STATISTICS

Use of Stability Analysis for Long-Term Soil Fertility Experiments

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ABSTRACT

Long-term fertility experiments with replications are often statistically analyzed as split plots in time. Years are often shown to be significantly different and the inconsistency of treatment effects over years enters into significant year-by-treatment interactions which are difficult to interpret. The objectives of this study were to evaluate long-term fertility experiments by stability analysis and relative stability and to observe possible benefits of these analyses to complement conventional analysis of variance procedures. Stability analysis which is the linear regression of treatment yield on the location/year environment mean yield was performed on long-term wheat (*Triticum aestivum*) and corn (*Zea mays* L.) fertility trials. Stability analysis on wheat data from the Magruder Plots, indicated that beef manure applications (269 kg N ha^{-1}) responded poorly compared to the NPK treatment when environment means were low (<2.0 Mg ha^{-1}) and visa versa when environment means were high (>2.0 Mg ha^{-1}). Similarly, anhydrous ammonia applied as sidedressing in an irrigated corn experiment at Mead, NE, was found to be superior to urea-ammonium nitrate applied either pre-plant or sidedressed when environment means were less than 8.0 Mg ha^{-1}. Stability analysis provided a simple method of interpreting significant year-by-treatment interactions detected in analysis of variance models from these long-term experiments. Stability analysis may also be useful for multilocation experiments and continuous site experiments where treatments are applied to the same plot year to year. However, stability analysis may be misleading when employed on continuous site experiments where autocorrelations are present year to year.

A MAJOR PURPOSE of long-term fertility trials is to provide a measure of the effect of the environment over time on the consistency of treatment effects. Assessing year-by-treatment interactions in long-term fertility experiments is an issue when more than 2 or 3 yr of data are present. However, interpretation of year-by-treatment interactions by conventional analysis of variance is difficult because of the complexity of factors affecting environment.

Initial use of regression to assess yield stability of genotypes across a wide range of environments was originally presented by Yates and Cochran (1938) and later followed by Finlay and Wilkinson (1963) and Eberhart and Russell (1966). The technique is useful in relating a measurement of environment, which is usually the mean yield across all genotypes for each environment, to performance of different genotypes tested. Work by Crossa (1988) has addressed other methods used in determining yield stability of genotypes over environments. Measurement of yield stability over time involves the evaluation of at least three distinct components: (i) relationship of yield with local environment, (ii) average yield level, and (iii) variability of yield (R. Mead, University of Reading, UK, 1989, personal communication). A stable system has been defined as one that changes least in response to changes in environment (Lightfoot et al., 1987). Eberhart and Russell (1966) characterize a stable genotype as having a linear regression coefficient of one and deviations from regression equal to zero. Other measures of yield stability include the use of relative stability, which is the analysis of functional linear relationships between pairs of varieties or cropping systems (Mead et al., 1986, Lightfoot et al., 1987). Although this technique was originally introduced to compare stability of intercropped versus monocropped systems, it can also be used for comparisons among agronomic treatments.

The extrapolation of some of these concepts to characterize the stability of agronomic treatments instead of genotypes seems to be a practical application in separating the response of treatments as a function of environment over time. This assumes that the lack of

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consistency of treatment effects over time (a treatment-by-year interaction) can be interpreted as a linear function of the environment mean on the mean yield for a given treatment. The use of regression on the environment mean to assess stability of genotypes as affected by fertilizer treatment on 14 unreplicated trials has been presented by Hildebrand (1984). Hildebrand (1984) stated that it is visually possible to compare treatments and to generalize these equation sets for various kinds of management practices; he further stated that the environment mean measures treatment response to good or poor environments regardless of the reasons these environments are good or bad. However, a major criticism of the technique for use in agronomic trials with few treatments lies in the non-independence of the individual values used in regressing the environment mean on treatment mean yields (Lightfoot et al., 1987). Non-independence of variables used in regression as well as potential interdependence of the different linear equations to be compared become critical considerations when one uses stability analysis to separate treatment response as a function of the environment mean. However, such problems are largely overcome as the number of treatments used in calculating the environment mean is increased (R. Mead, University of Reading, UK, 1989, personal communication). In the case of agronomic experiments with a few treatments, the amount of bias caused by large interdependence of regression equations can be avoided by use of relative stability which uses independent values.

Another approach to express stability is the evaluation of relative risk when two treatments are compared (Mead et al., 1986). Various other aspects have recently been investigated relative to proper analysis procedures for fertilizer response experiments, specifically the use of differential equations (Cochrane, 1988) and trend analysis (Tamura et al., 1988).

The objectives of this manuscript were to evaluate various long-term fertility experiments by stability analysis by means of regression of treatment yield on the location/year mean yield and relative stability among selected treatment pairs to assess treatment response as a function of environment and to detect the benefits of these analyses to complement conventional analysis of variance.

MATERIALS AND METHODS

Two long-term wheat fertility studies at Stillwater, OK (Experiment #222 and Magruder Plots) and one long-term corn fertility study at Mead, NE that had treatments applied to the same plots year after year were analyzed by conventional analysis of variance procedures, stability analysis (Finlay and Wilkinson, 1963, without the use of data transformations), and relative stability (Mead et al., 1986, and Lightfoot et al., 1987).

Conventional analysis of variance was performed by the design structure for each individual long-term trial. Because the Magruder plots did not employ replications, the only possible combined analysis included only sources of variation for year and treatment, with the interaction (year by treatment) as the error term. This analysis, although restrictive, does provide a measure of the consistency of treatment effects over time. Conventional analysis over years of Experiment #222 and the Mead, NE experiment employed split-plot-in-time designs since the same fertilizer treatments were applied each year to the same plots. Consistent with McIntosh (1983), considering year and treatments as random and fixed effects, respectively, in Experiment #222, the appropriate tests of hypothesis were made.

Stability analysis is the linear regression of treatment yield on the location/year environment mean yield (average yield of all treatments in a given year). Steps to determine differences in slope and intercept components for linear equations from the stability analysis were derived from Steel and Torrie (1980) and Cochran and Cox (1957).

Relative stability is assessed by studying the joint distribution of data pairs (mean for Treatments A and B in a given year) and by comparing slopes of the regression line when the average yield of the pair $(A+B)/2$ is regressed on the yield difference $(A-B)$ between the two treatments. A slope close to zero would indicate that the two treatments change similarly and are equally stable. A positive slope indicates that B is more stable than A since there is more variability in A. A strongly negative slope indicates that A is more stable than B. A probability level of $P < 0.05$ for the slope from the relative stability equation indicates that the slope is significantly different from zero. These probability levels are listed on each of the relative stability graphs discussed.

Due to various treatment changes in the Magruder plots over the past 90 yr, analyses on these plots were restricted to the last 31 yr where constant P-K-Lime rates were employed. Nitrogen was applied at 37 kg ha^{-1} prior to 1968 while plots receiving N since that date have received 67 kg ha^{-1}. Treatments analyzed in this experiment are defined in Table 1. The use of N, P, K and lime (L) as related to treatment comparisons are explained in Table 1. Further information relative to the Magruder Plots can be found in Webb et al. (1980). Treatment structure for the Mead, NE experiment which was conducted for 15 yr is discussed in Olson et al. (1986). A split-block design for individual year analysis was employed with four replications at this site. The three treatments from that corn experiment discussed in this manuscript were anhydrous ammonia injected sidedress at the 11 to 12 leaf stage (AA-IS), urea-ammonium nitrate sidedressed at the eight-leaf stage (UAN-SD) and urea-ammonium nitrate band applied at planting (UAN-PL), all at the 90 kg N ha^{-1} rate. Treatment structure for Experiment #222 which was established in 1969 is found in Table 2. This experiment used a randomized complete block design with four replications. Treatment means from all three experiments were compared by Fisher's Least Significant Differences (LSD) at $P = 0.05$. Given the limitations of the LSD test (prone to Type I errors and limitations of two mean comparisons, Swallow, 1984), non-orthogonal contrasts were also performed on selected treatment comparisons from the Magruder and #222 experiments. Contrasts of treatments receiving no N versus manure or other treatments receiving N were not targeted for discussion because of the distinct differences noted at these two locations. Only treatment mean data by year could be obtained for the Mead, NE experiment thus restricting further mean separation and related data analysis.

RESULTS

Magruder Plots

Analysis of Variance

A two-way analysis of variance was used to compare treatment means over the last 31 yr in this 97-yr-old experiment (Table 3). Tests for heterogeneity of error (problem associated with changing N rate mentioned in materials and methods) for yield data from 1958 through 1988 compared to 1968 through 1988 were not significant, therefore, since treatment means were also not different (1958-1988 compared to 1968-1988), means for the period of 1958 through 1988 were used in the discussion. The design structure employed does not permit

Table 1. Soil fertility treatment effects on Magruder Plot wheat grain yields, Stillwater, OK, 1958-1988.

	Treatment N	P	K	Grain Yield
	kg ha⁻¹			Mg ha⁻¹
1.+	Manure Only			2.11
2.	0	0	0	1.27
3.	0	14.6	0	1.39
4.	67.2	14.6	0	2.18
5.	67.2	14.6	27.9	2.11
6.‡	67.2	14.6	27.9 + Lime	2.31
LSD (0.05)				0.18

+ Beef manure applied at a rate of 269 kg ha^{-1} every fourth year.
‡ Lime applied when soil analysis indicated a pH of 5.5 or less.

Table 2. Soil fertility effects on Exp. #222 wheat grain yields, Stillwater, OK, 1969-1987.

	Treatment N	P	K	Grain Yield
	kg ha⁻¹			Mg ha⁻¹
1.	0	30	37	1.49
2.	45	30	37	1.87
3.	90	30	37	1.94
4.	135	30	37	1.97
5.	90	0	37	1.76
6.	90	15	37	1.96
7.	90	45	37	1.95
8.	90	30	0	1.82
9.	90	30	74	1.96
10.	0	0	0	1.47
11.	135	45	74	1.99
12.	135	45	0	1.79
LSD (0.05)				0.11

† N applied half in fall and half in spring.

Table 3. Two-way analysis of variance for wheat grain yield (Mg ha^{-1}), Magruder Plots, Stillwater, OK, 1958-1988. N rate from 1958-1967 was 37 kg ha^{-1}. N rate was constant from 1967-1988 at 67.2 kg ha^{-1}.

Source of variation	df	Mean square
Year	30	1.81**
Treatment	5	6.02**
Error (Year by Treatment)	149	0.12
CV, %		18.3

** Significant at $P = 0.01$.

partitioning of the year-by-treatment interaction since this source of variation was used as the error term to test treatment and year effects. With or without the restricted mean separation procedure employed, overall means showed little difference between any of the treatments either receiving manure or N plus other P-K-Lime combinations.

Stability Analysis

Consistent with results on unreplicated trials reported by Hildebrand (1984), stability analysis provided a valid means of assessing this data set while also allowing visual observation of treatment interactions with environment (Fig. 1 and Table 4). It was interesting to note that the variability about the intercept and slope components was decreased for the treatments receiving K (Table 4). Stability analysis of treatments regressed on the environment mean demonstrates a distinct advantage of N fertilization (Manure, NP, NPK, and NPK*L*), especially

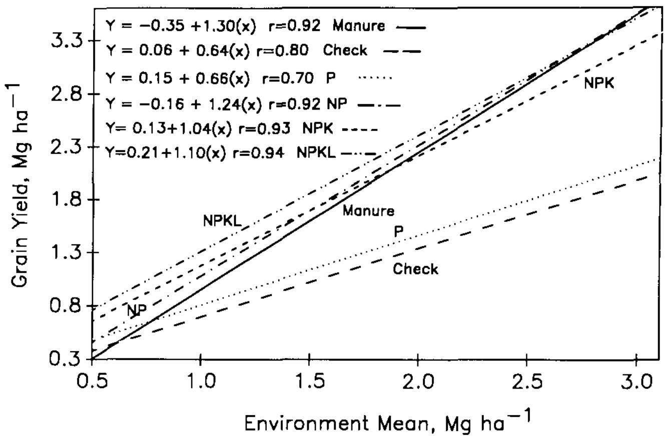

Fig. 1. Regression of wheat grain yield on the environment mean, Magruder Plots, Stillwater, OK, 1958–1988.

when environment yields were high when compared to the check (Fig. 1).

Applications of only P responded similarly to the check (no fertilization) indicating that P alone had little impact on yield regardless of the environment mean (Fig. 1). The manure treatment demonstrated superior response in high yielding environments versus lower yielding environments when compared to NPK and NPK*L* as evidenced by significant differences in slope and intercept components respectively (Table 5). It should be noted that the NP treatment responded in much the same manner as the manure treatment, having poor performance in low yielding environments and higher yields when the environment mean exceeded 2.5 Mg ha^{-1} (Fig. 1). In this regard, treatment response was considered to be environment specific since linear regression equations were all highly significant and ensuing significant differences in both slope and intercept components were found (Fig. 1 and Table 5).

Relative Stability

A significant linear trend was found when plotting wheat yields by environment for fertilizer treatments containing N when compared to manure (Fig. 2). Consistent with methods described by Mead et al. (1986), this permits the examination of relative stability of these three treatments (Fig. 3a-f). Two tail *t*-tests for slopes different from zero ($P < 0.05$) were used in all comparisons and probability levels are listed in Fig. 3a-f accordingly.

The manure treatment was subjectively chosen as the check comparison treatment because of its varied response observed in the stability analysis (Fig. 1). This comparison is of importance since the manure treatment represents not only inorganic nutrient additions but also the application of organic matter which can be thought of as an ecological method of sustaining soil productivity. This was also considered important since the manure application was made every 4 yr while other treatments were applied annually. There appeared to be a tendency of the manure treatment to yield less than the others at yields less than 2 Mg ha^{-1} (Fig. 1). A slope different from zero for the manure versus NPK comparison (Fig. 3c) suggests that the NPK treatment was less stable than

Table 4. Linear regression equations of grain yield on the environment mean, by treatment, Magruder Plots, 1958-1988. Stillwater, OK.

	Treatment N	Treatment P	Treatment K	Intercept	Std. error estimate	Slope	Std. error estimate	C.V.	r	Root MSE
	kg ha^{-1}							%		
1.†		Manure Only		−0.349	0.197	1.301	0.100	14	0.92	0.302
2.	0	0	0	0.059	0.174	0.640	0.088	21	0.80	0.266
3.	0	14.6	0	0.149	0.246	0.658	0.125	27	0.70	0.377
4.	67.2	14.6	0	−0.160	0.190	1.240	0.097	13	0.92	0.292
5.	67.2	14.6	27.9	0.134	0.145	1.043	0.074	11	0.93	0.222
6.‡	67.2	14.6	27.9	0.208	0.146	1.102	0.074	10	0.94	0.220

† Beef manure applied at a rate of 269 kg ha^{-1} every fourth year.
‡ Lime applied when soil analysis indicated a pH of 5.5 or less.

Table 5. Differences in slopes and intercepts for various treatment regression equations; Magruder Plots (wheat); Mead, NE (corn); and Exp. 222 (wheat).

COMPARISON†	*F*-calc‡ (*F*-MSE)	PR > *F*‡ (*F*-MSE)	*t*-calc‡ (*t*-slope)	PR > |*t*|‡ (*t*-slope)	*t*-calc (*t*-intercept)	PR > |*t*| (*t*-intercept)
Magruder Plots						
NPK*L* vs. Manure	1.88	0.05	1.60	0.12	2.27	0.03
NP vs. Manure	1.07	0.43	0.44	0.66	0.69	0.50
NPK vs. Manure	1.85	0.05	2.07	0.04	1.97	0.06
NPK vs. NP	1.73	0.07	1.61	0.11	1.23	0.22
NPK*L* vs. NP	1.76	0.07	1.13	0.27	1.53	0.14
NPK*L* vs. NPK	1.02	0.48	0.56	0.57	0.36	0.72
Mead, NE						
AA-IS vs. UAN-SD	2.81	0.01	2.05	0.05	2.40	0.02
AA-IS vs. UAN-PL	2.01	0.03	2.10	0.04	3.02	0.01
UAN-SD vs. UAN-PL	1.40	0.19	0.05	0.96	0.65	0.52
Exp. 222						
90-0-37 vs. 90-45-37	1.11	0.43	1.11	0.29	0.18	0.86
90-30-37 vs. 90-30-0	3.96	0.01	1.54	0.15	2.22	0.04
90-30-74 vs. 90-30-0	1.23	0.36	0.50	0.62	1.40	0.18

† NPK*L*, NPK, NP, and Manure refer to nitrogen, phosphorus, potassium, lime, and Manure combinations defined in Table 1. AA-IS - anhydrous ammonia injected sidedress at the 11-12 leaf stage, UAN-SD - urea-ammonium nitrate sidedressed at the eight-leaf stage, UAN-PL - urea-ammonium nitrate band applied at planting.
‡ PR > *F*, probability of a greater *F* statistic. PR > |*t*|, probability of a greater absolute value of *t*. *F*-calc, *F* test for homogeneity of error variance. *t*-calc, *t* test of differences in slopes and intercepts.

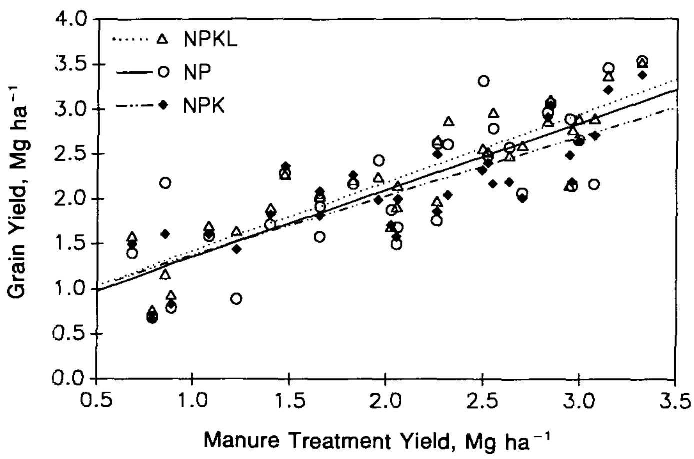

Fig. 2. Linear trend of NP, NPK, and NPK*L* vs. Manure, Magruder Plots, Stillwater, OK, 1958–1988.

the manure treatment above yield levels of 2 Mg ha^{-1}. Comparing NPK and NP (Fig. 3d) suggests that yields tended to be lower in high yielding environments with the application of K. Alternatively, additions of lime had a non-significant tendency to increase yields regardless of environment mean (NPK*L* vs NPK, Fig. 3f). Also, no environment specific response was observed for the NP versus manure comparison (Fig. 3b). In the absence of a N only treatment, this comparison seems to confirm that a controlling fertilizer factor over time is the application of N. It should be noted that this evaluation of stability is consistent with the lack of differences found when comparing means by conventional analysis. Nevertheless, this type of response was only observed in two of the six possible comparisons among means.

Mead, Nebraska

Conventional and Stability Analysis

Analysis of variance and means for this 18 treatment corn experiment are reported in Olson et al. (1986). Results from this study indicated no method-by-nitrogen-rate-by-year interaction for the dependent variable yield (Table 4.; Olson et al., 1986, p. 858). Significant differences between anhydrous ammonia injected sidedress and urea-ammonium nitrate sidedressed and urea-ammonium nitrate applied at planting were detected by stability analysis which in effect expresses treatment response as a function of temporal variability (variability within a given year as it relates to variability in another year which in most of these cases would have been a direct function of rainfall or moisture availability). Although this study also employed P-rates, this variable was not significant either as a main effect or as an interaction term with the other independent variables. Therefore stability analysis was performed on yield means over P rates. Stability

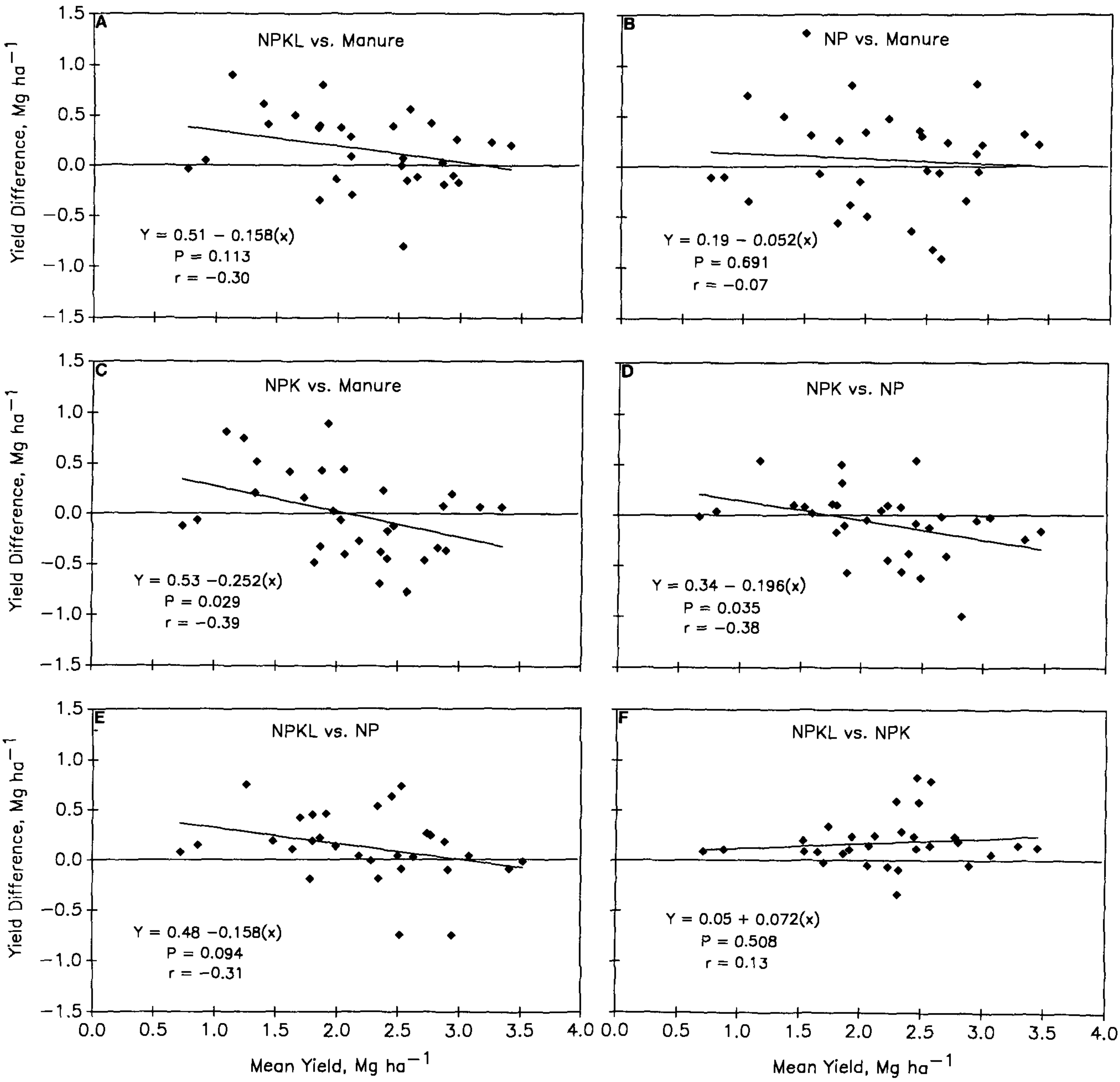

Fig. 3. (a-f). Relative stability of treatment pairs, Magruder Plots, Stillwater, OK, 1958–1988.

analysis illustrated that anhydrous ammonia applied sidedress at the low N rate (90 kg ha^{-1}) had significantly greater yields in low yielding environments versus urea-ammonium nitrate sidedressed and applied at planting method combinations (Fig. 4 and Table 6). This finding was further validated by demonstrating significant differences in slope and intercept components (Table 5). In this case, stability analysis provided a unique mechanism to detect and observe a year-by-treatment interaction.

Relative Stability

The results observed from regression on the environment mean are further substantiated by the regression on the difference of the mean corn yield for different treatment comparisons for the 90 kg ha^{-1} N rate. The slight negative slope of anhydrous ammonia applied sidedress versus urea-ammonium nitrate applied at planting and urea-ammonium nitrate applied sidedress indicates that the latter two are less stable than anhydrous ammonia applied sidedress (Fig. 5a and b, respectively). On the other hand, urea-ammonium nitrate applied at planting and urea-ammonium nitrate sidedressed were equally stable across environments as indicated by a slope near zero (Fig. 5c). However, urea-ammonium nitrate applied at planting tended to have average yields of 0.5 Mg ha^{-1} less than urea-ammonium nitrate sidedressed. This clearly illustrates the difficulties inherent in evaluating stability as a discrete component (yield variability versus yield level).

It is hypothesized that ammonium supply in stress environments may have added benefits compared to nitrate sources. Immediate glutamine formation can take place in the roots when ammonium is the absorbed ion whereas if nitrate is taken up by the root, it must be transported to the leaves, where it is subsequently reduced to ammonium before glutamine formation takes place (Bidwell, 1979). Although the latter would be subject to further evaluation, stability analysis provided the means to observe differences between ammonium and nitrate sources as a function of environment. Had the interaction term of method by nitrogen rate by year been significant in the analysis of variance model, obtaining similar conclusions from the conventional analysis would have depended on how the degrees of freedom in that term were partitioned. In effect, stability analysis proved to be complementary and provided a simple mechanism to observe treatment as a function of environment.

Experiment #222

Conventional Analysis

Mean separation and analysis of variance can be found in Tables 2 and 7 respectively. Other than treatments receiving no N, yield differences in this wheat experiment were small. Treatments receiving K applications (9 and 11) versus zero K (8 and 12 at equivalent N and P rates respectively) demonstrated significantly greater yields (Table 2). However, this analysis gives no indication as to whether increased yields from K applications were in poor or high yielding environments.

Stability Analysis

Stability analysis, while demonstrating similar differences for treatments receiving K, further suggests that K applications had an increasingly greater effect in low yielding environments (<2.0 Mg ha^{-1}) than when environment yields were greater than 2.0 Mg ha^{-1} (Fig. 6 and Table 8). As was noted in the Magruder, OK experiment, treatments receiving N, P, and K tended to have smaller variance about intercept and slope components (Table 8).

Annual applications of 90 kg N ha^{-1} in the presence of P and K (90-30-37 compared to 0-30-37) demonstrated consistent increases in grain yield across environments ranging from 0.5 to 3.5 Mg ha^{-1}. Predicted yield increases from N applications were 0.23, 0.46, and 0.69 Mg ha^{-1} for yield environments of 0.5, 2.0, and 3.5 Mg ha^{-1} respectively (Fig. 6).

Hypothetically, farmers with similar soil types that fit

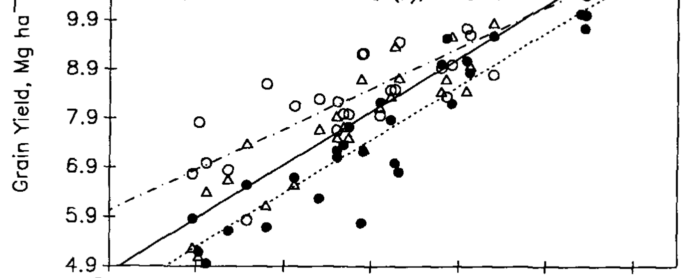

Fig. 4. Regression of corn grain yield on the environment mean, Mead, NE, 1969–1983.

into the lower yielding environmental mean range, conceivably due to lower average yearly precipitation, distribution, and/or other environmental factors, may benefit from K applications or alternatively, limited use of N fertilizers if yields are expected to be low. Biological interpretation of the effect of K in low versus high yielding environments is not clear, but this analysis identified an area in which additional research may be warranted. If realistic evaluation of treatment as a function of environment is considered, then the latter could be considered when applying recommendation strategies.

Relative Stability

Although differences were small, relative stability indicated that K applications provided greater stability when wheat yields were less than 2.5 Mg ha^{-1} (Fig. 7a) which in turn confirms the results of stability analysis. While similar trends were seen at the high K rate (Fig. 7b), neither this response nor that of having increased yields with P applications in higher yielding environments (Fig. 7c) were significant.

DISCUSSION

It is difficult to predict the environment mean since variety, rainfall, weed pressure, and disease are variable from year to year. In an additive linear model like those used in conventional analysis of variance, the mathematical sums of squares accounted by year, treatment, and year-by-treatment effects are removed from the random variation (residual error), yet year and year-by-treatment effects are seldom interpreted from a biological point of view. Limited biological interpretation of the lack of consistency of treatment effects over years (year-by-treatment interaction) decreases the value of conventional analysis in identifying treatment advantages as a function of environment. Mead (1988) states that the variability induced by time on the experimental units will usually be much greater than the changes effected by treatments. The consequence of this large variation in the condition of the experimental treatments is that the assumptions required for the analysis of variance are unlikely to be even approximately true (Mead, 1988).

The use of stability analysis implies that treatment is actually a linear function of temporal variability which would complement some of the limitations encountered in conventional analysis of variance. In general, the mean separation procedure and single degree of freedom nonorthogonal contrasts were found to provide the same information in terms of significant differences (Tables 1,2, and 9). However, the use of LSDs is customarily not considered valid for detecting differences in continuous variables.

Hildebrand (1984) states that stability analysis explicitly incorporates variation in farmer management as well as in soils and climate to help agronomists evaluate responses to treatments and partition farmers into recommendation domains. In depth analysis of year-by-treatment interactions suggests that the researcher should view changed treatment response within the specific environment in which the treatment differences were observed. When considering 2 or 3 yr of data, the year-by-treatment interaction can be separated easily into discrete components by specific comparisons by means of non-

Table 6. Linear regression equations of grain yield on the environment mean, by N treatments combined over P rates, Mead, NE, 1969-1983.

Treatment†	Intercept	Std. error estimate	Slope	Std. error estimate	C.V., %	*r*	Root MSE
1. AA-IS 90	1.834	0.638	0.834	0.075	7	0.90	0.602
2. UAN-PL 90	−1.222	0.691	1.086	0.082	8	0.93	0.425
3. UAN-SD 90	−0.611	0.634	1.081	0.075	7	0.94	0.359

† AA-IS - anhydrous ammonia injected sidedress at the 11-12 leaf stage, UAN-SD - urea-ammonium nitrate sidedressed at the eight-leaf stage, UAN-PL - urea-ammonium nitrate band applied at planting.

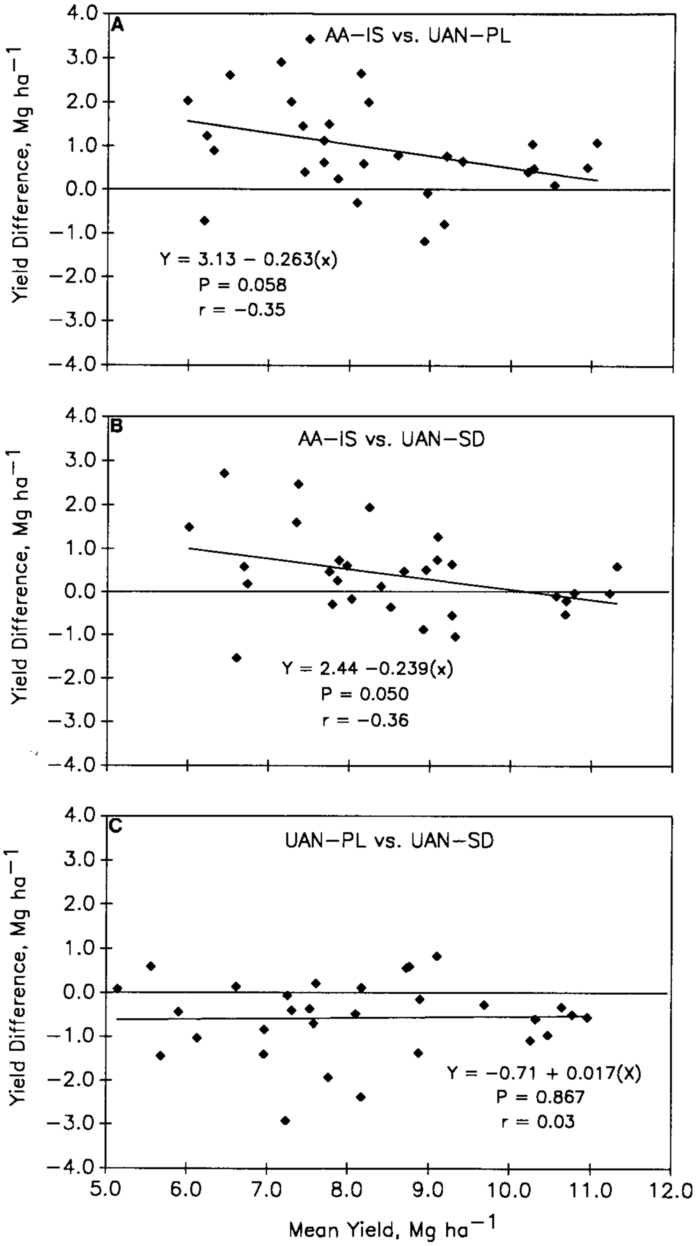

Fig. 5. (a-c). Relative stability of treatment pairs, Mead, ME, 1969–1983.

orthogonal contrasts. However, it is unlikely that biological interpretation of the year-by-treatment interaction will be achieved by conventional analysis when faced with 10 or more years of data. Alternatively, stability analysis is in effect somewhat restricted to long-term

Table 7. Split plot in time analysis of variance for wheat grain yield, Experiment #222, Stillwater, OK, 1969-1987.

Source of variation	df	Mean squares
Replication (*R*)	3	2.12**
Treatment (*T*)	11	2.19**
R × *T* (error *a*)	33	0.10
Year (*Y*)	16	30.59**
Y × *T*	176	0.27**
Error *b*	554	0.08
CV %		15.8

** - significant at $P = 0.01$. Year effects tested by the interaction *Y* × *T* (McIntosh, 1983). *Y* × *T* interaction tested by Error *b* (McIntosh, 1983).

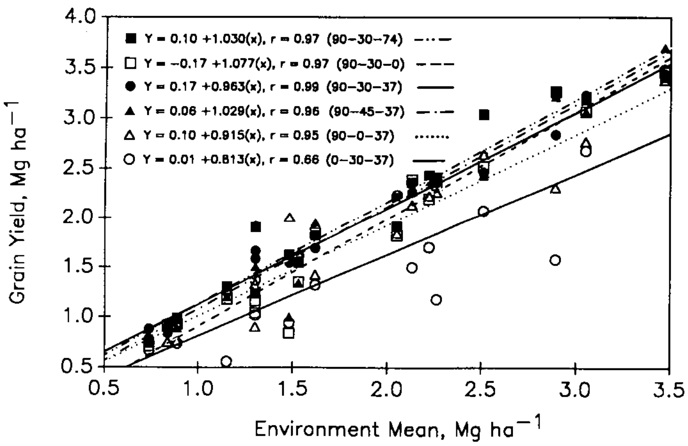

Fig. 6. Regression of wheat grain yield on the environment mean, Experiment #222, Stillwater, OK, 1969–1987.

experiments, multilocation experiments, or both, since adequate degrees of freedom are needed to obtain meaningful regressions.

The three data sets discussed demonstrate that treatments were strongly affected by temporal variability and that stability analysis and relative stability may be used to evaluate treatment performance over time. The major difference between stability analysis where yields are regressed on the environment mean and relative stability in detecting altered treatment response is that the latter method ensures the elimination of possible interdependence among regressions. Examples, illustrated by Mead et al. (1986), clearly demonstrate this point whereby the assessment of stability (Yates and Cochran, 1938; Finlay and Wilkinson, 1963; Eberhart and Russell, 1966) depends both on the environments included and the specific genotypes (5, 3, or 12 fertilizer treatments in this case for the respective experiments discussed) used to calculate the environment mean. Relative stability avoids this problem since only two treatments are compared at

Table 8. Linear regression equations of grain yield on the environment mean, by treatment, Experiment #222, 1969-87. Stillwater, OK.

Treatment N	Treatment P	Treatment K	Intercept	Std err of estimate	Slope	Std err of estimate	C.V.	r	Root MSE
kg ha⁻¹							%		
1. 0	30	37	0.002	0.248	0.813	0.123	26	0.86	0.401
2. 45	30	37	−0.104	0.077	1.078	0.038	7	0.99	0.124
3. 90	30	37	0.169	0.071	0.963	0.035	6	0.99	0.114
4. 135†	30	37	−0.015	0.160	1.079	0.079	13	0.96	0.258
5. 90	0	37	0.096	0.149	0.915	0.074	13	0.95	0.241
6. 90	15	37	−0.083	0.162	1.119	0.081	13	0.96	0.262
7. 90	45	37	0.060	0.141	1.028	0.070	11	0.96	0.229
8. 90	30	0	−0.166	0.141	1.077	0.069	12	0.97	0.227
9. 90	30	74	0.100	0.127	1.030	0.063	10	0.97	0.205
10. 0	0	0	0.061	0.209	0.768	0.104	23	0.88	0.338
11. 135	45	74	0.104	0.149	1.024	0.074	12	0.96	0.241
12. 135	45	0	−0.085	0.096	1.038	0.048	8	0.98	0.154

† N applied half in fall and half in spring.

Table 9. Non-orthogonal contrasts for various treatment comparisons from the Magruder plots and Experiment #222.

Comparison	Contrast Mean Square	PR > F
Magruder Plots		
NPK*L* vs Manure	0.520	0.04
NP vs Manure	0.083	0.40
NPK vs Manure	0.001	0.96
NPK vs NP	0.093	0.38
NPK*L* vs NP	0.189	0.21
NPK*L* vs NPK	0.542	0.02
Experiment #222		
90-0-37 vs 90-45-37	1.087	0.01
90-30-37 vs 90-30-0	0.539	0.03
90-30-74 vs 90-30-0	0.837	0.01

NPK*L*, NPK, NP, and Manure refer to nitrogen, phosphours, potassium, lime and Manure combinations defined in Table 1. 90-0-37, 90-30-37, 90-45-37, 90-30-0 and 90-30-74 refer to N-P-K treatment combinations in kg ha⁻¹ defined in Table 2.

a time and only those means are used to calculate the yield difference and mean yield used as the dependent and independent variables in regression. Alternatively, stability analysis uses all treatment means in the experiment to calculate the environment mean. Therefore, observing, slopes significantly different from zero in all three experiments from the relative stability analysis implies that environment specific treatment response did in fact exist.

Interestingly, both the Magruder and #222 experiments appeared to demonstrate increased yield response to K applications when environment means were low and, visa versa, when high. Biological interpretation of this observation is difficult. However, if this analysis were applied to a recommendation strategy, the final outcome would undoubtedly consider location specific temporal variability. Not that temporal variability is presently not considered when making recommendations, but rather that stability analysis provides a simple method to observe response differences as a function of environment if in fact they exist.

As has been demonstrated by Hildebrand (1984), other agronomic variables have been evaluated by stability analysis on several experiments conducted in the same year with varied sites. Because there were so many environment-specific response differences observed in this analysis, stability analysis may need to be considered when evaluating fertilizer application methods, timing,

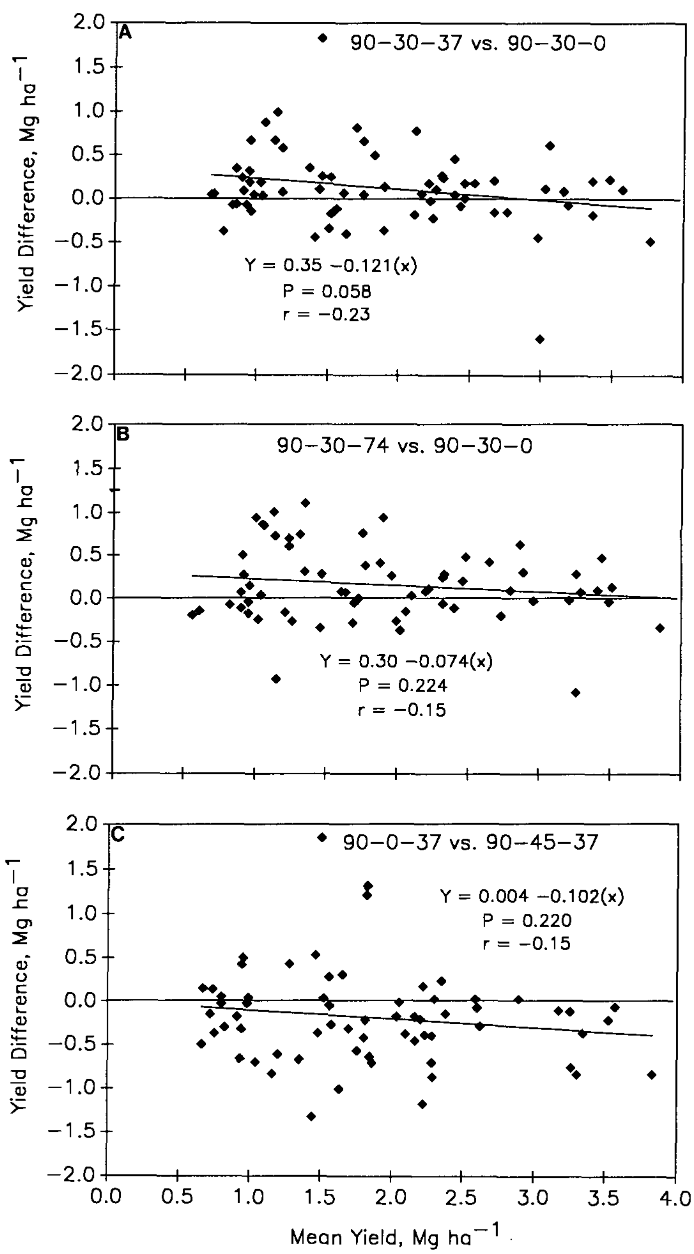

Fig. 7. (a-c). Relative stability of treatment pairs, Exp. #222, Stillwater, Ok, 1969–1987.

rates, and/or agronomic management practices. Subsequently, this would indicate that farmer recommendations possibly could be generated by assessing the temporal variability for a specific area (range in location/year mean yields) as a function of treatment response observed within that range.

In general, differences in environment means for these experiments can be attributed largely to moisture availability. This observation could assist in identifying potential differences between fertilizer treatments in either reduced or oxidized environments. Work by Olsen (1986) discusses the differences between ammonium and nitrate nutrition as related to energy use and factors which affect availability. These biological differences aid in explaining response differences between anhydrous ammonia applied sidedress and urea-ammonium nitrate applied sidedress and/or at planting in the Mead, NE maize experiment. Confounded method differences for the urea-ammonium nitrate treatments would obviously need to be investigated further.

It is of some concern as to how residual treatment effects influence yield in succeeding cycles. If treatment response were a function of a particular environment, then it seems reasonable that detection of residual treatment effects would be affected by the previous environment. However, plots of grain yield by year did not reveal any evident patterns of residual treatment effects. Furthermore, in stability analysis the environment mean while random, is in effect ordered in succession, thus confounding any detection of residual treatment effects if they existed. Nonetheless, conventional splot-plot-in-time analysis of variance models are no better in this regard since residual effects are also not evaluated. Other problems associated with years as repeated measures when analyzing long-term experiments should be considered, as has been addressed by Milliken and Johnson (1984). It also should be mentioned that stability analysis over locations versus one-site long-term experiments used in this work presents a problem of correlated yield results over time or autocorrelations in the data for the latter mentioned example.

When year-by-treatment interactions are detected in the conventional analysis of variance model, ensuing stability analysis provides a simple method of determining whether or not this interaction is a function of environment (cases used were one-site long-term experiments). Although this can also be achieved by partitioning the degrees of freedom in the year-by-treatment interaction from the analysis of variance model, stability analysis may provide a more direct method of assessing temporal variability in long-term experiments.

Recommendation strategies could possibly be refined by the added use of stability and relative stability analysis when assessing agronomic treatment response over time. As issues of sustainability become increasingly important, stability analysis and relative stability may assist in our understanding of yield as a function of environment, as well as identifying areas that warrant further investigation.

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