Research Bulletin No. 12 February 1969

Combining data from fertilizer experiments into a function useful for estimating specific fertilizer recommendations

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COMBINING DATA FROM FERTILIZER EXPERIMENTS INTO A FUNCTION USEFUL FOR ESTIMATING SPECIFIC FERTILIZER RECOMMENDATIONS

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The decision of greatest economic importance that farmers have to make in using fertilizers is the selection of the fertilizer treatment to employ. If the treatment selected includes an element that is not needed or a rate of an element higher than the economic optimum, the farmer will not realize the maximum returns from his investment in fertilizers and may even suffer a loss. On the other hand, if he applies less than the optimal amount of fertilizers, he will only be partially exploiting this source of added farm income.

The determination of optimal rates of fertilization is one of the most important functions of adaptive research. It is especially difficult to arrive at fertilizer recommendations for specific producing conditions as crop response to fertilization depends on the nature of the crop itself, the characteristics of the soil and climate at the location where it is grown, and the management practices employed in growing the crop. A significant change in any one of a large number of crop, soil, climatic, and management factors can greatly modify the reaction of the crop to fertilization. The optimal rate of nitrogen fertilization, for example, may depend just as much on the rainfall or the moisture retention characteristics of the soil as on the nature of the crop or the level of available soil nitrogen.

Ideally, two types of information are needed for making specific fertilizer recommendations: (a) The general yield equation for the crop with yield expressed as a function of applied fertilizer variables and the productivity factors, and (b) The levels of the productivity factors for the specific conditions for which a fertilizer recommendation is sought. Unfortunately

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The authors wish to acknowledge the assistance of the following persons: the farmers whose generous cooperation made this study possible, Biochemist Ruben Matabuena L. and Mr. Alfredo Lopez who analyzed the soil samples from the experiments and Dr. Henry Tucker, Visiting Professor of Statistics, Graduate College at Chapingo, who assisted in making the combined analysis. Special recognition is given to Dr. Rodolfo Moreno D., Head of the Soils Department of INIA, who contributed greatly toward the realization of this study, made helpful suggestions for the improvement of the report and finally translated the manuscript into Spanish.

This manuscript is being published simultaneously in Spanish by the Instituto Nacional de Investigaciones Agrícolas, Chapingo, Estado de México as INIA Folleto Técnico No. 54.

there are no well defined procedures to follow in generating a general yield equation and in characterizing the productivity factors. Consequently, the results obtained in field experiments are usually averaged over broad geographical areas to produce general fertilizer recommendations.

The present study was carried out with two principal objectives in mind: (a) To produce a general yield equation useful in estimating nitrogen fertilizer needs of unirrigated corn for specific producing conditions in a region with highly variable rainfall, and (b) To acquire a better understanding of the problems involved in measuring the productivity factors and in employing the multiple linear regression model for calculating a general yield function.

The experimental part of this study was conducted during the period 1962-1965. Simple fertilizer trials were carried out with unirrigated corn in farmer's fields in the Bajio area of Central Mexico. The results obtained in the first two years of this study have already been published (6), so only the results obtained in 1964 and 1965 will be reported here.

DESCRIPTION OF THE STUDY

Area of study

The area selected for this study is located in the western part of El Bajío and includes parts of the states of Guanajuato, Michoacán and Jalisco. It is situated geographically between parallels 101° 20′ and 102° 10′ west of Greenwich and latitudes 20° 15′ and 21° 10′ north, at elevations varying from 1710 to 1800 m above sea level. Approximately 90% of the total precipitation corresponds to the 5-month period, June-October, during which unirrigated corn is grown. Average rainfall and temperature data from 10 weather stations distributed through the area are presented in the earlier report (6).

Nineteen experiments were conducted in 1964 and 16 in 1965. It was planned initially to distribute the experiments uniformly throughout the area so that observations on fertilizer response could be made under the most varied rainfall conditions. Also, it was hoped to locate the experiments so as to sample the major differences in soil slope, depth and texture, because of the relation of these properties to water uptake and retention in an available form. However, it was not possible to distribute the experiments uniformly among the several rainfall and soil property categories because of the difficulty of finding farmers at the desired locations who could accurately maintain rainfall records. The geographical distribution of these experiments, plus the 47 conducted during 1962 and 1963, is shown in Fig. 1.

Rain gauges were installed around June 1 near the house of the cooperating farmer and within one kilometer of the experiment. The standard rain gauge employed by the Dirección de Geografía y Meteorología (1) was used.

Soil characteristics

Composite soil samples were taken from the 0-15 cm horizon of each experiment during July and August. Each composite consisted of 12 sub-

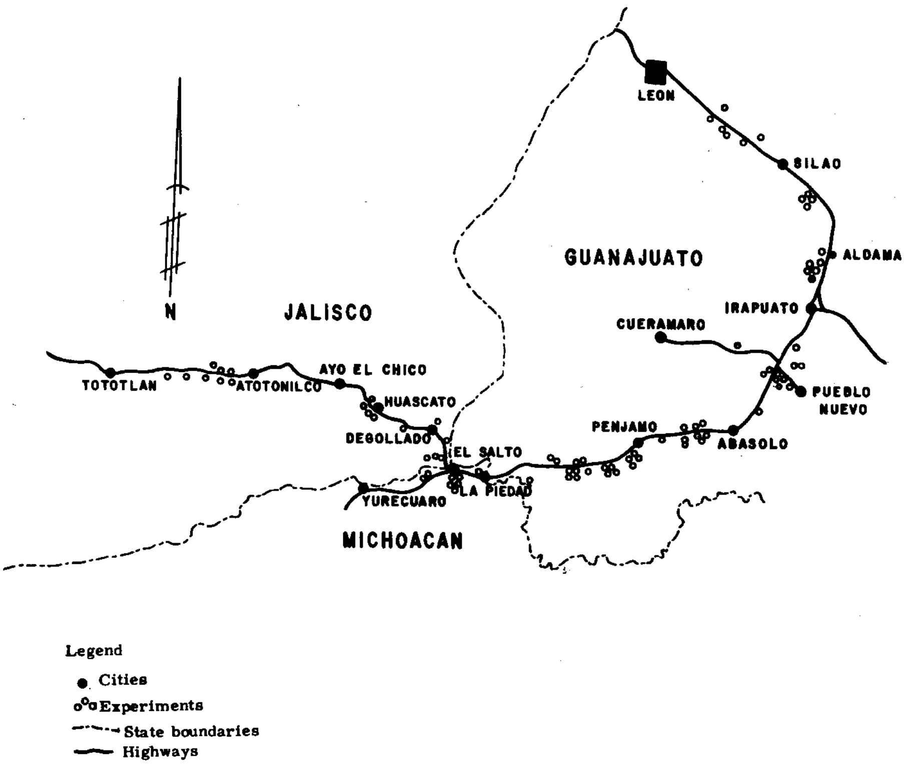

Fig. 1. Geographical location of 82 fertilizer trials carried out during the period 1962-1965.

samples, three taken from each of the four unfertilized plots in the experiment. During August and September, a pit was dug at a central location along one side of each experiment. Profile descriptions were made and samples were taken from the most important soil horizons.

Certain chemical properties of the 0-15 cm horizon of each experiment are presented in Table 1. The pH values varied from 5.4 to 8.3 with 71% oi the soils reporting values greater than 6.5. Organic matter contents were generally low with 89% of the soils having values less than 2%. The available calcium, magnesium, and potassium contens were highly variable but in most cases would be considered adequate for corn. The levels of available phosphorus, determined by both the Peech and Bray I methods, varied from very low to very high.

TABLE 1. Several chemical properties of the 0-15 cm horizons of the soils where the field trials were conducted.

No. of exp.	pH	Total nitrogen %	Organic matter %	Available nutrients (Peech Method)				Phosphorus (Bray I method) kg/ha
				Calcium ton/ha	Magnesium ton/ha	Potassium kg/ha	Phosphorus kg/ha	
402	6.4	0.046	0.57	1.9	0.2	330	4.8	8.3
405	6.3	0.072	1.08	4.7	0.3	390	2.9	9.1
406	6.5	0.056	0.64	3.1	0.5	300	1.9	5.6
408	6.8	0.064	1.00	9.3	1.5	180	4.0	4.8
409	6.0	0.075	1.22	3.5	0.3	360	2.4	6.4
410	6.0	0.095	1.52	3.4	0.3	540	8.8	15.1
411	5.4	0.113	1.90	2.2	0.4	520	1.7	5.7
412	5.9	0.046	0.60	1.3	0.2	190	2.6	9.0
413	6.3	0.060	1.00	3.9	0.5	280	1.4	3.1
414	6.9	0.047	0.81	10.9	1.8	430	1.2	3.1
415	6.9	0.059	1.30	9.6	2.7	270	1.4	3.3
416	6.9	0.072	1.57	9.8	2.7	220	1.4	4.2
417	6.9	0.061	1.16	13.2	1.8	250	1.0	3.2
418	7.3	0.081	1.33	15.3	0.7	430	3.8	8.9
419	7.0	0.129	2.41	11.6	1.7	920	18.4	34.9
420	6.8	0.075	1.76	13.6	2.3	370	1.5	6.8
421	7.2	0.058	1.22	13.0	1.6	560	1.2	1.9
422	6.8	0.084	1.85	14.0	2.2	430	1.8	6.7
423	7.1	0.123	2.15	9.7	1.7	730	11.6	22.2
501	7.0	0.087	0.96	4.4	1.0	390	6.4	22.4
502	7.0	0.090	0.76	6.8	0.6	440	2.6	15.4
503	8.3	0.124	1.60	18.1	1.7	500	65.4	34.2
504	8.1	0.101	1.37	8.7	1.5	230	10.9	16.0
505	6.3	0.099	1.21	3.3	0.3	320	1.9	16.0
506	6.4	0.069	0.76	1.4	0.2	250	3.9	23.4
507	6.6	0.105	1.21	3.1	0.4	780	18.4	58.5
508	7.3	0.094	1.30	14.6	1.9	610	2.4	11.5
509	7.6	0.077	0.87	18.6	1.7	580	1.9	5.4
510	7.3	0.058	1.64	12.6	1.5	570	3.2	15.7
511	7.4	0.054	0.87	14.8	1.1	320	1.7	6.1
512	7.4	0.074	1.86	16.5	1.3	420	2.5	12.3
513	6.6	0.111	2.05	29.0	1.4	540	1.6	10.6
514	7.2	0.125	2.25	24.8	1.4	920	77.6	131.3
515	7.0	0.084	1.60	27.7	2.4	280	2.5	15.7
516	7.0	0.067	1.57	33.1	2.0	330	1.9	11.2

Several characteristics of the horizons sampled at each location are given in Table 2. Eighteen of the soils are heavy-textured, 6 are medium-textured, and 11 are light-textured. Considering the maximum available moisture percentage as the difference between the field capacity and the permanent wilting percentage, this value is seen to vary from 5.7 in soil 409 to 28.4 in soil 516. Electrical conductivities are well below 2 milimhos per centimeter except in the upper horizon of soil 413 which has a value of 3.5.

TABLE 2. Some properties of the horizons of the soils where the experiments were conducted.

No. of exp.	Depth cm	pH	Sand %	Silt %	Clay %	Textural classification	Field capacity* %	Permanent wilting percentage**	Electrical conductivity (millimhos per cm at 25°C)
	0-13	6.8	80	11	9	Loamy sand	11.1	3.5	0.23
402	13-24	6.3	34	15	51	Clay	20.3	11.7	0.24
	24-40	6.3	61	16	23	Sandy clay loam	38.5	23.0	0.10
	0-17	6.1	73	17	10	Sandy loam	14.8	6.5	0.45
405	17-30	6.3	64	13	23	Sandy clay loam	28.4	13.0	0.25
	30-60	7.2	62	15	23	Sandy clay loam	39.9	19.0	0.20
	0-14	6.5	76	11	13	Sandy loam	14.0	6.6	0.57
406	14-30	6.5	57	17	26	Sandy clay loam	17.4	12.0	0.25
	30-60	6.8	28	9	63	Clay	44.5	22.6	0.07
	0-13	7.0	49	28	23	Loam	22.3	10.4	0.28
408	13-50	7.5	33	34	33	Clay loam	28.0	15.0	0.13
	50-90	8.2	18	40	42	Silty clay	31.2	16.5	0.36
	0-14	6.0	75	9	16	Sandy loam	14.2	8.5	0.40
409	14-40	6.0	51	8	41	Sandy clay	27.8	14.4	0.10
	40-60	6.4	54	9	37	Sandy clay	26.2	14.7	0.10
	0-13	6.0	61	22	17	Sandy loam	14.9	7.6	1.95
410	13-35	6.5	46	27	27	Sandy clay loam	22.2	11.4	0.10
	35-70	6.6	40	17	43	Clay	25.7	13.6	0.11

TABLE 2. (Continued). Some properties of the horizons of the soils where the experiments were conducted.

No. of exp.	Depth cm	pH	Sand %	Silt %	Clay %	Textural classification	Field capacity* %	Permanent wilting percentage**	Electrical conductivity (millimhos per cm at 25°C)
	0-13	5.3	43	34	23	Loam	17.8	9.5	1.29
411	13-22	6.0	30	41	29	Clay loam	21.7	12.2	0.25
	22-32	6.5	16	26	58	Clay	33.6	17.4	0.05
	0-15	6.4	49	27	24	Sandy clay loam	15.2	6.6	0.27
412	15-35	6.5	42	31	27	Loam	18.4	11.8	0.10
	0-13	5.1	66	19	15	Sandy loam	14.8	7.0	3.50
413	18-55	6.9	28	10	62	Clay	50.0	24.6	0.26
414	13-60	7.5	19	20	61	Clay	43.6	23.2	0.19
415	13-80	7.6	30	17	53	Clay	42.0	24.2	0.14
416	15-140	7.6	17	24	59	Clay	43.7	21.3	0.12
417	15-85	7.9	27	19	54	Clay	47.0	24.3	0.31
418	15-50	8.0	27	12	61	Clay	47.1	21.4	0.26
419	15-48	7.2	28	13	59	Clay	51.3	24.5	0.16
420	15-80	7.7	13	20	67	Clay	52.8	26.3	0.30

TABLE 2. (Continued). Some properties of the horizons of the soils where the experiments were conducted.

No. of exp.	Depth cm	pH	Sand %	Silt %	Clay %	Textural classification	Field capacity* %	Permanent wilting percentage**	Electrical conductivity (millimhos per cm at 25°C)
421	15-45	7.4	19	17	64	Clay	49.4	26.2	0.19
422	15-65	7.3	23	18	59	Clay	46.8	24.2	0.20
423	15-42	8.0	21	19	60	Clay	44.8	25.8	0.45
501	0-15	6.7	58	25	17	Sandy loam	19.9	7.8	0.45
	41-85	7.4	46	41	13	Loam	23.8	12.8	0.13
502	0-15	6.2	70	13	17	Sandy loam	18.2	7.6	0.38
	23-45	7.5	38	9	53	Clay	47.3	27.0	0.19
503	0-18	8.2	18	47	35	Silty clay loam	35.0	17.4	0.32
	37-60	8.1	39	28	33	Clay loam	29.4	16.2	0.20
504	0-16	7.8	38	41	21	Loam	26.6	11.6	0.40
	56-85	7.8	15	51	34	Silty clay loam	36.4	20.2	0.37
505	0-13	6.0	85	6	9	Loamy sand	15.0	5.9	0.38
	25-55	6.6	36	6	58	Clay	47.8	26.2	0.05
506	0-16	4.9	59	28	13	Sandy loam	17.6	7.8	0.58
	25-60	6.2	45	32	23	Loam	22.6	11.9	0.15

TABLE 2. (Continued). Some properties of the horizons of the soils where the experiments were conducted.

No. of exp.	Depth cm	pH	Sand %	Silt %	Clay %	Textural classification	Field capacity* %	Permanent wilting percentage**	Electrical conductivity (millimhos per cm at 25°C)
507	0-15	6.6	52	31	17	Sandy loam	21.2	8.7	0.10
	24-52	6.9	46	19	35	Sandy clay loam	44.6	24.2	0.20
	53-73	6.0	78	12	10	Sandy loam	16.4	6.2	0.72
508	16-130	8.0	16	21	63	Clay	58.0	31.6	0.15
509	17-85	8.0	17	27	56	Clay	54.1	29.9	0.20
510	17-50	7.6	24	27	49	Clay	50.0	29.1	0.20
511	16-35	8.0	42	21	37	Clay loam	51.8	25.8	0.15
512	21-65	7.8	31	18	51	Clay	50.8	30.2	0.22
513	15-45	6.3	33	24	43	Clay	38.8	22.2	0.10
514	16-80	7.2	23	24	53	Clay	48.8	27.4	0.08
515	16-50	7.3	20	18	62	Clay	53.5	26.5	0.17
516	16-90	7.8	16	17	67	Clay	59.0	30.6	0.20

* The field capacity was calculated from the following values· (a) the estimation of the field capacity using plastic cylinders, and (b) the moisture content of soil samples in equilibrium with a suction of 0.3 atmosphere (6).

** The permanent wilting percentage was calculated from the following values: (a) the moisture content of samples in equilibrium with a suction of 15 atmospheres, and (b) the permanent wilting percentages determined in the greenhouse with sunflower plants (6).

Additional information about the soils, based on observations made in the field, are given in Table 3. The soils have formed from relatively old extrusive volcanic materials. These vary from basaltic to rhyolitic in composition. Some were deposited in the form of flows, others by ash falls, and others by water. Twenty-one of the soils occupy hill positions, 7 are located on terraces, 2 on colluvial slopes, 2 on an old lacustrine plain, and 2 on bottoms. Eleven of the soils have a rooting depth less than 60 cm, 18 from 60 to 90 cm, and 6 more than 90 cm. Twenty-one of the soils have slopes less than 2% and 14 have values from 2 to 4%. Most of the heavy clays in this study were classified as Grumusols.

Experimental design

A randomized complete block design was employed with 4 replications of the following treatments:

0-0-0	120-60-0
0-60-0	80-0-0
40-60-0	80-30-0
80-60-0	120-60-0 + Zn

Each plot consisted of 4 rows 17 m long. Potassium was not applied as earlier studies had indicated a very low probability of a potassium deficiency in the soils of this area. Zinc was applied in combination with nitrogen and phosphorus at the rate of 75 kg/ha of zinc sulfate containing 22.5% zinc. The fertilizer sources employed were ammonium sulfate containing 20.5% nitrogen and calcium superphosphate containing 18.5% of P_2O_5.

Realization of the experiments

The experimental areas were prepared by the cooperating farmers in their customary way, which generally consisted in plowing the land in both directions with a wooden plow. Planting of the experiments began on June 4 and ended on July 15. All of the phosphorus and zinc plus one-fourth of the nitrogen were applied by hand along the furrows and, except in soils with adequate moisture, were covered lightly. An Aldrin dust containing 2½% active ingredient was applied in a 30 cm band along the row at the rate of 2 kg of pure Aldrin per hectare. Four to five seeds were placed in hills 59 cm apart in the bottom of the furrow and covered by foot or with the wooden plow. A suspension of Simazin or Atrazin was sprayed in a 30 cm band over the seed at the rate of 3.0 kg of the herbicide (50% active ingredient) per hectare.

The corn was thinned to two plants per hill (40,000 plants per hectare) approximately 2-4 weeks after planting. The second application of nitrogen was banded along one side of the row about 4-6 weeks after planting. Budworm *Spodoptera frugiperda* (J. F. Smith) attack was appreciable at 5 locations, and 2% granulated Telodrin was applied to the buds at the rate of about 15 kg/ha.

TABLE 3. Parent material, physiography, depth, and slope of the soils where the experiments were carried out.

No. of exp.	Parent material	Physiography	Depth of root penetration cm	Slope of land %	Slope of rows %
402	Alluvium over volcanic ash	Hill	40	2.3	0.5
405	Alluvium over andesitic ash	Hill	60	0.9	0.9
406	Alluvium over andesitic ash	Hill	60	3.1	0.7
408	Lacustrine deposit	Old lake bed	50	1.4	1.4
409	Alluvium over andesitic ash	Hill	65	2.3	0.5
410	Alluvium	Hill	70	2.1	0.5
411	Alluvium over andesitic ash	Hill	32	4.0	0.9
412	Alluvium over andesitic ash	Colluvial slope	35	1.7	0.9
413	Alluvium over andesitic ash	Colluvial slope	55	1.9	1.6
414	Andesitic ash	Low terrace	90	0.7	0.7
415	Andesitic ash	Low terrace	10	1.2	1.2
416	Andesitic ash	Low terrace	40	0.3	0.3
417	Mixture of andesitic ash and alluvium	Terrace	90	1.2	1.2
418	Andesitic ash	Hill	60	2.3	1.7
419	Mixture of andesitic ash and alluvium	Hill	55	3.8	0.7
420	Basalt	Hill	80	0.2	0.2
421	Andesitic ash	Hill	50	1.7	1.7
422	Basalt	Hill	75	2.1	2.1
423	Rhyolitic ash	Hill	42	2.8	2.4

TABLE 3. (Continued). Parent material, physiography, depth ,and slope of the soils where the experiments were carried out.

No. of exp.	Parent material	Physiography	Depth of root penetration cm	Slope of land %	Slope of rows %
501	Alluvium	Flood plain	120	0.2	0.2
502	Alluvium over andesitic ash	Hill	45	0.4	0.2
503	Lacustrine deposit	Old lake bed	72	0.4	0.4
504	Lacustrine deposit	Old lake bed	85	1.4	1.4
505	Alluvium over andesitic ash	Hill	55	1.7	0.5
506	Alluvium over andesitic ash	Hill	60	3.8	0.5
507	Alluvium over andesitic ash	Flood plain	73	1.7	0.5
508	Andesitic ash	Low terrace	120	0.4	0.4
509	Andesitic ash	Low terrace	120	0.9	0.9
510	Andesitic ash	Terrace	80	0.5	0.5
511	Andesitic ash	Hill	70	2.4	2.1
512	Andesitic ash and gravel	Hill	80	2.6	2.6
513	Andesitic ash and gravel	Hill	55	1.9	1.9
514	Andesitic ash and gravel	Hill	110	0.9	0.9
515	Basalt	Hill	60	3.0	3.0
516	Basalt	Hill	90	2.6	2.6

The previous crop, dates of several operations, length of the growing season, and vegetative responses to fertilizer applications are shown in Table 4. The corn hybrid, H-220, was planted in all experiments. Vegetative responses to nitrogen were observed at all locations, to phosphorus in 97% of the experiments, and to zinc in 51% of the trials.

TABLE 4. The previous crop, dates of the principal operations, length of the growing season, and vegetative response to applied fertilizers in the experiments conducted in 1964-1965.

No. of exp.	Previous crop	Date of planting	Date of thinning	Date of 2nd application of N	Date of control of budworm	No. of days from planting to physiological maturity	Vegetative response to:
402	Corn	Jun. 4	Jun. 27	Jul. 10	No	130	N,P
405	Sorghum	Jun. 17	Jul. 7	Jul. 10	No	131	N,P
406	Fallow	Jun. 17	Jul. 15	Jul. 16	No	129	N,P,Zn
408	Corn	Jun. 19	Jul. 16	Jul. 16	No	125	N,P
409	Corn	Jun. 19	Jul. 15	Jul. 15	No	127	N,P
410	Fallow	Jun. 18	Jul. 15	Jul. 15	Aug. 5	127	N,P
411	Corn	Jun. 12	Jul. 6	Jul. 14	No	130	N,P
412	Sorghum	Jun. 15	Jul. 6	Jul. 17	No	131	N,P
413	Fallow	Jun. 17	Jul. 6	Jul. 14	No	127	N,P
414	Sorghum	Jun. 19	Jul. 6	Jul. 17	No	127	N,P
415	Corn	Jun. 20	Jul. 13	Jul. 22	No	116	N,P
416	Sorghum	Jun. 18	Jul. 6	Jul. 22	No	126	N,P
417	Sorghum	Jun. 18	Jul. 6	Jul. 17	No	118	N,P,Zn
418	Sorghum	Jun. 13	Jul. 6	Jul. 17	No	128	N,P,Zn
419	Corn	Jun. 13	Jul. 6	Jul. 14	No	132	N,P
420	Chickpea	Jun. 15	Jul. 4	Jul. 15	Jul. 25	129	N,P,Zn
421	Sorghum	Jun. 16	Jul. 4	Jul. 15	Jul. 19	126	N,P,Zn
422	Corn	Jun. 15	Jul. 6	Jul. 15	Jul. 18	127	N,P,Zn
423	Corn	Jun. 11	Jun. 30	Jul. 15	Jul. 22	127	N
501	Corn	Jun. 23	Jul. 16	Jul. 22	No	134	N,P
502	Sorghum	Jul. 15	Aug. 19	Aug. 26	No	128	N,P,Zn
503	Corn	Jul. 7	Jul. 29	Aug. 6	No	130	N,P
504	Chickpea	Jul. 7	Jul. 29	Aug. 6	No	130	N,P,Zn
505	Onion	Jul. 6	Jul. 29	Aug. 17	No	127	N,P,Zn
506	Sorghum	Jun. 22	Jul. 16	Jul. 21	No	130	N,P
507	Fallow	Jun. 23	Jul. 16	Jul. 21	No	128	N,P
508	Corn	Jun. 19	Jul. 10	Jul. 20	No	129	N,P,Zn
509	Corn	Jun. 19	Jul. 10	Jul. 20	No	128	N,P,Zn
510	Corn	Jun. 19	Jul. 10	Jul. 22	No	124	N,P,Zn
511	Corn	Jun. 19	Jul. 9	Jul. 23	No	126	N,P,Zn
512	Corn	Jun. 19	Jul. 9	Jul. 23	No	128	N,P,Zn
513	Fallow-Chickpea	Jun. 19	Jul. 9	Jul. 23	No	128	N,P,Zn
514	Sorghum	Jun. 19	Jul. 9	Jul. 23	No	128	N,P,Zn
515	Fallow-Chickpea	Jun. 18	Jul. 9	Jul. 21	No	125	N,P,Zn
516	Sorghum	Jun. 19	Jul. 9	Jul. 30	No	124	N,P,Zn

Between October 16 and November 26 the corn was harvested from the two central rows of each plot in the 35 experiments. Just prior to harvest, the number of plants and hills, as well as the number of plants attacked by tassel smut [*Sphacelotheca reiliana* (Kühn) Clinton] and common smut [*Ustilago maydis* (D. C.) Corda], were counted. The moisture content of the grain was determined gravimetrically by drying in a forced-draft oven at 105°C. The pollination percentage and the proportion of rotten kernels were estimated for the several treatments at all locations.

Field observations

Each experiment was visited every week to 10 days, and observations were made on those conditions suspected of affecting adversely the development of the corn. The procedures followed in making observations on the different productivity factors are described elsewhere (7). The factors that may have limited corn yields in the 35 experiments are listed in Table 5.

Each day during which symptoms of wilting were observed in any part of an experiment was considered to be a drought day. In some instances, on arriving at an experiment, it was obvious that wilting had begun one or more days earlier; the date of initiation of wilting was estimated in these cases. Drought effects were noted in 14 of the experiments carried out in 1964 but in none of those conducted in 1965.

Rains were quite frequent during the last of August and the first of September, and the moisture content of some of the heavy-textured soils was maintained above the field capacity for extended periods. Based on the rainfall records and a field appreciation of the moisture content of the soil at the time of visits, the duration of the periods that the corn was adversely affected by excess moisture was estimated. As shown in Table 5, excess moisture effects were of greater significance in the 1965 than in the 1964 plantings.

At most locations weeds were adequately controlled by the application of herbicide and the cultivations. In 10 experiments some weeds continued to grow in the plots during the first month afted planting. In all cases, however, most of the weeds were removed before making the second application of nitrogen.

The dates and the degrees of hail damage are given in Table 5. Also, the degrees of leaf damage due to *Helminthosporium turcicum* are reported as very light or light, which correspond roughly to infestation categories 1 and 2, described by Elliott and Jenkins (4).

Statistical analyses

The yield data were corrected to a constant moisture percentage of 12. A covariance analysis with number of plants per plot as covariant was made of the yield data from each experiment. Average plot yields per treatment were corrected to a constant population equivalent to 40,000 plants per hectare.

A quadratic yield equation was calculated for each experiment from the average plot yields per treatment. These equations were obtained by regressing average treatment yields on the linear and quadratic effects of

TABLE 5. Indications of the effects of the principal factors limiting corn yields in the different experiments.

No. of exp.	Drought effect	Excess moisture effect	Weed competition	Hail damage	*Helminthosporium* damage
402	11 days (Jul. 19-29) 20 days (Aug. 8-23, 27-30)	No	No	Light Jul. 13	No
405	7 days (Jul. 21-27) 17 days (Aug. 8-21, 28-30)	No	No	Light Jul. 13	No
406	7 days (Jul. 21-27) 22 days (Aug. 4-21, 27-30)	Light	No	No	No
408	10 days (Jul. 21-30) 21 days (Aug. 7-23, 27-30)	No	Light	Severe Aug. 18	No
409	9 days (Jul. 21-29) 12 days (Aug. 11-22)	No	Light	Light Aug. 3	No
410	5 days (Jul. 25-29) 12 days (Aug. 11-22)	No	Light	No	No
411	8 days (Jul. 22-29) 11 days (Aug. 10-20)	Light	No	No	Very light
412	5 days (Jul. 24-28) 6 days (Aug. 15-20)	No	Light	No	Very light
413	6 days (Jul. 23-28)	No	Light	No	Very light
414	5 days (Jul. 24-28)	No	No	Light Aug. 19	Light
415	5 days (Jul. 24-28)	No	No	No	Light
416	5 days (Jul. 24-28)	No	No	No	Very light
417	5 days (Jul. 24-28)	No	No	No	Very light
418	No	No	No	No	Light
419	No	No	Light	No	Very light
420	No	No	No	No	Light
421	6 days (Jul. 15-20) 18 days (Aug. 5-22)	No	No	No	Very light
422	No	No	No	No	Very light
423	No	No	Light	No	Very light
501	No	Moderate	No	No	No
502	No	Light	No	No	No
503	No	Very light	No	Light Aug. 15	No
504	No	No	No	No	No
505	No	Very light	Light	Light Sept. 10	No
506	No	No	No	No	Very light
507	No	Light	Light	No	Very light
508	No	Moderate	No	No	Light
509	No	Moderate	No	No	Light
510	No	Moderate	No	No	Light
511	No	Moderate	No	No	Light
512	No	Moderate	No	Light Sept. 21	Light
513	No	Moderate	No	Light Sept. 21	Light
514	No	Light	No	No	Light
515	No	Moderate	No	No	Light
516	No	Moderate	Light	No	Light

applied nitrogen, the linear and quadratic effects of applied phosphorus, and the nitrogen x phosphorus interaction. The data corresponding to the treatment 120-60-0 + Zn, were not used in the regression analyses. These yield equations, in terms of kilograms of ear corn per plot, were converted to equations in terms of kilograms of grain per hectare by multiplying by the appropriate factor. Multiple linear regression procedures are described in detail by Draper and Smith (3) and in most text books on statistical methods.

A combined analysis was made of the data obtained in 76 of the 82 experiments conducted during 1962-1965. The experiments not included in the combined analysis and the reasons for discarding them are as follows:

201 — Used as a city dump a few years prior to 1962.
205 — Received annual applications of barnyard manure prior to 1962.
226 — The 60-85 cm soil horizon contained 23.6% exchangeable sodium.
317 — Plot yields were extremely variable giving a coefficient of variation of 48.7%.
322 — Red bottom soil at western edge of area. Considered to be the only soil of this type in the study.
502 — The average plant population of the experiment was only 59% of what it should have been.

Only the yield data obtained with the four levels of applied nitrogen were used in the combined analysis. The study as originally planned did not include a quantitative evaluation of the effect of applied phosphorus. The experiments carried out in 1962 included only two levels of phosphorus and those conducted in 1963-1965 only three levels. Also, the group of treatments used in the experiments did not permit a precise estimate of the N x P interaction.

The purpose of the combined analysis was to estimate the general yield equation in terms of applied nitrogen variables and productivity factors affecting yield, corresponding as closely as possible to the experience obtained at the 76 locations. Multiple linear regression was used for this purpose. The general regression model may be expressed as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots\cdots \beta_n X_n + \epsilon$$

Yield is represented by Y, the applied fertilized variables and productivity factors by X_1, X_2 ------ X_n, and the regression coefficients by β_0, β_1, β_2 ------ β_n. The element, ϵ, is the error, or the amount by which any observation is expected to differ from the value predicted from the regression equation.

The yield data or Y values used in the combined analysis were the grain yields in tons per hectare with 12% moisture corresponding to treatments 0-60-0, 40-60-0, 80-60-0, and 120-60-0 for the 76 experiments, a total of 304 observations. The 36 X-variables used in the full regression model are listed in Table 6. Two of these, the linear and quadratic effects of applied nitrogen, are fertilization variables. Ten X-variables —total soil nitrogen, excess moisture, drought, rooting depth, soil slope, soil texture, previous crop, hail, leaf blight *Helminthosporium turcicum,* and weed competition— are productivity factors. The remaining X-variables include 3 quadratic effects of productivity factors (A^2, B^2, G^2)*, 9 interactions between fertilizer variables and productivity factors (AN, AN^2, BN, BN^2, CN, DN, HN, JN, KN) and 12 interactions between productivity factors (BA, BA^2, CA, CB, DA, DB, HA, HB, JA, JB, KA, KB). Eleven X-variables, the 2 fertilizer variables plus the 9 interactions involving fertilizer variables, have different values for each of the 304 observations; these are called plot variables. The 25 X-variable corresponding to the linear and quadratic effects of the productivity factors plus interactions among these have the same value for the four observations at a given location; these are called site variables.

For the regression analysis the values of many of the X-variables were modified by multiplying or dividing by some number. Other productivity factors were described in the field in relative terms like light, moderate, and severe. These observations were converted to numerical values by using a scale. This process of reducing actual observations to values than can be used conveniently in the analysis is referred to as coding. In the fourth column of Table 6, the kind of coding employed for each variable is indicated.

The numerical values that were used to code different degrees of damage due to excess moisture, hail, *Helminthosporium turcicum,* and weed competition are given in Table 7. Experience indicates that the effect on yield of a given intensity of damage depends upon the stage of development of the corn at the time of the damage. Table 7 is a very preliminary attempt to estimate the relative importance of these four effects in relation to the intensity and time of presentation or duration of the damage. The calculation of the drought index is described in detail in a previous report (6). Soil textures varying from very light (more than 85% sand) to very heavy (more than 45% clay) were given numbers ranging from 1 to 5, respectively.

A regression analysis was made using the 304 sets of values for yield and the 36 X-variables. The following analysis of variance was obtained:

Source	*Degress of freedom*	*Sum of squares*	*Mean square*
Regression	36	458.6839	12.7412
Residual	267	101.9642	0.3819
R = 0.9045		$R^2 = 0.8181$	

The regression coefficients of 14 of the X-variables were not significant at the 5% level. This suggested that it should be possible to find a reduced regression model (one with fewer than 36 X-variables) that would satisfactorily express the relationship between yield and the important X-variables. The procedure followed in arriving at a suitable regression equation has been described by Laird and Cady (5). It was essentially an agronomic approach that involved the following steps: (a) The main effects of each of the

* The quadratic effects of soil nitrogen and previous crop were included as these factors were considered primarily as available nitrogen variables. The quadratic effect of texture was added as its relationship with yield was expected to be parabolic.

TABLE 6. The effects employed as independent variables in the combined analysis, the codification of these, and the general yield function which was calculated.

No. of variable	Effect	Symbol	Codification	Yield function	
				Coefficient	t value
1	Yield without fertilizer			— 1.2479	
2	Applied nitrogen (linear)	N	Kg/ha divided by 40	1.4405	7.59
3	Applied nitrogen (quadratic)	N^2	$(\text{Kg/ha divided by } 40)^2$	— 0.01537	— 0.25
4	Total soil nitrogen (linear)	A	% x 1000	0.04113	2.48
5	Total soil nitrogen (quadratic)	A^2	$(\% \times 100)^2$	— 0.02460	— 2.71
6	A x N	AN	A_c * x N_c x 0.1	— 0.01189	— 0.76
7	A x N^2	AN^2	A_c x N^2_c x 0.1	— 0.008642	— 1.70
8	Previous crop (linear)	B	scale of 10 to 25 was used	0.3526	5.39
9	Previous crop (quadratic)	B^2	$(B_c)^2$ x 0.1	— 0.05258	— 3.13
10	B x N	BN	B_c x N_c	0.005426	0.65
11	B x A	BA	B_c x A_c x 0.01	— 0.4279	— 4.29
12	B x N^2	BN^2	B_c x N^2_c x 0.1	— 0.04051	— 1.48
13	B x A^2	BA^2	B_c x A^2_c x 0.01	0.3089	5.04
14	Excess moisture	C	scale of 0 to 9 was used	— 0.2646	— 11.82
15	C x N	CN	C_c x N_c		
16	C x A	CA	C_c x A_c x 0.1		
17	C x B	CB	C_c x B_c x 0.1		
18	Drought	D	Drought index	0.009340	0.92

TABLE 6. (Continued). The effects employed as independent variables in the combined analysis, the codification of these, and the general yield function which was calculated.

No. of variable	Effect	Symbol	Codification	Yield function	
				Coefficient	t value
19	D x N	DN	D_c x N_c	— 0.009147	— 16.67
20	D x A	DA	D_c x A_c x 0.01	— 0.0007495	— 0.13
21	D x B	DB	D_c x B_c x 0.1	— 0.009498	— 1.49
22	Depth of root penetration	E	Depth in cm		
23	Slope of land	F	(Slope in %) x 10	— 0.006401	— 3.53
24	Texture of 0-15 cm horizon (linear)	G	scale of 1 to 5 was used		
25	Texture of 0-15 cm horizon (quadratic)	G^2	$(G_c)^2$		
26	Hail damage	H	scale of 0 to 6 was used	— 0.2325	— 6.84
27	H x N	HN	H_c x N_c		
28	H x A	HA	H_c x A_c x 0.1		
29	H x B	HB	H_c x B_c		
30	*Helminthosporium turcicum*	J	scale of 0 to 9 was used	— 0.07887	— 0.45
31	J x N	JN	J_c x N_c	0.02137	2.37
32	J x A	JA	J_c x A_c x 0.1	— 0.01672	— 1.17
33	J x B	JB	J_c x B_c	— 0.003237	— 0.79
34	Weed competition	K	scale of 0 to 6 was used		
35	K x N	KN	K_c x N_c		
36	K x A	KA	K_c x A_c x 0.1		
37	K x B	KB	K_c x B_c		

* The suffix c, indicates, that the variable is coded.

TABLE 7. Numerical values corresponding to different degrees of damage due to hail, leaf blight, weed competition and excess moisture when these occur during different parts of the corn growing season.

Observation	Excess moisture				Hail				Leaf blight				Weed competition		
	First 35 days	35-65 days	65-95 days	95 to maturity	First 35 days	35-65 days	65-95 days	95 to maturity	First 35 days	35-65 days	65-95 days	95 to maturity	For 30 days	For 45 days	For more than 45 days
Very light	0	0	1	0	0	0	2	0	0	1	1	0	0	1	2
Light	0	1	3	0	0	1	3	1	0	2	1	0	0	1	3
Moderate	0	2	5	1	0	2	4	1	0	4	3	1	1	2	4
Severe	1	3	7	2	1	3	5	2	1	7	5	2	2	3	5
Very severe	2	4	9	3	1	4	6	2	1	9	7	3	3	4	6

10 X-variables representing productivity factors were tested for significance at the 5% level with the other 9, plus the linear and quadratic applied nitrogen variables, present in the model. Insignificant variables, together with their interactions, were discarded; (b) A model was formed comprising N, N^2, the main effects of the remaining productivity factors, any quadratic effects of these factors that were present in the full model, and all interactions among nitrogen sources variables (N, A, B). Each of the interactions between applied nitrogen and the productivity factors (less those treated as nitrogen sources, A and B) was added separately to the model, regression analyses were made of the new models, and the resulting increases in the regression sum of squares were tested for significance; (c) All significant applied nitrogen x productivity factor interactions, together with the interactions between these same factors and the other nitrogen sources variables, were added to the X-variables mentioned in (b) above to give the final regression model.

EFFECTS OF FERTILIZATION ON CORN YIELDS

Response to nitrogen

The corn yields obtained with the different fertilizer treatments in the 35 experiments carried out in 1964 and 1965 are given in Table 8. Increases in yield due to the application of nitrogen were statistically significant in all experiments except 411 and 502. Unfertilized corn yields in the 35 experiments varied from 0.20 to 4.43 ton/ha with an average of 1.50 ton/ha.

Average increases in yield due to the application of 40, 80, and 120 kg of nitrogen per hectare were, respectively, 1.20, 1.99, and 2.46 ton/ha

TABLE 8. Corn yields obtained in the 35 experiments carried out in 1964-1965. Yields are expressed in metric tons per hectare of grain containing 12% moisture.

Fertilizer treatment	Number of experiment								
	402	405	406	408	409	410	411	412	413
0-0-0	0.98	2.20	0.85	1.51	1.64	2.41	1.17	0.81	1.23
0-60-0	0.98	1.91	0.67	1.00	2.64	2.47	2.57	0.99	1.39
40-60-0	1.79	3.18	1.81	1.60	3.60	3.90	2.89	2.53	2.52
80-60-0	2.67	3.72	2.17	1.78	3.93	4.32	2.64	3.56	2.66
120-60-0	2.82	4.15	2.48	1.87	3.94	4.25	2.88	3.61	3.29
80-0-0	2.14	3.44	1.07	1.41	1.58	3.83	0.89	3.45	2.06
80-30-0	2.51	3.78	1.90	1.45	3.39	3.78	2.40	3.34	2.82
120-60-0 + Zn	2.56	3.97	1.88	1.89	3.85	4.17	2.60	3.82	3.21
L.S.D. at 5% level	0.42	0.42	0.35	0.45	0.39	1.07	0.55	0.72	0.29
Coefficient of variability (%)	14.1	8.8	15.0	19.5	8.6	19.9	16.5	17.8	8.3

Fertilizer treatment	414	415	416	417	418	419	420	421	422
0-0-0	0.20	1.27	1.28	0.55	1.67	1.20	1.53	0.23	1.71
0-60-0	0.31	1.12	1.56	0.88	1.67	1.37	1.55	0.32	1.79
40-60-0	1.95	3.11	2.67	2.30	3.91	2.86	3.17	1.25	2.82
80-60-0	3.44	4.34	3.92	3.86	4.75	4.56	3.65	1.87	4.02
120-60-0	4.67	5.11	4.88	4.82	5.07	5.88	4.42	2.23	4.27
80-0-0	0.89	3.46	4.01	1.67	4.34	4.69	3.33	0.43	2.93
80-30-0	3.01	4.28	4.15	3.83	4.61	4.17	3.84	1.80	3.66
120-60-0 + Zn	4.16	4.78	4.68	5.20	5.17	5.93	5.09	2.22	4.59
L.S.D. at 5% level	0.29	0.42	0.73	0.40	0.80	0.41	1.23	0.44	0.59
Coefficient of variability (%)	8.5	8.3	14.7	9.4	14.1	7.2	15.7	23.3	8.8

Fertilizer treatment	423	501	502	503	504	505	506	507	508
0-0-0	4.36	2.51	1.74	4.43	3.09	1.19	1.95	2.78	1.20
0-60-0	4.55	2.16	2.49	4.46	3.45	0.99	2.38	3.22	1.73
40-60-0	4.74	3.41	2.51	4.64	4.14	2.80	3.55	3.71	2.90
80-60-0	5.85	3.77	2.34	5.01	4.30	3.11	4.82	4.76	3.73
120-60-0	5.94	4.00	2.31	4.86	4.47	3.32	5.17	5.01	4.37
80-0-0	5.73	4.10	2.15	4.82	4.49	1.66	4.34	4.58	3.60
80-30-0	5.56	3.85	2.58	4.74	4.66	3.11	4.81	4.87	3.64
120-60-0 + Zn	5.87	3.59	2.49	4.79	4.44	3.18	5.16	4.98	4.31
L.S.D. at 5% level	0.53	0.45	0.34	0.29	0.46	0.37	0.39	0.64	0.42
Coefficient of variability (%)	6.7	8.9	9.7	4.2	6.3	10.2	6.5	10.2	8.9

Fertilizer treatment	509	510	511	512	513	514	515	516
0-0-0	1.04	0.52	0.77	0.62	0.95	1.51	0.88	0.56
0-60-0	1.37	0.93	0.92	0.89	1.51	1.90	1.29	1.00
40-60-0	2.11	1.67	1.79	1.74	2.22	2.26	2.26	1.86
80-60-0	3.26	2.82	3.28	3.09	3.12	3.85	3.36	2.69
120-60-0	3.78	4.21	4.10	4.18	3.83	4.63	4.18	3.78
80-0-0	2.33	2.51	1.33	1.25	1.53	4.00	2.14	1.10
80-30-0	2.46	3.05	2.83	3.04	2.90	3.62	3.42	2.37
120-60-0 + Zn	4.24	4.20	4.04	4.18	3.79	4.54	4.10	3.66
L.S.D. at 5% level	0.42	0.47	0.54	0.41	0.25	0.59	0.48	0.42
Coefficient of variability (%)	11.1	12.9	12.8	11.9	7.1	12.1	12.1	11.7

in 1964 and 0.80, 1.66, and 2.22 ton/ha in 1965. As an average for the two years, the first, second, and third 40 kg/ha increment of nitrogen increased grain yields by 1.02, 0.82, and 0.51 ton/ha, respectively.

Response to phosphorus

Grain yields were significantly increased by the application of phosphorus in 20 or 57% of the experiments. Vegetative responses to the addition of phosphorus were noted during the early part of the growing season in all experiments except 423.

The average increases in yield due to the application of 30 and 60 kg of P_2O_5 per hectare were 0.68 and 0.86 ton/ha in 1964, and 0.63 and 0.71 ton/ha in 1965. As an average for the two years, the first and second 30 kg/ha increment of P_2O_5 increased grain yields by 0.66 and 0.13 ton/ha, respectively.

Yield functions

The yield equations corresponding to the data obtained in each of the 35 experiments are given in Table 9. The first coefficient in each case, b_0, is the predicted yield in kilograms of grain per hectare without the application of fertilizer. The coefficient, b_1, represents the linear effect of applied nitrogen on yield. It is the slope of the yield function at the origin (zero level of applied nitrogen and phosphorus) measured in the plane of the nitrogen axis. It is the predicted increase in yield per kilogram of applied nitrogen at this point. The coefficient, b_{11}, is the quadratic effect of applied nitrogen. It is a measure of the tendency of the yield function to deviate from a straight line in the plane of the nitrogen axis. Negative values mean that the function curves downward. The larger the absolute value of b_{11}, the greater the curvature away from the straight line. The coefficients, b_2 and b_{22}, are the linear and quadratic effects of applied phosphorus, respectively. They represent values comparable to the linear and quadratic effects of nitrogen, except they are measured in the plane of the phosphorus axis. The coefficient, b_{12}, represents the effect of the interaction between applied nitrogen and phosphorus. It is a measure of the extent to which the increase in yield from applied nitrogen or phosphorus differs when applied alone or in combination with the other. A positive b_{12} coefficient means that the increase in yield due to a given increment of either of the elements becomes progressivelv larger as the level of the other element is increased. The magnitude of the interaction coefficient is a measure of how much the response to one element is affected by the amount of the other element present in the soil.

An examination of the coefficients in Table 9 shows very clearly the great variability in yield without fertilizer and response to nitrogen and phosphorus in the different experiments. It was expected that the yield functions in all cases would have positive linear effects, negative quadratic effects, and positive nitrogen x phosphorus interactions. That is, it was expected that both elements would increase yields, that the rate of increase would be progressively smaller as the level of fertilization was increased,

TABLE 9. Regression coefficients for the quadratic equations ($Y = b_0 + b_1N + b_{11}N^2 + b_2P + b_{22}P^2 + b_{12}NP$) calculated from the yield data for each experiment. Yields are expressed in kilograms per hectare of grain containing 12% moisture and rates of nitrogen and P_2O_5 are given in kilograms per hectare. When the effects of nitrogen and phosphorus were not significant at the 10% level, the coefficients for these elements do not appear in the table.

No. of	Regression coefficients*					
exp.	b_0	b_1	b_{11}	b_2	b_{22}	b_{12}
402	980	22.82	− 0.1040	9.92	− 0.1776	0.0940
405	2199	25.86	− 0.1304	4.50	− 0.1467	0.1327
406	847	13.09	− 0.1291	13.04	− 0.2570	0.2820
408	1510	5.20	− 0.0801	− 19.71	0.1910	0.1897
409	1642	11.12	− 0.1483	57.60	− 0.6783	0.2868
410	2386	34.50	− 0.1589			
411	1026			62.90	− 0.5708	
412	894	50.26	− 0.2297			
413	1228	16.59	− 0.0780	27.22	− 0.3886	0.1233
414	201	13.67	− 0.0633	58.51	− 0.9458	0.5051
415	1270	42.64	− 0.1906	21.55	− 0.3975	0.2204
416	1399	38.10	− 0.0728			
417	548	19.85	− 0.0724	79.90	− 1.2488	0.3702
418	1724	56.68	− 0.2476			
419	1274	42.25	− 0.0313			
420	1526	33.26	− 0.1335	17.40	− 0.2642	0.0921
421	232	9.64	− 0.0892	44.65	− 0.7192	0.2825
422	1712	25.08	− 0.1226	17.92	− 0.2918	0.1860
423	4391	17.82	− 0.0320			
501	2308	31.99	− 0.1469			
502	1959			33.52	− 0.4339	
503	4433	7.74	− 0.0336			
504	3276	26.00	− 0.1346			
505	1203	24.61	− 0.2390	38.68	− 0.6828	0.3736
506	2011	39.26	− 0.1229	25.68	− 0.3458	− 0.0112
507	2784	25.53	− 0.0367	26.46	− 0.3361	− 0.0842
508	1488	35.67	− 0.1000			
509	997	18.13	− 0.0352	− 4.85	0.1738	0.1228
510	528	16.31	0.1039	32.93	− 0.4350	− 0.0255
511	775	8.85	− 0.0046	38.30	− 0.6122	0.3132
512	630	4.98	0.0405	62.95	− 0.9829	0.2930
513	961	7.66	− 0.0008	46.67	− 0.6340	0.1960
514	1651	24.74	0.0090			
515	869	17.81	− 0.0212	53.86	− 0.7900	0.1589
516	553	3.66	0.0445	36.19	− 0.4767	0.2369

* The regression coefficients are estimations of the following effects: b_0 = yield without fertilization; b_1 = linear effect of applied nitrogen; b_{11} = quadratic effect of applied nitrogen; b_2 = linear effect of applied phosphorus; b_{22} = quadratic effect of applied phosphorus; b_{12} = interaction between nitrogen and phosphorus.

and that the increase per increment of nitrogen or phosphorus would be larger when applied in the presence of the other. In general, it is seen that the nature of fertilizer response at the several locations is in agreement with expectations. Linear effects of nitrogen were always positive and quadratic effects were negative except in three experiments. The positive quadratic effect of nitrogen was not significant at the 10% level in experiments 512 and 514 and was significant at the 5% level in experiment 510. Linear and quadratic effects of phosphorus were positive and negative, respectively, except in experiments 408 and 509. The negative linear effect of phosphorus was not significant at the 10% level in experiment 408 but was highly significant in experiment 509. The negative N x P interactions (experiments 506, 507 and 510) were not significant at the 10% level.

Response to zinc

The application of zinc sulfate significantly increased the yield of grain in only one experiment, 509. Vegetative responses to zinc were observed during the early part of the growing season at 18 or 51% of the locations. The average effect of the application of 75 kg of zinc sulfate per hectare was a decrease in grain production of 0.04 ton/ha.

COMBINED ANALYSIS OF NITROGEN RESPONSE DATA

The combined analysis of the yield data corresponding to the 0-60-0, 40-60-0, 80-60-0 and 120-60-0 treatments at 76 locations produced the general yield function given in the fifth column in Table 6. The regression equation consists of a constant term and 23 independent variables. As seen in the last column of Table 6, eleven of the regression coefficients have t values less than 1.97, and so are not significant at the 5% level. These 11 variables were retained in the model because agronomic considerations, as mentioned earlier, lead to the conclusion that they should be present. The analysis of variance for this regression is given below:

Source	*Degrees of freedom*	*Sum of squares*	*Mean Square*
Regression	23	441.8715	19.2118
Residual	280	118.7766	0.4242

The R^2 for this regression equation is 0.788 which is a relative indication of the "goodness of fit" of this model to the experimental data (5). An F-test was made to appraise the significance of the regression sum of squares corresponding to the 13 variables discarded from the full model in arriving at the solution in Table 6. This value was 3.39 which was significant at the 1% level.

The coefficients in Table 6 are the values that are multiplied by the levels of the different independent variables in estimating yield for a specific set of conditions. Several of these regression coefficients have values that are greatly different from what one would expect their real effect to be. The main effects of drought and leaf blight, for example, are insignificant instead of large negative values. This failure of the regression coefficients to reflect the real effects of the different variables on yield was due to the fact that the independent variables were correlated with each other. Twenty-four of these simple correlation coefficients, for example, had absolute values greater than 0.90. Consequently, in the regression analysis, the variation in yield due to differences in levels of an independent variable, e.g., drought, was accounted for partially by the drought variable but also by other variables such as DN, DA and DB that were highly correlated with D. Thus, the true effect of a given independent variable was accounted for by a group of correlated variables, and the individual regression coefficients did not express the true influence of the different variables on yield.

The primary objective of this study was to produce a general yield equation useful in estimating fertilizer needs for specific conditions. For this purpose it makes little difference whether or not individual regression coefficients are meaningful. The relatively high percentage of the total variation in yield accounted for by the equation in Table 6 is reasonable assurance that this equation can be useful in estimating nitrogen needs for specific producing conditions.

USE OF THE GENERAL YIELD EQUATION FOR MAKING SPECIFIC NITROGEN RECOMMENDATIONS

The general yield equation in Table 6 is used to estimate nitrogen needs of corn for specific producing conditions in the area of the study. The productivity factors that appear as independent variables in the general equation are total soil nitrogen, excess moisture, previous crop, drought, soil slope, hail, and leaf blight. By knowing the values for these 7 factors corresponding to a specific field, the specific yield function for that field is readily calculated.

Total soil nitrogen is determined by analyzing a composite soil sample from the plow layer of the field to be fertilized. Soil slope is measured or estimated at the time of taking the soil sample. Information on previous crop is supplied by the farmer. An estimate is made of the expected damage due to hail and leaf blight based on previous experience. The probabilities of different drought indices are taken from Table 12 of the previous report (6) by knowing the geographical location, texture, and rooting depth of the soil (This information on probabilities is reproduced here as Table 10). The excess moisture effect is based on previous experience taking into account soil texture, depth and slope. Some of these productivity factors are easily and accurately characterized while others can only be roughly estimated. Therefore, an efficient agricultural advisory service is required for the effective use of this general equation in making specific fertilizer recommendations.

The use of the equation in Table 6 will be illustrated by calculating the nitrogen recommendations for growing corn under specific conditions in El Bajio. It will be assumed that the soil to be fertilized is a deep clay with 1.4% slope located two kilometers south of Pénjamo. The total nitrogen percentage of the plow layer is 0.085, the previous crop was corn, the effects of excess moisture and leaf blight are expected to be light, and the effect of hail is expected to be zero. The values corresponding to the

TABLE 10. Probabilities of different drought intensities, expressed as percentages, for four soil conditions at 10 locations in Guanajuato, Michoacan and Jalisco. [This is a reproduction of Table 12 from the previos report (6)].

Location and average annual precipitation	Soil condition	Categories of drought indices					
		0	10	30	50	80	120
Silao, Gto. 532 mm	I	12	12	23	12	18	23
	II	12	6	29	6	23	24
	III	6	6	23	6	35	24
	IV	0	6	6	12	47	29
Aldama, Gto. 647 mm	I	20	27	0	13	20	20
	II	20	13	13	13	20	21
	III	13	20	13	13	13	28
	IV	7	13	7	13	33	27
Irapuato, Gto. 645 mm	I	25	25	25	8	0	17
	II	25	17	33	8	0	17
	III	25	0	33	25	0	17
	IV	8	8	8	34	25	17
Abasolo, Gto. 677 mm	I	40	13	13	14	20	0
	II	34	20	13	13	20	0
	III	20	13	27	13	27	0
	IV	7	13	13	20	40	7
Pénjamo, Gto. 676 mm	I	44	19	6	19	6	6
	II	31	31	6	6	19	7
	III	6	37	19	13	19	6
	IV	0	12	19	25	25	19
La Piedad, Mich. 765 mm	I	50	36	0	14	0	0
	II	43	36	7	14	0	0
	III	21	43	14	22	0	0
	IV	7	29	29	14	21	0
El Salto, Mich. 938 mm	I	86	7	0	0	7	0
	II	71	14	7	0	8	0
	III	57	14	14	7	8	0
	IV	21	29	29	7	14	0
Ayo El Chico, Jal. 892 mm	I	69	15	8	8	0	0
	II	62	23	0	15	0	0
	III	31	54	0	7	8	0
	IV	8	23	46	15	8	0
Atotonilco, Jal. 860 mm	I	67	17	5	11	0	0
	II	56	22	11	11	0	0
	III	22	39	17	22	0	0
	IV	11	22	28	17	22	0
Tototlán, Jal. 846 mm	I	75	17	0	0	8	0
	II	67	25	0	0	8	0
	III	50	33	8	0	9	0
	IV	17	58	17	0	8	0

six site variables other than drought are substituted into the general yield function and, after collecting terms, the following equation is obtained:

$$\hat{Y} = 1.8451 + 1.4422N - 0.1496N^2 + 0.009340D - 0.009147DN - 0.0007495DA - 0.009498DB$$

Yield is expressed in tons per hectare and the unit of nitrogen is 40 kg/ha.

In the previous study (6) the probabilities of six drought indices (0, 10, 30, 50, 80, and 120) were reported for four soil conditions at ten locations in the area of study (Table 10). The next step, therefore, is to calculate the nitrogen response functions corresponding to these six drought indices by substituting in the above equation. These functions are plotted in Figure 2 and illustrated the influence of drought on corn yields. It is

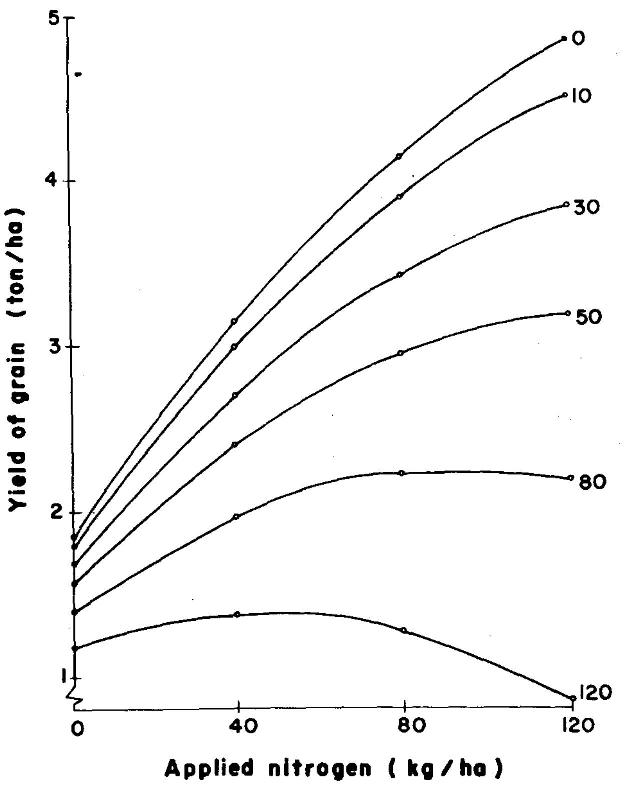

Fig. 2. Yield curves estimated from the general yield function for six different drought indices and average levels of the other site variables.

interesting to compare these curves with those in Figure 4 of the previous report which were based on a less precise estimate of the effect of drought. The shapes of the two sets of curves are very similar. The predicted yields at zero level of fertilization were unaffected by drought in the earlier calculation, while, with the function in Table 6, they decline as the drought index increases. This latter relationship is more in accord with general information on drought effects.

According to the information in Table 10 the probabilities expressed as percentage of years with indices of drought equal to 0, 10, 30, 50, 80 and 120 are 44, 19, 6, 19, 6 and 6 respectively, for deep clays near Penjamo. Also, as developed in the same report, the first derivative of the prediction equation (or slope of the yield curve) should be equal to 11.46 kg of grain per kilogram of applied nitrogen at the point on the abscissa corresponding to the optimal rate of fertilization. With these values one proceeds to estimate that optimal rate of fertilization using an iterative procedure. The first step is to guess the optimal rate. This was estimated to be 90 kg/ha and the first derivatives of the equations corresponding to the six categories of drought were solved for N = 90. The six solutions were multiplied by their respective probability percentages and the products were added. The resulting value was appreciably larger than 11.46, thus indicating that the estimated optimal rate, 90 kg/ha, was too small. The second guess was 105 kg/ha. Again the first derivatives of the 6 equations were solved for N = 105, multiplied by the corresponding probability percentages and totalled. The new value was slightly less than 11.46 indicating that the true optimal rate was less than 105 kg/ha. A third guess of 100 kg/ha was made and the calculations repeated. The resulting value was 11.59 which was considered to be sufficiently close to the desired value. Thus, the optimal rate of nitrogen fertilization for corn in deep clay soils near Penjamo was estimated to be 100 kg/ha.

Similar calculations were made using the probability percentages corresponding to the four soil conditions at each of the ten locations given in Table 10. The estimated optimal rates of nitrogen fertilization for the 40 ecological conditions are given in Table 11. It will be remembered that the other site characteristics used in these calculations were 0.085% total soil nitrogen in the plow layer, 1.4% slope, previous crop was corn, light effects of excess moisture and leaf blight, and zero effect of hail. These site characteristics, perhaps, are about average for the area so that the values in Table 11 represent nitrogen recommendations for four soil conditions at 10 locations with average values of the other producing conditions.

It may appear that the calculations involved in estimating the optimal rate of nitrogen fertilization for a given field are too long to permit the general use of this procedure for making specific fertilizer recommendations. Actually, however, the use of this equation can be greatly simplified by preparing tables of recommendations corresponding to a useful range of values for the 7 productivity factors. The specific recommendation for a given field, then, is taken directly from the table. If electronic computer facilities are available the use of the general equation for estimating specific nitrogen recommendations is further simplified.

TABLE 11. Optimal levels of nitrogen fertilization expressed in kilograms per hectare for four soil conditions in the vicinities of 10 weather stations in the region of study.

Weather Station	Average annual rainfall mm	Soil condition*			
		I	II	III	IV
Tototlan, Jal.	886	120**	120	115	110
Atotonilco, Jal.	860	120	118	107	86
Ayo El Chico, Jal.	892	120**	119	112	94
El Salto, Mich.	938	120**	119	112	99
La Piedad, Mich.	765	118	116	107	88
Pénjamo, Gto.	676	100	93	84	55
Abasolo, Gto.	677	97	96	85	63
Irapuato, Gto.	645	89	87	79	57
Aldama, Gto.	647	71	66	62	47
Silao, Gto.	532	63	58	49	32†

* Heavy clays with the following rooting depths: I - 90 cm; II - 70 cm; III - 50 cm; IV - 30 cm.

** More than 120 kg/ha.

† The application of nitrogen in this case is economical only when it is not necessary to apply phosphorus.

PHOSPHORUS RECOMMENDATIONS

As mentioned earlier only two levels of phosphorus were used in the experiments carried out in 1962 and only three levels were used in the subsequent studies. For this reason the combined analysis did not include applied phosphorus variables. Considerable information was accumulated in these trials, however, on corn response to phosphorus fertilization. Therefore, an attempt has been made to interpret these data and express the conclusions in a form useful for making specific recommendations on phosphorus needs.

Increases in grain yields due to the explication of 60 kg of P_2O_5 per hectare were calculated by substracting the yields obtained with the treatment 80-0-0 from those reported for the treatment 80-60-0. The correlations between these yield increases and the levels of available phosphorus in the soils, as determined using the Peech and Bray I methods, were calculated. The correlation coefficients, as shown in Table 12, were highly significant but relatively small.

The relative yields without applied phosphorus were calculated by dividing the yields obtained with the treatment 80-0-0 by those reported for the treatment 80-60-0 and multiplying the quotient by 100. Correlations between relative yields without phosphorus and (a) levels of available phosphorus as determined by the two methods as well as (b) the logarithms of

TABLE 12. Correlations between the effect of applied phosphorus on corn yields and the level of available phosphorus in the soil. All correlation coefficients are significant at the 1% level.

Effect of applied phosphorus expressed as:	Available phosphorus in the soil			
	Peech method		Bray I method	
	kg/ha	Log (kg/ha)	kg/ha	Log (kg/ha)
1 Increase in yield (80-60-0) – (80-0-0)	– 0.457	——	– 0.298	——
2 Relative yield $\frac{80\text{-}0\text{-}0}{80\text{-}60\text{-}0} \times 100$	0.507	0.607	0.333	0.379

the levels of available phosphorus, were calculated. As seen in Table 12 these correlation coefficients were somewhat larger than those obtained using yield increases. Also, relative yields were more highly correlated with the logarithms of the levels of available phosphorus than with the absolute levels of available phosphorus. It is seen that both increases in yield due to phosphorus fertilization and relative yields without phosphorus are more highly correlated with levels of available phosphorus as determined using the Peech method than those obtained with the Bray I method.

These correlations indicate that differences in levels of available soil phosphorus, as measured by these methods, account for relatively little of the variation in yield due to the application of phosphorus. Nevertheless, these soil test values are useful in predicting whether or not a soil will respond to added phosphorus. To arrive at a rough estimation of the level of available phosphorus to use in separating responding and non responding soils, relative yields without applied phosphorus were plotted against available soil phosphorus as determined by the Peech and Bray I methods. A line was drawn at a relative yield of 85 on the assumption that smaller values corresponded to a response and larger values to a lack of response. By trial and error the level of available soil phosphorus was identified, which would have been most successful in grouping the soils used in this study into responding and non responding categories. This level was 6 kg/ha for the Peech method and from 7 to 15 kg/ha for the Bray I method. Using these values as the limit between responding and non responding soils, the Peech method placed the soils of this study in the correct category in 77% of the cases while the Bray I method was successful 69% of the time. This procedure for finding the "critical soil test level" is very similar to that described by Cate and Nelson (2).

Thus, it appears that a soil test for available phosphorus can be useful in deciding whether or not to apply phosphorus to a given soil. Also, as mentioned in the earlier report (6), the physiographic position of a soil in the area of study is a useful indication of the need for phosphorus fertilizaton. Therefore, a decision can be made on the basis of a soil test or other information as to the need for applying phosphorus. The next step is to decide how much phosphorus to apply. The information on corn response to three levels of applied phosphorus, which is contained in the yield equations in Table 9, is useful for answering this question.

The equations in Table 9 were used to estimate the optimal rates of phosphorus fertilization for the 24 experiments at which a response to phosphorus was observed. The predicted optimal rates varied from 4 to 58 kg of P_2O_5 per hectare with an average of 33 kg/ha. Next, the interactions between nitrogen and phosphorus were examined and found to be positive, except in three cases with insignificant negative values. This means that, at a given level of available soil phosphorus, the optimal rate of phosphorus fertilization increases as the rate of nitrogen fertilization increases. The quantitative effect of this interaction on the optimal rate of phosphorus fertilization was estimated by calculating the optimal rates of this element corresponding to levels of nitrogen fertilization varying from 40 to 120 kg/ha. Nine of the yield equations in Table 9 predicted optimal rates of nitrogen of 120 kg/ha or more and were used for this calculation. The optimal rates of P_2O_5, averaged for the 9 equations, were 47.7, 39.8 and 31.9 kg/ha with the application of 120, 80 and 40 kg of nitrogen per hectare, respectively.

These results suggest a rule-of-thumb for use in estimating the recommended rate of phosphorus fertilization: Use the average optimal rate of phosphorus calculated for the 120 kg/ha rate of nitrogen fertilization (47.7 kg of P_2O_5 per hectare), as a reference. Estimate the recommended rate of nitrogen fertilization for the desired producing system from the general yield equation (Table 6). Reduce the optimal rate of phosphorus corresponding to 120 kg/ha of nitrogen by 0.1975 kg of P_2O_5 per hectare $\left[\frac{47.7 - 31.9}{120 - 40}\right]$ for each kilogram that the recommended rate of nitrogen fertilization is less than 120 kg/ha. For example, the nitrogen recommendation for soil condition III at Irapuato with other site variables at about average levels (Table 11), is 79 kg/ha. Therefore, the recommended rate of P_2O_5 should be $47.7 - [(120\text{-}79)(0.1975)] = 39.6$ kg/ha. This procedure, in which the recommended rate of nitrogen is used in estimating the phosphorus recommendation, can be employed more easily using the graph in Fig. 3.

This criterion for estimating recommended rates of phosphorus fertilization was used to calculated the amounts of this element to apply in combination with the nitrogen rates listed in Table 11. The resulting fertilizer recommendations for the 10 weather stations were then grouped into four rainfall categories. These general recommendations for four soil conditions in four areas receiving different amounts of rainfall are given in Table 13. These rates of fertilization were estimated for the lower limit of each of the four rainfall categories. Phosphorus rates were rounded off to the next lowest increment of 5 kilograms.

It will be remembered that the nitrogen rates in Table 11 were estimated for about average values of the site variables other than drought (0.085% total soil nitrogen, 1.4% soil slope, previous crop was corn, effects of excess moisture and leaf blight expected to be light, effect of hail expected to be zero). Therefore, the general recommendations in Table

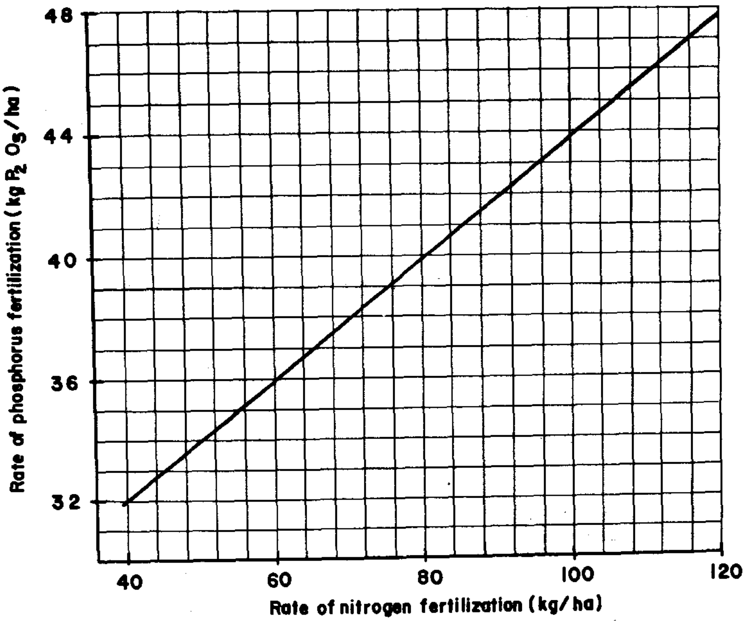

Fig. 3. The relationship between the recommended rates of nitrogen and phosphorus fertilization.

13 should be useful when specific information on site variables other than drought is not available. The general yield equation in Table 6 and the criterion for estimating phosphorus needs offer a more adequate means of estimating the best fertilizer treatment when information on all productivity factors is available for the specific field for which a recommendation is sought.

SUMMARY

Fertilizer experiments were carried out with unirrigated corn at 82 locations in the western part of El Bajio during the four-year period, 1962-1965. The results obtained in the experiments conducted during 1964 and 1965 are reported here; the results obtained in 1962 and 1963 were published earlier. The purpose of this study was to produce a general yield function useful in estimating nitrogen fertilizer needs of unirrigated corn for specific producing conditions and to acquire a better understanding of the problems involved in measuring the productivity factors and in calculating a general yield function.

The average annual rainfall in the area of study varies from slightly more than 500 mm in the north to about 900 mm in the south. The soils have formed from relatively old extrusive volcanic materials, varying from

TABLE 13. Fertilizer recommendations for growing unirrigated corn on four soil conditions in regions receiving different amounts on rainfall.

Soil properties	Average annual rainfall in mm			
	525-600	600-675	675-800	800-950
Heavy clays 90 cm in depth*	60-30**	70-35	100-40	120-45
Heavy clays 70 cm in depth or light-textured soils 110 cm deep	55-30	65-30	95-40	118-45
Heavy clays 50 cm in depth or light-textured soils 75 cm deep	45-30	60-30	85-35	110-40
Heavy clays 30 cm in depth or light-textured soils 45 cm deep	0-0	45-30	55-30	90-35

* Depth of root penetration.
** Kg/ha or nitrogen and P_2O_5, respectively.

basaltic to rhyolitic in composition. Eighteen of the soils studied in 1964-65 were heavy-textured, 6 were medium-textured, and 11 were light-textured. Eleven of the soils had rooting depths less than 60 cm, 18 from 60 to 90 cm, and 6 more than 90 cm.

Grain yields of unfertilized corn varied from 0.20 to 4.43 ton/ha with an average of 1.50 ton/ha. Corn responded significantly to the application of nitrogen at all locations except two. The application of 120 kg of nitrogen per hectare increased the average yield by 2.35 ton/ha.

Grain yields were increased significantly by the application of phosphorus in 20 or 57% of the experiments. The application of 60 kg of P_2O_5 per hectare increased the average yield by 0.79 ton/ha.

Vegetative responses to zinc during the early part of the growing season were observed at 18 or 51% of the locations. However, a significant increase in grain production was only noted in one experiment .

The yield data corresponding to four levels of nitrogen fertilization at 76 locations were combined into a general yield function comprising 23 independent variables. These consisted of the linear and quadratic effects of applied nitrogen, 7 productivity factors, 2 quadratic effects of productivity factors, and 12 interactions among applied nitrogen variables and productivity factors. An agronomic approach was followed in deriving the general yield equation.

The use of the general function in estimating nitrogen recommendations for specific producing conditions is illustrated. The estimated optimal rates for four soils conditions at ten locations were calculated.

The simple correlation between the relative yield without applied phosphorus and the logarithm of available soil phosphorus as determined by the Peech method was 0.607. Using 6 kg of P_2O_5 per hectare as the limit between responding and non responding soils, this method placed the soils of this study in the correct category in 77% of the cases.

Based on the observed responses to phosphorus fertilization and the magnitude of the nitrogen x phosphorus interactions, a rule-of-thumb was suggested for estimating the recommended rate of phosphorus fertilization. This criterion was used together with the general yield equation for nitrogen to calculate general fertilizer recommendations for four soil conditions in four areas receiving different amounts of rainfall. It was pointed out that these general recommendations may be used when specific information on site variables is not available. However, when information on the productivity factors is available for the field for which a recommendation is desired, the general yield equation and the criterion for estimating phosphorus needs offer a more adequate means of estimating the best fertilizer treatment.

LITERATURE CITED

1. Castillo Méndez, Roberto, 1965. Instrucciones para el uso de las estaciones climatológicas. Circular A. Décima Edición. Dir. de Geog. y Meteor., S.A.G., México.
2. Cate, Robert B., Jr. and Larry A. Nelson. 1965. A rapid method for correlation of soil test analyses with plant response data. Tech. Bul. No. 1, Int. Soil Testing Series, North Carolina State University, Raleigh, N. C.
3. Draper, N. R. and H. Smith. 1966. Applied Regression Analysis. John Wiley & Sons, Inc. New York.
4. Elliott, Charlotte and Merle T. Jenkins. 1946. *Helminthosporium turcicum* leaf blight of corn. Phytopathology 36:660-666.
5. Laird, R. J. and F. B. Cady. 1968. Combined analysis of yield data from fertilizer experiments. Agron. J. In press.
6. Laird, R. J. and J. Horacio Rodríguez G. 1965. Fertilización de maíz de temporal en regiones de Guanajuato, Michoacán y Jalisco. Folleto Técnico No. 50, I.N.I.A., S.A.G., México.
7. Laird, R. J. 1968. Field Technique for Fertilizer Experiments. Res. Bul. No. 9, CIMMYT, México.