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Influence of Fertilizer Application Nonuniformity on Crop Response

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ABSTRACT

Levels of nonuniformity in K fertilizer application were established in a field experiment on a K deficient soil. Measures of uniformity of fertilizer distribution (UCF) were calculated from the coefficient of variation (CV) of K application (UCV = 1 $\frac{CV}{100}$). The structure of spatial dependence of exchangeable soil K was used to estimate the proportion of a given experimental plot which should be below a specified threshold of exchangeable K. Fertilizer requirements were estimated on the basis of the proportion of the region that was deficient. If deficient areas were identified in the Field, then variable rates of fertilization could be applied. The response of chinese cabbage (*Brassica oleracea* L. Chinensis) to K application was strongly affected by the uniformity of fertilizer distribution. Maximum yield decreased 9.5% with nonuniformity of fertilizer distribution. Amounts of K associated with 95% maximum yield were 97, J 13, and 444 kg K ha^{-1} for UCF values of 1.0, 0.42, and – 0.02, respectively. Corresponding tissue K concentrations associated with 95% maximum yield were 3.5, 3.8, and 4.0%. Increased variation in exchangeable K from CV = 44.1% to CV = 96.6% resulted in critical levels of soil K of 0.28 and 0.73 $cmol_c$ ha-*, respectively.

UNIFORM APPLICATION OF FERTILIZERS is usually considered essential for maximum yield. Excess fertilizer in some spots within a field may decrease yield and profit. Investigations that describe relationships between nonuniform fertilizer application and crop yield are rare, however. Nonuniform fertilizer application can occur because of faulty machinery, faulty machine operation or because of fertilizer properties which adversely affect the performance of the machine. According to Green et al. (1968) equipment should be capable of applying fertilizers to meet agronomic standards. They proposed that "Fertilizer shall be applied so that when the application rate is measured on art-as not less than 1 foot by 1 foot and not greater than 1.5 feet by 1.5 feet, the measured variation from the mean rate shall be such that it can be guaranteed that on 95% of the total area the variation from the mean rate will not exceed ±20% on high-value crops and ± 30% on low-value crops: over the whole area the variation from the mean application rate shall not exceed ±30% and ± 45% for high and low crops, respectively." Even hand application of solid fertilizer in experimental plots may not meet these standards.

Rates of fertilizer application are usually determined by comparing soil test values with a critical value appropriate for the nutrient and situation under study. Although nutrient variability across a field may reduce yield and result in wasteful application, spatial variability of the soil nutrient is seldom considered. Geostatistical concepts and methods of studying two- and three-dimensional variation in soil properties provide new ways to quantify nutrient content and variability and may be useful for estimating rates of fertilizer application more precisely.

The objectives of this study were to (i) test the usefulness of geostatistical methods as tools for estimating rates of fertilizer application, (ii) investigate crop response to nonuniform K application using cabbage as an indicator crop.

MATERIALS AND METHODS

Site Description

The study was conducted on a 92- by 42-m fallow field at the University of Hawaii Volcano Research Station on the island of Hawaii. The experimental site was located at 1200 m elevation with a mean annual rainfall of 3000 mm and mean annual temperature of 14 °C. The soil was a medial over thixotropic, isomesic, Typic Hydrandept (Puaulu series). The Puaulu series consists of well-drained soils developed in geologically recent volcanic ash (Ikawa et al., 1985). The subsoils are smeary and dry irreversibly.

Spatial Structural Analysis of Soil Potassium

In order to assess the magnitude of soil K spatial variability. 161 samples of field soil from 0- to 15-cm depth were taken with a 7.5-cm diam. auger at 2-m intervals along four transects (N-S, E-W, NE-SW, SE-NW). Exchangeable K was extracted from field-moist soil samples with 1 *M* NH_4OAc pH 7.0. Potassium in NH_4OAc extracts was determined by atomic absorption spectrophotometry. Semivariograms were computed to investigate the degree of spatial dependence of exchangeable K (*Yost* et al., 1986). Semivariograms were computed from log-transformed data since exchangeable K was lognormally distributed. The semivariance is defined by

$$\gamma(h) = 1/2\ E[Z(x + h) - Z(x)]^2 . \qquad [1]$$

An unbiased estimate of semivariance is obtained by

$$y\ (h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad [2]$$

where *E* denotes expectation, $N(h)$ is the number of pairs of values $Z(x_i)$, $Z(x_i + h)$ separated by a distance h. Anisotropic variation of exchangeable K was evaluared by calculating semivariograms of four directions (45, 90, 135, and 180°), each subtending an arc of 45° (± 22.5°). Isotropic semivariograms, considering all samples taken in all directions (90° ± 90°), were also calculated.

A Geostatistical Approach to the Determination of Potassium Application Rate

The fitted isotropic semivariogram of exchangeable K was used to estimate the average level of exchangeable K of 8- by 4-m blocks using block kriging. These blocks were later used as experimental plots. Given a lognormal distribution of soil K test values, the cumulative probability density function of soil K is given by Eq. [3] (Matheron, 1955).

$$f(x) = \frac{1}{\sigma_x\sqrt{2\pi}}\, e^{-1/2\,\frac{(\ln x - \mu)^2}{\sigma^2}} \qquad [3]$$

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where μ is the median of the distribution. The mean of the lognormal (ln) distribution can be estimated by Eq. [4] (Matheron, 1955)

$$m = \mu e^{\frac{\sigma^2}{2}} . \qquad [4]$$

Rearranging Eq. [4] yields

$$\ln \mu = \ln m - \frac{\sigma^2}{2} , \qquad [5]$$

and let

$$Z = \frac{\ln x - \ln\mu}{\sigma} . \qquad [6]$$

The value of the integral $G(Z) = \dfrac{\int^{z} e^{-Z^2/2}}{2\pi}\, dZ$ can be found in standard statistical tables.

Then substituting Eq. [5] into Eq. [6] yields

$$Z = \frac{1}{\sigma} \ln \frac{x}{m} + \frac{\sigma}{2} . \qquad [7]$$

Given a critical level (X_c) of exchangeable K, the proportion of each block above that threshold is given by Eq. [8]

$$T_{(X_c)} = \int_{X_c}^{\infty} f(x)\, dx . \qquad [8]$$

For the lognormal case Eq. [8] becomes (David, 1977)

$$T_{(X_c)} = G\left(\frac{1}{\sigma} \ln \frac{X_c}{m_0} + \frac{\sigma}{2}\right) \qquad [9]$$

where X_c = critical level of exchangeable K and is co sid-ered as a random variable with a spatial component i , a regionalized variable, G = cumulative normal distrib ion function, m_0 = mean of exchangeable K (kriged value) a = square root of the estimation variance. The var nce term, commonly known as the dispersion variance or ock variance, is unique to the geostatistical approach. I de-scribes the way in which exchangeable K varies withi an area of specified dimensions.

From Eq. [8] the proportion of the area below the cr ical level (0.8 cmol_c/kg) was calculated as follows

$$A_{(X_c)} = 1 - G\left(\frac{1}{\sigma} \ln \frac{X_c}{m_0} + \frac{\sigma}{2}\right) \qquad [10]$$

The amount of" exchangeable K above X_c, expressed s a proportion to the total amount is given by Eq. [11] (D vid, 1977)

$$Q_{(X_c)} = \frac{\int_{X_c}^{\infty} x f(x)\, dx}{\int_{0}^{\infty} x f(x)\, dx} . \qquad [11]$$

For a lognormal distribution Eq. [11] becomes (David, 1 77)

$$Q_{(X_c)} = G\left(\frac{1}{\sigma} \ln \frac{X_c}{m_0} - \frac{\sigma}{2}\right) . \qquad [12]$$

From Eq. [12] the amount of exchangeable K in the defi ent zone, expressed as

$$B_{(X_c)} = 1 - G \frac{1}{\sigma} \ln \frac{X_c}{m_0} - \frac{\sigma}{2} . \qquad [13]$$

The level of exchangeable K in the deficient zone of the specified area was estimated by dividing the amount of nutrient in the deficient zone by the size of the zone

$$M_{(X_c)} = \frac{B_{(X_c)}}{A_{(X_c)}} m_0$$

$$= \frac{m_0\left[1 - G\left(\frac{1}{\sigma} \ln \frac{X_c}{m_0} - \frac{\sigma}{2}\right)\right]}{1 - G\left(\frac{1}{\sigma} \ln \frac{X_c}{m_0} + \frac{\sigma}{2}\right)} . \qquad [14]$$

The amount of K necessary to bring 0, 25, 50, and 100% of the deficient area up to the critical level was determined. This yielded four rates of K application (0, 70. 140, and 280 kg K ha^{-1}). An additional rate, 560 kg K ha-‘, was added to ensure sufficient K was added.

Experimental Design and Fertilizer Application

A 3 × 5 factorial arrangement of treatments with three replications was laid out in a split-plot design with three indices of fertilizer distribution as main plots and five rates of K as subplots. The index of fertilizer distribution was defined as the ratio of the area fertilized in each experimental plot to the total area and was determined as follows: a 1- by 1-m grid was superimposed over each 8- by 4-m plot. The percentage of grid cells randomly selected to receive K fertilizer applications was 100, 75, or 50. This resulted in three indices of fertilizer distribution (1.0, 0.75. 0.50) and consequently, three uniformity coefficients of fertilizer application.

Each experimental plot received a uniform fertilizer and lime application which consisted of 120 kg N ha^{-1} as $(NH_4)_2SO_4$, 235 kg P ha-’ as treble superphosphate, 15 kg ha-’ each of Ca and Zn as sulfate, 15 kg B ha^{-1} as borax, and dolomite at 2 t ha-‘, all incorporated into the soil with a rototiller. Potassium fertilizer was then applied by hand in grid cells and rototilled into the soil. Two weeks after fertilizer application the same 1- by 1-m moving grid used for fertilizer application was superimposed over each plot. Soil samples were taken from the 0- to 15-cm depth from the center of each cell with a 7.5-cm diam. auger. Exchangeable K was extracted with 1 *M* NH_4OAc pH 7. Seedlings of chinese cabbage were transplanted into experimental plots 3 wk after fertilizer application at a spacing of 90 by 40 cm. Four weeks after transplanting a top dressing of 120 kg N ha^{-1} as urea was applied. Cabbage heads were individually harvested and weighed in the field. Cabbage leaf samples were taken, dried at 60 “C, and nutrient contents were determined.

RESULTS AND DISCUSSION

Standard Statistical Analysis

Distribution function of exchangeable K was evaluated using a probability plot and the Kolmogorov-Smirnoff *D* statistic (Barr et al., 1979). The results indicated that exchangeable K could be approximated to a lognormal probability distribution. The mean of log-transformed exchangeable K re-expressed in terms of the original data (Haan, 1977) was 0.2 cmol_c kg-’ with a standard deviation of 0.025 and a coefficient of variation (CV) of 12.6%. The variability of exchangeable K was influenced by the support size (soil core). This is the classical volume-variante relationship (Froidevcaux; 1982) which states that the average values of large samples will be less dispersed (smaller variability) than the average values of small ones. Hence, the overall variability of the property under study will depend to a great extent on the size of the soil core. The number of samples necessary to estimate the mean value with a given level of certainty was calculated by Eq. [15]

$$N = t_\alpha^2 \frac{S^2}{d^2} \qquad [15]$$

where t_α is the two-tailed student's t with infinite degree of freedom at the confidence level α, d is the allowable error (precision required within the given limits of the true mean), and S^2 is the sample variance. The results of such calculations showed that six samples would be required to estimate the true mean of exchangeable K to within 10% of the sample mean at 0.05 probability.

While this information is useful, it is only a portion of the knowledge required to efficiently sample an area; it is also necessary to estimate the minimum distance for spacing the samples. The geostatistical analysis provides an estimate of the minimum sampling interval.

Spatial Analysis of Soil Potassium

The results of the analysis of directional semivariograms suggested that exchangeable K varied isotropically. The isotropic semivariogram of exchangeable K is shown in Fig. 1. It indicated the presence of a large nugget effect. The nugget variance accounted for 25% of the variance of exchangeable K. The range of spatial dependence was about 17 m. The range indicates a zone of influence of a sample and is an estimate of the minimum distance required for spacing of independent samples. Samples farther apart than the range are considered to be independent of each other. Regionalized variable theory can be applied to augment the classical approach which assumes that deviations about the mean have a random geographic distribution. Using the range, the number of samples required in Eq. [15] can be determined so that they are spatially independent.

The spherical model weighted for the number of pairs in each lag was fitted to the experimental semivariogram using the SAS nonlinear algorithm (Barr et al., 1979) to obtain semivariogram parameters

$$\gamma(h) = C_0 + C\left(1.5\frac{h}{a} - 0.5\frac{h^3}{a^3}\right) \text{ for } h < a$$

$$\gamma(h) = C_0 + C \text{ for } h > a \qquad [16]$$

where C = spatial covariance; a = range of spatial dependence; h = lag distance.

Yield Response to Nonuniform Potassium Application

The uniformity coefficient of fertilizer application for each plot was defined as

$$\mathrm{UCF} = 1 - \frac{S}{\bar{Q}} \qquad [17]$$

where UCF is the uniformity coefficient of fertilizer application, and S and $\bar{Q}$ are the standard deviation and the average rate of K application respectively. The uniformity coefficient provides an overall indication of the evenness of fertilizer application. The UCF values were calculated for each of the three levels of uniformity. However, for the case where 100% of the grid cells in each plot received the same amount of K fertilizer a UCF value of 1 was assumed.

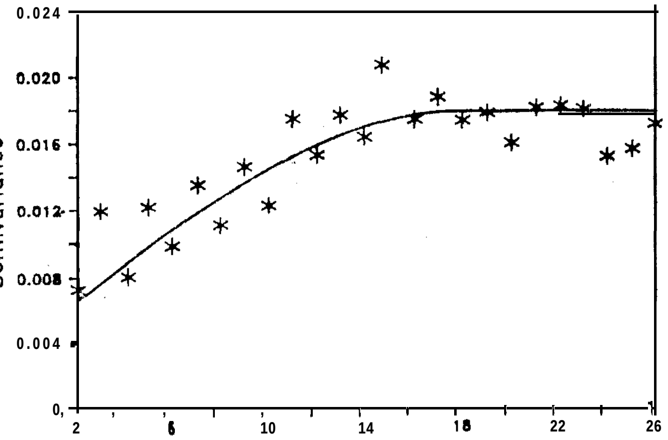

Fig. 1. Experimental (stars) and theoretical (solid line) semivariograms of exchangeable K.

The relationship between cabbage yield and K application is shown in Fig. 2 for the various uniformity coefficients. Cabbage yields decreased with increasing nonuniformity of fertilizer application. The spatial variability of soil properties across the field also significantly influenced yields. This can be seen from the differences in yield with no K application.

To quantify the relationship between yield and rates of K application the data were fitted to a Mitscherlich model

$$Y_{(Q)} = A - B\exp(-CQ) \qquad [18]$$

where $Y_{(Q)}$ = yield (Mg ha^{-1}), A = maximum yield, B and C are fitted coefficients, and Q = amount of K applied. The amount of K required to attain 95% of maximum yield was calculated from Eq. [18] as follows

$$KR_{95} = (\ln B - \ln A - \ln 0.05)/C. \qquad [19]$$

Values of KR_{95} for the three levels of variability were:

KR_{95} = 97 kg K ha^{-1} for UCF = 1.0.
KR_{95} = 113 kg K ha^{-1} for UCF = 0.42, and
KR_{95} = 446 kg K ha^{-1} for UCF = -0.02.

The geostatistical techniques employed earlier to determine rates of fertilizer application indicated that the application of 97 kg K ha^{-1} would bring 35% of the deficient area up to the critical level of 0.8 cmol$_c$ ha^{-1}. If a critical level of 0.5 cmol$_c$ ha^{-1} were selected, however, 97 kg K ha^{-1} would adjust 70% of the deficient area to the critical. In this manner the relationship of critical level to the proportion of each plot below the threshold can be estimated and, in turn, be used to determine rates of K application. Geostatistical methods provide relatively precise estimates of K content. ~~Rates of K application can be obtained by~~

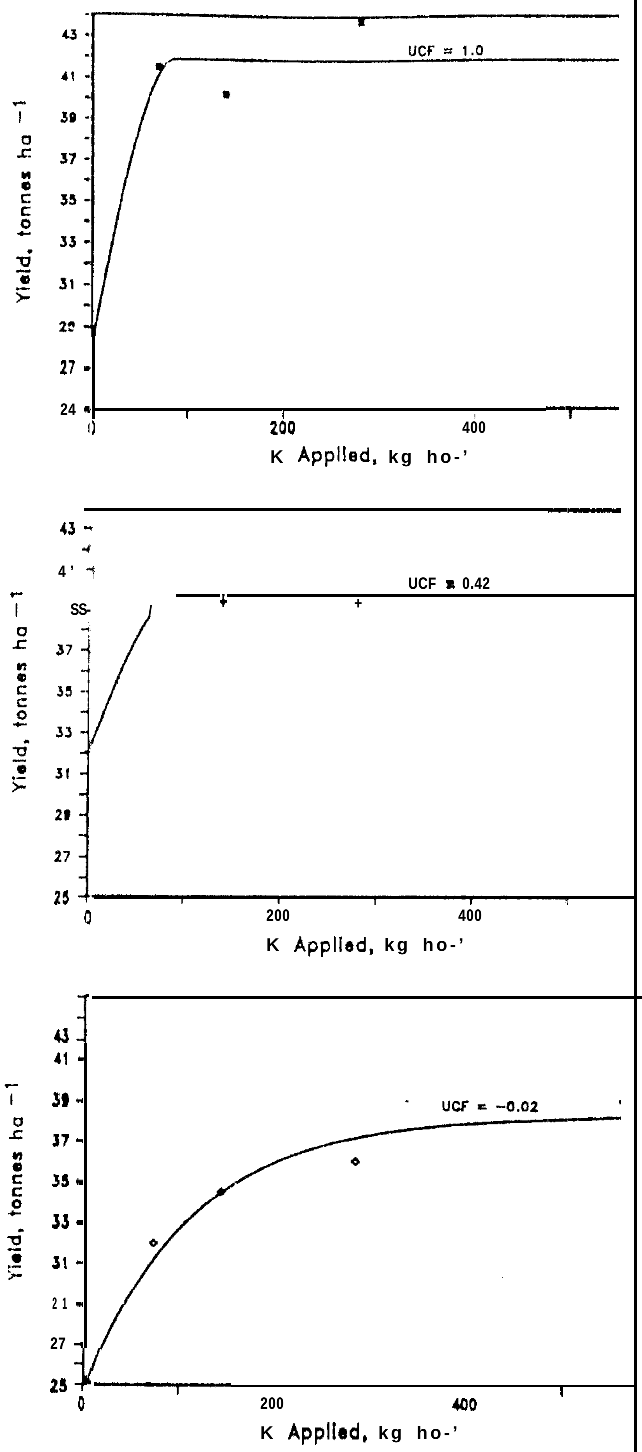

Fig. 2. Relationship between cabbage yield and rates of K applicat for various levels of uniformity of K fertilizer application.

methods described in Eq. [13] if the semivariogn of soil K is known, and if an adequate number samples are available. Fertilizer rates can then based on the proportion of the deficient area below standard. If the deficient zones are large and cont uous, they can be identified and fertilized separat Another method of applying fertilizer to nonunifo soils is possible with variable rate fertilizer spread which use maps of nutrient levels as a guide (Luell 1985). Geostatistical techniques described in this paper provide an optimal method to develop such maps from soil sample data.

Predicting Yield from Potassium Application and Nonuniformity

Because variation of K application significantly affected yield, and a relationship between yield per unit area and the application rate was established, it was useful to develop an expression for yield as a function of application rate and nonuniformity. Neglecting genetic factors, crop yield can be assumed to depend on both the average rate of K application over the area and the spatial deviations from that average (Zaslavsky and Mokady, 1967). The relevant expression is (Zaslavsky and Mokady)

$$\bar{Y}_{(Q)} = Y_{(\bar{Q})} + \frac{1}{2}\left(\frac{\partial^2 Y}{\partial Q^2}\right) S^2_{(Q)} \qquad [20]$$

where $\bar{Y}_{(Q)}$ is the spatial average crop yield, $Y_{(\bar{Q})}$ is the yield that would have been obtained with perfectly uniform application ($Q = \bar{Q}$, i.e., no fluctuation in Q), and $S^2_{(Q)}$ is the spatial variance of fertilizer application (Q), and is also called the fluctuation index (FI). The term $\frac{1}{2}\left(\frac{\partial^2 Y}{\partial Q^2}\right)$ is called the response index (RI). The product of FI and RI is the fluctuation response Index (FRI) and this expresses changes in average yield due to fluctuations in the level of applied nutrient.

In order to calculate the effects of nonuniformity of K fertilizer application on cabbage yield Eq. [18] was substituted into Eq. [20] to obtain

$$\bar{Y}_{(Q)} = A - R\exp(-CQ) + \frac{1}{2}\left(\frac{\partial^2 Y}{\partial Q^2}\right) S^2_{(Q)}. \qquad [21]$$

Rearranging Eq. [17] and substituting for S^2 in Eq. [21] one obtains

$$\bar{Y}_{(Q)} = A - B\exp(-C\bar{Q}) + \left[\frac{\partial^2 Y}{\partial Q^2}\right]\left[\bar{Q}(1 - \mathrm{UCF})\right]^2. \qquad [22]$$

Because yields of cabbage on no-K treatments varied due to inherent variability in soil properties, the yield-fertilizer function obtained with UCF = 1.0 could not be considered as $Y_{(\bar{Q})}$ in Eq. [20]. An estimate of Y was obtained by pooling the data from the entire experiment and fitting Eq. [18]. Therefore the fitting parameters A, *B*, and C in Eq. [22] are those estimated from the pooled data with A = 39.98, *B* = 10.17, and *C* = 0.0172. Using Eq. [22], cabbage yield was predicted for UCF values of 1.0, 0.42, and -0.02 and for different rates of K application. A plot of predicted yield against observed yield is shown in Fig. 3. A significant ($P < 0.05$) correlation coefficient (*r*) of 0.89 was found between observed and predicted cabbage yield.

Expressing yield as relative yield ($Y_r = \bar{Y}_{(Q)}/A$, with A = 39.98), curves of relative yield as a function of the nonuniformity of fertilizer application were drawn in Fig. 4 using Eq. [22]. It can be seen from this figure that the decrease in relative yield with decrease in uni-

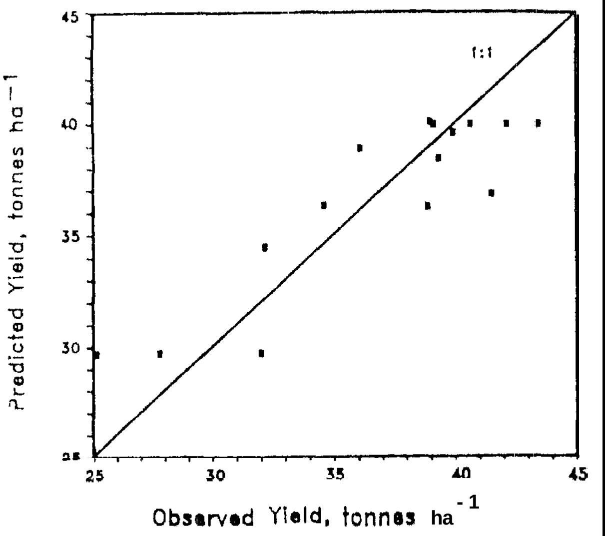

Fig. 3. Comparison of predicted and observed cabbage yield.

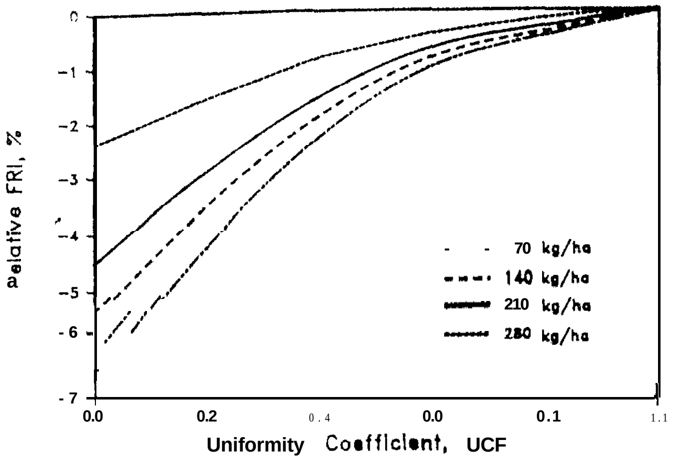

Fig. 5. Calculated relative fluctuation response index (FRI) as a function of uniformity coefficient of K fertilizer application for 4 rates of K application.

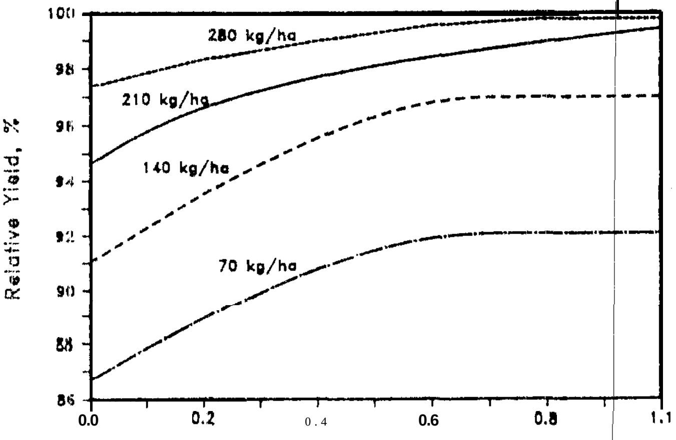

Fig. 4. Calculated relative yield of cabbage as a function of uniformity coefficient of K fertilizer application for four rates of K application.

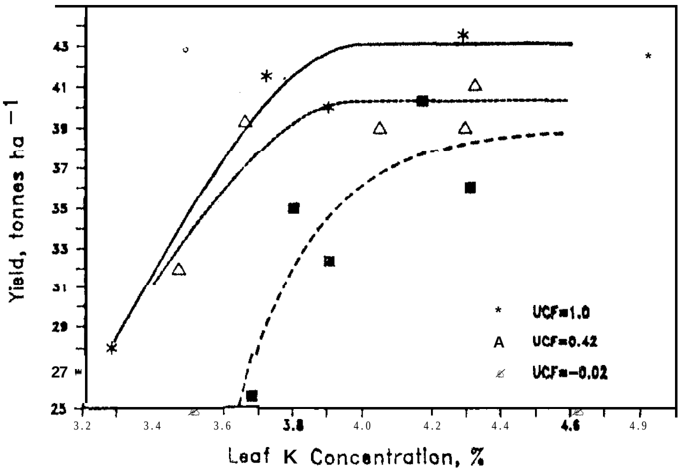

Fig. 6. Relationship between cabbage yield and K in dry matter as affected by uniformity of K application.

formity coefficient was most pronounced at application rates ≤140 kg K ha^{-1}. This is also shown in Fig. 5 by the relationship between relative fluctuation response index and uniformity coefficient. These calculations showed that the decrease in relative FRI with increase in UCF was much steeper for lower rates of fertilizer application.

There are some limitations on the use of data from experiments which measure crop response to nonuniform application of fertilizers. If areas of nonuniformity are sufficiently small, the nonuniformity may not be important because individual plants may draw nutrients from areas receiving both high and low dates of fertilizer. In this way, individual plants may average nonuniformity in fertilizer application rate. Little information is available on the minimum area over which nonuniformity of application should be considered. Prummel and Datema (1962) determined that inequalities in rate of application were only important when the areas of fertilized and unfertilized application were greater than 0.5 m. Factors which affect root zone volume, such as plant species, population density and row width, will probably influence the size of area that is sufficiently nonuniform to affect yields.

Increasing the uniformity of fertilizer application in order to improve crop yield must be viewed critically. Under certain conditions ensuring uniform fertilizer application may be expensive without commensurate increase in yield. Under other conditions, however, yield may be greatly increased through uniform application of fertilizer.

Yield-Tissue Potassium Concentration Relationship as Affected by Nonuniformity of Potassium Application

The relationship between yield and K concentration in cabbage leaf is shown in Fig. 6a, b, and c for UCF values of 1.0, 0.42 and -0.02, respectively. The results are in agreement with the general relationships reported in the literature between plant nutrient status and crop performance (Dow and Roberts, 1982). However, the scattering of points along each curve

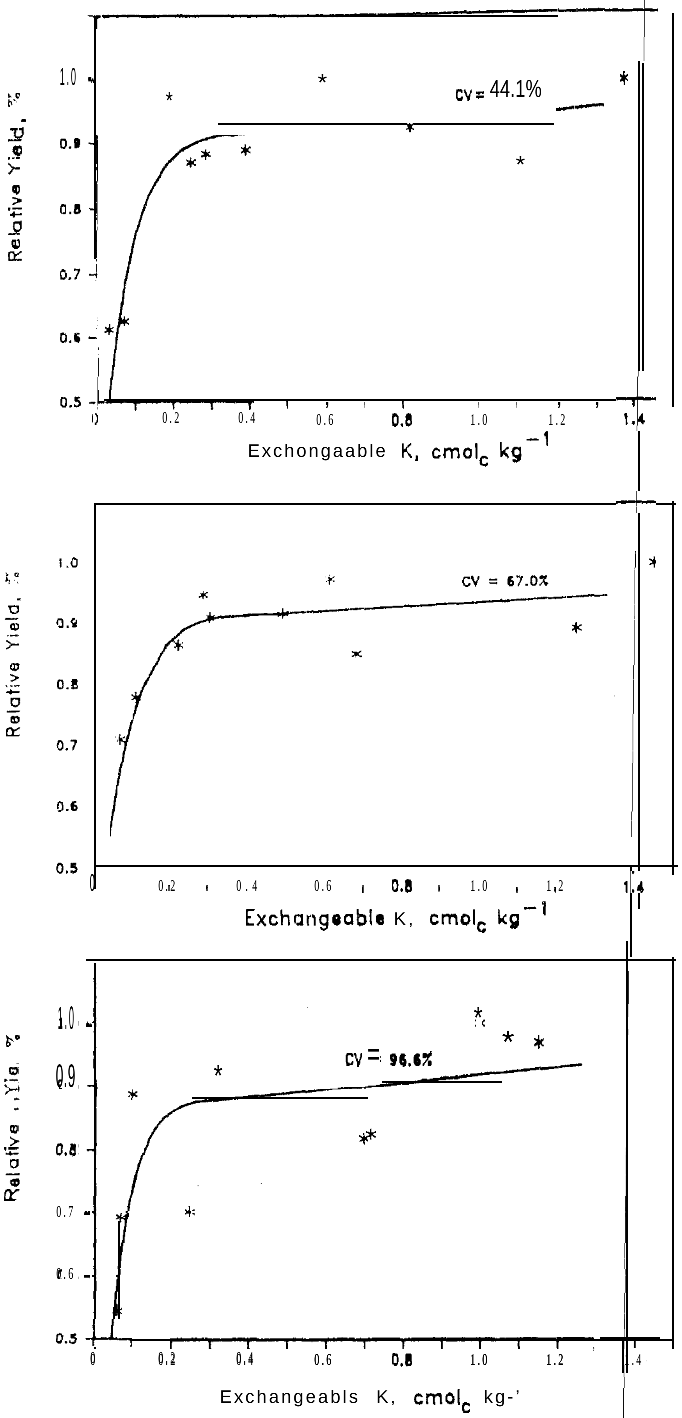

Fig. 7. Relationship between relative yield of cabbage and exchangeable K as affected by spatial variability of soil K.

indicates the difficulty of determining a specific percentage as the critical potassium concentration. Graphical determination of K associated with 95% maximum yield gave 3.6, 3.8, and 4.0% K for UCF values of 1.0, 4.2, and -0.02, respectively. Nevertheless the variation about the regression line supports the contention that a narrow range of concentrations rather than a single value seems more appropriate in evaluating nutrient status of crops (Dow and Roberts, 1982).

Cabbage Yield as Affected by Spatial Variability of Soil Potassium

The effectiveness of a soil K test is usually measured by its accuracy in predicting crop response to applied K. The goal of such a test is to measure the quantity of plant-available K and. therefore the test is negatively related to responsiveness and amount of K required to make up the deficit. Figures 7a, b, and c show the relationship between relative yield and exchangeable K for various coefficient of variation (CV) of soil K. The general form of the relationship was

$$Y = a + bx \qquad [23]$$

where Y = relative yield, x = exchangeable K, and a and b are constants. The level of exchangeable K associated with 90% maximum relative yield increased with increasing CV: 0.28 $cmol_c$ ha-' for CV = 44.1%. 0.31 $cmol_c$ ha^{-1} for 67 = 67.0%, and 0.73 $cmol_c$ ha^{-1} for CV = 96.6%. A critical level of 0.28 $cmol_c$ ha^{-1} is suggested by Boyer (1972) for tropical agriculture.

The range in nonuniformity in this study is within the ranges of nonuniformity reported in several studies. A CV value of 44.1% is consistent with values reported by Beckett and Webster (1971), and Courtin et al. (1983). However, Trangmar (1984) found a CV value of 105% in a study area of about 0.1 ha in Sitiung, Indonesia. He attributed this high heterogeneity to differences between burn sites, areas of exposed subsoil, and intermediate areas of surrounding soil. The results obtained in this study suggest that an average soil K test value may be misleading if the spatial variability K is **not** considered.

CONCLUSIONS

The response of chinese cabbage to K application was strongly dependent on the uniformity of fertilizer distribution. Different maximum yields were obtained with different levels of nonuniformity of K. With a uniformity coefficient of -0.02, the K requirement was four times greater than that for more uniform conditions.

The decrease in yield due to nonuniform application of fertilizer was quantitatively described by the fluctuation response index., The fluctuation response index value decreased with increasing rates of K application suggesting that at higher rates of application the areal uniformity of fertilizer application became a less important influence on overall yield.

The geostatistical approach used to determine rates of K fertilizer is a promising technique for determining fertilizer quantities needed to adjust fertility to a given critical level and for estimating the statistical distribution of nutrient in crop fields. Variable rates of fertilization can be applied if deficient zones have been identified in the field. The level of exchangeable K associated with 90% of maximum relative yield increased from 0.28 $cmol_c$ ha^{-1} for a CV of 44.1% to 0.73 $cmol_c$ ha^{-1} for a CV of 96.6%. The results suggest that an average soil K test value may be misleading if the spatial variability of soil K is not considered.

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Optimum Application Parameters for Point Injection of Nitrogen in Winter Wheat

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ABSTRACT

Point injection may enhance N fertilizer use efficiency in winter wheat but optimum application parameters have not been identified. Three field experiments, employing ^{15}N tracer techniques and manual injections on small plots, were established at two sites in southern Alberta, Canada, to identify optimum injection intervals and injection depth for spring point-injection of urea-ammonium nitrate solution (UAN). The optimum lateral (across-row) injection interval was found to be the equivalent of two row spacings (40 cm). Higher intervals resulted in unacceptable variability in N availability because wheat in rows not directly adjacent to injections assimilated comparatively little fertilizer-derived N. The optimum longitudinal injection interval was also approximately 40 cm. Analysis of fertilizer N distribution from the injection point demonstrated unacceptable variability when this interval was exceeded. Crop uptake of fertilizer N was reduced when the injection interval was increased from 40 to 60 cm. Adoption of smaller injection intervals in both dimensions, while not jeopardizing fertilizer use efficiency, would increase the cost of fertilizer application. The optimum injection depth was observed to be approximately 10 cm. Grain yield response and fertilizer N recovery in the crop increased four- and three-fold, respectively, when injection depth was increased from 2.5 to 10 cm. This effect was attributed to the inaccessibility of fertilizer N residing in dry surface soil. Injection of fertilizer at 15 cm rather than 10 cm demonstrated no additional advantage.

A PRIMARY LIMITATION of current production practices for winter wheat in the northern Great Plains region is the absence of an efficient means of applying N fertilizer. Fall-applied N is susceptible to substantial overwinter losses and may reduce the winter survival of wheat (Freyman and Kaldy, 1979; Grant et al., 1984, 1985). As a result, the currently recommended application strategy is to topdress N onto the winter wheat crop in spring (Black and Siddoway, 1977; Christenson and Meints, 1982; Fowler, 1982). The efficiency of top-dressed N, however, may be limited by volatile losses (Keller and Mengel, 1986; McInnes et al., 1986), biological immobilization in surface residues (Fredrickson et al., 1982; Sharpe et al., 1988), and inaccessibility to wheat roots in dry soil conditions (Harapiak et al., 1986).

An approach which may circumvent some limitations of conventional application methods for winter wheat is point injection of fluid N fertilizer, a method developed for fertilization of row crops (Baker et al., 1983). If adapted for winter wheat production, this method could facilitate effective N placement in spring without appreciable disturbance of the growing crop and thereby increase fertilizer use efficiency. Other potential advantages of this proposed method include compatibility with conservation tillage systems because of minimal soil disruption, and reduced energy consumption because of very low draft requirements relative to conventional banding methods.

The first step in the effective exploitation of point injection for the enhancement of fertilizer use efficiency in winter wheat is the identification of optimum application parameters. Two of the most important variables are the geometrical spacing of injection points and the depth of injection. Optimization of these variables is prerequisite to the meaningful comparison of point injection with conventional application methods.

The objective of this study, therefore, was to determine the optimum spatial arrangement and injection depths for point injection of N in winter wheat. This objective was addressed under field conditions using ^{15}N tracer techniques to quantify N distribution from injection points and determine fertilizer uptake efficiency as a function of injection interval and depth.

MATERIALS AND METHODS

Three field experiments were conducted in southern Alberta, Canada, during 1985 and 1986 to determine distri-

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