Water Supply: Yield Relationships Developed for Study of Water Management

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ABSTRACT

The USA's west-central Great Plains is a semiarid region with irrigation largely from the Ogallala aquifer, which has experienced extensive water-level declines. Farmers respond to reduced water supplies with alternative management, irrigation equipment, and crops; and, it is imperative the economics of these changes be studied. Profit and risk in water management depend on the crop–water relationships. Our objective was to describe the development of, and tabulate, yield–water supply relationships for six primary crops of the region: alfalfa (*Medicago sativa* L.), corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], soybean [*Glycine max* (L.) Merr.], sunflower (*Helianthus annuus* L.), and winter wheat (*Triticum aestivum* L.). Soils were deep silt loams that developed from loess. Input weather data were long-term, daily means of air temperature, solar radiation, and precipitation. Crop growth patterns were consistent with full-season cropping. Yields modeled with the Natural Resources Conservation Service (NRCS) net irrigation requirement (NIR) for 80% chance rainfall ranged from 92 to 97% of the maximum yields. This illustrated that if net irrigation exceeds the recommended NIR, there will be no appreciable yield increase. These calculated yield vs. water supply results will aid in studying water resource optimization and the associated economics.

Water shortage is the primary factor limiting dryland crop production in the west-central Great Plains of the USA, a region with limited and sporadic precipitation. Limited precipitation has provided the impetus for irrigation to be a driving force in the economic infrastructure. Irrigation depends primarily on groundwater from the Ogallala formation of the High Plains aquifer (McGrath and Dugan, 1993). Water-level declines in the Ogallala started soon after the beginning of extensive groundwater irrigation. With declining water levels, well yields are reduced and pumping costs are increased by the additional lift. Water-level declines from predevelopment (about 1950) to 2003 of 15 m or more are widespread in parts of western Kansas, eastern Colorado, and southwestern Nebraska, with some declines >45 m (McGuire, 2004).

With the limited precipitation, and declining water levels of the Ogallala, every effort should be made to increase water use efficiency (WUE) of the best system available to each producer. In cropping system strategies, methods can be used to improve WUE (Nielsen et al., 2005). Changes in irrigation management are influenced by a desire to improve WUE and/or conserve water while maintaining or increasing profits. As farmers consider making changes in management and/or equipment, it is imperative that they have the ability to consider economic effects of the changes. Profit and risk depend directly on the underlying crop–water production functions—the yield of a particular crop associated with levels of water application (Ayer and Hoyt, 1981).

Crop–water production relationships are altered by variations in soil and climate (Martin et al., 1989), and have not been well defined for most crops in most areas (Ayer and Hoyt, 1981). Through understanding and use of crop–water production relationships, conclusions can be drawn on optimal water

Impact Statement

In studying the production economics and environmental consequences of irrigation management strategies, there is need for basic information on crop yield response to water supply. This article describes the development of and presents yield vs. water supply values for six primary crops of the west-central Great Plains. These values can be used by students, extension educators, and water management personnel in the study of appropriate, and efficient, use of our water resources.

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Abbreviations: ASW, available soil water; ET, evapotranspiration; ET_a, actual ET; ET_e, effective ET; ET_m, maximum ET; ER_r, reference ET; HPRCC, High Plains Regional Climate Center; KSWB, Kansas water budget; NIR, net irrigation requirement; NRCS, Natural Resources Conservation Service; WUE, water use efficiency; WUE_m, maximum water use efficiency.

Table 1. Growth stages for crops in the KSWB software and spreadsheet models.

Crop	Growth stage	Date
Corn	plant emergence	16 May
	tasseling	18 July
	silking	24 July
	blister kernel	7 August
	dent	28 August
	physiological maturity	23 September
Grain sorghum	plant emergence	9 June
	boot	29 July
	head emergence	3 August
	50% flowering	8 August
	soft dough	18 August
	physiological maturity	26 September
Sunflower	plant emergence	9 June
	bud formation	13 July
	head beginning to open	28 July
	50% disk flowering	4 August
	petal drop	12 August
	physiological maturity	11 September
Winter wheat	plant emergence	17 September
	green up	1 March
	joint	20 April
	boot	8 May
	head emergence	19 May
	50% flowering	25 May
	physiological maturity	23 June
Soybean	plant emergence	28 May
	beginning bloom	7 July
	beginning pod	22 July
	beginning seed	11 August
	physiological maturity	26 September
Alfalfa	green up	22 March
	1st cutting	25 May
	2nd cutting	26 June
	3rd cutting	26 July
	4th cutting	4 September
	hard freeze	27 October
	5th cutting	28 October

application and the benefits derived from efficient water management (Barrett and Skogerboe, 1980). Often, lack of information on crop yield vs. water supply prevents the obtaining of full benefit from models that are designed to assess water management and irrigation systems. In response to the lack of information on crop yield vs. water supply, a field water-balance model was developed from empirical equations and was incorporated into a software package by Khan (1996). The Kansas Water Budget (KSWB) model provides output of crop yield, evapotranspiration (ET), and drainage of water from the soil profile (Khan et al., 1996).

The KSWB model provides output for corn, sorghum, sunflower, and wheat, and recently developed supplemental spreadsheets give output for alfalfa and soybean. Educators in extension, university classrooms, graduate student training, and the water industry have used, and are using, these crop yield vs. water supply output values in the educational process involving water resource management. Educational materials that were prepared by using these output include graduate student theses (Fredrickson, 2004; Ding, 2005) and extension releases (O'Brien et al., 2000; Klocke et al., 2004; Dhuyvetter et al., 2005). Requests have been made that output of crop yield vs. water supply, with discussion, be published to aid students and extension personnel in the educational aspects of water resource management. Therefore, our objectives were to: (1) describe the yield vs. water supply relationships of alfalfa and soybean developed by following the structure of Khan (1996); (2) use Khan's (1996) model to calculate yield vs. water supply of corn, grain sorghum, sunflower, and winter wheat; and (3) tabulate the yield vs. water supply results in a convenient form for use in water resource education.

Software Background and Spreadsheet Development

With the KSWB model and software being described by Khan (1996), Khan et al. (1996), and Stone et al. (1995), this article concentrates on: (1) its use to build tabular information on yield vs. water supply in corn, sorghum, sunflower, and wheat; (2) the development of supplemental spreadsheets (Excel 2000, Microsoft Corp., Redmond, WA) for alfalfa and soybean by using the same structure as the KSWB model; and (3) building tabular information on yield vs. water supply in alfalfa and soybean. Information on soil, crop, climate, irrigation scheduling, and so forth enable the understanding of yield vs. water supply results from the specific system modeled.

Data on weather, soil, and crops used with the KSWB model and software were collected from research and instrumentation located in western Kansas. Crop ET in the KSWB and spreadsheet models was calculated by using reference ET (ET_r) techniques of Jensen et al. (1970). Reference ET was calculated daily for all days of the year by using maximum and minimum air temperatures, solar radiation, and the ET_r equation of Jensen and Haise (1963). Maximum and minimum air temperatures and precipitation used in the alfalfa and soybean spreadsheets were the mean daily values from 92 years (1912–2003) collected at Tribune, KS (38°28′ N, 101°46′ W; 1103 m elev.) and obtained from the High Plains Regional Climate Center (HPRCC, 2004).

The long-term, mean, daily, minimum air temperature is ≥0°C from 6 April to 30 October, and the long-term, mean, annual precipitation is 420 mm. Solar radiation data used were the mean daily values from 22 years (1952–1973), measured at Goodland, KS (39°22′ N, 101°42′ W; 1111 m elev.).

The ratio of maximum ET (ET_m) of a cropped surface to ET_r is the ET crop coefficient. The distribution of ET coefficients for a particular crop as a function of time constitutes a crop curve. The mean ET crop coefficient values for alfalfa were patterned after those of Jensen et al. (1989) and Jensen (1974). The mean ET crop coefficient values for soybean were estimated by using data from Hattendorf et al. (1988) and Howell (1998). Coefficients for bare soil (times with no growing crop) were estimated by using the technique of Doorenbos and Pruitt (1977). Dates of growth stages consistent with full-season cropping in the west-central Great Plains are given in Table 1. The combined bare-soil coefficients and crop ET coefficients for alfalfa and soybean for the entire year are shown in Fig. 1. In our models, daily ET_m during the noncrop season was calculated by multiplying ET_r by the bare-soil coefficients, and daily ET_m during the crop season was calculated by multiplying ET_r by the crop ET coefficients. The ET_m of alfalfa and soybean during the year are shown in Fig. 1.

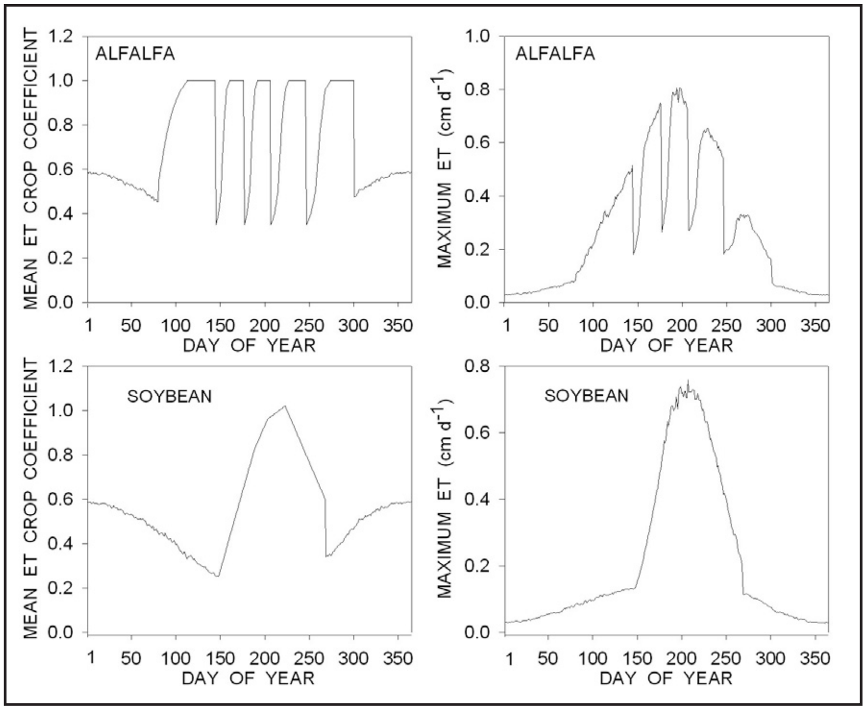

Fig. 1. Combined bare-soil and crop ET coefficients, and maximum ET, of alfalfa and soybean vs. day of year.

We calculated ET_m assuming that soil water was not limiting. If water supply did not meet a crop's water requirement, a crop's actual ET (ET_a) would be less than ET_m. The ET_a component of the water balance equation depends on weather conditions (ET_r), crop characteristics (ET crop coefficient curve), and water status of the soil. That is:

$$ET_a = ET_r \times \text{Mean ET crop coefficient} \times \text{Soil water availability factor} \quad [1]$$

The logarithmic relationship of Jensen et al. (1971) was used to describe the influence of soil water availability on ET.

Soil profile drainage equations and limits of available soil water (ASW) used in the software and spreadsheets were determined by Stone et al. (1987) for a Ulysses silt loam soil (fine-silty, mixed, mesic Aridic Haplustoll) with slope <1%, near Tribune, KS. The Ulysses are deep, well-drained soils that formed in loess, and similar soils occupy about 2.34 million ha of the west-central Great Plains (Aandahl, 1982). The drainage component of the water balance equation was calculated by using a Wilcox-type drainage equation (Miller and Aarstad, 1972) developed for the 1.83-m Ulysses soil profile. Limits of ASW (upper limit of 650 mm and lower limit of 290 mm) were determined for the same 1.83-m Ulysses soil profile.

Yield–ET relationships for the six crops of the KSWB software and spreadsheet models are given in Table 2. These relationships were developed from multiple sources of data and represent mean conditions consistent with full-season cropping. The yield–ET relationships for corn, sorghum, sunflower, and wheat were developed and used in the KSWB software (Khan, 1996). Recently, we developed the yield–ET relationships for soybean and alfalfa. Seed yield vs. ET of soybean was developed by using results from four locations in Kansas. The linear equation relating soybean yield and field-measured ET was determined by using PROC GLM of SAS (SAS Institute, 1985) and is:

$$Y = -2.40 + 0.121 \text{ ET} \quad [2]$$

with $n = 5$, $r^2 = 0.977$, and $P = 0.0015$, where Y represents seed yield in Mg ha^{-1} at water content (moist mass basis) of 130 g kg^{-1} and ET is in centimeters. Four of the five data points are means of yield and ET from multi-year, dryland soybean studies near Belleville, KS (3 years), Colby, KS (3 years), Manhattan, KS (2 years), and Tribune, KS (4 years). The

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fifth data point is upper-bound yield (4.74 Mg ha^{-1}) from irrigated performance tests of cultivars at Colby, and the seasonal ET_m (601 mm) is from running our model for mean long-term weather data with no water deficit. Soybean cultivars in the studies were typically from maturity groups III and IV, with most from group III.

The WUE (mass produced per unit of ET) of alfalfa varies with relative water use (Doorenbos and Kassam, 1979). Alfalfa WUE as a function of water conditions was evaluated in North Dakota (Bauder et al., 1978), Cyprus (Metochis and Orphanos, 1981), Minnesota (Carter and Sheaffer, 1983), and California (Donovan and Meek, 1983). Data from the four articles led to development of an equation describing the relationship between relative WUE decrease ($1 - WUE/WUE_m$) and relative ET deficit ($1 - ET_a/ET_m$). Curve fitting software (TableCurve 2D 5.01, Systat Software, Richmond, CA) was used to search for the best-fit, no-intercept equation relating the dependent variable [$(1 - (WUE/WUE_m)$], termed *Y*, and the independent variable [$1 - (\Sigma ET_a/\Sigma ET_m)$], termed *X*. The TableCurve analysis yielded:

Table 2. Yield-ET relationship for crops in the KSWB software and spreadsheet models.

Crop	Maximum crop ET	*Y* intercept	*X* intercept (threshold ET)	Slope of yield vs. ET
	cm	Mg ha^{-1}	cm	Mg ha^{-1} cm^{-1}
Corn	61.3	−11.55	27.7	0.416
Grain sorghum	51.8	−5.30	17.6	0.301
Sunflower	55.6	−1.33	13.8	0.096
Winter wheat	59.6	−4.06	25.5	0.159
Soybean	60.1	−2.40	19.8	0.121
Alfalfa	90.7	0.00	0.0	0.265

$$Y = 0.88X^{1.5} \quad [3]$$

Statistics of the selected equation ($n = 10$, $R^2 = 0.83$, and $P < 0.0001$) were determined by using PROC GLM of SAS (SAS Institute, 1985). The equation expressing the relative WUE decrease of alfalfa as a function of relative ET deficit became:

$$[1 - (WUE/WUE_m)] = 0.88[1 - (\Sigma ET_a/\Sigma ET_m)]^{1.5} \quad [4]$$

where WUE is for a particular cutting with its condition of relative ET ($\Sigma ET_a/\Sigma ET_m$), WUE_m is the maximum WUE for alfalfa, and ET_a and ET_m are summed for the particular cutting. For alfalfa, WUE_m was 0.265 Mg ha^{-1} cm^{-1} at water content (moist mass basis) of 150 g kg^{-1}, based on data from Metochis and Orphanos (1981), Retta and Hanks (1980), Carter and Sheaffer (1983), and Hanks (1983).

Yield sensitivity to water deficit during various growth periods (e.g., vegetative, flowering, grain formation, and ripening) differs among crops. In general, grain crops are more sensitive to water deficit during flowering and early seed formation than during vegetative and ripening (Doorenbos and Kassam, 1979). Soybean is more sensitive to water stress during bean formation than during flowering or vegetative. Yield sensitivity to water deficit of the five grain crops is expressed through ET weighting factors (Table 3). The relative sensitivity to water deficit of growth periods is indicated by the weighting factor per cm of ET_m (Table 3). The flowering stage in corn is

Table 3. Weighting factors of ET for grain crops in the KSWB software and spreadsheet models.

Crop	Growth period	No. of days	ET_m† (cm)	WF‡	WF per cm of ET_m
Corn	vegetative	70	31.8	36	1.13
	flowering	10	7.6	33	4.34
	seed formation	30	16.8	25	1.49
	ripening	20	5.1	6	1.18
Grain sorghum	vegetative	56	28.1	44	1.57
	flowering	20	12.1	39	3.22
	seed formation	23	9.0	14	1.56
	ripening	10	2.6	3	1.15
Sunflower	vegetative	50	27.6	43	1.56
	flowering	15	12.4	33	2.66
	seed formation	22	13.2	23	1.74
	ripening	7	2.4	1	0.42
Winter wheat	vegetative	245	36.6	49	1.34
	flowering	14	9.0	31	3.44
	seed formation	15	11.1	19	1.71
	ripening	5	2.9	1	0.34
Soybean	vegetative	40	14.9	6.9	0.46
	flowering	35	24.8	45.9	1.85
	bean formation	46	20.4	47.2	2.31

† ET_m = maximum ET summed within the growth period.

‡ WF = weighting factor.

Table 4. Alfalfa forage yield calculated by using the spreadsheet model with varying amounts of annual precipitation and net irrigation.

Net irrigation	Annual precipitation, cm										
	27.94	30.48	33.02	35.56	38.10	40.64	43.18	45.72	48.26	50.80	53.34
cm	alfalfa forage yield, Mg ha^{-1} at 150 g of water kg^{-1}										
0.00	3.12	3.62	4.16	4.72	5.31	5.92	6.57	7.23	7.92	8.64	9.37
2.54	3.79	4.32	4.88	5.46	6.07	6.70	7.36	8.05	8.75	9.48	10.22
5.08	4.52	5.07	5.64	6.24	6.86	7.51	8.18	8.87	9.59	10.33	11.09
7.62	5.17	5.74	6.34	6.95	7.60	8.27	8.96	9.67	10.41	11.16	11.93
10.16	5.86	6.44	7.06	7.70	8.36	9.05	9.76	10.49	11.24	12.00	12.78
12.70	6.47	7.09	7.74	8.41	9.10	9.81	10.54	11.28	12.05	12.82	13.62
15.24	7.15	7.80	8.46	9.15	9.86	10.59	11.34	12.10	12.87	13.66	14.46
17.78	7.75	8.43	9.13	9.85	10.58	11.33	12.10	12.88	13.67	14.47	15.28
20.32	8.44	9.13	9.85	10.59	11.34	12.10	12.88	13.67	14.48	15.29	16.11
22.86	9.00	9.73	10.47	11.24	12.01	12.80	13.61	14.42	15.24	16.07	16.90
25.40	9.64	10.39	11.15	11.94	12.74	13.55	14.37	15.20	16.03	16.87	17.69
27.94	10.48	11.25	12.02	12.82	13.62	14.44	15.26	16.09	16.92	17.74	18.53
30.48	11.35	12.12	12.90	13.70	14.51	15.33	16.15	16.97	17.78	18.57	19.29
33.02	12.19	12.97	13.76	14.57	15.38	16.20	17.02	17.83	18.61	19.34	19.99
35.56	13.04	13.83	14.63	15.44	16.25	17.06	17.87	18.64	19.37	20.00	20.54
38.10	13.88	14.67	15.48	16.29	17.10	17.91	18.69	19.42	20.07	20.61	21.05
40.64	14.71	15.51	16.32	17.13	17.94	18.72	19.45	20.10	20.65	21.08	21.42
43.18	15.51	16.32	17.14	17.94	18.73	19.47	20.13	20.70	21.14	21.48	21.75
45.72	16.32	17.14	17.95	18.74	19.48	20.15	20.72	21.17	21.51	21.78	22.00
48.26	17.09	17.91	18.70	19.46	20.13	20.70	21.15	21.50	21.77	21.98	22.15
50.80	17.87	18.67	19.42	20.09	20.66	21.11	21.46	21.72	21.94	22.12	22.26
53.34	18.69	19.44	20.12	20.69	21.14	21.49	21.76	21.98	22.15	22.30	22.42
55.88	19.45	20.12	20.69	21.14	21.49	21.76	21.98	22.15	22.30	22.43	22.54
58.42	20.18	20.74	21.19	21.54	21.81	22.02	22.20	22.34	22.46	22.57	22.66
60.96	20.77	21.22	21.56	21.83	22.04	22.21	22.35	22.47	22.57	22.67	22.75
63.50	21.23	21.58	21.85	22.06	22.23	22.37	22.50	22.60	22.69	22.78	22.85
66.04	21.56	21.83	22.05	22.22	22.37	22.50	22.60	22.70	22.78	22.86	22.92
68.58	21.86	22.08	22.26	22.40	22.52	22.63	22.73	22.81	22.88	22.95	23.01
71.12	22.08	22.26	22.40	22.53	22.64	22.73	22.81	22.89	22.95	23.01	23.07
73.66	22.23	22.37	22.50	22.61	22.70	22.79	22.86	22.93	22.99	23.05	23.10
76.20	22.32	22.45	22.56	22.66	22.75	22.82	22.90	22.96	23.02	23.07	23.12
78.74	22.48	22.59	22.68	22.77	22.84	22.91	22.98	23.03	23.09	23.13	23.18
81.28	22.59	22.68	22.77	22.84	22.91	22.97	23.03	23.08	23.13	23.17	23.22
83.82	22.70	22.79	22.86	22.93	22.99	23.05	23.10	23.15	23.19	23.24	23.27
86.36	22.78	22.86	22.93	22.99	23.05	23.10	23.15	23.19	23.24	23.28	23.31
88.90	22.87	22.94	23.00	23.06	23.11	23.16	23.21	23.25	23.29	23.33	23.36
91.44	22.93	23.00	23.06	23.11	23.16	23.21	23.25	23.29	23.33	23.37	23.40

3.84 times as sensitive to ET deficit as the vegetative period (4.34/1.13 = 3.84). If growth is under water-short conditions, water application at the most water-sensitive growth period will provide more yield increase than if water is applied during other growth periods. Water deficit at the most sensitive growth period, similarly, will cause the greatest yield loss for a given amount of ET deficit.

The ET weighting factors of Table 3 were used to transform ET_a to an effective ET (ET_e). Effective ET was then used with the yield–ET relationships of Table 2 to calculate grain yield. The ET values of Table 2 become the crop-season's ET_e values, not the ET_a values. Under water-short conditions, if water application is beneficially timed, $ET_e > ET_a$ and yield can be obtained even when $ET_a <$ threshold ET. But,

Table 5. Corn grain yield calculated by using the KSWB software model with varying amounts of annual precipitation and net irrigation.

Net irrigation	Annual precipitation, cm										
	27.94	30.48	33.02	35.56	38.10	40.64	43.18	45.72	48.26	50.80	53.34
cm	––corn grain yield, Mg ha^{-1} at 155 g of water kg^{-1}––										
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	1.61	2.50	3.39
2.54	0.00	0.00	0.00	0.00	0.03	0.78	1.56	2.35	3.14	3.94	4.73
5.08	0.00	0.00	0.26	0.91	1.58	2.27	2.98	3.70	4.44	5.17	5.91
7.62	0.24	0.84	1.47	2.11	2.77	3.44	4.13	4.83	5.52	6.23	6.93
10.16	1.27	1.88	2.51	3.15	3.80	4.47	5.14	5.82	6.50	7.19	7.87
12.70	2.31	2.92	3.53	4.16	4.80	5.45	6.10	6.77	7.43	8.10	8.76
15.24	3.25	3.85	4.47	5.09	5.72	6.35	7.00	7.65	8.30	8.96	9.60
17.78	4.18	4.78	5.37	5.98	6.60	7.23	7.86	8.50	9.15	9.78	10.38
20.32	5.04	5.63	6.22	6.83	7.44	8.07	8.69	9.32	9.94	10.53	11.05
22.86	5.89	6.47	7.06	7.65	8.26	8.88	9.49	10.09	10.66	11.17	11.58
25.40	6.70	7.27	7.86	8.45	9.05	9.65	10.24	10.78	11.27	11.66	11.96
27.94	7.49	8.06	8.64	9.23	9.81	10.38	10.90	11.35	11.72	12.00	12.22
30.48	8.26	8.83	9.40	9.96	10.51	11.00	11.43	11.77	12.03	12.23	12.39
33.02	8.96	9.52	10.08	10.62	11.12	11.54	11.88	12.15	12.35	12.50	12.63
35.56	9.52	10.08	10.54	11.13	11.56	11.91	12.18	12.39	12.55	12.69	12.79
38.10	10.10	10.65	11.15	11.59	11.94	12.21	12.43	12.59	12.72	12.83	12.92
40.64	10.65	11.16	11.60	11.95	12.23	12.44	12.61	12.75	12.85	12.95	13.02
43.18	11.15	11.59	11.94	12.22	12.44	12.61	12.75	12.87	12.96	13.04	13.11
45.72	11.57	11.93	12.20	12.43	12.60	12.75	12.87	12.96	13.04	13.11	13.17
48.26	12.01	12.27	12.48	12.65	12.79	12.89	12.99	13.06	13.12	13.18	13.23
50.80	12.35	12.54	12.70	12.82	12.92	13.01	13.07	13.13	13.19	13.23	13.27
53.34	12.52	12.69	12.81	12.92	13.01	13.07	13.14	13.19	13.24	13.28	13.32
55.88	12.65	12.79	12.89	12.99	13.06	13.13	13.19	13.23	13.28	13.32	13.35
58.42	12.74	12.85	12.95	13.03	13.11	13.16	13.22	13.26	13.31	13.34	13.38
60.96	12.79	12.89	12.98	13.06	13.12	13.18	13.23	13.28	13.32	13.35	13.39

if water application is poorly timed under water-short conditions, $ET_e < ET_a$ and yield may not be obtained even though ET_a > threshold ET. In the five grain crops, impact of water (ET) deficit was calculated by adjusting ET_a to determine ET_e used in grain yield calculations. With alfalfa, the impact of water deficit was calculated by adjusting WUE (slope of yield–ET), the WUE for a cutting cycle decreasing with decreasing relative ET.

Determination of Yield: Water Supply Results

KSWB Software: Corn, Grain Sorghum, Sunflower, and Winter Wheat

Grain yields of corn, sorghum, sunflower, and wheat were calculated as a function of annual rainfall and irrigation amount for silt loam soils in the west-central Great Plains by using the KSWB software. For calculation of yield, annual rainfall was varied from 27.94 to 53.34 cm in 2.54-cm (1.0-inch) increments. Irrigation amounts entered in the software are adjusted to account for application efficiency, such that the model used the amount of irrigation water that entered the soil profile. For calculation of yield, irrigation amount at 100% application efficiency was varied from 0 to a total of 50.80 to 60.96 cm in 2.54-cm increments, the total irrigation amount differing by crop. Each irrigation event was either a 2.54-cm or a 5.08-cm (2.0-inch) application amount used to achieve the total irrigation amount sought. Application amounts were selected to get the water into the soil profile in a reasonable fashion, not to mimic the application amounts of a particular system.

Yields for continuous, dryland cropping were calculated by entering total annual rainfall in 2.54-cm increments with no irrigation. For all software runs and crops, the initial 2.54-cm irrigation was applied (at 100% application efficiency) on the date resulting in the greatest crop yield increase. In the KSWB software, the greatest calculated yield increase from a 2.54-cm water application occurred at silking in

Table 6. Sorghum grain yield calculated by using the KSWB software model with varying amounts of annual precipitation and net irrigation.

	Annual precipitation, cm										
Net irrigation	**27.94**	**30.48**	**33.02**	**35.56**	**38.10**	**40.64**	**43.18**	**45.72**	**48.26**	**50.80**	**53.34**
cm	––––sorghum grain yield, Mg ha^{-1} at 125 g of water kg^{-1}––––										
0.00	0.00	0.00	0.31	0.85	1.41	1.99	2.57	3.15	3.66	4.27	4.81
2.54	0.46	0.94	1.44	1.94	2.46	2.98	3.50	4.02	4.53	5.03	5.52
5.08	1.47	1.92	2.38	2.85	3.32	3.80	4.28	4.76	5.23	5.70	6.16
7.62	2.25	2.69	3.13	3.58	4.04	4.49	4.95	5.40	5.86	6.31	6.75
10.16	2.94	3.37	3.80	4.24	4.68	5.12	5.56	6.00	6.45	6.89	7.32
12.70	3.61	4.02	4.44	4.86	5.28	5.71	6.14	6.58	7.01	7.43	7.84
15.24	4.23	4.63	5.04	5.45	5.86	6.28	6.71	7.13	7.55	7.95	8.32
17.78	4.82	5.21	5.61	6.01	6.42	6.84	7.25	7.66	8.05	8.41	8.72
20.32	5.39	5.77	6.16	6.56	6.97	7.37	7.77	8.15	8.50	8.79	9.02
22.86	5.94	6.31	6.70	7.09	7.49	7.88	8.25	8.58	8.85	9.06	9.23
25.40	6.25	6.65	7.06	7.46	7.86	8.24	8.58	8.86	9.09	9.26	9.38
27.94	6.79	7.18	7.58	7.97	8.33	8.66	8.93	9.14	9.30	9.42	9.52
30.48	7.31	7.70	8.07	8.42	8.74	8.99	9.19	9.34	9.46	9.55	9.62
33.02	7.81	8.18	8.52	8.81	9.04	9.23	9.37	9.48	9.57	9.63	9.69
35.56	8.29	8.61	8.89	9.11	9.28	9.41	9.51	9.59	9.65	9.70	9.75
38.10	8.63	8.91	9.13	9.30	9.43	9.53	9.62	9.68	9.74	9.78	9.82
40.64	8.89	9.11	9.29	9.43	9.53	9.62	9.69	9.75	9.79	9.83	9.86
43.18	9.09	9.27	9.41	9.52	9.61	9.68	9.74	9.79	9.83	9.87	9.90
45.72	9.25	9.39	9.50	9.59	9.67	9.73	9.78	9.82	9.86	9.89	9.92
48.26	9.35	9.47	9.56	9.64	9.71	9.76	9.81	9.85	9.89	9.92	9.94
50.80	9.42	9.52	9.60	9.67	9.73	9.78	9.82	9.86	9.89	9.92	9.95

corn, head emergence in sorghum and wheat, and head beginning to open in sunflower (Table 1). When 5.08 cm of irrigation was applied, the entire amount was applied on the same date as the initial 2.54-cm irrigation. Irrigation amount never exceeded 5.08 cm on any date and, after setting the date of a 5.08-cm irrigation, the application and date were not moved or omitted. Next, 7.62 cm of irrigation was applied using ET_m (daily ET_r multiplied by the crop ET coefficient) to determine the date of the next irrigation (application of 2.54 cm to give 7.62 cm of total irrigation). Two different dates were found by using cumulative ET_m, the one preceding and the one following (by ΣET_m = 2.54 cm) the date of the initial 5.08-cm irrigation. Both irrigation dates were tested with the software, and whichever had the larger "calculated grain yield" was the date we applied the 2.54-cm irrigation. Next, 10.16 cm of irrigation was applied keeping the date of the initial 5.08-cm irrigation fixed. As with the application to reach 7.62 cm of irrigation, ET_m determined the date of the second 5.08-cm irrigation to reach 10.16 cm of total irrigation. After 10.16 cm of irrigation was applied, all 2.54-cm irrigation dates were selected as with the 7.62 cm of total irrigation to time the latest 2.54-cm application, and all 5.08-cm irrigation dates were selected as with the 10.16 cm of total irrigation to time the latest 5.08-cm application.

Spreadsheets: Soybean and Alfalfa

Yields of soybean and alfalfa were calculated by using spreadsheets and climate, soil, and crop information consistent with the west-central Great Plains. To run the spreadsheets, annual precipitation amounts and information on irrigation events (application date, depth of water pumped per unit area, and application efficiency) were entered. Annual precipitation was varied from 27.94 to 53.34 cm in 2.54-cm increments, and irrigation amount at 100% application efficiency was varied from 0 to 55.88 cm for soybean and 0 to 91.44 cm for alfalfa, in 2.54-cm increments. Each irrigation event was either a 2.54-cm or a 5.08-cm application used to achieve the total irrigation amount.

Yields for continuous, dryland cropping of soybean and alfalfa were calculated by going through each rainfall amount (2.54-cm increments) with no irrigation. The initial 2.54-cm irrigation was applied (at 100% application efficiency) on the date for greatest crop yield increase. This date for soybean (at beginning seed, Table 1) was also the date used for the first 5.08-cm irrigation. Thereafter, irrigation dates

Table 7. Sunflower achene yield calculated by using the KSWB software model with varying amounts of annual precipitation and net irrigation.

Net irrigation	Annual precipitation, cm 27.94	30.48	33.02	35.56	38.10	40.64	43.18	45.72	48.26	50.80	53.34
cm	sunflower achene yield, Mg ha^{-1} at 100 g of water kg^{-1}										
0.00	0.05	0.20	0.35	0.52	0.69	0.86	1.04	1.23	1.42	1.60	1.78
2.54	0.40	0.55	0.70	0.86	1.02	1.19	1.36	1.54	1.71	1.88	2.05
5.08	0.72	0.87	1.01	1.17	1.33	1.48	1.65	1.81	1.97	2.12	2.28
7.62	0.99	1.13	1.28	1.43	1.58	1.74	1.89	2.04	2.19	2.34	2.49
10.16	1.24	1.38	1.52	1.67	1.82	1.97	2.11	2.26	2.40	2.54	2.68
12.70	1.48	1.62	1.76	1.90	2.04	2.18	2.32	2.45	2.59	2.73	2.87
15.24	1.70	1.84	1.97	2.11	2.24	2.38	2.51	2.64	2.78	2.91	3.05
17.78	1.92	2.05	2.17	2.30	2.43	2.56	2.69	2.83	2.96	3.09	3.21
20.32	2.12	2.25	2.37	2.49	2.62	2.75	2.87	3.00	3.13	3.25	3.37
22.86	2.31	2.43	2.55	2.67	2.80	2.92	3.05	3.17	3.29	3.40	3.49
25.40	2.50	2.62	2.73	2.85	2.97	3.09	3.21	3.32	3.43	3.52	3.59
27.94	2.68	2.79	2.90	3.02	3.14	3.25	3.36	3.46	3.54	3.60	3.65
30.48	2.77	2.89	3.01	3.13	3.25	3.36	3.47	3.56	3.63	3.68	3.72
33.02	2.99	3.10	3.21	3.32	3.42	3.51	3.58	3.64	3.69	3.72	3.75
35.56	3.11	3.22	3.33	3.43	3.53	3.60	3.66	3.71	3.75	3.77	3.80
38.10	3.23	3.34	3.44	3.54	3.61	3.67	3.72	3.76	3.79	3.81	3.83
40.64	3.34	3.45	3.54	3.62	3.68	3.73	3.77	3.80	3.82	3.84	3.85
43.18	3.45	3.54	3.62	3.68	3.73	3.77	3.80	3.82	3.84	3.86	3.87
45.72	3.54	3.62	3.68	3.73	3.77	3.80	3.82	3.85	3.86	3.88	3.89
48.26	3.61	3.67	3.72	3.76	3.80	3.82	3.84	3.86	3.88	3.89	3.90
50.80	3.66	3.71	3.75	3.78	3.81	3.83	3.85	3.87	3.88	3.89	3.90
53.34	3.69	3.74	3.77	3.80	3.82	3.84	3.86	3.88	3.89	3.90	3.91
55.88	3.71	3.75	3.78	3.80	3.83	3.85	3.86	3.88	3.89	3.90	3.91

with soybean were found by the same procedure as that used with the KSWB software, and described in the previous sub-section.

For alfalfa, five dates (4 days after green-up and 4 days after each of Cuttings 1 to 4) were tested to find which irrigation date produced the largest yield. The optimum date for the first 2.54-cm irrigation was found to be 26 March. The first 5.08-cm irrigation was also applied on 26 March. Irrigation amount never exceeded 5.08 cm on any date, and after setting the date of a 5.08-cm irrigation, the application and date were not moved or omitted. We applied 7.62 cm of irrigation by testing the remaining four dates of the initial five dates to see which produced the largest yield, and the additional 2.54 cm of irrigation was applied on this date. The second 5.08-cm irrigation was also then applied on this date. For the remaining three dates, the same procedure was used to time the latest 2.54-cm application, and then the latest 5.08-cm irrigation was always applied on that same date. A second set of five dates (where ΣET_m was 5.08 cm from each of the five previous irrigations, one irrigation in each of the five cutting cycles) was determined, and the same procedure as before was followed. After these five dates were used, we used a third set of five dates. We then used a set of three dates (two cutting cycles did not contain sufficient ET_m capacity to allow a fourth 5.08-cm irrigation) and followed the same procedure.

Yields of the six crops as calculated by using the spreadsheets and KSWB software are given in Tables 4 to 9, and illustrated in Fig. 2. Yield is expressed in relation to net irrigation (the same value as applied irrigation depth if irrigation application efficiency is 100%) and annual precipitation [with runoff fractions (RF) of 0.12, 0.13, 0.15, 0.02, 0.02, and 0.13 used in calculating effective precipitation for corn, sorghum, sunflower, wheat, alfalfa, and soybean, respectively].

Discussion

Yields presented in Tables 4 to 9 and Fig. 2 can be adjusted by the user to tailor to their conditions of maximum expected yield, runoff from precipitation, and irrigation application efficiency. If the user has information that their maximum, non-water-limited yield is different than the tabular maximum yield,

Table 8. Winter wheat grain yield calculated by using the KSWB software model with varying amounts of annual precipitation and net irrigation.

Net irrigation	Annual precipitation, cm										
	27.94	30.48	33.02	35.56	38.10	40.64	43.18	45.72	48.26	50.80	53.34
cm	winter wheat grain yield, Mg ha^{-1} at 125 g of water kg^{-1}										
0.00	0.00	0.00	0.00	0.15	0.51	0.87	1.24	1.60	1.95	2.30	2.64
2.54	0.00	0.10	0.42	0.74	1.07	1.40	1.73	2.06	2.38	2.70	3.03
5.08	0.33	0.62	0.91	1.22	1.53	1.83	2.15	2.45	2.77	3.08	3.38
7.62	0.75	1.04	1.32	1.61	1.91	2.21	2.52	2.82	3.12	3.42	3.70
10.16	1.12	1.40	1.69	1.98	2.27	2.56	2.86	3.16	3.46	3.74	3.99
12.70	1.47	1.75	2.03	2.32	2.61	2.91	3.20	3.49	3.77	4.03	4.24
15.24	1.81	2.08	2.37	2.65	2.95	3.23	3.52	3.81	4.06	4.28	4.44
17.78	2.13	2.41	2.69	2.98	3.27	3.55	3.83	4.08	4.30	4.47	4.59
20.32	2.45	2.73	3.01	3.30	3.58	3.85	4.11	4.32	4.49	4.61	4.70
22.86	2.76	3.04	3.32	3.60	3.87	4.12	4.34	4.51	4.63	4.71	4.78
25.40	3.07	3.35	3.62	3.89	4.14	4.34	4.51	4.63	4.72	4.79	4.84
27.94	3.38	3.65	3.91	4.14	4.34	4.51	4.63	4.72	4.79	4.84	4.89
30.48	3.69	3.95	4.19	4.38	4.54	4.65	4.73	4.79	4.85	4.88	4.92
33.02	3.96	4.20	4.40	4.55	4.67	4.75	4.82	4.87	4.91	4.94	4.97
35.56	4.17	4.38	4.54	4.66	4.75	4.82	4.86	4.90	4.94	4.97	5.00
38.10	4.38	4.55	4.67	4.75	4.82	4.88	4.92	4.95	4.98	5.00	5.03
40.64	4.55	4.67	4.76	4.83	4.88	4.93	4.96	4.99	5.02	5.04	5.06
43.18	4.67	4.75	4.83	4.88	4.93	4.96	5.00	5.02	5.04	5.06	5.08
45.72	4.75	4.82	4.88	4.93	4.96	5.00	5.02	5.05	5.07	5.08	5.10
48.26	4.81	4.87	4.92	4.96	5.00	5.02	5.05	5.07	5.09	5.10	5.12
50.80	4.86	4.91	4.95	4.99	5.02	5.04	5.07	5.09	5.10	5.12	5.14
53.34	4.92	4.96	5.00	5.02	5.05	5.07	5.09	5.11	5.12	5.14	5.15
55.88	4.94	4.98	5.01	5.04	5.06	5.08	5.10	5.12	5.13	5.14	5.16

then the user can, and should, adjust the tabular yields to reflect their crop production conditions. An acceptable approach is to determine the mean yield from the top-yielding 3 years that were under non-water-limiting conditions. Under dryland conditions, the maximum irrigated yields of the user's region should be used. The yield adjustment would be made as:

$$UAY = TY \times UMY/TMY \quad [5]$$

where UAY and TY are the user's adjusted yield and tabular yield (Tables 4–9), respectively, for the specified water supply conditions of precipitation and irrigation; UMY is the user's maximum non-water-limited yield, and TMY is the tabular maximum yield for the particular crop.

A user's maximum expected yield could differ from the values in Tables 4 to 9 for several reasons, including conditions of inherent soil fertility and soil quality, cultural management, appropriateness of selected cultivars, and genetic improvement over time. The change in maximum yield over years through genetic improvement has been greater in some crops than in others and, therefore, adjustment of yields in Tables 4 to 9 will be more of an issue with some crops than with others.

To evaluate corn yield change over years, a change attributed largely to genetic improvement, we tabulated annual mean yields of full-season cultivars from irrigated performance tests at Garden City, Tribune, and Colby, KS. Using linear regression to relate corn grain yield of 1973 to 2004 and year, yield increased at a significant rate of 0.173, 0.139, and 0.177 Mg ha^{-1} yr^{-1} for Garden City, Tribune, and Colby, respectively. Maximum yields from those same tests were 15.9, 14.4, and 16.5 Mg ha^{-1} for Garden City, Tribune, and Colby, respectively. These values were greater than the maximum corn grain yield of 13.4 Mg ha^{-1} in Table 5, illustrating the usefulness of the yield adjustment.

Yield change of sorghum and wheat over years was evaluated by using annual mean yields of cultivars entered in irrigated performance tests at Tribune, KS. Linear regression relating sorghum grain yield of 1973 to 2003 and year produced a nonsig-

Table 9. Soybean seed yield calculated by using the spreadsheet model with varying amounts of annual precipitation and net irrigation.

Net irrigation	Annual precipitation, cm										
	27.94	30.48	33.02	35.56	38.10	40.64	43.18	45.72	48.26	50.80	53.34
cm	soybean seed yield, Mg ha^{-1} at 130 g of water kg^{-1}										
0.00	0.00	0.00	0.00	0.00	0.11	0.34	0.58	0.82	1.07	1.32	1.57
2.54	0.00	0.00	0.09	0.31	0.53	0.75	0.98	1.22	1.45	1.69	1.93
5.08	0.09	0.28	0.48	0.69	0.90	1.12	1.34	1.57	1.80	2.02	2.25
7.62	0.45	0.63	0.83	1.03	1.24	1.45	1.67	1.89	2.11	2.33	2.55
10.16	0.78	0.97	1.16	1.36	1.56	1.77	1.98	2.19	2.41	2.62	2.84
12.70	1.10	1.28	1.47	1.66	1.86	2.07	2.28	2.48	2.69	2.90	3.11
15.24	1.41	1.59	1.77	1.97	2.16	2.36	2.56	2.77	2.97	3.18	3.38
17.78	1.71	1.88	2.06	2.25	2.45	2.64	2.84	3.04	3.24	3.44	3.62
20.32	2.00	2.17	2.35	2.54	2.73	2.92	3.11	3.31	3.50	3.68	3.85
22.86	2.29	2.46	2.63	2.81	3.00	3.19	3.37	3.56	3.74	3.90	4.04
25.40	2.57	2.74	2.91	3.08	3.27	3.45	3.63	3.80	3.95	4.08	4.19
27.94	2.84	3.01	3.17	3.35	3.52	3.69	3.85	4.00	4.13	4.23	4.30
30.48	3.11	3.26	3.43	3.59	3.76	3.92	4.06	4.17	4.27	4.34	4.39
33.02	3.34	3.50	3.66	3.82	3.96	4.10	4.21	4.29	4.36	4.41	4.46
35.56	3.55	3.71	3.86	4.00	4.13	4.23	4.32	4.38	4.43	4.47	4.50
38.10	3.74	3.89	4.03	4.15	4.25	4.33	4.40	4.45	4.49	4.52	4.55
40.64	3.91	4.05	4.17	4.27	4.35	4.41	4.46	4.50	4.53	4.56	4.59
43.18	4.08	4.20	4.29	4.37	4.43	4.47	4.51	4.55	4.57	4.59	4.61
45.72	4.22	4.31	4.39	4.44	4.49	4.52	4.55	4.58	4.60	4.61	4.63
48.26	4.32	4.40	4.45	4.50	4.53	4.57	4.59	4.61	4.63	4.64	4.66
50.80	4.40	4.46	4.50	4.54	4.57	4.60	4.62	4.64	4.66	4.67	4.68
53.34	4.45	4.50	4.54	4.57	4.60	4.62	4.64	4.66	4.67	4.69	4.70
55.88	4.49	4.53	4.56	4.59	4.62	4.64	4.66	4.67	4.69	4.70	4.71

Table 10. Net irrigation depths and corresponding calculated crop yields for Tribune, KS (Greeley County), rainfall conditions.

Item	Crop				
	Alfalfa	Corn	Sorghum	Wheat	Soybean
Max. net irrigation from respective yield table, cm	91.44	60.96	50.80	55.88	55.88
Max. yield from respective table, Mg ha^{-1}	23.23	13.20	9.80	5.09	4.65
NRCS† seasonal NIR with 80% chance rainfall, cm	66.04	41.91	36.32	32.00	35.05
Yield from respective table with NIR for 80% chance rainfall, Mg ha^{-1}	22.55	12.62	9.50	4.75	4.26
Yield (80% chance)/yield max. for Greeley County	0.971	0.956	0.969	0.933	0.916
NRCS seasonal NIR with 50% chance rainfall, cm	59.94	37.34	32.77	27.94	30.73
Yield from respective table with NIR for 50% chance rainfall, Mg ha^{-1}	22.22	12.25	9.29	4.57	4.01
Yield (50% chance)/yield max. for Greeley County	0.957	0.928	0.948	0.898	0.862

† NRCS is Natural Resources Conservation Service and NIR is net irrigation requirement.

nificant slope of 0.019 Mg ha^{-1} yr^{-1}. The analysis with wheat grain yield of 1974 to 2004 also produced a nonsignificant slope (0.014 Mg ha^{-1} yr^{-1}). Maximum yields from those same tests were 10.0 Mg ha^{-1} (sorghum) and 5.3 Mg ha^{-1} (wheat); values in agreement with maximum values of Table 6 (sorghum) and Table 8 (wheat).

Runoff from precipitation is influenced by many factors and the estimation of effective rainfall was described by Cahoon et al. (1992), and can be used to guide a user if different runoff values are appropriate for their field conditions. Yields with precipitation runoff different than for our model can be obtained by altering the runoff fraction for a crop. This can be achieved by varying the annual precipitation used in the crop's yield table in accordance with:

$$AAP = [UAP/(1 - RF)] \times (1 - NRF) \qquad [6]$$

where AAP is the adjusted annual precipitation the user can use in the yield tables, UAP is the actual annual precipitation for the user, RF is the runoff fraction we used in building the yield table for the particular crop, and NRF is the new runoff fraction specified by the user.

The net irrigation depths in Tables 4 to 9 represent the portion of the water applied to a field that is in the crop root zone immediately after an irrigation. That water is then available for evaporation, ET, drainage from the soil profile, or storage in the soil profile. Net irrigation depths are the same values as applied irrigation depths if the irrigation system has an application efficiency of 100%. The user will need to adjust the yield tables to account for their irrigation application efficiency being <100% by use of:

$$TID = AID \times (IAE/100) \qquad [7]$$

where TID is the tabular net irrigation depth, AID is the user's applied irrigation depth, and IAE is the irrigation application efficiency expressed as a percentage.

The irrigation guide of the USDA-NRCS (NRCS, 1997) defines NIR as the water need of the specified crop, over and above effective rainfall and carryover soil water. The NIR values based on 80 or 50% chance rainfall are listed by county and the NIR based on 80% chance rainfall is larger than the NIR based on 50% chance rainfall, with the 80% chance rainfall normally used to determine crop irrigation requirements (NRCS, 1997).

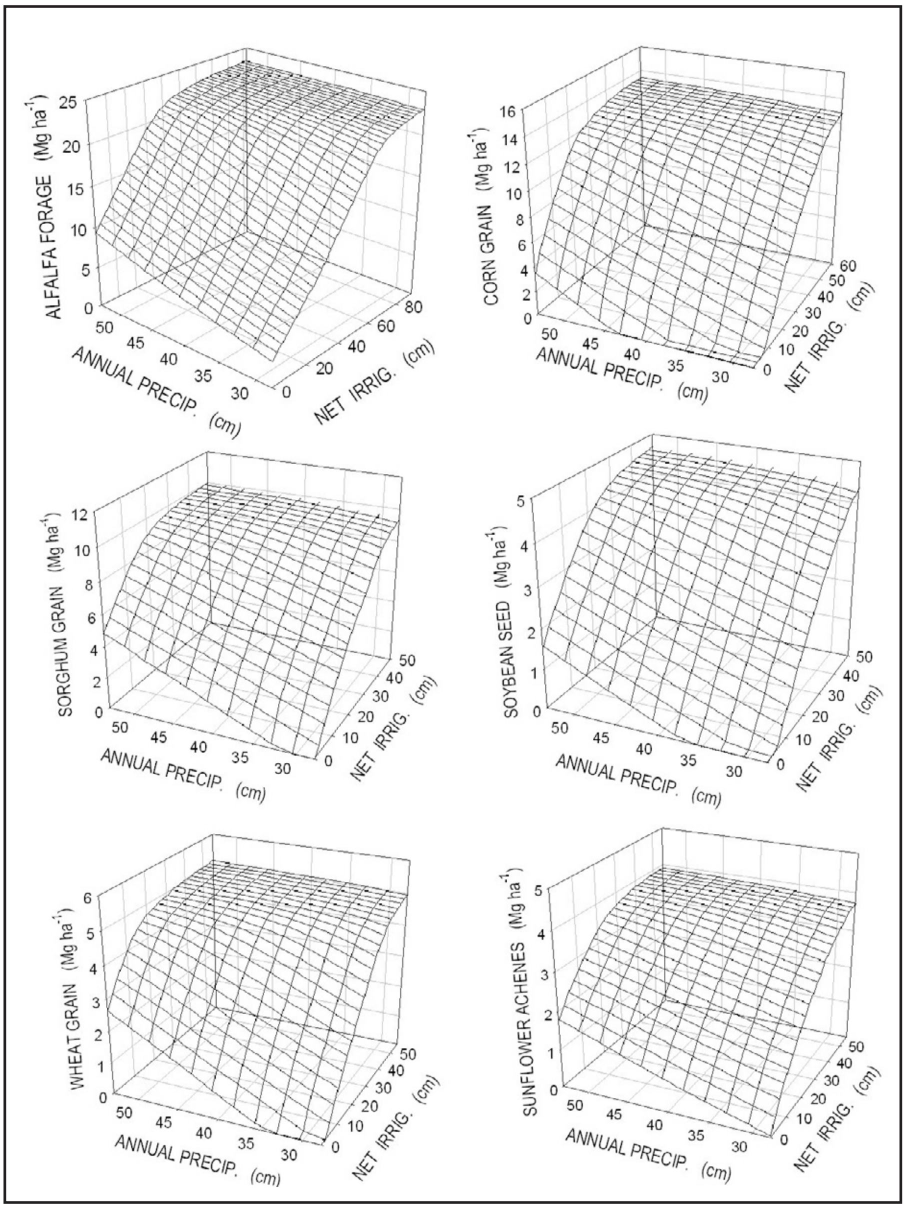

Fig. 2. Yield of six crops calculated in relation to net irrigation and annual precipitation in the west-central Great Plains.

Crop yields calculated for three amounts of seasonal net irrigation are presented in Table 10. The three amounts were the maximum net irrigation that was possible by considering the ΣET_m value for each crop, and the NRCS seasonal NIR with 80 or 50% chance rainfall for Greeley County, Kansas. Yields were calculated for the mean, long-term, annual precipitation of 42.0 cm for Greeley County. The NRCS NIR for 80% chance rainfall ranged from 57 to 72% of maximum net irrigation (Table 10), and associated crop yields ranged from 92 to 97% of maximum modeled yield. The NRCS NIR for 50% chance rainfall ranged from 50 to 66% of maximum net irrigation, and associated crop yields ranged from 86 to 96% of maximum modeled yield.

If more net irrigation is achieved from increased efficiency of irrigation, or by more gross application of irrigation, crop yields would not appreciably exceed the values in Tables 4 to 9 that are in line with the NRCS-recommended NIR values. Additional water placed in the soil would increase runoff from subsequent rainfall and/or irrigations, be lost from the soil as through-profile drainage, or contribute to a spike in evaporation; the additional water intercepted by the soil profile would not translate into additional yield. Calculated yields of Tables 4 to 9 are for mean, long-term conditions of weather and growing season length. Drier years would require more irrigation to maintain productivity; wetter years would require less.

Our approach in developing yield vs. water supply tables was to maximize yield from the water available. Less beneficial timing of irrigations would reduce yields, compared with our calculated yields. No penalty was imposed for yield limiting factors of soil compaction, leaching of nutrients, lack of aeration, or disease build-up that could be associated with the larger irrigation amounts. With relatively dry conditions, harvesting of the low yields might not be feasible. For example, alfalfa yields in Table 4 are the sum of production from all five cuttings. With drier conditions, some alfalfa production would probably not have been harvested. Also, the fifth alfalfa cutting was harvested after the mean date (27 October) for a hard freeze (−4.5°C). The fifth cutting was harvested so all modeled forage production for the growing season could be reported. In practice, that final growth might be left uncut to protect the health of the alfalfa stand.

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Summary

Calculated yield in relation to water supply are presented for six crops of the west-central Great Plains of the USA. Results are consistent with full-season cropping on the deep silt loam soils that developed from loess. Yield values can be adjusted by the user to mimic their crop production potential. Runoff from precipitation and the irrigation application efficiency can be varied by the user to increase the relevance of calculated yields to their particular field environment and irrigation system's performance. These crop yield vs. water supply values will aid in the study of management strategies to make the most efficient use of water resources and maintain economic viability.

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