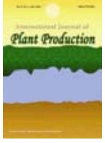

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Corn yield and yield stability under varying nutrient management, crop rotation, and rainfall

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Abstract

Long-term yield performance and yield stability of common cropping systems needs to be simultaneously assessed at various fertility regimes. Based on a consecutive 19-year field trial, including eight fertilization treatments with different combinations of nitrogen (N), phosphorus (P), potassium (K) and recycled manure (RM), the effects of fertilization and crop rotation on corn (*Zea mays* L.) yield performance and stability were evaluated. The results showed that although the fertility regimes had greater influence on yield increase (average 2.94 Mg ha^{-1}) than crop rotation (averge 0.42 Mg ha^{-1}) [corn-corn-soybean (*Glycine max*)], the rotation effect on yield increase was almost 51% of that of fertilizer N under low nutrient availability conditions. A synergistic effect between RM and crop rotation was observed in the present study, in detail, yield-increasing effect of RM, on average, were 0.98 and 1.04 Mg ha^{-1} in continuous and rotation cropping systems, respectively. Stability analysis revealed that RM improved yield stability under nutrient absence conditions rather than under balanced fertilization conditions. Moreover, crop rotation substantially improved yield stability. High and stable yields were obtained in test years with arid index ranged from 1.08 to 1.16, which can be regarded as proper environment in this region. Ranking the statistical parameters indicated that they are similar in general, and considering the amount of RM resource, NPM which achieved high and stable yield was the most recommendable fertility regime in this region.

Keywords: Yield performance and stability; Fertilization regimes; Rotation effect; Recycled manure; Long-term trial.

Introduction

The worldwide agricultural production has steadily increased over the last century, and fertility management plays a key role on crop yield increase (Ladha et al., 2003; Ludwig et al., 2011). Most studies focus on average crop yields and overlook yield stability, which is also an important factor for food security (Piepho, 1998). The yield stability is influenced by several factors, such as environmental factors, agricultural managements and pest pressures (Hu and Buyanovsky, 2003; Berzsenyi and Dang, 2008). This suggests that it was difficult to analyze the yield stability using the conventional approaches. The interactions between managements and environments were considered as important sources of year-to-year yield variation (Mohammadi and Amri, 2009), and some statistical methods with the aim of explaining these interactions have been used to assess the stability, such as stability parameter analysis, regression analysis and multivariate statistical analysis (Piepho, 1998). Raun et al. (1993) analyzed the wheat and corn yield stability by regression approach for assessing long-term fertility regimes, and Grover et al. (2009) investigated the effect of crop rotation on yield stability by the same method.

Northeastern China is an important agricultural region, and the main crop is corn (*Zea mays* L.) (Wu et al., 2008), which is periodically rotated with soybean (*Glycine max*) in conventional cultivation due to the advantages of rotation, such as optimized nutrients partitioning, enhanced nutrients uptake, improved soil quality, etc. (Karlen et al., 1994; Hernandez-Ramirez et al., 2009a). Because corn is an important staple crop for food, livestock feed and biofuels (Edgerton, 2009), continuous corn cropping system has gradually increased in recent years for achieving and sustaining optimum yield, threatening sustainability and stability of corn based cropping system in this region. Meanwhile, traditional use of manure as main nutrient source has been replaced by large amount application of mineral fertilizers, causing soil physical and chemical properties deterioration and low nutrient use efficiency (Gong et al., 2009; Hernandez-Ramirez et al., 2011b). These managements influenced the yield performance, as well as the yield stability (Adediran et al., 2004; Varvel, 2000).

The long-term experiments (LTEs) proved unique possibilities to explore the effects of different management practices on crops with time (Stanger et al., 2008), which could reveal yield stability. Recently, the additive main effects and multiplicative interaction (AMMI) analysis model, combining the analysis of variance (ANOVA) and principal components analysis (PCA), has emerged as a powerful analytical tool to interpret the interaction and widely applied in breeding researches (Gauch, 2006; Madry et al., 2011). Therefore, the objectives of this study were to evaluate effects of long-term fertility regimes and crop rotation in a rainfed agricultural region on corn yield and stability by AMMI and other stability analysis methods. The results of stability analysis would be compared and analyzed for recommendation of site-specific managements and selection of efficient statistic approach to assess yield stability in long-term experiment.

Materials and Methods

Experimental site, design and treatments

The experiment was conducted from 1990 to 2008 at the Shenyang Ecological Experimental Station of Institute of Applied Ecology, Chinese Academy of Sciences (41° 32' N, 123° 23' E, 31 m elevation) in the low reach of Liaohe River Plain, on an alfisol soil (Figure 1). The experimental site is in the temperate sub-humid mainland climate, with a mean air temperatures 7.5 °C, annual precipitation 680 mm (Figure 1), and the frost-free period ranging from 147 to 164 days. The initial properties of the surface soil (0-20 cm depth) in 1990 were as follows: pH 6.5, soil organic carbon of 12.3 g kg^{-1}, total N of 1.13 g kg^{-1}, total P of 0.44 g kg^{-1}, total K of 16.4 g kg^{-1}, soil Olsen-P of 10.6 mg kg^{-1}, and exchangeable K of 88.0 mg kg^{-1}.

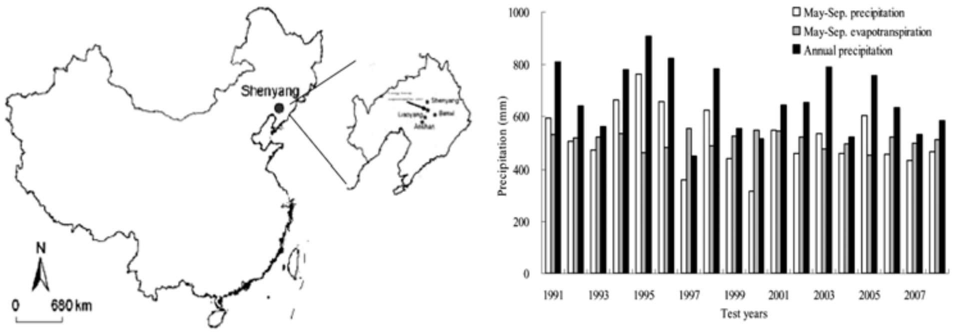

Figure 1. Geographical location of the long-term experiment site; annual and growing seasonal (May-Sep.) precipitation and evapotranspiration from 1991-2008.

The experiment included eight treatments: (1) no fertilizer or manure (CK), (2) recycled pig manure (M), (3) N, (4) NM, (5) NP, (6) NPM, (7) NPK, (8) NPKM. Urea, triple superphosphate and potassium sulfate were used as the N, P and K source. Application rates of fertilizers N, P, K were

150, 25 and 60 kg ha^{-1} $year^{-1}$ for corn. All fertilizers P, K and 40 kg ha^{-1} of N were basal-applied prior to sowing and 110 kg ha^{-1} of N fertilizer was top-dressed at the stem-elongation stage. Nitrogen rate corresponded to 25 kg ha^{-1} $year^{-1}$ for soybean, and P, K fertilizers applied at the same rates as those for corn. N, P and K fertilizers were basal-applied in the spring before sowing. All the recycled manure (RM) used in this experiment came from the agroecosystem itself. Through feeding-composing cycles, the 80% harvested grain, 100% soybean straw, and 50% corn stalk were returned back to the original treatments. This completed a nutrient recycling process consisted of "fertilization-crop absorption-feeding composting-return back to fields". The macronutrient inputs with RM were listed in Table 1. The composted pig manure was applied surfacely in the subsequent spring followed by plowing and sowing.

Table 1. Total macronutrient inputs with recycled manure in different treatments from 1991 to 2008 (kg ha^{-1}).

	M	NM	NPM	NPKM
N	784.3	920.1	975.7	1041.9
P	159.4	175.5	221.4	248.2
K	423.9	475.7	594.5	643.8

The treatments M, NM, NPM and NPKM contained combinations of nitrogen (N), phosphorus (P), patassium (K) and recycled manure (M), respectively.

The experiment was a two-factorial complete-block design with a split-plot arrangement of eight fertility regimes as main plots, cropping systems as subplots, and three replications. The subplot size was 9 m × 6 m × three replications=162 m^2 and the main plot size was 162 $m^2 \times 3$ cropping systems= 486 m^2. A three-course rotation was conducted (soybean, 2×corn) in each subplot, and soybean, the 1st corn and the 2nd corn were planted in the three subplots, respectively. Therefore, the 1st corn in a rotation was the soybean-corn rotation cropping system (SC), and the 2nd corn was the corn-corn cropping system (CC). The experiment design was similar with the Broadbalk experiment in Rothamsted experiment station (Moss et al., 2004). This kind of crop rotation not only ensured the continuity of planting, but also helped consecutively compare and analyze responses of the crops to environmental changes. The corn variety "Danyu-13"was sown in 1990 to 1995, "Tiedan-10" from 1996 to 2002, and "Fuyou-1" from 2003 to 2008. Irrigation and herbicides were not applied and weeds were removed by hand-hoeing. During the growing season, pesticides and fungicide were applied when needed, and all the crops were cut with scythes in autumn. Grain yields were recorded and corn ears (n=8) were collected in each replication for measurement of drying rate, which was used to calculate the oven dried grain yield.

Statistical analysis

To analyze the corn yield stability, the statistics parameters were used, including ecovalence (W) (Wricke, 1962), stability variance (σ^2) (Shukla, 1972) and regression coefficient (b) (Finlay and Wilkinson, 1963). A low W or σ^2 value indicates high relative stability. The coefficient (b) was estimated by regressing the treatment means on to an environmental index estimated as the mean of all the treatments in a test year. Coefficients above unit describe treatments with greater specificity of adaptability to high-yielding test years, whereas the coefficient values below unit indicate specific adaptability to low-yielding test years. A cropping system with an estimate of b close to unit shows an average response to environmental conditions (Eberhart and Russell, 1966).

The additive main effects and multiplicative interaction (AMMI) calculates treatment and test year additive (main) effects using ANOVA firstly and then analyzes the residual from this model (interaction) using PCA (Gauch, 1988). The AMMI model equation is:

$$y_{ij} = \mu + \alpha_i + \beta_j + \Sigma_n \lambda_n \gamma_{in} \delta_{jn} + \rho_{ij} + \varepsilon_{ijn} \qquad (1)$$

Where, y_{ij} is the yield of ith treatment in jth test year; μ is the grand mean, α_i the treatment deviation from grand mean and the test year deviation β_j. λ_n is the eigen value of PCA axis n; γ_{in} and δ_{jn} are the treatment and test year PCA scores for PCA axis n; ρ_{ij} is the residual of AMMI model and ε_{ijn} is the random error. The interaction principal components analysis axis (IPCA) provides indicator of stability to assess responses of both treatments and test years (Grausgruber et al., 2000). The absolute value of first IPCA scores represented the simplest measure of yield stability. To further describe stability using AMMI analysis, the statistic coefficient (D) for test of treatments or test years is calculated as follows:

$$\mathrm{D} = \sqrt{\sum_{r=1}^{N} \gamma_{is}^2} \qquad (i = 1, 2, \ldots, n) \qquad (2)$$

Where D_i is the distance of interaction principal component (IPC) point with origin in space, N is the number of significant IPCs, and γ_{is} is the score of *i*th treatment in IPCs. The D gives the interaction estimate, and the treatment with the lowest value of the statistic D would be more stable (Zhang et al., 1998). The AMMI analysis is also interpreted by plotting the IPCAs of treatment and test year in biplot. Data Processing System (DPS) software was used for AMMI analysis (Tang and Feng, 2007).

The AMMI stability value (*ASV*) is also a stability measure developed by Purchase et al. (2000), which is also based on the AMMI model's IPCA 1 and IPCA 2 scores. Because the IPCA 1 score contributes more to the interaction sum of squares (SS), a weighted value is needed. The weight is calculated based on the relative contribution of IPCA 1 to IPCA 2 to the interaction SS as follows:

$$ASV=\sqrt{\left[\frac{SS_{IPCA1}}{SS_{IPCA2}}(\text{IPCA1 score})\right]^2+(\text{IPCA2 score})^2} \qquad (3)$$

Where SS_{IPCA1}/SS_{IPCA2} is the weight given to the IPCA 1 value by dividing the IPCA 1 SS by the IPCA2 SS; and IPCA1 and IPCA2 scores are the treatment scores in AMMI model.

Microsoft Excel 2003, SPSS 13.0, and DPS 9.5 were used to record and analyze data. The yields of corn grain were analyzed by ANOVA followed by Duncan's multiple range test for multiple comparisons of paired means of treatments.

For exploring the relationship between the water conditions and the potential evapotranspiration (Allen et al., 1998) during the growing period, aridity index (AI) was estimated and calculated as follows:

$$\text{AI}=\frac{\text{Potential evapotranspiration}}{\text{Precipitation}} \qquad (4)$$

Result and Discussion

Yield response

The fertility regimes exhibited greater influence on yield increase than crop rotation (Table 2). Magnitude of yield increases, on average, were 3.26

and 0.98 Mg ha^{-1} caused by mineral fertilizers and RM in CC system, respectively; they were 2.19 and 1.04 Mg ha^{-1} in SC system, respectively, indicating that rotation effect diminished the contribution of mineral fertilizer to yield increase, whereas the yield-increasing effect of RM was slightly promoted in SC system. Nitrogen played an important role in corn production in the experiment. Combined application of N with P was an efficient way to improve crop yield significantly. Ladha et al. (2003) pointed that fertilizer K was indispensable to production in a long-term rice-wheat cropping system in Asia. However, potassium had little effect on the corn yield in this region (Ma et al., 2006).

Although the manure-based treatments achieved higher yield than the corresponding treatments without RM (e.g., M > CK, NM > N; Table 2), the effect of RM on yield enhancement was lower than that of synthetic N fertilizer in our study. Conversely, Cooke (1976), Kofoed and Nemming (1976) reported that yield-increasing effects of both mineral nutrients and manure were similar in their LETs. The discrepancies were mainly ascribed to the amount and resource of the organic manure. For instance, the amount of manure application was generally based on the macronutrients requirement of the crop or equal to the mineral nutrient levels in the most organic manure experiments (Hernandez-Ramirez et al., 2011b; Huang et al., 2010), where the manure applied both at the rates of 255 kg N ha^{-1} year^{-1}, resulting in similar crop yield between manured and balanced chemical fertilization treatments. Coupled with high rate of fertilizer or manure supply and inappropriate management, environmental pollution is becoming a serious issue (Miao et al., 2011). Fertilization was an important role on greenhouse gas emissions and water contamination (Hansen et al., 2004; Lokupitiya and Paustian, 2006; Huang et al., 2011), especially when the liquid manure was applied (Hernandez-Ramirez et al., 2009b; Hernandez-Ramirez et al., 2011a). Therefore, the amounts and timing of synthetic and organic fertilizers application should be optimized for sustainable development of agriculture. Considering the manure used in our experiment and crop production were linked, however, the limited organic manure resources were not sufficient for crop growth, as evidenced by the remarkable difference on yields between the treatments M and NPK due to the low amount of manure production and input (Tables 1 and 2). According to the results of our study, nutrient cycling was only an auxiliary fertility management for intensive agriculture aimed at high and stable yield.

The rotation effect on yield increase was almost 51% of that of fertilizer N, and the increase of yield was greater in nutrient absence conditions (Table 2), similar to the results of previous studies for the soybean-corn rotation (Gentry et al., 2001; Bergerou et al., 2004). The yield increased substantially in the CK and M treatments by 1.19 and 1.29 Mg ha^{-1} due to rotation effect, respectively, while this rotation effect was substantially counteracted by mineral fertilizers supply, specifically where fertilizer N was added.. Yusuf et al. (2009) also reported that fertilizer N addition diminished the returns due to crop rotation. Similarly, results by Kaye et al. (2007) indicate that amendment of soil with organic manure, comparable amounts to mineral N, has not exhibited benefit to rotation effect enhancement. However, average yield increase (0.45 Mg ha^{-1}) due to rotation in the manure-based treatments was slightly higher than that (0.39 Mg ha^{-1}) in the remaining treatments, suggesting RM enhanced the rotation effect in our research. The reason for this incremental response could be that the starter dose of nitrogen in our study (25 kg ha^{-1}) was lower than that in the previous study (41 kg ha^{-1}; Kaye et al., 2007), and thereby the effect of manure on soybean growth and N-contribution via symbiotic fixation was more significant than fertilizer N addition in our study.

Table 2. Effect of fertilization and rotation on corn grain yield from 1991 to 2008 (Mg ha^{-1}).

Treatments	Yield response*		Yield-increase effect of fertilizer		Yield-increase effect of rotation
	CC[a]	SC	CC	SC	
CK	3.30^{Be}	4.49^{Ad}	-	-	1.19^{a}
M	4.77^{Bd}	6.06^{Ac}	1.46^{Ac}	1.56^{Acd}	1.29^{a}
N	5.64^{Acd}	5.87^{Ac}	2.34^{Ac}	1.37^{Bd}	0.23^{b}
NM	7.02^{Bab}	7.21^{Aab}	3.72^{Aab}	2.71^{Bab}	0.19^{b}
NP	6.57^{Abc}	6.70^{Abc}	3.27^{Ab}	2.20^{Bbc}	0.13^{b}
NPM	7.38^{Aab}	7.52^{Aab}	4.08^{Aab}	3.03^{Ba}	0.14^{b}
NPK	7.48^{Aab}	7.50^{Aab}	4.18^{Aab}	3.01^{Bab}	0.02^{b}
NPKM	7.75^{Ba}	7.94^{Aa}	4.45^{Aa}	3.45^{Ba}	0.19^{b}

Different capital letters indicate significant differences between different crop rotations within a treatment (row); small letters indicate significant differences among different treatments within a rotation (column), $P \leq 0.05$.

[a] CC and SC indicate corn-corn cropping system and soybean-corn rotation system, respectively.

The treatment CK was unfertilized. The remaining treatments contained combinations of nitrogen (N), phosphorus (P), patassium (K) and recycled manure (M), respectively.

Stability analysis

AMMI analysis

The AMMI analysis showed that the main effects of treatment, test year and the interaction between treatment and environment (T×E) were highly significant ($P<0.01$; Table 3). The ratios of SS of treatment, test year and interaction to the total SS were 50.8, 37.8, 11.4% in CC system, respectively, and they were 31.9, 58.7, 9.4% in SC system, respectively. It clearly revealed that the effects of fertilization and interaction on yield were diminished by rotation effect, whereas the environmental condition of test year was more important in SC system, indicating that the crop rotation enhance the adaptability of corn to the local climate condition. The information contained in the interaction was explained adequately by IPCA. Two IPCAs were significant ($P<0.01$), and they accounted for a total of 86.0 and 85.9% of the interaction in CC and SC systems, respectively, with 37.0% for the corresponding interaction degrees of freedom in the model (Table 3). Furthermore, the IPCA1 had a significantly higher contribution to the interaction than IPCA2. For further description of yield stability using AMMI analysis, the AMMI biplot was conducted, which can be interpreted by comparing the interaction scores for each treatment and test year.

Table 3. AMMI analysis in the long-term experiment (1991-2008).

Source	CC[a]				SC			
	df	SS	MS	F value	df	SS	MS	F value
Total	143	602.31	4.21		143	508.97	3.56	
Treatments	7	306.06	43.72	421.19**	7	162.55	23.22	317.47**
Test years	17	227.47	13.38	128.90**	17	298.61	17.57	240.14**
Interactions	119	68.77	0.58	5.57**	119	47.80	0.40	5.49**
IPCA1	23	46.71	2.03	19.56**	23	26.14	1.14	15.54**
IPCA2	21	12.47	0.59	5.72**	21	14.92	0.71	9.71**
Residual	75	9.59	0.13		75	6.75	0.09	

** indicate significant at $P<0.01$.

df, degrees of freedom; SS, sums of squares; MS, mean squares.

[a] CC and SC indicate corn-corn cropping system and soybean-corn rotation system, respectively.

AMMI, additive main effects and multiplicative interaction; IPCA, interaction principal component axes (Gauch, 1988).

AMMI biplot analysis

The AMMI biplot was conducted with treatment and test year mean yields and their IPCA1 scores on the X- and Y-axis (Figure 2), respectively, and the interactions in the biplot are identified from the IPCA1 scores of the treatment and test year. The points with the IPCA1 score close to zero can be considered as stable treatment or test year with negligible interaction, and when a treatment and a test year have the same signs on the IPCA1 axis, their interaction is positive, whereas those of opposite signs indicate negative interactions. The biplot accounted for 96.3 and 95.7% of the total SS, namely the sum of SS of the treatment, test year and IPCA1 to the whole SS ratio, in CC and SC systems, respectively. According to the IPCA1 score, the treatments were separated into several groups.

In the CC system, the treatments M and N were clustered into one group due to deficient or unbalanced nutrient supply, and the treatments NP and NPK were divided into one group (Figure 2a). Treatment CK showed special adaptability to low-yielding test years as indicated by lower year-to-year variation. The treatments with combined use of manure and mineral fertilizers were grouped together with synergistic interact with high-yielding years. Therefore the effect of combined application of manure and mineral fertilizers on yield increase was attributed to both the nutrients derived from manure and the interaction between fertilization and environment. Unlikely the CC system, the N-based treatments were clustered into one group, except the treatment N in the SC system (Figure 2b), indicating that crop rotation compensated the effect of organic manure. Therefore, it also can be concluded that the effect of mineral fertilizers on yield increase in crop rotation system was ascribed to the synergistic interaction between mineral fertilization and environment. The benefits of crop rotation to subsequent cereal were usually attributed to the N fixed by legume (Peoples and Craswell, 1992; Carpenter-Boggs et al., 2000), but the other non-N benefits were responsible for the higher cereal yield. These beneficial effects lead to promoted activity of soil microorganisms, improved soil fertility properties, and reduced pest infestations (Helmers et al., 2001; Grover et al., 2009). However, effect of T×E interaction should not be neglected, and the greatest increment of yield due to interaction increased up to 2.47 Mg ha^{-1}, accounted for 44.9% of the whole yield increase in this region (Ma et al., 2007). Hillel (1980), Anderson (1998) and Tanaka et al. (2005) also reported that amendment with organic manure or crop rotation promoted crop root growth, improved soil water holding capacity, increased crop water use efficiency and enhanced synergistic effect between fertilizer and water, especially in the dryland (Shisanya et al., 2009). Furthermore, these rotation effects were of benefit to yield stability improvement as also found by Berzsenyi et al. (2000) and Grover et al. (2009), and IPCA1 scores of the treatments were lower in SC system than in CC system in our study.

The treatment N with the highest IPCA had the greatest contribution to the interaction, implying the poorest stability. Varvel (2000), however, pointed that N fertility is one of the most important aspects in reducing yield variability, and crop yield stability was generally improved with increasing level of agricultural management inputs provided for crops (Berzsenyi and Dang, 2008). The discrepancy between studies was probably attributed to the well-managed irrigation in Varvel (2000), while the great year-to-year yield variation had high contribution to the T×E interaction in our study due to the lack of irrigation and drainage facilities.

Recycled manure improved the yield stability to some extent, when it was applied alone or combined application with N. The treatments NPM and NPKM, however, failed to obtain stable yield compared with the treatments NP and NPK, respectively, and the treatments with combined use of manure and mineral fertilizers had a positive interaction with high-yielding environments. Therefore, the yield stability was improved with RM applied under the nutrient absence conditions, whereas RM supply with balanced artificial macronutrients primarily improved yield performance and enhanced the interaction between fertilization and environment. Analysis of other researches also observed greater yield variation in manure-amended systems (Clark et al., 1999; Hernandez-Ramirez et al., 2011b), and results of other long-term experiments found no evidence that manure supply altered temporal yield variability (Aref and Wander, 1998). This finding was also observed by Eghball et al. (1995) under the adequate nutrient and water management due to their high rate of manure supplement and irrigation. In contrast, reports by Lotter et al. (2003) and Mallory and Porter (2007) are partially consistent with our results. They both observed that yield stability was improved in the manure-amended soil system because their studies were conducted under water stress condition or the test crop sensitive to sources of temporal variation.

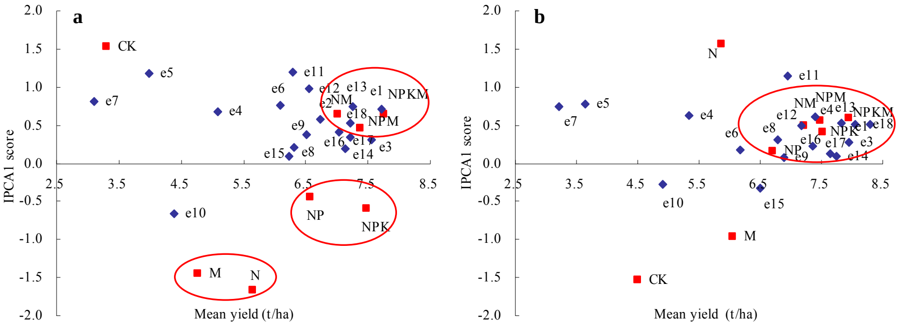

Figure 2. Biplot of the first interaction principal component axis (IPCA1) versus mean yields of fertilization treatments (squares) and test years (diamond) in different cropping systems (a, corn-corn cropping system; b, soybean-corn rotation cropping system).
The treatment CK was unfertilized. The remaining treatments contained combinations of nitrogen (N), phosphorus (P), patassium (K) and recycled manure (M), respectively.

The test years, e5 (tested in 1995) and e11, had the greatest contribution to the interaction and this can be attributed to the improper environmental conditions (data location Figure 2). The test year e5 with a rainfall of 823mm in the crop growing season was the most severe waterlogging year during the experiment, and the lowest and highest yields were 1.27 and 5.92 Mg ha^{-1} obtained in CK and NPM treatments, respectively. The greatest IPCA1 in e11 can be explained by the inadequate precipitation distribution. In further detail, the rainfall was 7mm at the seedling stage (April-May) and significantly lower than the mean level (79.5 mm), although the precipitation in the growing season was moderate. The lowest and highest yields were 1.28 and 9.07 Mg ha^{-1} in the treatments CK and NPKM, respectively, indicating the greatest yield variation among treatments. However, the yield variation decreased in the drought year e7 due to the most severe water stress (with a rainfall of 315 mm), resulted in a minimal effect of fertilization on yield increase, and the extreme yields were 1.49 and 4.00 Mg ha^{-1} in CK and NPM, respectively. It was generally recognized in the literature that variation in the amount and timing of rainfall is one of the primary causes of yield variation in crop production (Batchelor et al., 2002). In our study, the results revealed that yield of all treatments decreased significantly in climatically adverse years, especially in drought years; however, our results also showed that yield losses caused by inadequate distribution of precipitation can be mitigated by balanced nutrient supply. It was also concluded that appropriate water management at early stage was very important for achieving moderate yield with low nutrient availability conditions, while the proper water availability at mid and late growth stages was necessary to maximize the yield-increasing effect of fertilization. In addition, the test years, e3, e9, e14, e16 and e17, had high and stable yield, and it was interesting to note that their AI ranged from 1.08 to 1.16. They were all normal precipitation years (400-550 mm) and can be considered as proper environmental conditions (Ma et al., 2010). The moderate and unstable yield was obtained in the year with AI > 1.16 or < 0.90, suggesting the greater yield variation among the treatments and the better in fertilization treatment discrimination. The test years with AI < 0.75, namely e4 and e5, or > 1.55, i.e. e7 and e10, were waterlogging years (> 650 mm) and drought years (< 400 mm), respectively, in this region. Corn grain yield and yield stability declined significantly in these years. With the exception of the test years e8 and e15 which exhibited high yield stability, and their AI were 0.78 and 0.75, respectively. For the even distribution and sufficient precipitation, yield variation was lower in these years. Therefore, the yield with balanced nutrients supply was significantly influenced by the amount of rainfall, whereas the precipitation distribution was more important for the agricultural production due to good rainfall distribution helping with nutrient uptake in particular where low nutrient availability is predominant. (Batchelor et al., 2002). Under these conditions, well distributed or managed water is more important than total amount in a given season.

Relationship among stability parameters

The statistic parameters, IPCA1, D, ASV, W and σ^2 were significantly positive correlated (P<0.01), implying that they were similar and credible in ranking of the treatments, although they based on different approaches (Tables 4 and 5). Among these parameters, the results obtained for the σ^2 and W were identical, so it is sufficient to use one of them in a yield stability assessment. This observation is supported by Mohebodini et al. (2006) and it can be mainly attributed to the calculation methods of the two parameters (Kang et al., 1987). The IPCA2 showed no correlation with the other parameters due to the lower information of the interaction contained (Table 5), and yield stability evaluation only depending on IPCA2 was unreliable. In terms of the regression coefficient *b*, N-based treatments had high stability or specific adaptation to high-yielding test years, whereas the treatments CK and M with the lower *b* adapted to the low-yielding environments. In general, the *b* values of the treatments in SC system were closer to unit than in CC system, except for NPM, implying the yield stability improved by crop rotation. Although these results were partially confirmed by the AMMI analysis, *b* was usually not correlated with other parameters (Abdulahi et al., 2009; Mohammadi and Amri, 2009), and it probably was the interpretation that linear regression analysis only explained a small portion of the interaction (Zobel et al., 1988).

Table 4. Stability parameters and their ranks for 8 treatments over the experimental period (1991-2008).

Cropping system	Treatments	IPCA1	IPCA2	*D*	*ASV*	*b*	*W*	σ^2
CC[a]	CK	1.53 (7)[*]	0.27 (5)	1.56 (7)	5.76 (7)	0.65 (8)	17.52 (7)	1.28 (7)
	M	-1.44 (6)	-0.37 (6)	1.49 (6)	5.42 (6)	0.70 (7)	8.80 (6)	0.59 (6)
	N	-1.66 (8)	0.02 (1)	1.66 (8)	6.21 (8)	1.15 (4)	20.24 (8)	1.49 (8)
	NM	0.64 (4)	0.07 (2)	0.65 (3)	2.41 (4)	1.24 (6)	4.25 (3)	0.24 (3)
	NP	-0.44 (1)	0.07 (3)	0.44 (1)	1.63 (1)	0.94 (2)	3.18 (1)	0.15 (1)
	NPM	0.46 (2)	-0.49 (8)	0.67 (4)	1.78 (2)	1.05 (1)	3.61 (2)	0.19 (2)
	NPK	-0.60 (3)	-0.23 (4)	0.64 (2)	2.25 (3)	1.17 (5)	5.01 (4)	0.30 (4)
	NPKM	0.65 (5)	-0.46 (7)	0.80 (5)	2.47 (5)	1.11 (3)	6.16 (5)	0.39 (5)
SC	CK	-1.53 (7)	-0.34 (5)	1.57 (7)	2.71 (7)	0.71 (8)	9.58 (7)	0.68 (7)
	M	-0.96 (6)	-0.59 (8)	1.13 (6)	1.78 (6)	0.85 (7)	6.76 (6)	0.46 (6)
	N	1.56 (8)	-0.21 (2)	1.58 (8)	2.74 (8)	1.02 (2)	13.33 (8)	0.98 (8)
	NM	0.50 (3)	0.02 (1)	0.50 (2)	0.87 (2)	1.13 (5)	2.15 (1)	0.10 (1)
	NP	0.17 (1)	0.38 (6)	0.41 (1)	0.48 (1)	1.01 (1)	3.03 (2)	0.17 (2)
	NPM	0.41 (2)	-0.53 (7)	0.67 (5)	0.90 (3)	1.14 (6)	3.71 (3)	0.22 (3)
	NPK	0.56 (4)	-0.31 (4)	0.64 (3)	1.02 (4)	1.10 (4)	5.20 (5)	0.34 (5)
	NPKM	0.60 (5)	-0.27 (3)	0.66 (4)	1.08 (5)	1.03 (3)	4.03 (4)	0.25 (4)

[*] The ranks of the statistic parameters were present in parenthesis.

[a] CC and SC indicate corn-corn cropping system and soybean-corn rotation system, respectively. The treatment CK was unfertilized. The remaining treatments contained combinations of nitrogen (N), phosphorus (P), patassium (K) and recycled manure (M), respectively.

IPCA: interaction principal component axes (Gauch, 1988); *D*: additive main effects and multiplicative interaction (AMMI) statistic coefficient (Zhang et al., 1998); *ASV*: AMMI stability value (Purchase et al., 2000); *b*: regression coefficient (Finlay and Wilkinson, 1963); *W*: ecovalence (Wricke, 1962); σ^2: stability variance (Shukla, 1972).

The results revealed that the mean yield had significantly negative relationship with all statistic parameters, except for IPCA2, indicating that high yield coupled with stable yield due to balanced fertilization, optimized water condition and integrated crop rotation in long-term experiments. It differed from the multi-environment trials (METs) in breeding programs, and yield stability sometimes was correlated with low yield in METs (Abdulahi et al., 2009). Moreover, simultaneous evaluation of AMMI analysis for treatments and environments facilitates the explanation and identification of the interactions, and it was proved efficient in METs assessment and widely suggested by many researchers (Zobel et al., 1988; Piepho, 1998; Vargas et al., 1999). In the present study, the results also demonstrated the advantage of AMMI analysis for the yield stability of fertilization and environment assessment in single-site long-term experiment.

Table 5. Person's correlation among the ranks of stability parameters and mean grain yield of treatments.

	Mean yield	IPCA1	IPCA2	D	ASV	b	W	σ^2
Mean yield	1.00							
IPCA1	-0.61^{*}	1.00						
IPCA2	ns	ns	1.00					
D	-0.61^{*}	0.89^{**}	ns	1.00				
ASV	-0.61^{*}	0.99^{**}	ns	0.93^{**}	1.00			
b	-0.57^{*}	ns	ns	ns	0.45	1.00		
W	-0.62^{*}	0.94^{**}	ns	0.89^{**}	0.96^{**}	ns	1.00	
σ^2	-0.62^{*}	0.94^{**}	ns	0.89^{**}	0.96^{**}	ns	1.00^{**}	1.00

* Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level; ns is not significant.

IPCA: interaction principal component axes (Gauch, 1988); D: additive main effects and multiplicative interaction (AMMI) statistic coefficient (Zhang et al., 1998); ASV: AMMI stability value (Purchase et al., 2000); b: regression coefficient (Finlay and Wilkinson, 1963); W: ecovalence (Wricke, 1962); σ^2: stability variance (Shukla, 1972).

When considering the yield stability, the treatment NP can be regarded as the most stable treatment, and the NPKM with the highest yield was a relatively unstable fertility regime. Potassium in organic manure (35 kg ha^{-1} year^{-1}) basically met the crop requirement, specifically in crop rotation system. Also, soil K supply capability can be maintained due to sufficient K in alfisol soil and the homeostasis existed between soil-exchangeable K and non-exchangeable K (Yu et al., 2009). Therefore, the amount or frequency of fertilizer K application can be reduced for increasing the farmers' economic incomes where recycled manure applied. At the same time, based on the limited amount of the local organic manure resource, amendment of soil with manure or mineral N (150 kg ha^{-1}) alone was inadequate for maintaining soil N balance, but further increase of mineral N application would lead to the lower nitrogen use efficiency and more fertilizer N entry into environment (Ma et al., 2010). Combination manure with mineral N was an effective way to maintain the N supplying ability of soil and achieve high yield due to the slow release of N from manure resulting in relatively low loss of N (Bhandari et al., 1992; Yadav et al., 2000). As a result, treatment NPM with high and stable yield was the most desirable fertility regime.

In the present study, it also can be conclude that health growth status at seedling stage was necessary to obtain stable yield in barren land or low nutrient input farmland, and more attention to improving drought resistance or drainage should be paid in mid and later growth periods to maximize the effect of fertilizer on yield increase in fertile fields or under balanced nutrients supply. Furthermore, crop rotation, including N-fixation legumes, had beneficial effects on yield performance and stability improvement, and was an efficient way to reduce the inputs for obtaining high and stable yield. Therefore, application of both mineral fertilizers and organic manure, optimized water management at the key stage and integrated crop rotation should be taken into account for agricultural management practices in this region.

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