted in each quadrant (Figure 1). Most of the specimens were transplanted from small starts (2 to 4 inch pots) obtained from a native plants nursery. All plants were irrigated uniformly for establishment until August 2003 when drip irrigation treatments were initiated and each quadrant received a different level of weekly irrigation (0, 20, 40, or 60% of ET_{RS}) or treatment factor (TF).

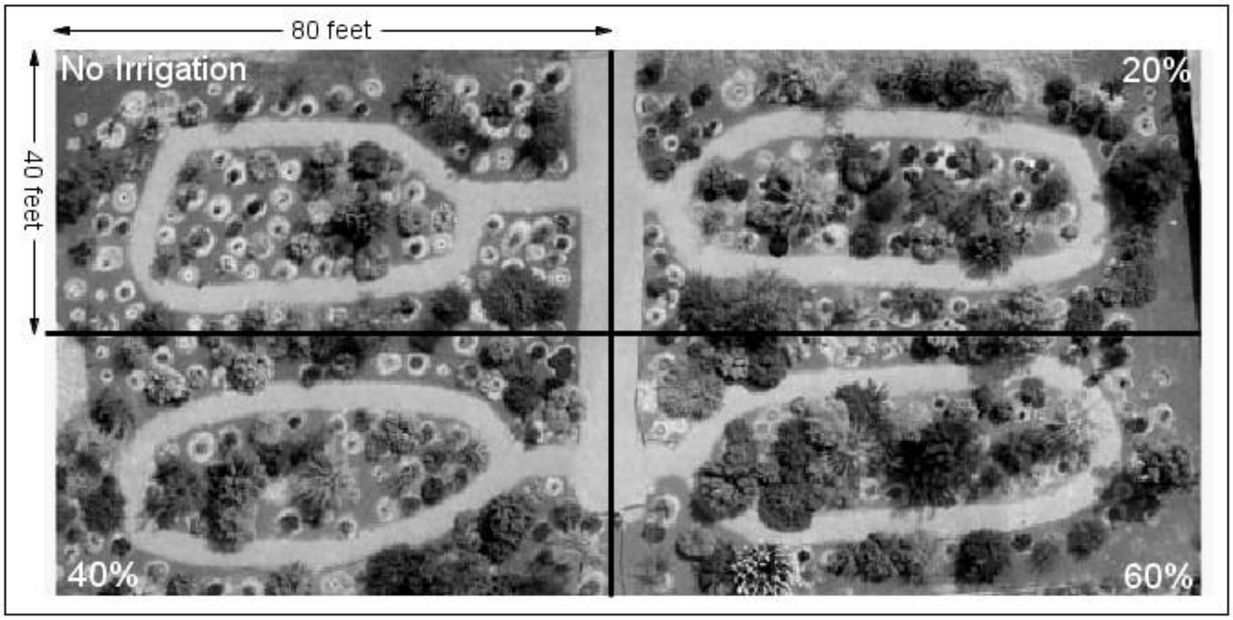

Figure 1. Overhead view of the demonstration garden used to estimate landscape coefficients (K_L) for various xeric-adapted plant species at NMSU's Agricultural Science Center at Farmington. Values represent irrigation as percentages of ET_{RS} times an average plant canopy area of 12.5 ft^2.

From 2004 thru 2009, a mean per plant canopy area (CA) of 12.5 ft^2 (4 ft diameter) was used to schedule irrigations on all plants using Equation 1. Adjustments were then made based on the actual measured plant CA in the lowest irrigation quadrant (minimum TF) where acceptable plant quality was observed for each species to derive a suggested landscape coefficient (K_L) for that species. Since water in most municipalities is billed by volumetric units, irrigation requirements are expressed in gallons.

Equation 1: Calculation of irrigation volume for treatments.

$$I = (ET_{RS} - P_E) \times TF \times CA \times 0.623$$

Where:

I	irrigation applied, gallons per plant (gpp)
ET_{RS}	sum of daily Penman-Monteith reference ET values for tall canopy since last irrigation, inches
P_E	effective precipitation since last irrigation (60% of the sum of per event amounts greater than 0.2 inch), inches
TF	treatment factor (0, 0.2, 0.4, and 0.6 in xeriscape; re. Table 1 for vegetables)
CA	canopy area per plant in square feet ($D^2 \times 0.785$); where D = plant diameter in feet
0.623	conversion factor for gallons/sq ft from inches

Vegetable Garden

For the vegetable crops, chile pepper, tomato, and sweet corn were planted in alternating block or randomized block designs with varying drip irrigation as treatments (Table 1) and the mean measured live (variable) canopy area per plant was used to schedule irrigations. Planting and plot information are shown in Table 1. In all years, the chile and tomato were planted in late May or early June from 1-in^2 transplants received from a local nursery. In 2005, these transplants were planted by hand but from 2006 thru 2009, a mechanical, tractor-drawn transplanter was used. Sweet corn seed was planted by hand about 1 to 2 weeks after the tomato and chile in all years.

Table 1. Planting and plot information for the studies designed to evaluate the effects of irrigation on the yield of chile pepper, tomato and sweet corn from 2005 thru 2009.

		YEAR				
	Crop[1]	2005	2006	2007	2008	2009
Planting Dates	C	9 June	23 May	7 June	2 June	N/A
	T	N/A	24 May	7 June	3 June	19 May
	SC	17 June	1 June	20 June	12 June	N/A
Plot Size (sq. ft.)	C	216	204	204	272	N/A
	T	N/A	204	204	272	151
	SC	216	204	136	272	N/A
Row Spacing (in.)	all	36	34	34	34	32
Plant Spacing within Row (in.)	C	18	12	12	12	N/A
	T	N/A	24	24	24	28
	SC	12	12	12	12	N/A
Plants/1000 square feet	C	222	353	353	353	N/A
	T	N/A	177	177	177	159
	SC	333	353	353	353	N/A
Replicates	all	3	3	3	4	4
Irrigation Treatments (Percent of ET_{RS})	C	100, 75, 50	105, 85, 65	100, 75, 50	85, 70, 55	N/A
	T	N/A	105, 85, 65	100, 75, 50	105, 90, 75	72, 80, 88, 96
	SC	100, 75, 50	105, 85, 65	100, 75, 50	85, 70, 55	N/A
Final Harvest Date	C	21 Oct	20 Sep	3 Oct	3 Oct	N/A
	T	N/A	12 Sep	3 Oct	1 Oct	17 Sep
	SC	8 Sep	17 Aug	6 Sep	6 Sep	N/A

[1] C – chile pepper, T – tomato, SC – sweet corn

Specific materials and methods for both of these studies, including plot plans, itemized irrigation and fertilization, harvesting dates and techniques, etc. can be found by referring to the Annual Progress Reports of the ASCF at the center's website: http://farmingtonsc.nmsu.edu (Projects and Results).

Irrigation

Establishment Periods

During establishment (2002 and early 2003) the plants in the xeric plant garden were irrigated with between 0.25 and 3 gallons of water per week. Irrigation frequency and amount within this range varied with plant size, age and atmospheric demand. Generally, newly planted specimens from 2 to 4 inch pots were irrigated every other day with about 1 quart of water per application during the first few weeks. As the plants became established and new growth was evident, irrigation frequency was reduced to once or twice per week and irrigation volume increased to between 1 and 3 gallons per application.

In all years except 2009, the vegetable garden area was irrigated uniformly with a sprinkler system to bring the top 2 feet of the soil profile up to field capacity (approximately 1.5 inches per foot) prior to planting. Two or three additional light sprinkler irrigations (less than 0.5 inch) were applied until the drip system could be assembled. These depth measurements, along with effective precipitation depths were converted to gallons per plant and have been added to the water applied in Table 3, Table 4, and Table 5. In 2009, the drip system was constructed immediately after planting. To insure successful establishment of the transplants, they were irrigated uniformly with the drip system at a K_C of 2.0 (due to the oasis effect) and a wetted area per emitter of 0.8 feet for the first 2-3 weeks after transplanting.

Irrigation Treatments

After the 2-3 week establishment period, the water volume applied per plant per irrigation (I) at the various treatments in both the xeric demonstration garden and the vegetable gardens was calculated using Equation 1. The landscape species were irrigated once per week from about mid-April to mid-October. The chile and tomatoes were irrigated every 2 to 3 days from about mid-June to final harvest (Table 1).

Results and Discussion

Reference ET

Total ET_{rs} during the 2005 thru 2009 growing seasons (April 1 thru October 31) averaged 66.5 inches. Daily ET_{rs} increased from about 0.24 inch in early April to 0.38 inch in mid June but varied widely from day to day during the spring due to significant fluctuations in temperature and wind (Figure 2). Average ET_{rs} then decreased gradually from 0.38 inch in late-June to about 0.16 inch in late October. The day to day fluctuation was much less due to more stable weather conditions in summer and early fall.

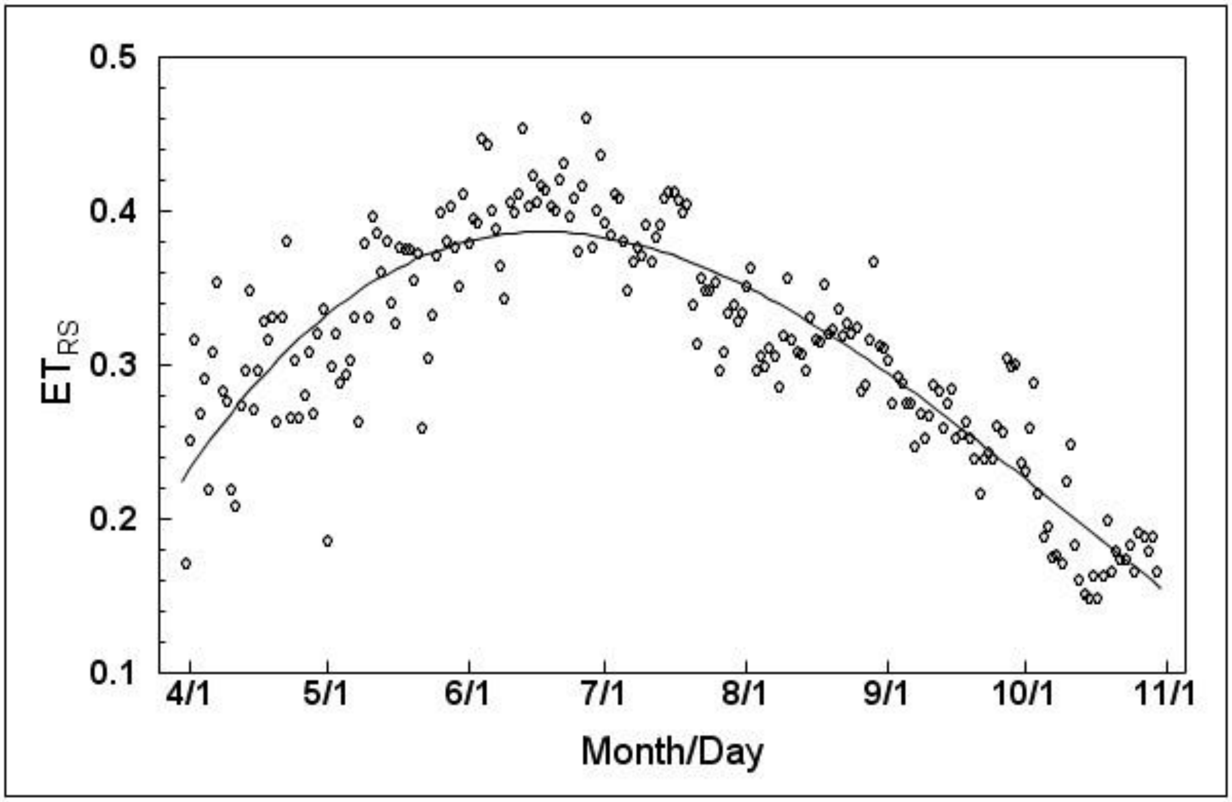

Figure 2. Average daily ET_{rs} between April 1 and October 31 during the five year period 2005-2009 at the ASC Farmington.

Xeric Plant Demonstration Garden

Suggested constant K_L values for plant species in the xeric plant garden, considering measured, variable plant CA and quality observations at the four different drip treatments, ranged from 0.05 for plants that exhibited acceptable quality in the zero irrigation quadrant (average annual effective precipitation of 3.0 inches) to 1.26 for a relatively small plant (*Echinacea purpurea*) that did well only in the quadrant receiving the highest irrigation (Table 2). The recommended irrigation requirement (IR) for each plant (Table 2) was then calculated using Equation 2.

Equation 2:

$$IR = ET_{RS} \times K_L \times D^2 \times 0.49$$

Where:

IR = irrigation requirement per plant, gallons (assuming no rain)
ET_{RS} = total P-M tall canopy reference ET since last irrigation, inches
K_L = landscape coefficient derived from minimum acceptable TF and actual CA
D = measured plant diameter, feet
0.49 = constant for conversion (inches to gallons and plant diameter to CA)

Table 2. Sample list of species in the xeric plant demonstration garden with canopy diameter (D), suggested landscape (crop) coefficient (K_L), and recommended weekly irrigation requirement per plant (IR) after five years of growth based on observed plant quality at four different levels of drip irrigation.

PLANT SPECIES	D	K_L	IR PER WEEK[†]
	feet		gals/plant
Artemisia tridentata (big sagebrush)	5.0	0.05	1.6
Berlandiera lyrata (chocolate flower)	2.5	0.05	0.4
Buddleja davidii (butterfly bush)	3.5	0.42	6.2
Caryopteris clandonensis (blue mist spirea)	4.0	0.24	4.6
Cerastium tomentosum (snow in summer)	2.5	0.78	5.8
Cercocarpus montanus (true mtn. mahogany)	5.0	0.11	3.4
Chilopsis linearis (willow-leaf catalpa)	8.0	0.05	4.0
Echinacea purpurea (purple coneflower)	2.5	1.26	9.4
Fallugia paradoxa (Apache plume)	4.0	0.05	1.0
Forestiera neomexicana (New Mexico olive)	5.0	0.05	1.6
Helianthus maximiliani (Maximilian sunflower)	5.5	0.30	11.0
Hesperaloe parviflora (red yucca)	4.0	0.15	2.8
Agastache foeniculum (blue giant hyssop)	2.5	1.02	7.6
Amelanchier utahensis (Utah serviceberry)	6.0	0.05	2.3
Caragana arborescens (Siberian peashrub)	4.5	0.05	1.3
Centranthus ruber (Jupiter's beard)	3.5	0.36	5.3
Chamaebatiaria millefolium (fernbush)	5.0	0.05	1.6
Gaillardia aristata (blanket flower)	3.0	0.64	6.9
Juniperus scopulorum (Rocky Mountain juniper)	4.5	0.13	3.1
Koelreuteria paniculata (goldenrain tree)	6.5	0.12	6.3
Penstemon ambiguus (bush penstemon)	4.0	0.05	1.0
Prunus besseyi (western sandcherry)	5.0	0.14	4.3
Hylotelephium telephium (autumn joy sedum)	3.0	0.39	4.2
Penstemon strictus (Rocky Mountain penstemon)	3.0	0.55	6.0
Penstemon "abuelitas" (Abuelita penstemon)	2.5	0.29	2.2
Rhus trilobata (3-leaf sumac)	5.0	0.11	3.4
Perovskia atriplicifolia (Russian sage)	4.5	0.13	3.1
Yucca baccata (banana yucca)	3.5	0.05	0.8
Sporobolus wrightii (giant sacaton)	5.0	0.17	5.2
Zinnia grandiflora (desert zinnia)	2.5	0.53	4.0

[†] Assuming no rain. If rain occurs during the week (or period), subtract 60% of the sum from events greater than 0.2 inch from ET_{rs}.

Vegetable Garden

Table 3, Table 4 and Table 5 show the total water applied per plant and marketable yields of chile peppers, tomato and sweet corn, respectively at the different irrigation treatments during four years of study. 'Rowpac' tomatoes were not planted in 2005 and neither 'Big Jim' chile nor sweet corn was planted in 2009. Two suggested constant K_C values for scheduling irrigations on each vegetable crop are also shown. The mean of the conservative K_C values shown in the 'ANOVA' column is suggested for use where water availability may be restricted or expensive and there is a probability that no further increase in yields will be provided at higher irrigation levels. The more liberal mean K_C shown in the 'Max Yield' column is suggested for use where availability of water is not limited or excessively expensive and the grower wants to insure a higher probability of producing maximum yields.

Chile peppers

Chile yield increased with irrigation level in all years except 2006 in which an inverse, but not statistically significant, relationship occurred (Table 3). This lack of response to irrigation in 2006 may have been due to a premature end to the growing season by an early frost that occurred on 23 September. In 2005, 2007, and 2008, statistical ANOVA indicated no significant difference between marketable chile yields produced at the high and medium irrigation treatments (Table 3). The relatively low yields in 2005 were due to a 15% loss of plants and delay in plant growth after planting due to curly top virus. The average suggested K_C values for irrigation scheduling on 'Big Jim' chile peppers were 0.71 and 0.88 for the conservative and more liberal scenarios, respectively.

Table 3. Yields of 'Big Jim' chile peppers at various drip irrigation treatment levels (TF) and suggested K_C values for scheduling drip irrigation based on ANOVA and maximum yield each year.

	TF	**WATER APPLIED**	**MKT. YIELD†**	**SUGGESTED K_C BASED ON…**	
Year	**I/ET_{RS}**	**gals/plant**	**lbs/1000 sq ft**	**ANOVA**	**Max Yield**
2005	1.00	47	743.8 a		1.00
	0.75	40	537.2 ab	0.75	
	0.50	34	427.0 b		
2006	1.05	50	803.5		
	0.85	42	840.2		
	0.65	34	932.0	0.65	0.65
2007	1.00	48	1147.8 a		1.00
	0.75	39	1092.7 a	0.75	
	0.50	31	835.6 b		
2008	0.85	32	1271.8 a		0.85
	0.70	27	1005.5 ab	0.70	
	0.55	22	775.9 b		
			Mean K_C	**0.71**	**0.88**

†ANOVA: Yield values within a year followed by the same letter are not significantly different from each other at the 5% level of confidence based on Tukey's HSD means comparison. The absence of letters indicates no significant difference in yields between treatments within the year.

Tomatoes

No statistically significant difference was found between tomato yields at the different irrigation treatments within any of four years (Table 4). The suggested average constant K_C for scheduling drip irrigations on tomatoes using Equation 2 ranged from 0.57 (based on ANOVA) to 0.77 at plots where maximum yield was observed (Table 4). The lower irrigation amounts and marketable yields of 2006 and 2007, as compared to 2008 and 2009, reflect reduced growth and canopy area in 2006 and 2007 due to disease.

Table 4. Yields of 'Rowpac' tomato at various drip irrigation treatment levels (TF) and suggested K_C values based on ANOVA and maximum yield each year.

		IRRIGATION	**MKT. YIELD†**	**SUGGESTED K_C**	
Year	**TF**	**Gals/plant**	**(lbs/1000 sq ft)**	**By ANOVA**	**By Max Yield**
2006	1.0	43	1455		
	0.75	36	1524		0.75
	0.50	28	1336	0.50	
2007	1.0	48	1263		
	0.75	39	1276		0.75
	0.50	31	909	0.50	
2008	0.85	77	2433		0.85
	0.70	64	2231		
	0.55	51	2218	0.55	
2009	0.96	93	3880		
	0.88	85	3880		
	0.80	78	3770		
	0.72	70	4178	0.72	0.72
			Mean K_C	**0.57**	**0.77**

†ANOVA indicated no significant difference in yields between treatments within any year.

Sweet corn

Maximum yield of sweet corn occurred at the highest level of irrigation (mean K_C = 0.95) in all four years (2005 thru 2008) of study but ANOVA indicated no statistically significant difference between yields at all three irrigation treatments in 2005 nor between the high and medium irrigation treatments in 2006, 2007, and 2008 (Table 5). The average suggested constant K_C values for scheduling irrigations were 0.68 based on ANOVA and 0.95 based on maximum observed yield (Table 5).

Table 5. Yield of sweet corn at various drip irrigation treatment levels (TF) and suggested K_C values based on ANOVA and maximum yield each year.

		IRRIGATION	YIELDS PER 1000 SQ FT		SUGGESTED K_C	
Year	TF	Gals/plant	No. Ears	lbs*	By ANOVA	By Max Yield
2005	1.00	29	611	354		1.00
	0.75	26	540	298		
	0.50	23	537	303	0.50	
2006	1.00	33	690 a	303 a		1.00
	0.75	30	618 a	266 ab	0.75	
	0.50	27	521 b	211 b		
2007	1.00	33	603 a	285 a		1.00
	0.75	26	584 a	275 a	0.75	
	0.50	20	422 b	174 b		
2008	0.80	28	622 a	340 a		0.80
	0.70	24	584 ab	321 ab	0.70	
	0.60	20	554 b	298 b		
				MEAN K_C	**0.68**	**0.95**

†ANOVA: Yield values within a year followed by the same letter are not significantly different from each other at the 5% level of confidence based on Tukey's HSD means comparison. The absence of letters indicates no significant difference in yields between treatments within the year.

Conclusion

Irrigation studies were conducted in an effort to develop drip irrigation scheduling coefficients for drought-tolerant landscape plants (K_L) and three vegetable crops (K_C) commonly grown in small gardens in northwest New Mexico. The xeriscape demonstration garden, with its differentially irrigated quadrants, conveyed some valuable information on the potential growth and quality of more than 90 species of plants at various levels of drip irrigation. While there was considerable variability between suggested K_L values for the different species, an overall K_L of 0.3 is suggested for estimating the water requirements of a mixed-species xeriscape. This is considerably lower than the commonly cited K_L values of 0.6 and 0.8 for warm season and cool season turfgrasses at full green canopy, respectively. Since live canopy area (CA) is an element of the computational procedure for estimating the ET_C or irrigation requirement of all plants, a constant K_L is suggested for use throughout the entire growing season. This is in agreement with the procedures used in California's 'Water Use Classification of Landscape Species' (WUCOLS) guide (Costello and Jones, 1994).

There was also considerable variability in the K_C values of vegetable crops both between species and between years. Conservative mean constant K_C values were 0.57, 0.68, and 0.71 for tomato, sweet corn and chile, respectively, but maximum yields were observed at more liberal mean K_C values of 0.77, 0.95, and 0.88 for the respective crops. As in the xeriscape study, the same procedures for calculating drip irrigation treatments and formulating K_C values and estimating irrigation requirements were used; that is, a single constant K_C for the entire growing season was used with variable live per plant canopy area in the equations. This method has some advantages over the commonly published K_C curves that exhibit a linear increase in K_C during the crop development stage and then a linear decline in late season (Allen et al., 1998), in that it compensates for non-standard conditions such as variability in plant spacing, plant varietal differences, plant health, and other factors which may affect live canopy area.

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