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Rotation effect on sorghum response to nitrogen fertilizer under different rainfall and temperature environments

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Abstract

Cropping sequence effects on sorghum (*Sorghum bicolor* L. Moench) response to nitrogen fertilizer under different rainfall and temperature regimes were evaluated in eastern Nebraska. The Standardized Precipitation Index (SPI) and temperature *Z*-scores were used to characterize the 18-yr cropping period into eight sets of contrasting cropping environments. Mean sorghum yields ranged from 4050 to 6260 kg/ha in continuous cropping, and from 5130 to 7120 kg/ha in rotation with soybean (*Glycine max*), a significant increase with crop rotation. Yields were lower in dry years with hot April temperatures than in dry years with cool April temperatures. Hot April temperatures improved yields in wet years. April temperature did not affect yield if a wet pre-season was followed by a dry cropping season. Sorghum responded more to fertilizer N in dry than in wet years, reflecting less available N from soybean and the soil nutrient complex in the previous year. Sorghum grown in rotation with soybean did not generally respond to fertilizer N, suggesting that high fertilizer N rates are unnecessary in rotation systems. Low September temperatures reduced final yields. Given the high probability of confronting adverse cropping conditions, it is strongly recommended that sorghum be considered as an important component of rainfed cropping systems in eastern Nebraska to ensure minimum crop loss to farmers. Greater economic gains can be achieved by using rotations with soybean because of higher sorghum yields and lower fertilizer costs, and these are most likely under the favorable rainfall and temperature regimes identified in this study. The results provide useful information for fine-tuning management options to maximize sorghum yields and reduce input costs in atypical years. © 1998 Elsevier Science B.V.

Keywords: N response; Pre-season weather; Stress management; Standardized precipitation index; Temperature *Z*-score

1. Introduction

Rotation of cereals and legumes is usually preferred to sole cropping of either crop because yields are higher (Adams, 1974; Baldock et al., 1981; Shrader et al., 1966) and production costs are lower (Helmers et al., 1986; Higgs et al., 1990; Zentner et al., 1984). Soil fertility improvement and pest control are ancillary benefits from legume–cereal rotations or mixing crops with unrelated growth characteristics. Examples of systems involving crops with dissimilar resource requirements are corn–soybean and sorghum–soybean sequential cropping, and these rotations are commonplace in eastern Nebraska. Earlier studies in this area have established significant

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yield advantage to sorghum following soybean (Clegg, 1982; Gakale and Clegg, 1987; Bagayoko et al., 1992; Franzleubbers et al., 1994).

Clegg (1982) reported that a system with soybean preceding sorghum supplied about 76 kg N/ha and raised sorghum yield by 42%. Also, Bagayoko et al. (1992) noted residual soil nitrate nitrogen up to 53 kg/ha after soybean, which increased subsequent sorghum yield between 0.1 and 2.0 Mg/ha compared to continuous cropping of sorghum. The low inorganic nitrogen requirement of crops grown in rotations has added to recent recognition of the system as a means to curb groundwater pollution by fertilizer nitrogen in high-input farming systems (Keeney, 1982). However, as shown by Peterson et al. (1990), the observed gains from rotations are contingent upon crop types and sequencing as well as climate. Findings from recent studies of Peterson et al. (1990), Gakale and Clegg (1987), and Claassen and Kissel (1984) substantiate the existing notion that sorghum is more tolerant than corn to extreme weather conditions (Doggett, 1970; Wall and Ross, 1970). Doggett (1970) summarized physiological characteristics enabling sorghum to withstand extreme climates as: (1) deposition of silica in the endodermis of the roots, (2) large root system and a high root-to-leaf ratio, and (3) quick recovery of the stomata after prolonged drought. Thus, apart from limitations imposed by low soil fertility, sorghum can be grown successfully in seasons and areas where corn and soybean will normally be less productive (Doggett, 1970; Wall and Ross, 1970). A low fertility constraint can be removed through inorganic fertilization and/or use of rotations; therefore, the resilience of sorghum to adverse climatic conditions allows farmers to crop continuously their fields to corn and soybean in good years and sorghum in abnormal years if these can be adequately predicted.

From an agricultural production standpoint, abnormal years are typically characterized by drought conditions that may occur before planting, in the course of the growing season, or during both preplanting and growing seasons (Wilhite and Glantz, 1985). Furthermore, in some years, extreme temperatures alone or in concert with rainfall irregularities create more unfavorable growing environments for field crops. Elevated July and August temperatures are harmful to corn and soybean yield (Teigen and Thomas, 1995; Stooksbury and Michaels, 1994); whereas, warm April and May positively affect sorghum yield (Adams, 1962; Yamoah et al., 1997b). The hypothesis here is that sorghum's response to N fertilizer and potential legume nitrogen contribution in cropping systems will vary based on prevailing climatic factors. The present study evaluates long-term performance of sorghum under different temperature and moisture stress conditions in relation to N fertilizer response in rotations and continuous cropping systems.

2. Materials and methods

The experiment was carried out from 1974 to 1994 at the Agricultural Research and Development Center (ARDC) near Mead in eastern Nebraska. Eighteen years were included in the analyses; those years had complete data available. The soils of the experimental site are Argiudolls with high calcium and magnesium in the exchange complex. Feldspar, a component of the parent material, makes the soils sufficient in potassium. Table 1 presents data on long-term precipitation and temperature at the Mead area in eastern Nebraska. The shaded area in Fig. 1 delineates agroecological zones of crop districts where findings of this study may be applicable (W.J. Waltman and C.F. Yamoah, personal communication). The treatments consisted of continuous sorghum or a 2-yr sorghum–soybean rotation, each receiving 0, 50, 100, and 150 kg N fertilizer/ha applied to sorghum. The rotations were designed such that each crop appeared every year. There were six rows of crops in plots measuring 3.8×12 m; yield calculation was based on 3 m of the center two rows to prevent soil mixing (all tillage practices were in the direction of the longer plot dimension) and reported at 13% seed moisture. The experiment was laid out as a randomized complete block design with four replications. Sorghum hybrids used in the study were RS-626 (1974–1975), DKE57 (1976–1977), DKE57 + (1978–1979), DK59 + (1982–1987), DK48 (1988–1990), and DK41Y (1991–1995). Soybean varieties were Amsoy (1974–1975), Amsoy 71 (1976–1986), Hack (1987), Winchester (1988–

Table 1
Long-term precipitation and temperature in eastern Nebraska, 1969–1995

Month	Precipitation (mm)			Temperature (°C)		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
January	12	0	28	−6.7	−13.8	0.5
February	12	2	32	−3.3	−11.0	3.3
March	46	0.2	129	3.4	−1.7	8.3
April	67	9	166	10.4	7.2	15.4
May	104	22	224	16.5	12.7	19.8
June	95	26	252	21.9	19.3	25.3
July	82	3	250	24.2	20.9	27.0
August	86	13	220	22.8	19.3	27.0
September	75	4	193	18.0	14.9	20.4
October	59	0	141	11.0	8.3	13.8
November	37	0	89	3.0	−1.7	6.6
December	20	0	83	−3.5	−12.1	0.0

1990), Hamilton (1991–1994), and Dunbar (1995). Changes in cultivar were made when appropriate to keep up with genetic advances by breeders in both crops. The seeding rate was 125,000 plants/ha for sorghum and 513,000 plants/ha for soybean. Seedbed preparation was disking followed by harrowing. Pre-emergence herbicide for soybean was the recommended rate of chloramben (3-amino-2,5-dichlorobenzoic acid); for sorghum, it was atrazine (2-chloro-4-ethylamino-6-isopropylamine-6-triazine)/propachlor (2-chloro-*N*-isopropyl-acetanilide). Later the herbicide dual (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide) was used as it was compatible with both crops. Seeding was in the last two weeks of May or first week in June.

Growing years were classified into eight drought categories based on the standardized precipitation index (SPI) (McKee et al., 1993) and temperature *Z*-scores. Standardized precipitation index and temperature *Z*-scores were calculated as the difference of precipitation or temperature from the long-term mean (> 30 yr) divided by the standard deviation. The SPI values were adjusted for normality using the gamma function, whereas the temperature *Z*-scores were not. Values of SPI greater than zero indicate wetter than average conditions, and values less than zero signify potential for drought conditions. Standardized precipitation indices of less than −2.0 or greater than 2.0 represent extreme dry and wet seasons. The moisture classes based on SPI were defined as: (1) negative pre-season (dry September to April) and negative growing season (dry May to August), (2) positive pre-season (wet) and positive growing season, (3) positive pre-season and negative growing season, and (4) negative pre-season and positive growing season. Major crop management decisions such as crop choice are made before planting in May. Therefore, pre-season temperatures and precipitation that appear to influence sorghum yield are important (Adams, 1962). April temperature was chosen based on results of previous studies (Adams, 1962; Yamoah et al., 1997b). Temperatures before and after physiological maturity are purported to affect final sorghum yield as well (Clegg, personal communication). The authors used correlations to identify the temperature *Z*-score that had the greatest effect on final yield after physiological maturity. As with the SPI, negative temperature *Z*-scores are below normal or cool, and positive *Z*-scores, are above normal or hot.

The data were analyzed using the full data set followed by second-order regressions with yield (Y) as the dependent and $N(x)$, N^2 the independent variables in the rainfall temperature categories. Furthermore, N fertilizer was transformed logarithmically and regressed with yield as $Y = \log_{10}(N+1)$. This transformation was done to linearize the second-order relations and allow statistical comparisons of slopes and intercepts between rainfall/temperature environments and cropping systems. Maximum yield and optimum N rate to achieve the maximum

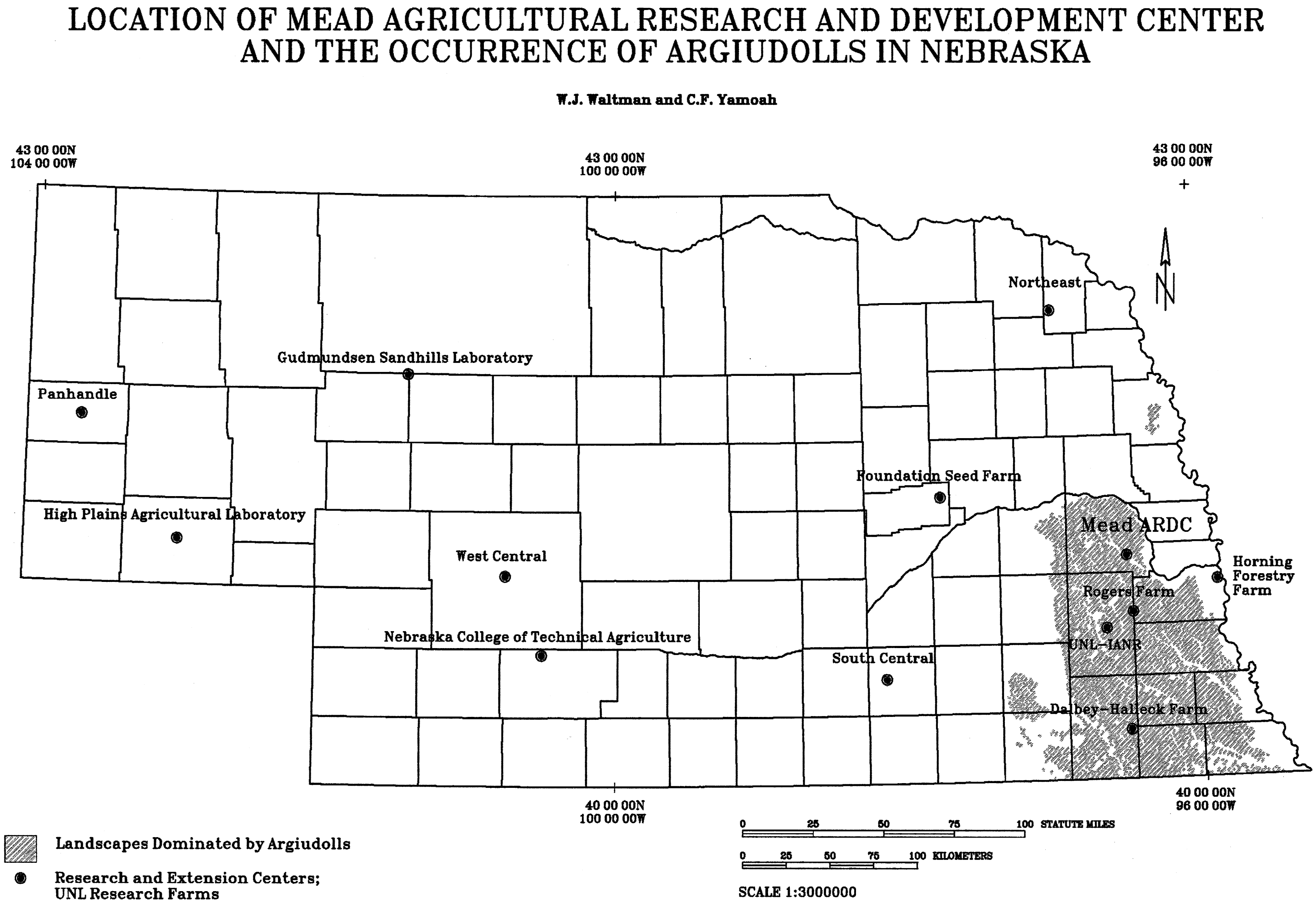

Fig. 1. Location of Mead Agricultural Research and Development Center and the occurrence of Argiudolls in Nebraska.

yield were determined by rewriting the conventional form of the quadratic function:

$$Y = a + bx + cx^2 \qquad (1)$$

as

$$Y = k + c(B + x)^2 \qquad (2)$$

where $k = a - b^2/4c$, i.e., the maximum yield; $-B = -b/2c$, i.e., the optimum x; $c =$ the rate of change of yield as N deviates from the optimum. Nitrogen contribution of the soybean rotation system was estimated using regressions, and the amounts were added to the N fertilizer rates to develop common N response models for sorghum (Shrader et al., 1966; Baldock and Musgrave, 1980; Clegg, 1982). The SAS system for regression (Freund and Littell, 1991) was used for the statistical analysis.

3. Results and discussion

3.1. Yields in cropping environments

A classification of the 18 growing seasons based on SPI and April temperature Z-scores allowed grouping them into eight rainfall/temperature environments (Table 2). In addition, there was a total of 16 cropping environments within a year depending on whether sorghum was monocropped or grown in rotation with soybean. During the 18-yr time span, 60% of the period had wet pre-plant seasons or SPI values > 0, and 55% of the same period had cool pre-plant temperatures, or April temperature Z-scores < 0. Thus, the probability of encountering each of the rainfall/temperature conditions is almost equal and quite high. The authors think this confirms the need for an in-depth analysis of sorghum performance in distinct growing environments. The degree of wetness, dryness or coolness obviously varied from year to year, but the general effects of weather on sorghum yield followed a consistent pattern (Table 3). In general, sorghum in rotation produced higher yields than continuous sorghum; mean yields ranged from 4050 to 6260 kg/ha in continuous sorghum and from 5130 to 7120 kg/ha in rotation with soybean.

Yields differed ($P < 0.0001$) with respect to years, cropping systems and N fertilization (Table 3). There were significant interactions ($P < 0.0001$) between cropping systems and years, N fertilization and years, as well as N fertilization and cropping systems. There was also a three-way interaction of cropping system, years and N fertilization ($P = 0.023$). The significant yield differences described above are expected, given the various rainfall and temperature environments depicted in Table 2. Table 3 gives mean yields in the rainfall/temperature categories for continuous cropping and rotations. Generally, a cool pre-plant season improved sorghum yield in monocrop and rotation systems when both pre-season and growing season were dry. A hot pre-plant season became advantageous when the pre-season and growing season were both wet. Pre-plant temperature did not appear to have any consistent pattern on yield when a wet pre-season was followed by a dry growing season. However, a cool pre-plant season resulted in high yields when the pre-season was dry and the growing season wet. In almost all cases,

Table 2
Drought classification based on preseason and growing season standardized precipitation index and April temperature Z-scores near Mead, NE, 1975–1994

Class	Pre-season SPI	Growing season SPI	April temperature Z	Year
1A	Dry	Dry	Cool	1975, 1988
1B	Dry	Dry	Hot	1989
2A	Wet	Wet	Cool	1982, 1993
2B	Wet	Wet	Hot	1985, 1986, 1987
3A	Wet	Dry	Hot	1978, 1991
3B	Wet	Dry	Cool	1979, 1983, 1984, 1992
4A	Dry	Wet	Hot	1980, 1981
4B	Dry	Wet	Cool	1990, 1994

Table 3
Sorghum yield (kg/ha) as influenced by pre-season and growing season rainfall/temperature environments and cropping systems near Mead, NE, 1975–1994

Environment	Continuous sorghum		Sorghum in rotation with soybean	
	Cool years ($-Z$)	Hot years ($+Z$)	Cool years ($-Z$)	Hot years ($+Z$)
Dry–dry [a]	6080	5360	6580	5140
Wet–wet	4050	6160	5130	7120
Wet–dry	5980	6145	7050	6735
Dry–wet	6260	5820	6820	6490

LSD (0.05) for cropping systems × cropping years = 457 kg/ha

Analysis of variance

Source of variation	*df*	Mean squares	Probability
Cropping system (CS)	1	77,840,226	0.0001
Year (Y)	17	26,198,396	0.0001
CS × Y	17	1,691,958	0.0001
Nitrogen fertilizer (N)	3	12,021,415	0.0001
CS × N	3	51,093,588	0.0001
$Y \times N$	51	1,130,168	0.0001
CS × $Y \times N$	51	617,885	0.0230

[a] Dry–dry = dry pre-season followed by a dry growing season; wet–wet = wet pre-season followed by a wet growing season; dry–wet = dry pre-season followed by a wet growing season; wet–dry = wet pre-season followed by a dry growing season.

yields in rotations were superior to their continuous cropped counterparts.

Knowledge of the effects of pre-plant moisture conditions and temperature may be useful for farm management. Corn and sorghum dominate the cereal-based systems in eastern Nebraska, but corn is less able than sorghum to withstand low moisture conditions (Peterson et al., 1990; Claassen and Kissel, 1984; Doggett, 1970; Wall and Ross, 1970; Yamoah et al., 1997a). The results here confirm that sorghum maintains reasonable yields in a wide range of growing season moisture conditions. Therefore, it would be appropriate to grow sorghum if there is a pre-season moisture deficit, especially in years with cool April temperatures. High yields can still be expected even if the growing season becomes wet. Sorghum and/or corn may be grown in years with adequate pre-season moisture. A diversification of corn and sorghum from knowledge of pre-season weather therefore insures against crop loss, given an almost equal probability of confronting an adverse or a favorable growing season. These conclusions are based on sorghum yields under a range of climatic conditions, and not on the sorghum–corn comparison in this experiment.

3.2. Yield response to N fertilizer in cropping environments

Sorghum responded differently to N fertilizer in the various growing environments (Table 4). Slopes and intercepts were different in the continuous cropping systems; whereas only the intercepts varied in rotations. Yield response to N fertilizer was similar in rotations and continuous cropping systems in years with both dry pre-season and growing season. However, the responses differed in the other years de-

Table 4
Comparison of slopes and intercepts (probabilities of statistical significance) of sorghum yield response to N in different pre-season temperatures for given rainfall classes, near Mead, NE, 1975–1994

Classes	Continuous sorghum		Sorghum in rotation with soybean	
	Slope	Intercept	Slope	Intercept
DDC vs. DDH	ns	0.01	ns	0.01
WWC vs. WWH	0.01	0.01	ns	0.01
WDH vs. WDC	ns	ns	ns	0.10
DWH vs. DWC	0.05	0.05	ns	ns

D = dry, W = wet, C = cool, H = hot (see Table 1).
ns: non-significant.

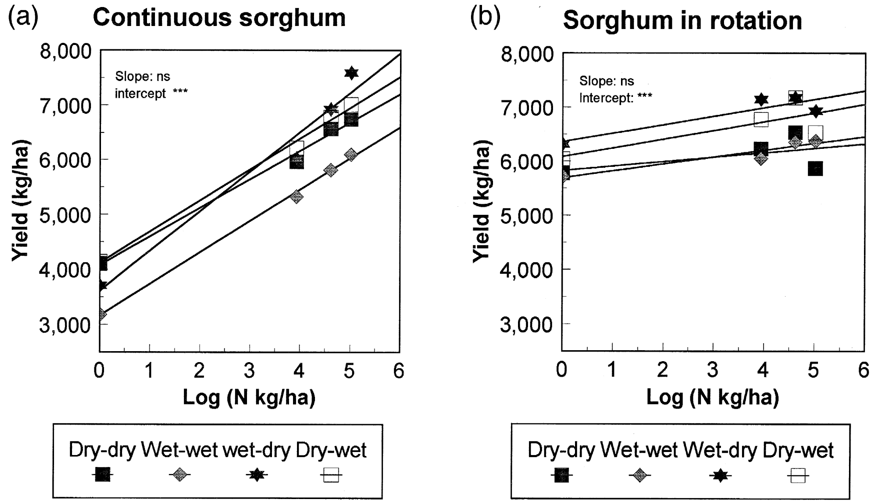

Fig. 2. (a) Slopes and intercepts of sorghum response to N in pre-season and growing season drought environments—continuous sorghum; (b) Slopes and intercepts of sorghum response to N in pre-season and growing season drought environments—sorghum in rotation.

pending on whether the pre-season was cool or hot. In situations where a wet pre-season preceded a dry growing season, sorghum response to N was almost the same in the cropping systems irrespective of pre-season temperature. The non-significant differences for slopes and intercepts between pre-plant temperatures suggest a common N fertilizer response function for yields in this rainfall/temperature environment.

Fig. 2a,b show the yield response to N fertilizer averaged across pre-season temperatures. The response lines are parallel, signifying that they have equal slopes but different intercepts. In relative terms, the lowest intercept was when sorghum was continuously cropped in years with wet pre-season and growing seasons. Sorghum is valued primarily for its ability to withstand moisture stress, but it is known also to be able to tolerate some degree of wetness (Doggett, 1970). Yields were higher in rotations (Fig. 2b), but a succession of wetness (wet–wet) or dryness (dry–dry) in a growing year resulted in lower intercepts than in situations where either the pre-season or growing season was wet and the other dry. It is difficult to predict growing season weather conditions; therefore, the high performance of sorghum under dry pre-season conditions in both cropping systems is noteworthy. The observed resilience of sorghum to low pre-season moisture reduces the probability of a total crop loss if sorghum is part of a cropping system. Planting sorghum allows farmers to make gains in the event of inadequate or excessive growing season precipitation that could destroy other susceptible crops. Pre-season drought decreases germination rate, restricts root growth, and causes poor crop establishment. These are known to depress crop yield more than growing season moisture deficits (Wilhite and Glantz, 1985).

Fig. 3a–d compare sorghum response to N fertilizer between cropping systems in four weather patterns. Slopes and intercepts differed between continuous cropping and rotations in all environments. Overall, sorghum in rotations outyielded the continuous crop at low N fertilizer rates. Yields of continuous sorghum surpassed those in rotations at the highest N fertilizer rate in the continuous crop under continuous dry moisture conditions (Fig. 3a). Under dry conditions, the yield response lines of continuous vs. rotated intersected at a lower N fertilizer rate than under wet conditions (Fig. 3b). Specifically, the crossing point was 50 kg N/ha for both dry pre-season and growing season and >150 kg N/ha in seasons when they were both wet. The response line for the continuous cropping system intersected that of the rotation at a point slightly beyond the 100 kg N fertilizer during wet pre-season and dry growing season. However, the two response lines met at the

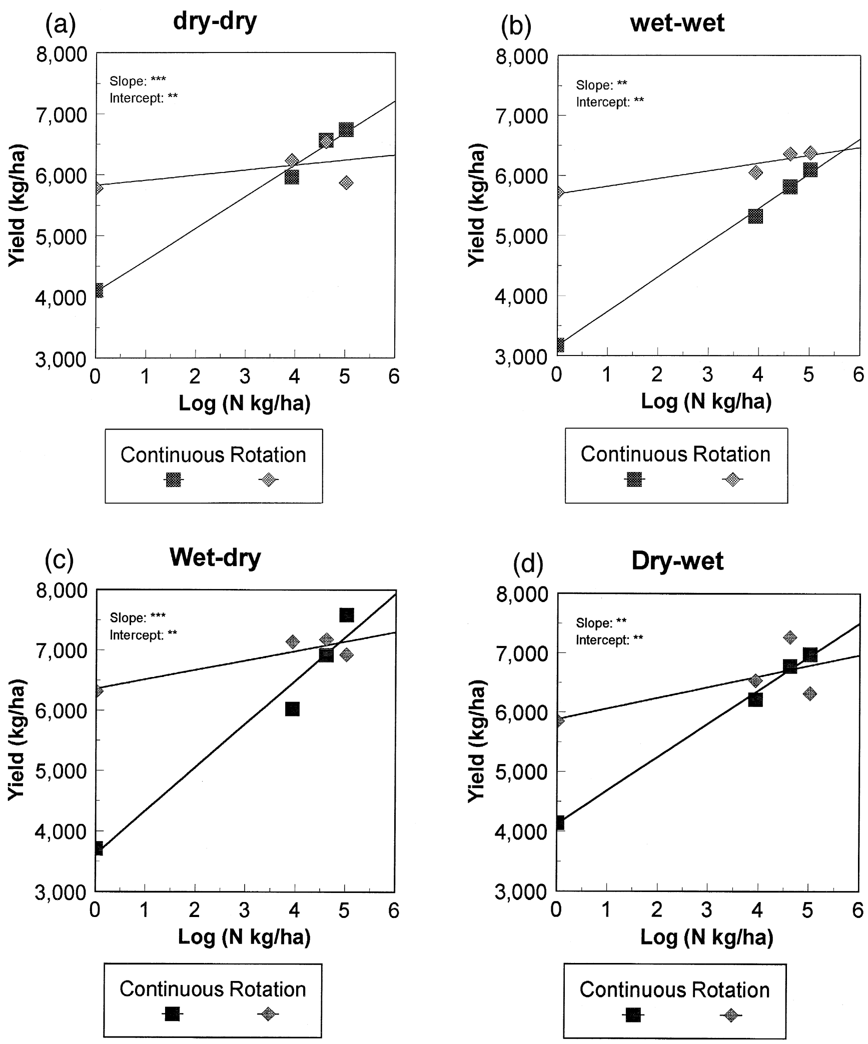

Fig. 3. (a) Slopes and intercepts of sorghum response to N as affected by cropping systems: dry–dry; (b) Slopes and intercepts of sorghum response to N as affected by cropping systems: wet–wet; (c) Slopes and intercepts of sorghum response to N as affected by cropping systems: wet–dry; (d) Slopes and intercepts of sorghum response to N as affected by cropping systems: dry–wet.

100 kg N fertilizer increment when a dry period preceded a wet growing season. It is possible that a wet pre-season created an ideal environment for N flush at the onset of the cropping period and enhanced crop performance in the rotational systems. An earlier study revealed a negative correlation between pre-season precipitation and N use efficiency in continuous sorghum, but not when planted in rotation with soybean (Yamoah et al., 1997a). Sorghum in continuous systems received the required amount of N fertilizer every year as opposed to rotations that were fertilized in alternate years. The large N reserves developed through the years in the continuous system as a result of the differential fertilization scheme may have contributed to the slight yield advantage of the continuous system over the rotations at high N rates.

The high yield intercept with zero N of the rotational systems is expected and is credited principally to N supply and other beneficial rotational effects from the soybean–sorghum rotational sequence. Nitrogen contribution of a soybean year to subsequent

Table 5
Proportion of sorghum yield variability (R^2) attributed to N fertilizer; maximum yield (Y_{max}) and optimum N (X_{opt}) (kg/ha) in different rainfall/temperature environments

Growing environment	R^2	Y_{max}	X_{opt}	$Y_{max}:X_{opt}$
Dry–dry, cool, continuous	0.74**	6940	131	53
Dry–dry, hot, continuous	0.99***	6482	111	58
Dry–dry, cool, rotation	0.19 ns	6967	85	82
Dry–dry, hot, rotation	0.79 ns	5448	68	80
Wet–wet, cool, continuous	0.91***	4925	128	38
Wet–wet, hot, continuous	0.75***	8009	123	65
Wet–wet, cool, rotation	0.29 ns	5415	109	50
Wet–wet, hot, rotation	0.08 ns	8150	–	–
Wet–dry, continuous	0.77***	7628	152	50
Wet–dry, rotation	0.11 ns	7256	94	77
Dry–wet, cool, continuous	0.93***	120	120	58
Dry–wet, hot, continuous	0.93***	7169	136	53
Dry–wet, cool, rotation	0.75**	7063	90	78
Dry–wet, hot, rotation	0.53 ns	7118	86	83

, * denote statistical significance at 0.05, and 0.01 probability levels, respectively.
ns: non-significant.

sorghum was previously estimated as 76 kg/ha by Clegg (1982). Estimates of N contribution in the rotation from this study is in agreement with Clegg (1982) and ranged between 34 and 83 kg/ha subject to rainfall/temperature conditions. The above analyses demonstrate that it is unnecessary to apply additional high rates of N fertilizer (> 100 kg/ha) to maximize sorghum yield if it is grown with soybean in rotation. Application of the low N fertilizer (50 kg/ha) to sorghum obviously is both economical and more environmentally benign than using high rates (> 100 kg N/ha) under all climatic scenarios.

Table 5 shows variation of yield attributed to N fertilizer in the various rainfall and temperature environments. Overall, N fertilizer contributed less to yield in rotations than in continuous systems as indicated by the high significance of R^2 for the continuous systems and non-significance in rotations. Apparently, there is no difference in maximum yields among growing environments. However, the amount of N fertilizer needed to attain maximum yield was lower for rotations than continuous systems. Consequently, the ratio $Y_{max}:X_{opt}$, an indicator of N fertilizer efficiency, was higher for rotations than continuous systems. Table 6 reveals that the lowest N contribution of soybean was produced under a combination of drought and high pre-season temperature. Interestingly, it was under these same conditions that sorghum exhibited the highest response ($R^2 = 0.99^{***}$) to N fertilizer probably because the amount supplied by the soybean–sorghum rotation was inadequate (Table 5). Thus, sorghum had to rely heavily on external N fertilizer for growth and yield. The comparatively high N contribution of soybean in wet seasons may be the result of improved mineralization of residues throughout the cropping season.

Table 6 shows coefficients of determination (R^2) of the combined N response equations relating sorghum yield to total N supplied under the various rainfall/temperature regimes were highly significant ($P < 0.003$ to 0.0001). This implies that N fertilizer and N contribution of the soybean–sorghum rotations were both important for sorghum yield. A practical value of the common response functions is their use to estimate the potential N contribution of soybean in the various cropping environments so that adjustments can be made for additional fertilizer N required to attain a given yield. Consequently, a useful agronomic trend that seems to emerge from the information in Table 6 is that N supply from the rotation year soybean is relatively low (34 to 61 kg/ha) when the pre-season is dry and moderately high (63 to 83 kg/ha) when wet. High N fertilizer may therefore be required in dry pre-seasons to compensate for the low N supply from the soybean year; Table 5 shows this with generally high R^2 values for yield response to N fertilizer for continuous sorghum under dry pre-seasons. Additional investigations are needed to firmly establish this assertion.

Table 6
N contribution of soybean ($N_s \pm$ s.e.) and combined N response equations for sorghum yield in different rainfall/temperature environments

Environment	N_s (kg/ha)	a	b	c	R^2
Dry–dry–cool	55 ± 7.4	4520	35.5	0.13	0.59
Dry–dry–hot	34 ± 1.0	3539	46.2	0.21	0.83
Wet–wet–cool	83 ± 3.7	2370	27.1	0.07	0.89
Wet–wet–hot	71 ± 4.9	4286	38.7	0.12	0.58
Wet–dry–both	63 ± 3.7	3700	50.3	0.17	0.59
Dry–wet–cool	46 ± 3.6	3776	50.3	0.19	0.91
Dry–wet–hot	61 ± 3.0	4762	33.4	0.12	0.89

R^2 values are all statistically significant at < 0.01 probability level.
Yield model: $Y = a + bX - cX^2$.

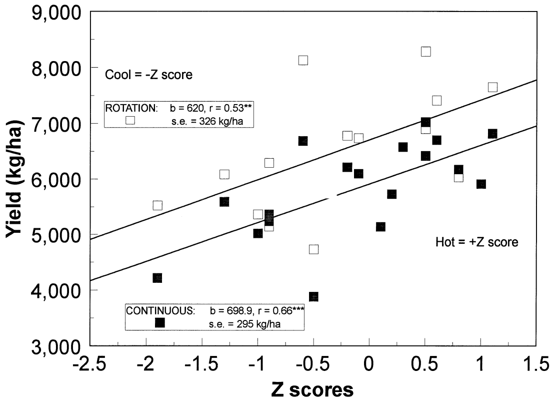

Fig. 4. Sorghum yield as affected by September temperature (Z-score) on cropping systems.

Fig. 4 illustrates the effect of September temperature on final crop yield. Sorghum in southeast Nebraska usually reaches physiological maturity in mid-September. Therefore, it is assumed that adverse weather may contribute to further yield losses. Clearly, sorghum yields are lower in a cool September ($-Z$-scores) than in a hot September ($+Z$-scores). Slopes of continuous cropping and rotations are parallel, suggesting that yields in both systems are affected to the same degree by September temperature; but both slopes are significantly different from zero ($P < 0.05$). The lower intercept of the continuous system reflects the overall yield advantage of growing crops in rotations. Early planting with short season hybrids could bypass or minimize the negative effect of low September temperatures on yield, depending on how much potential yield is reduced in favorable rainfall years by planting the earlier hybrids. The data here indicate that sorghum yield changed by about 700 kg/ha ($P < 0.001$) in continuous cropping and 620 kg/ha ($P < 0.05$) in rotations for a unit change in September temperature Z-score.

4. Conclusions

Using standardized precipitation index and temperature Z-scores in combination with cropping systems, 16 different cropping environments were identified. Sorghum yielded reasonably well in all the environments. The estimated N contribution of a soybean year in rotation was generally higher in wet than dry years. Thus, the N fertilizer response differed in the cropping environments and was mostly significant for continuous sorghum in dry years. Sorghum in rotations, in general, did respond to N fertilizer regardless of weather factors. Low September temperatures caused a yield reduction. The common summer row crops in Nebraska are corn, sorghum and soybean. Based on past experience with corn and soybean, and the current information on the effect of rainfall and temperature on sorghum performance, the authors strongly recommend that sorghum be made part of cropping systems to reduce risk of total crop failure. Yields can be optimized by choosing the appropriate crops and cropping systems that will respond to prevailing rainfall and temperature combinations; results of the present analyses can be used as a guide.

References

Adams, J.E., 1962. Effect of soil temperature on grain sorghum growth and yield. Agron. J. 54, 257–261.

Adams, J.E., 1974. Residual effects of crop rotations on water intake, soil loss and sorghum yield. Agron. J. 66, 299–304.

Bagayoko, M., Mason, S.C., Sabata, R.J., 1992. Effects of previous cropping systems on soil nitrogen and grain sorghum yield. Agron. J. 84, 862–868.

Baldock, B.O., Musgrave, R.B., 1980. Manure and mineral fertilizer effects in continuous and rotational crop sequences in central New York. Agron. J. 72, 511–518.

Baldock, B.O., Higgs, R.L., Paulson, W.H., Jackobs, J.A., Shrader, W.D., 1981. Legume and mineral fertilizer effects on crop yields in several crop sequences in the Upper Mississippi Valley. Agron. J. 73, 885–890.

Claassen, M.M., Kissel, D.E., 1984. Rotation with soybean increases corn and grain sorghum yields. Better Crops Plant Food 68, 28–30.

Clegg, M.D., 1982. Effect of soybean on yield and nitrogen response of subsequent sorghum crops in eastern Nebraska. Field Crops Res. 5, 233–239.

Doggett, H., 1970. Sorghum. Longman, p. 187.

Franzleubbers, A.J., Francis, C.A., Walters, D.T., 1994. Nitrogen fertilizer response potential of corn and sorghum in continuous and rotated crop sequences. J. Prod. Agric. 7, 193–284.

Freund, R.J., Littell, R.C., 1991. SAS System for Regression, 2nd edn. SAS Inst., Raleigh, NC.

Gakale, M.P., Clegg, M.D., 1987. Nitrogen from soybean for dryland sorghum. Agron. J. 79, 1057–1061.

Helmers, G.A., Langemeier, M.R., Atwood, J., 1986. An economic analysis of alternative cropping systems for East-Central Nebraska. Am. J. Alter. Agric. 1, 153–158.

Higgs, R.L., Peterson, A.E., Paulson, W.H., 1990. Crop rotations: sustainable and profitable. Soil Water Cons. 45, 68–70.

Keeney, D.R., 1982. Nitrogen management for maximum efficiency and minimum pollution. In: Stevenson, F.G. (Ed.), Nitrogen in Agricultural Soils. Agronomy Monograph 22. Am. Soc. of Agron., Madison, WI, pp. 605–649.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. Preprints, 8th Conf. on Appl. Climatology, 17–22 Jan, Anaheim, CA, pp. 179–184.

Peterson, T.A., Shapiro, C.A., Flowerday, A.D., 1990. Rainfall and previous crop effects on crop yields. Am. J. Alter. Agric. 5, 33–37.

Shrader, W.D., Caldwell, A.R., Cady, F.B., 1966. Estimation of a common nitrogen response function of corn (*Zea mays*) in different crop rotations. Agron. J. 58, 397–401.

Stooksbury, D.E., Michaels, P.J., 1994. Climate change and large-area corn yield in the southern United States. Agron. J. 86, 564–569.

Teigen, L.D., Thomas, M., Jr., 1995. Weather and Yield, 1950–1994, Relationships, distributions, and data. Commercial Agriculture Division, Economic Research Service, US Department of Agriculture. Staff Paper No. 9627, Washington, DC.

Wall, J.S., Ross, W.M., 1970. Sorghum Production and Utilization. The AVI Publishing, Westport, CA, p. 167.

Wilhite, D.A., Glantz, M.H., 1985. Understanding the drought phenomenon: the role of definitions. Water Int. 10, 110–120.

Yamoah, C.F., Varvel, G.E., Waltman, W.J., Francis, C.A., 1997a. Long-term nitrogen use continuous crops and rotations. Field Crop Res., in review.

Yamoah, C.F., Varvel, G.E., Waltman, W.J., Francis, C.A., 1997b. Weather and management impact on crop yield variability in rotations. J. Prod. Agric., USA, in review.

Zentner, R.P., Campbell, C.A., Read, D.W.L., Anderson, C.H., 1984. An economic evaluation of crop rotations in southwestern Saskatchewan. Can. J. Agric. Econ. 32, 37–54.