RESPONSE IN YIELD AND LEAF COMPOSITION OF SOYBEAN VARIETIES TO PHOSPHORUS, POTASSIUM, AND CALCIUM CARBONATE MATERIALS

C. J. deMooy and John Pesek

Department of Agronomy

Agriculture and Home Economics Experiment Station
Iowa State University of Science and Technology
Research Bulletin 572. . .August 1971. . .Ames, Iowa

CONTENTS

Response in Yield and Leaf Composition of Soybean Varieties to Phosphorus, Potassium, and Calcium Carbonate Materials[1]

C.J. deMooy and John Pesek[2]

Yield responses of soybeans [*Glycine Max* (L.) Merrill] to phosphorus and potassium fertilizers have the reputation of being small and inconsistent unless the soil tests low to very low with respect to these elements. Consequently, soybean fertilization is commonly left to the residual effect of fertilization of other crops in the rotation such as corn. Field experiments were conducted with the general objective to investigate means whereby the magnitude and consistency of soybean responses to fertilization may be improved.

Differential responses exist in corn. Jones (18) concluded that some inbred lines have a lower K requirement than others and also are more sensitive to high K levels. Differential responses among soybean varieties may be studied in a side-by-side comparison in fertilizer trials, and measurement of differential responses among four varieties was the primary objective of this work.

High rates of fertilization have not been investigated previously in sufficient detail and might be required to show consistent trends where the responses per unit of fertilizer are small. Also, if interaction effects occur, a response to one nutrient may not be found until another nutrient is present in high amount. In addition, the need for nutrients other than phosphorus and potassium could cause inconsistent responses. A third element, calcium, therefore was included as a variable at one site to cover the possibility of important interaction effects.

To meet the objectives, four commercial varieties in Iowa were grown side by side in field trials laid out at two locations in the state, with rates of fertilization considerably exceeding the economically justifiable range of application. Because of the large number of plots needed for an experiment with four varieties at nine levels of each of three nutrients, a composite design was used to limit the size of the experiments.

EXPERIMENTAL PLANS AND PROCEDURES

Field Technique and Laboratory Procedures

Four varieties were compared in both field experiments: Chippewa, Blackhawk, Harosoy, and Hawkeye. In the following discussion, these will be referred to as Ch, Bl, Hr, and Hk, respectively.

The use of composite designs made it possible to reduce the number of experimental units considerably below that required for a full factorial combination without loss of information on effects of interest. Modification of the composite designs proposed by Box and Wilson (4) for quadratic surfaces resulted in a $3(2^n) + 2n + 1$ design for the Howard County experiment and a $3(2^n) + 2(2n) + 1$ design for the Carrington-Clyde experiment, both with two replications. The treatment combinations are given in table 1.

Table 1. Rates of P, K, and Ca applied and yield of the soybean varieties Chippewa, Blackhawk, Harosoy, and Hawkeye at the Howard County and Carrington-Clyde experimental farms, Iowa.

Treatment number	Element applied (lb./acre)			Yield (bu/acre) 1961				1963
	K	P	Ca	Ch[a]	Bl	Hr	Hk	Ch
				HOWARD COUNTY				
17	0	0	0	28.0	28.1	33.2	27.8	28.4
21	0	0	2,000	30.3	30.0	32.5	26.7	29.5
28	0	200	1,000	19.8	22.2	23.3	22.0	29.1
18	0	400	0	19.5	26.1	31.3	24.2	26.7
22	0	400	2,000	19.6	22.2	30.0	28.0	23.6
9	200	100	500	39.4	37.9	43.1	33.0	32.4
13	200	100	1,500	35.7	36.2	41.5	32.1	32.1
10	200	300	500	38.5	36.9	39.2	42.3	34.8
14	200	300	1,500	39.4	38.9	42.8	38.1	33.1
1	300	150	750	40.0	37.5	45.2	42.6	32.6
5	300	150	1,250	37.1	38.5	44.5	43.7	35.2
2	300	250	750	37.4	39.7	49.3	30.6	36.9
6	300	250	1,250	39.4	37.0	41.4	40.2	36.4
26	400	0	1,000	29.4	35.6	38.3	34.4	32.8
30	400	200	0	37.8	37.3	34.6	36.6	31.7
25	400	200	1,000	40.3	38.1	44.2	30.7	34.7
31	400	200	2,000	36.3	36.2	43.1	36.9	34.1
27	400	400	1,000	39.7	38.4	48.0	37.0	35.1
3	500	150	750	39.8	37.5	35.5	34.3	34.7
7	500	150	1,250	35.4	38.8	43.5	37.1	32.1
4	500	250	750	41.0	37.3	43.8	34.4	36.2
8	500	250	1,250	36.6	38.4	44.6	35.4	33.8
11	600	100	500	34.0	30.0	43.8	37.2	35.3
15	600	100	1,500	36.9	36.6	42.3	35.9	35.1
12	600	300	500	34.2	37.8	40.6	34.7	32.2
16	600	300	1,500	39.2	35.9	41.2	38.1	34.8

[1] Project 1530 of the Iowa Agriculture and Home Economics Experiment Station.

[2] Assistant professor and professor and head, Department of Agronomy.

Table 1. (cont.)

Treatment number	Element applied (lb./acre) K	P	Ca	Yield (bu/acre) 1961 Ch[a]	Bl	Hr	Hk	1963 Ch
19	800	0	0	32.2	31.7	36.7	33.9	32.5
23	800	0	2,000	27.6	30.7	40.8	33.2	32.8
29	800	200	1,000	37.4	35.9	44.7	35.9	36.0
20	800	400	0	34.7	35.0	45.2	35.4	34.1
24	800	400	2,000	33.5	35.5	45.4	40.0	34.2
CARRINGTON-CLYDE FARM								
9	0	0		34.5	32.3	41.2	31.7	
16	0	200		33.6	31.5	37.2	36.7	
10	0	400		35.0	33.9	38.8	32.5	
20	100	200		35.9	34.6	37.8	32.3	
5	200	100		35.6	36.5	40.7	39.1	
6	200	300		33.7	34.9	39.6	33.7	
1	300	150		35.3	34.1	41.1	33.2	
2	300	250		33.7	35.7	41.8	36.3	
14	400	0		30.9	33.4	39.9	34.7	
18	400	50		32.7	36.8	37.2	36.2	
13	400	200		31.3	35.9	39.4	36.6	
19	400	350		33.3	33.4	41.5	33.2	
15	400	400		34.2	37.3	39.1	37.5	
3	500	150		32.8	35.3	41.2	38.2	
4	500	250		32.7	34.5	40.0	35.7	
7	600	100		31.1	35.8	41.0	32.9	
8	600	300		30.1	34.9	38.1	32.6	
21	700	200		29.1	35.0	38.1	31.9	
11	800	0		28.7	30.6	32.9	32.6	
17	800	200		31.4	34.1	35.3	36.0	
12	800	400		26.2	33.7	35.6	31.9	

[a]Ch = Chippewa; Bl = Blackhawk; Hr = Harosoy; Hk = Hawkeye.

A split-plot technique was used at both locations, with random allocation of the fertilizer treatments to the whole plots within each block. The two blocks were laid out so as to remove as much variation due to slope position as possible. The varieties Ch, Bl, Hr, and Hk mature in this order and were allotted to the subplots in this or reverse order at random. The two outside varieties were bordered by their own kind.

The field trial located on the Howard County Experimental Farm in 1961 was laid out on Cresco loam. The site had been under alfalfa since 1959. The main-plot size was 21 x 40 feet, which accommodated four experimental rows (the subplots) and two border rows 40 feet long.

The amount of fertilizer applied per acre covered the range from 0 to 400 lb. of P by 50-lb. increments, 0 to 800 lb. of K by 100-lb. increments, and 0 to 2,000 lb. of Ca per acre by 250-lb. increments. P was applied as concentrated superphosphate (20% P), K as potassium chloride (50% K), and Ca as barn lime (finely ground 99% calcitic limestone). The P and K and one-fourth of the Ca were applied about 2 weeks before planting and plowed under. The remainder of the Ca was then spread and disked in separately to reduce the possibility of P fixation. The field was wheel-hoed twice, hand weeded, and cultivated several times. Two feet of row were sampled at the end of flowering. The content of N, P, K, Ca, and Mg was determined on the leaflets after drying and grinding. Maturity data and degree of lodging were recorded. Sixteen feet of each experimental row were harvested to measure yield on Oct. 16. Two years later, after an intervening crop of corn, which was fertilized with 150 lb. per acre of 5-20-20 starter fertilizer, the area was planted to Chippewa soybeans. Leaf samples again were collected at the end of flowering, this time by collection of 12 plants at random over 40 feet of row in every main plot. Sixteen feet, from an adjoining row in the same main plot, were harvested for grain yield.

The initial soil-fertility level at the Howard County Farm was evaluated from soil samples taken from six sites in the experimental field and at two depths (0-6 inches and 6-12 inches) before fertilization (table 2). Three of the sites were situated in the first replication, and three in the second. Each sample was a composite of three borings about 10 feet apart. The soil analyses were carried out at the Iowa State University Soil Testing Laboratory. The soil testing methods have been described by Hanway and Heidel[3]. P tested very low (less than 2.5 pp2m P) in the surface soil over most of the field. A portion of the area had a P test of 3.5 pp2m, in the low range, but sometimes considered the upper limit for yield response in soybeans. K was low over the entire trial field, although twice as high in the surface soil of replication I as in replication II where it was approximately 50 pp2m. Nitrifiable N tested low in the surface soil and varied from 63 to 96 pp2m. It was even lower in the subsurface layer (24 to

[3]J.J. Hanway and H. Heidel. Soil analysis methods as used in the Iowa State College Soil Testing Laboratory. Agron. 57. (Mimeo.) Coop. Ext. Serv., Agronomy Department, Ames, Iowa. 1957.

Table 2. Soil-test values from soil samples taken at two locations before fertilization in 1961, expressed as pH and pp2m N, P, and K[a].

Replication	Site	Depth (inches)	Howard County Farm pH	N	P	K	Carrington-Clyde Farm pH	N	P	K
I	1	0-6	5.7	87	2.0	112	6.8	96	6.5	108
		6-12	5.7	57	1.0	84	6.1	48	2.0	96
	2	0-6	5.4	84	3.5	68	6.8	78	4.0	92
		6-12	5.5	56	2.5	60	6.0	45	1.5	80
	3	0-6	5.4	84	3.5	104	6.1	87	6.0	136
		6-12	5.4	42	1.5	60	5.9	45	1.0	128
II	1	0-6	5.9	81	1.5	52	6.3	81	4.0	100
		6-12	5.3	30	0.5	44	6.2	63	2.0	108
	2	0-6	5.8	63	1.0	48	6.2	84	5.0	100
		6-12	5.6	24	1.0	52	6.3	75	2.0	88
	3	0-6	6.6	96	2.5	48	6.8	84	6.0	108
		6-12	5.7	27	1.0	52	6.6	45	1.0	100

[a]P soil-test values up to 7.5 pp2m, K values to 130 pp2m, and N values to 100 pp2m are in the low range; P values from 8 to 18 pp2m, K values from 130 to 250 pp2m, and N values from 100 to 150 pp2m are in the medium range.

57 pp2m). The soil reaction was acid, with most pH values between 5.4 to 5.7 and a range from 5.3 to 6.6. Site numbers 1, 2, and 3 in table 2 indicate relative positions within each replication along a line from east to west.

Two years later, after harvest of the 1963 Chippewa crop, composite soil samples were taken from each main plot at a depth of 0-12 inches. The soil-testing methods used were somewhat different from those used in 1961. Field-moist soil was used for all tests. Mineralizable N was determined by a method described by Waring and Bremner (29): Five grams of soil and 10 ml of water are incubated under anaerobic conditions for one week. The NH_4^+ content of an unincubated and an incubated sample are determined by steam distillation. The soil pH was read with a glass electrode in a 1:2 soil-water suspension. Soil P was extracted in a 1:10 dilution ratio with the Bray and Kurtz No. 1 phosphorus extractant (0.03*N* NH_4F and 0.025*N* HCl) and determined colorimetrically by using an ammonium molybdate solution and a reducing agent made up of 1-amino-2-naphthol-4-sulfonic acid, sodium sulfite, and sodium pyro sulfite. K was extracted from the soil in a 1:5 dilution ration with *N* ammonium acetate and determined by a flame photometer. The results clearly reflect the fertilization of 1961, even after a crop of corn in 1962 and a crop of soybeans in 1963 (table 3).

The field trial located at the Carrington-Clyde Experimental Farm in 1961 was laid out on an area of Floyd silt loam. The rates of fertilization were the same as in the Howard County experiment, except that no Ca was applied and that the fertilizer was disked in rather than plowed under. The experiment was planted on May 26. Layout of the experiment, management, sampling, and harvesting largely followed the same procedures as in the Howard County trial in 1961. All four varieties were sampled twice at short intervals at about the end of flowering. The first sample was taken when the varieties Ch and Bl had reached this stage. The second sampling, 9 days later, was chosen as an approximation for the other two varieties to reach this stage of development.

The initial fertility of the area was low, as follows from the data in table 2. P tested low (4-6 pp2m) in the surface and very low (1-2 pp2m) in the subsoil. K also was low in the surface (100-136 pp2m) and somewhat lower in the subsoil. The pH was between 6.1 and 6.8 in the surface 6 inches of soil and slightly lower in the subsurface layer.

Chemical analysis of the ground, plant material for P and K followed the analytical procedures described by Hanway (15): Dried and ground plant samples of 0.5 g were digested in concentrated H_2SO_4 with Cu as a catalyst. P was determined colorimetrically by a vanadomolybdate method. K was determined flame photometrically with Li as an internal standard. N was determined on an aliquot from the same digest by steam distillation of NH_3 from an aliquot made alkaline with NaOH. The NH_3 was trapped in boric acid and titrated with H_2SO_4. Ca and Mg were also determined on the same sulfuric-acid digest by a modification

Table 3. Soil test values from soil samples taken in 1963 to a depth of 12 inches at the Howard County Experimental Farm 2 years after fertilization, expressed as pH and pp2m N, P, and K[a].

Treatment number[b]	Replication I				Replication II			
	pH	N	P	K	pH	N	P	K
1	6.00	59	50	141	6.28	35	43	94
2	6.09	26	76	114	6.28	35	81	97
3	5.72	35	36	216	6.03	37	33	140
4	6.16	30	56	162	6.25	18	57	101
5	5.91	46	38	132	6.08	32	32	103
6	6.27	28	79	118	6.42	32	48	96
7	6.23	31	42	162	6.25	34	29	134
8	5.95	39	48	125	6.28	36	56	133
9	5.94	39	22	93	6.43	27	35	78
10	5.87	36	45	84	6.06	25	83	78
11	6.26	30	46	214	5.95	20	26	108
12	5.90	28	59	235	6.12	28	59	176
13	5.97	37	31	86	6.57	19	37	86
14	6.19	37	66	104	6.66	24	100	98
15	6.23	35	22	147	6.32	20	36	156
16	6.07	41	70	214	6.27	26	65	111
17	5.85	33	15	74	5.95	34	16	52
18	5.74	29	94	63	5.78	29	61	64
19	5.51	28	13	229	6.06	33	20	189
20	5.35	39	100	291	5.79	29	73	181
21	6.21	25	20	71	6.46	25	14	65
22	6.20	44	98	57	6.70	28	94	49
23	6.60	28	15	250	6.72	15	15	199
24	6.65	29	92	250	6.60	38	80	213
25	5.95	38	39	108	6.00	38	50	145
26	5.98	33	20	157	6.40	36	21	116
27	5.93	27	99	153	6.10	18	67	108
28	5.93	26	50	60	6.20	34	35	63
29	5.62	20	56	266	6.39	39	32	261
30	5.71	23	46	106	6.15	35	61	88
31	6.42	27	64	146	6.30	45	24	93

[a]P soil-test values up to 25 pp2m, K values to 125 pp2m, and N values to 80 pp2m are in the low range; P values from 26 to 45 pp2m, K values from 126 to 200 pp2m, and N values from 80 to 120 pp2m are in the medium range.

[b]See table 1 for treatments applied in 1961.

of the method described by Ward and Johnston (28). Fifty milliliters of digest were heated until dry on a hot plate. Upon cooling, the residue was dissolved in 5 ml of 6*N* HCl and diluted to 100 ml. Ca and Mg were determined on 10- or 20-ml aliquot diluted to 200 ml with deionized water to avoid phosphate interference during titration. The titration with disodium dihydrogen ethylenediaminetetraacetate (EDTA) followed the procedure of Ward and Johnston, wherein Mg content is found from the difference of the amounts of EDTA used for Ca plus Mg and for determination of Ca. Eriochrome Black T dissolved in triethanolamine (2) was used as an indicator for the Ca-plus-Mg determination. A calcein-thymolphtalein solution was used as an indicator for the calcium end point as described by Tucker (26).

Oil and protein content were determined on ground soybean material at the U.S. Regional Soybean Laboratory, Urbana, Illinois.

Statistical Methods

The statistical analysis followed the principles given by Anderson and Bancroft (1). Other procedures used have been described in detail by Snedecor (25) and Williams (30). The quadratic form of the multiple-regression equation was used to relate each of the dependent variables (yield of soybeans, the dry-weight production of various plant parts, and any relevant growth characteristics for which quantitative measurements were recorded) in turn to the fertilizer input factors.

The equation fitted to the data in most instances was of the form

$$Y_i = b_0 + b_1P + b_2K + b_3Ca + b_{11}P^2 + b_{22}K^2 + b_{33}Ca^2 + b_{12}PK + b_{13}PCa + b_{23}KCa + b_{123}PKCa \quad [1]$$

where the elements refer to those applied as fertilizer or limestone. Ca was not involved as a variable in the field experiment at the Carrington-Clyde Experimental Farm, and the model was reduced accordingly.

The rates of application given in table 1 served as the design matrix after correction of the calcium rates for the amount of calcium contained in the phosphate application. The assumption was thereby made that the two sources of calcium were equally available to the plant.

The yield of soybeans as a dependent variable can be similarly expressed as a function of the chemical composition of a certain plant part or a combination of terms from several plant parts. In our study, soybean yield, weight of roots, plant tops, and leaves served as the dependent variables in this type of relationship. The independent variables were entered as deviations from their overall means to avoid computational difficulties in obtaining an inverse matrix. The model fitted to the percentage content of five nutrients in the plant tissue was of the form

$$Y_1 = b_0 + b_1P + b_2K + b_3Ca + b_4Mg + b_5N + b_{11}P^2 + b_{22}K^2 + b_{33}Ca^2 + b_{44}Mg^2 + b_{55}N^2 + b_{12}PK + b_{13}PCa + b_{14}PMg + b_{15}PN + B_{23}KCa + b_{24}KMg + b_{25}KN + b_{34}CaMg + b_{35}CaN + b_{45}MgN \quad [2]$$

Miller (21) analyzed various plant parts at several stages of development to determine the best correlation with soybean yield. The relationships, based on chemical composition at the end of flowering, were as good or better than at other developmental stages, and the upper leaves and petioles could be used equally well. He also compared the square-root and quadratic forms of regression equations and found little reason for preference under the conditions. In our present work, leaf composition at the end of flowering was used to express the relationships between yield and composition of the plant.

The computation of the X'X matrix, the X'Y products, the elements of the inverse matrix, the partial regression coefficients, their standard deviations, and the value of t to test the null hypothesis that the partial-regression coefficients are equal to 0 was performed on an IBM-7074 computer at the Iowa State University Computation Center.

The general procedure was to obtain similar equations for each variety in the experiment. Sets of analogous partial regression coefficients can then be tested for differences among them by F-tests (Williams, 30). The difference between a partial regression coefficient for a certain fertilizer effect in a regression equation and a corresponding coefficient from a similar equation for another variety amounts to a measure of differential response since it expresses the amount by which the effect of a fertilizer factor on one variety fails to be the same as for another variety. Therefore, it seems justified to introduce "error b" from the analysis of variance as the denominator in the F-test when dealing with split-plot designs rather than introducing the combined deviations from regression as proposed by Williams. The general formula to calculate the mean square for the numerator in the F-test is

$$MS = ({}_r\Sigma b_{ri}{}^2/t_r{}^{ii} - b_i{}^2{}_r\Sigma 1/t_r{}^{ii})/m-1 \quad [3]$$

where t_r^{ii} is the c_{ii} element for the rth set, b_i is the weighted mean of the coefficients b_{ri}

$$b_i = ({}_r\Sigma b_{ri}/t_r{}^{ii})/({}_r\Sigma 1/t_r{}^{ii}) \quad [4]$$

and m is the number of sets of data. In the special case where the t_r^{ii} are the same in each set, and with four sets, the formula simplifies to

$$MS = ({}_r\Sigma b_{ri}{}^2 - 4b_i{}^2)/3c_{ii} \quad [5]$$

where b_i is the mean of the coefficients b_{ri}.

Where only two varieties are involved, the difference in response between varieties was tested by the t-test by using the formula

$$t = (b_{1i} - b_{2i})/(c_{ii}\, s_e{}^2 2)^{1/2} \quad [6]$$

where s_e^2 denotes the experimental error from the analysis of variance. This t-test is identical with Williams' F-test when two varieties are being compared.

Combination of individual regression equations can be carried out unless heterogeneity of variance is indicated by Bartlett's test (25, p. 286). To develop a combined equation for the four varieties, some arbitrary decisions have to be made with regard to the significance level required for factors to enter the equation.

Terms were selected when the coefficients for one or more varietes reached significance at the 0.20 level of probability or better in a t-test. If differences appeared among the four varieties with respect to any factor at the 0.25-probability level in an F-test on the deviations of the individual partial-regression coefficients from their mean, then that factor was replaced by four terms representing its interaction with the individual varieties. This allows a final test on the significance of varietal differences in the combined equation.

Duncan's multiple-range procedure (10) can be adapted to test the differential responses expressed by the difference between partial regression coefficients. A standard error can be computed by using the quantity

$$s_{b_i - b_i}' = s_{eb}(c_{ii/2} - c_{ii}' + c_i'{}_i'/2)^{1/2} \qquad [7]$$

as standard error, where s_{eb}^2 represents error b of the analysis of variance of the split-plot design. The c_{ii} and $c_i'{}_i'$ are the inverse matrix elements for the interactions of an independent variable on a variety basis and the associated dummy variable. The required off-diagonal c_{ii}' elements are known since the combined regression equation is used for this test on differential responses.

When the independent variables represent fertilizer treatment combinations or soil fertility values applying to whole plots, the inverse elements for comparison of any two varietal regression coefficients in a set of b_i are equal and the computations are simplified. Duncan's multiple-range test provides a check on the conclusions based on Williams' F-test and specifies the varieties that actually differ in a particular response.

To arrive at final equations, further terms were deleted upon inspection of the individual t-values in the combined regression by using the same criterion as before. Linear terms were maintained when the factor also occurred in a qualifying interaction term. Partial regression coefficients were expressed on the basis of 100-lb. units of P, K, and Ca per acre applied for all equations designated as final equations. Elsewhere, the coefficients are based on the coded treatment combinations of the statistical design used.

Production surfaces and isoquants were calculated by using the partial-regression coefficients of the fitted regression equations (16). A vertical projection of the isoquants was used to illustrate the magnitude of responses and differential responses over the range of fertilizer input. Isoquant curves may be of one of three types, depending on the terms deleted from the full model and on the signs of the partial-regression coefficients for quadratic terms. The graph of a quadratic equation is either elliptic, hyperbolic, or parabolic. It is elliptic when two squared terms of the same sign are involved, hyperbolic if they have unlike signs, and parabolic if one squared term is deleted from the equation. Ellipsoidal production surfaces are often preferred because they reflect the decrease in yield known to exist at excessive levels of nutrient input. They require that quadratic terms be retained, irrespective of their significance. On the basis of previous knowledge or assumed behavior of the variable, it may be desirable to restrict deletion of squared terms to the case where none of the terms containing that factor is of any consequence, and all can be deleted.

In cases involving the yield of soybeans, this reasoning was followed to retain the squared terms for P and K. Actually, a downward trend may not follow at once after maximum production is reached, and the question of whether a quadratic term should be maintained or deleted can be resolved satisfactorily only by testing a wider range of models. In most instances, all three forms of production surfaces are acceptable provided that no attempt is made to extrapolate outside the area investigated, a procedure for which quadratic polynomials are notoriously untrustworthy.

The lines of intersection between production surfaces for comparable quantities, Y_i and Y_j, expressed in the same units, may be determined from isoquant maps. Their projection on the horizontal plane delineates the area of fertilization where the surface for quantity Y_i is above that for quantity Y_j (i and j may represent different varieties or dates of sampling).

Isoquant maps may be further used to provide the approximate location of the fertilizer combination required for maximum production. For an exact solution, partial derivatives of the production equation are taken with respect to each of the nutrients. These are set equal to 0 and solved simultaneously. An approximate graphical solution may be obtained from interpretation of isoquant maps produced by an IBM 7074 computer plotter. For two-variable designs, the solution is immediate. For three or more variables, the point is approached by plotting Y_i as a function of two variables at a time, holding the others at a certain value, in an iterative procedure. This method was adopted here and may be used to special advantage in quadratic equations or certain higher-order models in which the computations become tedious.

Critical nutrient percentages were computed by using the graphically estimated fertilizer combinations for maximum production by substituting these values into each of the multiple-regression equations expressing the nutrient content of the leaves as a function of factors of fertilization. The solutions form a set of critical percentages valid under the experimental conditions. Methods have not been fully developed for calculating the standard error of these estimates. Fuller (14) described an iterative procedure to set confidence limits on input factors associated with a given yield for production functions involving two factors. His method could be expanded for three or more variables and would then apply to equations expressing crop yields as a function of the content of several nutrients in the leaves.

As will be shown later, such multiple-regression relationships involving three or five nutrients were not satisfactory. For this reason, the alternative procedure described earlier was adopted for determining critical percentages. To arrive at a standard error for this procedure, it would be necessary to use the confidence intervals on the input factors as a basis for estimating a corresponding range in critical nutrient percentages. This would add to the size of the standard error associated with the critical nutrient percentage. A method to estimate the reliability of such derived functions could be designed, but would be iterative, and the computations would require the use of a computer.

RESULTS AND DISCUSSION

Experiment at the Howard County Experimental Farm

Yield of soybeans as a function of fertilizer variables

The yields of the four varieties are shown in table 1. The multiple regression of yield on the fertilizer input variables was run for each variety, and the partial-regression coefficients were tested by using deviations from regression. Analysis of variance of the regressions showed that the yield of all varieties was strongly affected by fertilization ($P \leq 0.01$). The regression equation for each of the four varieties presented in table 4 presents a case of a strong effect of K on the yield of soybeans. The effect of P was statistically insignificant despite the low P status of the soil. More detailed analysis showed that a P x K interaction effect existed, which will be discussed later. This fact is also borne out by the data presented in table 1 and figures 1 and 2. The response to 100 lb. of K was of the order of 4 bu per acre.

The residual effect of fertilization after 2 years can be assessed from the 1963 results for the variety Ch. Ignoring the possible effect of seasonal differences, the two sets of coefficients are clearly related (table 4). The linear effects of P and K were reduced to 1/2 and 1/3, respectively, whereas that of Ca was 6.5 times larger. The residual effect of 250 lb. of P applied with a basal rate of 400 lb. of K per acre was 0.6 bu compared with 2.2 bu in the year of application. The K applied in 1961 still had a significant effect on the yield of soybean grown 2 years later. The residual effect of 400 lb. of K applied with a basal rate of 250 lb. of P/acre was 4.5 bu compared with 13.4 bu in the year of application. Ca applied at the rate of 1000 lb. per acre had little effect the first year, but raised the yield of Chippewa by 2.4 bu 2 years later. This agrees with the notion that responses to liming do not develop fully in the year of application. In agreement with this, the residual P x K interaction effect was smaller, and the P x Ca interaction effect was stronger than in the year of fertilization.

Williams' (30) procedure, when applied to sets of four corresponding partial-regression coefficients, showed no significant differences among the varieties when unfertilized or in varietal yield response to fertilizers at the 0.05 level. There was a dif-

Table 4. Partial regression coefficients relating the yield of the Chippewa, Blackhawk, Harosoy, and Hawkeye varieties grown at the Howard County Experimental Farm to fertilization[a].

	1961				1963
Factor	Chippewa	Blackhawk	Harosoy	Hawkeye	Chippewa
b_0	26.8735**	27.6679**	32.2739**	28.0515**	27.6787 **
P	0.5984	−0.0641	−1.4656	−0.1641	0.2722
K	4.6481**	4.2422**	3.8066**	4.0443**	1.5685**
Ca	0.1688	0.4443	1.0302	−0.6774	1.1003
P^2	−0.1628+	−0.0001	0.1409	−0.0080	−0.0439
K^2	−0.5304**	−0.4991**	−0.4295**	−0.4205**	−0.1352++
Ca^2	−0.0030	−0.0245	−0.1296	0.0659	−0.1133+
PK	0.1634+	0.0847	0.1530	0.0351	0.0183
KCa	−0.0897	−0.0248	0.0770	0.0039	−0.0152
PCa	−0.0146	−0.0808	0.0386	0.0485	−0.0370
PKCa	0.0107	0.0114	−0.0070	0.0036	0.0095
R^2	0.6149	0.5776	0.4271	0.4020	0.5175

[a] The symbols **, *, ++, and + indicate the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

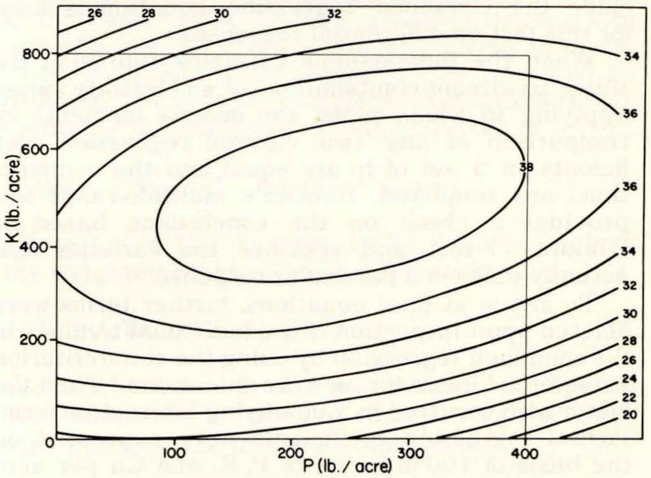

Fig. 1. Yield isoquants derived from the final equation for the variety Chippewa grown at the Howard County Experimental Farm, expressed in bushels of soybeans per acre and with applied P and K as variables.

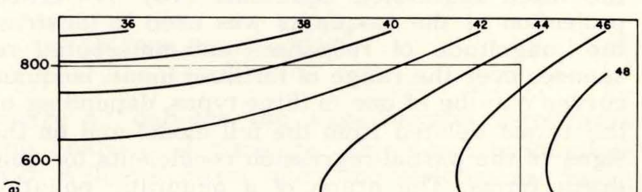

Fig. 2. Yield isoquants derived from the final equation for the variety Harosoy grown at the Howard County Experimental Farm, expressed in bushels per acre and with applied P and K as variables.

ference in the quadratic effect of P at the 0.10 level. This difference can be related to the nonconformity of Hr in this respect. It had a positive regression coefficient for P^2, whereas the others were negative.

The results permit combination of the yield equations for the four varieties as

$$Y = b_{0Ch}Ch + b_{0Bl}Bl + b_{0Hr}Hr + b_{0Hk}Hk + b_1P + b_2K + b_{11Ch}P^2Ch + b_{11Bl}P^2Bl + b_{11Hr}P^2Hr + B_{11Hk}P^2Hk + b_{22}K^2 + b_{12}PK \quad [8]$$

Tests on the coefficients involving varieties were made by using error b of the analysis of variance. Fertilizer effects were tested by using error a. The resulting equation for all data combined is:

$$Y = 28.2001Ch^{**} + 27.9833Bl^{**} + 32.7752Hr^{**} + 27.1826Hk^{**} - 0.2256P + 4.2172K^{**} - 0.0460P^2Ch - 0.0249P^2Bl + 0.0148P^2Hr - 0.0004P^2Hk - 0.4785K^{2**} + 0.1320PK^{**} \quad [9]$$

In addition to the K and K^2 effects, which were recognized before, the P × K interaction now shows a highly significant effect. Differences involving varieties were compared by Duncan's multiple-range test. The high yield level of Hr differed from the other varieties at the 0.01-probability level. The varieties Hr and Ch differed in response to the P^2 factor at the 0.05 level.

The final yield equation for each variety is shown in table 5. The significance of the partial regression coefficients was tested by using the experimental error from analysis of variance.

Isoquant maps were drawn for the varieties Ch and Hr by using these yield-prediction equations. Differences between figs. 1 and 2 express the largest differential effects existing among the four varieties in response to P application. For example, at 500 lb. of K per acre, the response to 250 lb. of P per acre is of the order of 2 to 3 bu for Ch and 1 to 2 bu per acre for Hr. Clearly, the differential yield responses were significant, but of small order.

Table 5. Partial regression coefficients, b_i, of final yield equations for individual varieties at the Howard County Experimental Farm, expressed in bushels per 100 lb. of P and K applied per acre[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	27.4896**	28.7470**	32.5834**	27.3216**
P	1.0422	−0.6554	−1.7656	−0.4258
K	4.2909**	4.2108**	4.5142**	3.8525**
P^2	−0.6400	−0.0604	0.3624	0.1116
K^2	−0.5315**	−0.5087	−0.4788**	−0.3949*
PK	0.4112	0.2800+	0.2564+	0.1084
R^2	0.6058	0.5670	0.4072	0.3762

[a]The symbols **, *, and + refer to the 0.01, 0.05, and 0.20 significance levels, respectively.

Figure 1 shows that the yield of Ch was reduced by as much as 6 bu when the P application was raised from 0 to 400 lb. without K application. The original data suggested an even stronger yield depression from P-induced K deficiency for this variety than is expressed by the equation (table 1). Benefit from P fertilization was obtained only at high rates of K application because of the significant effect of the P x K interaction.

The combination of P and K fertilization for maximum yield of Ch was approximately 250 lb. of P and 500 lb. of K per acre, amounts unlikely to be applied in practice. The rate of K application leading to the maximum yield of soybeans at an arbitrary rate of 250 lb. of P per acre can also be calculated by taking the partial derivative of the individual prediction equations with respect to K, substituting the appropriate value for P, and equating to 0. In this instance, the rates of K for maximum yields of the varieties Ch, Bl, Hr, and Hk were 500, 483, 538, and 522 lb. per acre, respectively. At low rates of K application, the yield responses were small. One-hundred pounds of K per acre (equivalent to 201 lb. of potassium chloride) raised the yield by approximately 4 bu. Under existing crop-rotation practices, the effective quantity of K applied may be only a fraction of this amount, and this could explain why some soybeans fail to respond to fertilization and yet yield better on land of high natural fertility.

Leaf composition as a function of fertilizer variables

Percentage P in the leaves: A multiple-regression equation expressing the percentage P in the leaves as a function of the fertilizer variables of equation 1 was derived for each variety. The partial regression coefficients listed in table 6 show that the percentage P in the leaves was affected by P and K application. Also, the P x K interaction effect reached significance at the 0.01 level for two varieties. The varieties Ch and Hk seemed to differ in response to K application, but F-tests on the partial regression coefficients showed a lack of differential response among the varieties. Only the coefficients for the P x K x Ca interaction term differed at the 0.25-probability level. Therefore, it seems that the differential yield responses due to P application are not supported by differential responses in percentage P. Possibly, the total P content of the leaves may be differentially affected rather than the percentage. The chemical composition, however, was evaluated for only one organ, the leaves, and at one particular time. The results might have been different if other plant parts and stages of development had been considered. Indirect effects from P form a possibility also. The differential response to P might have been caused primarily by the effect of P on the uptake of other elements or by some other growth-controlling mechanism in the plant.

The original data on percentage P in the leaves of the four varieties (table A-1) can be combined into the equation

$$\text{Percentage } P = b_0 + b_1P + b_2K + b_3Ca + B_{11}P^2 + b_{22}K^2 + b_{33}Ca^2 + b_{12}PK + b_{13}PCa \quad [10]$$

where the elements refer to those applied to the soil. The partial regression coefficients of the equation were tested by using the relevant error terms from analysis of variance. The significance of the various terms agreed with the earlier analysis for the individual varieties.

Differential responses to the P x K x Ca interaction were compared by Duncan's multiple-range test. The variety Bl differed from all other varieties in its response to the P x K x Ca interaction effect. The difference reached the 0.01 level of probability when Bl is compared with Hr and Hk. The final equation of the percentage P for each variety is given in table 7.

The contour map of the percentage P in the leaves of Ch as a function of P and K applied at Ca = 0 is reproduced in fig. 3. In the absence of considerable differential response, similar graphs for the other varieties had a similar shape. The contours show higher P percentages with increasing rate of P application up to the limit of the investigated range. At low levels of K, this effect was very strong. At high rates of K, the rise in percentage P leveled off when the rate of P application exceeded 200 lb. per acre. As was seen in fig. 1, this is the area of maximum yield of soybeans.

Table 6. Partial regression coefficients relating the percentage P in soybean leaves at the end of flowering at the Howard County Experimental Farm to fertilization[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	0.32815**	0.34238**	0.32431**	0.31659**
P	0.02989**	0.01970**	0.02743**	0.02534**
K	−0.01803*	−0.01488*	−0.01065+	−0.00675
Ca	0.01080+	0.00041	0.00613	0.00748
P^2	−0.00075	−0.00115++	−0.00114+	−0.00149*
K^2	0.00217**	0.00156*	0.00158*	0.00117++
Ca^2	−0.00112+	−0.00001	−0.00092	−0.00055
PK	−0.00219**	−0.00071	−0.00188**	−0.00069
KCa	−0.00009	−0.00015	0.00045	−0.00016
PCa	−0.00072	0.00016	0.00086+	0.00040
PKCa	0.00013	0.00005	−0.00008	−0.00007
R^2	0.7380	0.6459	0.7533	0.6706

[a] The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

Table 7. Partial regression coefficients, b_i, of the final equations for the percentage P in soybean leaves at the Howard County Experimental Farm at the end of flowering, expressed as percentage P per 100 lb. of P, K, and Ca applied per acre[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	0.34067**	0.34235**	0.31443**	0.31683**
P	0.06042**	0.04068*	0.06738**	0.05732**
K	−0.01502+	−0.01546+	−0.00592	−0.00567
Ca	−0.00023	0.00015	0.00066	0.00132
P^2	−0.00496	−0.00452	−0.00576	−0.00668+
K^2	0.00173+	0.00155+	0.00122	0.00095
PK	−0.00306*	−0.00140	−0.00446**	−0.00150
PKCa	--	0.00004	--	−0.00006
R^2	0.7081	0.6434	0.7395	0.6628

[a] The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

Percentage K in the leaves: The K content of the leaves (table A-1) was strongly affected by K fertilization, and this effect was distinctly curvilinear. Multiple-regression equations for the percentage K in the leaves showed significant K and K^2 terms for all varieties at the 0.01 level, except for a 0.05-level test of the K^2 term for Hr. Comparison of corresponding partial-regression coefficients between varieties showed that the four varieties differed in their response to K. In accordance with these results, the following regression equation was computed for the combined data

$$\text{Percentage K} = 0.9822^{**} - 0.0331P^{+} + 0.2826KCh^{**} + 0.3208KBl^{**} + 0.2231KHr^{**} + 0.3458KHk^{**} - 0.0233Ca^{*} + 0.0043P^{2++} - 0.0209K^2Ch^{**} - 0.0253K^2Bl^{**} - 0.0144K^2Hr^{**} - 0.0390K^2Hk^{**} - 0.0009KCa - 0.0043PCa^{**} \quad [11]$$

In this equation, the partial-regression coefficient for Ca reached the 0.05 level of significance, whereas it had no significance in the original equations. The coefficients for the P, P^2, and P x Ca terms gained in significance. Duncan's test on the coefficients for K and K^2 showed differential responses between Hk and Hr and also between Bl and Hr at the 0.01 level of significance. Differences at the 0.05 level of probability occurred between Hk and Ch with respect to K and K^2 and between Hr and Ch with respect to K. The final equations for the percentage K in the leaves of each variety are given in table 8. Most of the Ca coefficients lost their significance and became positive as they were in the original equations. The intermediate equation 11 served to preserve the Ca term in the final equation for the variety Bl.

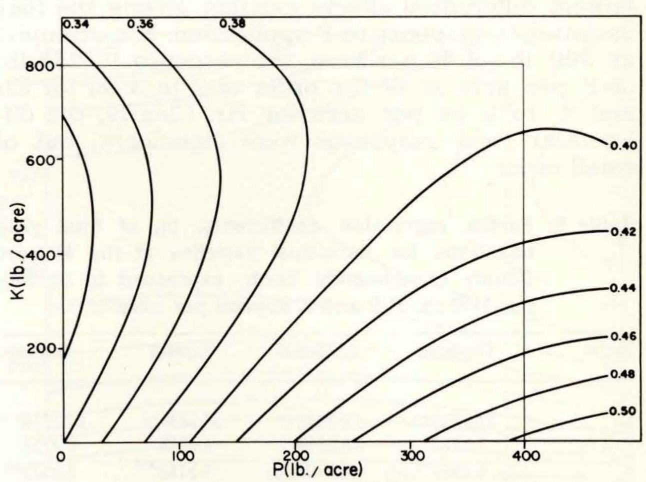

Fig. 3. Contours for the percentage P in the leaves at the end of flowering, derived from the final equation for the variety Chippewa at the Howard County Experimental Farm, with P and K applied as variables and holding the Ca application constant at 0 lb. per acre.

Table 8. Partial regression coefficients, b_i, of the final equations for the percentage K in the leaves at the end of flowering at the Howard County Experimental Farm, expressed as percentage K per 100 lb. of P, K, and Ca applied per acre[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	1.0271**	0.9579**	0.9611**	1.0448**
P	−0.1124	−0.0228	−0.0044	−0.1250+
K	0.2895**	0.2954**	0.2158**	0.3561**
Ca	0.0074	0.0147*	0.0050	0.0049
P^2	0.0256	0.0063	0.0111	0.0259
K^2	−0.0222**	−0.0229**	−0.0138**	−0.0307**
PCa	−0.0030	−0.0046++	−0.0043++	−0.0018
R^2	0.7950	0.8380	0.6782	0.8547

[a]The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

The contours reproduced in figs. 4 and 5 show that the rise in K content of the leaves leveled off with increasing rates of K at any level of P application. The decrease in percentage K at very high levels of K application is not real and is a result of fitting a quadratic function. The graphs for Hr and Hk illustrate the strongest differential responses existing among the four varieties. When no K was applied, the two varieties had about the same percentage K content in the leaves, but at almost any other point in the region of fertilization, the variety Hk had a higher content than did Hr. At a level of 250 lb. of P per acre, an application of 600 lb. of K caused an additional 0.8% K in Hr leaves and an additional 1.0% K in Hk leaves. The differential responses were therefore small despite their high level of significance.

Percentage N in the leaves: The N content of the leaves was little affected by fertilization (table A-1). The R^2 values for the multiple-regression equations were low, and F-tests on the significance of regression showed that an insignificant amount of variation at the end of flowering had been accounted for by the regressions for the varieties Hr and Hk. F-values of 2.46 and 1.73 for the varieties Bl and Ch were significant at the 0.05 and 0.25 level, respectively. It is mainly the effects from P and Ca application and their interactions that reached significance at the 0.20 level or better, and there was no conformity among the varieties in this respect. The low R^2 values indicate that other factors not considered exerted a more important influence on the percentage N.

One such factor may be identified from the 1963 data. The regression of the percentage N in Ch on fertilizer input variables accounted for little more variation than in 1961, and none of the coefficients reached the 0.05 level of significance. The regression of the percentage N on soil fertility values, on the other hand, indicated a significant influence of soil pH (equation 12).

$$\text{Percentage N} = 5.3296^{**} + 0.2690\text{pH}^{*} + 0.0026N_s - 0.0002P_s + 0.0008K_s^{++} - 0.7691(\text{pH})^{2*} - 0.0001(N_s)^2 - 0.0311\text{pH} \times N_s^{*} + 0.0031\text{pH} \times P_s + 0.0026\text{pH} \times K_s^{*} - 0.0001N_s \times P_s \quad [12]$$

The linear and quadratic components of the pH effect as well as the pH x N_s and pH x K_s interactions reached significance at the 0.05 level. The effect of pH on the N content of soybean leaves is presumably an indirect one. Since the N supply of soybeans is largely dependent on nodulation, the pH influence may possibly be one of control of the nodulation environment.

No differential responses in percentage N in the leaves were identified by F-tests, and the following equation was fitted to the combined data for all varieties:

$$\text{Percentage N} = b_0 + b_1P + b_2K + b_3Ca + b_{11}P^2 + b_{22}K^2 + b_{33}Ca^2 + b_{23}KCa + b_{123}PKCa \quad [13]$$

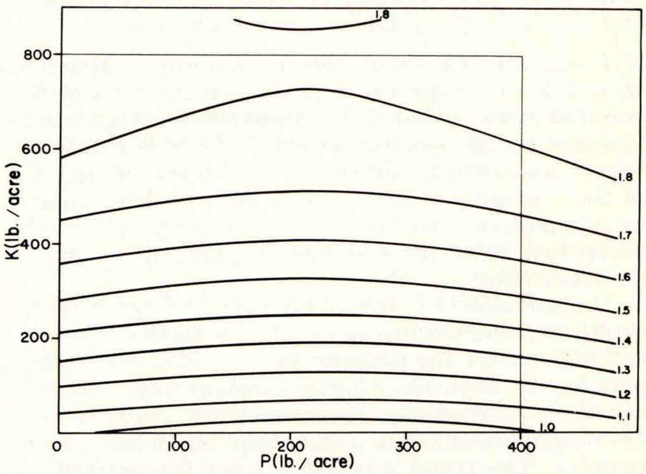

Fig. 4. Contours for the percentage K in the leaves at the end of flowering, derived from the final equation for the variety Harosoy at the Howard County Experimental Farm, with applied P and K as variables and holding applied Ca constant at 1,000 lb. per acre.

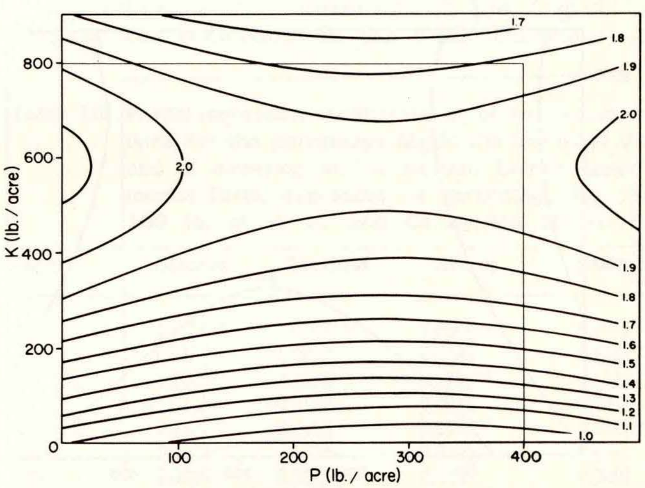

Fig. 5. Contours for the percentage K in the leaves at the end of flowering, derived from the final equation for the variety Hawkeye at the Howard County Experimental Farm, with applied P and K as variables and holding applied Ca constant at 1,000 lb. per acre.

The partial regression coefficients for the factors, K, K^2, K × Ca, and P × K × Ca did not reach 0.20-level significance. Deletion of these terms led to equation 14.

$$\text{Percentage N} = 5.0077^{**} - 0.0794P^{**} + 0.0421Ca^{+} + 0.0073P^{2*} - 0.0029Ca^2 \quad [14]$$

The value of R^2 for the equation is very low (0.085), but the F value of 5.64 for the test on the overall regression is more than sufficient for significance at the 0.01 probability level.

The dependence of the percentage N in the leaves of P and Ca application is illustrated in fig. 6, which applies to all four varieties. The contour lines show that the effect of P on the percentage N, although significant, is rather small.

Percentage Ca in the leaves: Ca application had no effect on the percentage Ca in the leaves of the four varieties (table A-2). Analysis of variance and multiple regressions showed that P and K fertilizers had a significant influence on the percentage Ca of the varieties Bl and Hk,P in a positive and K in a negative direction. The percentage Ca in the other two varieties was hardly affected by any of the treatments.

Similar effects have been reported by Nelson, Burkhart, and Colwell (24), who found that K application lowered the percentage Ca in the leaves and petioles of soybean plants considerably. Another relevant relationship found in their study was a downward trend in the percentage Mg in leaves and petioles. The trend was weak since the percentage Mg was already low. The percentage P was also somewhat depressed by K application. This also was found in our present study (fig. 3).

F-tests suggested that differential responses to K existed and almost reached 0.05 significance. The data were combined accordingly in the following equation

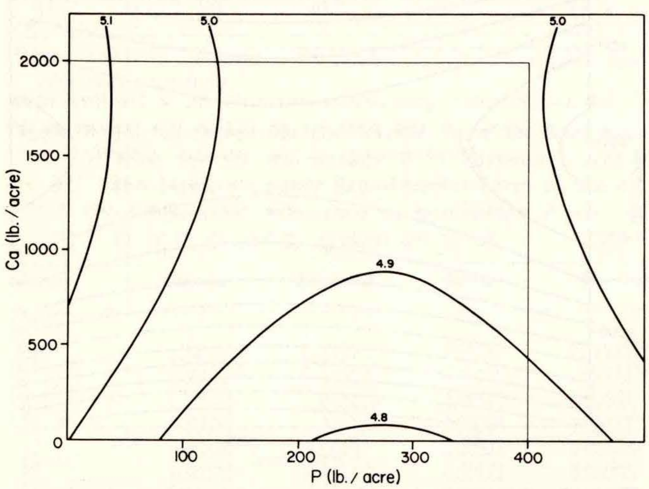

Fig. 6. Contours for the percentage N in the leaves at the end of flowering, derived from the final equation applying to all four varieties at the Howard County Experimental Farm, with applied P and Ca as variables.

$$\text{Percentage Ca} = 2.1474^{**} + 0.0692P^{**} - 0.0212KCh - 0.0280KBl^{+} - 0.1250KHr^{+} - 0.1254KHk^{**} + 0.0018Ca - 0.0046P^{2++} - 0.0001K^2Ch - 0.0010K^2Bl + 0.0008K^2Hr + 0.0092K^2Hk^{**} + 0.0016PCa \quad [15]$$

The significance level of the factors involved changed very little compared with the original equations. Duncan's multiple-range test on the coefficients for K and K^2 indicated that Ch differed from the other varieties with respect to the factor K and that Hk differed from the others with respect to the quadratic effect of K at 0.01 significance. The final equations for the percentage Ca in the leaves of individual varieties are shown in table 9. P and K effects reached 0.05 significance in nearly all instances. P^2 and K^2 were only significant for the percentage Ca in the variety Hk. The percentage Ca of the Hk variety increased with the amount of P applied, whereas it was reduced by any application of K (fig. 7).

Table 9. Partial regression coefficients, b_i, of the final equations for the percentage Ca in the leaves at the end of flowering at the Howard County Experimental Farm expressed as percentage Ca per 100 lb. of P, K, and Ca applied per acre[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	2.1113**	2.2470**	2.1518**	2.1109**
P	0.1534*	0.1405*	0.1160++	0.2038*
K	−0.0202*	−0.0510**	−0.0217*	−0.1230**
P^2	−0.0120	−0.0136	−0.0132	−0.0336++
K^2	--	--	--	0.0097*
R^2	0.5216	0.5432	0.2171	0.5576

[a] The symbols **, *, and ++ refer to the 0.01, 0.05, and 0.10 significance levels, respectively.

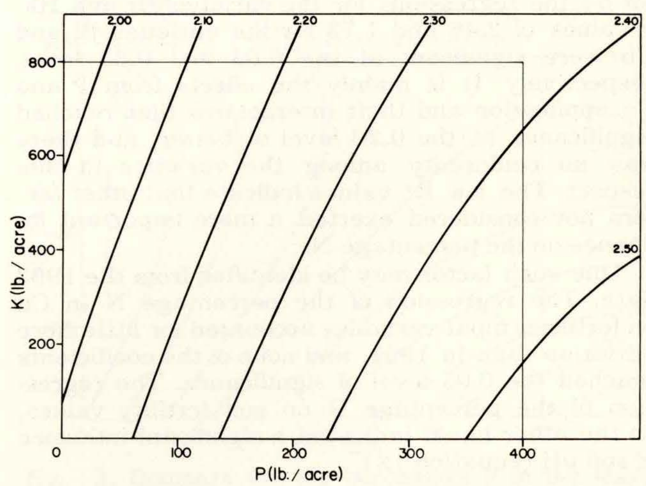

Fig. 7. Contours for the percentage Ca in the leaves at the end of flowering, derived from the final equation for the variety Hawkeye at the Howard County Experimental Farm, with applied P and K as variables.

The strongest differential responses in percentage Ca as a result of K fertilization occurred between the varieties Ch and Hk. As can be seen from figs. 7 and 8, the two varieties had practically the same Ca content when unfertilized. With higher rates of K and (or) P applications, the difference in percentage Ca between Ch and Hk increased, with Ch having the higher content. Application of 640 lb. of K with 300-lb. basal application of P per acre raised the Ca percentage of the variety Hk by an additional 0.1% and that of Ch by 0.4%; thus, the differential effect is three times stronger than is the response of Ch at this point in the investigated range. Even at this, the differential responses between varieties are of small order.

Percentage Mg in the leaves: The percentage Mg was very strongly and curvilinearly affected by K in all varieties. P had little effect, except through interaction with Ca for the varieties Bl and Hr at 0.05 significance. The K x Ca and P x K x Ca interactions had some effect at lower levels of significance in the same varieties. F-tests for differential responses reached 0.25 significance, suggesting some possibility of difference in percentage Mg in the leaves among varieties and differences in the linear and quadratic effects of Ca. The following regression equation was derived for the combined data on Mg content of the four varieties:

$$\text{Percentage Mg} = 1.1360\text{Ch}^{**} + 1.0422\text{Bl}^{**} + 1.0793\text{Hr}^{**} + 0.9538\text{Hk}^{**} + 0.0053\text{P} - 0.1870\text{K}^{**} - 0.0433\text{CaCh}^{**} - 0.0320\text{CaBl}^{*} + 0.027\text{CaHr}^{+} + 0.0022\text{CaHk} + 0.0152\text{K}^{2**} + 0.0033\text{Ca}^2\text{Ch}^{*} + 0.0017\text{Ca}^2\text{Bl} - 0.0039\text{Ca}^2\text{Hr}^{*} - 0.0019\text{Ca}^2\text{Hk} + 0.0021\text{KCa}^{+} + 0.0032\text{PCa}^{*} - 0.0003\text{PKCa}^{++} \quad [16]$$

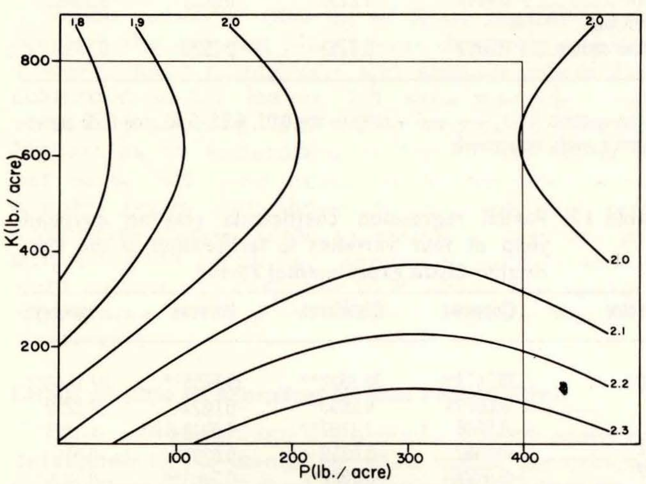

Fig. 8. Contours for the percentage Ca in the leaves at the end of flowering, derived from the final equation for the variety Chippewa at the Howard County Experimental Farm, with applied P and K as variables.

In addition to the highly significant K and K^2 effects and the significant P x Ca interaction effect, all varieties except Hk now showed Ca effects at 0.01 or 0.05 significance. Duncan's test on the partial-regression coefficients for Ca and Ca^2 indicated differential responses between the varieties Hr versus Ch and Bl. Furthermore, Ch differed from Hk in its linear and quadratic response to Ca. Differences also existed among the varieties when unfertilized.

The final equations given in table 10 show the dependence of the percentage Mg in the leaves on fertilizer application for conditions similar to those of the experiment.

Figures 9 and 10 show the contours for the percentage Mg in the leaves at the end of flowering for the two varieties exhibiting the strongest differential responses to Ca. Whereas the contours for the variety Ch are elliptic, those for Hr are hyperbolic. The Mg content is of the order of 1% when no K is applied and is strongly depressed by K application. The effect of liming is relatively weak, although statistically significant. The inverse relation between K application and percentage Mg in plants has been known for years (3). One reason for the weak calcium effect presumably is that the reaction of the applied calcium carbonate with the soil takes longer than one season to develop.

The projection of the lines of intersection of the two Mg surfaces on the horizontal plane indicates that the variety Hr had a higher Mg content than did Ch, due to varietal differences and differential responses to calcium over most of the region investigated.

Lodging as influenced by fertilization

Observations on the degree of lodging were expressed on a scale of 1 to 5. Perfectly erect rows were recorded as 1, and 5 indicated complete lodging.

An influence of fertilization on the degree of lodging was noticeable in the field. The multiple

Table 10. Partial regression coefficients, b_i, of the final equations for the percentage Mg in the leaves at the end of flowering at the Howard County Experimental Farm, expressed as percentage Mg per 100 lb. of P, K, and Ca applied per acre[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	1.1304**	1.0707**	1.0501**	0.9592**
P	0.0120	−0.0042	0.0149	0.0186
K	−0.2007**	−0.1968**	−0.1708**	−0.1813**
Ca	−0.0118	−0.0108++	0.0038	−0.0012
K2	0.0171**	0.0159**	0.0138**	0.0144**
Ca2	0.0003	--	−0.0005	--
KCa	0.0004	0.0014	0.0011	0.0004
PCa	0.0028	0.0039++	0.0033+	0.0003
PKCa	−0.0003	−0.0003	−0.0004	−0.0001
R2	0.8222	0.8625	0.7937	0.8688

[a] The symbols **, ++, and + refer to the 0.01, 0.10, 0.20 significance levels, respectively.

regressions shown in table 11 suggest the linear and quadratic effects of K and, possibly, the K x P interaction as causal factors. The variety Bl was an exception. The R^2 of the equation was very low, and the F-test on the over-all regression failed to reach the 0.25 level of significance. Differential responses were not tested because Bartlett's test indicated highly significant heterogeneity of variance; i.e., $Chi^2 = 28.4041$.

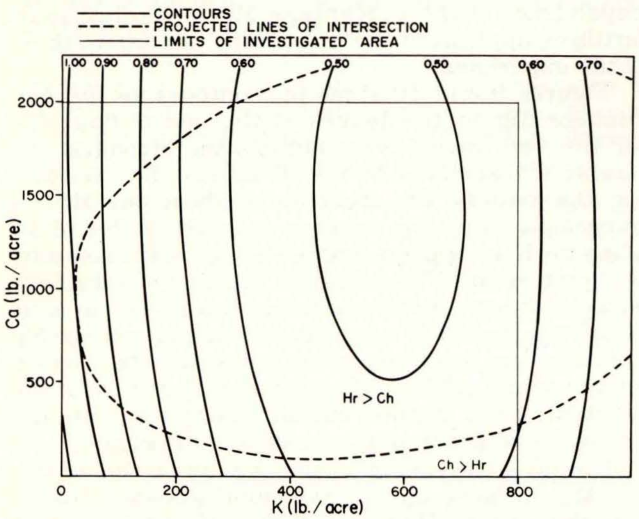

Fig. 9. Contours for the percentage Mg in the leaves at the end of flowering, derived from the final equation for the variety Chippewa grown at the Howard County Experimental Farm, with applied K and Ca as variables and at 0 addition of P, and the area in which the surface for the Harosoy variety is above that for Chippewa.

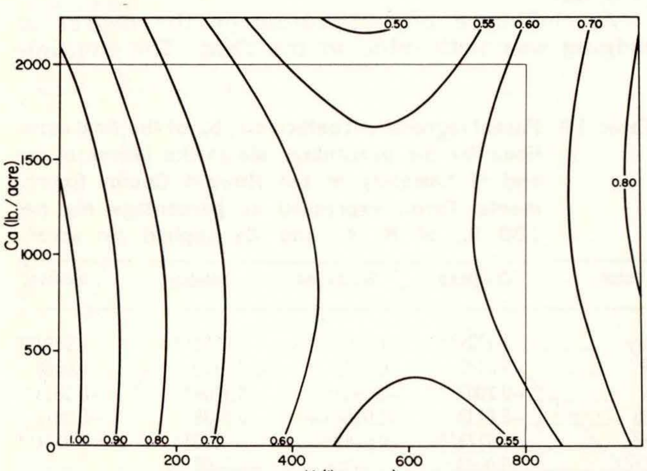

Fig. 10. Contours for the percentage Mg in the leaves at the end of flowering, derived from the final equation for the variety Harosoy grown at the Howard County Experimental Farm, with applied K and Ca as variables and at 0 addition of P.

Experiment at the Carrington-Clyde Experimental Farm

Yield of soybeans as a function of fertilizer input variables

The yield of grain of the four varieties is shown in table 1. The multiple regression of yield on the fertilizer-input variables was calculated for each variety, and the partial regression coefficients were tested by using deviations from regression. The analysis of variance of the regressions showed that all varieties were affected by the fertilizer factor. The regression for the variety Hk reached only 0.25 significance, and the R^2 values were very low. The yield responses observed for the varieties Bl, Hr, and Hk were due to the linear and quadratic components of the K effect (table 12). Tests for differential effects showed that yield differences among varieties, when not fertilized, reached the 0.01 level of significance and that differential fertilizer responses at the 0.10 and 0.25 level of significance were associated with K and K^2, respective-

Table 11. Partial regression coefficients of lodging at maturity of four varieties of soybeans on nutrients applied at the Howard County Experimental Farm[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	1.0527**	1.2885**	1.1871**	1.2471**
P	0.0738+	−0.0144	0.1281	0.1024
K	0.0866++	0.0398	0.2960**	0.1715++
Ca	0.0040	0.0836	−0.0183	−0.0690
P^2	−0.0095++	−0.0013	−0.0145+	−0.0119
K^2	−0.0082+	−0.0075	−0.0343**	−0.0213*
Ca^2	−0.0004	−0.0122+	0.0000	0.0052
PK	0.0069+	0.0112+	0.0195*	0.0114
KCa	0.0000	0.0027	0.0022	0.0049
PCa	0.0002	0.0076	0.0025	0.0029
PKCa	−0.0005	−0.0013	−0.0025+	−0.0011
R^2	0.4718	0.2190	0.5651	0.3546
Residual mean square	0.0352	0.1158	0.1523	0.1456

[a]The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

Table 12. Partial regression coefficients relating soybean yield of four varieties to fertilization at the Carrington-Clyde Experimental Farm[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	33.7578**	32.3822**	39.5655**	32.1540**
P	0.6079+	0.2689	−0.0824	0.1299
K	−0.0546	1.1797**	0.9919++	1.6200*
P^2	−0.0562	−0.0259	−0.0205	−0.0193
K^2	−0.0726+	−0.1562**	−0.2103**	−0.1919*
PK	−0.0402	0.0226	0.0667	−0.0092
R^2	0.5801	0.3102	0.3819	0.1887

[a]The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

ly. Combination of the yield equations for the four varieties resulted in the equation:

$$Y = 34.6815Ch^{**} + 32.7037Bl^{**} + 38.4186Hr^{**} + 32.0845Hk^{**} + 0.0272P - 0.0986KCh + 1.3242KBl^{**} + 1.3013KHr^{**} + 1.6235KHk^{**} - 0.0873K^2Ch^{++} - 0.1630K^2Bl^{**} - 0.2156K^2Hr^{**} - 0.1969K^2Hk^{**} \quad [17]$$

Tests on partial-regression coefficients of this equation were made by using error "b" from the analysis of variance where variety effects were involved. The K^2 effect for Ch now reached 0.10 significance, and the factor K was maintained in the yield equation for this variety.

Differences between varieties were tested by Duncan's multiple-range test. Hr differed from the other varieties at the 0.01 level and yielded highest when not fertilized in the experiment, and Hk yielded lowest. Ch differed significantly from the other varieties in response to K and also is the only variety that showed a negative response to K at all rates of application. None of the varieties differed with respect to K^2.

Final yield equations for the individual varieties are shown in table 13. F-values for the multiple regressions of the varieties Ch, Bl, and Hr were significant at the 0.01 level; Hk, at the 0.05 level.

Response curves to K were drawn by using the final equations. Figure 11 shows almost identical responses to K for Bl and Hk. Hr outyielded all other varieties at any level of K ferilization. Ch yielded highest when no K was applied. The maximum yield for the varieties Bl, Hr, and Hk occurred at 406, 303, and 414 lb. of K per acre, respectively. The magnitude of the predicted responses at this rate of K application is of the order of 3 bu per acre. The range of application was sufficiently wide to include a portion of the region of negative responses due to excess KCl in the curves.

When rates of 600 lb. of K or higher were applied, the growing plants were distinctly smaller 4 weeks after emergence and showed yellow discoloration of the leaves. Ch often was the most seriously affected. The other varieties yielded highest at an application of 300 to 400 lb. of K per acre, but even here, the leaves often were a paler green than those on the check plots and sometimes showed slight yellowing. It is somewhat surprising that small, but significant, yield increases were obtained in response to K where the healthy appearance of the plant suffered from the fertilizer treatments.

Table 13. Partial regression coefficients of final yield equations for individual varieties at the Carrington-Clyde Experimental Farm, expressed in bushels per 100 lb. of K applied per acre and their significance[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	34.7980**	32.8123**	38.5272**	32.1931**
K	−0.0985	1.3242	1.3013*	1.6235**
K^2	−0.0873	−0.1630*	−0.2156**	−0.1969**
R^2	0.5532	0.2643	0.3538	0.1876

[a]The symbols ** and * refer to the 0.01 and 0.05 significance levels, respectively.

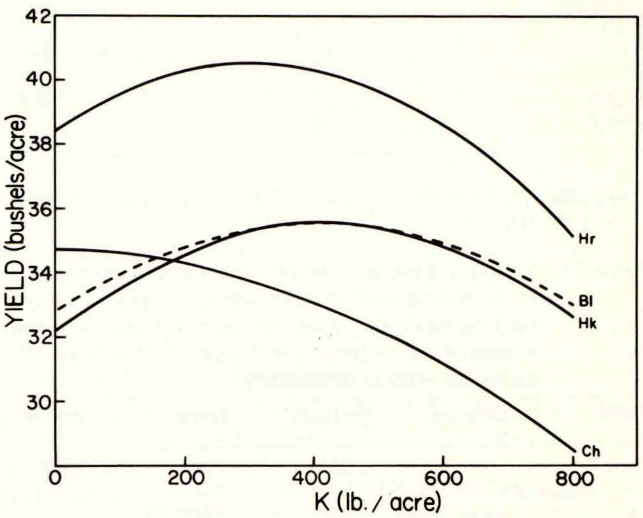

Fig. 11. Yield in bushels per acre of four varieties of soybeans in response to K application at the Carrington-Clyde Experimental Farm.

Effect of time of sampling on leaf composition

Separate samplings were made 9 days apart to determine if the sampling time might be critical for measuring the effect of fertilization on leaf composition at about the end of flowering.

Percentage P in the leaves: The original data show a general downward trend in the P content of the leaves between the first and second sampling (table A-3). The first sampling marked the end of flowering of the varieties Ch and Bl and, the second sampling, that of the other two varieties.

The analysis of variance for the percentage P in table 14 shows highly significant differences between dates of sampling (stage of development). The highly significant V x S interaction indicates that the effect of time of sampling differed from one variety to another. This was to be expected because two varieties developed through a stage past the end of bloom. The T x S interaction reached 0.10 significance, indicating that the treatment effect was not the same at the two stages of development.

Partial-regression coefficients of the equations for the percentage P in the leaves of four varieties sampled at two stages of development were calculated, and t-tests made, comparing corresponding coefficients between the first and second sampling by using error "c" from the analysis of variance. The values of t in the first line of table 15 specify the V x S interaction effect of the analysis of variance as being due largely to the Bl and Hr varieties.

Table 14. Analysis of variance of N, P, and K percentages in leaves of four varieties of soybeans sampled at two times near the end of flowering at the Carrington-Clyde Experimental Farm[a].

Source of variation	Degree of freedom	F-values		
		N	P	K
Main plots				
Replications	1	12.00**	1.71+	1.08
Treatments (T)	20	2.97**	5.13**	12.76**
Error a	20	--	--	--
Subplots				
Varieties (V)	3	4.32**	55.26**	46.30**
T x V	60	1.03	1.80*	< 1
Error b	63	--	--	--
Sub-subplots				
Stage (S)	1	75.61**	115.09**	28.25**
T x S	20	1.39+	1.62++	2.99**
V x S	3	15.77**	8.20**	13.88**
T x V x S	60	< 1	1.29+	1.36+
Error C	84	--	--	--

[a]The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

Table 15. Values of t for differential responses in percentage P in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm, between two stages of development and significant at the 0.20 or higher level of probability[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	--	2.34*	2.00*	1.80++
P	--	--	--	--
K	--	--	3.44**	--
P^2	--	--	--	--
K^2	--	--	3.32**	--
PK	1.90++	--	--	--

[a]The symbols **, *, and ++ refer to the 0.01, 0.05, and 0.10 significance levels, respectively.

In both varieties, the P content of the leaves decreased significantly over the 9-day period. The t-tests for the Hr variety show further that the linear and quadratic components of K differed in their effects at the two dates of sampling. The linear effect increased, and the quadratic effect decreased, with time. The effect of K on the percentage P in the leaves was not significant either before or after the 9-day period, but the significant increase in the linear effect of K suggests a tendency for K fertilization to compensate for the loss of P from the leaves due to translocation or dilution effects in this variety.

Percentage K in the leaves: The data are summarized in table A-3. The analysis of variance in table 14 shows highly significant effects due to stage of sampling and its interactions with varieties and fertilizer treatments.

The percentage K in the leaves of the varieties was significantly affected by linear and quadratic K effects at both dates of sampling. The K content of the variety Bl was significantly reduced at the later date of sampling, which specifies the corresponding V x S interaction in the analysis of variance. The t-tests comparing corresponding coefficients between stages showed that the linear and quadratic effects of K application were responsible for the T x S interaction effect and that this occurred at different levels of significance in all varieties (table 16).

The change in variety effect, together with that in the effect of the treatments, determines if the percentage composition will increase or decrease with time. Where significant to any degree, the change in the variety effect with time was consistently downward. This indicates that the nutrient content of the leaves decreased with time if no fertilizer is applied. Where this holds for any nutrient in the varieties Hr and Hk, it means that the dilution effect or movement out of the leaves started at or before the end of flowering because Hr and Hk had not quite reached this stage at the first sampling.

The linear component of the effect of K on the K content of the leaves increased between the two sampling dates for every variety, and this would tend to compensate for the decrease in K from the leaves that occurs with time. Contour maps for the percentage K of the leaves at the first and second sampling were constructed by using the respective regression equations. Those for the Bl variety illustrate the most significant compensation effect and are presented in fig. 12. The broken lines represent a projection of the lines of intersection between the two surfaces on the horizontal plane. The area between the broken lines indicates the P and K fertilizer combinations resulting in a higher surface of percentage K for the later sampling.

The percentage K in the leaves would generally be expected to decrease after completion of flowering due to translocation of nutrients to the growing soybeans. This is borne out by the contours in fig. 12. The surface for the percentage K at the later stage is generally situated below that for the earlier sampling. The trend can be reversed by applying K fertilizer between the levels of 300 and 700 lb. of K per acre. This means that the percentage

Table 16. Values of t for differential responses in percentage K in the leaves of four varieties grown at the Carrington-Clyde Experimental Farm between two stages of development and significant at the 0.20 or higher level of probability[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	--	3.12**	--	--
P	--	--	--	--
K	1.41+	3.72**	1.92++	2.52*
P^2	--	--	--	--
K^2	--	3.45**	1.30+	2.81**
PK	--	--	--	--

[a]The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

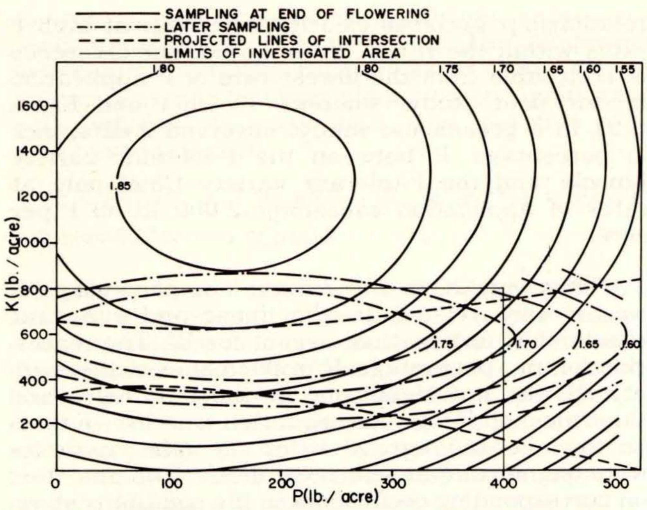

Fig. 12. Contours for the percentage K in the leaves of the variety Blackhawk sampled at the end of flowering and 9 days thereafter at the Carrington-Clyde Experimental Farm, with applied P and K as variables, and the projection of the lines of intersection between the two surfaces.

K in the leaves can be maintained at a high level longer under certain high rates of K application than is true without K application. Contour maps similar to those for Bl showed that effective compensation in Ch required rates of K exceeding 250 lb. of K per acre. For Hr, approximately 100 lb. of K was sufficient. In the late-maturing Hk variety, K application merely raised the K concentration because reduction in K content had not yet started at the second sampling time.

It would be interesting to know how long after the beginning of bean formation the compensatory trend can be maintained. The phenomenon is largely independent of P application, as can be seen from the position of the projected lines of intersection between the two surfaces. That maxima occur at a certain level of K application, whereas the percentage K drops with further increase in K application, may have little meaning and, presumably, is due to the type of function (quadratic) fitted to the data. That the maxima of the surfaces occur at a level of 150 lb. of P per acre presumably is a correct estimation of actual plant behavior.

Percentage N in the leaves: The data are summarized in table A-3. The effects of stage of sampling and its interaction with varieties were highly significant in the analysis of variance shown in table 14, but the treatment x stage of sampling (T x S) interaction was significant only at the 0.25 level.

It is evident from the partial-regression coefficients of the equations for the percentage N in the leaves of the four varieties and from t-tests on corresponding coefficients at the first and second sampling that the K treatment differed in its effect on the N content of the leaves on the two sampling dates just as for the P and K leaf contents. The differential linear and quadratic effects of K were significant at the 0.05 and 0.10 levels of probability for the varieties Bl and Hr. The effects involved resulted in intersecting surfaces for the percentage N of the leaves for the Hr variety (fig. 13). The area between the broken lines indicates the combinations of P and K fertilizer resulting in a lower N content at the later sampling date. The highest N content (4.70%) at the first sampling occurred when no P and 500 to 600 lb. of K were applied per acre. This level was not reached at the later date, irrespective of fertilization with P and K. For the Bl variety, the N content was lower at the later sampling over the entire region of fertilization investigated.

Leaf composition as a function of fertilizer variables

Percentage P in the leaves: Because some highly significant differences in variety and treatment effects developed during a 9-day period at about the end of flowering, it is important to sample the growing plant as close to the intended stage of development as possible. The comparison of the chemical composition of the four varieties therefore was made on the data from the first sampling for Ch and Bl and from the second sampling for the varieties Hr and Hk.

The percentage P in soybean leaves was not closely related to the P and K supplied to the soil. F-tests on the over-all regressions were significant at the 0.01 level for the varieties Ch, Bl, and Hk and, at the 0.05 level, for the variety Hr, but the values of R^2 were low. Only for Bl and Hk did the linear effect of P have a significant effect on the percentage P in the leaves at the 0.05 level.

The differences between the varieties were tested by Williams' technique, using error "b" from

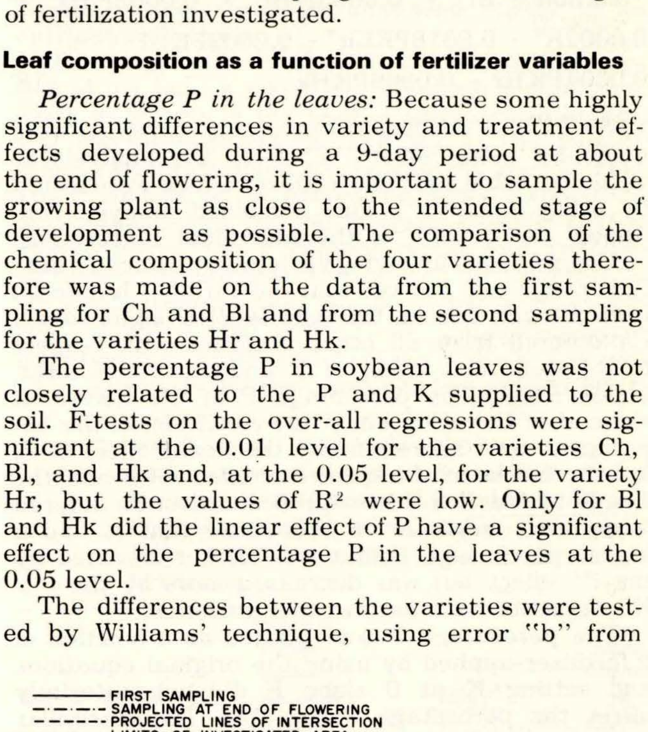

Fig. 13. Contours for the percentage N in the leaves of the variety Harosoy samples 9 days before the end of flowering and at the end of flowering at the Carrington-Clyde Experimental Farm, with applied P and K as variables, and the projection of the lines of intersection between the two surfaces.

the analysis of variance for the percentage P. Significant differences occurred among the varieties with respect to P x K interaction at the 0.05 level and at a lower level of probability with regard to P^2. It was evident from the partial regression coefficients that Ch was the nonconforming variety in this respect.

The data for the four varieties were combined in equation 18.

$$Y = 0.3637Ch^{**} + 0.3349Bl^{**} + 0.3470Hr^{**} + 0.3387Hk^{**} - 0.0111P^{*} + 0.0017K + 0.0013P^2Ch^{++} - 0.0005P^2Bl - 0.0005P^2Hr - 0.0002P^2Hk - 0.0002K^2 - 0.0018PKCh^{*} - 0.0002PKBl - 0.0004PKHr - 0.0009PKHk \quad [18]$$

Tests on the coefficients involving varieties were made by using error "b" from the analysis of variance (table 14). The fertilizer effects were tested by using error "a". This combined analysis confirmed the results of the individual regressions.

Comparisons involving varieties by Duncan's multiple-range test showed that the variety Ch differed from Bl and Hk at the 0.01 level of significance. Ch differed from all other varieties with respect to the quadratic effect of P and the P x K interaction effect. The percentage P in the leaves at the end of flowering under the conditions of the experiment was influenced by the linear effect of P; for Ch, however, the quadratic effect of P and the P x K interaction were significant also. Ch differed from other varieties in the sense that it had a higher percentage P that was further elevated by the P^2 effect but was decreased more by the P x K interaction than for the other varieties.

The percentage P was plotted as a function of P fertilizer applied by using the original equations and setting K at 0 since K did not materially affect the percentage P (fig. 14). The dissimilar behavior of Ch is interesting in view of Howell and Bernard's (17) finding that Ch belongs to the group of soybean varieties very sensitive to high P concentrations in nutrient culture. Its P content reached higher values than that of other varieties under identical fertilization in the field. Also, this relationship becomes clearly curvilinear at high P rates within the range investigated. The difference is noticeable from the lowest rate of P application in our field study, whereas Fletcher and Kurtz (12), in a greenhouse study, observed a difference in percentage P between the P-tolerant variety Lincoln and the P-tolerant variety Chief only at rates of application exceeding 2,000 lb. of P per acre.

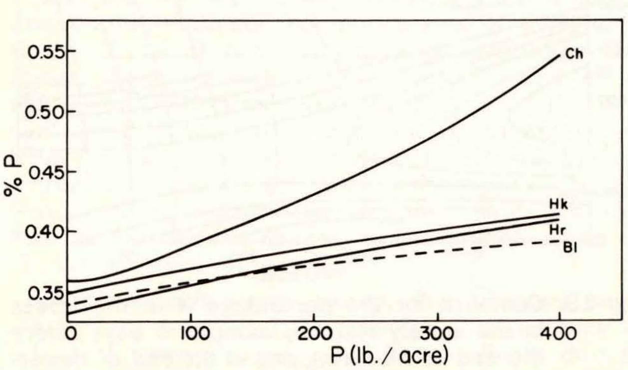

Fig. 14. Percentage P in the leaves at the end of flowering as a function of P application at 0 lb. of K for four varieties grown at the Carrington-Clyde Experimental Farm.

Percentage K in the leaves: The percentage K was closely related to the linear and quadratic effects of K fertilization, except for Bl. The regression for the percentage K in the leaves of the variety Bl was not significant at the 0.05 level, and the value of R^2 for the equation was low. F-tests on the over-all regression for the other varieties were significant at the 0.01 level. Williams' test on corresponding coefficients in the equations showed highly significant differences in response among the varieties with respect to the linear and quadratic effects of K. Without fertilization, there were varietal differences in percentage K at the 0.10 level.

According to these findings, the data for the four varieties were combined in equation 19:

$$Y = 1.3906Ch^{**} + 1.5287Bl^{**} + 1.2545Hr^{**} + 1.3602Hk^{**} + 0.0010P - 0.0021P^2 + 0.1101KCh^{**} + 0.0545KBl^{++} + 0.1520KHr^{**} + 0.2332KHk^{**} - 0.0110K^2Ch^{**} - 0.0033K^2Bl - 0.0132K^2Hr^{**} - 0.0219K^2Hk^{**} + 0.0022PK \quad [19]$$

Tests on the coefficients involving varieties were made by using error "b" of the analysis of variance (table 14). The fertilizer effects were tested by using error "a." The analysis for the four varieties combined confirmed the results from the individual regressions. The significant P x K interaction for Hk, however, does not show in the pooled coefficient for this interaction.

Varietal differences and differential responses to K among varieties were tested by Duncan's multiple-range procedure. Highly significant varietal differences in percentage K occurred between Bl and Hr, and Bl differed from Hk at the 0.05 level. Bl differed from Hk at the 0.01 and from Hr at the 0.05 level with respect to both the linear and quadratic components of K.

The change in percentage K with increasing K application and without applied P was calculated. The variety Hk had a higher K content in the leaves over most of the range of K applied than did the other varieties.

Percentage N in the leaves: Multiple-regression equations for the percentage N in the leaves at the end of flowering as a function of P and K fertilization showed that the N content was generally little influenced by the nutrients applied, but that the N content of Bl was related to K application. The values of multiple R^2 were low, and none of the regressions could explain sufficient variation to reach significance at the 0.05 level. The differences between the varieties themselves or their differential responses to fertilizer did not reach significance with Williams' test. All data were therefore combined in equation 20.

$$Y = 4.4725^{**} - 0.0096P + 0.0599K^{**} + 0.0007P^2 - 0.0600K^{2**} - 0.0022PK \quad [20]$$

The analysis confirms the earlier conclusion that only K affected the percentage N in the leaves. The dependence of the percentage N with increasing K application and O applied P is represented graphically in fig. 15. The only significant relationship may be that of the influence of K application on the percentage N in the leaves of the variety Bl. Bl reached a maximum percentage N at approximately 450 lb. of K per acre.

Discussion

The absence of significant seed-yield responses to P at both locations on soils low to very low in available P confirmed earlier experiences that soybeans are generally less responsive to fertilizer than are most other crops, at least as far as P is concerned. Weak yield responses to P presumably existed at the Howard County Experimental Farm, and only one variety (Ch) showed a significant P x K interaction effect. The existence of such weak responses combined with a high fertilizer requirement for maximum yield and a sizable P x K interaction effect can explain the failure of soybeans to respond at low rates of fertilization. The question remains as to why the response to P remains so low when care is taken to supply sufficient K and Ca. This may be caused by one or both of two factors: (a) the inability of the plant to absorb an appreciably larger amount of nutrient when more is made available to soil and (b) the inability of the plant to utilize the additional amounts of absorbed nutrients for grain production.

As to (a), it is possible that soybeans absorb sufficient P from the soil even when available P is present in very small amounts. When no P fertil-

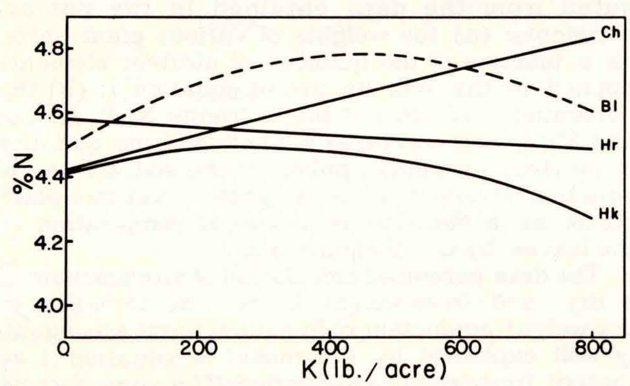

Fig. 15. Percentage N in the leaves at the end of flowering as a function of K application at 0 lb. of P for four varieties grown at the Carrington-Clyde Experimental Farm.

izer was applied, the average P content of the four varieties at Howard County was 0.33%, in the sufficiency range of P contents (20, 23). Even then, it remains questionable if absorption from soils low in available P is sufficient for maximum yield. Some rather spectacular responses, however, resulted from P application in pot trials with soil testing low in P (5, 6, 7, 8). Highly significant P responses were obtained even at a young stage of development (two trifoliolate leaves). Also, since the percentage content of P in the leaves was increased 8-fold at the same young stage of growth, it may be assumed that at least certain soybean varieties absorb P freely from an increased supply of the nutrient in the soil.

The magnitude of change in nutrient composition of the leaves under the influence of significant fertilizer factors in the field is summarized in table 17. The percentages K and Mg at the Howard County Farm changed freely when K was applied. The P content of the leaves responded consistently to P application. At the Howard County Experimental Farm, the P content of the four varieties increased by an average of 27% in response to an application of 300 lb. of P per acre at a K level of 400 lb. per acre. At the Carrington-Clyde Experimental Farm, the average change was only 14%. These responses confirm the conclusion of

Table 17. Magnitude of statistically adjusted changes in nutrient content of soybean leaves at the end of flowering at the Howard County and Carrington-Clyde experimental farms, each involving one or more significant effects from P, K, and Ca fertilization.

Nutrient (%)	Experimental farm[b]	Amount of element applied (lb./acre) P	K	Ca	Variety[a] Ch	Bl	Hr	Hk	Varietal difference in response[c]
P	H.C.	0	400	0	0.31	0.31	0.31	0.31	
		300	400	0	0.40	0.37	0.41	0.40	0.04
		300	0	0	0.48	0.42			
		300	400	0	0.40	0.37			
	C.C.	0	400		0.37	0.34	0.35	0.34	
		300	400		0.43	0.38	0.40	0.38	0.02
		300	0				0.39		
		300	400				0.40		
K	H.C.	300	0	1000			1.00	0.90	
		300	400	1000			1.60	1.80	0.30
	C.C.	0	0		1.35	1.22	1.45		
		0	400		1.64	1.66	1.98		0.24
Ca	H.C.	0	400		2.05			1.80	
		300	400		2.40			2.10	
		300	0		2.45			2.42	
		300	400		2.40			2.10	0.27
Mg	H.C.	0	0	1000	1.05		1.03		
		0	400	1000	0.53		0.52		
		0	400	0	0.60		0.58		
		0	400	1000	0.53		0.62		0.11

[a] Ch = Chippewa; Bl = Blackhawk; Hr = Harosoy; Hk = Hawkeye.
[b] H.C. and C.C. = Howard County and Carrington-Clyde experimental farms, respectively.
[c] Largest minus smallest response among the four varieties (e.g., 0.10 - 0.06 = 0.04).

pot experiments (5, 6, 7, 8) that the nutrient absorption of soybeans responds to a supply of the elements concerned.

The size of the responses in the field was small, however, in comparison with those obtained in pot experiments, and it may be that a certain fraction of the roots of soybean plants in the field pass through the fertilized surface soil. They then depend on nutrient absorption from deeper layers to a considerable extent. Such a trend would be accentuated by periods of dry weather. It would, therefore, be of interest to study nutrient accumulation in the field under fertilizer placement conditions approaching those prevailing in the pot trials (5, 6, 7, 8). This would entail the supply of fertilizers, particularly P, to as large a portion of the rooting zone of the plant as practicable and in the most uniform distribution obtainable under field conditions.

Yield, Leaf-Composition Relationships

A relationship between the yield of soybeans and the nutrient composition of the leaves at certain stages of development may be reasonably expected. Frequently, the yield is related to the nutrient content of the leaves with respect to one element. Dumenil (9) expressed the yield of corn as a function of two elements, N and P, and Miller et al. (22) related the yield of soybeans to the P and K contents of leaves or petioles determined at various developmental stages. Dumenil (9) reported equations that were satisfactory for determination of critical nutrient levels. A highly significant correlation existed between the percentages N and P, but he decided that the interpretation was not seriously affected (9).

Some difficulties exist with similar relationships for soybeans. Miller et al. (22) reported a rather variable distribution of significant terms in the fitted equations over various experiments and plant parts chosen for nutrient determination. Many factors may have contributed to this situation; one of them could have been that the nutrient composition of some plant parts may hold better relationships with grain production than do others.

The data obtained in the experiment at the Howard County Experimental Farm were used in an attempt to relate soybean yield to the percentage composition of the leaves with respect to five elements: N, P, K, Ca, and Mg. The resulting multiple-regression equation for each variety is given in table 18. Employed were the deviations from the means of the analytical values, their squares, and some of the cross products. Although between 57% and 83% of the variation in yield can be explained by the variables chosen, few coefficients reached a significance level of 0.05 or higher.

In Ch, the percentage N and percentage Ca and three interaction terms involving either the percentage N or percentage Ca reached significance at the 0.05 level. The percentage Mg, influenced only indirectly by varying the amounts of P, K, and Ca, reached the 0.10 level; so did its interactions with the percentage P and the percentage Ca in the leaves. None of the squared terms was of any consequence in any of the varieties. That the percentage K, which might be expected to be of utmost importance, did not reach any level of significance throws doubt on the value of the yield-composition relationships in the experiment.

Table 18. Partial regression coefficients relating the yield of soybeans at the Howard County Experimental Farm to the percentage composition of the leaves at the end of flowering[a].

Factor	Chippewa	Blackhawk	Harosoy	Hawkeye
b_0	36.1449**	37.1183**	41.6879**	30.8845**
%N	−4.4099*	−1.0514	7.1702+	−7.6814
%P	−5.9022	43.8664+	38.1099	66.5533++
%K	−2.7155	5.3475	1.4249	−8.2066
%Ca	13.3873**	−2.5010	3.1235	−5.7169
%Mg	−10.5935++	2.0983	6.9007	−33.2147 ++
$(\%N)^2$	3.4587	1.9571	10.3762	7.9494
$(\%P)^2$	71.5115	347.8372	−70.2172	−32.6592
$(\%K)^2$	2.0074	3.6413	−5.1573	−0.0431
$(\%Ca)^2$	7.0911	13.6788	6.4487	−0.3838
$(\%Mg)^2$	2.6120	68.9877	34.8983	17.6408
(%P)x(%K)	−78.8602	−39.8990	102.6488	22.5981
(%P)x(%Ca)	252.1292*	−3.1930	−56.5695	239.7270+
(%P)x(%Mg)	290.8960++	−294.9440	85.7590	−144.3019
(%K)x(%Ca)	24.3680	4.3512	−47.1390+	−38.7344+
(%K)x(%Mg)	12.5262	80.2514	58.1345+	26.6617
(%Ca)x(%Mg)	66.1368++	−0.5867	−64.8630	−81.6651+
(%N)x(%P)	195.0520**	49.8349	−90.2942	58.1048
(%N)x(%Ca)	38.5380*	−7.1964	6.9546	−17.4954
R^2	0.8307	0.7131	0.5762	0.6500

[a]The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

Similar yield-composition relationships derived from the data obtained at the Carrington-Clyde Experimental Farm for the same four varieties were equally unsatisfactory.

Some insight into the cause of the problem was obtained from similar yield, leaf-composition relationships derived from pot experiments described elsewhere (5, 6, 7, 8). The following multiple-regression relationships were computed from the data obtained in the pot experiments: (a) the weights of various plant parts, as a function of the quantity of nutrient elements applied to the soil, by use of equation 1; (b) the percentages of each of the nutrients N, P, K, Ca, and Mg in the leaves, as a function of the quantity of nutrient elements applied to the soil, by use of equation 1; and (c) the weights of various plant parts, as a function of chemical composition of the leaves, by use of equation 2.

The data permitted calculation of all equations on a dry- and fresh-weight basis. The variation in dry-weight production of five plant parts was equally well explained by the model of equation 1 as that of fresh-weight production. The same factors were responsible for the variation. The associated significance levels and t-values were very similar. Similarly close relationships were obtained when the percentages of individual nutrients in the leaves expressed on a dry- or fresh-weight basis were used as dependent variables with the nutrients added to the soil as independent variables. It was therefore expected, (a) that a good relationship, through use of equation 2} would exist between the weight of plant parts and the chemical composition of the leaves or roots and (b) that it would make little difference whether dry- or fresh-weight percentages were entered as independent variables. Few leaf composition variables, however, made a significant contribution in explaining the dry weight of soybean plants at the 0.05 level or higher. The expected similarities did not appear. The equations for different varieties or fresh- versus dry-weight had few or no significant factors in common. The example presented in table 19 illustrates the inconsistencies.

The results indicate that rather minor changes, due to choice of a set of input values, may cause differences beyond reason in magnitude and significance of the estimated partial-regression coefficients. The cause lies presumably in a high degree of interdependence among independent variables. P application affected the percentages K and N as well as the percentage P. Similarly, application of K influenced the percentages Ca and Mg as well as the percentage K.

Others have encountered similar difficulties (13, 11). This interdependence of the nutrient contents in the leaves will occur more frequently as regression equations are expanded to contain more leaf-nutrient variables and will be stronger with soybeans than with corn because of the added relationships involving P and nodulation. That no meaningful relationships were derived between yield and leaf composition does not necessarily mean that no such relationships exist. It indicates only that the model fitted to the data is unable to express the relation even if it exists. Several ways are open to reduce the interference:

1. It may be possible to enter terms that have a closer empirical relationship with yield and are more nearly independent of each other. For example, the K supply of the plant may possibly be evaluated as the total content of K in the petioles, whereas the percentage P of the leaves may be a more critical estimate of the P supply.

2. Nutrient contents of plant tissue alone may be unable to reflect the full yield-composition relationships. Other variables, as yet undefined, may be needed as single terms or in interaction with nutrient variables.

3. When it is known that variables in a given set are interconnected by cause-and-effect relationships, it is sometimes possible to compute the effect of a change in one of them on the change in another and also the magnitude of their direct effects on yield. The estimates for such influences are called path coefficients (11). Path coefficients may therefore be used to advantage when it is desired to restrict the size of a partial-regression coefficient to the independent contribution of a factor to yield.

Table 19. Values of t for partial regression coefficients reaching the 0.20 significance level or higher in equations relating dry-matter production of soybeans to leaf composition expressed as dry-weight or fresh-weight percentages[a].

Independent variables and R^2	Variety 1		Variety 2	
	Dry-weight	Fresh-weight	Dry-weight	Fresh-weight
	%	%	%	%
b_0	19.47**	14.08**	10.64**	10.44**
P		1.80++		2.09*
K	1.65+	2.02++		
Ca				1.50+
Mg		1.46+		
N			1.70+	
P^2	1.92++	3.67**		
K^2	1.70+			
Ca^2				
Mg^2	1.84++			
N^2				
PK	2.18*			1.87++
PCa				
PMg	2.59*			2.07*
PN		3.56**	1.46+	1.78++
KCa			1.63+	
KMg	2.01++			
KN				
CaMg				
CaN				
MgN				
R^2	0.8687	0.8301	0.8504	0.8726

[a]The symbols **, *, ++, and + refer to the 0.01, 0.05, 0.10, and 0.20 significance levels, respectively.

The primary purpose of the attempt to express yield as a function of leaf-composition variables in multiple-regression equations is the estimation of critical nutrient percentages in the leaves. An alternative computational method to arrive at critical percentages was therefore adopted by using multiple-regression equations expressing the leaf content of each nutrient as a function of fertilizer input variables and an equation relating the yield to the same factors of fertilization.

The latter type of equation was used to determine graphically the fertilizer combination corresponding to maximum yield. The critical nutrient percentages were then found by substitution of the required fertilizer rates into each of the prediction equations for the percentage nutrient in the leaves.

The concept of critical nutrient percentage has been variously defined. Macy (19) defined it as the content at the transition from poverty adjustment to the luxury-consumption region. Tyner (27) interpreted it as that concentration above which doubtful or decreasing responses occur. The critical nutrient percentages presented in table 20 refer to the nutrient contents at maximum seed yield predicted from statistically adjusted data. The critical values for the percentages P, K, and Ca in the leaves at the end of flowering in Howard County were remarkably similar for all varieties. The supply of Mg and N was not varied in the experiment, and no critical values can be given. From interpretation of fig. 6, a value of approximately 5% may be suggested for N as an average for the four vari-

Table 20. Fertilizer combination for maximum yield, critical nutrient percentages in the leaves at the end of flowering, and predicted maximum yield of soybeans and yield when unfertilized at the Howard County Experimental Farm.

Variety	Fertilizer combination for maximum yield (lb./acre) P	K	Critical nutrient percentage %P	%K	%Ca	Yield when unfertilized (bu/acre)	Maximum predicted yield (bu/acre)
Chippewa	240	500	0.39	1.80	2.31	27	39
Blackhawk	400[a]	580	0.36	1.91	2.30	29	40
Harosoy	400[a]	520	0.40	1.87	2.29	33	47
Hawkeye	400[a]	540	0.40	1.99	2.01	27	39

[a]The limit of the investigated range is shown where the actual optimum rate exceeded the highest rate applied.

eties involved when it is assumed that soybeans depend largely on symbiotic activity for their N supply.

Critical percentages based on data from the Carrington-Clyde Experimental Farm are not discussed since responses to P were practically absent in this experiment. Critical values for the percentage K in the leaves may be read directly from fig. 11 at the rate of K application that maximized the seed yield of the variety concerned.

CONCLUSIONS

Highly significant yield responses to K application occurred at both locations on soils testing low in available P and K. Responses to P, if existing, were not sufficiently strong to reach significance at either location under the conditions of the experiments.

At the Howard County Experimental Farm, the K responses were equally strong for all varieties. Their magnitude was of the order of 4 bu for the first 100 lb. of K applied per acre. Weak P responses presumably occurred in this experiment. Their magnitude was estimated from graphic interpretation at up to 3 bu in response to an application of 250 lb. of P per acre. A negative response of soybeans from P occurred in some instances due to a P x K interaction effect if less than 400 lb. of K was applied. This, and the limited magnitude of P and K responses in fields of low fertility, may explain some of the inconsistencies in yield responses of soybeans to fertilization if low rates are used.

At the Carrington-Clyde Experimental Farm, the K responses were smaller than at Howard County. The maximum predicted response to K was of the order of 3 bu per acre at very high rates of fertilization. The variety Chippewa differed significantly from the other varieties in response to K, and this divergence reached the 0.01 level of significance in comparison with Hawkeye. In the Howard County experiment, a similar indication of differential yield effects occurred with respect to P^2. This was due to a difference between the varieties Chippewa and Harosoy. The effect was small, but significant at the 0.05 level.

At both locations, the variety Harosoy yielded higher than the other varieties at all fertilizer combinations.

Yield-estimation equations valid under the conditions of the experiments were computed, and the rate of fertilization required for maximum yield was determined for each variety at both locations. Maximum yields occurred at very high rates of fertilization not economical in practice.

The residual effect of fertilization was evaluated 2 years later at the Howard County Farm. The effects of P and K were reduced, although there was still a significant response to K. The influence of Ca on yield was several times larger than in the year of application, which suggested that the effect of liming takes more than one season to fully develop.

Critical nutrient percentages for P, K, and Ca in the leaves were very similar for the four varieties. The average percentages were 0.39% P, 1.89% K, and 2.23% Ca. The chemical composition of the leaves at the end of flowering was significantly affected by fertilization. The percentage P responded very significantly to P and K application in the Howard County experiment. There also was significant P x K interaction effect. The four varieties behaved similarly with respect to these factors.

In the Carrington-Clyde experiment, the percentage P was affected by P application at the 0.05 level of significance. Chippewa differed from the other varieties by a higher P content of the leaves and by its response to the P2 and the P^2 x K interaction effects, which together raised the P content to approximately 0.55% compared with 0.40% for the other varieties. This may reflect the high P-sensitivity of this variety.

Chippewa also had the highest P content over a similar range of P application at the Howard County Farm. The content of Harosoy, however, was nearly as high as that of Chippewa there, and the differences were not significant.

The percentage K in the leaves was significantly affected, and the varieties were differentially affected by the K and K^2 effects at both locations. In both experiments, Hawkeye had the highest K content in the leaves over most of the range of fertilization.

The percentage Ca in the leaves was increased by P and decreased by K application for some varieties in Howard County. Liming had no influence. Some varieties differed at the 0.01 level of significance in the response of the Ca content of the leaves to K application.

The percentage Mg was significantly reduced by K application, and the effect of liming was significant for all varieties except Hawkeye when the data were combined. Differential responses to Ca also existed.

The percentage N in the leaves was hardly altered by fertilization. Soil-test values from Howard County in 1963 showed that the content of the leaves is affected by soil pH and interactions between soil pH, mineralizable N, and available K in the soil.

In the Carrington-Clyde experiment, the P, K, and N content in the leaves of certain soybean varieties decreased significantly over a 9-day period near the end of flowering. A significant change occurred in the effect of K application on the percentage P in the leaves of Harosoy. The percentage K in the leaves of several varieties was influenced differently by K application at the two times of sampling. The general downward trend of the K content in the leaves of Blackhawk, which occurred over the 9-day period, was reversed by applying certain high rates of K. K application also affected and reversed the trend in percentage N in the leaves with sampling time.

Multiple-regression equations relating the yield of soybeans to the chemical composition of the leaves were unsatisfactory. Interdependence of independent variables in the equations is thought to interfere with derivation of these relationships. The problem is expected to occur more frequently as more nutrient variables enter the relationships, and more so for soybeans than for corn because of the effect of P application on nodulation and N nutrition. Critical nutrient percentages may, therefore, better be determined from yield-estimation equations and equations for nutrient contents in the leaves, both expressed as a function of fertilizers applied.

Differential effects were strongest with respect to responses of the percentage K in the leaves to K application. At one location (Carrington-Clyde), this was associated with differential yield responses.

LITERATURE CITED

1. Anderson, R.L., and T.A. Bancroft. Statistical theory in research. McGraw-Hill Book Co., Inc.. New York. 1952.
2. Barnard, A.J., Jr., W.C. Broad, and H. Flaschka. The EDTA titration: Nature and methods of end point detection: I. Chemist-Analyst 45:86-93, 111-112. 1956.
3. Beckenbach, J.R., W.R. Robbins, and J.W. Shive. Nutrition studies with corn: II. A statistical interpretation of the relation between the ionic concentration of the culture solutions and the element content of the tissue. Soil Sci. 45:403-426. 1938.
4. Box, G.E.P., and K.B. Wilson. On the experimental attainment of optimum conditions. J. Roy. Statist. Soc. (Ser. B.) 13:1-45. 1951.
5. deMooy, C.J. Differential responses of soybean varieties to application of phosphorus, potassium and calcium carbonate materials with respect to leaf composition and yield. Ph.D. Thesis. Iowa State University. 365pp. (Mic. 65-7682, Univ. Microfilms, Ann Arbor, Mich.) (Diss. Abstr. 65-7602). 1965.
6. deMooy, C.J., and John Pesek. Nodulation responses to phosphorus, potassium, and calcium in soybeans. Agron. J. 58:276-280. 1966.
7. deMooy, C.J., and John Pesek. Growth and yield of soybean lines in relation to phosphorus toxicity and phosphorus, potassium, and calcium requirements. Crop Sci. 9:130-134. 1969.
8. deMooy, C.J., and John Pesek. Differential effects of P, K, and Ca salts on leaf composition, yield and seed size of soybean lines. Crop Sci. 10:72-77. 1970.
9. Dumenil, L.C. Nitrogen and phosphorus composition of corn leaves and corn yields in relation to critical levels and nutrient balance. Soil Sci. Soc. Amer. Proc. 25:295-298. 1961.
10. Duncan, D.B. Multiple range and multiple F tests. Biometrics 11:1-42. 1945.
11. Ferrari, Th.J. Causal soil-plant relationships and path coefficients. Plant and Soil 19:81-96. 1963.
12. Fletcher, H.F., and L.T. Kurtz. Differential effects of phosphorus fertility on soybean varieties. Soil Sci. Soc. Amer. Proc. 28:225-228. 1964.
13. Fox, K.A., and J.F. Cooney, Jr. Effects of intercorrelation upon multiple correlation and regression measures. U.S. Dept. Agr., Agr. Market. Serv. Washington, D.C. 28pp. 1954.
14. Fuller, W.A. Estimating the reliability of quantities derived from empirical production functions. J. Farm Econ. 49:82-99. 1962.
15. Hanway, J.J. Corn growth and composition in relation to soil fertility. II. Uptake of N, P, and K and their distribution in different plant parts during the growing season. Agron. J. 54:217-222. 1962.
16. Heady, E.O., J.T. Pesek, and W.G. Brown. Crop response surfaces and economic optima in fertilizer use. Iowa Agr. and Home Econ. Exp. Sta. Res. Bul. 424. 44pp. 1955.
17. Howell, R.W., and R.L. Bernard. Phosphorus response of soybean varieties. Crop Sci. 1: 311-313. 1962.
18. Jones, J.B., Jr. Nutrient element requirements for several inbred lines of corn. Trans., 7th Int. Soil Sci. Congr. (Madison, Wisc.) 3:336-342. 1960.
19. Macy, P. The quantitative mineral nutrient requirements of plants. Plant Physiol. 11:749-764. 1936.
20. Melsted, S.W., H.L. Motto, and T.R. Peck. Critical plant nutrient composition values useful in interpreting plant analysis data. Agron. J. 61: 17-20. 1969.
21. Miller, R.J. Soybean yield responses and plant composition as affected by phosphorus fertilizers. Ph.D. Thesis. Iowa State University. (Mic. 60-4902, Univ. Microfilms, Ann Arbor, Mich. 1960.
22. Miller, R.J., J.T. Pesek, J.J. Hanway, and L.C. Dumenil. Soybean yield and plant composition as affected by phosphorus and potassium fertilizers. Iowa Agr. and Home Econ. Exp. Sta. Res. Bul. 524. 20pp. 1964.
23. Nelson, W.L., and S.A. Barber. Nutrient deficiencies in legumes for grain and forage. In: H.B. Sprague (ed.) Hunger signs in crops. David McKay Co. New York. 1964.
24. Nelson, W.L., L. Burkhart, and W.E. Colwell. Fruit development, seed quality, chemical composition and yield of soybeans as affected by potassium and magnesium. Soil Sci. Soc. Amer. Proc. 10:224-229. 1945.
25. Snedecor, G.W. Statistical methods. (5th ed.) Iowa State University Press. Ames. 1956.
26. Tucker, B.M. Calcein as an indicator for the titration of calcium with ethylenediaminetetraacetate. Analyst 82:284-285. 1957.
27. Tyner, E.H. The relation of corn yield to leaf nitrogen, phosphorus and potassium content. Soil Sci. Soc. Amer. Proc. 11:317-323. 1946.
28. Ward, G.H., and F.B. Johnston. Chemical methods of plant analysis. Publication 1064. Canadian Dept. Agr., Research Branch, Ottawa, Ontario. 1960.
29. Waring, S.A., and J.M. Bremner. Ammonium production in soil under water-logged conditions as an index of nitrogen availability. Nature 201:951-952. 1964.
30. Williams, E.J. Regression analysis. John Wiley and Sons, Inc. New York. 1959.

APPENDIX

Table A-1. Rates of P, K, and Ca applied and percentages N, P, and K in the leaves of the soybean varieties Chippewa, Blackhawk, Harosoy, and Hawkeye at the Howard County Experimental Farm.

Treatment	Element applied (lb./acre)			N				P				K			
no.	K	P	Ca	Ch[a]	Bl	Hr	Hk	Ch	Bl	Hr	Hk	Ch	Bl	Hr	Hk
17	0	0	0	5.05	5.20	5.06	4.77	0.32	0.34	0.32	0.31	0.90	0.96	0.92	0.99
21	0	0	2000	5.31	5.16	4.93	4.97	0.33	0.35	0.31	0.33	1.20	1.21	1.05	1.01
28	0	200	1000	5.39	4.78	5.20	5.07	0.46	0.40	0.44	0.44	0.99	0.92	0.85	0.75
18	0	400	0	4.87	4.77	5.13	4.76	0.55	0.44	0.50	0.44	0.97	0.98	1.03	1.00
22	0	400	2000	5.38	5.01	5.14	4.65	0.49	0.46	0.52	0.48	0.83	0.79	0.87	0.94
9	200	100	500	5.00	4.93	4.91	4.86	0.38	0.36	0.37	0.37	1.60	1.59	1.53	1.69
13	200	100	1500	5.19	5.07	5.00	4.89	0.38	0.35	0.38	0.39	1.58	1.89	1.25	1.74
10	200	300	500	4.78	4.62	4.92	4.94	0.41	0.38	0.43	0.41	1.43	1.50	1.38	1.59
14	200	300	1500	4.95	4.99	5.20	4.70	0.40	0.39	0.45	0.42	1.56	1.46	1.40	1.67
1	300	150	750	4.62	5.02	4.97	4.82	0.37	0.36	0.39	0.39	1.57	1.72	1.71	1.71
5	300	150	1250	4.93	5.07	5.12	4.87	0.40	0.38	0.40	0.40	1.66	1.69	1.57	1.87
2	300	250	750	4.88	5.30	5.06	4.95	0.40	0.37	0.41	0.37	1.56	1.54	1.44	1.61
6	300	250	1250	5.01	4.77	4.95	4.82	0.40	0.36	0.39	0.43	1.60	1.84	1.54	1.66
26	400	0	1000	5.21	5.15	5.16	4.94	0.32	0.32	0.34	0.34	1.89	1.97	1.81	1.99
30	400	200	0	4.73	4.86	4.86	4.66	0.37	0.37	0.37	0.39	1.55	1.83	1.57	1.87
25	400	200	1000	4.90	4.47	5.04	5.02	0.38	0.35	0.41	0.39	1.74	1.82	1.63	1.90
31	400	200	2000	4.85	4.92	4.96	4.86	0.37	0.36	0.39	0.40	1.86	1.78	1.68	1.92
27	400	400	1000	5.05	4.98	4.92	4.96	0.42	0.38	0.42	0.43	1.73	1.63	1.51	1.85
3	500	150	750	4.70	4.71	4.96	5.04	0.37	0.35	0.38	0.37	1.84	1.86	1.63	1.84
7	500	150	1250	5.13	4.86	5.36	4.85	0.39	0.35	0.40	0.38	1.88	1.74	1.77	1.88
4	500	250	750	5.05	5.00	5.19	5.19	0.40	0.38	0.40	0.41	1.79	2.02	1.58	1.87
8	500	250	1250	5.15	5.03	5.28	4.78	0.38	0.39	0.40	0.40	1.82	1.77	1.56	1.90
11	600	100	500	5.16	5.08	5.20	4.89	0.38	0.35	0.37	0.38	2.07	1.85	1.60	1.82
15	600	100	1500	5.03	4.86	5.09	4.90	0.37	0.35	0.37	0.41	1.63	1.93	1.61	1.94
12	600	300	500	4.88	4.50	5.02	4.98	0.37	0.36	0.40	0.40	1.74	1.94	1.75	1.81
16	600	300	1500	5.00	4.73	4.78	4.84	0.40	0.38	0.40	0.39	1.67	2.01	1.61	1.92
19	800	0	0	5.12	5.16	5.05	4.99	0.31	0.31	0.34	0.33	2.02	1.83	1.78	2.07
23	800	0	2000	5.15	5.43	5.19	4.86	0.32	0.31	0.35	0.34	2.05	2.20	1.86	2.13
29	800	200	1000	4.93	4.93	4.95	4.80	0.38	0.39	0.40	0.41	1.83	1.93	1.96	1.91
20	800	400	0	4.72	4.94	4.78	4.85	0.40	0.36	0.39	0.41	1.97	1.81	2.12	1.84
24	800	400	2000	4.95	5.04	5.22	4.88	0.40	0.40	0.40	0.41	1.78	1.92	1.69	1.68

[a] Ch = Chippewa; Bl = Blackhawk; Hr = Harosoy; Hk = Hawkeye.

Table A-2. Rates of P, K, and Ca applied and percentages Ca and Mg in the leaves of the soybean varieties Chippewa, Blackhawk, Harosoy, and Hawkeye at the Howard County Experimental Farm.

Treatment	Element applied (lb./acre)			Ca				Mg			
no.	K	P	Ca	Ch[a]	Bl	Hr	Hk	Ch	Bl	Hr	Hk
17	0	0	0	2.11	2.24	2.07	1.96	1.14	1.11	1.06	0.99
21	0	0	2000	2.07	2.22	2.17	2.15	1.07	0.90	0.91	0.97
28	0	200	1000	2.30	2.53	2.35	2.35	1.13	1.04	1.20	1.03
18	0	400	0	2.37	2.48	2.25	2.28	1.21	1.10	1.09	1.07
22	0	400	2000	2.69	2.76	2.25	2.52	1.41	1.18	1.21	1.07
9	200	100	500	2.22	2.36	2.22	2.17	0.66	0.63	0.80	0.58
13	200	100	1500	2.34	2.13	2.28	2.14	0.75	0.51	0.84	0.63
10	200	300	500	2.47	2.54	2.59	2.31	0.74	0.64	0.87	0.59
14	200	300	1500	2.55	2.70	2.62	2.22	0.75	0.75	0.91	0.60
1	300	150	750	2.37	2.07	2.21	2.09	0.72	0.58	0.74	0.56
5	300	150	1250	2.30	2.28	1.99	2.07	0.67	0.59	0.63	0.55
2	300	250	750	2.32	2.50	2.36	2.10	0.72	0.69	0.79	0.59
6	300	250	1250	2.13	2.28	2.51	2.18	0.56	0.59	0.80	0.60
26	400	0	1000	1.95	1.93	2.10	1.79	0.55	0.53	0.68	0.44
30	400	200	0	2.21	2.15	2.26	1.99	0.70	0.56	0.71	0.52
25	400	200	1000	2.40	2.29	2.41	1.92	0.53	0.46	0.63	0.53
31	400	200	2000	2.33	2.15	2.20	2.08	0.56	0.56	0.61	0.48
27	400	400	1000	2.65	2.23	2.53	2.11	0.70	0.57	0.83	0.56
3	500	150	750	2.14	2.32	2.06	2.11	0.52	0.44	0.57	0.51
7	500	150	1250	2.15	2.00	2.02	1.99	0.57	0.52	0.64	0.53
4	500	250	750	2.38	2.15	2.15	2.02	0.63	0.53	0.64	0.53
8	500	250	1250	2.22	2.18	2.16	1.88	0.64	0.55	0.68	0.49
11	600	100	500	2.27	2.16	1.96	1.83	0.58	0.52	0.52	0.45
15	600	100	1500	2.15	2.20	2.26	1.79	0.51	0.54	0.61	0.46
12	600	300	500	2.30	2.09	2.20	2.07	0.55	0.43	0.66	0.47
16	600	300	1500	2.24	2.27	2.21	1.98	0.64	0.53	0.62	0.49
19	800	0	0	2.05	2.00	1.92	1.75	0.57	0.49	0.56	0.40
23	800	0	2000	1.89	1.85	2.21	1.82	0.56	0.48	0.64	0.44
29	800	200	1000	2.26	2.03	2.19	2.14	0.61	0.47	0.66	0.49
20	800	400	0	2.38	2.11	1.74	1.94	0.60	0.53	0.69	0.46
24	800	400	2000	2.27	2.28	2.29	2.04	0.70	0.59	0.70	0.49

[a] Ch = Chippewa; Bl = Blackhawk; Hr = Harosoy; Hk = Hawkeye.

Table A-3. Rates of P and K applied and percentages N, P, and K in the leaves of the soybean varieties Chippewa, Blackhawk, Harosoy, and Hawkeye sampled twice at the Carrington-Clyde Experimental Farm.

Treatment no.	Element applied (lb./acre)		N				P				K			
	K	P	Ch[a]	Bl	Hr	Hk	Ch	Bl	Hr	Hk	Ch	Bl	Hr	Hk
							First Sampling							
9	0	0	4.70	4.44	4.47	4.33	0.37	0.34	0.35	0.37	1.24	1.26	1.25	1.38
16	0	200	4.41	4.43	4.19	4.28	0.44	0.38	0.49	0.44	1.35	1.67	1.22	1.62
10	0	400	4.52	4.29	4.53	4.16	0.56	0.40	0.49	0.44	1.26	1.26	1.12	1.17
20	100	200	4.72	4.56	4.54	4.20	0.42	0.36	0.37	0.37	1.55	1.71	1.44	1.48
5	200	100	4.46	4.68	3.94	4.40	0.40	0.37	0.37	0.39	1.64	1.40	1.39	1.59
6	200	300	4.65	4.37	4.53	4.26	0.44	0.39	0.48	0.41	1.65	1.90	1.46	1.53
1	300	150	4.62	4.82	4.25	4.42	0.39	0.37	0.35	0.37	1.58	1.69	1.35	1.68
2	300	250	5.01	4.61	4.78	4.36	0.43	0.37	0.38	0.40	1.60	1.49	1.36	1.72
14	400	0	4.12	4.67	4.54	4.97	0.35	0.34	0.35	0.37	1.66	1.87	1.54	1.76
18	400	50	4.63	4.63	5.01	4.67	0.37	0.34	0.38	0.37	1.66	1.82	1.64	1.87
13	400	200	4.06	4.85	4.86	4.32	0.39	0.38	0.39	0.38	1.63	1.73	1.41	1.66
19	400	350	4.74	4.58	4.60	4.55	0.43	0.37	0.40	0.40	1.62	1.67	1.47	1.72
15	400	400	5.02	4.73	4.33	4.53	0.52	0.39	0.41	0.41	1.54	1.40	1.38	1.81
3	500	150	4.55	4.64	4.83	4.25	0.40	0.36	0.38	0.38	1.72	1.73	1.56	1.81
4	500	250	4.60	4.68	4.93	4.67	0.40	0.39	0.42	0.41	1.61	1.44	1.55	1.71
7	600	100	4.96	4.75	4.63	4.47	0.39	0.36	0.36	0.38	1.68	1.71	1.40	1.73
8	600	300	4.48	4.87	4.16	4.25	0.40	0.39	0.36	0.37	1.44	1.68	1.29	1.74
21	700	200	4.84	4.68	4.56	4.55	0.42	0.38	0.39	0.36	1.69	1.97	1.54	1.71
11	800	0	5.03	4.78	4.67	4.28	0.37	0.34	0.35	0.35	1.56	1.78	1.51	1.76
17	800	200	4.47	4.23	4.20	4.46	0.39	0.34	0.35	0.38	1.61	1.66	1.38	1.89
12	800	400	4.35	4.70	4.22	4.35	0.41	0.39	0.42	0.40	1.71	1.90	1.43	1.96
							Second sampling							
9	0	0	4.02	4.33	4.55	4.17	0.33	0.31	0.34	0.34	1.14	1.14	1.15	1.35
16	0	200	4.33	3.88	4.42	4.49	0.45	0.34	0.40	0.41	1.20	1.10	1.11	1.28
10	0	400	4.06	4.09	4.42	4.35	0.48	0.38	0.39	0.41	1.17	1.27	1.13	1.06
20	100	200	4.28	4.32	4.69	4.31	0.37	0.32	0.36	0.39	1.65	1.66	1.51	1.68
5	200	100	4.03	4.18	4.51	4.52	0.35	0.32	0.36	0.38	1.62	1.72	1.59	1.84
6	200	300	4.22	4.14	4.37	4.52	0.41	0.35	0.46	0.40	1.70	1.41	1.59	1.86
1	300	150	4.06	4.32	4.68	4.59	0.38	0.33	0.37	0.38	1.63	1.70	1.64	1.93
2	300	250	4.14	4.25	4.69	4.38	0.37	0.35	0.39	0.36	1.57	1.81	1.66	1.93
14	400	0	4.17	4.00	4.48	4.61	0.34	0.29	0.37	0.33	1.74	1.66	1.73	1.81
18	400	50	4.37	4.25	4.79	4.51	0.35	0.30	0.37	0.36	1.75	1.81	1.63	2.13
13	400	200	4.15	4.27	4.62	4.28	0.36	0.33	0.38	0.37	1.63	1.72	1.53	1.91
19	400	350	4.19	4.16	4.55	4.31	0.39	0.32	0.40	0.37	1.65	1.63	1.62	1.85
15	400	400	3.91	3.79	4.14	4.04	0.50	0.34	0.43	0.41	1.65	1.65	1.65	1.96
3	500	150	4.19	4.13	4.28	4.27	0.37	0.32	0.35	0.35	1.70	1.77	1.44	1.88
4	500	250	4.04	4.24	4.59	4.20	0.39	0.35	0.38	0.37	1.69	1.71	1.64	1.83
7	600	100	4.34	4.21	4.60	4.45	0.36	0.32	0.37	0.38	1.60	1.72	1.66	1.88
8	600	300	4.19	4.13	4.26	4.28	0.39	0.33	0.41	0.40	1.70	1.69	1.69	1.90
21	700	200	4.57	4.45	4.71	4.48	0.40	0.35	0.41	0.36	1.74	1.82	1.77	1.88
11	800	0	4.44	4.13	4.59	4.28	0.34	0.28	0.35	0.32	1.76	1.70	1.68	1.89
17	800	200	4.09	4.16	4.34	3.67	0.40	0.32	0.37	0.34	1.69	1.71	1.64	1.83
12	800	400	4.44	4.29	4.53	4.37	0.39	0.34	0.37	0.37	1.78	1.71	1.69	2.04

[a] Ch = Chippewa; Bl = Blackhawk; Hr = Harosoy; Hk = Hawkeye.