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Standardized precipitation index and nitrogen rate effects on crop yields and risk distribution in maize

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Abstract

Crop performance in rainfed cropping systems generally is dependent on rainfall amount and distribution. The objective of this study was to analyze the long-term consequences of rainfall expressed as a standardized precipitation index (SPI) and fertilizer nitrogen (N) on yields and risk probabilities of maize in the udic-ustic moisture regimes in the Great Plains in Nebraska. The SPI is a precipitation index for classifying drought stress conditions. The study was conducted on a Kennebec silt loam (Cumulic Hapludoll) over an 11-year period, 1986–1996, using monoculture maize (*Zea mays* L.) and maize in rotation with soybean (*Glycine max*.(L.) Merr.) in combination with N fertilizer levels between 0 and 160 kg ha^{-1}. Maize yields in monoculture ranged from 4.8 to 5.7 Mg ha^{-1}, and from 6.4 to 6.8 Mg ha^{-1} in rotation. The differences in yields between monoculture and rotation were larger at low N rates and decreased as N fertilizer increased above 40 kg ha^{-1}. Current year's maize yields either exhibited a weak or no response to N fertilizer in years when the preceding preseason (October–April) and the previous growing season (May–August) were dry (negative SPI value). Regression of yield as the dependent variable and the 12-month April SPI as the independent variable explained up to 64% of yield variability in a curvilinear relationship. Optimum SPI values were in the range of −1.0 to 1.0, substantiating the adaptability and performance of crops under mild stress as proposed by other scientists. Prediction of subsequent yields using past SPI data was relatively better in rotations (R^2=41–50%) than in monoculture (R^2=15–40%). Risk, calculated as the lower confidence limit of maize returns over variable cost of fertilizer, was less in rotations than in monoculture, and in both cropping systems returns were maximized with the application of N fertilizer at 40 kg ha^{-1}. Used with other criteria, the SPI can be a practical guide to choice of crops, N levels, and management decisions to conserve water in rainfed systems.

Keywords: Climate; Crop rotations; Rainfed cropping systems; Risk analysis; Nebraska USA

1. Introduction

Agricultural success in non-irrigated cropping systems depends on efficient use of precipitation. Farmer decisions on which crops to plant and cultural practices such as mulching or reduced tillage that conserve soil moisture are determined in part by rainfall up to planting time. Crop rotations and multiple cropping

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systems that include two or more crops grown on a parcel of land may exploit moisture at different soil depths (Francis, 1989). Rotational systems use water more efficiently than monocrops (Pierce and Rice, 1988; Campbell et al., 1990; Varvel, 1994). These are practical options available to farmers in the udic-ustic moisture regimes in the Great Plains.

Halvorson (1990) compared adequately fertilized 3-year and annual crop rotations with a wheat (*Triticum aestivum* L.)-fallow rotation and found the former more profitable. Different crops and cropping systems have been shown to exhibit marked differences in efficiency of water use. Varvel (1994) reported precipitation use efficiency (PUE) of 36–137 $\mathrm{kg\,ha^{-1}\,cm^{-1}}$ for continuous maize as compared with 57–165 $\mathrm{kg\,ha^{-1}\,cm^{-1}}$ in maize–soybean rotations. Varvel (1995) also found that PUE for soybean averaged 30 $\mathrm{kg\,ha^{-1}\,cm^{-1}}$, whereas sorghum (*Sorghum bicolor* (L.) Moench) was 89 $\mathrm{kg\,ha^{-1}\,cm^{-1}}$ during an 8-year period. Interactions between precipitation and N rates are well documented. These several factors may influence the differences in rainfall use between monoculture maize and maize–soybean rotations.

The purpose of this study was to evaluate the effects of the standardized precipitation index and N rate on yields and risk of maize-based cropping systems, as measured by maize yields, under limited-rainfall conditions in northeast Nebraska. The goal was to provide farmers with practical guidelines on nitrogen application according to preseason rainfall, based on long-term experimental results. Most empirical studies of precipitation use efficiency and N-use include only short-term datasets, whereas the results reported here are based on 11-year experimental results.

2. Materials and methods

2.1. Field experiment

The study was conducted from 1986 to 1996 at the University of Nebraska Northeast Research and Extension Center near Concord. The soil is a Kennebec silt loam with average organic matter=4.1%, pH=5.7, exchangeable soil K=0.13 $\mathrm{cmol\,kg^{-1}}$, and Bray P1 extractable P=40.1 ppm. Mean rainfall in this site is 610 mm per year. The experiment design was a split-plot factorial with four replications. Main treatments were tillage: spring no-till, spring plow, and disk; subplots were rotation: maize–soybean rotation and continuous maize; sub-subplots were five N rates (0, 40, 80, 120 and 160 $\mathrm{kg\,ha^{-1}}$) broadcast pre-plant as ammonium nitrate (33-0-0) to maize crops only. This corresponds to normal farmer practice in the area, although a delay in application of part of the required N fertilizer may be a more efficient practice. No fertilizer was applied in 1989 because a severe drought in 1988 (average maize yield=2.7 $\mathrm{Mg\,ha^{-1}}$) resulted in soil nitrate concentrations exceeding 250 kg N ha-$\mathrm{m^{-1}}$. Although soil moisture storage and crop water use are dependent on many factors, precipitation and soil N status are the two that were studied in this experiment.

Maize (Pioneer hybrid ‘3575’, 100-day relative maturity) was seeded in early May each year at approximately 45,400 plants $\mathrm{ha^{-1}}$. Seeding rate of soybean (‘Century 84’) was 90 $\mathrm{kg\,ha^{-1}}$. Herbicides were used to control weeds using current recommendations. Maize was harvested by hand around 1 October and soybean was combine-harvested 1 week later. Treatments were compared using analysis of variance with a minimum significant different criterion set at the 0.05 probability level. Years were used as replications with each data point the mean of four replications in each year and treatment.

2.2. Risk analysis

Probabilities of risk associated with maize incomes were examined only for the period between 1986 and 1996, a decade of highly variable rainfall. Risk can be quantified by determining the lowest expected yield or income at a given level of probability using confidence intervals. Yield and income uncertainties or risk levels were calculated as the lower confidence limit of the mean yields and net returns according to the formula:

$$\mathrm{Risk} = Y - \frac{(t_{\mathrm{df}=n-1})(S_{\mathrm{d}})}{n^{1/2}}$$

where, S_{d} is the standard deviation, n is the number of observations, and t is the probability level from a one-tailed t table (Hildebrand and Russell, 1996). Yields of the maize(c)–soybean(s) system were converted to total incomes or returns by multiplying individual crop yields (Y) with their respective yearly average prices (P) for each year less the variable cost of N fertilizer (V) for maize production, i.e. Returns=$(Y_c \times P_c)-(V_c)$. In computation of returns, the variable cost of fertilizer at US\$ 0.33 kg^{-1} and assumed other costs such as land preparation, herbicides, and insecticides were the same for both cropping systems. Input costs were based on current prices and cropping practices in Nebraska (Selley et al., 1996).

2.3. Effects of the SPI on yields

Rainfed farming in northeastern Nebraska is not entirely dependable without supplemental irrigation (Peterson et al., 1990). As both soil water storage and crop water use are influenced by precipitation, the SPI model (McKee et al., 1993) was applied to predict current year yield from previous years' rainfall events. Precipitation is not normally distributed, therefore, absolute rainfall values are usually more poorly correlated with yields than when rainfall values are standardized (McKee et al., 1993; Teigen and Thomas, 1995). Calculation of the SPI requires a long-term monthly precipitation data base with 30 years or more of data. The probability distribution function is determined from the long-term records by fitting a Gamma function to the data (Mood and Graybill, 1963). The cumulative distribution is then transformed using equal probability to a normal distribution with a mean of 0 and a standard deviation of 1 (Edwards and McKee, 1997). A particular precipitation total for a specified time period corresponds to an SPI value consistent with the probability of that precipitation value occurring. Positive SPI values signify greater than median precipitation, whereas negative values signify less than median precipitation. An SPI of 0 indicates average conditions and values greater than $+2$ or less than -2 generally indicate extreme conditions associated with events that occur only 5% of the time. Obviously, current year precipitation is a very important determinant of maize yield; however, this study takes into account precipitation from the previous growing season and the intervening fallow months before planting. Growing season precipitation in this region is insufficient for full expression of maize yield potential and soil water storage is an important component of total crop water supply. Preseason precipitation would then provide an effective estimate of potential soil water storage at the start of the current growing season. These are the data available to farmers that can influence crop choice and nitrogen application before planting.

3. Results and discussion

3.1. Yields and variability

Table 1 shows the effect of N fertilizer and cropping systems on maize yields and variability across 11 years. As expected, maize yields in rotations with soybean were higher (P=0.0001) than maize yields in the monoculture system. The yield ranges for monoculture were 4.8–5.7 Mg ha^{-1}, and for maize in rotation yields ranged between 6.4 and 6.8 Mg ha^{-1}. The variability as indicated by variance (s^2) and the confidence intervals of variances were larger in monoculture maize than maize in rotation. There was a significant interaction (P=0.04) between cropping systems and N rate. Yield differences between rotation and monoculture were larger at lower N rates (0–40 kg ha^{-1}) and narrowed as N fertilizer rate increased, indicating that physiological N use efficiency or N recovery efficiency was not the same between rotations.

3.2. Effect of SPI on maize response to N

Table 2 indicates how previous rainfall conditions influence maize response to N fertilizer in the two cropping systems. In general, current year's maize yields did not respond to N fertilizer in years when the preceding preseason (October–April) and the previous growing season were dry as portrayed by negative 5- and/or 7-month SPIs. The magnitude of the moisture deficit during growing seasons and/or below average moisture recharge may contribute to poor crop performance for the subsequent growing season. Standardized precipitation index values in the range of -0.99 to 0.99 are usually considered mild stress conditions for cropping systems adapted to the region (McKee et al., 1993) and may be favorable to crop growth in some years depending on other climatic factors such as temperature. Outside this range, particularly -1.0 or less constitutes moderate to severe moisture stress, which could cause yield reduction in rainfed farming conditions.

Table 1
Cropping systems and N rate effects on maize yield and its variability (s^2) over a 11-year period (1986–1996) in Nebraska

System interval	N rate (kg ha^{-1})	Yield (Mg ha^{-1})	s^2 (Mg ha^{-1})	Confidence
Continuous maize	0	4.79	3.09	1.41–8.1
	40	5.22	4.04	1.85–10.6
	80	5.49	5.01	2.28–13.1
	120	5.64	5.88	2.68–15.4
	160	5.69	5.93	2.72–15.5
Maize in rotation	0	6.42	4.05	1.85–10.6
	40	6.66	4.18	1.91–11.0
	80	6.71	4.30	1.96–11.3
	120	6.83	4.40	2.00–11.6
	180	6.79	4.35	1.98–11.4
Level of significance				
Year (Y)	0.0001			
Cropping system (CS)	0.0001			
N rate (N)	0.0001			
$Y\times$CS	0.0001			
$Y\times N$	0.2395			
CS$\times N$	0.0383			

Response of maize to N fertilizer in continuous maize was high when SPI was positive. Nitrogen fertilizer accounted for 80–97% of the variability of maize yields during 1986, 1992, 1993 and 1994 (Table 2). On the contrary, R^2-values for maize response in rotations for the same years were low and explained only 55–72% of the variability, not significant at the 5% probability level (Table 2). The lack of response to N fertilizer of maize in soybean–maize rotation is common (Varvel, 1994; Green and Blackmer, 1995) and may be caused by the soil ameliorative effects of legume–cereal rotational systems such as N transfer during the soybean year. In addition, the non-soil related factors such as the reduction of insects and pathogens that are reduced by rotations may improve yields.

The practical application of this finding would be more advantageous to farmers who used improved

Table 2
Maize yield response to N fertilizer under different preseason moisture conditions over an 11-year period (1986–1996) in Nebraska

Year	Standardized precipitation index		Maize response to increasing N rate, R^2 (significance level)	
	5-month SPI[a]	7-month SPI[b]	Continuous maize	Maize rotation with soybean
1986	0.58	0.88	0.80 (p=0.041)	0.55 (p=0.340)
1987	−0.01	0.06	0.35 (p=0.295)	0.46 (p=0.205)
1988	−0.59	−0.98	0.62 (p=0.111)	0.54 (p=0.157)
1989	−1.92	−1.58	0.01 (p=0.852)	0.22 (p=0.427)
1990	−0.94	−1.18	0.32 (p=0.320)	0.02 (p=0.810)
1991	−0.63	−0.08	0.02 (p=0.814)	0.54 (p=0.156)
1992	1.41	0.70	0.97 (p=0.002)	0.72 (p=0.066)
1993	1.21	1.07	0.97 (p=0.002)	0.58 (p=0.132)
1994	0.49	−0.08	0.90 (p=0.013)	0.62 (p=0.116)
1995	0.65	0.79	0.28 (p=0.363)	0.36 (p=0.285)
1996	−0.20	−0.68	0.86 (p=0.022)	0.48 (p=0.193)

[a] The 5-month standardized precipitation index (SPI) was based on rainfall from 1 May to 30 September of the previous growing season.

[b] The 7-month standardized precipitation index (SPI) was based on rainfall from 1 October of the previous season to 31 April in the current preseason.

Table 3
Regression equations estimating current maize yields from previous rainfall records

System	N rate (kg ha^{-1})	Intercept	5-month SPI[a]	7-month SPI[b]	R^2	Significance level
Continuous maize	0	5.05	0.91	−0.56	0.15	0.55
	40	5.54	1.14	−0.40	0.25	0.36
	80	5.80	1.50	−0.70	0.29	0.30
	120	5.96	1.82	−0.88	0.34	0.22
	160	6.02	1.91	−0.84	0.40	0.16
Maize in rotation with soybean	0	6.56	1.67	−0.49	0.42	0.14
	40	6.75	1.75	−0.60	0.41	0.16
	80	6.81	1.78	−0.54	0.44	0.13
	120	6.94	1.80	−0.40	0.50	0.09
	160	6.92	1.75	−0.54	0.42	0.15

[a] The 5-month standardized precipitation index (SPI) was based on rainfall from 1 May to 30 September of the previous growing season.

[b] The 7-month standardized precipitation index (SPI) was based on rainfall from 1 October of the previous season to 31 April in the current preseason.

cultivars or hybrids that are more responsive to N fertilization. Such farmers may apply high N rates (about 80–120 kg ha^{-1}) and expect to get high yields in monoculture when both the previous crop season and the current preseason moisture are high, e.g. positive SPI value. It would be advisable to use less N fertilizer (<100 kg ha^{-1}) for maize in rotation to reduce cost and prevent excessive leaching of nitrate under similar climate conditions. Also, farmers may avoid growing maize and plant a more drought tolerant crop such as sorghum when the previous season and pre-plant moisture conditions are below average, as noted in an earlier study in eastern Nebraska (Yamoah et al., 1998).

3.3. Estimation of yields from previous moisture conditions

The objective in relating SPI as a function of yield is to advise farmers on adjusting their cropping plans ahead of time to maximize returns or reduce costs. Table 3 shows regression equations predicting yields from past rainfall events. Evidently, predictions were better in rotations than in continuous maize using the R^2 value as indicator of predictive power. The R^2 values in monoculture varied from 15 to 40%; the respective range in rotations was 41–50% and none were significant at the 5% level of probability. The fact that R^2 increased as N rate increased indicates that SPI works best in predicting yield when N is non-limiting with optimum management practices as alluded to by Dirks and Bolton (1981). Given the importance of food production on a global scale, it would seem rational to accept significance levels identified by maize in rotation for previous moisture alone, recognizing that fertilizers, cultivars, management, and other variables are equally important factors that may contribute to the variability in yields.

Among the predictor variables, the 5-month September SPI was found to be relatively more important (*t*-value not shown) than the 7-month April SPI. Agronomically, moisture status at the end of the previous growing season is most critical for the next crop because it controls mineralization of residues if the soil surface is not frozen. Usually loss of soil moisture through evapotranspiration is small during winters and in addition snow may contribute to the soil moisture reserve as well. It appears that 5-month SPI governs water deficit and that 7-month SPI is a much weaker predictor because loss of water during the 7 months is not well described by a simple 7-month index.

3.4. Effect of SPI and N on yields

As the 5- and 7-month SPI values were almost universally positive or negative within a given year (Table 2), a 12-month SPI was calculated and regressed against yield. The 12-month SPI (May–April) has a curvilinear relationship with maize yields. The degree of the relationship is a function of the system (monoculture versus rotation) and fertility status

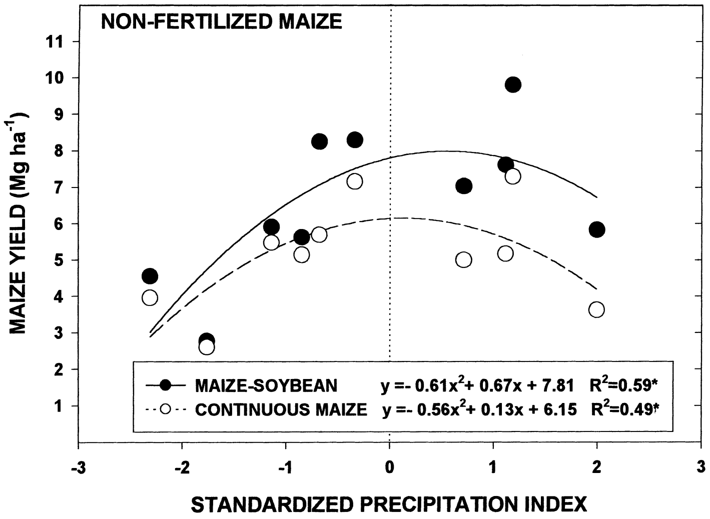

Fig. 1. The 12-month standardized precipitation index (SPI) (May–April) effect on yields of non-fertilized maize in monoculture and in rotation with soybean.

(fertilized as an average of all N rates and unfertilized) (Figs. 1 and 2). The 12-month April SPI alone explained about 60% of variation in maize yields in non-fertilized soybean–maize rotations and almost 50% of maize yields in non-fertilized monoculture systems (Fig. 1). Similarly, precipitation accounted for 64 and 51%, respectively, of maize yields in fertilized rotations and monoculture systems (Fig. 2). Examination of the scatter points in Figs. 1 and 2 indicate that maize yields seemed to be highest in the SPI range of −1 to +1. This range appears to confirm the positive effects of mild stress conditions as described by McKee et al. (1993).

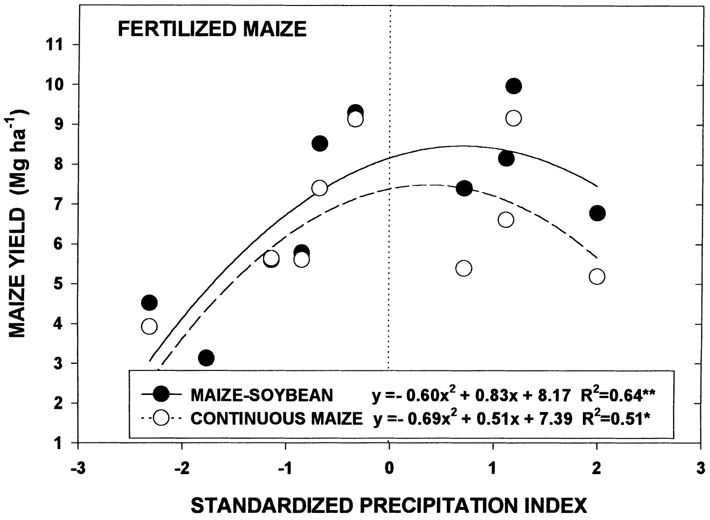

Fig. 2. The 12-month standardized precipitation index (SPI) (May–April) effect on yields of fertilized maize in monoculture and in rotation with soybean.

Table 4
Risk analysis of maize returns in continuous and rotational systems

System	Probability	Lower confidence limit (US\$ ha^{-1}) with N rate (kg ha^{-1}) of				
		0	40	80	120	160
Continuous maize	0.005	313	322	294	285	275
	0.01	338	349	326	319	310
	0.05	396	413	401	400	390
	0.10	422	443	436	438	427
	0.20	452	476	476	480	469
	0.30	473	499	502	509	480
Maize in rotation	0.005	473	481	458	453	442
	0.01	500	510	488	483	472
	0.05	562	580	558	553	542
	0.10	591	612	590	586	574
	0.20	624	648	626	622	610
	0.30	646	673	651	647	634

3.5. *Risk of production and income*

The objective of the risk analysis is to provide information and potential tools that can be used by farmers to make decisions based on their specific circumstances. Table 4 shows risk analysis of maize returns over variable cost of fertilizer N. Overall, risks are lower in rotations than for maize in monoculture. For instance, at the 5% probability level maize returns over variable costs of 40 kg N ha^{-1} were US\$ 413 ha^{-1} for monoculture compared with US\$ 580 ha^{-1} in rotations. Practically, this implies that profit from maize when grown in rotation with soybean will be at least US\$ 580 ha^{-1} in 95 out of 100 years compared with US\$ 413 ha^{-1} for monoculture. Risk seemed to increase as N rate increased above 40 kg ha^{-1} especially for the rotation system. However, producers who are less risk averse would be prone to increase fertilization rate up to 120 kg N ha^{-1} under monoculture (continuous) maize. Application of 160 kg ha^{-1} fertilizer in both monoculture and rotations tended to be riskier, probably arising from year-to-year weather fluctuations, vis-a-vis the cost of fertilizer. In drought years, maize returns over cost of N fertilizer may be expected to decrease with increasing rates of applied N.

4. Conclusions

Farmers in Nebraska often make crop, cultivar, rotation, and nitrogen application decisions based on past experience and the results of the preceding year's crop performance. There are few quantitative tools available to better summarize recent weather data and how this information could be used to make rational decisions for the coming cropping season. The SPI takes into account the previous year's precipitation as well as long-term average for a given site, and allows the farmer to add this information to other current data such as crop prices and prospects, soil test N levels, characteristics of newly-available crop cultivars, and options for crop rotation.

The experiment comparing monoculture (continuous) maize with maize in rotation with soybean over 11 years showed that yields are higher and relatively more stable in the rotation system. Optimum conditions and highest maize yields were observed when the SPI was between -1.0 and $+1.0$, indicating conditions with moderate stress to above-average rainfall in the period before planting. As indicated by the lower confidence limit from analysis of variance for contrasting systems and N applications, the lower risk was with 40 kg N ha^{-1} and in maize in rotation, compared with higher levels of N and monoculture. In regions where soil water recharge is a significant yield determinant, the SPI provides a reasonable estimate of the probability of obtaining an economic response to N fertilization. SPI might also be used to study the historical trends between fertilizer consumption and weather variability to test hypotheses about farmer's perception of risk.

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