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A METHOD OF ECONOMIC ANALYSIS APPLIED TO NITROGEN FERTILIZER RATE
PASCHAL, J L ; FRENCH, B L 1 OF 1

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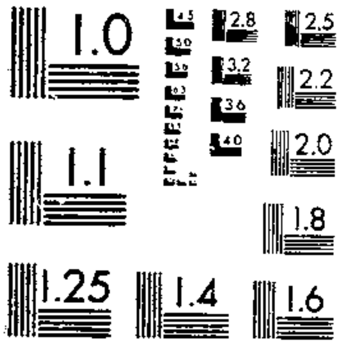
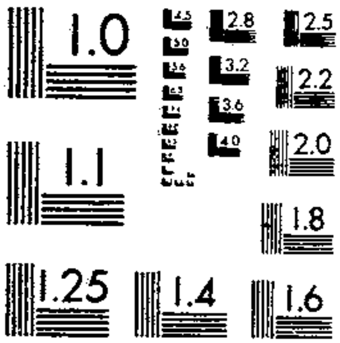


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



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A Method of Economic Analysis Applied to Nitrogen Fertilizer Rate Experiments on Irrigated Corn[1]

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SUMMARY

Marginal economic analysis can be applied to the relationship between nitrogen fertilizer as an input factor and crop yields to determine the rate of application of fertilizer that will maximize returns from its application. This method of analysis is supplemental to other analyses of experimental data by methods specified by the designs of agronomic experiments. This bulletin reports on the application of a method of economic analysis illustrated by experimental results from plots designed to test the application of nitrogen fertilizer on irrigated corn in Oregon, Washington, and Nebraska. Under existing information, the exponential function ($Y_j = M - AR^{X_i}$) is a logical function to represent the relationship for the application of a single input. This function is used to represent the yield response curve of experimental data.

Unless the economic implications of the most profitable rate in terms of the comparative returns to nitrogen are observed, the relative importance of different rates may be overlooked. The most profitable rate of application at which returns to nitrogen will be maximized may be identical for two different situations but the returns to nitrogen may differ greatly. The comparative returns to nitrogen form the primary criterion by which one situation can be selected over the other.

Differences between the most profitable rates of nitrogen application for an estimated yield curve and its confidence limit curves may be substantial, but the differences in the return to nitrogen are small. The most profitable rate is located on a section of the response curve on which errors of 20 to 40 pounds of nitrogen applied per acre will result in relatively small differences in the return to nitrogen. If the price–cost relationship should change so that the most profitable rate is located nearer the zero application, where the slope of the response curve is larger, errors of that magnitude would produce larger differences in the return to nitrogen by "underapplication."

The difference between the price of corn estimated at the time nitrogen is applied and the actual price at harvesttime must be quite large before the most profitable rate and the return to nitrogen at that rate are changed appreciably. Errors in prediction of the price of corn within the applicable range of the different response curves, therefore, are negligible. They may be offset by many other uncertain factors. Year-to-year changes in the price of nitrogen of less than 20 percent affect the return to nitrogen only slightly.

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In the few experiments for which data were available, the first-year residual nitrogen produced a yield sufficient to pay much, if not all, of the cost of nitrogen applied. Indications are that on fields of low fertility the increased crude protein (6.25 × N) content of the corn (grain) more than paid the cost of nitrogen applied. On such fields the value of the increased yield and quality of the corn stover, if measured, might have paid for the greater part of the fertilizer applied. The data suggest that the most profitable rate computed in this study on the yield of grain alone is conservative, if the potential quality factors of grain and stover and the yield response to residual nitrogen are included in the value of the product.

Data reviewed in this study suggest the need of more specific characterization of yield curves as a basis for economic analysis of fertilizer-response data. This is especially true for the upper end of the yield curve. Measurement of total plant yields and of quality factors are also needed to evaluate more fully the returns associated with fertility and other treatments. The methodology of economic analysis needs to include these evaluations of response associated with fertilizer. It should also evaluate increased consumption of other plant nutrients as yield is increased.

Most of the Washington and Oregon experiments studied were on plots of low fertility, with adequate water applied. Ordinarily the most profitable rates of nitrogen application ranged between 100 and 200 pounds per acre. The return to nitrogen above its cost per acre was $50 or more for a majority of the experiments and above $30 for most of them when corn was valued at $1.40 a bushel and nitrogen at 15 cents a pound. In 2 experiments in Washington the return to nitrogen exceeded $100 per acre.

INTRODUCTION

How to use commercial fertilizer is a problem that confronts farm operators and others who are concerned with farm production. Many interrelated factors are involved in developing a fertility program for a given farm. Some of these are type of soil, kind of crop, crop rotations and tillage practices, number and kind of livestock, and amount of moisture available. Full information on the precise contribution of each of the factors to the final product is never available. Comprehensive research on all phases of the farm production process as a unit is not attempted in controlled experiments because of the cost and complexity of such research. Separate factors are studied in detail and findings are coordinated in an attempt to achieve maximum net returns for the farm.

Use of commercial fertilizers has become increasingly important in the West. Studies have been made to determine yields to be obtained from varying rates and methods of application. Notable increases in the yields of irrigated corn have been obtained with nitrogen fertilizers. It has been found that yields of corn on irrigated soils are rarely limited by lack of phosphorus (*13*).[2] As yields of corn can be increased with nitrogen, additional information is needed on how much to use to get the most profitable response. Experiments by agronomists who have investigated the response of corn to nitrogen have been conducted under various controlled conditions at selected

[2] Italic figures in parentheses refer to Literature Cited, p. 62.

locations. Results of these experiments provide valuable data which, together with experiences of farmers, may be used to help guide fertilizer programs for specific farm situations.

Experimental data from 3 Western States on the response of irrigated corn to 3 or more rates of applied nitrogen are used in this study.[3] The objectives of the study are to illustrate some of the problems involved in economic analysis of fertilizer-rate experiments and to suggest procedures that may improve the results of such analysis. The most profitable rate of application of nitrogen for each experimental situation has been estimated from the methods used. In addition, economic implications of the results are shown, including the effect of underapplication or overapplication of nitrogen, the effect of deviations from the estimated response curve, and the effect of changes in the price of corn and of nitrogen.

CHARACTER OF DATA FOR ECONOMIC INTERPRETATION

To estimate the most profitable rate of nitrogen application for specified conditions, approximation of the functional relationship between yields of corn and nitrogen fertilizer is necessary. This functional relationship should be based on yields obtained from four or more rates of application at a given location in a season. Actually, relatively few experiments have included four or more rates. The highest rate of nitrogen application should indicate the point at which additional fertilizer would produce little, if any, additional yield.

Essentially all nitrogen-rate experiments in the irrigated sections of the West having four or more rates of application were considered for this report. Some experiments were omitted because they did not have rates that extended over a wide enough range to permit an adequate description of the response relationship. Others were omitted because the response patterns were indefinite and still others because they were affected by nonexperimental factors such as frost or bird damage. Few experiments have been repeated sufficiently under similar test conditions to establish definite response patterns for specific conditions. Therefore, results of these experiments apply only to the particular experimental site and to the conditions described. The accuracy with which the results can be extended to other fields depends on the extent to which the conditions of the experiment represent conditions in the field to be fertilized.

METHODS OF ANALYSIS

PRINCIPLES OF ECONOMIC ANALYSIS

A relationship exists between the yield of corn and the quantity of nitrogen fertilizer applied per acre, as illustrated by the total physical product (*TPP*) curve in figure 1-A. As more nitrogen is applied, the additional quantity of corn produced with each successive unit of nitrogen becomes smaller until a maximum yield is obtained. The total cost of nitrogen—expressed in bushels of corn—also is shown in figure 1-A. Return above the cost of nitrogen at any rate of application is illustrated by the vertical distance between the total cost and

[3] In this study, the zero rate (check plot) is one of the rates of nitrogen application.

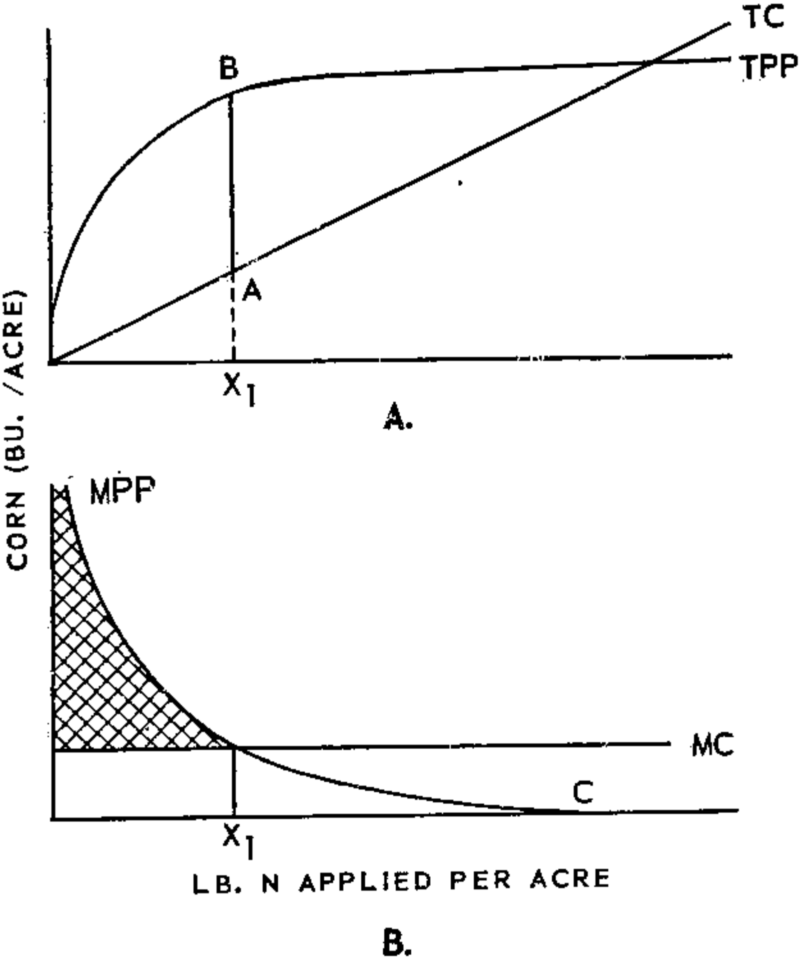

FIGURE 1.—Physical product and costs of corn related to applied nitrogen.

the total product curves as, for example, in line *AB*. If the cost of nitrogen is the only cost to be considered, the most profitable quantity to apply is that quantity or rate at which the distance between the two curves is greatest. Line *AB* in figure 1-A is so drawn.

Bushels of corn associated with each additional quantity of nitrogen are shown in figure 1-B as the marginal physical product (*MPP*). The marginal yield diminishes with successive units of nitrogen until it reaches zero, as shown by point *C* in figure 1-B. Each successive unit of nitrogen used costs the same as the preceding unit so the marginal costs of nitrogen are constant, as shown by line *MC* in figure 1-B. The net return to nitrogen is greatest when nitrogen is applied at that rate at which the last unit just pays for itself in terms of the additional corn produced by it. The most profitable rate of application as illustrated in figure 1-B is at point X_1. At this rate of application the total return to nitrogen is greatest, as illustrated by the shaded area of figure 1-B.

Return to nitrogen as used subsequently in this report refers to the difference between the cost of the total application of nitrogen at any given rate and the value of the increase in yield associated with the given rate of application. It is a net value of the increase in yield associated with the rate of fertilizer application. Return to nitrogen is the basis for comparisons and evaluations of the experimental data used in this report.

Economic analysis of fertilizer-rate experiments requires an understanding of both the nature of the experiments and the methods used in experimental design and in the statistical interpretation of their results. Experimental results must be interpreted in such a way as to isolate the effects of fertilizer on yield from the effects of other factors. The functional relationships between fertilizer and yield then can be described and used as a basis for economic analysis.

EXPERIMENTAL DESIGNS AND FUNCTIONAL RELATIONSHIPS

Field experiments are designed to compare results obtained from different controllable factors. The bases of comparisons are the differences in the quantity or quality of the product obtained from variations in methods of applying fertilizer and rates of application, methods of applying water or the quantity of water applied, the timing of water application, and so on. Studies of more than one of these factors within the same experiment often are combined for economy. Each of the controlled factors included in the experiment, as well as uncontrolled sources of variation, influence the results. Experiments must be designed and analyzed in such a way that significant differences resulting from each of the controlled factors can be isolated for analysis.

For one such design, equation (1) expresses the relationships between yield response and factors, the effects of which are to be appraised:

$$(1) \qquad Y_{ij}=\mu+\beta_i+\tau_j+\epsilon_{ij},\ i=1,\ 2,\ 3,\ 4;\ j=1,\ 2,\ .\ .\ .,\ 12;$$

in which μ is the mean effect, β_i is the *i*th block effect, τ_j is the *j*th level of nitrogen effect, and ϵ_{ij} is the random plot error. The effects of each of these factors may be identified and tested for the reality of a difference between the means of the levels of nitrogen, and between the means of different replications. Differences between the yields of individual plots can be related to the levels of nitrogen application, excluding or removing random variation between plots.

The quantity of nitrogen applied to obtain an increase in yield that can be specifically attributed to fertilizer is determined by the test of least significant difference (*LSD*).[4] If the increased yield between two successive treatments is greater than the least significant difference, the increase in yield between treatments is considered to be greater than could have occurred by chance. The value for the increase in yield is then computed and compared with the cost of the added fertilizer to determine the profitability of that particular rate of application.

[4] $LSD=t_\alpha s\sqrt{2/r}$, in which t_α is Student's *t* at α probability level, *s* is the square root of the error mean square from the analysis of variance, and *r* is the number of replications.

This method is illustrated with data from a 12-rate experiment. The treatment mean yields are shown in table 1. The analysis of variance for this experiment is:

Source of variation	*Degrees of freedom*	*Sums of squares*	*Mean squares*
Replications	3	945.29	315.10
Fertilizers	11	30,622.42	2,783.85
Error	33	2,191.95	66.66
Total	47	33,767.67	

On the average, the variation between the treatment means and the overall mean is greater than the variation of the treatment plots about each treatment mean.

The least significant difference with a probability of 0.05 is 11.78 bushels. In comparing the least significant difference with the changes in yields, it will be seen that a significant increase is obtained between applications of 80 and 100 pounds of nitrogen per acre, as the increase in yield is greater than 11.78 bushels which might have occurred by chance. Any increase in yield from the application of more than 100 pounds of nitrogen per acre might be attributed to differences in the soil between plots, uneven operation of fertilizer spreader, and so on.

An increased yield of 14.2 bushels of corn was obtained by adding 20 pounds of nitrogen to the 80-pound rate. At $1.40 per bushel, this extra corn is worth $19.88, whereas at $0.15 a pound, the added 20 pounds of nitrogen costs $3. Thus, the increased yield will more than pay for the additional 20 pounds of nitrogen.

A continuous relationship between the treatment mean yields and the quantity of nitrogen applied may be a function of the form

$$\overline{Y}_j = M - AR^{X_j} \quad (2)$$ [5]

in which $\overline{Y}_j$ is the mean yield for the jth treatment, M is the maximum yield which is approached as the quantity of fertilizer is increased, A is the increased yield which theoretically might be possible between the yield at no application of fertilizer and the maximum attainable yield, R is the ratio between successive increments in the yield for uniform increments in quantity of fertilizer applied, and X_j is the quantity of fertilizer applied to the jth treatment measured in units that are multiples of q pounds. This relationship between the treatment mean yields and the units of fertilizer applied is supplemental to equation (1) rather than a substitute for it.

Variation in yields attributed to treatment is further subdivided into that explained by the functional relationship and the deviations from the functional relationship. This procedure is equivalent to that used in tests of the linear, quadratic, or cubic effects in the treatments for factorial experimental designs. The complete analysis of variance is now:

Source of variation	*Degrees of freedom*		*Sums of squares*		*Mean squares*	
Replications	3		945.29		315.10	
Fertilizers	11		30,622.42		2,783.85	
Due to regression	--	2	--------	29,567.41	--------	14,783.71
Deviations about regression	--	9	--------	1,063.53	--------	118.17
Error	33		2,191.95		66.66	
Total	47		33,767.67			

[5] A discussion of the choice of the function is presented in a later section.

By comparing the mean squares for that part of the variation that is due to regression with the part that arises from deviations about regression of the fertilizer treatments, or the error mean square, we find that the regression or functional relationship is very significant. Approximately 88 percent of the total variation—measured by the ratio of the sums of squares that are due to regression to the total sums of squares—is explained by relating the treatment mean yields to nitrogen.

The maximum return from applying fertilizer can be determined by equating the value of the increments in yield with the value of the increments in fertilizer as

$$(\Delta Y)P_y=(\Delta X)P_x \tag{3}$$

in which ΔY is the yield increment, ΔX is the fertilizer increment, P_y is the value of the product per unit, and P_x is the cost of q pounds of fertilizer. In table 1 the fertilizer increment, ΔX, is 20 pounds, and the yield increment, ΔY, is the yield obtained with each successive unit of nitrogen. With corn at $1.40 per bushel and nitrogen at $3 for 20 pounds, the value of the yield increment exceeds the cost of the fertilizer increment for each unit up to and including the sixth, and it would pay to apply at least 6 units, or 120 pounds of fertilizer. The value of the corn produced by the sixth unit is $11.62.

TABLE 1.—*Incremental costs of and returns to nitrogen on irrigated corn, experiment 10, Ontario, Oreg., 1952* [1]

Nitrogen applied per acre		Y (mean yield per acre)	ΔY (change in yield per acre)	$(\Delta Y)P_y$ (value of change in yield)	$(\Delta X)P_x$ (cost of added fertilizer)
Units	*Pounds*	*Bushels*	*Bushels*	*Dollars*	*Dollars*
0	0	64.6			
2	40	90.4	25.8	36.12	6.00
4	80	118.2	27.8	38.92	6.00
5	100	132.4	14.2	19.88	3.00
6	120	140.7	8.3	11.62	3.00
7	140	141.0	.3	.42	3.00
8	160	146.8	5.8	8.12	3.00
9	180	141.2	−5.6	−7.84	3.00
10	200	147.1	5.9	8.26	3.00
12	240	145.8	−1.3	−1.82	6.00
14	280	147.4	1.6	2.24	6.00
16	320	143.6	−3.8	−5.32	6.00

[1] Corn is valued at $1.40 per bushel and nitrogen at 15 cents a pound, or $3 for 20 pounds.

The exponential function implies that any increase in fertilizer however small, produces an increase in yield. If the most profitable application is estimated by the fitted function, it is found to be 172 pounds of nitrogen. If the increases in nitrogen application are stopped at 100 pounds (estimated by the least significant difference method from reported yields) the maximum return may not be attained. An additional 72 pounds of fertilizer may be applied, each of which can be expected to produce an additional return that exceeds the additional cost.

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FORM OF THE FUNCTIONAL RELATIONSHIP

The functional relationship used in this analysis to estimate yield response of corn to nitrogen fertilizer is expressed by the exponential form:

$$\hat{Y}_j = M - AR^{X_j} \quad (4)$$

in which $\hat{Y}_j$ is the yield of corn at the jth rate of fertilizer application, M is the maximum yield that may be obtained by the addition of nitrogen fertilizer, A is the increase in yield attributable to nitrogen fertilizer, and X_j is the quantity of fertilizer applied at the jth rate of application. This form of the yield function is attributed to Spillman (*17*). Mitscherlich (*11*) developed a function equivalent to that of Spillman. The values of M, A, and R are constant for a given experiment. However, they vary between experiments because of different levels of other plant nutrients available, plant populations, level of soil fertility, temperature, soil condition, and many other factors.

The exponential form of the function is consistent with the principle of diminishing increments. As additional units of nitrogen are applied, the yields of corn increase at a diminishing rate. However, the ratio of each yield increment to the preceding yield increment, R, is constant for all increments of a particular experimental function. The use of this function is consistent with existing experimental evidence.

There are some limitations in using the exponential function to characterize the yield response to fertilizer. This function does not provide for decrements. The level at which this function may be inaccurate, however, generally involves rates of application beyond the range that is economically feasible. Although the mathematical least-squares method of estimating the constants for the exponential function provides standard errors of each constant, the sampling distributions of the constants have not been discovered (*18*). Nevertheless, the standard errors make it possible to evaluate these constants in terms of the variability of the experimental data.

Analysts have used several other functions to reflect the relationships between responses to fertilizers (*4, 7*). Precise selection of any specific mathematical function to express the relationship of plant growth to an input factor depends on detailed experimental evidence. Until such evidence is available, the choice of the function is somewhat arbitrary. The exponential function is considered adequate for the data in this report.[6]

COMPUTATIONAL PROCEDURE FOR EXPONENTIAL FUNCTIONS

Procedures developed by Spillman (*17*), which were used in earlier studies (*6, pp. 8–15; 12, pp. 3–11*), provide least-squares estimates

[6] One that closely approximates the exponential function over the range of most of the experimental data available is the quadratic square root $\hat{Y}_j = a + b_1 X_j + b_2\sqrt{X_j}$, in which $\hat{Y}_j$ is the yield that results from the jth rate of fertilizer application and X_j is the quantity of fertilizer applied at the jth rate. The terms a, b_1, and b_2 are constants obtained in a multiple regression analysis. The quadratic square-root function is of the polynomial form of the second degree with the inputs, X_j, transformed to the square root of the input, $\sqrt{X_j}$. An advantage of this function is that it provides for decrements to the higher rates of application.

of the constants in the exponential equation, $Y_j = M - AR^{X_j}$. However, estimates cannot be made of the standard errors of the constants. To overcome this limitation, a procedure is available for a least-squares solution which provides estimates of the standard errors (*18*). The computations are straightforward, though tedious. They require an initial estimate of R, the ratio between successive increments of yield response. Equations to be solved for M, A, and $A\delta R$, when δR is the correction to be made in the trial R, are

$$(5)\quad \begin{cases} nM + A\sum_{j=1}^{n} R^{X_j} + AR\sum_{j=1}^{n} X_j R^{X_j-1} = \sum_{j=1}^{n} Y_j \\ M\sum_{j=1}^{n} R^{X_j} + A\sum_{j=1}^{n} R^{2X_j} + AR\sum_{j=1}^{n} X_j R^{2X_j-1} = \sum_{j=1}^{n} R^{X_j} Y_j \\ M\sum_{j=1}^{n} X_j R^{X_j-1} + A\sum_{j=1}^{n} X_j R^{2X_j-1} + AR\sum_{j=1}^{n} X_j R^{2X_j-2} = \sum_{j=1}^{n} X_j R^{X_j-1} Y_j \end{cases}$$

in which n is the number of treatment means, Y_j is the mean yield for the jth treatment, X_j is the number of q-pound units of fertilizer applied to the jth treatment, and $j=1$ . . . . is the summation over the n values of X_j or Y_j. The solution of these simultaneous equations may follow such methods as the Doolittle or abbreviated Doolittle. The equations in matrix form are:

(6) $B \cdot C = G$; with

$$B = \begin{pmatrix} n & \sum_{j=1}^{n} R^{X_j} & \sum_{j=1}^{n} X_j R^{(X_j-1)} \\ \sum_{j=1}^{n} R^{X_j} & \sum_{j=1}^{n} R^{2X_j} & \sum_{j=1}^{n} X_j R^{(2X_j-1)} \\ \sum_{j=1}^{n} X_j R^{(X_j-1)} & \sum_{j=1}^{n} X_j R^{(2X_j-1)} & \sum_{j=1}^{n} X_j^2 R^{(2X_j-2)} \end{pmatrix}$$

$$C = \begin{pmatrix} M \\ A \\ A\delta R \end{pmatrix}, \text{ and } G = \begin{pmatrix} \sum_{j=1}^{n} Y_j \\ \sum_{j=1}^{n} R^{X_j} Y_j \\ \sum_{j=1}^{n} X_j R^{(X_j-1)} Y_j \end{pmatrix}$$

By inverting the matrix B to provide B^{-1} and multiplying both sides of (6) by the inverse, we have

$$(7)\qquad C = B^{-1} \cdot G,$$

when

$$B^{-1} = D = \begin{pmatrix} D_{11} & D_{12} & D_{13} \\ D_{12} & D_{22} & D_{23} \\ D_{13} & D_{23} & D_{33} \end{pmatrix}$$

and

$$(8)\quad \begin{cases} M=D_{11}\sum_{j=1}^{n}Y_j+D_{12}\sum_{j=1}^{n}R^{X_j}Y_j+D_{13}\sum_{j=1}^{n}X_jR^{(X_j-1)}Y_j \\ A=D_{12}\sum_{j=1}^{n}Y_j+D_{22}\sum_{j=1}^{n}R^{X_j}Y_j+D_{23}\sum_{j=1}^{n}X_jR^{(X_j-1)}Y_j \\ A\delta R=D_{13}\sum_{j=1}^{n}Y_j+D_{23}\sum_{j=1}^{n}R^{X_j}Y_j+D_{33}\sum_{j=1}^{n}X_jR^{(X_j-1)}Y_j. \end{cases}$$

The adjusted $R'=\delta R+R$ is used as a second estimated R and the computations are repeated, each time using the new estimated R' until the value of δR is approximately equal to zero. Computational procedures for inverting the matrix are provided in several references (*1, 2*).

The sums of the squares of the deviations from the fitted regression curve

$$(9)\qquad \sum_{j=1}^{n}(Y_j-\hat{Y}_j)^2$$

are computed by determining the predicted yield, $\hat{Y}_j$, for each applied treatment and squaring the deviations from the experimental yield. The estimated residual variance is $s^2=\sum_{j=1}^{n}(Y_j-\hat{Y}_j)^2/(n-3)$ in which $(n-3)$ is the number of degrees of freedom for the exponential curve.

The estimated variance of the constants are:

$$(10)\qquad s_M^2=s^2D_{11};\ s_A^2=s^2D_{22};\ s_R^2=s^2(D_{33}/A^2).$$

By assuming that the sampling distributions of the constants are normally distributed about their population value and using the upper and lower confidence limits of the constants, we might determine an upper and lower limit curve as follows:

$$(11)\quad \begin{aligned} \hat{Y}^{(1)}&=(M-s_Mt_{\alpha,\,n-3})+(A+s_At_{\alpha,\,n-3})(R-s_Rt_{\alpha,\,n-3})^X \\ \hat{Y}^{(2)}&=(M+s_Mt_{\alpha,\,n-3})+(A-s_At_{\alpha,\,n-3})(R+s_Rt_{\alpha,\,n-3})^X \end{aligned}$$

in which $Y^{(1)}$ is the lower limit function and $Y^{(2)}$ is the upper limit function. These limit curves represent the limits within which we have α confidence that the population or "true" curve under the conditions of the experiment will be included. For the study reported here, the value of α is taken to be 0.67.

The variance of the predicted yield for any unit value of fertilizer input is

$$(12)\quad s^2_{\hat{Y}_{X=k}}=s^2[D_{11}+X^2R^{(2X-2)}D_{33}+R^{2X}D_{22}+ 2XR^{(X-1)}D_{13}+2R^XD_{12}+2XR^{(2X-1)}D_{23}].$$

The initial estimate for R may be obtained in various ways. Stevens (*18*) gives the formula

$$R = \frac{Y_n - Y_1}{Y_{(n-1)} - Y_o} \tag{13}$$

in which Y_o is the response to the zero application, Y_1 to the first rate, Y_n to the last rate, and $Y_{(n-1)}$ to the next to the last rate applied. Use of this formula requires that the number of q units of fertilizer between the zero rate and the first rate be equal to the number between the last rate and the next to the last rate. Usually a closer estimate for R for initial computations has been obtained by the graphic method of estimation outlined by Ibach and Mendum (*6*). Fewer iterations are required to obtain the best fit when the initial estimate of R is closer to the least-squares estimate.

In analyzing the experimental data reported here, both the mathematical method and the graphic method of least-squares estimation of the constants are used. The decision as to which should be used on the different experiments was somewhat arbitrary. In general, mathematical methods of estimation were obtained for all experiments with rates adequate to characterize the response curves.

ANALYSIS OF TREATMENTS OTHER THAN NITROGEN

Many factors other than fertilizers affect the yield of crops. They include spacing, application of moisture, level of moisture, placement of fertilizer, type of material carrying fertilizer nutrients, and others. The methods of analyzing the effects of these factors differ. A functional relationship between input factors and the product can be expressed, if the input factor can be quantified in specific terms. For example

$$Y = f(X_1, X_2) \tag{14}$$

in which Y is the yield, X_1 is nitrogen fertilizer, X_2 is the quantity of water applied, and $f(. . . .)$ denotes some functional relationship.

However, few input factors can be quantified so specifically. The quantity of water applied (both in the form of irrigation and in rainfall) can be measured, but other conditions, such as the time and method of application, may have as much effect on yield as the total quantity. Two treatments in which the same quantity of water is applied in the same number of applications, but at different dates, may produce different yields. On the other hand, two treatments in which twice the quantity of water is applied in one as in the other may produce nearly the same yield if the smaller quantity is applied at critical periods (*14, p. 23*).

The best, and most valid, comparisons of such nonquantifiable factors may be the effect of these factors on the response to fertilizer (*3*). The curves may approach the same maximum, but one factor may cause the yield to approach the maximum at a lower rate of fertilizer input than another.

In some experiments, tests of hypotheses outlined by the experimental design resulted in no significant differences between treatments other than nitrogen fertilizer. The test of significance determines whether or not the differences *between* treatments are greater than the differences *within* treatments. Even though the test reveals no greater difference between treatments than within treatments, it cannot be concluded that there are, in fact, no substantial differences between treatments. The analysis of variance test of a hypothesis minimizes the possibility of indicating a difference between treatments when no real difference exists. However, this test may fail to measure differences that do exist. Therefore, merely not rejecting a hypothesis of no difference between levels of other treatments, such as phosphorus, does not permit pooling of data for all levels when estimating the nitrogen response curve. It is known, a priori, that there is a difference, for example, between plots receiving no phosphate and plots receiving 100 pounds of phosphate. Therefore, the nitrogen response curve for each nonnitrogen treatment has been analyzed independently and the comparisons have been made between the maximum returns to nitrogen for each response curve.

LIMITATIONS OF COST AND BENEFIT CALCULATIONS

When fertilizer is used, costs are increased by more than just the cost of the fertilizer. The cost of applying fertilizer is not directly related to the quantity used. It decreases per pound applied in other than a direct relation. However, these differences are so small that for purposes of analysis the cost per pound of nitrogen is computed to include the average cost of application.

Costs of harvesting the product on a per acre basis—the unit for which the yield of corn is measured—are not increased in direct proportion to the increase in yield. As yields increase, harvesting costs per acre also increase for items such as labor, fuel, and equipment use. The effect, however, is to reduce the average per unit cost for all units harvested. Marginal costs of harvesting incurred with increases in yields may be relatively small and difficult to estimate. In the study reported here, corn is valued at an assumed market price minus a flat charge per bushel for harvesting.

Additional use of other plant nutrients, such as P_2O_5, K_2O, and water, may be an added cost of the higher yields obtained by using different rates of nitrogen. In most experiments reported here, data are not available to evaluate this increased use of the other elements.

The increase of crude protein in corn grain obtained by nitrogen fertilizer may be considered in terms of higher feeding values as a product of the application of nitrogen. This response is a potential benefit which was not fully evaluated in the analysis reported here.

Still another benefit of nitrogen fertilizer that was not reported for these experiments is the yield and quality of corn stover, that is, stalks and leaves without the grain. The yield response to the residual nitrogen in successive years after the initial application is a product of the application of nitrogen, but data from only a relatively few experiments are available for evaluating these residual effects. The value of both general soil improvement and erosion control as a result of increased production of organic matter and its return to the soil needs to be considered, but experimental data with which evaluations could be made were not recorded for the experiments studied.

EXPERIMENTS STUDIED

LOCATION

Thirteen experiments on the application of nitrogen to irrigated corn were conducted in east-central Oregon. Four of these were at the Malheur Experiment Station at Ontario, Oreg., and nine were on farms in adjoining areas. Seven experiments were in south-central Washington, in the Grand Coulee irrigation project. Five of these were on the Moses Lake Development Farm, and two were on the Irrigation Experiment Station Farm at Prosser. An experiment at the Umatilla Field Station at Hermiston, Oreg., was also in this general area. In the irrigated areas of Nebraska, seven experiments were at the Scotts Bluff Experiment Station in western Nebraska, and one was on a farm near Hardy in south-central Nebraska.

OBJECT OF EXPERIMENTS

Nitrogen was known to increase yields greatly in areas in which the experiments were conducted, but additional information was needed to ascertain the response to different rates of nitrogen applied in conjunction with different cultural practices. To obtain the maximum information from available research resources, as many different conditions as possible were included in the experiments with nitrogen. Only three experiments were designed and conducted specifically for the purpose of ascertaining the most profitable rate of application by procedures used in this report. These were experiment 10 at Ontario, Oreg., experiment 51 at Hardy, Nebr., and experiment 32 at Prosser, Wash. These experiments were designed primarily to obtain information on yield response for use in investigating the technical aspects of economic analysis of fertilizer-rate experiments.

TEST SITUATIONS

In all these areas, the growing season is adequate and the climate suitable for production of irrigated corn at yields that exceed 100 bushels per acre. Irrigation is essential to successful production of corn in all these areas except south-central Nebraska. In Washington and Oregon precipitation is limited. Ordinarily it is of little consequence in the growing season. For this reason, the moisture variable can be controlled by proper irrigation. At the Scotts Bluff station in Nebraska, precipitation in the growing season sometimes alters the number and extent of irrigations needed.

The number of irrigations applied in the various experiments ranged from 3 to 15. In general, in the experiments in south-central Washington, more irrigations were applied than are commonly applied by farmers. On the plots in the Ontario, Oreg., area, the most common number of irrigations by farmers was 5. The quantity of water applied in each irrigation apparently varied considerably, but in only a few instances was the quantity reported.

The irrigation schedule for 3 experiments in Washington and 1 each at Hermiston, Oreg., and Scottsbluff, Nebr., was determined by tensiometers which measure soil moisture. In the remaining experiments, the plots were irrigated on the basis of experience and judgment by the technicians and, in the case of farm experiments, by the farm operators.

All soils in the Washington area experiments are fine sandy loams of the Ritzville and Ephrata series. Those at Scottsbluff, Nebr., are Tripp very fine sandy loam. At Hardy, Nebr., they are Waukesha silty clay loams. At Ontario, Oreg., most of the soils are silt loams but they are not formally classified.

Ordinarily, phosphate is not applied to corn in any area studied. Experimental evidence does not indicate need for phosphorus at Ontario, Oreg. Phosphorus was applied, however, at a single rate to the plots in several nitrogen experiments as a precaution in case it became a limiting factor when high rates of nitrogen were applied.

Adapted corn hybrids were used in each experiment. Idahybrid 544 was used in 11 of the 13 experiments at Ontario, Oreg. In Nebraska, adapted hybrids, Nebraska 301 and 504 and Iowa 4316, were used, and in the Washington experiments, hybrid Iowa 939 was used.

ONTARIO, OREG., EXPERIMENTS

On eight experiments conducted on farm fields, the farmer performed all production practices; irrigation, including timing and quantity of water applied, was done in the usual way. Technicians selected a site within the field, applied the fertilizer, and harvested and measured the yields. These experiments are numbers 2, 3, 5, 6, 7, 11, 12, and 13 (table 2). The number of irrigations for these experiments varied from 4 to 15, but the quantity of water was not measured. Most farmers irrigated 5 times in the growing season, but 1 farmer irrigated every 4 or 5 days in June, July, and August. The plant population varied from 9,700 to 21,400 plants per acre. The rate of planting varied between farms. (See appendix table 40 for details of test conditions of these experiments.)

Response to nitrogen was studied in experiments using both 100 pounds of P_2O_5 per acre and no P_2O_5. The analysis indicated no significant difference between yields with and without P_2O_5 (*5*). In 6 of the 8 experiments, corn followed several years of row crops to which very little commercial fertilizer or manure had been applied. In the other two experiments, corn followed alfalfa.

Results of these experiments indicate that nitrogen increased yields on 6 of the 8 farms to a level of approximately 110 bushels per acre, as shown in table 2. Little increase in yield was obtained from nitrogen in experiments 5 and 6, both of which were on alfalfa land. The yield on the check plots in experiment 6, which followed 1 year of alfalfa, was 125 bushels per acre with a plant population of 21,000, and the yield on the check plots in experiment 5, which followed 4 years of alfalfa, was 110 bushels per acre, with a plant population of 11,000.

Technicians controlled all operations in planning and conducting experiments 1, 4, 8, and 9. Most operations also were controlled in experiment 10 which was conducted on a farm field. In 1 experiment, corn was irrigated 4 times; in 3 experiments, 5 times; and in 1 experiment, 8 times. The plant population ranged from 15,120 to 23,230 plants per acre. Experiments 1 and 4 at the Malheur Experiment Station indicated that there was no response to phosphate fertilizer, as shown in table 2. (See appendix table 40 for details of test conditions of these experiments.)

TABLE 2.—*Yield of irrigated corn per acre, in response to applied phosphate and nitrogen, Ontario, Oreg., 1950, 1951, and 1952* [1]

Experiment	Farm and year	P_2O_5 applied per acre	Yield, by nitrogen applied per acre [2]				
			0 pounds	50 pounds	100 pounds	150 pounds	200 pounds
		Pounds	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
1	Malheur Expt. Station, 1950.	0	130.8	142.0	135.6	137.9	------
		100	131.1	139.6	140.9	------	------
2	Moeller, 1950	0	44.5	83.1	106.7	117.1	------
		100	48.4	88.4	113.8	108.3	111.2
3	Hobson, 1950	0	39.8	64.5	66.3	78.4	------
		100	49.1	63.1	64.6	57.9	80.2
4	Malheur Expt. Station, 1951.	0	81.4	100.8	117.2	96.0	------
		100	89.8	105.7	120.9	109.5	------
5	Van de Water, 1951	0	110.9	117.1	105.3	112.3	103.9
		100	107.7	114.4	116.1	109.8	95.8
6	Custer, 1951	0	124.5	128.7	124.4	118.2	117.9
		100	113.6	127.3	128.0	123.8	120.6
7	Moeller, 1951	0	64.0	87.4	104.0	114.3	110.4
		100	58.9	98.7	108.9	111.4	107.7
8	Malheur Expt. Station, 1951.	0	112.9	130.2	135.5	135.2	------
11	Cloud, 1952	0	55.7	97.6	104.6	114.2	110.5
		100	62.8	98.7	107.9	112.7	114.7
12	Martin, 1952	0	71.3	95.9	107.7	98.3	112.7
		100	63.9	92.1	98.5	102.2	113.5
13	Benedict, 1952	0	90.5	109.0	105.9	113.2	108.0
		100	82.8	109.8	108.5	108.1	104.9

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 40 for reference and test conditions.

[2] Applied as ammonium sulfate a few days after planting, approximately 4 inches from one side of the row and 3 to 5 inches deep.

Corn followed several years of row crops in experiments 4, 9, and 10. Experiments 4 and 9 were on land that had been well fertilized in previous years. Experiment 10 was on land that had received 20 pounds of nitrogen the previous year; it had had no fertilizer for the 7 preceding years. Experiments 1 and 8 were on land that had recently been in alfalfa.

The yield pattern for experiments controlled by technicians appeared to be somewhat higher than for experiments on farmer-controlled fields (see tables 2 and 3). For 3 technician-controlled experiments—1, 8, and 9—yields ranged from 95 bushels or more per acre for the check plots to about 130 bushels per acre with 150 pounds of nitrogen. In experiment 4, the yield was 80 bushels per acre with no nitrogen and 117 bushels with 100 pounds of nitrogen. The range in yields for experiment 10, which was on a field of relatively low fertility, was from 65 bushels per acre with no nitrogen to 146 bushels with 240 pounds of nitrogen applied per acre (table 4).

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TABLE 3.—*Yield of irrigated corn per acre, in response to applied nitrogen, experiment 9, Malheur Experiment Station, Ontario, Oreg., 1952* [1]

Nitrogen applied per acre (pounds) [2]	Yield by spacing between rows [3]			
	30 inches	36 inches	38 inches	42 inches
	Bushels	*Bushels*	*Bushels*	*Bushels*
0	98.0	94.6	96.7	100.1
50	110.8	126.4	120.4	121.9
100	130.4	134.2	129.3	128.9
150	140.2	138.4	134.5	119.4

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 40 for reference and test conditions.
[2] Applied as ammonium sulfate a few days after planting, approximately 4 inches from one side of the row and 3 to 5 inches deep.
[3] Within-the-row spacing 9 inches in all rows.

TABLE 4.—*Yield of irrigated corn and crude protein per acre, in response to 12 rates of applied nitrogen, Western States, 1952–53* [1]

Nitrogen applied per acre (pounds)	Average yield per acre						
	Experiment 10 [2]			Experiment 51 [3]			Experiment 32 [4]
	Corn	Nitrogen	Protein (6.25xN)	Corn	Nitrogen	Protein (6.25xN)	Corn
	Bushels	*Percent*	*Pounds*	*Bushels*	*Percent*	*Pounds*	*Bushels*
0	64.6	1.11	250	22.6	1.38	109	12.5
40	90.4	1.16	368	69.6	1.33	324	49.9
80	118.2	1.26	520	102.2	1.42	508	89.3
100	132.4	1.29	598	111.2	1.50	584	----
120	140.7	1.35	666	113.1	1.66	657	107.5
140	141.0	1.35	668	125.6	1.67	734	----
160	146.8	1.40	718	121.2	1.70	721	113.5
180	141.2	1.44	712	125.7	1.68	739	----
200	147.1	1.49	766	119.4	1.78	744	134.4
240	145.8	1.47	749	129.2	1.78	805	133.1
280	147.4	1.53	788	129.6	1.68	762	140.3
320	143.6	1.53	770	123.9	1.74	755	134.3
360	----	----	----	----	----	----	153.2
440	----	----	----	----	----	----	155.7
520	----	----	----	----	----	----	149.9

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications.
[2] 50 pounds of P_2O_5 per acre applied to all plots in experiment 10, Ontario, Oreg. Nitrogen applied as ammonium sulfate. See appendix table 40 for reference and test conditions.
[3] See appendix table 42 for reference and test conditions on experiment 51, Hardy, Nebr.
[4] See appendix table 41 for reference and test conditions on experiment 32, Prosser, Wash. Crude protein yield not available.

EXPERIMENTS IN CENTRAL WASHINGTON AND AT HERMISTON, OREG.

Eight experiments of nitrogen application to irrigated corn were conducted in this area (*9, 15, 19, 20*). (See appendix table 41 for details of test conditions of these experiments).[7] Technicians controlled all phases of these experiments. Except for experiment 33 at Hermiston, Oreg., and experiment 29 at Moses Lake, Wash., they were conducted on virgin soils. Some of the virgin soils had to be leveled before the corn was planted and irrigated. In experiment 30, the virgin soil was seeded to alfalfa and cropped for 3 years before it was plowed and used for the corn experiment.

The number of irrigations in these experiments ranged from 3 to 15. Moisture control in 4 experiments was guided by means of tensiometers. Experiment 27 included 2 moisture levels, with the lower level limited to 3 irrigations, which were insufficient to insure satisfactory response to nitrogen. In all other experiments in this area, irrigations ranged from 7 to 15, and apparently they varied considerably in the quantity of water applied at each irrigation period. In experiment 30 at Moses Lake 3.08 acre-feet of water was applied in 9 irrigations. In experiment 33 at Hermiston, Oreg., in the southern part of this south-central area, 5.07 acre-feet of water was applied in 15 irrigations, 3.65 acre-feet in 11 irrigations, and 4.21 acre-feet in 13 irrigations.

Experiments 26 and 33 included 3 levels of moisture and 2 rates of plant spacing. Experiment 29 tested 3 methods of placing the fertilizer, and experiment 31 tested differences among 5 nitrogen carriers. In experiment 27 the effect of a vetch cover crop preceding corn and 2 levels of moisture was studied, and in experiment 28 the response to the residual nitrogen from experiment 27 was measured. Experiment 32, at Prosser, included 12 rates of nitrogen application ranging from 0 to 520 pounds per acre. This was done to learn the response to nitrogen at high rates of application and to provide data with which to compare different functions for the yield curve.

Plant populations ranged from 14,500 to 32,700 plants per acre in experiments 26 and 33. Plant populations were constant in each of the other experiments, but they varied among experiments. In all instances the virgin soils apparently were low in available nitrogen, and large increases in yield were obtained from the application of nitrogen fertilizer, as shown in tables 4 to 10. In this area, soil phosphorus is considered sufficient for production of corn. With adequate moisture, application of nitrogen resulted in yields of up to approximately 150 bushels of corn per acre.

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[7] 1953 ANNUAL REPORT, COLUMBIA BASIN INVESTIGATIONS. Division of Soil Management, Irrigated and Dry Land Regions, BPISAE. [Unpublished.]

Nelson, C. E., and Viets, F. G., [Jr.] A COMPARISON OF SIDE PLACING, SIDE DRESSING AND BROADCASTING COMMERCIAL FERTILIZER ON FIELD CORN. U. S. Bur. Plant Indus., Soils, and Agr. Engin., Res. Rpt. 184, 5 pp., illus. 1950. [Unpublished.]

TABLE 5.—*Yield of irrigated corn per acre, in response to various fertility treatments, 3 moisture levels, and 3 plant spacings, experiment 26, Prosser, Wash., 1947* [1]

Nitrogen applied per acre—		Yield, by moisture level [2] and plant spacing [3]					
At planting time (pounds)	Later (pounds)	M_1S_1	M_1S_2	M_2S_1	M_2S_2	M_3S_1	M_3S_2
		Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
0	0	20. 9	9. 7	24. 6	11. 6	19. 8	13. 6
40	0	48. 3	47. 5	49. 2	38. 9	54. 2	33. 8
60	0	77. 3	60. 1	77. 4	72. 5	72. 3	62. 7
80	0	95. 7	76. 7	77. 2	78. 7	92. 5	85. 9
120	0	120. 1	105. 4	110. 9	120. 6	118. 7	122. 6
40	40	83. 2	62. 0	81. 8	71. 3	72. 1	78. 9
60	60	107. 6	91. 4	101. 6	106. 1	99. 8	101. 2
80	80	115. 4	125. 1	126. 7	126. 4	141. 1	132. 1
120	120	136. 2	159. 3	148. 2	147. 1	145. 2	156. 1
20	60	102. 4	108. 8	110. 5	91. 2	111. 8	93. 1
120 [4]	0	152. 5	158. 8	143. 2	162. 9	150. 2	173. 4
60 [5]	60	102. 1	103. 1	102. 9	101. 8	102. 0	89. 3

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 41 for reference and test conditions.

[2] M_1=irrigated when soil moisture tension reached 300 cm. water @ 9″, 11 irrigations; M_2=irrigated when soil moisture tension reached 4 atmospheres @ 9″, 5 irrigations; M_3=irrigated when soil moisture tension reached 4 atmospheres @ 9″ until silking, then irrigated at 300 cm. water for rest of season, 8 irrigations.

[3] S_1=12″ x 36″ spacing, 14,500 plants per acre; S_2=8″ x 24″ spacing, 32,700 plants per acre.

[4] Plus 15 tons of manure.

[5] Plus 100 pounds of P_2O_5.

TABLE 6.—*Yield of irrigated corn per acre, in response to various fertility treatments, 3 moisture levels and 3 plant spacings, experiment 33, Hermiston, Oreg., 1947* [1]

Nitrogen applied per acre—		P_2O_5 applied per acre	Yield, by moisture level [2] and plant spacing [3]					
At planting time (pounds)	Later (pounds)		M_1S_1	M_1S_2	M_2S_1	M_2S_2	M_3S_1	M_3S_2
		Pounds	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
40	0	100	71. 2	38. 6	65. 1	36. 3	49. 0	34. 2
60	0	100	77. 2	56. 6	82. 0	40. 2	81. 4	52. 4
80	0	100	81. 8	78. 6	88. 9	72. 0	77. 2	65. 9
120	0	100	111. 6	88. 2	109. 0	70. 5	118. 4	83. 8
40	40	100	92. 3	62. 2	102. 6	62. 7	97. 6	65. 1
60	60	100	107. 0	104. 4	112. 1	90. 8	116. 5	95. 0
80	80	100	113. 4	123. 7	130. 4	99. 6	117. 3	110. 3
120	120	100	127. 3	135. 8	122. 6	90. 5	132. 0	130. 4
120 [4]	0	100	109. 6	98. 1	115. 3	105. 4	116. 8	114. 5
60	60	0	110. 2	99. 1	109. 0	68. 8	120. 7	87. 6

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 41 for reference and test conditions.

[2] M_1=irrigated when soil moisture tension reached 400 cm. water @ 9″, 15 irrigations; M_2=irrigated when soil moisture tension reached 9 atmospheres @ 9″, 11 irrigations; M_3=irrigated when soil moisture tension reached 9 atmospheres until silking, then irrigated when tension reached 400 cm. for 3 weeks during pollination and silking, and then continued as before.

[3] S_1=12″ x 36″ spacing, 14,500 plants per acre; S_2=8″ x 24″ spacing, 32,700 plants per acre.

[4] Plus 15 tons of manure.

TABLE 7.—*Yield of irrigated corn per acre, in response to different rates of applied nitrogen at 2 moisture levels, with and without vetch cover crop, experiments 27 and 28, Moses Lake, Wash., 1948 and 1949* [1]

Nitrogen applied per acre, 1948 (pounds)	Treatment in 1948 and yields in 1948 and 1949 [2]											
	M_1V_1			M_1V_2			M_2V_1			M_2V_2		
	1948	1949 [3]	Total	1948	1949 [3]	Total	1948	1949 [3]	Total	1948	1949 [3]	Total
	Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
0	44. 8	19. 0	63. 8	77. 7	15. 0	92. 7	58. 9	25. 8	84. 7	80. 1	23. 7	103. 8
40	82. 4	22. 1	104. 5	105. 7	27. 0	132. 7	77. 3	20. 3	97. 6	96. 2	27. 1	123. 3
80	103. 4	23. 6	127. 0	113. 9	26. 1	140. 0	103. 6	28. 3	132. 4	100. 4	30. 3	130. 7
120	129. 4	45. 3	174. 7	143. 0	50. 6	193. 6	94. 6	42. 0	136. 6	103. 2	54. 8	158. 0
160	120. 8	22. 6	143. 4	143. 1	61. 9	205. 0	106. 0	27. 2	133. 2	119. 4	79. 5	198. 9
240	135. 4	42. 8	178. 2	144. 4	84. 8	229. 2	93. 9	65. 2	159. 1	116. 1	94. 2	210. 3

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 41 for reference and test conditions.

[2] M_1=low moisture tension, 8 irrigations; M_2=high moisture tension, 3 irrigations; V_1=no vetch cover crop; V_2=vetch cover crop (plowed under).

[3] No fertilizer was applied and irrigation was uniform and ample.

TABLE 8.—*Yield of irrigated corn per acre, in response to nitrogen applied by 3 different methods, experiment 29, Moses Lake, Wash., 1949* [1]

Nitrogen applied per acre, 1949 (pounds) [2]	Yield, by method of applying nitrogen [3]		
	Broadcast [4] (1)	Sideplaced (2)	Sidedressed (3)
	Bushels	*Bushels*	*Bushels*
0	44.2	87.4	51.5
40	68.1	115.8	91.7
80	71.4	117.3	116.3
120	60.1	113.1	118.7
160	65.7	135.6	134.8
240	65.2	145.7	130.0

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 41 for reference and test conditions.

[2] 50 pounds of P_2O_5 per acre broadcast over entire area.

[3] Ammonium nitrate: (1) Broadcast and harrowed in before seeding; (2) sideplaced, 3 inches to the side and 2 inches below seed at seeding time, May 11; and (3) sidedressed, 4 inches to the side and 4 inches deep when the corn was 12 inches high, June 9.

[4] Precipitation was very light. The infiltration rate was low so the surface soil was not all wetted at an irrigation. Therefore, some of the applied nitrogen may not have reached the root systems.

TABLE 9.—*Yield of irrigated corn per acre, in response to different rates of applied nitrogen, experiment 30, Moses Lake, Washington, 1951* [1]

Units	Nitrogen applied per acre [2]	Yield
	Pounds	*Bushels*
0	0	125.8
1	40	140.2
2	80	166.8
3	120	164.3
4	160	168.5
5	200	161.8
3 [3]	[3] 120	161.1

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 41 for reference and test conditions.

[2] Fertilizers applied 2 inches below and 3 inches to the side of seed.

[3] Plus 60 pounds of P_2O_5 applied as superphosphate (43-percent P_2O_5).

TABLE 10.—*Yield of irrigated corn per acre, in response to 5 forms and different rates of applied nitrogen, experiment 31, Moses Lake, Wash., 1952* [1]

Form of nitrogen applied	Yield, by nitrogen applied per acre [2]			
	0 pounds	40 pounds	80 pounds	160 pounds
	Bushels	*Bushels*	*Bushels*	*Bushels*
Anhydrous ammonia	76.2	97.4	128.8	160.3
Ammonium sulfate	76.2	111.1	143.8	159.8
Ammonium nitrate	76.2	107.1	132.8	155.5
Calcium nitrate	76.2	101.6	112.4	138.5
Urea	76.2	101.8	123.1	147.9

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 41 for reference and test conditions.

[2] Sidedressed after emergence.

NEBRASKA EXPERIMENTS

Technicians controlled 7 experiments at the Scotts Bluff Experiment Station. The cultural practices for experiment 51 at Hardy in south-central Nebraska were farmer-controlled (*14*).[8] (See appendix table 42 for details of test conditions.) This experiment was on a field of low fertility, and 12 rates of nitrogen ranging from 0 to 320 pounds per acre were applied. It was conducted primarily to obtain data with which to characterize the yield curve of irrigated corn treated with nitrogen (table 4).

At the Scotts Bluff station, in experiment 52, 5 rates of nitrogen ranging from 0 to 320 pounds per acre were studied. Three spacing variables and three moisture variables were included (table 11). In experiment 53, nitrogen was applied to potatoes in 1949 at the rates of 0, 40, 80, 160, and 320 pounds per acre. In 1950 the plots were split. Half of each plot received no further fertilizer. Corn was grown on these plots in 1950, sugar beets in 1951, and corn again in 1952. On the remaining half of each plot corn was grown with an application of 40 pounds of nitrogen in 1950, sugar beets with an application of 80 pounds of nitrogen in 1951, and corn again with an application of 80 pounds of nitrogen in 1952 (table 12).

TABLE 11.—*Yield of irrigated corn per acre, in response to 3 methods of irrigation, 3 plant spacings, and different rates of nitrogen application, experiment 52, Scottsbluff, Nebr., 1949* [1]

Plant spacing, and moisture level [2]	Yield, by nitrogen applied per acre [3]				
	0 pounds	40 pounds	80 pounds	160 pounds	320 pounds
	Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*
36-inch spacing:					
M_1	124	120	122	121	118
M_2	116	119	124	127	126
M_3	120	132	133	135	135
28-inch spacing:					
M_1	125	136	136	139	135
M_2	120	136	135	139	144
M_3	140	139	139	147	144
20-inch spacing:					
M_1	136	134	134	130	128
M_2	124	130	136	135	136
M_3	133	148	147	147	145

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 42 for reference and test conditions.

[2] M_1=irrigated when readings of 10,000 ohms resistance were obtained in gypsum blocks; M_2=irrigated when readings of 800 ohms resistance were obtained in gypsum blocks; M_3=irrigated when readings of 250 mm. Hg. were obtained in tensiometers.

[3] Additional fertilizer was applied to each different replication as: (1) 25 tons of manure; (2) 25 tons of manure and 160 pounds of nitrogen; and (3) 40 pounds of P_2O_5 and 40 pounds of nitrogen per acre. One replication had no additional fertilizer besides the nitrogen.

[8] Unpublished data of the Scotts Bluff Experiment Station, Scottsbluff, Nebr.

TABLE 12.—*Residual yield of irrigated corn per acre, first year residual and third year residuals following potatoes and sugar beets, experiment 53, Scottsbluff, Nebr.*[1]

Nitrogen applied per acre, 1949 (pounds)	1950 residual yield		1952 residual yield	
	0 lb. N–1950 [2]	40 lbs. N–1950 [2]	0 lb. N–1951–52 [2]	80 lbs. N–1951–52 [2]
	Bushels	*Bushels*	*Bushels*	*Bushels*
0	122	128	113	116
80	125	132	109	113
160	126	129	108	117
320	132	130	110	117

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 42 for reference and test conditions.

[2] 1949 plots with nitrogen applied to potatoes were split and half of each plot was carried through with no additional nitrogen applied. The other half of each plot had 40 additional pounds of nitrogen applied to corn in 1950, 80 pounds to sugar beets in 1951, and 80 pounds to corn in 1952.

In experiments 54 to 57, inclusive, at the Scotts Bluff Experiment Station, nitrogen was applied at 0, 40, 80, and 120 pounds per acre; and at each rate it was applied at 4 different times: (1) Before plowing, (2) at planting time, (3) when the corn was 6 to 12 inches high, and (4) when it was 30 to 36 inches high (tables 13 to 16, inclusive). In the following year, the yield response of corn to residual nitrogen was measured at each initial rate of application. Two experiments were on fields of low fertility, 1 was on a field of medium fertility, and 1 was on a field of high fertility. The crop history varied between experiments but none included legumes.

TABLE 13.—*Yield of irrigated corn per acre, first and residual years, from different times and rates of nitrogen application, low fertility field, experiment 54, Scottsbluff, Nebr.*[1]

Nitrogen applied per acre (pounds)	Year	Yield, by time of nitrogen application			
		Before plowing	At planting time	Corn 6 to 12 inches high	Corn 30 to 36 inches high
		Bushels	*Bushels*	*Bushels*	*Bushels*
0	1950	45. 6	45. 6	45. 6	45. 6
0	1951	24. 8	24. 8	24. 8	24. 8
40	1950	72. 5	72. 9	83. 9	84. 8
0	1951	26. 4	22. 6	24. 5	30. 8
80	1950	99. 1	105. 6	105. 3	100. 4
0	1951	27. 6	28. 7	27. 3	38. 3
120	1950	114. 3	115. 1	120. 1	115. 1
0	1951	33. 3	33. 1	33. 4	36. 5

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 42 for reference and test conditions.

TABLE 14.—*Yield of irrigated corn per acre, first and residual years from different times and rates of nitrogen application, high fertility field, experiment 55, Scottsbluff, Nebr.*[1]

Nitrogen applied per acre (pounds)	Year	Yield, by time of nitrogen application			
		Before plowing	At planting time	Corn 6 to 12 inches high	Corn 30 to 36 inches high
		Bushels	*Bushels*	*Bushels*	*Bushels*
0	1951	59.0	59.0	59.0	59.0
0	1952	92.3	92.3	92.3	92.3
40	1951	67.7	66.3	63.9	61.5
0	1952	90.2	93.5	96.0	104.2
80	1951	60.5	61.4	58.8	61.5
0	1952	123.1	112.8	121.6	122.7
120	1951	71.1	54.8	59.8	72.5
0	1952	122.6	115.2	122.2	125.9

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 42 for reference and test conditions.

TABLE 15.—*Yield of irrigated corn per acre, first and residual years from different times and rates of nitrogen application, medium fertility field, experiment 56, Scottsbluff, Nebr.*[1]

Nitrogen applied per acre (pounds)	Year	Yield, by time of nitrogen application			
		Before plowing	At planting time	Corn 6 to 12 inches high	Corn 30 to 36 inches high
		Bushels	*Bushels*	*Bushels*	*Bushels*
0	1951	33.6	33.6	33.6	33.6
0	1952	35.1	35.1	35.1	35.1
40	1951	57.0	57.6	38.7	49.7
0	1952	45.0	38.0	46.8	50.1
80	1951	61.5	51.2	51.2	44.1
0	1952	45.3	52.0	67.9	55.2
120	1951	58.3	70.3	52.9	44.0
0	1952	75.2	72.5	80.0	68.5

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 42 for reference and test conditions.

TABLE 16.—*Yield of irrigated corn per acre, first and residual years, from different times and rates of nitrogen application, low fertility field, experiment 57, Scottsbluff, Nebr.*[1]

Nitrogen applied per acre (pounds)	Year	Yield, by time of nitrogen application			
		Before plowing	At planting time	Corn 6 to 12 inches high	Corn 30 to 36 inches high
		Bushels	*Bushels*	*Bushels*	*Bushels*
0	1952	32.1	32.1	32.1	32.1
0	1953	26.3	26.3	26.3	26.3
40	1952	61.5	64.2	70.5	62.2
0	1953	25.6	28.3	33.2	54.1
80	1952	94.1	84.9	79.4	74.1
0	1953	29.1	32.9	34.2	73.9
120	1952	107.5	109.6	107.5	90.8
0	1953	32.0	48.4	51.8	81.5

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 42 for reference and test conditions.

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In experiment 58, rates of nitrogen up to 160 pounds per acre were studied alone and following an application of 12 tons of manure per acre (table 17).

TABLE 17.—*Yield of irrigated corn per acre, for different rates of nitrogen application, without manure and with 12 tons of manure, experiment 58, Scottsbluff, Nebr., 1953* [1]

Nitrogen applied per acre, 1953 (pounds)	No manure		12 tons of manure	
	A [2]	B [2]	C [2]	D [2]
	Bushels	*Bushels*	*Bushels*	*Bushels*
0	28.1	60.2	119.8	120.0
40	59.6	105.5	125.7	131.6
80	76.3	124.6	136.9	136.2
120	94.3	141.0	136.9	158.7
160	101.0	135.9	125.0	142.7
120 [3]	113.2	137.7	124.1	152.0

[1] Yields in bushels of 56 pounds at 15.5 percent of moisture, average of replications. See appendix table 42 for reference and test conditions.

[2] A and C were on fields that had been in continuous corn since 1912, and B and D were on fields that had been in potato-sugar beet rotation from 1912–49, and in corn from 1950–52.

[3] 40 pounds of P_2O_5 applied.

In experiments 52 and 53, and that part of experiment 58 on which manure was used, the response to nitrogen was slight (tables 11, 12, 17). In each of these instances, soil fertility was high before the application of nitrogen. In experiment 51 the highest yield approximated the yields in experiments 52, 53, and 58, but the yield without nitrogen was only 23 bushels per acre (table 4). Yields on check plots were relatively low for the other experiments, so large increases in yield resulted from applying nitrogen at rates up to 120 pounds per acre in all experiments except 55 and 56. Adverse weather, including severe cold and hailstorms, depressed yields in these two experiments. Rates of nitrogen were not high enough in experiments 54 to 58 to ascertain where the yields level off under favorable climatic conditions.

All of the Nebraska experiments were on Tripp very fine sandy loam, except experiment 51, at Hardy, which was on Waukesha silty clay loam. These soils had been in production for many years.

ECONOMIC ANALYSIS OF EXPERIMENTAL DATA

Basic to the economic analysis of the response of corn to nitrogen fertilizer are the functional relationships between the quantity of nitrogen applied and the yield of corn. Estimates of the yield functions have been made for the experimental data in Oregon, Washington, and Nebraska, when yields appeared to follow a functional relationship with meaningful economic interpretation. The constants for these functions and estimates of the variability of some of the constants are shown in appendix tables 43 and 44. Yield functions are shown in figures 2 to 4 and 8 to 10.

The additional increase in yield of corn that is associated with each additional 20-pound unit of nitrogen applied was computed. This provides information on which recommendations relative to the most profitable application of nitrogen may be made. The functional relationships reflect the differences inherent in soil, location, previous soil management, and other factors purposely incorporated in the experiments. Calculated yield increments for 14 representative experiments are presented in table 18. It is possible from these increments to estimate the most profitable application of nitrogen.

Table 18.—*Calculated yield increments per acre of corn for grain, associated with each additional 20-pound unit of nitrogen application* [1]

Nitrogen applied per acre		Experiment						
		32	10	51	27	29 [2]	29 [3]	30
Units	*Pounds*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
0	0	---	---	---	---	---	---	---
1	20	23.23	22.35	31.34	22.35	24.57	11.07	14.14
2	40	19.40	16.76	22.14	17.04	17.26	9.02	9.59
3	60	16.20	12.57	15.64	12.98	12.11	7.35	6.50
4	80	13.52	9.43	11.05	9.90	8.51	5.98	4.40
5	100	11.30	7.07	7.81	7.55	5.97	4.88	2.99
6	120	9.43	5.30	5.52	5.75	4.20	3.97	2.02
7	140	7.87	3.98	3.90	4.38	2.94	3.23	1.38
8	160	6.58	2.99	2.75	3.35	2.07	2.64	.92
9	180	5.49	2.24	1.95	2.54	1.45	2.14	.64
10	200	4.59	1.68	1.37	1.95	1.02	1.75	.42
11	220	3.83	1.26	.97	1.48	.71	1.43	---
12	240	3.20	.94	.69	1.12	.51	1.16	---
13	260	2.67	.71	.49	---	---	---	---
14	280	2.23	.53	.34	---	---	---	---
15	300	1.86	.40	.24	---	---	---	---
16	320	1.55	.30	.17	---	---	---	---

Nitrogen applied per acre		Experiment						
		2	7	7	11	11	12	12
		100 pounds P_2O_5	100 pounds P_2O_5	0 pounds P_2O_5	100 pounds P_2O_5	0 pounds P_2O_5	100 pounds P_2O_5	0 pounds P_2O_5
Units	*Pound*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
0	0	---	---	---	---	---	---	---
1	20	23.70	17.99	12.66	18.83	22.62	11.51	13.50
2	40	15.13	11.95	9.71	11.96	13.52	8.76	8.49
3	60	9.66	7.94	7.45	7.60	8.08	6.66	5.34
4	80	6.16	5.27	5.72	4.83	4.83	5.07	3.36
5	100	3.93	3.50	4.39	3.07	2.89	3.86	2.11
6	120	2.51	2.33	3.36	1.95	1.73	2.93	1.33
7	140	1.60	1.55	2.58	1.24	1.03	2.23	.83
8	160	1.02	1.03	1.98	.79	.62	1.70	.52
9	180	.65	.68	1.52	.50	.37	1.29	.33
10	200	.42	.45	1.17	.32	.22	.98	.21

[1] In using this table to find the most profitable rate, divide the cost of 20 pounds of nitrogen by the price per bushel of corn standing in the field. The result is bushels of corn equal in value to 20 pounds of nitrogen. Locate in the appropriate column the figure which most nearly equals this result, and from the lefthand column read the rate of application with which it is associated. This is approximately the most profitable rate.

[2] Sidedressed.

[3] Sideplaced.

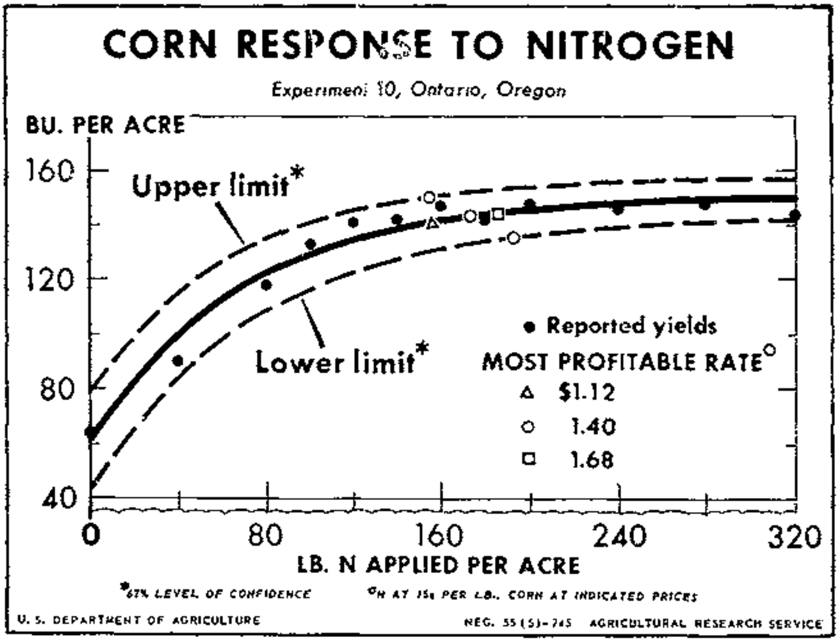

FIGURE 2.—Yield response curve, 67 percent confidence limit curves, reported yields, and yield at the most profitable rate of nitrogen application, irrigated corn–nitrogen rate experiment 10, Ontario, Oreg., 1952.

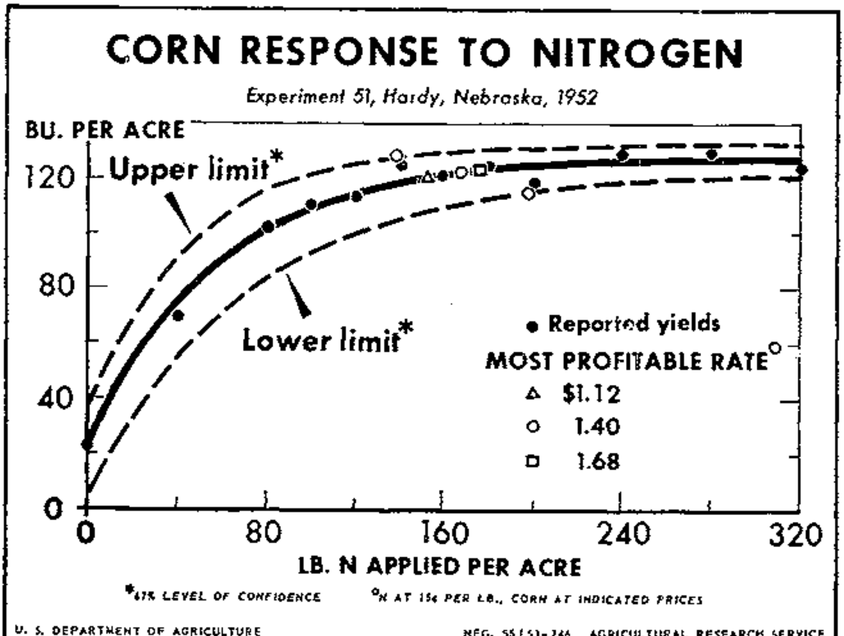

FIGURE 3.—Yield response curve, 67 percent confidence limit curves, reported yields, and yield at the most profitable rate of nitrogen application, irrigated corn–nitrogen rate experiment 51, Hardy, Nebr., 1952.

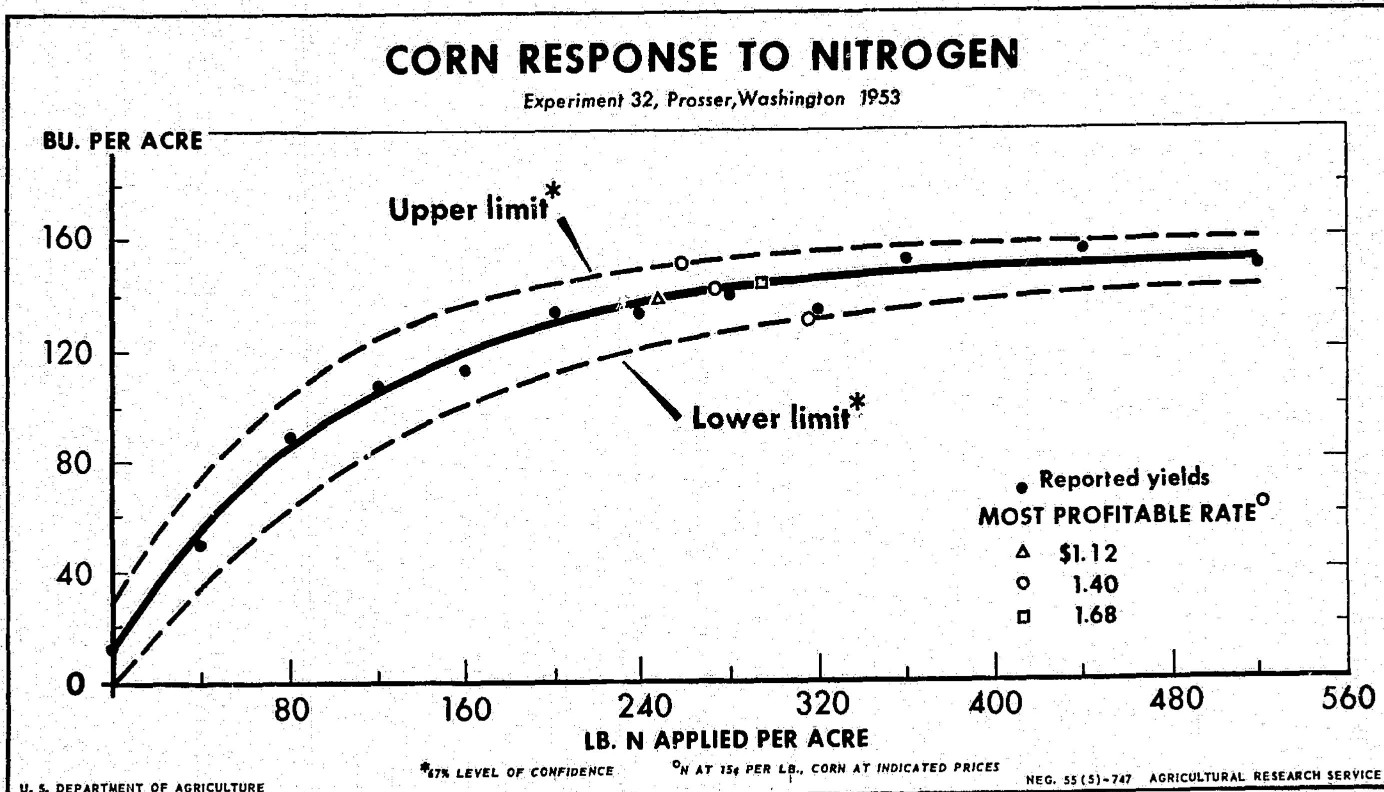

FIGURE 4.—Yield response curve, 67 percent confidence limit curves, reported yields, and yield at the most profitable rate of nitrogen application, irrigated corn-nitrogen rate experiment 32, Prosser, Wash., 1952.

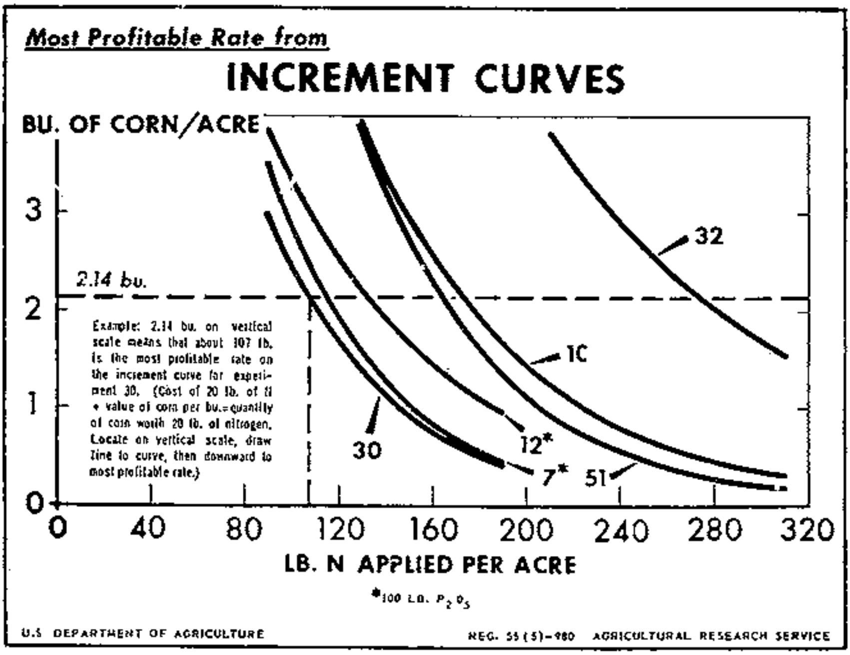

FIGURE 5.—Using increment yield curves to find the rate for the highest return to nitrogen.

With corn valued at $1.40 a bushel after harvest costs are deducted, and with a 20-pound unit of nitrogen at $3, 2.14 bushels of corn are required to pay for 1 unit of nitrogen. In experiment 30 in table 18, for example, the fifth unit of nitrogen increased the yield by 2.99 bushels, a quantity greater than that required to pay for the added fertilizer. The sixth unit increased the yield of corn by 2.02 bushels, or just a little less than enough to pay for the added nitrogen. The most profitable rate—that rate which maximizes the return to nitrogen—is somewhere between the fifth and sixth increments. As shown in figure 5, it is 5.4 units of nitrogen. This is the quantity of nitrogen at which the fertilizer increment will produce an added yield that will just pay for itself.

This can be computed directly from the constants for the yield functions, as outlined in the methods of computation in which the most profitable rate (MPR) is

$$MPR=\frac{\log (P_X/P_Y)-\log[A(\ln R)]}{\log R} \qquad (15)$$

These most profitable rates were computed for the yield functions with the price of corn (P_Y) at $1.12, $1.40, and $1.68, and the price of 20 pounds of nitrogen (P_X) at $3, as shown in tables 19 and 20. These computations result in an exact expression of the most profitable rate, an approximate estimate of which is illustrated in figure 5.

TABLE 19.—*Most profitable rate of nitrogen application per acre, with nitrogen at 15 cents a pound and corn at different prices per bushel, irrigated corn–nitrogen rate experiments, Oregon, Washington, and Nebraska, 1947–53* [1]

Experiment	P_2O_5 applied per acre	Most profitable rate of nitrogen application per acre, when corn is—		
		$1.12 per bushel	$1.40 per bushel	$1.68 per bushel
	Pounds	*Pounds*	*Pounds*	*Pounds*
2	0	173	192	207
	100	107	117	125
7	0	127	144	158
	100	103	114	123
10	50	157	172	185
11	0	92	101	108
	100	95	105	113
12	0	79	89	97
	100	116	133	146
27: [2]				
M_1V_1	0	166	183	196
M_1V_2	[3] 65	162	181	196
M_2V_1	0	86	95	103
M_2V_2	[3] 65	116	141	161
29:				
Sideplaced	0	148	170	188
Sidedressed	0	135	148	158
30	0	95	107	116
32	0	250	274	295
51	0	155	168	178

[1] Form of the yield function is $Y = M - AR^X$. Functions estimated by mathematical methods.
[2] See table 7, footnote 2.
[3] 65 pounds of P_2O_5 and 50 pounds of sulfur applied before seeding vetch.

The most profitable rate of nitrogen application per acre is between 100 and 200 pounds for 21 of the experiments when nitrogen is 15 cents a pound and corn is $1.40 a bushel. It is between 75 and 100 pounds for a few experiments. For 15 experiments in which the computed most profitable rate exceeds 200 pounds, sufficiently high rates of nitrogen were not applied to characterize adequately the upper end of the response curve. One exception is experiment 33 in which 240 pounds was the highest rate applied.

MEASURES OF RETURN TO NITROGEN APPLIED

The most profitable rate provides information on the quantity of nitrogen that will maximize the return obtained by applying nitrogen fertilizer. Evaluation of this rate in such terms as the return on investment and comparative profits under various conditions requires that the return to nitrogen be estimated. A substantial return to nitrogen does not necessarily indicate that production of corn is profitable. The cost of fertilizer is only one of the costs of producing a crop. Without fertilizer the yields may be too low to pay the other costs. Additional nitrogen may result in yields sufficient to change production of corn into a profitable enterprise.

TABLE 20.—*Most profitable rate of nitrogen application per acre, with nitrogen at 15 cents a pound and corn at different prices per bushel, irrigated corn-nitrogen rate experiments, Oregon, Washington, and Nebraska, 1947–58* [1]

Experiment	P_2O_5 applied per acre	Most profitable rate of nitrogen application per acre, when corn is—		
		$1.12 per bushel	$1.40 per bushel	$1.68 per bushel
	Pounds	*Pounds*	*Pounds*	*Pounds*
4	0	86	100	112
	100	79	92	103
8	0	66	76	84
9:				
30-inch row	0	343	418	480
36-inch row	0	99	110	120
38-inch row	0	102	116	128
42-inch row	0	44	50	54
13	0	72	92	109
	100	72	82	91
26: [2]				
M_1S_1	0	262	290	313
M_1S_2	0	578	645	700
M_2S_1	0	387	433	470
M_2S_2	0	335	369	397
M_3S_1	0	368	408	442
M_3S_2	0	407	450	486
31:				
Calcium nitrate	0	224	256	283
Ammonium sulfate	0	159	175	187
Ammonium nitrate	0	183	202	218
Anhydrous ammonia	0	327	367	400
Urea	0	225	254	277
33: [3]				
M_1S_1	0	213	242	266
M_1S_2	0	201	212	221
M_2S_1	0	149	159	167
M_2S_2	0	136	141	145
M_3S_1	0	191	211	228
M_3S_2	0	200	220	237

[1] Form of the yield function is $Y=M-AR^x$. Functions estimated by graphic procedure.
[2] See table 7, footnote 2.
[3] See table 6, footnote 2.

Several measures of return useful in evaluating yield response to fertilizer applications are presented in tables 21 to 23, inclusive, for experiments 10, 32, and 51. Each table was prepared from the results of experiments that were conducted on fields of relatively low fertility and were designed to measure yield response over a wide range of fertilizer rates. Data in columns 1 through 6 are for individual successive 20-pound units of nitrogen. Data in columns 8 through 10 are results for rates of application shown in column 7. In each experiment a well-adapted hybrid was planted; care was taken to supply adequate moisture at all times; and precautions were taken to insure satisfactory growing conditions.

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TABLE 21.—*Measures of return from application of nitrogen at varying rates to irrigated corn, experiment 10, Ontario, Oreg., 1952*

	Results by successive 20-pound units of nitrogen					Cumulative results from increasing rates of nitrogen application					
Nitrogen applied per acre, 1952 (units)	Increase in yield	Value of additional increase in yield	Cost of additional unit of nitrogen	Return above cost of additional unit of nitrogen (col. 3−col. 4)	Return per dollar on the last unit of nitrogen (col. 3÷col. 4)	Total application of nitrogen		Total increase in yield		Total return to nitrogen (col. 8−col. 7)	Average return per dollar spent on nitrogen (col. 8÷col. 7)
(1)	(2)	(3)	(4)	(5)	(6)	(7)		(8)		(9)	(10)
	Bushels	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Pounds*	*Dollars*	*Bushels*	*Dollars*	*Dollars*	*Dollars*
1	22. 35	31. 29	3. 00	28. 29	10. 43	20	3. 00	22. 35	31. 29	28. 29	10. 43
2	16. 76	23. 46	3. 00	20. 46	7. 82	40	6. 00	39. 11	54. 75	48. 75	9. 12
3	12. 57	17. 60	3. 00	14. 60	5. 87	60	9. 00	51. 68	72. 35	63. 35	8. 04
4	9. 43	13. 20	3. 00	10. 20	4. 40	80	12. 00	61. 11	85. 55	73. 55	7. 13
5	7. 07	9. 90	3. 00	6. 90	3. 30	100	15. 00	68. 18	95. 45	80. 45	6. 36
6	5. 30	7. 42	3. 00	4. 42	2. 47	120	18. 00	73. 48	102. 87	84. 87	5. 72
7	3. 98	5. 57	3. 00	2. 57	1. 86	140	21. 00	77. 46	108. 44	87. 44	5. 16
8	2. 98	4. 17	3. 00	1. 17	1. 39	160	24. 00	80. 44	112. 62	88. 62	4. 69
9	2. 24	3. 14	3. 00	. 14	1. 05	180	27. 00	82. 68	115. 75	88. 75	4. 29
10	1. 68	2. 35	3. 00	−. 65	. 78	200	30. 00	84. 36	118. 10	88. 10	3. 94
11	1. 26	1. 76	3. 00	−1. 24	. 59	220	33. 00	85. 62	119. 87	86. 87	3. 63
12	. 94	1. 32	3. 00	−1. 68	. 44	240	36. 00	86. 56	121. 18	85. 18	3. 37
13	. 71	. 99	3. 00	−2. 01	. 33	260	39. 00	87. 27	122. 18	83. 18	3. 13
14	. 53	. 74	3. 00	−2. 26	. 25	280	42. 00	87. 80	122. 92	80. 92	2. 93

TABLE 22.—*Measures of return from application of nitrogen at varying rates to irrigated corn, experiment 32, Prosser, Wash., 1952*

Results by successive 20-pound units of nitrogen						Cumulative results from increasing rates of nitrogen application					
Nitrogen applied per acre, 1952 (units) (1)	Increase in yield (2)	Value of additional increase in yield (3)	Cost of additional unit of nitrogen (4)	Return above cost of additional unit of nitrogen (col. 3−col. 4) (5)	Return per dollar on the last unit of nitrogen (col. 3÷col. 4) (6)	Total application of nitrogen (7)		Total increase in yield (8)		Total return to nitrogen (col. 8−col. 7) (9)	Average return per dollar spent on nitrogen (col. 8÷col. 7) (10)
	Bushels	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Pounds*	*Dollars*	*Bushels*	*Dollars*	*Dollars*	*Dollars*
1	23. 23	32. 52	3. 00	29. 52	10. 83	20	3. 00	23. 23	32. 52	29. 52	10. 84
2	19. 40	27. 16	3. 00	24. 16	9. 04	40	6. 00	42. 63	59. 68	53. 68	9. 95
3	16. 20	22. 68	3. 00	19. 68	7. 55	60	9. 00	58. 83	82. 36	73. 36	9. 15
4	13. 52	18. 93	3. 00	15. 93	6. 30	80	12. 00	72. 35	101. 29	89. 29	8. 44
5	11. 30	15. 82	3. 00	12. 82	5. 27	100	15. 00	83. 65	117. 11	102. 11	7. 81
6	9. 43	13. 20	3. 00	10. 20	4. 40	120	18. 00	93. 08	130. 31	112. 31	7. 24
7	7. 87	11. 02	3. 00	8. 02	3. 67	140	21. 00	100. 95	141. 33	120. 33	6. 73
8	6. 58	9. 21	3. 00	6. 21	3. 07	160	24. 00	107. 53	150. 54	126. 54	6. 27
9	5. 49	7. 69	3. 00	4. 69	2. 56	180	27. 00	113. 02	158. 23	131. 23	5. 86
10	4. 59	6. 41	3. 00	3. 41	2. 13	200	30. 00	117. 61	164. 65	134. 65	5. 49
11	3. 83	5. 36	3. 00	2. 36	1. 78	220	33. 00	121. 43	170. 00	137. 00	5. 15
12	3. 20	4. 48	3. 00	1. 48	1. 49	240	36. 00	124. 63	174. 48	138. 48	4. 85
13	2. 67	3. 74	3. 00	. 74	1. 24	260	39. 00	127. 30	178. 22	139. 22	4. 57
14	2. 23	3. 12	3. 00	. 12	1. 04	280	42. 00	129. 53	181. 34	139. 34	4. 32
15	1. 86	2. 60	3. 00	−. 40	. 87	300	45. 00	131. 39	183. 94	138. 94	4. 09
16	1. 55	2. 17	3. 00	−. 83	. 72	320	48. 00	132. 94	186. 62	138. 62	3. 89
17	1. 30	1. 82	3. 00	−1. 18	. 61	340	51. 00	134. 24	187. 94	136. 94	3. 68
18	1. 08	1. 51	3. 00	−1. 49	. 50	360	54. 00	135. 33	189. 46	135. 46	3. 51
19	. 91	1. 27	3. 00	−1. 73	. 42	380	57. 00	136. 23	190. 72	133. 72	3. 35
20	. 76	1. 06	3. 00	−1. 94	. 35	400	60. 00	136. 99	191. 79	131. 79	3. 20
21	. 63	. 88	3. 00	−2. 12	. 29	420	63. 00	137. 62	192. 67	129. 67	3. 06
22	. 53	. 74	3. 00	−2. 26	. 25	440	66. 00	138. 14	193. 40	127. 40	2. 93
23	. 44	. 62	3. 00	−2. 38	. 21	460	69. 00	138. 58	194. 01	125. 01	2. 81
24	. 37	. 52	3. 00	−2. 48	. 17	480	72. 00	138. 95	194. 53	122. 53	2. 70
25	. 31	. 43	3. 00	−2. 57	. 14	500	75. 00	139. 26	194. 96	119. 96	2. 60
26	. 26	. 36	3. 00	−2. 64	. 12	520	78. 00	139. 52	195. 33	117. 33	2. 50

TABLE 23.—*Measures of return from application of nitrogen at varying rates to irrigated corn, experiment 51, Hardy, Nebr., 1952*

Results by successive 20-pound units of nitrogen						Cumulative results from increasing rates of nitrogen application					
Nitrogen applied per acre, 1952 (units) (1)	Increase in yield (2)	Value of additional increase in yield (3)	Cost of additional unit of nitrogen (4)	Return above cost of additional unit of nitrogen (col. 3−col. 4) (5)	Return per dollar on the last unit of nitrogen (col. 3÷col. 4) (6)	Total application of nitrogen (7)		Total increase in yield (8)		Total return to nitrogen (col. 8−col. 7) (9)	Average return per dollar spent on nitrogen (col. 8÷col. 7) (10)
	Bushels	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Pounds*	*Dollars*	*Bushels*	*Dollars*	*Dollars*	*Dollars*
1	31. 34	43. 87	3. 00	40. 87	14. 62	20	3. 00	31. 34	43. 87	40. 87	14. 62
2	22. 14	31. 00	3. 00	28. 00	10. 33	40	6. 00	53. 48	74. 87	68. 87	12. 48
3	15. 64	21. 90	3. 00	18. 90	7. 30	60	9. 00	69. 12	96. 77	87. 77	10. 75
4	11. 05	15. 47	3. 00	12. 47	5. 16	80	12. 00	80. 17	112. 24	100. 24	9. 35
5	7. 81	10. 93	3. 00	7. 93	3. 64	100	15. 00	87. 98	123. 17	108. 17	8. 21
6	5. 52	7. 72	3. 00	4. 72	2. 57	120	18. 00	93. 50	130. 90	112. 90	7. 27
7	3. 90	5. 46	3. 00	2. 46	1. 82	140	21. 00	97. 40	136. 36	115. 36	6. 49
8	2. 75	3. 86	3. 00	. 86	1. 29	160	24. 00	100. 15	140. 21	116. 21	5. 84
9	1. 95	2. 73	3. 00	−. 27	. 91	180	27. 00	102. 10	142. 94	115. 94	5. 29
10	1. 37	1. 92	3. 00	−. 11	. 64	200	30. 00	103. 47	144. 86	114. 86	4. 83
11	. 97	1. 36	3. 00	−1. 64	. 45	220	33. 00	104. 44	146. 22	113. 22	4. 43
12	. 69	. 96	3. 00	−2. 04	. 32	240	36. 00	105. 13	147. 18	111. 18	4. 09
13	. 49	. 68	3. 00	−2. 32	. 23	260	39. 00	105. 61	147. 85	108. 85	3. 79
14	. 34	. 48	3. 00	−2. 52	. 16	280	42. 00	105. 96	148. 34	106. 34	3. 53
15	. 24	. 34	3. 00	−2. 66	. 11	300	45. 00	106. 20	148. 68	103. 68	3. 30
16	. 17	. 24	3. 00	−2. 76	. 08	320	48. 00	106. 37	148. 92	100. 92	3. 10

The reported yields and estimated yield curves are shown for each of these experiments in figures 2 to 4. The most profitable rate of nitrogen is shown on each curve.

The ability of nitrogen to increase yield decreases as additional units are applied. For example, in experiment 10, the 1st 20-pound unit returned 22.35 bushels of corn, the 2d 16.76 bushels, and the 12th about 1 bushel. The cost of each unit of nitrogen is the same—$3 for 20 pounds—but the value of the resulting increased yield declines as successive units are applied. The value of the increase in yield from the first unit is approximately 10 times the cost of the unit of fertilizer; but the value of the increase from the 12th unit is less than half the cost of the fertilizer. As shown in column 5, the return above the cost of 1 unit of nitrogen, that is, the value of the increase in yield minus the cost of the 20 pounds of nitrogen, or $3, becomes smaller until the cost of the unit of nitrogen exceeds the value of the yield it produces. This occurs with the 10th unit. This is illustrated in figure 6 where the values in column 5 of table 21, or the marginal returns, are plotted at the midpoint between increments.

The return per dollar spent for nitrogen is $1.05 for the 9th unit, showing a margin of 5 cents for each dollar spent at the 9th unit. The 10th unit returned only 78 cents on the dollar, which indicates a loss from the application of this unit. Thus, it is evident that profitable application of nitrogen does not go beyond the 9th unit. Column 6 in table 21 and the value of additional yield increase curve in figure 6 illustrate this point.

The quantity of nitrogen to apply for the largest net return is shown to be 172 pounds where the net marginal return crosses the zero line (fig. 6). This rate is calculated by use of the formula on page 28. The area between the zero line and the curve represents the return to nitrogen applied, and amounts to $88.78 per acre.

The average return per dollar spent for nitrogen (col. 10, tables 21 to 23, inclusive), is a measure of the profitableness of total expenditures for nitrogen at a specific rate. A return of $3.13 per dollar spent on 260 pounds of nitrogen appears to be profitable but the return per dollar spent on the 13th unit is $0.33 (table 21). At the most profitable rate of 180 pounds, the average return per dollar is $4.29 compared with $1.05 per dollar spent for the 9th unit. Therefore, as the units of nitrogen applied are increased from 9 to 13 there is an increasing loss per dollar spent. The difference in the total return per acre is a loss of $5.57 between the 9th and 13th units.

CONFIDENCE LIMITS

Inherent in fertilizer-rate experiments are nonidentifiable factors that vary the experimental yields. Therefore, the yield response curve is only an estimate of the "true" curve that exists. Confidence limits about the estimated curve provide an indication of what might be expected to occur with successive experiments under similar conditions.

The effects of these nonidentifiable factors are measured by the deviations of the observed yields from the estimated yield response curve. Using these deviations as a measure of variability, an estimate was made of the variability of the sample estimates of each constant in the yield equation about its population value—s_M, the standard error of the possible maximum yield; s_A, the standard error of the increase in yield that might be expected; and s_R, the standard error of

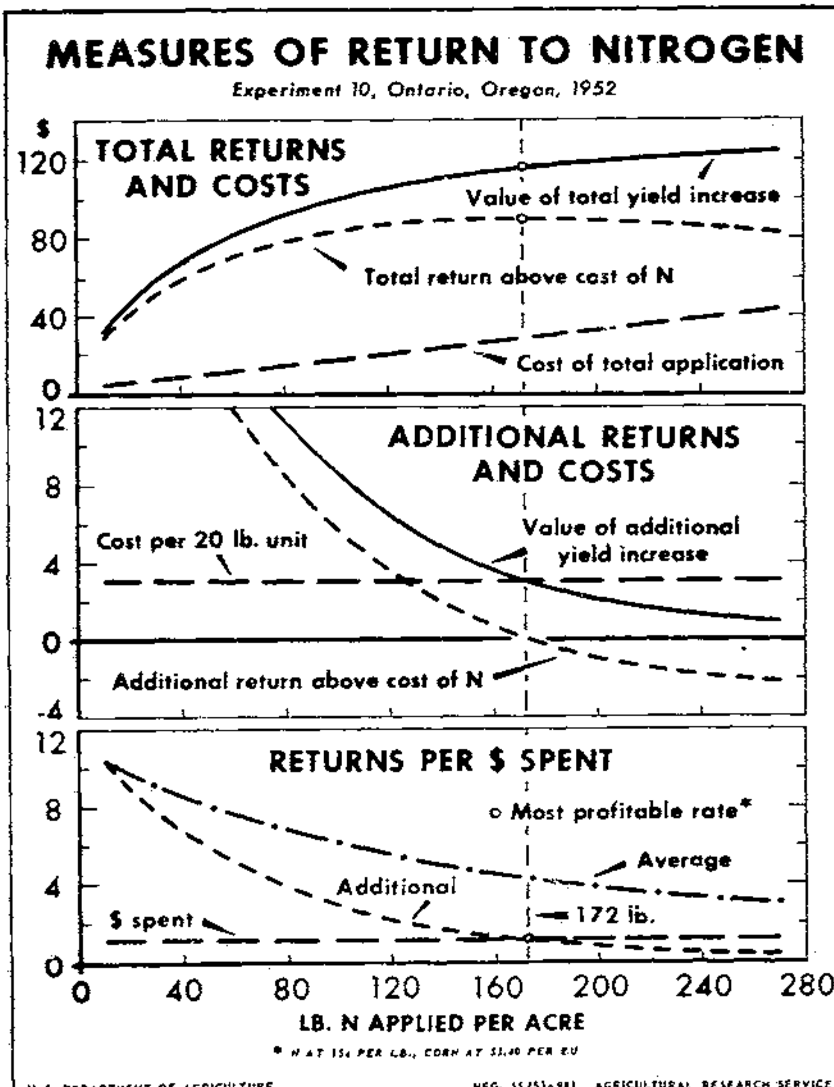

FIGURE 6.—Measures of cost and returns from the application of nitrogen at different rates to irrigated corn, experiment 10, Ontario, Oreg., 1952.

the ratio of successive increments. (See appendix table 43.) The sampling distributions of the sample estimates are not known, but to set confidence limits about each constant, the distributions were all assumed to be normal.

Using equation (*11*), page 10, confidence limit curves were determined for several experiments.[9] They are illustrated in figures 2 to 4,

[9] The limits pertain to the curves and not to the most profitable rate of application. As the rate of nitrogen is assumed to be fixed at each level, confidence limits cannot be set for the most profitable rates of application estimated from the calculated curve.

inclusive. Consequences with respect to the change in the rate of nitrogen application that would be needed to produce the most profitable response at the upper and lower limits, respectively, are presented in table 24. Columns 4 to 7, table 24, show the results that would follow: (1) If the upper confidence limit response pattern (*U*) were obtained and the appropriate most profitable rate applied; (2) if the estimated response pattern (*E*) were obtained and the appropriate rate applied; and (3) if the lower confidence limit response pattern (*L*) were obtained and the appropriate most profitable rate applied.

Large differences between yields estimated by the three curves at zero application of nitrogen are observed in each experiment. Also, there are substantial differences between the estimated most profitable rates for the respective curves for each experiment. Likewise for each experiment there are substantial differences between yields at the most profitable rate of nitrogen application for the respective curves. It is apparent that the difference in yield both at zero application and at the most profitable rate of application for the respective curves for each experiment would result in some very substantial differences in both gross income and production per acre. These differences attributable to variation in the response pattern should not be confused with the effects of application of nitrogen fertilizer. There are some exceptions, but in many instances the differences between the return to nitrogen on the estimated curve and on the limit curves are $5 or less per acre (table 24, col. 7). These differences are calculated on the assumption that the response pattern at the limits could be anticipated, and the rates adjusted accordingly. Obviously this is impossible, and a farmer would be inclined to apply the most profitable rate calculated for the estimated or most probable curve and take his chances on the results that might be obtained.

By assuming application of the most profitable rate for the estimated curve, the return to nitrogen is shown in column 10, table 24, for the upper limit response pattern, for the estimated curve response pattern, and for the lower limit response pattern. The difference, then, in return to nitrogen (col. 7 vs. col. 10, table 24) that might be obtained anywhere within the confidence limit curves, as prepared in this report, is in most cases relatively small, as shown in column 10, table 24.

Substantial differences in yield per acre might be expected, as indicated by the various yield curves that might occur between the limit curves. Differences of this kind caused by variability in the experiments are minor as they affect the return to nitrogen based on the expected most profitable rate. The variations in the yield curves, and the most profitable rates related to conditions that differ from those reported in the experiments, are likely to be more important in predicting the yield response to fertilizer than the variability within an experiment. Little, if any, data are available to indicate the variations in yield response that might occur if the experiment were repeated in different areas and in successive years. The source of these variations would include climatic conditions, irrigations, and so on.

CHANGES IN THE PRICE OF CORN

The price of corn is not constant, and at the time nitrogen is applied it is impossible to foresee what the price of corn will be at harvesttime.

The effect of changes in price on the most profitable rate of application and the return to nitrogen needs to be evaluated. At a fixed price for nitrogen fertilizer, the yield curve governs the change in the most profitable rate as price per bushel of corn changes. As the exponential yield equation provides a constant rate of decreasing increments, successive unit increases in the price of corn increase the most profitable rate of nitrogen application at a decreasing rate. For example, with each equivalent price rise of 28 cents from 84 cents per bushel (20 percent of $1.40 per bushel), the most profitable rate of nitrogen application increases, respectively, by 20, 15, 13, and 11 pounds per acre for experiment 10 (table 25). This relationship differs in magnitude for each yield curve. Without a change in the rate of nitrogen applied or the price per pound of nitrogen, the increase in the return to nitrogen above its cost would be proportional to the increase in the price of corn.

As shown in table 25, however, a unit change in the price of corn results in a change in the most profitable rate of nitrogen application. This change affects the return to nitrogen slightly more than would changes per unit in the price of corn alone. For example, progressive increases of 28 cents in the price of corn from 84 cents a bushel increases the return to nitrogen, respectively, by $22.03, $22.71, $23.14, and $23.43 (table 25, col. 6). By comparison, these increases would be constant at $22.94 for each increase of 28 cents above 84 cents in the price of corn, if the rate of nitrogen application were not adjusted to the most profitable rate determined by each price of corn (table 25, col. 7).

In practice, it is impossible at the time nitrogen fertilizer is applied to foresee the exact price of corn at harvesttime. What, then, is the effect of an inaccurate estimate of the expected price of corn on the return to nitrogen above its cost? Exclusive of the direct effect that deviations in the sale price of the crop have on return, as illustrated above, there is an additional loss in return. This loss is due to inaccurate forecasting of the price of corn, and hence to the application of nitrogen at other than the most profitable rate. These relationships are shown in table 25. The return to nitrogen is reduced less than 25 cents per acre when the actual sale price is 28 cents above or below the predicted price on which the most profitable rate is calculated. If the predicted price is higher than the actual price, the reduction in return is real because of overapplication; but if the predicted price is lower than the actual price, the reduction lies in the potential return that might have been obtained by the higher rate of application. When the difference between predicted price and actual price is 56 cents a bushel, the return to nitrogen is reduced less than $1.15 per acre. Reductions in return to nitrogen are smaller for "overestimates" of the price than for "underestimates" of an equal amount.

Thus, the return to nitrogen is affected only slightly when, because of inaccurate estimates of the expected price of corn, the quantity of nitrogen applied to the crop deviates from the most profitable rate. These results are based on the assumption that the exact relationships expressed by the estimated curve are obtained.

Details of computations illustrating results when the rate of nitrogen application is not adjusted to changes in price are shown in table 26 for experiment 10. Application of 172.46 pounds of nitrogen, the most profitable rate when corn is $1.40 per bushel, represents an over-

TABLE 24.—*Effect of 67-percent confidence limit curves on most profitable rate of nitrogen and on return to nitrogen, irrigated corn-nitrogen rate experiments, Oregon, Washington, and Nebraska, 1947–53*

Experiment	P_2O_5 applied per acre	Yield curve [1]	Results from application of the most profitable rate of nitrogen for the upper curve, the estimated curve, and the lower curve: Yield at 0 application of nitrogen	Yield at most profitable rate of application [2]	Most profitable rate of application	Return to nitrogen at most profitable rate [3]	Results from application of the most profitable rate of nitrogen from the estimated curve on the upper curve and on the lower curve [4]: Most profitable rate for estimated curve	Yield at most profitable rate for estimated curve	Return to nitrogen [5]	Difference in return to nitrogen [6]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Pounds		*Bushels*	*Bushels*	*Pounds*	*Dollars*	*Pounds*	*Bushels*	*Dollars*	*Dollars*
2	0	U.	56. 0	130. 5	171. 8	78. 53	191. 6	132. 3	78. 08	0. 45
		E.	44. 4	123. 4	191. 6	81. 86	191. 6	123. 4	81. 86	0
		L.	32. 7	116. 0	213. 9	84. 54	191. 6	113. 4	84. 24	. 30
	100	U.	65. 2	115. 9	52. 7	63. 08	116. 7	120. 4	59. 78	3. 30
		E.	47. 9	108. 7	116. 7	67. 62	116. 7	108. 7	67. 62	0
		L.	30. 5	97. 3	179. 0	66. 67	116. 7	87. 4	62. 16	4. 51
7	0	U.	81. 4	121. 2	106. 1	39. 80	143. 9	124. 0	35. 06	4. 64
		E.	63. 4	109. 7	143. 9	43. 24	143. 9	109. 7	43. 24	0
		L.	45. 4	95. 9	193. 6	41. 66	143. 9	89. 2	39. 74	1. 92
	100	U.	71. 5	114. 1	84. 3	47. 00	106. 7	116. 1	46. 44	. 56
		E.	58. 4	113. 7	106. 7	61. 42	106. 7	113. 7	61. 42	0
		L.	45. 2	98. 6	149. 7	52. 30	106. 7	93. 6	51. 76	. 54
10	50	U.	78. 8	150. 1	154. 9	76. 58	172. 5	151. 7	76. 18	. 41
		E.	60. 8	142. 7	172. 5	88. 78	172. 5	142. 7	88. 78	0
		L.	42. 8	135. 2	192. 2	100. 53	172. 5	132. 8	100. 12	. 40
11	0	U.	64. 8	112. 8	80. 5	55. 12	101. 2	114. 0	53. 70	1. 42
		E.	55. 8	107. 9	101. 2	57. 76	101. 2	107. 9	57. 76	0
		L.	43. 8	100. 1	124. 0	60. 22	101. 2	97. 0	59. 30	. 92
	100	U.	68. 2	111. 6	97. 5	46. 14	105. 0	112. 4	46. 13	. 01
		E.	62. 9	109. 8	105. 0	49. 91	105. 0	109. 8	49. 91	0
		L.	59. 6	108. 0	113. 8	50. 69	105. 0	106. 9	50. 47	. 22
12	0	U.	92. 5	113. 1	61. 7	19. 58	89. 0	115. 1	18. 29	1. 29
		E.	71. 3	103. 1	89. 0	31. 17	89. 0	103. 1	31. 17	0
		L.	50. 2	92. 7	119. 6	41. 56	89. 0	88. 4	40. 13	1. 43
	100	U.	86. 1	118. 8	88. 0	32. 58	132. 8	121. 7	29. 92	2. 66
		E.	64. 8	105. 1	132. 8	36. 50	132. 8	105. 1	36. 50	0
		L.	43. 6	87. 0	194. 3	31. 62	132. 8	78. 8	29. 36	2. 26

27:										
M_1V_1	0	U.	65.9	142.5	144.7	85.54	132.5	145.5	84.06	1.48
		E.	44.2	130.3	182.5	93.16	182.5	130.3	93.16	0
		L.	22.5	116.9	233.7	97.10	182.5	109.8	94.84	2.36
M_1V_2	65	U.	104.7	160.3	129.9	58.36	180.9	163.8	55.60	2.76
		E.	76.9	143.4	180.9	65.96	180.9	143.4	65.96	0
		L.	49.1	122.9	259.0	64.47	180.9	112.0	60.92	3.55
M_2V_1	0	U.	77.1	106.2	51.1	33.08	95.0	108.1	29.15	3.93
		E.	57.6	96.2	95.0	39.79	95.0	96.2	39.79	0
		L.	37.9	82.9	160.5	38.92	95.0	72.8	34.61	4.31
M_2V_2	65	U.	108.6	127.4	97.7	11.66	140.8	131.1	10.38	1.28
		E.	80.8	110.8	140.8	20.88	140.8	110.8	20.88	0
		L.	53.1	93.0	185.4	28.05	140.8	87.4	26.90	1.15
29:										
SD	0	U.	64.1	123.4	123.9	79.84	147.7	136.4	79.06	.78
		E.	51.2	127.6	147.7	84.80	147.7	127.6	84.80	0
		L.	38.3	131.5	176.8	88.56	147.7	116.6	87.46	1.10
SP	0	U.	110.4	149.9	149.2	32.92	169.9	151.9	32.62	.30
		E.	89.4	138.6	169.9	43.40	169.9	138.6	43.40	0
		L.	68.3	127.3	189.5	54.18	169.9	125.0	53.90	.28
30	0	U.	143.3	173.6	65.9	32.54	106.7	175.9	29.64	2.90
		E.	124.1	162.4	106.7	37.62	106.7	162.4	37.62	0
		L.	104.8	147.8	167.8	35.03	106.7	139.0	31.88	3.15
32	0	U.	28.8	151.2	259.0	132.51	274.2	152.4	131.91	.60
		E.	11.9	140.9	274.2	139.47	274.2	140.9	139.47	0
		L.	(7)	131.7	315.6	137.04	274.2	126.5	135.97	1.07
51	0	U.	36.4	128.0	138.6	107.45	167.7	130.3	106.30	1.15
		E.	21.0	122.0	167.7	116.24	167.7	122.0	116.24	0
		L.	5.6	114.7	197.4	123.13	167.7	110.8	122.12	1.01

[1] *E*=estimated curve fitted to reported yields; *U*=upper limit of 67-percent confidence curve, based on estimated curve; *L*=lower limit of 67-percent confidence curve, based on estimated curve.

[2] Most profitable rate of nitrogen application per acre with corn at $1.40 per bushel and nitrogen at 15 cents a pound.

[3] Value of increased yield minus the cost of nitrogen application at most profitable rate.

[4] The estimated curve represents the most probable yield situation and hence application of the most profitable rate for this curve is assumed. If either the upper or lower curve of the confidence limit materializes, then the incorrect rate has been used and results altered as indicated in this section.

[5] Return to nitrogen for each of the respective yield curves, when the most profitable rate of application for the *estimated curve* is assumed.

[6] Difference between return at the most profitable rate on the respective curve and the return at the most profitable rate of application for the estimated curve confidence limit curves. In each case the difference is a decrease in return to nitrogen because the rate applied was not the most profitable rate for the specific confidence curve. Compare columns 7 and 10.

[7] Computed yields were negative on lower limit curve.

TABLE 25.—*Relation of price of corn to the most profitable rate of nitrogen application and to return to nitrogen per acre, experiment 10, Oregon, 1952*

Price of corn per bushel (dollars) (1)	Most profitable rate of nitrogen application [1] (2)	Cost of nitrogen at most profitable rate (3)	Increase in yield at most profitable rate [2] (4)	Value of increase in yield (5)	Return to nitrogen at most profitable rate [3] (6)	Return to nitrogen at 172.46 pounds [4] (7)	Difference in return to nitrogen between application at fixed rate and at most profitable rate (8)
	Pounds	*Dollars*	*Bushels*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
0.84	137. 26	20. 59	77. 00	64. 68	44. 09	42. 95	−1. 14
1.12	156. 98	23. 55	80. 06	89. 67	66. 12	65. 89	−. 23
1.40	172. 46	25. 87	81. 93	114. 70	88. 83	88. 83	0
1.68	185. 16	27. 77	83. 18	139. 74	111. 97	111. 77	−. 20
1.96	196. 16	29. 42	84. 09	164. 82	135. 40	134. 71	−. 69

[1] Most profitable rate of nitrogen application per acre when nitrogen is $0.15 a pound and corn is indicated price.

[2] Yield without nitrogen=60.76 bushels.

[3] Return per acre to nitrogen above its cost, that is, value of increase in yield minus cost of nitrogen.

[4] Rate of nitrogen application per acre is held constant at 172.46 pounds per acre, which is the most profitable rate when corn is $1.40 per bushel. Cost of nitrogen ($0.15×172.46, or $25.87) remains unchanged, as does increase in yield at 81.93 bushels per acre. Difference in return to nitrogen above its cost is due entirely to the price received for corn.

TABLE 26.—*Loss in return to nitrogen when rate of application remains constant as price of corn changes, experiment 10, Oregon, 1952*

Price of corn per bushel (dollars) (1)	Most profitable rate of nitrogen application (2)	Nitrogen applied per acre [1] (3)	Over (+) or under (−) application [2] (4)	Difference in cost of nitrogen applied (5)	Yield at most profitable rate of application (6)	Yield from 172.46 pounds of nitrogen (7)	Difference in yield (8)	Value of difference in yield [3] (9)	Loss in return to nitrogen [4] (10)
	Pounds	*Pounds*	*Pounds*	*Dollars*	*Bushels*	*Bushels*	*Bushels*	*Dollars*	*Dollars*
0.84	137. 26	172. 46	+35. 20	+5. 28	137. 76	142. 69	+4. 93	+4. 14	1. 14
1.12	156. 98	172. 46	+15. 48	+2. 32	140. 82	142. 69	+1. 87	+2. 09	. 23
1.40	172. 46	172. 46	0	0	142. 69	142. 69	0	0	0
1.68	185. 16	172. 46	−12. 70	−1. 90	143. 94	142. 69	−1. 25	−2. 10	. 20
1.96	196. 16	172. 46	−23. 70	−3. 55	144. 85	142. 69	−2. 16	−4. 23	. 68

[1] Held constant at all prices of corn. This is the most profitable rate when corn is $1.40 per bushel.

[2] As compared with most profitable rate.

[3] Between yield at most profitable rate and yield at 172.46 pounds of nitrogen at each price of corn.

[4] This is the difference between the difference in the cost of nitrogen applied (col. 5) and the value of the difference in yield (col. 9). A direct loss occurs when corn is $0.84 and $1.12 per bushel, as the additional yield will not pay for the 172.46 pounds of nitrogen. When corn is $1.68 and $1.96 per bushel, an indirect loss occurs, as the additional nitrogen that should have been applied would have produced enough additional corn to more than pay the cost of the additional nitrogen.

application of about 35 pounds when the price of corn drops to 84 cents a bushel. This represents an overexpenditure of $5.28 per acre for nitrogen. But this overapplication produced an increased yield of 4.93 bushels, valued at $4.14, so the reduction from potential return is only $1.14 per acre even though the rate of application was not adjusted from 172 pounds to 137 pounds per acre.

CHANGES IN THE PRICE OF NITROGEN

In actual practice, the price of nitrogen is a variable, and it may affect the most profitable rate of application and the return to nitrogen. With the price of corn constant at $1.40 per bushel, a change of 1 to 3 cents a pound in the price of nitrogen results in relatively small changes in the most profitable rate of application per acre (table 27).

TABLE 27.—*The effect of price per pound of nitrogen on the most profitable rate of nitrogen application per acre and on increase in yield of irrigated corn*

MOST PROFITABLE RATE OF NITROGEN APPLICATION [1]

Experiment	Price of nitrogen per pound					
	13 cents	14 cents	15 cents	16 cents	17 cents	18 cents
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
2 [2]	203.5	197.3	191.6	186.1	181.0	176.2
7 [2]	154.6	149.0	143.9	138.9	134.4	130.1
10 [2]	183.0	177.9	172.5	168.6	164.3	160.3
11 [2]	106.7	103.8	101.2	98.6	96.3	94.1
12 [2]	95.1	91.9	89.0	86.2	83.6	81.1
27:						
M_1V_1 [3]	193.1	187.6	182.5	177.8	173.3	169.1
29:						
Sidedressed	155.8	151.6	147.7	144.0	140.6	137.4
Sideplaced	183.9	176.7	169.9	163.7	157.8	152.2
30	114.1	110.3	106.7	103.4	100.3	97.4
32	290.2	281.9	274.2	267.1	260.4	254.1
51	172.4	168.(	167.7	160.4	156.9	153.7

INCREASE IN YIELD [4]

Experiment	13 cents	14 cents	15 cents	16 cents	17 cents	18 cents
	Bushels	*Bushels*	*Bushels*	*Bushels*	*Bushels*	*Bushels*
2 [2]	80.2	79.6	79.0	78.4	77.8	77.2
7 [2]	47.4	46.8	46.3	45.8	45.2	44.7
10 [2]	82.9	82.4	81.9	81.4	80.9	80.4
11 [2]	52.6	52.4	52.1	51.8	51.5	51.3
12 [2]	32.4	32.1	31.8	31.5	31.2	30.9
27:						
M_1V_1 [3]	87.2	86.7	86.1	85.6	85.1	84.6
29:						
Sidedressed	77.2	76.8	76.4	76.0	75.6	75.2
Sideplaced	50.6	49.9	49.2	48.5	47.8	47.1
30	73.8	73.4	73.1	72.7	72.3	72.0
32	130.5	129.7	129.0	128.2	127.4	126.6
51	101.4	101.0	101.0	100.2	99.8	99.4

[1] Most profitable rate computed at $1.40 price for corn.
[2] No P_2O_5 applied.
[3] For explanation, see table 7, footnote 2.
[4] Increase in yield over no application of nitrogen.

For most of the experiments a change of 3 cents a pound in the price of nitrogen alters the most profitable rate by only 10 to 20 pounds per acre. The change in yield is relatively small as the most profitable rate is adjusted to the price of nitrogen (table 27). As the price per pound of nitrogen increases the most profitable rate decreases; but the total cost per acre of the application of nitrogen increases, and the value of the yield per acre decreases (tables 27 and 28). A decrease in the price of nitrogen produces opposite effects.

TABLE 28.—*The effect of price of nitrogen per pound on the cost of nitrogen per acre, and the value of the increased yield at the most profitable rate of nitrogen per acre on irrigated corn*

Experiment	Price of nitrogen per pound					
	13 cents	14 cents	15 cents	16 cents	17 cents	18 cents
	COST OF NITROGEN PER ACRE [1]					
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
2 [2]	26.46	27.62	28.74	29.78	30.77	31.72
7 [2]	20.10	20.86	21.58	22.22	22.85	23.42
10 [2]	23.79	24.91	25.88	26.98	27.93	28.85
11 [2]	13.87	14.53	15.18	15.38	16.37	16.94
12 [2]	12.36	12.87	13.35	13.79	14.21	14.60
27:						
M_1V_1 [3]	25.10	26.26	27.38	28.45	29.46	30.44
29:						
Sidedressed	20.25	21.22	22.16	23.04	23.90	24.73
Sideplaced	23.91	24.74	25.48	26.19	26.83	27.40
30	14.83	15.44	16.00	16.54	17.05	17.53
32	37.73	39.17	41.13	42.74	44.27	45.74
51	22.41	23.53	25.16	25.66	26.67	27.67
	VALUE OF INCREASED YIELD PER ACRE					
2 [2]	112.28	111.44	110.60	109.76	108.92	108.08
7 [2]	66.36	65.52	64.82	64.12	63.28	62.58
10 [2]	116.06	115.36	114.66	113.96	113.26	112.56
11 [2]	73.64	73.36	72.94	72.52	72.10	71.82
12 [2]	45.36	44.94	44.52	44.10	43.68	43.26
27:						
M_1V_1 [2]	122.08	121.38	120.54	119.84	119.14	118.44
29:						
Sidedressed	108.08	107.52	106.96	106.40	105.84	105.28
Sideplaced	70.84	69.86	68.88	67.90	66.92	65.94
30	103.32	102.76	102.34	101.78	101.22	100.80
32	182.70	181.58	180.60	179.48	178.36	177.24
51	141.96	141.40	141.40	140.28	139.72	139.16

[1] At the most profitable rate of application per acre with nitrogen at the indicated price per pound. See table 19 for pounds of nitrogen per acre and bushels of increased yield of corn.

[2] No P_2O_5 applied.

[3] For explanation, see table 7, footnote 2.

The return to nitrogen decreases as the price of nitrogen increases if the rate of application is adjusted to the higher price (table 29). The return also decreases as the price of nitrogen increases when the rate of application remains constant (table 29). The differences between the return to nitrogen for a constant rate of application determined at a price of 15 cents a pound and the return to nitrogen for a rate of application that is changed as the price of nitrogen changes are very small (tables 29 and 30).

TABLE 29.—*Return to nitrogen when nitrogen is applied at the most profitable rate according to price per pound, and when the rate of application remains constant regardless of actual price* [1]

Experiment	Return to nitrogen when price of nitrogen per pound is—					
	13 cents	14 cents	15 cents	16 cents	17 cents	18 cents
AT MOST PROFITABLE RATE OF APPLICATION						
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
2 [2]	85.89	83.88	81.93	80.05	78.22	76.43
7 [2]	46.22	44.70	43.23	41.82	40.45	39.13
10 [2]	92.32	90.54	88.83	87.08	85.38	83.77
11 [2]	59.80	58.74	57.71	56.72	55.73	54.79
12 [2]	32.97	32.03	31.12	30.24	29.39	28.58
27:						
M_1V_1 [3]	96.94	95.05	93.19	91.38	89.64	87.92
29:						
Sidedressed	87.90	86.36	84.87	83.41	81.98	80.60
Sideplaced	47.01	45.12	43.35	41.81	40.20	38.64
30	39.95	38.84	37.74	36.70	35.69	34.70
32	144.99	142.17	139.47	136.68	134.01	131.44
51	119.60	117.91	116.24	114.61	113.03	111.47
AT CONSTANT RATE OF APPLICATION [1]						
2 [2]	85.77	83.85	81.93	80.01	78.09	76.17
7 [2]	46.11	44.67	43.23	41.79	40.35	38.91
10 [2]	92.27	90.53	88.83	87.07	85.38	83.67
11 [2]	59.73	58.72	57.71	56.70	55.69	54.68
12 [2]	32.90	32.01	31.12	30.23	29.34	28.45
27:						
M_1V_1 [3]	96.83	95.01	93.19	91.37	89.55	87.73
29:						
Sidedressed	87.83	86.35	84.87	83.39	81.91	80.43
Sideplaced	46.85	45.15	43.45	41.75	40.05	38.35
30	39.88	38.81	37.74	36.67	35.60	34.53
32	144.95	142.17	139.47	136.67	133.99	131.25
51	119.55	117.87	116.24	114.56	112.88	111.20

[1] In this instance, the constant rate for each experiment is the most profitable rate of application when nitrogen is 15 cents a pound.
[2] No P_2O_5 applied.
[3] For explanation, see table 7, footnote 2.

RESPONSE UNDER VARIED CULTURAL CONDITIONS

Many different cultural conditions occur in the areas in which nitrogen is applied to corn. Some of these conditions that affect yields are use of nutrients other than nitrogen, previous use of commercial fertilizers, use of legumes in the crop rotations, levels of moisture applied, and plant populations. The effect of these conditions on the response to nitrogen varies. The study of nitrogen alone will not provide the answer to situations in which other conditions vary. Experiments are analyzed in terms of the varying returns to nitrogen under each type of situation.

TABLE 30.—*Loss in return to nitrogen when the rate of application remains constant and the price of nitrogen changes* [1]

Experiment	Loss in return to nitrogen when the price of nitrogen per pound is [2]—					
	13 cents	14 cents	15 cents	16 cents	17 cents	18 cents
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
2 [3]	0.12	0.03	0	0.04	0.13	0.26
7 [3]	.11	.03	0	.03	.10	.22
10 [3]	.05	.01	0	.01	.00	.10
11 [3]	.07	.02	0	.02	.04	.11
12 [3]	.07	.02	0	.01	.05	.13
27:						
M_1V_1 [4]	.11	.04	0	.01	.09	.19
29:						
Sidedressed	.07	.01	0	.02	.07	.17
Sideplaced	.16	.06	0	.06	.15	.29
30	.07	.03	0	.03	.09	.17
32	.04	.00	0	.01	.02	.19
51	.05	.03	0	.05	.15	.27

[1] In this instance, the constant rate for each experiment is the most profitable rate when nitrogen is 15 cents a pound.
[2] Difference between the return to nitrogen when the most profitable rate at each price is applied and when the most profitable rate at 15 cents a pound is applied regardless of actual price.
[3] No P_2O_5 applied.
[4] For explanation, see table 7, footnote 2.

TECHNICIAN-CONTROLLED VERSUS FARMER-CONTROLLED EXPERIMENTS

At Ontario, Oreg., several experiments were conducted at the Malheur Experiment Station and on different farms. Technicians controlled the experimental factors that were studied in experiments 8, 9, and 10. In other experiments, farmers controlled the cultural practices with the recording of farmer operations, harvesting of plots, and collection of other data performed or supervised by technicians. In general, yields were higher at the most profitable rates of application of nitrogen in technician-controlled experiments than in farmer-controlled experiments (table 31 and fig. 7). The returns to nitrogen varied widely.

Although, in general, yields both with and without fertilizer were lower for experiments in which cultural operations were controlled by farm operators, the returns to nitrogen were substantial (table 31). If the yields on farmer-controlled fields could be raised to the general level of top yields for the technician-controlled experiments, the return to nitrogen for farmer-controlled experiments could probably be increased considerably. The problem is how to decide which, if any, cultural practices would enable the farmers to obtain the higher yields.

EFFECT OF P_2O_5 ON YIELD RESPONSE TO NITROGEN

Additional P_2O_5 fertilizer is not needed for production of corn in the western irrigated areas, according to existing evidence. However, several experiments at Ontario, Oreg., were conducted to determine the effect of P_2O_5 on yield response to nitrogen. In each, the response to nitrogen was measured on plots with an application of 100 pounds

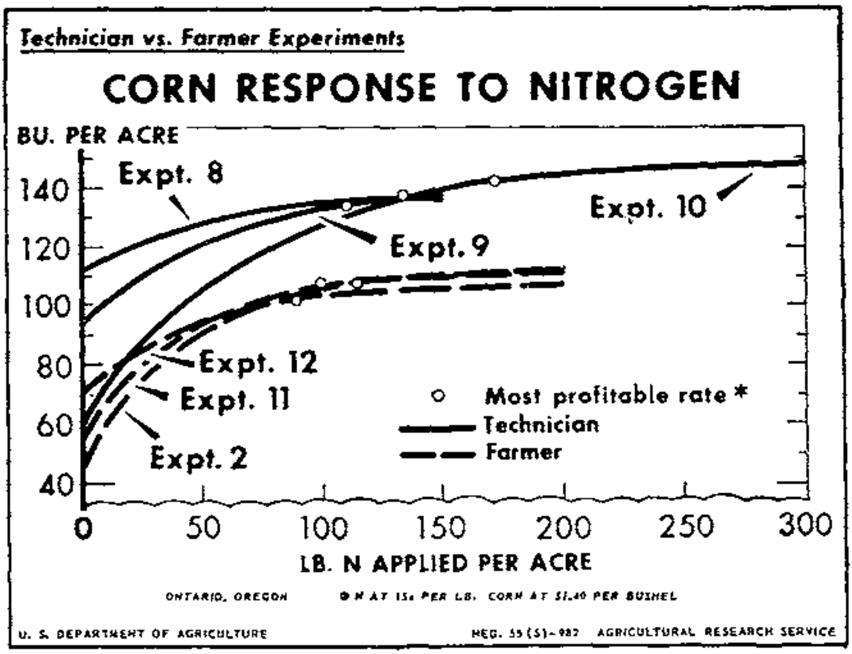

FIGURE 7.—Yield response curves and the most profitable rate of nitrogen application, irrigated corn-nitrogen rate experiments on farmer-controlled plots and on technician-controlled plots.

TABLE 31. *Increase in yield per acre and return to nitrogen, technician-controlled and farmer-controlled experiments, Ontario, Oreg.*

Experiment	Yield at 0 nitrogen application	Yield at most profitable rate of nitrogen application	Increase in yield	Most profitable rate of nitrogen application	Return to nitrogen [1]
Controlled by technicians:	*Bushels*	*Bushels*	*Bushels*	*Pounds*	*Dollars*
8	112. 1	133. 4	21. 3	76. 1	18. 40
9	94. 6	135. 4	40. 8	110. 0	40. 62
10 [2]	60. 8	142. 7	81. 9	172. 5	88. 78
Controlled by farmers:					
2 [3]	47. 9	108. 7	60. 8	116. 7	67. 62
2	44. 4	123. 4	79. 0	191. 6	81. 86
11	55. 8	107. 9	52. 1	101. 2	57. 76
12	71. 3	103. 1	31. 8	89. 0	31. 17
13	90. 2	107. 3	17. 1	92. 0	10. 14
7	63. 4	109. 7	46. 3	143. 9	43. 24

[1] Difference between value of increase in yield of corn at $1.40 per bushel, less cost of nitrogen at 15 cents a pound applied at most profitable rate.
[2] On farmer's field, but essentially controlled by technicians.
[3] 100 pounds of P_2O_5 per acre also applied.

of P_2O_5 per acre and on plots with no P_2O_5. Between these two levels of P_2O_5 the differences in average yields, for all levels of nitrogen, were within the range of yields that could have occurred by chance (*5*). Economic analysis based on the response curves to nitrogen shows 3 experiments with a greater return to nitrogen when P_2O_5 was not applied and 3 experiments with a greater return to nitrogen when P_2O_5 was applied (table 32). The differences, however, are relatively small.

TABLE 32.—*Effect of phosphate fertilizer on the return to nitrogen at the most profitable rate of nitrogen application, Ontario, Oreg.*

Experiment [1]	P_2O_5 applied per acre	Yield at 0 nitrogen application	Yield at most profitable rate of nitrogen application	Increase in yield	Most profitable rate of nitrogen application	Return to nitrogen [2]
	Pounds	*Bushels*	*Bushels*	*Bushels*	*Pounds*	*Dollars*
2	0	44.4	123.4	79.0	191.6	81.86
	100	47.9	108.7	60.8	116.7	67.62
4	0	81.4	106.8	25.4	100.0	20.56
	100	89.8	112.3	22.5	92.0	17.70
11	0	55.8	107.9	52.1	101.2	57.76
	100	62.9	109.8	46.9	105.0	49.91
7	0	63.4	109.7	46.3	143.9	43.24
	100	58.4	113.7	55.3	106.7	61.42
12	0	71.3	103.1	31.8	89.0	31.17
	100	64.8	105.1	40.3	132.8	36.50
13	0	90.2	107.3	17.1	92.0	10.14
	100	81.7	106.1	24.4	82.0	21.86

[1] See appendix table 40 for details of each experiment.
[2] Difference between value of increase in yield of corn at \$1.40 per bushel, less cost of nitrogen at 15 cents a pound applied at most profitable rate.

Only in experiments 7 and 13 were the increased returns to nitrogen sufficient to pay the cost of the 100 pounds of P_2O_5 applied per acre (fig. 8). Experiment 7 was conducted in the same field but not on the same plots as experiment 2 in the previous year. The return to nitrogen was \$18.18 more with the use of 100 pounds of P_2O_5 in experiment 7 in 1951, but for the previous year the return to nitrogen was \$14.24 more with no P_2O_5 in experiment 2. In experiment 13 the return to nitrogen without P_2O_5 was \$10.14; with P_2O_5 it was \$21.86. In this instance, the margin above the cost of 100 pounds of P_2O_5 is \$2.72 per acre (table 32).

PREVIOUS FERTILIZER PRACTICES

Legume cropping.—Legume crops add nitrogen to the soil. Addition of nitrogen following legumes may not increase crop yields materially. At Ontario, Oreg., addition of nitrogen did not increase the yield of corn following alfalfa in the three experiments for which alfalfa was the preceding crop. The yield without nitrogen was 111, 124, and 131 bushels per acre, respectively, for experiments 5, 6, and 1 (table 2). In experiment 8, also at Ontario, corn planted after barley, which had followed 3 years of alfalfa, yielded 133 bushels at the most profitable rate of 76.1 pounds of nitrogen per acre (fig. 9 and table 33). The increase in yield was 21.3 bushels and the return to nitrogen was \$18.40. Sixty pounds of nitrogen had been applied to the barley crop.

At Moses Lake, Wash., experiment 30 was conducted following 3 years of alfalfa which had been seeded on virgin soil. The yield of

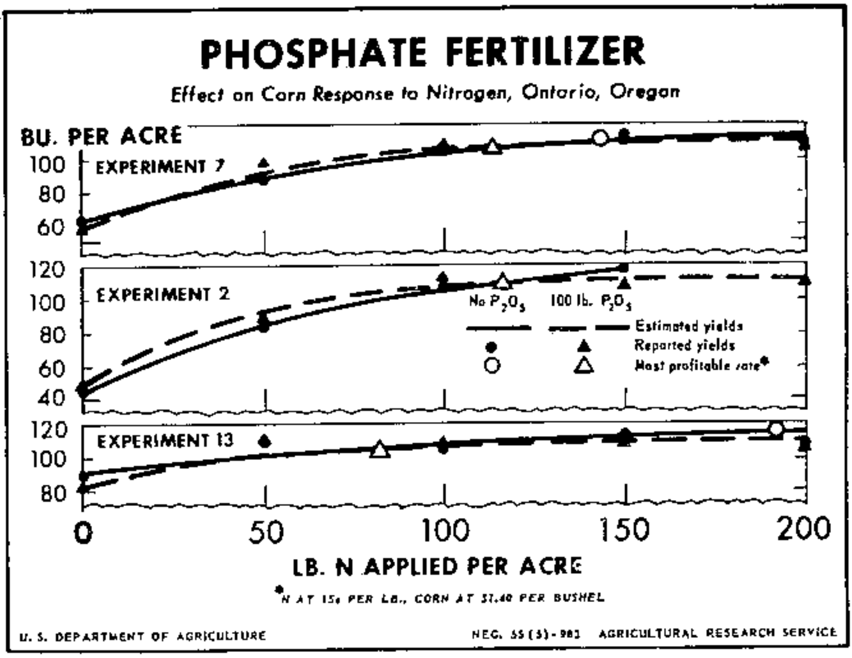

FIGURE 8.—Yield response curves, reported yields, and yield at the most profitable rate of nitrogen application, indicating the effect of P_2O_5 on yield responses, irrigated corn–nitrogen rate experiments, Ontario, Oreg.

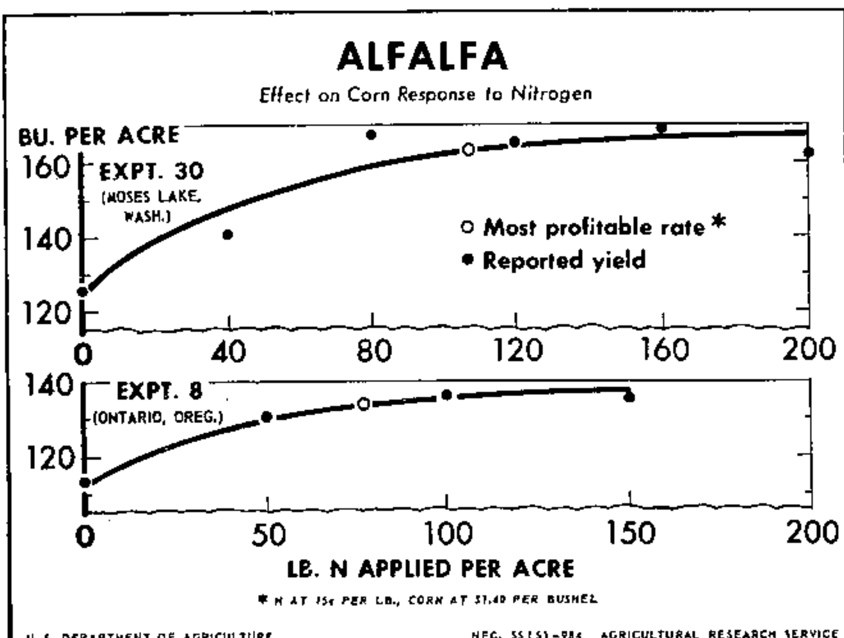

FIGURE 9.—Yield response curves, reported yields, and yield at the most profitable rate of nitrogen applied for irrigated corn–nitrogen rate experiments following 3 years of alfalfa at Moses Lake, Wash., and Ontario, Oreg.

TABLE 33.—*Increase in yield per acre and return to nitrogen on irrigated corn following a legume crop, Ontario, Oreg., and Moses Lake, Wash.*

Experiment [1]	Yield at 0 nitrogen application	Yield at most profitable rate of nitrogen application	Increase in yield	Most profitable rate of nitrogen [2]	Return to nitrogen [3]
	Bushels	*Bushels*	*Bushels*	*Pounds*	*Dollars*
8	112.1	133.4	21.3	76.1	18.40
27:					
M_1V_1 (1948)	44.2	130.3	86.1	182.5	93.16
M_1V_2 (1948)	76.9	143.4	66.5	180.9	65.96
M_2V_1 (1948)	57.6	96.2	38.6	95.0	39.79
M_2V_2 (1948)	80.8	110.8	30.0	140.8	20.88
27+28:					
M_1V_1 (1948–49)	62.8	166.7	103.9	182.5	118.08
M_1V_2 (1948–49)	91.9	214.4	122.5	180.9	144.36
M_2V_1 (1948–49)	83.3	126.9	43.6	95.0	46.78
M_2V_2 (1948–49)	103.8	177.6	73.8	140.8	82.13
30	124.1	162.4	38.3	106.7	37.62

[1] See appendix tables 40 and 41 for details of experiments and tables 2 and 9 for yields. M_1=8 irrigations 1948, M_2=3 irrigations 1948, V_1=no vetch 1948, V_2=winter vetch plowed under before corn.

[2] As computed from first-year response.

[3] Difference between value of increase in yield of corn at $1.40 per bushel, less cost of nitrogen at 15 cents a pound applied at most profitable rate.

corn without nitrogen was 124 bushels per acre. The yield was increased 38 bushels by the application of nitrogen at the most profitable rate, 107 pounds per acre (table 33). The return to nitrogen was $37.62.

In experiment 27 at Moses Lake, Wash., nitrogen was applied with and without a cover crop of winter vetch plowed under before the corn was planted in 1948 (table 7 and fig. 10). The following year in experiment 28 all plots were given adequate irrigation water, but no additional fertilizer was applied. In 1948, vetch increased the yield on the plots about 33 bushels (table 33). Nitrogen at the rate of 180.9 pounds per acre increased yields an additional 66.5 bushels per acre, and the return to nitrogen was $65.96. The return to nitrogen ($65.96) plus the value of the increased yield (33 bushels at $1.40 per bushel), with no application of nitrogen when corn followed a vetch cover crop, totaled $112.36 compared with $93.16, which is the return to nitrogen on corn grown without a cover crop. A difference of $19.00 is available to pay the cost of a cover crop above the return to nitrogen without cover crop (table 33).

The response to nitrogen at the low-moisture level (M_2) was more sustained on the plots that followed vetch than on the no-vetch plots. Evidently the vetch cover crop increased the available moisture at planting time. The sustained yield is reflected in a most profitable rate of 141 pounds of nitrogen for the vetch plots, compared with 95 pounds for the no-vetch plots.

The combined yields for 1948 and 1949 show that the check plots (no nitrogen), preceded by the vetch cover crop had a 29-bushel greater yield than the check plots without vetch. The return to nitrogen was $144.36 for the check plots following a vetch cover crop compared with $118.08 for plots on which the cover crop was not grown, or a difference of $26.28.

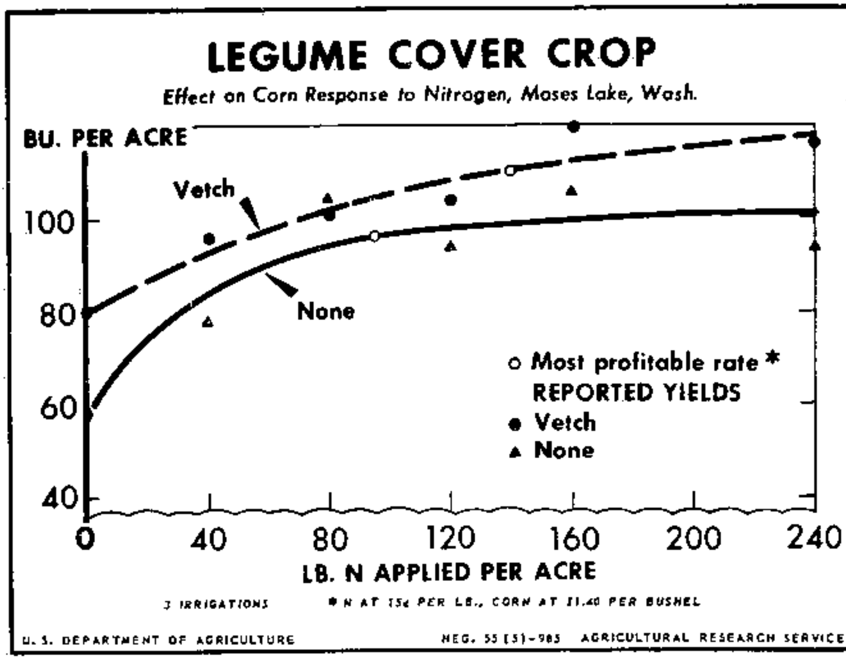

FIGURE 10.—Effect of a vetch cover crop on yield response curves, reported yields and yield at the most profitable rate of nitrogen application, irrigated corn-nitrogen rate experiment 27, Moses Lake, Wash., 1948.

The value of the increase in yield with no nitrogen and no cover crop (29.1 bushels at $1.40 per bushel) amounted to $40.74. Thus, there was a total increase of $67.02, which might be considered as available to pay for the vetch cover crop. This is in addition to the return to nitrogen of $118.08 per acre, when applied without the benefit of the cover crop (table 33). An additional benefit of winter vetch is the control of wind erosion. However, this analysis was not designed to evaluate this benefit.

Commercial fertilizer history.—The use of commercial fertilizer in years preceding production of corn may affect considerably the yield response to nitrogen. At Ontario, Oreg., commercial fertilizer was applied in small quantities in the year preceding corn on only two of the experiments conducted on farms (appendix table 40). Three of the experiments conducted at the experiment station were on soils that had grown row crops in the year preceding the experiment, and on which 40 to 60 pounds of nitrogen had been applied. Data on the fertilizer history of the experimental sites are so limited that they are of relatively little value in evaluating the residual effect of commercial fertilizer.

Manure was not applied to the crops that immediately preceded corn in any of the Oregon or Washington experiments studied. Preceding the initiation of experiment 52 in Nebraska, the plots had been treated with manure annually for several years.

The cropping history of plots on which experiments 54 to 57, inclusive, were conducted included short rotations of row crops. Small quantities of nitrogen and P_2O_5 were applied to crops preceding experiments 54 and 57. Preceding experiment 55 there were no practices for maintenance of fertility but in experiment 56, 12 tons of manure was applied every 2 or 3 years. Corn was grown continuously from 1912 on 2 replications and a sugar beet–potato rotation from 1912 to 1949 on 2 replications prior to experiment 58. In this experiment half the plots were treated with 12 tons of manure in addition to the nitrogen.

MOISTURE LEVELS

Adequate water is essential to enable corn to utilize nitrogen most effectively. In a few experiments, the quantity of water applied by irrigation was varied to study the yield response to nitrogen under different levels. In experiment 26, the quantity of nitrogen applied was so low that the estimated response curve did not include the estimated most profitable rates of application (tables 5 and 20). The difference in return to nitrogen at 400 pounds per acre and at the most profitable rate for any one of the M_2 (5 irrigations) or M_3 (8 irrigations) treatments would be very small. The most profitable rate with the S_1 spacing for the M_1 (11 irrigations) treatment is approximately 100 pounds smaller than for either the M_2 or the M_3 treatment. With the S_2 spacing the most profitable rate is much greater for the M_1 (11 irrigations) treatment, than for either the M_2 or the M_3 treatment with the same spacing. These differences for the M_1 treatment are neither consistent with the other 4 most profitable rates for this experiment nor with relationships shown in experiment 33 (tables 6 and 20).

Differences in the most profitable rates between the M_1 (15 irrigations) and M_2 (13 irrigations) treatments were small in experiment 33 (tables 6 and 20). Lower most profitable rates were obtained with the S_1 and S_2 spacings. This indicates that lack of moisture limited the response to nitrogen. The return to nitrogen was not computed because no zero nitrogen rates were included in the experiment.

At Moses Lake, Wash., in experiment 27, moisture was applied to corn at 2 levels consisting of 3 and 8 irrigations, both following a winter vetch crop and without vetch (tables 7 and 33, fig. 11). Without the cover crop the most profitable rate of nitrogen application was 182.5 pounds per acre with 8 irrigations, but with 3 irrigations the most profitable rate was only 95 pounds per acre. At the respective most profitable rates, increase in yield for 8 irrigations was 47.5 bushels greater than for 3 irrigations and the return to nitrogen was $53.37 more (table 33).

With corn following the vetch cover crop, there was a difference of about 40 pounds in the most profitable rate of nitrogen application per acre between the 2 moisture levels. At the respective most profitable rates, the increase in yield for 8 irrigations was 36.5 bushels greater than for 3 irrigations and the return to nitrogen was $45.08 more. The difference in return to nitrogen for 8 irrigations, as compared with 3, might be considered as the amount available to pay for the cost of the additional irrigations.

When return to nitrogen applied in 1948 is based on the total yield response for both 1948 and 1949, with the vetch cover crop it was $144.36 for 8 irrigations and $82.13 for 3 irrigations. Without the cover crop, the return was $118.08 and $46.78, respectively (table 33).

The return of $49.00 per acre to 150 pounds of nitrogen was obtained in experiment 7, with 6 irrigations and a plant population of 12,740 per acre.

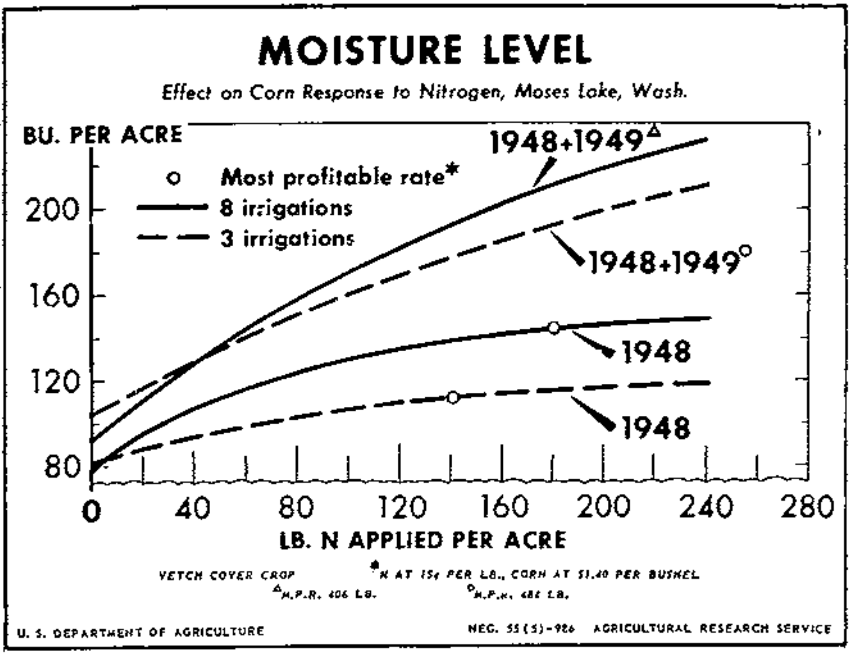

FIGURE 11.—Effect of two moisture levels on yield response curves and calculated most profitable rate of nitrogen application on irrigated corn after a vetch cover crop, for 1948 and the total for 1948 and 1949. experiments 27 and 28, Moses Lake, Wash.

Experiments 7 and 10 were conducted in successive years on the same farm, but on different plots. In experiment 10 the return to nitrogen of $88.00 per acre at 150 pounds of nitrogen was obtained with 8 irrigations and a plant population of 18,170 per acre (fig. 12).

Yield at zero application of nitrogen was approximately the same for each of these experiments. As nearly as can be determined, a difference of 2 irrigations, possibly some differences in timing of the irrigations, plus a few pounds of seed may have made a difference of nearly $40.00 per acre in the return to nitrogen. Observations by technicians in charge of these experiments indicate that 1951 and 1952 were comparable so far as corn was concerned. These results are not conclusive evidence as to the effect of additional irrigations and some extra seed. They do suggest that these two factors are important as they affect the return to nitrogen.

At a rate of 172 pounds per acre the return to nitrogen was $64.01 in experiment 2, $47.00 in experiment 7, and $88.90 in experiment 10 (table 34). At this rate, an overapplication of about 57 pounds of nitrogen per acre was made in experiments 2 and 7, and the return to nitrogen was reduced approximately $3.50. This loss is small compared with the greater increase in return that might have been realized from a thicker stand and better irrigation. In experiment 10 an application of 115 pounds of nitrogen, instead of 172 pounds, the most profitable rate, forfeited $6.37 in return to nitrogen.

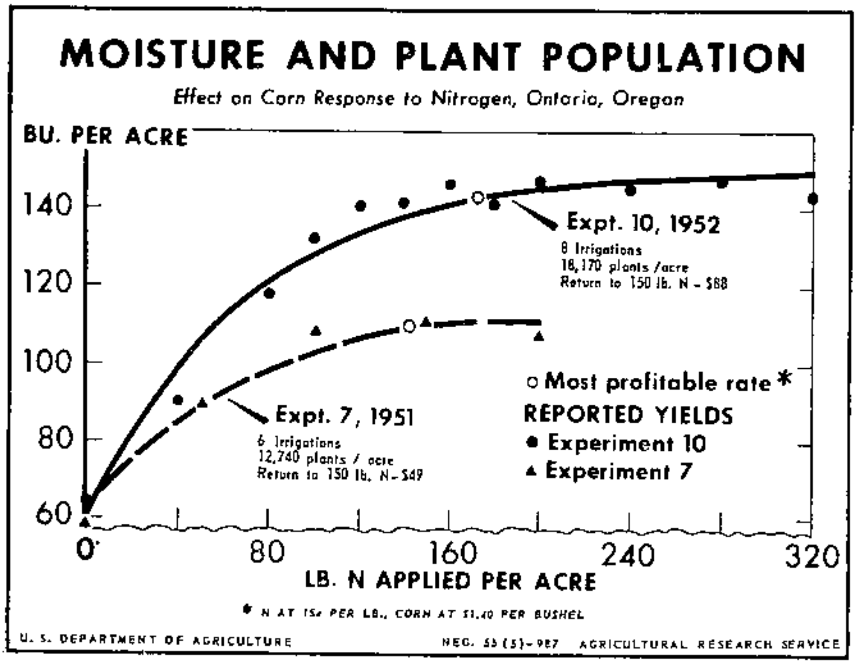

FIGURE 12.—Effect of two moisture levels and plant populations on yield response curves, reported yields, and yield at the most profitable rate of nitrogen application for experiments on the same field in 2 different years, irrigated corn–nitrogen rate experiments 7 and 10, Ontario, Oreg., 1951 and 1952.

TABLE 34.—*Return to nitrogen at two rates on the Moeller field, Ontario, Oreg., 1950–52*

Experiment	Year	Plant population per acre [1]	Irrigations	Return to nitrogen		
				115 pounds applied per acre [2]	172 pounds applied per acre	Difference [3]
		Number	*Number*	*Dollars*	*Dollars*	*Dollars*
2 [4]	1950	15, 280	5	67. 55	64. 01	−3. 54
7 [4]	1951	12, 740	6	50. 64	47. 00	−3. 64
10	1952	18, 170	8	82. 53	88. 90	+6. 37

[1] Idahybrid 544.
[2] Most profitable rate for experiment 2 was 117 pounds of nitrogen per acre. For experiment 7 it was 114 pounds, and for experiment 10, 115 pounds.
[3] Between return to nitrogen at 115 pounds and at 172 pounds per acre.
[4] No P_2O_5 applied.

SPACING

Additional nitrogen will support a higher plant population. The optimum number of plants, consistent with limitations of existing machinery, is important as it affects the return to nitrogen. In experiment 52, at Scottsbluff, Nebr., the fertility level was high and there was little response to nitrogen beyond the 40-pound rate, as shown in table 11. Curves were not fitted as a basis for comparing returns to nitrogen for moisture and spacing variables because of this small response to nitrogen. Rhoades and others (*14*) reported a 12-bushel difference in yield between the 36-inch spacing and the 28- and 20-inch spacings. The plant population per acre for these rates was 14,520, 18,669, and 26,136, respectively. The percentage of broken stalks was approximately 10 percent for the 28-inch spacing and 25 percent or more for the 20-inch spacing. The percentage of broken stalks in not related to the level of nitrogen. Ten percent or more of broken stalks is probably high enough to preclude machine harvesting, especially with other complications that arise from using equipment on narrow rows.

In experiment 26 at Prosser, Wash., within the range of rates of nitrogen applied—0 to 240 pounds—the yield curves for treatments M_2S_1, M_2S_2, M_3S_1 and M_3S_2 appeared to vary little. The most profitable rate of application was 433, 369, 408, and 450 pounds of nitrogen per acre, respectively. The most profitable rate for M_1S_1 was 290 pounds (table 20). For M_1S_2 it was 645 pounds. These most profitable rates are much higher than those for any other experiment studied here, in which experimental rates were high enough to characterize adequately the yield curve. For this reason, information on return to nitrogen based on the above rates is not presented here.

At Hermiston, Oreg., in experiment 33, plant populations of 14,500 and 32,700 plants per acre were studied (table 6). Yield curves were prepared only for the rates applied in two applications. For the S_2 spacing (14,500 plants per acre) extrapolation of the yield curve resulted in a negative yield at zero application. Consequently, the return to nitrogen has not been calculated. The most profitable rate of nitrogen application per acre is approximately 200 pounds for M_1—15 irrigations—and M_3—13 irrigations. The M_2—11 irrigations—treatment apparently depressed yields at the higher rates of nitrogen, and the most profitable rate is 141 pounds per acre.

The most profitable rates for the S_1 spacing (32,700 plants per acre) are greater than for the S_2 spacing (14,500 plants per acre) by 30 pounds for the M_1 treatment and by 18 pounds for the M_2 treatment. The difference between the most profitable rates for the 2 spacings for the M_3 treatment is 9 pounds. None of these rates differ enough between spacings at a given moisture level to affect return to nitrogen to any great extent. Effect of change in rate on the return to nitrogen is illustrated by the results in experiments 10, 32, and 51 (tables 21 to 23, col. 9).

In experiment 9 at Ontario, Oreg., corn was planted at 4 row-spacings, with constant distances of 9 inches within the row (table 3). Row spacings were 30, 36, 38, and 42 inches, and plant populations per acre were 23,230, 19,360, 18,340, and 17,140, respectively. Yield response for the 42-inch spacing differed significantly from that for the other 3 spacings. The most profitable rates of nitrogen application per acre were 110 pounds for the 36-inch spacing and 116 pounds for the 38-inch spacing (table 20). The most profitable rate for the 30-inch spacing was 418 pounds of nitrogen per acre. This rate is not consistent with any other rate ascertained for the Ontario area. Much higher rates than the maximum of 150 pounds applied in the experiments are needed to learn where the curve would level off. Further evidence is also needed with respect to the 42-inch spacing. The yield pattern for this spacing deviates from the general pattern for any of the other areas studied without any reasonable explanation.

NITROGEN CARRIERS

Nitrogen may be applied to corn in the form of different materials. The yield response to nitrogen from each form is important in choosing the material to use. In experiment 31 at Moses Lake, Wash., the results show that no appreciable differences in yields were obtained among the 5 different carriers of nitrogen. The highest rate applied in the test was 160 pounds per acre. This was not high enough to ascertain at what point the yield curve for each carrier tends to level off (table 10). The calculated most profitable rate of application is 175 pounds per acre for ammonium sulfate and from 202 to 367 pounds for the other 4 carriers (table 20).

At the most profitable rate of application for each, the return to calcium nitrate was $67.16; urea, $83.28; ammonium nitrate, $88.84; ammonium sulfate, $93.57; and anhydrous ammonia, $124.85. These results are for 1 year only. They are based on an insufficient range in rates applied, and they do not include benefits from the residual nitrogen.

TIME AND PLACEMENT OF NITROGEN APPLICATION

Nitrogen applied at different stages of plant growth and in different positions in relation to the plant may affect the yield response. In experiment 29, at Moses Lake, Wash., ammonium nitrate was applied at 6 rates, which ranged from 0 to 240 pounds of nitrogen per acre, and by 3 different methods at each rate: (1) Before seeding, the fertilizer was broadcast and harrowed into the soil; (2) at seeding time, it was sideplaced 3 inches to one side and 2 inches below the seed; and (3) when the corn was 12 inches high, the fertilizer was sidedressed 4 inches to the side and 4 inches deep.

Soil fertility varied greatly among the replications. Yields of the check plots ranged from 17.2 to 110.8 bushels per acre. The infiltration rate of irrigation water was slow and precipitation in the growing season was slight. No yield response relationship to nitrogen was obtained from the broadcast application beyond the 40-pound application (table 8). Analysis of the yield data showed no difference between the average yield obtained by sideplacing at planting time and that obtained by sidedressing when the corn was 12 inches high, because of the large variations in yields within each method of treatment. The most profitable rate of nitrogen application computed from the yield response curves is 170 pounds for the sideplaced method and 148 pounds for the sidedressed method (table 19).

For the sidedressed method the yield at zero application of nitrogen was 51 bushels and the increase in yield at the most profitable rate was 76 bushels. The return to nitrogen amounted to $84.80. This is approximately twice the return to nitrogen obtained with the sideplaced method, for which the yield at zero application estimated on the yield curve was 89 bushels, the increase in yield only 49 bushels, and the return to nitrogen $43. The difference in the check yields of the different methods of application is due to the design of the experiment. This was a split-plot experiment in which the three methods of application were the main plots and the rates of nitrogen application were the subplots. A zero rate of application was included in each subplot. With this design, the yields from the different zero rates are comparable only with the other yields of that particular method of application.

In Nebraska, at the Scotts Bluff station, experiments 54 through 57 included time of application as a variable. Nitrogen was plowed under before the corn was planted, sidedressed at the time corn was planted, sidedressed when the corn was 6 to 12 inches high, and sidedressed when the corn was 30 to 36 inches high. Apparently there is little difference in the yield response pattern for these times of application.

YIELD RESPONSE TO RESIDUAL NITROGEN

Corn may not use all of the applied nitrogen in the first season. If the residual nitrogen is not lost through leaching it may be utilized by the crop that follows. Therefore, the product from residual nitrogen should be included in determining the quantity of nitrogen to be applied. At Moses Lake, Wash., in 1948, experiment 27 was conducted on virgin Ephrata fine sandy loam soil. There were 2 moisture levels, one of 3 irrigations, and one of 8. Each moisture treatment was applied to plots in which winter vetch had been grown and plowed under just before the corn was planted and to plots without a vetch cover crop (appendix table 41, tables 7 and 35, and fig. 11). In the following year, plots in this experiment were adequately irrigated throughout the growing season, but no fertilizer was applied. Yields for the residual year are shown in table 7. At the most profitable rate of nitrogen application for 1948 on the no-vetch plots, the residual response for the 3-irrigation treatment (M_2V_1) in 1949 was 5 bushels and for the 8-irrigation treatment (M_1V_1) it was 18 bushels (table 35). The value of this residual yield, which is the difference between the return to nitrogen for 1948 and 1949 and the return for 1948 alone, is $6.99 and $24.92, respectively.

TABLE 35.—*Effect of residual nitrogen on yield response and return to nitrogen at the most profitable rates, high and low moisture, with and without cover crop, year of applications followed by uniform, adequate irrigation residual year, experiments 27 and 28, Moses Lake, Wash., 1948 and 1949*

Treatment [1]	Increase in yield			Return to nitrogen		
	Total	1948	1949	Total	1948	1949
	Bushels	*Bushels*	*Bushels*	*Dollars*	*Dollars*	*Dollars*
M_1V_1	103.9	86.1	17.8	118.08	93.16	24.92
M_2V_1	43.6	38.6	5.0	46.78	39.79	6.99
M_1V_2	122.5	66.5	56.0	144.36	65.96	78.40
M_2V_2	73.8	30.0	43.8	82.13	20.88	61.25

[1] 1948 crop: M_1=8 irrigations; M_2=3 irrigations; V_1=no vetch; V_2=following winter vetch crop. Adequate irrigation was applied uniformly to all plots in 1949.

On plots with a vetch cover crop, residual response was 56 bushels for 8 irrigations (M_1V_2) and 44 bushels for 3 irrigations (M_2V_2). The value of the residual response was $78.40 and $61.25, respectively (table 35).

The residual response on the high-moisture nonvetch plots (M_1V_1) nearly paid for the 183 pounds of nitrogen applied the first year (tables

19 and 35). The value of the residual response on the high-moisture vetch plots (M_1V_2) was almost 3 times the cost of the 181 pounds of nitrogen applied. On the low-moisture vetch plots (M_2V_2), the value of the residual response was 3 times the cost of the 141 pounds of nitrogen applied.

At a uniform application of 180 pounds of nitrogen to each moisture and vetch treatment, the residual response on the nonvetch plots paid the entire cost of the application of nitrogen (table 36). On the vetch plots, the residual response was valued at about 2½ times the cost of the 180-pound application of nitrogen.

TABLE 36.—*Residual response of irrigated corn to 180 pounds of nitrogen at 2 moisture levels, with and without vetch cover crop, experiment 28, Moses Lake, Wash., 1949*

Treatment	Return per acre to nitrogen		
	1948	1948 and 1949	Residual
	Dollars	*Dollars*	*Dollars*
M_1V_1	93. 10	118. 25	25. 15
M_2V_1	32. 46	62. 45	29. 99
Irrigation difference	60. 64	55. 80	
M_1V_2	65. 90	139. 03	73. 13
M_2V_2	20. 00	96. 41	76. 41
Irrigation difference	45. 90	52. 62	

At the Scotts Bluff, Nebr., station, in experiments 54 to 57, inclusive, 40, 80, and 120 pounds of nitrogen were applied per acre, as ammonium nitrate (tables 13–16, appendix table 42). In each experiment, the series of nitrogen rates were applied at 4 different times. These were plowed under when the seedbed was prepared, sidedressed at planting time, and sidedressed when the corn was 6 to 12 inches high, and when the corn was 30 to 36 inches high. The response to residual nitrogen fertilizer was measured in each experiment. The results are summarized in table 37. The maximum rate of 120 pounds of nitrogen applied in each of these experiments was not high enough to characterize adequately the yield curve so that it would indicate where yields tend to level off. With corn at $1.40 a bushel and nitrogen at 15 cents a pound, in most instances, the calculated most profitable rate is more than 120 pounds. Therefore, it would be found in the extrapolated portion of the yield curve. However, the results illustrate the importance of evaluating the total response when the effect of nitrogen fertilizer is interpreted.

Yields in 1951 were seriously affected by adverse weather. Apparently growth was so retarded that very substantial residual responses were observed in 1952 (tables 14, 15, and fig. 13). A flood and two frosts were experienced in June 1951, two small hailstorms in summer, and the retarded corn was killed by frost before maturity. These conditions affected experiments 54 to 56.

In experiment 54 there was little residual response in 1951, following the good crop in 1950 (tables 13, 37, and fig. 13). In 1952, in experi-

TABLE 37.—*Yield of irrigated corn per acre in response to residual nitrogen fertilizer, Scottsbluff, Nebr., 1951, 1952, and 1953*

Experiment	Year of residual response	Yield response to residual nitrogen by time of nitrogen application[1]			
		Before plowing	At planting time	When corn was— 6 to 12 inches high	When corn was— 30 to 36 inches high
		Bushels	*Bushels*	*Bushels*	*Bushels*
54	1951	8.5	8.3	8.6	11.7
55	1952	30.3	22.9	29.9	33.6
56	1952	40.1	37.4	44.9	33.4
57	1953	5.7	22.1	25.5	55.2

[1] 120 pounds of nitrogen per acre applied preceding year.

ment 55, however, response to nitrogen was large following the poor corn year of 1951, in which yields were low and there was no response to nitrogen (table 14). In experiment 56, the response to nitrogen was substantial in 1951, and the response to residual nitrogen was even greater in 1952 (tables 15 and 37). In experiment 57, at 120 pounds of nitrogen, the response to nitrogen was more than 60 bushels and the residual response was about 25 bushels (tables 16, 37, and fig. 13).

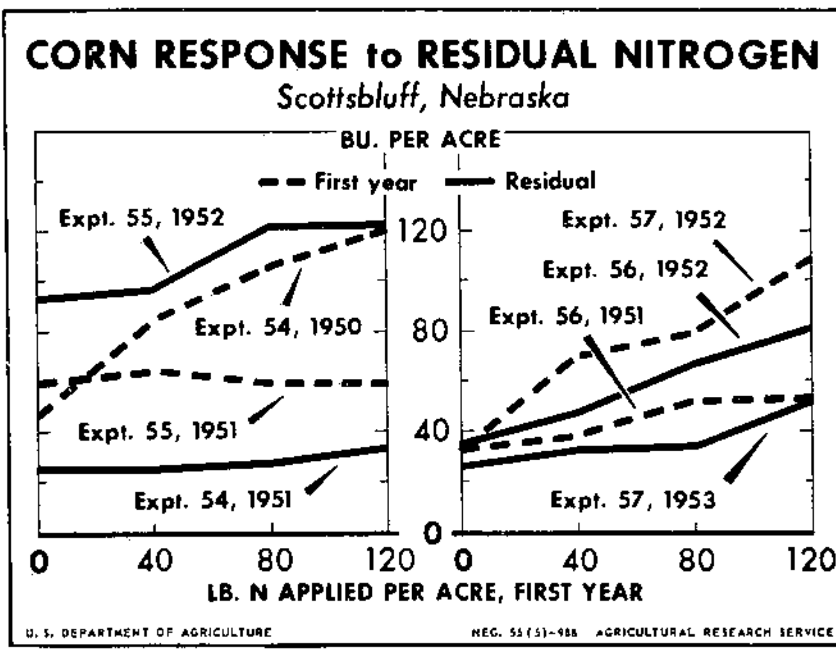

FIGURE 13.—Reported yield response of irrigated corn to nitrogen fertilizer sidedressed when corn was 6 to 12 inches high, and the residual yield the following year, experiments 54 to 57, Scottsbluff, Nebr., 1950–52.

Residual nitrogen from original 120-pound applications of nitrogen produced the increases in yield summarized in table 37. Although 1951 was a poor corn year, the residual response in experiment 54 would pay for approximately 80 pounds of nitrogen. Residual response in experiments 55 and 56 following a poor corn year was sufficient to pay for the 120-pound application and to leave a return of more than $25 per acre. In experiment 57, the residual response was much greater than the cost of the fertilizer for all applications except "plowed under." The most profitable rates of nitrogen applied in successive years may depend to a considerable extent on the residual nitrogen from previous applications.

OTHER RESPONSE BENEFITS FROM NITROGEN APPLICATION

An additional benefit which results from applying nitrogen fertilizer is the increase in the crude protein content of the corn that is obtained from increases in the rate of nitrogen applied (tables 38 and 39). Crude protein is expressed as the quantity of nitrogen in the corn times the constant 6.25 (6.25 × N). For purposes of discussion, and in the absence of a definite value obtained in feeding trials, the value of increased protein in the grain is assumed to be $0.075 a pound.

TABLE 38.—*Effect of nitrogen fertilizer on crude protein content (6.25 × N) of irrigated corn grain, Ontario, Oreg.*

Experiment	Yield of crude protein, by nitrogen applied per acre				
	0 pounds	50 pounds	100 pounds	150 pounds	200 pounds
	Percent	*Percent*	*Percent*	*Percent*	*Percent*
2 [1]	6.15	6.95	8.03	9.12	----------
4 [1]	7.68	8.74	8.45	8.95	----------
7 [1]	6.59	7.19	8.12	9.04	9.69
9	7.35	8.45	9.27	9.14	----------
11 [1]	7.65	8.64	9.87	10.33	10.42
12 [1]	7.19	8.24	9.48	9.46	10.21
13 [1]	8.27	9.34	10.60	10.69	10.46
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*
2 [1]	153.3	323.5	479.8	598.1	----------
4 [1]	350.0	493.4	554.6	481.2	----------
7 [1]	236.2	351.9	472.9	578.7	599.0
9	389.4	598.1	696.6	708.4	----------
11 [1]	238.6	472.3	578.2	660.6	644.8
12 [1]	287.1	442.5	571.7	520.8	644.4
13 [1]	419.1	570.1	628.6	677.6	632.6

[1] No P_2O_5 applied.

The most profitable rate for the experiments in table 38 is approximately 100 pounds of nitrogen per acre. This costs $15.00. At this rate, the increase in crude protein is roughly 200 pounds per acre for experiments 4, 7, and 13. This increase is valued at $15, which is sufficient to pay the entire cost of the nitrogen. The increase in protein for each of the other 4 experiments is roughly 300 pounds per acre, valued at $7.50 above the cost of nitrogen.

TABLE 39.—*Effect of nitrogen fertilizer on crude protein content (6.25 × N) of irrigated corn grain, Scottsbluff and Hardy, Nebr., and Ontario, Oreg.*

Experiment	Yield of crude protein, by nitrogen applied per acre						
	0 pounds	40 pounds	80 pounds	120 pounds	160 pounds	240 pounds	320 pounds
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
10 [1]	6. 92	7. 27	7. 86	8. 45	8. 74	9. 17	9. 58
51 [2]	8. 62	8. 31	8. 88	10. 38	10. 62	11. 12	10. 88
54 (1950): [3]							
Plowed under	7. 00	8. 00	9. 06	10. 19	------	------	------
Planting time	7. 00	7. 88	9. 00	9. 75	------	------	------
Corn 6-12″	7. 00	7. 94	9. 12	9. 31	------	------	------
Corn 30-36″	7. 00	8. 38	8. 94	9. 38	------	------	------
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
10 [1]	250. 3	368. 0	520. 3	665. 8	718. 5	748. 7	770. 4
51 [2]	92. 2	273. 6	429. 4	555. 5	609. 0	679. 9	637. 9
54 (1950): [3]							
Plowed under	150. 6	274. 4	425. 0	550. 6	------	------	------
Planting time	150. 6	282. 5	449. 4	530. 6	------	------	------
Corn 6-12″	150. 6	315. 0	454. 4	528. 8	------	------	------
Corn 30-36″	150. 6	335. 6	424. 4	510. 6	------	------	------

[1] Ontario, Oreg.
[2] Hardy, Nebr.
[3] Scottsbluff, Nebr.

In experiment 54, 120 pounds of applied nitrogen increased the protein yield by 360 to 400 pounds per acre (table 39). The nitrogen cost $18 and the value of the increased protein ranged from $27 to $30 per acre. The increased protein was worth more than the cost of 170 pounds of nitrogen in experiments 10 and 51 (table 39).

For the experiments in tables 38 and 39, at least, the value of the increased yield of protein at the most profitable rate of nitrogen application, based on grain alone, is more than enough to pay for the nitrogen. The value of the increased yield of corn, including residual response to nitrogen, is then net return.

The yield and quality of stover was not measured for any experiment included in this study. However, experiments from other areas suggest that substantial increases in the yield and quality of stover may be obtained with applications of nitrogen. In North Carolina, an application of 160 pounds of nitrogen increased yields of stover by 1,700 pounds (*8*). In Illinois, 125 pounds of applied nitrogen increased the yields of stover 840 pounds per acre, the percentage of crude protein 3 points, and the yield of crude protein nearly 200 pounds. At the same time the yields of grain increased 17 bushels per acre, and the crude protein in the grain increased 290 pounds.[10] The increase in yield and quality of stover approximately paid the cost of the fertilizer applied. Benefits from stover are especially important in an area in which stover is harvested for forage or cut for silage. When stover is returned directly to the soil, the increased yields are valuable in controlling erosion and in increasing organic matter in the soil (*16*).

[10] Bray, R. H., Department of Agronomy, University of Illinois, personal communication.

RESEARCH PROBLEMS

Experiments need to be repeated throughout a period of years on the same land and at different locations in the same year, so that a yield pattern may be obtained for use in making recommendations for wider areas. Test conditions and soil tests need to be identified in sufficient detail so that each farmer can relate his situation to particular experiments. Experiments conducted in different years will provide a measure of the effect of varying weather on the most profitable rate of application of nitrogen and the related return to nitrogen.

In making the economic analyses of these experiments, several problems arose. Many experiments had an insufficient number of rates of nitrogen fertilizer to permit accurate characterization of the yield curve. Even though 4-rate experiments have been analyzed, 5 rates of fertilizer are more desirable for estimating the constants of a particular response curve if the functional relationship to be used is any one of the curvilinear functions. Otherwise, the number of degrees of freedom is small and the estimates of the variability of the experimental data about the function may be large.

The range of rates should be great enough so that increases in experimental yields are small at the high rates of application. In the experiments in which the rates of application were at low levels, the resulting estimated response curve did not approach a maximum yield at reasonable rates of nitrogen. The slope of the curve was changing slowly and the estimated most profitable rates exceeded the highest rate applied and appeared to be too high compared with estimates from more complete experiments under somewhat similar conditions. So that the increase in yield resulting from the application of fertilizer may be evaluated, each experiment should include a check plot (zero application). In some instances, when no check plot was included in the experiment, the calculated yield at zero application was a negative number.

The exponential, or any other curvilinear function, may not reflect the yield responses throughout the range of applications. As the yield approaches the maximum, the differences between the yield responses to different rates of fertilizer applied are small and they are not all positive. The function for this segment of the yield curve might be a straight line with 0 slope. There is a paucity of yield data with which to study these problems. Immediate and serious consideration is needed in planning fertilizer experiments which will produce yield data that will more definitely identify the mathematical form of the yield response function to improve economic interpretation of experiments.

In addition to data on yield of grain, information on other costs and benefits associated with application of fertilizer also are needed. Some of the benefits as related to corn include crude protein content of grain and of stover, increased yield of stover, and the response to residual nitrogen in the second, and possibly succeeding, years. Chemical analysis of the product is essential in measuring some of these benefits and in measuring the increased use by the plant of other nutrients that may be associated with use of nitrogen fertilizer.

Further study is needed on how to evaluate some of these benefits in establishing the most profitable rate of application and computing the related return to nitrogen. Yield differences between the most profitable rate of application and a smaller rate of application may not be large enough to be recognized by farmers. Thus, they may apply the smaller rate and ignore the higher rates that would be justified if such other benefits as quality of grain and forage are considered.

Research procedures supplemental to, or in lieu of, rate studies designed for fitting response curves may offer an alternative method of estimating the most profitable use of fertilizer. The desirability of applying fertilizer at a rate high enough to eliminate it as a limiting factor should be investigated, especially in areas of favorable climatic conditions where the supply of moisture can be controlled. Special attention could then be given to other factors which might limit production. Soil tests, chemical tests of the product, and related factors would be studied in an effort to ascertain the minimum application of fertilizer that would be nonlimiting to plant growth.

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APPENDIX

Table 40.—*Test conditions for irrigated corn–nitrogen rate experiments, Ontario, Oreg., 1950–52* [1]

Item	Experiment 1	Experiment 2
Location	Malheur Experiment Station.	Paul Moeller farm.
Year	1950	1950.
Soil [2]	Greenleaf silt loam	Greenleaf silt loam.
Crop history	Grain, 1946; alfalfa, 1947–49.	Carrots, 1945; beets, 1946; barley, 1947; corn, 1948–49.
Fertilizer history	No fertilizer on alfalfa or grain; 12 tons of manure, spring 1950.	No fertilizer for at least 6 years.
Irrigation	5 irrigations (July 7, 13, 28; Aug. 9, 20).	5 irrigations (July 5, 15, 28; Aug. 11, 28).
Moisture control [3]	By technicians	By the farmer.
Variety of corn	Iowa 4316	Idahybrid 544.
Date planted	May 7	
Plant spacing___inches	11.5 x 36	11.4 x 36.
Plants per acre_number	15,120	15,280.
Yield data	Table 2	Table 2.
Replications___number	4	4.
Reference	(5)	(5).

See footnotes at end of table.

TABLE 40.—*Test conditions for irrigated corn-nitrogen rate experiments, Ontario, Oreg., 1950–52* [1]—Continued

Item	Experiment 3	Experiment 4
Location	Joseph Hobson farm	Malheur Experiment Station.
Year	1950	1951.
Soil [2]	Malheur silt loam	Greenleaf silt loam.
Crop history	Grain, 1949	Alfalfa, 1946–48; corn, 1949; barley, 1950.
Fertilizer history		No fertilizer on alfalfa; 10 tons of manure, 1949; 40 lbs. N, 1950.
Irrigation		5 irrigations (June 30; July 17, 25; Aug. 3, 17).
Moisture control [3]	By the farmer	By technicians.
Variety of corn	Idahybrid 544	Idahybrid 544.
Date planted	May 22	May 16.
Plant spacing...inches	9.5 x 36	8.4 x 36.
Plants per acre...number	18,260	20,680.
Yield data	Table 2	Table 2.
Replications...number	4	4.
Reference	(*5*)	(*5*).

Item	Experiment 5	Experiment 6
Location	Boyce Van de Water farm	Charles Custer farm.
Year	1951	1951.
Soil [2]	Very fine sandy loam (not classified).	Greenleaf loam.
Crop history	Alfalfa, 1946–50	Grain with alfalfa, 1950; alfalfa plowed, spring 1951.
Fertilizer history	Some P_2O_5 on alfalfa	
Irrigation	Irrigated at about 12-day intervals in summer.	5 irrigations (July 7, 19, 29; Aug. 13).[4]
Moisture control [3]	By the farmer	By the farmer.
Variety of corn	Idahybrid 544	Idahybrid 544.
Date planted	May 8	May 5.
Plant spacing...inches	15.4 x 36	8.1 x 36.
Plants per acre...number	11,270	21,400.
Yield data	Table 2	Table 2.
Replications...number	4	4.
Reference	(*5*)	(*5*).

See footnotes at end of table.

TABLE 40.—*Test conditions for irrigated corn–nitrogen rate experiments, Ontario, Oreg., 1950–52* [1]—Continued

Item	Experiment 7	Experiment 8
Location	Paul Moeller farm	Malheur Experiment Station.
Year	1951	1951.
Soil [2]	Greenleaf silt loam	Greenleaf silt loam.
Crop history	Beets, 1946; barley, 1947; corn, 1948–50.	Alfalfa, 1948–49; corn, 1950; barley, 1951.
Fertilizer history	No fertilizer for at least 7 years.	60 lbs. N, 1951.
Irrigation	6 irrigations (July 7, 18, 28; Aug. 9, 22; Sept. 9).	4 irrigations (July 9, 23; Aug. 10, 23).
Moisture control [3]	By the farmer	By technicians.
Variety of corn	Idahybrid 544	Idahybrid 544.
Date planted	May 18	May 12.
Plant spacing inches	17.2 x 36	10.4 x 36.
Plants per acre number	12,740	16,780.
Yield data	Table 2	Table 2.
Replications number	4	4.
Reference	(5)	(5).

Item	Experiment 9	Experiment 10
Location	Malheur Experiment Station.	Paul Moeller farm.
Year	1952	1952.
Soil [2]	Owyhee silt loam	Greenleaf silt loam.
Crop history	Corn, 1948; oats, 1949; corn, 1950; barley, 1951.	Beets, 1946; barley, 1947; corn, 1948–51.
Fertilizer history	12 tons of manure and 100 lbs. N, 1950; 60 lbs. N, 1951.	About 20 lbs. N, 1951; no fertilizer for at least 7 years before.
Irrigation	5 irrigations (June 28; July 11, 23; Aug. 12, 22).	8 irrigations (July 8, 14, 23, 31; Aug. 6, 11, 23; Sept. 3).
Moisture control [3]	By technicians	By the farmer.
Variety of corn	Idahybrid 544	Idahybrid 544.
Date planted	May 13	May 13.
Plant spacing inches	9 x 30; 9 x 36; 9 x 38; 9 x 42.	9.59 x 36.
Plants per acre number	23,230; 19,360; 18,340; 17,140.	18,170.
Yield data	Table 3	Table 4.
Replications number	3	4.
Reference	(5)	(5).

See footnotes at end of table.

TABLE 40.—*Test conditions for irrigated corn–nitrogen rate experiments, Ontario, Oreg., 1950–52* [1]—Continued

Item	Experiment 11	Experiment 12
Location	Joe Cloud farm	Henry Martin farm.
Year	1952	1952.
Soil [2]	Feltham fine sandy loam	Rebecca silt loam.
Crop history	Grain, 1947; alfalfa, 1948–49; potatoes, 1950; corn, 1951.	Sugar beets, 1949; beans, 1950; barley, 1951.
Fertilizer history	300 lbs. 16-20-0, 1950; 40 lbs. N, 1951.	No fertilizer for at least 5 years.
Irrigation	Every 4 or 5 days in June, July, and August.	7 irrigations (June 23; July 6, 14, 19;[5] Aug. 4, 20, 27).
Moisture control [3]	By the farmer	By the farmer.
Variety of corn	Idahybrid 544	Western hybrid 101.
Date planted	May 1	May 5.
Plant spacing...inches	16.16 x 40	10.62 x 38.
Plants per acre...number	9,700	15,540.
Yield data	Table 2	Table 2.
Replications...number	4	4.
Reference	(5)	(5).

Item	Experiment 13
Location	D. L. Benedict farm.
Year	1952.
Soil [2]	Owyhee silt loam.
Crop history	Clover, 1944, 1946, 1948, 1950; barley, 1945, 1947, 1949, 1951.
Fertilizer history	No fertilizer in recent years.
Irrigation	Every 12 days in summer.
Moisture control [3]	By the farmer.
Variety of corn	Idahybrid 544.
Date planted	April 29.
Plant spacing...inches	14.26 x 40.
Plants per acre...number	11,000.
Yield data	Table 2.
Replications...number	4.
Reference	(5).

[1] Fertilizer applied a few days after planting in bands approximately 4 inches from one side of row and 3 to 5 inches deep. Nitrogen applied as ammonium sulfate.

[2] Series names are tentative.

[3] Precipitation, usually not more than 2 to 3 inches in the growing season, is not an important factor because adequate irrigation water is available on demand. In experiments 1, 4, 8, and 9, corn was irrigated according to usual practice at the station; in other experiments, corn was irrigated according to usual practice of the farmer.

[4] Should have had 1 more irrigation about August 25.

[5] Water not available for 1 irrigation.

TABLE 41.—*Test conditions for irrigated corn–nitrogen rate experiments, central Washington area* [1]

Item	Experiment 26	Experiment 27
Location	Prosser [2]	Moses Lake.[3]
Year	1947	1948.
Soil	Ritzville fine sandy loam	Ephrata fine sandy loam.
Crop history	Virgin soil	Virgin soil. Vetch plots seeded, fall 1947.
Fertilization history	Virgin soil	Vetch plots, 50 lbs. sulfur and 50 lbs. P_2O_5 before seeding.
Fertilization	Ammonium nitrate—single application, 5 rates; split application, 4 rates.	Ammonium nitrate—6 rates sideplaced at emergence.
Irrigation	M_1—11 irrigations; irrigated when *SMT* reached 300 cm. at 9 inches. M_2—5 irrigations; irrigated when *SMT* reached 4 atmospheres at 9 inches. M_3—8 irrigations; same as M_2 until silking, then same as M_1. Water not measured.	M_1—8 irrigations (July 1, 17, 27; Aug. 6, 12, 13; Sept. 2, 16). Maintain *SMT* below 800 cm. Net intake—vetch and no vetch plots, 24 inches. M_2—3 irrigations (July 12, Aug. 8, Sept. 3). Irrigated when resistance=10,000 ohms. Net intake—vetch plots, 11 inches; no vetch plots, 12 inches.
Variety of corn	Iowa 939	Iowa 939.
Date planted	May 12	
Plant spacing...inches	S_1—12 x 36; S_2—8 x 24	12 x 34.
Plants per acre..number		15,374.
Yield data	Table 5	Table 7.
Replications...number	4	4.
Reference	*(15)*	*(15)*.

Item	Experiment 28	Experiment 29
Location	Moses Lake [3]	Moses Lake.[3]
Year	1949	1949.
Soil	Ephrata fine sandy loam	Ephrata fine sandy loam.
Crop history	This experiment followed experiment 27.	Virgin soil (extensive leveling).
Fertilization history	See experiment 27	Virgin soil.
Fertilization	No fertilizer in 1949; residual response only.	Ammonium nitrate—6 rates, 3 timing combinations.
Irrigation	7 irrigations; adequate moisture.	9 irrigations (May 2; June 16, 29; July 8, 13, 20; Aug. 2, 11, 23).[5] Not measured.
Variety of corn	Iowa 939	Iowa 939.
Date planted		May 11.
Plant spacing...inches		12 x 32.
Plants per acre..number		16,335.
Yield data	Table 7	Table 8.
Replications...number		5.
Reference	*(15)*	([6]).

See footnotes at end of table.

TABLE 41.—*Test conditions for irrigated corn–nitrogen rate experiments, central Washington area*[1]—Continued

Item	Experiment 30	Experiment 31
Location	Moses Lake[3]	Moses Lake.[3]
Year	1951	1952.
Soil	Ephrata fine sandy loam.	Ephrata fine sandy loam.
Crop history	Alfalfa, 1948–50	Virgin soil.
Fertilization history	No fertilizer, 1948–50	Virgin soil.
Fertilization	Ammonium nitrate—6 rates placed 2 inches below and 3 inches to side of seed.	Ammonium sulfate, ammonium nitrate, anhydrous ammonia, urea, and calcium nitrate each applied at 4 rates, sidedressed after emergence.
Irrigation	9 irrigations (Apr. 27; June 30; July 12, 19, 24; Aug. 1, 7, 15, 21). Net intake, 36.91 inches.	*SMT* below 800 cm. at 9 inches throughout the season.
Variety of corn	Iowa 939	Iowa 939.
Date planted	May 9	May 11.
Plant spacing...inches	10–12 x 34	10.5 x 34.
Plants per acre...number	16,772	17,500.
Yield data	Table 9	Table 10.
Replications...number	4	5.
Reference	*(20)*	*(20)*.

Item	Experiment 32	Experiment 33
Location	Prosser[2]	Hermiston, Oreg.
Year	1953	1947.
Soil	Ritzville very fine sandy loam, 60-inch depth.	
Crop history	Virgin soil	Virgin soil.
Fertilization history	Virgin soil	Virgin soil.
Fertilization	Ammonium nitrate—12 rates sidedressed.	Ammonium nitrate—single applications, 4 rates; split applications, 4 rates; 100 pounds P_2O_5. One 120-pound rate with 15 tons of manure.
Irrigation	Adequate irrigation	M_1—15 irrigations (irrigated when *SMT* was below 400 cm. at 9 inches); total, 5.07 feet. M_2—11 irrigations (irrigated when *SMT* was below 9 atmospheres at 9 inches); total, 3.65 feet. M_3—13 irrigations (irrigated same as M_2 except 3 weeks during silking and pollination; then same as M_1); total, 4.21 feet.
Variety of corn	Iowa 939	U. S. 13.
Date planted	May 12	April 15.

See footnotes at end of table.

TABLE 41.—*Test conditions for irrigated corn–nitrogen rate experiments, central Washington area* [1]—Continued

Item	Experiment 32	Experiment 33
Plant spacing___inches	12 x 30	S_1—12 x 36; S_2—8 x 24.
Plants per acre_number	17,500	S_1—14,500; S_2—32,700.
Yield data	Table 4	Table 6.
Replications___number		4.
Reference	(6)	(*15*).

[1] Precipitation, usually very little in the growing season, is not an important factor because adequate irrigation water for these experiments was available on demand.
[2] Irrigation Experiment Station, Prosser, Wash.
[3] Moses Lake, Wash., Development Farm.
[4] Net intake.
[5] Irrigations were for longer durations and more frequent than is commonly practiced on the fine sandy loams in the Yakima Valley.
[6] Unpublished data from Irrigation Experiment Station, Prosser, Wash.

TABLE 42.—*Test conditions for irrigated corn–nitrogen rate experiments, Nebraska, 1949–53*

Item	Experiment 51	Experiment 52
Year	1952	1949.
Soil	Waukesha silty clay loam	Tripp very fine sandy loam.
Crop history	Dryland corn for many years; brought under irrigation in 1951.	
Fertilization history		"Liberal" manure for many years.
Fertilization	Ammonium nitrate—12 rates ranging from 0 to 320 lbs. per acre, sidedressed at second cultivation.	Ammonium nitrate—0, 40, 80, 160, and 320 lbs. N. and 25 tons of manure per acre; 160 lbs. N. and 25 tons of manure per acre; 40 lbs. N. and 40 lbs. P_2O_5 per acre.
Irrigation	Adequate irrigation supervised by extension agricultural engineer.	M_1—3 irrigations (July 5–7, Aug. 1–3, Aug. 30). M_2—3 irrigations (July 5–7, Aug. 1–3, Aug. 23). M_3—5 irrigations (July 5–7, July 23, Aug. 6, Aug. 19, Sept. 2).
Variety of corn	Nebraska 504	Iowa 4316.
Date planted	May 14	May 12–14.
Plant spacing___inches	9 x 40	S_1—9 x 36; S_2—9 x 28; S_3—9 x 20.
Plants per acre_number	17,670	S_1—14,520; S_2—18,669; S_3—26,136.
Yield data	Table 4	Table 11.
Replications___number	5	4.
Reference	(*10, 14*)	(*14*).

See footnote at end of table.

TABLE 42.—*Test conditions for irrigated corn–nitrogen rate experiments, Nebraska, 1949–53*—Continued

Item	Experiment 53	Experiment 54
Year	1950, 1952	1950, 1951 (residual).
Soil	Tripp very fine sandy loam.	Tripp very fine sandy loam, low fertility.
Crop history	Bromegrass irrigated pasture, 1938–48; potatoes, 1949; corn, 1950; sugar beets, 1951; corn, 1952.	Each replication had a different crop in 1949; no legumes.
Fertilization history	1949—0, 80, 160, and 320 lb. N; 160 lb. N and 80 lb. P_2O_5; 160 lb. N, 80 lb. P_2O_5, and 80 lb. K_2O.	Each replication different.
Fertilization	Plots split in 1950. Half of plots received no additional nitrogen; other half had 40 lbs. additional N applied to corn in 1950; 80 lbs. N to sugar beets in 1951; and 80 lbs. N to corn in 1952. P_2O_5 and K_2O treatments same in 1951 as 1949.	Ammonium nitrate—0, 40, 80, and 120 lb. N per acre in 1950: (1) Plowed under, (2) at planting time, (3) corn 6–12 inches, (4) corn 30–36 inches high. None in 1951.
Irrigation	1949—potatoes, 8 irrigations. 1950—corn, 5 irrigations. 1951—sugar beets, 5 irrigations, 1952—corn, 4 irrigations.	1950 and 1951—4 irrigations.
Variety of corn	Nebraska 301	1950—Iowa 4316 1951—Nebraska 301.
Date planted	1950—May 12 1952—May 9	1950—May 15. 1951—May 14.
Plant spacing ... inches	1949—potatoes, 9 x 36; 1950—corn, 11 x 36; 1951—sugar beets, 14 x 20; 1952—corn, 15 x 36.	1950—12 x 30 1951—22 x 36
Plants per acre ... number	1949—19,360; 1950—15,840; 1951—22,400; 1952—11,600.	1950—17,400. 1951—11,600.
Yield data	Table 12	Table 13.
Replications ... number	5 on west field; 4 on east field.	4.
Reference	([1])	([1]).

Item	Experiment 55	Experiment 56
Year	1951; 1952 (residual)	1951; 1952 (residual).
Soil	Tripp very fine sandy loam, high fertility.	Tripp very fine sandy loam, medium fertility.
Crop history	Uniform rotation, 1912–48; no legumes. Each replication different, 1949.	Uniform rotation, 1912–49.

See footnote at end of table.

TABLE 42.—*Test conditions for irrigated corn–nitrogen rate experiments, Nebraska, 1949–53*—Continued

Item	Experiment 55	Experiment 56
Fertilization history	Each replication different; no practices for maintaining fertility.	Each replication different; manure applied at various times.
Fertilization	Ammonium nitrate—0, 40, 80, and 120 lbs. N in 1951: (1) Plowed under, (2) at planting time, (3) corn 6–12 inches, and (4) corn 30–36 inches. None in 1952.	Ammonium nitrate—0, 40, 80, and 120 lbs. N in 1951: (1) Plowed under, (2) at planting time, (3) corn 6–12 inches, and (4) corn 30–36 inches. None in 1952.
Irrigation	4 irrigations, 1951; 4 irrigations, 1952.	4 irrigations, 1951; 4 irrigations, 1952.
Variety of corn	Nebraska 301	Nebraska 301.
Date planted	1951—May 14 1952—May 8	1951—May 14. 1952—May 8.
Plant spacing...inches	1951—20 x 36 1952—12 x 36	1951—20 x 36 1952—12 x 36.
Plants per acre number	1951—8,700 1952—14,500	1951—8,700 1952—14,500.
Yield data	Table 14	Table 15.
Replications...number	2	2.
Reference	[1]	[1].

Item	Experiment 57	Experiment 58
Year	1952, 1953 (residual)	1953.
Soil	Tripp very fine sandy loam, low fertility.	Tripp very sandy loam.
Crop history	Uniform cropping, 1912–48; no legumes. Each replication different, 1949. Corn, 1950 and 1951.	A and C—corn since 1912. B and D—sugar beet-potato rotation, 1912–50; corn, 1950–52.
Fertilization history	See experiment 54	A and B—12 tons of manure, 1942–52. C and D—12 tons of manure every 2 years, 1912–52.
Fertilization	Ammonium nitrate—0, 40, 80, and 120 lbs. N in 1952: (1) Plowed under, (2) planting time, (3) corn 6–12 inches, (4) corn 30–36 inches. None in 1953.	A, B, C, and D—0, 40, 80, 120, and 160 lbs. N.; 120 lbs. N. and 40 lbs. P_2O_5; C and D—12 tons of manure.
Irrigation	4 irrigations, 1952; 4 irrigations, 1953.	3 irrigations.
Variety of corn	Nebraska 301	Nebraska 301.
Date planted	1952—May 8 1953—May 7	May 7.
Plant spacing...inches	12 x 36	11 x 36.
Plants per acre...number	14,500	15,800.
Yield data	Table 16	Table 17.
Replications...number	4	2.
Reference	[1]	[1].

[1] Unpublished data of the Scotts Bluff Experiment Station, Scottsbluff, Nebr.

TABLE 43.—*Constants determined by mathematical method of estimation for the response curve $Y=M-AR^X$ and the standard errors of the constants, irrigated corn–nitrogen rate experiments, Oregon, Washington, and Nebraska*

Experiment	P_2O_5 per acre (pounds)	M	$-A$	R [1]	s_M	s_A	s_R
2	0	132.39	88.05	0.78804	4.58	4.47	0.0367
	100	113.39	65.52	.63825	5.48	7.97	.1754
7	0	117.79	54.37	.76718	6.78	7.17	.1170
	100	111.96	53.59	.66434	4.36	5.87	.1106
10	50	150.17	89.40	.75000	6.70	11.31	.0204
11	0	112.05	56.22	.59767	2.72	4.28	.0780
	100	114.55	51.62	.63533	1.04	1.51	.0299
12	0	107.70	36.37	.62870	6.82	9.62	.0849
	100	112.98	48.13	.76088	7.97	8.54	.1599
27:							
M_1V_1	0	138.22	94.01	.76225	8.71	9.87	.0851
M_1V_2	[2] 65	152.65	75.77	.79187	11.62	12.18	.1197
M_2V_1	0	100.67	43.06	.62171	6.48	10.39	.2305
M_2V_2	[2] 65	122.89	42.10	.83727	12.14	11.60	.0517
27 and 28:							
M_1V_1	0	181.93	119.09	.79642	28.13	28.99	.0559
M_1V_2	[2] 65	296.39	204.48	.90794	82.16	77.58	.1061
M_2V_1	0	171.12	87.84	.86559	30.62	28.56	.0247
M_2V_2 [3]	[2] 65	281.76	177.87	.9268	-----	-----	-----
29:							
Sideplaced	0	149.07	59.71	.81457	8.63	8.75	.0107
Sidedressed	0	133.70	82.50	.70220	4.72	6.34	.0689
30	0	167.98	43.90	.67780	6.79	9.15	.1987
32	0	152.74	140.81	.83504	6.46	9.79	.0435
51	0	127.78	106.78	.70652	5.05	9.82	.0520

[1] In terms of 20-pound units of nitrogen.

[2] 65 pounds of P_2O_5 and 50 pounds of sulfur applied before seeding vetch cover crop preceding corn in experiment 27.

[3] Constants for this response curve were determined by the graphic method of estimation.

TABLE 44.—*Constants determined by graphic method of estimation for the response curve $Y=M-AR^X$, irrigated corn–nitrogen rate experiments, Oregon, Washington, and Nebraska*

Experiment	P_2O_5 per acre (pounds)	M	$-A$	R [1]
4	0	113.84	32.44	0.73795
	100	118.71	29.91	.71582
8	0	137.34	24.44	.62355
9:				
30-inch row	0	221.00	125.00	.94240
36-inch row	0	141.01	46.41	.68112
38-inch row	0	138.59	41.89	.73264
42-inch row	0	125.06	19.06	.46482
13	0	117.08	26.88	.80658
	100	111.06	29.36	.64924
26:				
M_1S_1	0	156.08	135.08	.85342
M_1S_2	0	280.03	276.03	.93552
M_2S_1	0	205.25	182.25	.90672
M_2S_2	0	187.21	181.21	.88025
M_3S_1	0	199.21	184.21	.89523
M_3S_2	0	219.46	209.46	.90308
31:				
Calcium nitrate	0	167.25	90.25	.87258
Ammonium sulfate	0	169.09	93.09	.74971
Ammonium nitrate	0	170.70	94.50	.79577
Anhydrous ammonia	0	220.84	147.84	.89516
Urea	0	176.41	100.41	.85360
33:				
M_1S_1	0	141.40	48.40	.85950
M_1S_2	0	138.76	76.56	.66564
M_2S_1	0	127.84	27.84	.64083
M_2S_2	0	98.03	35.33	.41410
M_3S_1	0	139.14	41.14	.80313
M_3S_2	0	144.10	79.00	.80381

[1] In terms of 20-pound units of nitrogen.

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END