ESTIMATING CROP WATER PRODUCTION FUNCTIONS BASED ON TRANSPIRATION AND CROP GROWTH CURVES THROUGH MODELING

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ABSTRACT

This report concerns the development of crop growth curves based upon growing degree days instead of calendar days and the development of crop water production functions based upon transpiration.

Lysimeter data to carry out these procedures for alfalfa, corn, wheat, barley, grain sorghum and cotton was available from four New Mexico sites with different climates. Once the crop growth curves were derived, they were statistically compared to determine if they were similar in spite of the climatological differences. Results indicate that the crop growth curves were statistically ($P \geq 0.05$) similar for crops grown from northern to southern New Mexico.

Lysimeter data was not available for lettuce, onions, chile, potatoes or pinto beans. Thus, crop coefficients were derived from the literature and a modeling approach was utilized to devise the crop growth curves based upon growing degree days.

The development of crop water production functions based upon transpiration also was carried out for the above crops. This step was undertaken to remove some of the variability caused by the evaporation component of evapotranspiration. These functions can be used statewide and on various soil types.

Key words: crop water production functions, transpiration,
lysimeters, crop growth curves, modeling.

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BACKGROUND RESEARCH DESIGN AND RESULTS

Production functions were developed in various WRRI studies for corn, alfalfa, winter wheat, cotton, sorghum, and spring and winter barley (Sammis 1979, 1981, 1983a, 1983b). These studies focused on measuring evapotranspiration (E_t) or consumptive crop-water use and yield under varying irrigation levels. Table 1 presents the crops investigated in these studies and the location where the research was conducted.

Evapotranspiration was measured using the water balance technique as stated in equation 1:

$$E_t = I + R - D + \Delta SM \qquad (1)$$

where:

I = irrigation

R = rainfall

D = drainage

ΔSM = the change in soil moisture

Nonweighing lysimeters installed in field plots in a 1976-1977 study were used to measure non-stressed E_t for each crop (Sammis 1979). Yield was measured at the end of the growing season.

In other studies (Sammis 1981, 1982, 1983a, 1983b; Kallsen et al. 1983, 1984), the plots were irrigated by a sprinkler line source (Hanks 1976). This technique allowed non-stress water amounts to be applied near the sprinkler line and decreasing water amounts to be applied perpendicular to the line. Evapotranspiration at selected locations away from the sprinkler line was measured based on the water balance equation 1. Drainage water was pumped from the lysimeters and measured during several days following irrigation.

Table 1

Crops grown at New Mexico State University agricultural experiment stations, 1976, 1977, and 1978.

Location	1976[1]	1977[1]	1978[2]
Las Cruces - Plant Science Research Center	Alfalfa, Mesilla Sorghum, RS671[3] Cotton, 1517V	Alfalfa, Mesilla Sorghum, RS671[3] Cotton 1517V Barley Sudangrass	Alfalfa, Hairy Peruvian Cotton, 1517-75
Artesia - Southeastern Branch	Alfalfa, Mesilla Barley, Penasco Sorghum, RS671 Cotton, 1517V	Alfalfa, Mesilla Barley, Penasco Sorghum, RS671 Cotton, 1517V	
Clovis - Plains Branch Station	Alfalfa, Mesilla Sorghum, De Kalb E59+ Corn, Pfizer TXS-115A Wheat, Centruck	Alfalfa, Mesilla Sorghum, De Kalb E59+ Corn, Pfizer TXS-115A Wheat, Centruck	
Farmington - San Juan Branch Station	Alfalfa, Mesilla Sorghum, RS671 Barley, Steptoe Corn, PX610	Alfalfa, Mesilla Sorghum, RS671 Barley, Steptoe Corn, PX610	

[1] Crops grown in lysimeters with surface flooding.

[2] Crops grown in field plots with sprinkler irrigation.

[3] Crop yields were omitted due to damage by birds.

The resulting yield under the decreased water applications was also measured. From the experimental data, based on the lysimeter and sprinkler line source experiments, the E_t-yield relationship was estimated by least-squares regression. These functions are presented in Table 2.

TRANSPIRATION VS. YIELD FUNCTIONS

Crop water requirements are a function of type of plant, plant growth stage, and weather conditions. Transpiration is difficult to measure in the field, consequently, evaporation is normally measured using a water balance technique, or lysimeters. Yield at harvest time is generally considered to be a direct linear function of the amount of E_t during the growing season. However, because of differences in irrigation applications, soil types, and other variables, the soil evaporation component (E_s) of E_t can cause the function to become nonlinear (Kallsen et al. 1984). A better estimator of the relationship between consumptive use and crop yield is a function that relates crop yield to transpiration (T). Transpiration is directly related to the photosynthesis rate, whereas soil evaporation contributes nothing to plant growth and yield. For these reasons, a method was devised to separate E_t into its components.

Evapotranspiration was separated into its components by using an irrigation scheduling model developed by Sammis (IRRSCH) to model E_t, E_s, and T. IRRSCH is based on the water balance concept as outlined in equation 1. The model takes into account differences in soil

Table 2

Original E_t-yield production functions used as input in IRRSCH[*].

Crop	Production Function	R^2
Alfalfa	$y = -1.36 + .11E_t$[**]	87.00
Corn	$y = -7,674 + 173E_t$	94.90
Sorghum	$y = -955 + 126E_t$	99.37
Cotton	$y = -74 + 12E_t$	62.12
Wheat	$y = -996 + 74E_t$	88.00
Winter Barley	$y = -5,127 + 194E_t$	94.57

[*] Production functions were derived from the following sources: alfalfa--"Effects of Decreased Watering on Crop Yields," WRRI Report No. 136, August 1981, p. 9; corn--"The Effect of Moisture Stress On Corn Production in the High Plains," WRRI Report No. 171, May 1983, p. 10; sorghum and cotton--"Consumptive Use and Yields of Crops in New Mexico," WRRI Report No. 115; winter wheat and barley--"The Effects of Decreased Watering on Wheat and Barley Yields," WRRI Report No. 179, January 1983, pp. 14-28.

[**] Yield is expressed in kilograms per hectare for all crops but alfalfa and E_t is expressed in centimeters. Alfalfa yield is expressed in tons per hectare.

type, application uniformity, management practices and weather variation.[1]

In order to model E_t, E_s and T, each crop's original data on irrigation frequency and amount of water from the sprinkler line source were used as input data in IRRSCH along with climatological data needed to run the model.

RESULTS

The model's output included the amount of soil evaporation that had occurred during the growing season. The evaporation component was subtracted from E_t to derive the amount of T that had occurred. Tables 3 through 8 present, by crop, the original amounts of E_t, the modeled E and T, and the yield data from the field studies. For alfalfa, the measured E_t and the modeled E_t were very similar for all levels of measured E_t in the irrigation studies. This similarity was also true for corn, barley, and grain sorghum. The measured E_t for cotton grown in the lysimeters and under the sprinkler line and the modeling of that data were difficult to match up as reflected in table 5. There was wide variation in the measured and modeled E_t, indicating either that the irrigation studies lacked validity, or that the modeling of cotton growth required some change in the structure of the model. This was also true for the measured and modeled E_t of wheat.

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[1] For a complete discussion on the IRRSCH model, see Lansford et al. 1982, or Mapel 1984.

Table 3

Measured vs. modeled E_t, E, T, and yield for alfalfa.

Measured E_t	Modeled E_t	E	T	Yield	Modeled Rooting Depth
(centimeters)				(kg/hectare)	(meters)
36.6	35.8	12.9	23.6	.4	.91
40.6	40.1	12.9	27.8	1.2	.91
45.0	43.7	12.7	32.3	1.5	.91
50.4	49.5	12.6	37.8	2.2	.91
55.6	56.4	12.6	43.0	5.1	.91
65.6	64.5	15.1	50.5	6.7	.91
76.5	73.4	18.0	58.5	8.9	.91
89.2	85.9	19.4	69.8	10.8	.91
116.3	96.0	19.1	97.2	11.8	.91
111.3	106.7	19.8	91.5	15.1	.91
121.0	122.2	20.7	100.2	14.3	.91
131.3	131.3	20.6	110.7	15.2	1.20
147.1	142.7	21.3	125.8	15.1	1.20
156.7	150.1	23.0	133.7	15.0	1.20
149.0	152.1	23.0	126.0	15.2	1.20
163.0	154.4	24.1	138.7	14.1	1.20
152.2	143.0	23.6	128.6	12.7	1.20
141.0	140.7	22.3	118.8	12.4	1.20
124.0	123.4	21.3	102.7	12.8	.91
116.0	117.1	21.4	94.6	12.7	.91
105.0	104.4	20.4	82.0	11.8	.91
98.1	99.3	20.3	77.8	10.2	.91
89.6	89.7	20.3	69.3	10.6	.91
79.4	81.8	18.3	59.8	8.7	.91
69.2	72.4	16.5	52.7	7.6	.91
58.3	67.3	14.8	43.5	6.1	.91
48.1	60.5	14.5	33.6	5.7	.91

Source of measured E_t and yield: "Effects of Decreased Watering on Crop Yields," WRRI Report No. 136, August 1981, p. 8, table 2, 1980 E_t - yield data.

Table 4

Measured vs. modeled E_t, E, T, and yield for corn.

Measured E_t	Modeled E_t	E	T	Yield	Modeled Rooting Depth
(centimeters)				(kg/hectare)	(meters)
39.3	42.2	15.2	24.1	103	1.2
44.3	46.7	15.2	29.1	116	1.2
57.5	59.7	20.3	37.2	610	1.2
69.5	69.3	19.6	50.0	3,542	1.2
87.4	85.9	21.6	65.8	8,197	1.2
96.5	92.5	20.1	76.4	9,763	1.2
98.6	91.9	21.8	77.0	9,572	1.2
100.5	91.9	20.1	80.4	9,555	1.2
97.8	93.0	21.8	76.0	9,218	1.2
91.1	85.3	20.1	71.0	8,234	1.2
75.1	76.2	20.8	54.3	5,411	1.2
64.7	64.0	17.5	47.2	2,834	1.2
53.1	54.4	17.8	35.3	1,023	1.2
46.4	45.2	15.0	31.4	256	1.2
36.7	38.4	12.7	24.0	100	1.2
39.2	39.4	13.5	25.7	58	1.2
47.9	46.7	16.0	31.9	591	1.2
58.8	58.4	18.8	40.0	2,074	1.2
70.8	66.8	17.5	53.3	4,550	1.2
83.3	71.4	19.1	64.3	6,871	1.2
91.2	89.2	20.3	70.9	8,699	1.2
94.0	93.0	21.8	72.2	8,879	1.2
100.5	92.5	20.3	80.2	9,702	1.2
94.0	91.9	20.3	73.7	8,954	1.2
86.4	91.2	21.1	65.3	7,825	1.2
78.4	77.0	19.3	59.1	4,805	1.2
65.4	62.2	19.1	46.4	889	1.2
54.4	51.1	17.3	37.3	455	1.2
46.3	42.7	14.5	31.8	123	1.2
39.5	38.4	12.7	26.8	518	1.2

Source of measured E_t and yield: "The Effects of Moisture Stress on Corn Production in the High Plains". Water Resources Research Institute Technical Report No. 171, May 1983, p. 10, table 3, 1980 E_t-yield data.

Table 5

Measured vs. modeled E_t, E, T, and yield for barley.

Measured E_t	Modeled E_t	E	T	Yield	Modeled Rooting Depth
(centimeters)				(kg/hectare)	(meters)
55.6	52.3	16.5	39.2	5,735	.91
54.5	49.5	16.9	37.6	5,199	.91
51.6	45.7	14.6	37.0	5,143	.91
44.6	46.2	14.5	30.1	3,168	.91
42.3	42.9	13.8	28.5	3,580	.91
42.3	40.9	13.9	28.4	3,122	.91
39.2	39.4	13.8	25.3	2,237	.91

Source of measured E_t and yield: "The Effects of Decreased Watering on Wheat and Barley Yields," WRRI Report No. 179, January 1983, p. 14, table 4, subplot receiving 168 kg N/ha.

Table 6

Measured vs. modeled E_t, E, T, and yield for cotton.

Measured E_t	Modeled E_t	E	T	Yield	Modeled Rooting Depth
(centimeters)				(kg/hectare)	(meters)
34.5	39.4	11.9	22.5	397	.91
40.3	41.9	11.8	28.4	470	.91
44.3	44.7	11.8	32.5	567	.91
51.3	56.6	16.8	34.5	527	.91
53.4	58.9	18.1	35.4	646	.91
52.9	57.4	17.7	35.2	469	.91
58.6	61.2	18.3	40.4	586	.91
46.2	56.1	17.9	28.3	595	.91
43.5	43.4	14.5	29.0	429	.91
41.7	43.7	12.1	29.5	380	.91
39.7	38.7	11.9	27.8	304	.91
37.2	37.9	11.8	25.4	292	.91
31.6	33.8	10.9	20.7	287	.91

Source of measured E_t and yield: "Consumptive Use and Yields of Crops in New Mexico," WRRI Report No. 115, original data used with outlying points omitted.

Table 7

Measured vs. modeled E_t, E, T, and yield for wheat.

Measured E_t	Modeled E_t	E	T	Yield	Modeled Rooting Depth
(centimeters)				(kg/hectare)	(meters)
28.5	36.6	9.7	18.8	1,204	.91
30.3	37.8	9.7	20.7	1,268	.91
33.7	42.1	11.7	22.0	1,692	.91
42.2	47.2	12.7	29.7	2,196	.91
46.8	53.1	15.5	31.3	2,600	.91
52.0	57.4	16.3	35.7	3,173	.91
55.8	58.9	18.5	37.3	2,718	.91
57.7	62.0	19.8	37.9	2,898	.91
52.8	59.9	19.1	35.4	3,374	.91
49.7	56.1	16.3	33.5	2,697	.91
45.7	52.1	14.5	31.2	2,227	.91
36.4	47.8	14.5	21.9	1,641	.91
32.8	42.9	12.2	20.6	1,325	.91
32.4	41.1	12.7	19.7	891	.91

Source of measured E_t and yield: "The Effects of Decreased Watering on Wheat and Barley Yields," WRRI Report No. 179, January 1983, p. 28, table 12, plot for 1981.

Table 8

Measured vs. modeled E_t, E, T, and yield for sorghum.

Measured E_t	Modeled E_t	E	T	Yield	Modeled Rooting Depth
(centimeters)				(kg/hectare)	(meters)
32.3	32.3	13.2	19.1	3,016	.91
48.3	48.3	13.7	34.5	5,337	.91
64.0	64.0	19.3	44.7	6,862	.91
71.1	71.1	19.8	51.3	7,843	.91
73.9	73.9	18.5	55.4	8,462	.91
75.9	75.9	19.3	56.6	8,643	.91

Source of measured E_t and yield: "Consumptive Use and Yields of Crops in New Mexico," WRRI Report No. 115, original data base used with outlying points omitted.

To derive the transpiration yield functions, T was then regressed on the original yield data from the field studies. Table 9 presents the estimated crop water production functions based solely on transpiration. Comparing the results of table 9 to those in table 2 shows some differences. These differences in the functions reflect removal of the evaporation component, and the decreased variability caused by it. The coefficient of determination (R^2) ranges from 99.04 for grain sorghum to 53.64 for cotton, with most determinations falling in the upper range. This finding indicates that for most of the crops, yield formation is highly dependent on transpiration. For cotton, the low coefficient of determination implies that some yield determining component has been omitted.

Growing Degree Days

One other modeling technique used involved a theoretical agronomic relationship between heat units accumulated over the growing season and physiological crop development. The technique involved the concept of growing degree days (G) and its relationship to crop coefficients, physiological crop maturity, and final crop yield (Shaw 1978).

Crop coefficients have been used to estimate evapotranspiration (E_t) for particular crops from estimates or measurements of potential or reference evapotranspiration (E_o). Crop coefficients are the empirical ratio of E_t to E_o and are derived from experimental data. Coefficients for a particular crop vary with time and constitute a crop curve. They are used in computerized irrigation scheduling programs such as described by Jensen et al. (1971) and Heermann et al. (1976). Crop coefficients are normally derived under conditions

Table 9

Crop water production functions based on transpiration.

Crop	Function	R^2
Alfalfa	$Y = .06 + .12T$	88.37
Corn	$Y = -5,689 + 195T$	96.07
Sorghum	$Y = 164 + 150T$	99.00
Cotton	$Y = -31 + 16T$	54.30
Winter Wheat	$Y = -810 + 104T$	99.45
Winter Barley	$Y = -3,638 + 237T$	96.62
Spring Barley*	$Y = -222 + 162T$	98.00

*Function developed by Kallsen, et al., 1984.

Where: Y is measured in kilograms per hectare for all crops but alfalfa and t is measured in centimeters. Y alfalfa is in tons per hectare.

where growth is not limited by moisture, insects, or any other climatological or physiological factors.

When moisture stress becomes limiting, the ratio of E_t to E_o decreases along with yield. Hanks' (1974) irrigation scheduling model incorporates the effect of moisture stress on E_t and yield. Crop curves can be expressed as a ratio of E_t/E_o versus time (Wright 1982), where time can be a Julian date or days since planting. Crop curves can also be expressed as a function of crop stage where the crop coefficient may be constant or linearly increasing over that stage. The crop stages are divided into the initial stage, development stage, mid-season stage, and late stage. The number of days at each stage is then specified (Doorenbos and Kassam 1979). Crop curves may be expressed as a function of percent effective cover from 0 to 100, and then days after effective cover (Jensen 1974). All of these methods require either knowledge about the development rate of the crop measured in the field, or are a time based procedure assuming that the development rate of the crop is constant from year to year, does not vary with location, and is equal to the same rate of crop development as when the initial measurements were made to estimate the crop curves.

Originally, for modeling purposes, the calendar year was used to simulate crop development during the growing season. For example, corn might be planted April 15 and harvested October 10 with an approximate growing season of 180 days. Time based functions were developed that used that number of days to model physiological development and to account for final crop yield. The growing degree day concept is a different type of crop development measure.

The concept of the growing degree day involves the determination of the number of degrees by which the daily mean temperature on a given day exceeds an appropriate base temperature. Each degree in excess is called a growing degree day. The greater the number of growing degree days for a given day the greater is crop development.

Crop development is generally dependent on heat units, and a physiological clock can be developed based on growing degree days. Mederski et al. (1973) reported that the coefficient of variation was small and was half as variable in describing the timing of physiological development of corn based on accumulated heat units, compared to the calendar day method. Growing degree days also have been used to develop physiological clocks for sorghum (Arkin et al. 1976), alfalfa (Holt et al. 1975), cotton (Stapleton 1970), and soybean (Major 1975).

One purpose of this paper is to present a method of calculating crop curves based on growing-degree-days, in order to account for the year to year climatological variability affecting crop growth and to determine if a crop curve developed under a particular climatic condition can be transferred to an area with a different climate.

Base, Maximum, and Minimum Temperatures

To arrive at the number of growing degree days for a given calendar day, the maximum and minimum temperatures are averaged to arrive at the daily mean temperature. Certain crops require a daily mean temperature of at least 10 degrees centigrade before crop development will occur. Others may require more or less heat in order for crop development to occur. These temperatures are called the base temperatures (Shaw 1978).

In addition to base temperatures, there are also maximum and minimum cutoff temperatures. Many crops grow best within a certain range of temperatures. Corn, for example, grows best when the temperatures range is from 30 to 10 degrees centigrade. To acknowledge this fact, maximum and minimum cutoff temperatures are set at those temperatures. Any day above 30 degrees is set to 30 degrees and any temperature below 10 degrees is set to 10 degrees. Thus, any excess growing degrees during the day in which crop development has ceased or slowed are not counted and any day when growing degrees fall below the optimal temperature is not counted. The growing degree days are determined for each day in this manner and accumulated for a growing season. Growing degree days are calculated according to equation 2.

$$G = \frac{T_{min} + T_{max}}{2} - \text{BASET} \qquad (2)$$

where:

T_{max} = the maximum temperature on a given day

T_{min} = the minimum temperature on a given day

BASET = a predetermined temperature which represents the minimum temperature at which a crop will grow.

The concept of the G has been proposed to be a better indicator of crop development than days between planting and harvest (Shaw 1978). Weather conditions can and will vary from location to location and from year to year. In New Mexico, this is certainly true. Growing degree days, on the other hand, when accumulated over the growing season (G_T), will not vary as much from site to site or from year to year. Generally, no matter where or when a crop is planted, similar varieties require approximately the same number of growing degree days to reach physiological maturity. Hypothetically, accumulated G and the rate of physiological crop development will be the same regardless of the year or location.

This relationship was tested for each of the crops grown at the locations in table 1. The optimal temperature ranges used for each crop are presented in table 10. Weather data were collected and G_T were calculated for each of the study sites and for each of the crops where E_t and yield were measured. The temperature ranges shown in table 10 were used for these calculations.

RESULTS AND DISCUSSION

Table 11 shows the number of accumulated G calculated for each site by crop and year. As can be seen from the table, the number of G_T did not vary considerably from year to year or from site to site in spite of different planting and harvesting dates. These similarities indicate that G_T for similar crop varieties grown in four locations in New Mexico are similar. This stability also indicates that phenological crop development is similar at each of the locations for each of the years the crops were grown. To test the relationship between G_T and crop development, crop growth coefficients developed by Sammis (1979) were fitted through multiple regression to the data in the form of a 3d-order polynomial:

$$AKC = B_o + B_1(G_T) + B_2(G_T{}^2) + B_3(G_T{}^3) \qquad (3)$$

Table 10

Maximum, minimum, and base temperatures, lysimeter grown crops.

Crop	Maximum Temperature	Minimum Temperature	Base Temperature
	------------(degrees	centigrade)------------	
Alfalfa	--	--	5
Corn	30	10	10
Sorghum	--	--	7
Cotton	30	12	12
Winter Wheat	--	3	3
Winter Barley	30	5	5

Source: Arkin et al. 1971 and Lansford et al. 1983.

Table 11

Growing degree days by crop and location,
1976 and 1977, based on planting and harvest dates.

Crop	Location	Planting Date	Harvest Date	Accumulated Growing Degree Days
Alfalfa	Artesia	1-1-77	12-31-77	4,037
	Clovis	1-1-77	12-31-77	3,420
	Farmington	3-1-77	11-31-77	3,064
	Las Cruces	1-1-76	12-31-76	3,691
	Las Cruces	1-1-77	12-31-77	3,960
	Mean: 3,634			
	Standard Deviation:	401		
Corn	Clovis	4-7-76	10-8-76	1,796
	Clovis	4-7-77	9-21-77	1,716
	Farmington	5-10-76	10-21-76	1,681
	Farmington	5-09-77	10-13-77	1,710
	Mean: 1,725			
	Standard Deviation:	49		
Sorghum	Artesia	5-18-76	10-1-76	2,193
	Artesia	5-17-77	9-27-77	2,329
	Clovis	5-3-76	10-20-76	2,179
	Clovis	5-19-77	10-14-77	2,097
	Farmington	5-20-76	10-21-76	2,076
	Las Cruces	5-25-76	9-18-76	1,967
	Las Cruces	5-18-77	9-23-77	2,228
	Mean: 2,152			
	Standard Deviation:	117		
Wheat	Clovis	10-14-76	6-23-77	1,970
Barley	Artesia	9-15-76	5-23-77	1,809
Cotton	Artesia	4-13-76	10-21-76	1,708
	Artesia	4-20-77	10-13-77	1,800
	Las Cruces	5-06-76	10-27-76	1,645
	Las Cruces	4-22-77	10-23-77	1,823
	Mean: 1,744			
	Standard Deviation:	83		

Source: Data on planting and harvesting dates can be found in WRRI Report 115, 1979.

where:

AKC is the monthly ratio of E_t to E_o and represents crop development (Sammis 1979).

The above model was tested on all of the crops, for both years and for all of the sites. Table 12 presents, for each of the crops, the coefficients derived by this method for the single and combined 3d-order polynomials. For example, the coefficients for the Clovis 1976 corn polynomial are presented as well as the 1977 coefficients and the combined 1976 and 1977 polynomial. This procedure is repeated for corn grown in Farmington in 1976 and 1977 and its combined form. Table 12 also presents the crop coefficients for corn for the polynomial derived by combining the Clovis and Farmington data for 1976 and 1977. This process is presented for each of the lysimeter based crops, with the exception of winter wheat and winter barley. The polynomials for these crops are not shown because they were only grown in one location for one year.

The 3d-order polynomials for each year, site, and crop were statistically compared to one another by using an F test as shown in equation 4.

$$F = \frac{\dfrac{\text{SS Residuals}_T - \text{SS Residuals}_1 - \text{Residuals}_2}{(N_1 + N_2 - 4) - (N_1 - 4) - (N_2 - 4)}}{\dfrac{\text{SS Residuals}_1 + \text{SS Residuals}_2}{(N_1 - 4) + (N_2 - 4)}} \tag{4}$$

Table 12

Yearly and combined coefficients for 3rd-order polynomials, by crop and location.

CROP	SITE	YEAR	B_0	B_1	B_2	B_3	R^2	S.E.
Alfalfa	Clovis	1977	2.7e-1	1.1e-3	-2.8e-7	-6.6e-12	79.82	.20766
Alfalfa	Artesia	1977	4.02e-1	1.2e-3	-5.7e-7	7.1e-11	70.27	.19142
Combined - - - - - - - - -			2.3e-1	1.5e-3	-6.9e-7	7.9e-11	81.38	.16727
Alfalfa	Las Cruces	1976 (b)	5.22e-1	1.08e-3	-5.4e-7	7.7e-11	67.06	.67888
Alfalfa	Las Cruces	1977 (a)	3.58e-1	1.11e-3	-3.2e-7	5.4e-12	87.25	.18624
Alfalfa	Las Cruces	1977 (b)	1.51e-1	1.25e-3	-3.7e-7	1.6e-11	93.99	.11703
Alfalfa	Las Cruces	1977 (c)	3.4e-1	1.23e-3	-4.0e-7	2.0e-11	78.85	.25177
Alfalfa	Farmington	1977	5.5e-1	6.8e-4	-2.8e-8	-6.6e-11	79.64	.18922
1977 Combined a & b								
Las Cruces - - - - - -			2.1e-1	1.3e-3	-3.8e-7	1.5e-11	87.67	.16736
1977 Combined a & c								
Las Cruces - - - - - -			2.9e-1	1.3e-3	-4.2e-7	2.0e-11	82.52	.20766
1977 Combined b & c								
Las Cruces - - - - - -			2.44e-1	1.24e-3	-3.8e-7	1.8e-11	83.25	.19124
1977 Combined a, b & c								
Las Cruces - - - - - -			2.3e-1	1.3e-3	-4.1e-7	1.9e-11	84.11	.18814
Combined b 1976 & a 1977								
Las Cruces - - - - - -			4.59e-1	9.1e-4	-2.5e-7	3.0e-13	75.28	.20335
Combined b 1976 & b 1977								
Las Cruces - - - - - -			3.4e-1	1.0e-3	-3.2e-7	1.6e-11	75.81	.19853
Combined b 1976 & c 1977								
Las Cruces - - - - - -			4.46e-1	9.7e-4	-2.9e-7	8.2e-12	69.78	.23341
1976 & 1977 Combined								
Las Cruces - - - - - -			2.9e-1	1.2e-3	-3.7e-7	1.7e-11	78.80	.20509
Combined Artesia &								
Las Cruces - - - - - -			3.5e-1	1.1e-3	-4.0e-7	2.9e-11	73.76	.20347
Combined Clovis &								
Las Cruces - - - - - -			3.2e-1	1.2e-3	-4.1e-7	2.5e-11	75.72	.20443
Combined Artesia, Clovis &								
Las Cruces - - - - - -			3.0e-1	1.3e-3	-5.0e-7	4.4e-11	74.87	.20338
Combined All Of State- -			4.1e-1	1.1e-3	-4.3e-7	3.6e-11	70.00	.20391

Table 12 (Continued)

CROP	SITE	YEAR	B_0	B_1	B_2	B_3	R^2	S.E.
Sorghum	Clovis	1976	5.3e-2	1.4e-3	-1.4e-7	-2.2e-10	92.16	.18025
Sorghum	Clovis	1977	9.9e-2	1.9e-3	-1.5e-6	3.3e-10	94.56	.08075
	Combined Clovis- - - - -		8.6e-2	1.6e-3	-7.5e-7	2.1e-11	78.42	.17190
Sorghum	Artesia	1976	2.1e-1	9.6e-4	-2.7e-7	-5.4e-11	99.84	.01876
Sorghum	Artesia	1977	COULD NOT BE REGRESSED-NOT ENOUGH DEGREES OF FREEDOM FOR REGRESSION					
	Combined Artesia - - - -		6.8e-2	1.4e-3	-6.9e-7	6.7e-11	92.92	.09448
	Combined Artesia & Clovis		8.4e-2	1.4e-3	-5.8e-7	-1.7e-11	80.29	.14047
Sorghum	Farmington	1976 (s)	-9.7e-2	2.3e-3	-1.2e-6	6.8e-11	97.56	.10316
Sorghum	Farmington	1976 (n)	-1.5e-1	1.3e-3	-1.5e-7	-2.6e-10	88.81	.22523
	Combined Farmington- - -		2.5e-2	1.8e-3	-6.9e-7	-9.8e-11	91.48	.13819
	Combined Farm, Clovis & Artesia- - - - - - - -		3.1e-2	1.8e-3	-8.4e-7	1.2e-11	76.76	.17983
Sorghum	Las Cruces	1976 (a)	4.3e-2	1.4e-3	-1.3e-7	-2.6e-10	91.80	.21993
Sorghum	Las Cruces	1976 (c)	1.9e-1	1.7e-3	-7.9e-7	-2.8e-11	82.58	.30252
	Combined Las Cruces 1976 a & c - - - - - - -		1.2e-1	1.5e-3	-4.6e-7	-1.5e-10	84.39	.17208
Sorghum	Las Cruces	1977 (a)	-2.7e-3	1.4e-3	-5.9e-7	-7.1e-12	95.42	.12559
Sorghum	Las Cruces	1977 (b)	1.1e-2	1.9e-3	-1.2e-6	1.3e-10	98.95	.07403
Sorghum	Las Cruces	1977 (c)	-9.3e-2	2.1e-3	-1.4e-6	2.6e-10	93.46	.15269
	Combined Las Cruces 1977 a & b - - - - - - -		4.2e-3	1.7e-3	-9.0e-7	6.2e-11	92.43	.10462
	Combined Las Cruces 1977 a & c - - - - - - -		-4.8e-2	1.7e-3	-1.0e-6	1.3e-10	93.29	.08853
	Combined Las Cruces 1977 c & b - - - - - - -		-4.1e-2	2.0e-3	-1.3e-6	1.9e-10	91.65	.11072
	Combined Las Cruces 1977 a, b & c- - - - - -		-2.8e-2	1.8e-3	-1.1e-6	1.3e-10	91.08	.00680
	Combined all sites, 1976 & 1977- - - - - -		3.0e-2	1.7e-3	-9.4e-7	6.3e-11	83.17	.14218
	Combined All Of State All Years- - - - - - -		8.9E-2	1.6E-3	-7.5E-7	8.4E-13	74.44	.17367

Table 12 (Continued)

CROP	SITE	YEAR	B_0	B_1	B_2	B_3	R^2	S.E.
Cotton	Artesia	1976	1.3e-1	1.5e-5	1.5e-6	-8.4e-10	81.82	.19168
Cotton	Artesia	1977	-1.9e-1	3.4e-3	-2.6e-6	5.5e-10	83.99	.26087
	Combined Artesia 1976 & 1977- - - - - -		1.0e-2	1.6e-3	-4.8e-7	-1.4e-10	69.95	.25108
Cotton	Las Cruces	1976 (a)	1.9e-1	2.4e-5	2.7e-6	-1.7e-9	88.55	.24092
Cotton	Las Cruces	1976 (b)	1.8e-1	-1.6e-4	3.2e-6	-1.9e-9	80.11	.25693
Cotton	Las Cruces	1976 (c)	9.8e-3	2.1e-3	-1.2e-6	9.7e-11	66.51	.33333
	Combined Las Cruces a & b		1.9e-1	-6.9e-5	3.0e-6	-1.8e-9	83.56	.21724
	Combined Las Cruces a & c		1.0e-1	1.1e-3	7.5e-7	-7.8e-10	74.03	.23388
	Combined Las Cruces b & c		9.7e-2	9.8e-4	9.9e-7	-9.0e-10	68.70	.27593
	Las Cruces a, b & c		-1.3e-1	2.7e-3	-1.5e-6	9.9e-11	70.45	.25019
Cotton	Las Cruces	1977 (a)	-4.6e-2	6.7e-4	1.6e-6	-1.0e-9	89.20	.23324
Cotton	Las Cruces	1977 (b)	-1.1e-2	3.7e-4	2.0e-6	-1.2e-9	91.08	.21761
Cotton	Las Cruces	1977 (c)	2.5e-2	3.3e-4	1.7e-6	-9.9e-10	93.91	.14780
Cotton	Las Cruces	1977 a/b	-2.8e-2	5.2e-4	1.8e-6	-1.1e-9	90.03	.17593
Cotton	Las Cruces	1977 a/c	-1.1e-2	5.0e-4	1.6e-6	-9.9e-10	90.38	.15792
Cotton	Las Cruces	1977 b/c	6.9e-3	3.5e-4	1.9e-6	-1.1e-9	90.04	.15596
	Combined 1977 a, b & c		-1.1e-2	4.6e-4	1.8e-6	-1.1e-9	90.20	.15552
	Combined 1976 & 1977 Las Cruces		-4.1e-3	1.1e-3	8.1e-7	-7.4e-10	78.72	.21153
ALL COTTON ALL YEARS & SITES			4.2e-4	1.2e-3	4.6e-7	-5.8e-10	75.47	.21877
Corn	Clovis	1976	-2.092e	-2.57e-3	-8.7e-7	-2.66e-10	98.26	.09077
Corn	Clovis	1977	8.87e-1	-2.88e-4	2.51e-6	-1.47e-9	96.37	.11156
	Combined - - - - - - - - -		2.63e-2	1.62e-3	5.28e-8	-5.4e-10	89.75	.15532
Corn	Farmington	1976	1.17e-2	3.1e-3	-2.0e-6	7.8e-11	90.28	.23705
Corn	Farmington	1976	1.27e-1	8.25e-4	1.94e-6	-1.5e-9	98.85	.09684
	Combined - - - - - - - - -		5.8e-2	2.1e-3	-2.4e-7	-6.3e-10	89.73	.17146
Corn	Farmington	1977	3.4e-1	9.9e-4	7.27e-8	-3.2e-10	97.29	.08108
Corn	Farmington	1977	3.78e-1	-2.1e-4	2.49e-6	-1.5e-9	92.58	.17988
	Combined - - - - - - - - -		3.3e-1	7.7e-4	5.6e-7	-6.5e-10	90.64	.11153
TOTAL FARMINGTON COMBINED - -			2.1e-1	1.38e-3	1.78e-7	-6.4e-10	84.35	.16105
TOTAL STATE COMBINED - - -			1.2e-1	1.7e-3	-2.5e-7	-4.4e-10	82.62	.16943

where:

SS Residuals_T = the sums of squares residuals from the combined polynomial

SS Residuals_1 = the sums of squares residuals from polynomial 1

SS Residuals_2 = the sums of squares residuals from polynomial 2

N = the number of data points.

This test was used to determine if the crop growth polynomials were similar even though the crops were grown in different locations and in different years. For example, the polynomial for corn grown at Clovis in 1976 was statistically compared to the polynomial for corn grown at Clovis in 1977. The data points used to derive these polynomials were combined and the resulting polynomial was compared to the polynomial for corn grown in Farmington in 1976 and 1977. Each of the tests resulted in an F score. The resulting F score was compared to a tabularized value. If the calculated F score was less than the tabular F value at the 5 percent level, the polynomials were considered to be statistically the same. This testing method was done for each of the crops that could be tested in this manner. Table 13 presents the coefficients by crop for the final combined 3d-order polynomials. The equations were statistically the same for each of the crops tested. The resulting equations were incorporated into IRRSCH and validated by running the model using the sprinkler line source data.

NONLYSIMETER BASED CROPS

Production functions based upon transpiration rather than evapotranspiration were developed for alfalfa, corn, cotton, winter

Table 13

Growing degree day coefficients for physical model, 3d-order polynomial, by crop.

Crop: Alfalfa
Lysimeter Data Base: Artesia, Clovis, Farmington, and Las Cruces
B_0 = 4.05E-1 R^2 = 69.65
B_1 = 1.11E-3 F tabulated = 2.53
B_2 = -4.25E-7 F calculated = .6037
B_3 = 3.56E-11 Conclusion: Accept Null Hypothesis*

Crop: Corn
Lysimeter Data Base: Clovis and Farmington
B_0 = 1.20E-1 R^2 = 82.62
B_1 = 1.68E-3 F tabulated = 2.80
B_2 = -2.46E-7 F calculated = 1.73
B_3 = -4.37E-10 Conclusion: Accept Null Hypothesis

Crop: Sorghum
Lysimeter Data Base: Artesia, Clovis, Farmington, and Las Cruces
B_0 = 8.93E-2 R^2 = 74.44
B_1 = 1.59E-3 F tabulated = 2.53
B_2 = -7.46E-7 F calculated = 2.44
B_3 = 8.36E-13 Conclusion: Accept Null Hypothesis

Crop: Wheat (1st Polynomial)**
Lysimeter Data Base: Clovis
B_0 = 4.17E-2 R^2 = 91.30
B_1 = 5.12E-3
B_2 = -1.25E-5
B_3 = 7.45E-9

Second Polynomial for Wheat
B_0 = 1.13E-1 R^2 = 76.40
B_1 = 1.62E-3
B_2 = -7.32E-7
B_3 = -8.85E-11

Crop: Barley (1st Polynomial)**
Lysimeter Data: Artesia
B_0 = 1.46E-1 R^2 = 78.87
B_1 = 1.39E-4
B_2 = 3.02E-6
B_3 = -3.35E-9

Table 13 (Continued)

Second Polynomial for Barley

B_0 = 4.46E-1 R^2 = 88.34

B_1 = 7.92E-4

B_2 = 2.62E-6

B_3 = -3.29E-9

Crop: Cotton

Lysimeter Data: Artesia and Las Cruces

B_0 = 4.24E-4 R^2 = 75.47

B_1 = 1.20E-3 F tabulated = 2.61

B_2 = 4.62E-7 F calculated = .11

B_3 = -5.77E-10 Conclusion: Accept Null Hypothesis

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[*] Acceptance of the null hypothesis implies that the polynomials derived at different sites and for different years are not statistically different.

[**] Wheat and barley divided into two separate polynomials to reflect overwintering of crop.

wheat and barley, and grain sorghum using data points derived from lysimeter and sprinkler line source studies. Similarly, crop growth polynomials were derived for these crops using growing degree days from the same lysimeter studies.

No such lysimeter data bases were available for chile, lettuce, pinto beans, potatoes, or onion crops. Therefore, crop growth polynomials were derived using the techniques discussed above, but the data bases for the derivation of the curves were developed from various literature sources and the transpiration vs. yield production functions were developed through modeling.

METHODS

Crop growth functions were developed for the Las Cruces, New Mexico, area for lettuce, onions, and green chile, and for the Farmington area for potatoes, spring barley and pinto beans. A three-stage approach was utilized to derive the crop growth polynomials based upon growing degree days. First, crop growth coefficients were derived from the literature for chile, fall onions, and spring and fall lettuce. Secondly, growing degree days were calculated for each crop using 1976 Las Cruces and Farmington, New Mexico climatological data. Finally, the crop growth coefficients were fitted to a 3d-order polynomial through multiple regression.

Table 14 presents the maximum, minimum, and base temperatures used for calculation of the growing degree days for the Las Cruces and Farmington climate files. Growing degree days were calculated for these crops in the same manner as the lysimeter based crops.

Table 14

Maximum, minimum, and base temperatures, nonlysimeter grown crops.

Crop	Maximum Temperature	Minimum Temperature	Base Temperature
	(degrees centigrade)		
Lettuce	20	10	10
Chile	30	5	5
Onions	25	7	7
Potatoes	21	2	2
Pinto Beans	25	5	5
Spring Barley	30	5	5

Source: Hackett, Edible Horticultural Crops, 1982.

Monthly crop growth coefficients (K) were obtained from various literature sources. The coefficients for lettuce and onions were obtained from FAO Report 24 by Doorenbos, et al. (1977), and FAO Report 33 by Doorenbos et al. (1979), while the coefficients for green chile were obtained from Saddiq (1982). Crop coefficients for pinto beans were taken from studies done at the San Juan Branch Experiment Station (Kallsen et al. 1981, 1983). The monthly K coefficients were then regressed against the accumulated monthly growing degree days in the form of a 3rd-order polynomial.

RESULTS AND DISCUSSION

Table 15 presents, by crop, the planting and harvesting dates, the K coefficients, the growing degree days, and the coefficients derived by the regression analysis, along with the R^2 for each polynomial. The polynomials were validated by incorporating them into the IRRSCH model and comparing the seasonal modeled consumptive use to that found in the original, respective data bases.

DEVELOPMENT OF TRANSPIRATION YIELD FUNCTIONS

The transpiration yield functions were derived in the same manner that the functions were derived for the lysimeter-based crops. However, the IRRSCH model could not be set up to simulate the lysimeter studies because of the lack of such data. Water production functions were derived from various published literature sources for each of the crops and are presented in table 16. These production functions were initially used in the IRRSCH model. Secondly, the IRRSCH model was run with the crop growth curves derived earlier, and for each crop the model returned as output the amount of evaporation

Table 15

Planting and harvesting dates, K coefficients, growing degree days, and crop growth polynomials, Las Cruces and Farmington, New Mexico.

Crop	Planting Date	Harvest Date	K^* (E_t/E_o)	Growing Deg. Day	Polynomial	R^2
Spring Lettuce	1-15	5-15	0.2	0	B0 = 2.03e-1	99.81
			0.5	151	B1 = 1.3e-3	
			0.75	298	B2 = 5.3e-6	
			0.9	441	B3 = -1.1e-8	
			0.8	488		
Fall Lettuce	8-15	10-30	0.2	0	B0 = 2.01e-1	99.04
			0.5	193	B1 = 5.7e-4	
			0.75	375	B2 = 7.0e-6	
			0.9	506	B3 = -1.1e-8	
			0.8	529		
Chile	3-15	9-15	0.26	0	B0 = 9.8e-2	93.9
			0.33	468	B1 = 6.0e-5	
			0.38	562	B2 = 6.2e-7	
			0.35	683	B3 = -1.9e-10	
			0.6	780		
			0.4	1,071		
			0.55	1,238		
			0.74	1,368		
			1.04	1,489		
			1.05	1,642		
			1.14	1,795		
			1.2	1,944		
			1.22	2,040		
			1.27	2,257		
			1.15	2,547		
Fall Onions	10-15	7-01	0.0	0	B0 = 0.028	94.72
			0.13	300	B1 = -2.6e-4	
			0.66	1,219	B2 = 1.6e-6	
			1.00	1,422	B3 = -7.1e-10	
			0.60	1,824		
			0.01	2,093		

Table 15 (Continued)

Crop	Planting Date	Harvest Date	K* (E_t/E_o)	Growing Deg. Day	Polynomial	R^2
Pinto Beans**	5-14	9-03	0.36	134	B0 = 3.7e-1	98.81
			0.65	385	B1 = -5.9e-4	
			0.86	644	B2 = 3.4e-6	
			1.25	900	B3 = -1.9e-9	
			1.25	1,151		
			0.60	1,518		
Potatoes**			0.2	0	B0 = 1.4e-1	95.83
			0.5	241	B1 = 2.0e-3	
			1.15	576	B2 = -1.1e-6	
			1.15	1,261	B3 = 8.6e-11	
			0.75	1,759		
Spring Barley**	4-11	8-03	0.18	74	B0 = -6.4e-2	89.75
			0.61	333	B1 = 3.9e-3	
			0.98	758	B2 = 4.8e-6	
			0.25	1294	B3 = 1.5e-9	
			0.10	1654		

*Coefficients derived for spring and fall lettuce from FAO Report 24; chile, Saddiq (1982); fall onions, Hinckley (1976); pinto beans and potatoes, Kallsen (1981), and spring barley, Kallsen, et al. (1984).

**Farmington, New Mexico.

Table 16

Initial water production functions[*] used as input in IRRSCH for modeling purposes.

Crop	Function[**]
Spring and Fall Lettuce	$y = -1559 + 13240E_t$
Fall Onions	$y = -4414 + 834E_t$
Green Chile	$y = -4.5 + .231E_t$
Pinto Beans	$y = -347 + 56E_t$
Potatoes	$y = -3300 + 576E_t$

[*] Production functions derived from the following sources: spring and fall lettuce, Sammis (1976); fall onions, FAO Report 33 (1976); green chile, Wierenga (1983); and pinto beans and potatoes, Kallsen (1982).

[**] Where yield (y) is kilograms per hectare and T is measured in centimeters.

(E), transpiration (T), and crop yield. Finally, the transpiration yield function was derived using simple linear regression.

RESULTS

Table 17 presents the transpiration yield data for each crop and table 18 presents the derived production functions for each crop. There are some differences between these functions and those that were initially derived from the literature and used in the model. These differences represent the reduction in variability caused by removal of the soil evaporation component. This reduction is reflected in the differences that can be seen in the intercepts and, to some extent, the differences in slopes. There is no way of proving, short of actual field tests, if these functions have any validity. For modeling purposes, these functions are suitable because they behave as expected, but they must be used and reported with caution.

Table 17

Modeled transpiration and yield by crop,
Las Cruces and Farmington, New Mexico, 1976.

Crop	Transpiration	Yield	Maximum Rooting Depth**
	(centimeters)	(kg/hectare)	(meters)
Spring Lettuce	7.9	4,956.0	.61
	13.7	9,972.5	
	20.1	15,181.6	
	26.4	20,547.5	
	33.3	26,154.2	
	36.8	29,117.8	
Fall Lettuce	7.4	7,757.1	.61
	9.1	9,997.1	
	11.9	13,572.5	
	15.2	17,906.6	
	18.3	21,918.4	
	20.3	24,281.6	
Fall Onions	5.6	939.7	.61
	17.3	9,914.2	
	29.7	20,186.9	
	41.9	30,468.5	
	53.6	40,184.5	
	61.5	46,705.1	
Green Chile	32.0	2,499.8	.91
	33.8	3,700.5	
	35.9	5,600.0	
	41.0	11,800.3	
	34.7	10,999.5	
	40.2	14,200.5	
	45.7	16,300.5	
	51.3	19,100.5	
	48.3	12,999.5	
	52.7	18,800.3	

Table 17 (Continued)

Crop	Transpiration	Yield	Maximum Rooting Depth**
	(centimeters)	(kg/hectare)	(meters)
Green Chile (Cont)	57.3	18,100.3	
	59.2	22,799.8	
	56.5	18,800.3	
	63.8	28,906.1	
	72.7	30,199.7	
	80.6	28,900.5	
	69.1	24,599.7	
	78.4	33,200.7	
	85.1	37,199.7	
	99.2	33,600.0	
Pinto Beans*	11.4	294.6	.91
	18.5	682.1	
	26.4	1,126.7	
	36.1	1,655.4	
	42.4	2,007.0	
	46.2	2,226.6	
	47.5	2,297.1	
	48.3	2,331.8	
Potatoes*	19.1	10,595.2	1.2
	34.7	19,574.4	
	43.4	23,083.2	
	45.0	26,115.0	
	51.6	27,846.6	
	52.7	28,384.2	

*Farmington, New Mexico, 1976.

**Rooting depth coefficients per growing degree days are .10 centimeters for spring lettuce, potatoes, and pinto beans; .08 for fall lettuce; .03 for onions; and .15 for green chile.

Table 18

Modeled production functions
by crop, Las Cruces and Farmington, New Mexico.

Crop	Production Function[**]
Spring Lettuce	$y = -1544 + 834T$
Fall Lettuce	$y = -1726 + 1287T$
Fall Onions	$y = -4032 + 823T$
Green Chile	$y = -9.1 + 1.3T$
Pinto Beans	$y = -340 + 55T$
Potatoes	$y = 727 + 532T$

[*] Production functions derived from the following sources: spring and fall lettuce, Sammis (1976); fall onions, FAO Report 33 (1976); green chile, Wierenga (1983); and pinto beans and potatoes, Kallsen (1982).

[**] Where yield (y) is in kilograms per hectare and T is measured in centimeters.

SUMMARY

This report concerns the development of crop growth curves based upon growing degree days and crop water production functions based upon transpiration. Crops investigated in this section are alfalfa, corn, sorghum, cotton, wheat, spring/winter barley, fall/spring lettuce, onions, chile, pinto beans and potatoes. Results indicate that when crop growth curves are developed utilizing growing degree days, crop development is statistically the same even though there are widespread climatological differences. The crop water production functions based on transpiration are more stable than those based upon evapotranspiration.

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