Author's personal copy

Field Crops Research 118 (2010) 259–263

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Critical precipitation period for dryland maize production

David C. Nielsen[a,*], Ardell D. Halvorson[b], Merle F. Vigil[a]

[a] USDA-ARS, Central Great Plains Research Station, 40335 County Road GG, Akron, CO 80720, United States
[b] USDA-ARS, 2150 Centre Ave, Building D, Ste. 100, Fort Collins, CO 80526-8119, United States

ARTICLE INFO

Article history:
Received 22 March 2010
Received in revised form 1 June 2010
Accepted 3 June 2010

Keywords:
Maize
Yield
Precipitation
Soil water

ABSTRACT

Grain yields for dryland maize (*Zea mays* L.) production in the semi-arid Great Plains of the United States can be unpredictable because of the erratic nature of growing season precipitation. Because of the high input costs for maize production, farmers need to have a tool that will help them assess the risk associated with dryland maize production. The objectives of this work were to determine the critical period for precipitation during the maize growing season and to develop a relationship between critical period precipitation and maize yield to use as a tool to quantify expected yield variability associated with dryland maize production in this region. Maize yield data were collected at Akron, CO from two dryland cropping systems experiments (1984–2009) in which maize was grown in a 3-year winter wheat (*Triticum aestivum* L.)–maize–fallow rotation. Yields were correlated with weekly precipitation amounts from planting to harvest in search of the period of time in which yield was most influenced by precipitation. Soil water contents at planting were measured either by gravimetric sampling or by neutron attenuation. Yields were found to be most closely correlated with precipitation occurring during the 6-week period between 16 July and 26 August. The data separated into two linear relationships defined by whether the sum of available soil water at planting and May precipitation was less than or greater than 250 mm. These two linear relationships between precipitation during this critical period and yield were used with long-term precipitation records to determine the probability of obtaining a maize yield of at least 2500 kg ha^{-1} (generally considered to be a break-even yield) at three locations across the central Great Plains precipitation gradient. This analysis quantified the production risk associated with the highly variable corn yields that result from erratic summer precipitation in this region.

Published by Elsevier B.V.

1. Introduction

Maize has been increasingly used as a component of winter wheat-based dryland cropping systems in the central Great Plains (Farahani et al., 1998; Anderson et al., 1999; Nielsen et al., 2005; Bowman et al., 1999; Peterson and Westfall, 2004; Norwood and Currie, 1998; Lyon et al., 2003). For example, in Colorado the fraction of dryland hectares planted to maize has risen from 0.6% in 1984 to about 12% in 2001, and thereafter remained relatively constant between 10 and 15% of planted dryland hectares (USDA-NASS Quick Stats-Crops, available at http://www.nass.usda.gov/QuickStats, verified 5/21/2010). The primary production system for dryland maize in Colorado is wheat–maize–fallow. But dryland maize yield can be greatly reduced by water stress that occurs during the reproductive stages of tasseling, silking, and pollination when the number of ovules that will be fertilized is being determined (Shaw, 1976; Robins and Domingo, 1953; Denmead and Shaw, 1960; Claassen and Shaw, 1970). Soil water depletion to the wilting point for 2 days during tasseling or pollination was reported by Robins and Domingo (1953) to decrease maize yield by 22%, while a 6–8-day period of such soil moisture stress could cause a yield reduction of 50%. Water stress at tasseling and silking reduces viability of maize pollen, delays silk emergence past pollen shed, and results in desiccation of silks, while subsequent water stress can induce embryo abortion or reduce the potential size of kernels (Waldren, 1983; Hall, 2001). Westgate (1994) provided a comprehensive review of literature describing the effects of water stress on the physiology of the maize plant in reproductive development that ultimately results in decreased seed yield.

In a more recent study, Nielsen et al. (2009) showed that maize yields in northeastern Colorado increased as soil water content at planting increased, but that the relationship between these two quantities was greatly influenced by the precipitation that fell from 15 July to 25 August (approximately 10 days prior to tasseling through the middle of grain filling). The yield response to available soil water at planting increased dramatically as the amount of precipitation during this critical phase of development increased.

* Corresponding author. Tel.: +1 970 345 0507; fax: +1 970 345 2088.
E-mail address: david.nielsen@ars.usda.gov (D.C. Nielsen).

0378-4290/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.fcr.2010.06.004

Author's personal copy

Because the effects of water stress during the critical reproductive developmental stage can be so extremely devastating to maize yield, the highly variable growing season precipitation in the semi-arid Great Plains of the United States can result in highly variable maize yields. Therefore, the objectives of this analysis were to (1) determine the critical period for precipitation during the maize growing season, (2) develop a relationship between critical period precipitation and maize yield to use as a tool to quantify expected yield variability associated with dryland maize production in this region, and (3) determine the probability of achieving a dryland maize yield of 2500 kg ha^{-1} (generally considered to be a break-even yield).

2. Materials and methods

Two dryland cropping systems experiments were conducted from 1984 to 2008 at the USDA-ARS Central Great Plains Research Station (40°09′N, 103°09′W, 1383 m elevation) located near Akron, CO. Experiment 1 (years 1984–1992) was a nitrogen fertility rate experiment with four replications in a randomized complete block design conducted on a Platner loam (fine, smectitic, mesic Aridic Paleustoll). Experiment 2 (years 1993–2009) was a cropping systems experiment with three replications in a randomized complete block design conducted on a Weld silt loam (fine, smectitic, mesic Aridic Argiustoll). In both experiments maize was no-till seeded into winter wheat stubble in a winter wheat–maize–fallow cropping system with maize planted in 0.76 cm row spacings and with seeding rates between 29,650 and 41,000 seeds ha^{-1} (averaging about 35,000 seeds ha^{-1}). Maize was typically planted in early to mid-May. Details regarding the cultural practices employed in both experiments can be found in Halvorson et al. (2004), Anderson et al. (1999), and Bowman et al. (1999). Data from 1987, 1997, and 2000 were excluded from the analysis due to hail damage. The yield data taken from Experiment 1 were the average of the 56 and 84 kg N ha^{-1} fertility treatments, which most closely matched the average N application rate used in Experiment 2 (72 kg N ha^{-1}).

Soil water content was measured at planting by gravimetric sampling at 30 cm depth intervals (0–180 cm) in Experiment 1, and by time-domain reflectometry in the 0–30 cm soil layer and neutron attenuation at 45, 75, 105, 135, and 165 cm soil depths in Experiment 2. Measurement sites were located near the center of each plot. Gravimetric soil water contents were converted to volumetric water content by multiplying by the soil bulk density (assumed to be 1.32 g cm^{-3} throughout the soil profile in both experiments). Amount of plant available water was determined by subtracting field observed lower limits of plant water extraction (Ritchie, 1981; Ratliff et al., 1983) at each site from the total water content at each sampling depth. Lower limits for water extraction were 0.110, 0.135, 0.087, 0.074, 0.079, and 0.101 cm^3 cm^{-3}, respectively, at six soil depth intervals (0–30 cm down to 150–180 cm).

Precipitation was measured at a weather station approximately 730 m from the plot area in Experiment 1 and in the plot area in Experiment 2. Weekly precipitation amounts were computed. Yields were averaged across replicate measurements and correlated with various combinations of weekly precipitation using STATISTIX 9 software (Analytical Software, Tallahassee, FL).

3. Results

3.1. Precipitation

Growing season precipitation (7 May to 30 September) varied widely from 135 mm (2002) to 418 mm (1996), averaging 272 mm (Table 1). The distribution of average precipitation indicates a maximum of about 20 mm per week during two periods: 28 May to 10 June and 30 July to 12 August. The greatest weekly precipitation amount recorded (77 mm) occurred 7 May to 13 May 1995 and 2003. Almost 20% of the weeks of record shown in Table 1 received no precipitation. This data set provided a wide range of precipitation timing situations and subsequent water stress conditions from which to determine the critical period for precipitation with regard to dryland maize yield.

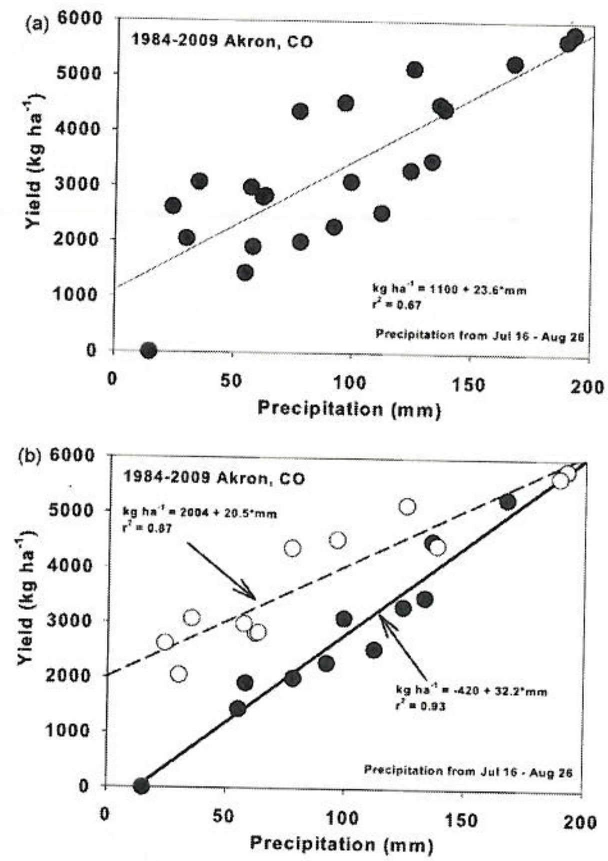

Fig. 1. Relationship between dryland maize yield and precipitation occurring between 16 July and 26 August at Akron, CO (1984–2009, excluding 1987, 1997, and 2000 when yields were reduced by hail). A shows all data collected; B shows data separated by early season water condition: open circles are years when the sum of available soil water at planting and May precipitation was greater than 250 mm, closed circles are years when the sum was less than 250 mm.

3.2. Regression analysis

Maize yields ranged from 0 to nearly 6000 kg ha^{-1} (Fig. 1A) as a result of the highly variable nature of growing season precipitation, both in amount and timing. Maize yields were regressed against weekly precipitation amounts for each weekly period and for longer periods of time. A sampling of those results are shown in Table 2. Significant linear relationships for single week periods occurred between 23 July and 19 August, as indicated by P values less than 0.10, but those relationships only explained 13–28% of the variation in yield. Many other more highly significant ($P < 0.01$) linear increases in yield with increases in precipitation were found for longer periods of precipitation (2–10 week periods) from 25 June to 2 September. The precipitation period that was most closely associated with changes in maize yield was 16 July to 26 August. Precipitation during this 6-week period explained 67% of the variation in yield (Table 2 and Fig. 1A). Yield increased at a rate of

Author's personal copy

Table 1
Weekly precipitation at Akron, CO during the maize growing season (1984–2008).

Year	Week ending																					
	5/13	5/20	5/27	6/3	6/10	6/17	6/24	7/1	7/8	7/15	7/22	7/29	8/5	8/12	8/19	8/26	9/2	9/9	9/16	9/23	9/30	Total
												(mm)										
1984	0	17	8	6	17	24	13	21	11	0	20	0	47	58	2	9	5	0	2	1	5	266
1985	45	22	1	5	17	1	3	8	1	1	64	3	59	1	11	0	28	8	3	13	9	303
1986	14	22	0	39	70	0	7	1	0	2	6	0	4	6	6	2	10	12	1	1	1	204
1987	6	23	26	1	16	3	29	10	37	11	17	0	54	15	4	28	0	10	12	9	0	311
1988	0	72	11	11	4	3	6	30	33	6	15	11	3	26	8	0	2	0	15	0	8	264
1989	10	11	0	20	67	0	12	14	0	36	0	0	11	56	5	5	17	10	13	2	0	289
1990	16	9	50	28	10	12	0	1	35	5	29	51	34	17	54	7	0	1	0	11	6	376
1991	0	31	24	58	9	5	1	3	7	24	21	24	6	4	1	0	15	0	3	0	0	236
1992	3	0	12	44	2	14	25	38	11	13	15	12	5	11	13	70	4	0	0	1	0	293
1993	0	0	12	7	25	2	17	0	15	10	45	30	4	11	15	6	1	1	9	14	0	224
1994	8	3	12	0	1	0	5	0	11	26	20	13	6	11	4	5	5	0	1	7	0	138
1995	77	6	36	53	49	0	28	7	3	18	17	0	1	13	0	0	7	24	1	20	16	376
1996	21	2	66	27	3	34	22	6	36	17	1	17	26	4	15	15	22	1	11	65	7	418
1997	0	6	38	21	19	10	2	38	1	2	7	21	15	17	7	5	18	22	0	3	0	252
1998	10	1	9	2	2	0	6	0	22	12	17	28	34	44	1	0	0	0	2	6	0	196
1999	0	15	0	40	19	23	4	15	0	5	29	6	75	30	0	27	41	0	0	11	28	368
2000	3	9	5	3	0	15	0	3	3	15	47	0	13	0	9	16	17	5	0	24	10	197
2001	0	5	0	45	13	13	0	2	2	27	0	37	37	6	14	1	0	25	18	1	0	246
2002	1	6	3	1	22	2	19	0	1	0	0	2	11	1	0	2	27	13	23	0	1	135
2003	77	7	2	16	19	64	13	5	11	6	0	6	2	22	4	1	0	20	1	1	1	278
2004	8	15	3	13	6	12	38	11	16	0	15	19	2	45	5	12	9	14	12	10	5	270
2005	17	1	16	26	36	7	21	12	23	49	0	8	8	23	4	49	0	9	0	0	2	311
2006	5	0	29	3	0	13	2	3	18	2	17	20	6	2	3	7	73	3	3	21	0	230
2007	5	8	16	23	0	32	3	0	0	4	2	42	0	17	47	26	0	2	2	1	11	241
2008	3	0	13	8	61	0	3	0	13	0	5	26	6	90	63	0	0	22	10	0	0	323
2009	7	0	24	32	13	48	13	13	40	4	6	40	4	8	3	4	10	7	1	0	0	277
Average	13	12	16	20	19	13	11	9	13	12	16	16	18	21	12	12	12	8	6	9	4	272

23.6 kg ha^{-1} for every additional mm of precipitation received during this 6-week period.

Inspection of the data points in Fig. 1A indicated two distinctly different responses to precipitation during this period. All but two of the 14 points that are above the regression line in Fig. 1A came from years when the sum of available soil water at planting and May precipitation (ASWP + MP) was greater than 250 mm (Table 3). Fig. 1B shows the data separated into the two categories defined by ASWP + MP greater than 250 mm (open circles) and ASWP + MP less than 250 mm (closed circles).

Table 2
Linear regression (yield [kg ha^{-1}] = $a + b \times$ precipitation [mm]) statistics for several relationships between precipitation during various periods and dryland maize yield at Akron, CO (1984–2009).

Precipitation period	Weeks	a	b	R^2	P
2 July–8 July	1	2829	32.8	0.06	0.27
9 July–15 July	1	3528	−26.3	0.05	0.32
16 July–22 July	1	3119	5.6	0.00	0.78
23 July–29 July	1	2517	45.3	0.18	0.04
30 July–5 August	1	2550	38.2	0.26	0.01
6 August–12 August	1	2680	24.7	0.13	0.09
13 August–19 August	1	2634	47.0	0.28	<0.01
20 August–26 August	1	3268	−4.1	0.00	0.82
27 August–2 September	1	3492	−22.7	0.06	0.24
23 July–5 August	2	1844	41.9	0.45	<0.01
23 July–12 August	3	1462	32.2	0.52	<0.01
23 July–19 August	4	1478	26.0	0.58	<0.01
16 July–19 August	5	1275	23.2	0.53	<0.01
16 July–26 August	6	1100	23.6	0.67	<0.01
16 July–2 September	7	921	21.4	0.48	<0.01
9 July–26 August	7	716	23.4	0.54	<0.01
9 July–2 September	8	655	21.5	0.44	<0.01
2 July–26 August	8	611	22.0	0.55	<0.01
2 July–2 September	9	501	20.8	0.46	<0.01
25 June–26 August	9	496	21.5	0.57	<0.01
25 June–2 September	10	375	20.5	0.49	<0.01

Yield increased at a rate of 20.5 kg ha^{-1} per mm of precipitation when ASWP + MP was greater than 250 mm (open circles, top line in Fig. 1B). This regression relationship explained 87% of the yield variation occurring in these 12 years. But under drier early season conditions (ASWP + MP less than 250 mm, filled circles, lower line in Fig. 1B) maize yields were distinctly lower for the same amount of precipitation between 16 July and 26 August. Under these drier conditions yield increased at a rate of 32.2 kg ha^{-1} per

Table 3
Available soil water at maize planting (ASWP) and May precipitation (MP) at Akron, CO.

Year	ASWP (mm)	MP (mm)	ASWP + MP (mm)
1984	165	59	224
1985	201	85	286
1986	276	56	332
1987	249	113	362
1988	160	136	296
1989	127	24	151
1990	197	104	301
1991	212	104	316
1992	234	28	262
1993	151	27	178
1994	156	29	185
1995	316	145	461
1996	173	116	289
1997	170	53	223
1998	132	25	157
1999	79	80	159
2000	243	20	263
2001	320	107	427
2002	162	13	175
2003	197	92	289
2004	142	38	180
2005	106	68	174
2006	162	37	199
2007	192	57	249
2008	268	53	311
2009	215	39	254

Author's personal copy

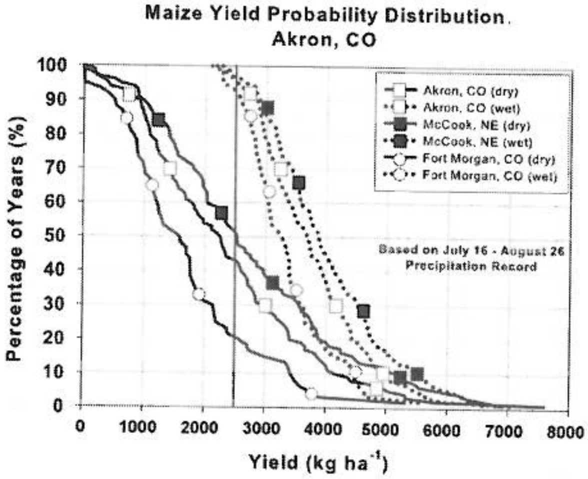

Fig. 2. Probability of producing at least a 2500 kg ha^{-1} maize grain yield at Akron, CO, McCook, NE, and Fort Morgan, CO based on precipitation between 16 July and 26 August. Solid lines (dry) are applicable when the sum of available soil water at planting and May precipitation is less than 250 mm. Dotted lines (wet) are applicable when the sum of available soil water at planting and May precipitation is greater than 250 mm.

mm of precipitation between 16 July and 26 August. This steeper slope is what would be expected as maize yields are potentially reduced more with reductions in critical period precipitation when there is less available stored soil water to draw from to meet evapotranspirational demand at this time. This second regression relationship explained 93% of the yield variation occurring in these 11 years.

From the data analyzed in this study it appears that conditions defining the two relationships shown in Fig. 1B occur with essentially equal frequency in the winter wheat–maize–fallow cropping system; that is, about half of the years would have ASWP + MP greater than 250 mm and about half of the years would have ASWP + MP less than 250 mm. Therefore, both relationships would be needed to make an assessment of the probability of receiving a certain yield based on the historical precipitation records.

3.3. *Frequency distributions of yield*

Annual precipitation in the west-central Great Plains (in the rain shadow of the Rocky Mountains) increases from west to east at a rate of about 63 mm every 100 km (Martin, 2007). Using precipitation records from Fort Morgan, CO (40°16′N, 103°57′W) from 1948 to 2007, Akron, CO from 1908 to 2007, and McCook, NE (40°12′N, 100°37′W) from 1909 to 2007, and with the linear relationships given in Fig. 1B, we constructed probability distributions of yield (Fig. 2) to make an assessment of risk involved in dryland maize production across the west-central Great Plains region for both the dry (ASWP + MP < 250 mm, solid lines) and wet (ASWP + MP > 250 mm, dotted lines) initial water conditions. A dryland yield of about 2500 kg ha^{-1} has been considered by farmers in this region to be an approximate break-even yield and is used as an example of how Fig. 2 might be used by a farmer to assess production risk. The probability of receiving enough precipitation between 16 July and 26 August to produce at least 2500 kg ha^{-1} (bold vertical line in Fig. 2) would be 21% at Fort Morgan, 43% at Akron, and 52% at McCook for the half of the years when ASWP + MP < 250 mm. But in the other half of the years with greater beginning soil water at planting and/or early season precipitation, the probability of producing at least 2500 kg ha^{-1} would be 93% at Fort Morgan, 96% at Akron, and 97% at McCook.

For the 26 years of data used in this analysis, 46% of the years had ASWP + MP < 250 mm and 54% of the years had ASWP + MP > 250 mm (Table 3). Using these percentages with the percentages from the probability distributions, we would expect the chance of producing a maize yield of at least 2500 kg ha^{-1} to be between 20% (43% probability occurring 46% of the time) and 52% (96% probability occurring 54% of the time) at Akron for maize grown in a winter wheat–maize–fallow rotation. We are unable to make this assessment for Fort Morgan and McCook as we do not have soil water data to compute the frequency of occurrences of ASWP + MP greater than or less than 250 mm in a winter wheat–maize–fallow production system.

4. Discussion

The variability in maize yield (0–5808 kg ha^{-1}) seen over the 23 years of this study was similar to that reported at other central Great Plains locations for shorter term studies [878–6711 kg ha^{-1} by Peterson et al. (1999) over 13 years in northeastern Colorado; 0–7276 kg ha^{-1} by Schlegel et al. (2007) over 12 years in western Kansas; 1500–5800 kg ha^{-1} by Lyon et al. (2003) over 2 years in western Nebraska]. Those studies all reported generalized conclusions about the effects of water availability on maize yield, but none of those previous studies correlated yield to growing season precipitation or critical period precipitation.

The data from the current study clearly show that two linear relationships define maize yield response to critical period precipitation with the slopes of those relationships differing depending upon water availability early in the growing season. The potential for maize to make better use of precipitation during the critical period was greater when ASWP + MP was greater than 250 mm because more water was available for evapotranspiration throughout the growing season. Greater amounts of stored soil water at planting have been shown to be positively correlated with vegetative biomass development in maize (Lyon et al., 1995). This greater early season biomass accumulation leads to greater collection of solar radiation and greater photosynthesis during tasseling, silking, and grain filling, ultimately leading to greater yield development when water stress is reduced by precipitation during this critical period.

As the amount of critical period precipitation increases, maize grain yields from both the wet and dry conditions shown in Fig. 1B approach the same value (about 6000 kg ha^{-1}). This result indicates that when critical period precipitation is high (greater than about 150 mm), the effects on yield of the large amounts of stored water at planting or precipitation stored early in the season in May (prior to large root system development and soil water extraction) are minimized.

The distinctly higher probabilities of producing a break-even maize yield when ASWP + MP > 250 mm (Fig. 2) confirm the conclusions of Lyon et al. (2003) in which dryland maize production in the Nebraska Panhandle was modeled with APSIM (Keating et al., 2003). Their conclusion was that production risk was reduced with greater amounts of stored soil water at planting.

5. Conclusions

This long-term study determined that dryland maize yields are highly correlated with precipitation falling between 16 July and 26 August, verifying the findings of many shorter term studies with controlled water stress that the critical time for water stress effects on maize yield is from just prior to tasseling through the middle of grain filling. Precipitation during this 6-week period is highly variable in the central Great Plains resulting in maize yields which are highly variable. The relationship between maize yield and this

Author's personal copy

critical period precipitation was found to be linear, with the slope of the response being dependent on the sum of available soil water at planting and May precipitation. When that sum was greater than 250 mm, maize yield increased 20.5 kg ha^{-1} per mm of precipitation falling between 16 July and 26 August. The slope of the response was 32.2 kg ha^{-1} per mm of precipitation under drier early season conditions when the sum of available soil water at planting and May precipitation was less than 250 mm.

The two well defined linear relationships between maize yield and critical period precipitation were used with long-term precipitation records from three Central Great Plains locations to construct yield probability distributions. Those probability distributions indicated that the probability of achieving at least a break-even yield of 2500 kg ha^{-1} ranged from 20% (Fort Morgan) to 52% (McCook) when the sum of available soil water at planting was less than 250 mm, but that the probabilities increased to 93% (Fort Morgan) to 97% (McCook) when early season water availability was greater. These results confirm the conclusion of Nielsen et al. (2009) that profitable dryland maize production in the central Great Plains remains a highly risky enterprise, but the risk is significantly lower when available soil water at planting is near field capacity and/or if May precipitation is much above average resulting in significant early season precipitation storage. This suggests that farmers could use measurements of available soil water at planting and long-term precipitation records to quantify the risk associated with dryland maize production and to make a decision about whether or not to plant maize.

Acknowledgement

The authors express their appreciation to Tawney Bleak for assistance with data analysis.

References

Anderson, R.L., Bowman, R.A., Nielsen, D.C., Vigil, M.F., Aiken, R.M., Benjamin, J.G., 1999. Alternative crop rotations for the central Great Plains. J. Prod. Agric. 12, 95–99.

Bowman, R.A., Vigil, M.F., Nielsen, D.C., Anderson, R.L., 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63, 186–191.

Claassen, M.M., Shaw, R.H., 1970. Water deficit effects on corn. II. Grain components. Agron. J. 62, 652–655.

Denmead, O.T., Shaw, R.H., 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52, 272–274.

Farahani, H.J., Peterson, G.A., Westfall, D.G., 1998. Dryland cropping intensification: a fundamental solution to efficient use of precipitation. Adv. Agron. 64, 197–223.

Hall, A.E., 2001. Crop Responses to Environment. CRC Press, New York.

Halvorson, A.D., Nielsen, D.C., Reule, C.A., 2004. Nitrogen fertilization and rotation effects on no-till dryland wheat production. Agron. J. 96, 1196–1201.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Lyon, D., Boa, J.F., Arkebauer, T.J., 1995. Water-yield relations of several spring-planted dryland crops following winter wheat. J. Prod. Agric. 8, 281–286.

Lyon, D.J., Hammer, G.L., McLean, G.B., Blumenthal, J.M., 2003. Simulation supplements field studies to determine no-till dryland corn population recommendations for semiarid western Nebraska. Agron. J. 95, 884–891.

Martin, D., 2007. Impact of advances in irrigation engineering and management. In: 2007 Water Law, Policy and Science Conference, The Future of Water Use in Agriculture, University of Nebraksa, Lincoln, NE, 26–27 March 2007 (available at http://watercenter.unl.edu/WaterConference/2007WLPS/PPTs/Martin.pdf, verified 3/23/2010).

Nielsen, D.C., Unger, P.W., Miller, P.R., 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron. J. 97, 364–372.

Nielsen, D.C., Vigil, M.F., Benjamin, J.G., 2009. The variable response of dryland corn grain yield to soil water content at planting. Agric. Water Manage. 96, 330–336.

Norwood, C.A., Currie, R.S., 1998. An agronomic and economic comparison of the wheat-corn-fallow and wheat-sorghum-fallow rotations. J. Prod. Agric. 11, 67–73.

Peterson, G.A., Westfall, D.G., 2004. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144, 127–138.

Peterson, G.A., Westfall, D.G., Peairs, F.B., Sherrod, L., Gangloff, W., Larson, K., Thompson, D.L., Ahuja, L.R., Koch, M.D., Walker, C.B., 1999. Sustainable dryland agroecosystem management. Tech. Bull. TB99-1. Colorado State University Agricultural Experiment Station, Fort Collins (available at http://www.colostate.edu/Depts/AES/Pubs/pdf/tb99-1.pdf, verified 3/23/2010).

Ratliff, L.F., Ritchie, J.T., Cassel, D.K., 1983. A survey of field-measured limits of soil water availability and related laboratory-measured properties. Soil Sci. Soc. Am. J. 47, 770–775.

Ritchie, J.T., 1981. Soil water availability. Plant Soil 58, 327–338.

Robins, J.S., Domingo, C.E., 1953. Some effects of severe soil moisture deficits at specific growth stages in corn. Agron. J. 45, 618–621.

Schlegel, A., Thompson, C., Dumler, T., 2007. Large-scale dryland cropping systems. Kansas State University (available on-line at http://www.wkarc.org/DesktopDefault.aspx?tabid=81, verified 3/23/2010).

Shaw, R.H., 1976. Climatic requirement. In: Sprague, G.F. (Ed.), Corn and Corn Improvement. Agronomy 18, 591–623.

Waldren, R.P., 1983. Corn. In: Teare, I.D., Peet, M.M. (Eds.), Crop-Water Relations. John Wiley and Sons, Inc., New York, pp. 187–211.

Westgate, M.E., 1994. Seed formation in maize during drought. In: Boote, K.J., Bennett, J.M., Sinclair, T.R., Paulsen, G.M. (Eds.), Physiology and determination of crop yield. ASA-CSSA-SSSA, Madison, WI, pp. 361–364.