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# Determination of Crop Production Functions as Related to Soil Moisture and Nitrogen

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# DETERMINATION OF CROP PRODUCTION FUNCTIONS AS RELATED TO SOIL MOISTURE AND NITROGEN

by

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| | |
|---|---|
| $\hat{Y}$ | Estimate yield (kg/ha) |
| $\alpha$ | Y intercept of production surface |
| $\beta i$ | Partial regression coefficient |
| W | Soil moisture level |
| N | N fertilizer level (kg/ha) |
| Ri | Replicate number |
| $\psi m$ | Matric potential (-bars) |
| Ymax | Estimated maximum yield (kg/ha) |
| Wmax | Maximum soil moisture level |
| Nmax | Maximum N fertilizer level (kg/ha) |
| P | Probability (%) |
| $R^2$ | Multiple correlation coefficient |
| $\theta$ | Volumetric soil moisture content |
| Wopt | Soil moisture level associated with optimum yield |
| Nopt | N fertilizer level associated with optimum yield (kg/ha) |

# ABSTRACT

Determination of Crop Production Functions as

Related to Soil Moisture and Nitrogen

by

James W. Bauder, Doctor of Philosophy

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Major Professor: Dr. R. J. Hanks
Department: Soil Science and Biometeorology

Soil moisture and nitrogen are often the primary controlling factors of crop production. Production functions are valuable in describing crop responses to such controlling factors. Such functions are also needed for determining the economic reliability of crop production.

Soil moisture and nitrogen fertilizer were maintained at various levels to determine the response of field corn to these controlling factors. A conventional split plot design, a continuous function experimental design, and a confined barrel plot design were used to obtain data for determining production functions.

The complete factorial, conventional split plot data was successfully used to generate reliable production functions in two locations. The multiple correlation coefficient was approximately 0.68. The continuous function design consisted of a large number of treatment combinations with only small sequential increments in treatment levels, from plot to plot. This made it possible to eliminate border rows and use a much smaller plot size. The design was tested in two locations, using 10 soil moisture levels and 22 nitrogen fertilizer levels. The multiple correlation coefficients were about 0.33 and 0.49. Using this design, it was necessary to replicate entire blocks.

The production functions from the conventional split plot design and continuous variable plot design compared favorably within locations, but not between locations. Production functions were also determined for relative yields and treatments. The inputs were expressed as fractions relative to both the maximum and optimum levels. The relative production functions were similar for both locations. The production functions were tested for transferability by making adjustments in the input data to account for site specific controlling factors. No definite conclusions were possible although the results suggest that transferability is possible.

Several reduced field designs were also tested using the data obtained. Three different incomplete factorial, split plot designs appear to be suitable for generating production functions. Grouping of the continuous function plots to as few as four soil moisture levels by four fertilizer levels also gave reliable production functions. Several suggestions regarding the use of reduced field designs are presented along with suggested future research needs in this area. The data indicate that the continuous variable design is quite useful for determining production functions. The barrel plots consisted of field corn grown under various treatment combinations on undisturbed soil cores. The data obtained from these barrel plots (210 liters) were too variable to generate a reliable production function.

(112 pages)

# INTRODUCTION

Within the past decade both the domestic and world food markets have experienced supplies inadequate to meet consumers' demands. Several factors have contributed to the increasing shortage, including an increasing population, changing consumer habits, and changing land use. At the same time, several avenues are available whereby the burden of demand can be answered. One means of increasing production in the United States and abroad is to increase the efficiency of crop cultivation and production practices.

Agronomists are particularly concerned with the optimum utilization of our resources. Presently, considerable attention is being given to the study of many of the factors that influence crop growth. The objective is to determine the levels of various inputs necessary to obtain maximum economic return from the land. Consequently, considerable importance has been placed on the collection of data relating crop yields to various factors such as location, soil fertility, available soil moisture, crop variety, parasites, and others.

There is little doubt that crop production is a function of many variables. The problem of examining each of these variables in detail is evident because of the number and magnitude involved. In order to efficiently examine crop production, study techniques should be designed to provide a maximum amount of useful information while requiring a minimum amount of resource inputs.

In view of these conditions much agricultural research has been focused toward the combined effects of various controlling factors on crop growth. Soil moisture and nitrogen fertility have received considerable attention. Much past research has treated these two variables somewhat separately, either neglecting or over-looking the possibilities of interactions and their effects on crop production. This has led to inconclusive results in many instances.

In an attempt to determine efficient irrigation and nitrogen fertilization practices, research has increased in recent times. By determining the levels of soil moisture and fertility as related to crop production and the significance of the interaction of these two variables, it should be possible to develop reliable prediction equations, which would provide a means for efficient irrigation and fertilization programs that would result in maximum economic return. This research was undertaken with these objectives.

## Objectives

The specific objectives of this research have been to provide the information and means by which reliable prediction equations could be determined for field corn grown under conditions of controlled soil moisture and nitrogren fertilizer. The specific objectives were:

(1) to determine if crop production functions can be developed in the field,

(2) to determine the consistancy of crop production functions for a particular crop (field corn) grown under two conditions, namely in field plots and in barrel plots in two locations,

(3) to evaluate the continuous variable plot design method for determining crop production functions with respect to soil moisture and fertility,

(a) compare the population described by the continuous variable design with that of the conventional design,

(b) determine the maximum amount of grouping and elimination of replications that is possible and still be able to develop a reliable production function,

(4) to examine the transferability of the production functions determined in different locations and years.

# LITERATURE REVIEW

Crop production, whether in semi-arid or sub-tropic climates, is dependent on many factors. Some of those factors include availability of moisture, temperature conditions, light intensity, and nutrient availability. Certainly the interaction of many of these factors markedly influences plant growth. Various agricultural management practices provide a means for controlling or influencing some of the environmental factors that affect crop production. Soil moisture supply and nutrient availability can easily be influenced through the practices of irrigation and fertilization.

## Soil moisture and crop growth

The influence of soil moisture availability on crop growth is fairly well understood. An extensive amount of research concerning this subject has been carried out (Kramer, 1963; Ashton, 1956; Letey and Peters, 1959; Moss, Musgrave, and Lemon, 1961; Veihmeyer and Hendrickson, 1950; Holt and Van Doren, 1961; Parks and Knetsch, 1959). Extensive research has demonstrated that maximum yields of agricultural crops are most often obtained when the rate of water application is equal to the potential evapotranspiration, provided that fertility is not a limiting factor. Among the researchers who have shown this to be the case for various crops are Dreibelbis and Harrold (1958) and Penman (1956), working with grass, and Pearson, Cleasby, and Thompson (1961), working with sugar cane.

For many crops the soil moisture level necessary for maximum production has been determined. Examining the optimum levels for several different crops suggests that there is no single optimum moisture level applicable to all crops. Many crops may produce maximum yields at unique soil water contents. For example, soil moisture levels greater than 50 percent of the total storage capacity result in maximum production of alfalfa (Lucey and Tesar, 1965), tobacco (van Bavel, 1953), sweet potatoes (Jones, 1961), and peaches (West and Perkman, 1953). Tomatoes (Moore, Kattan, and Fleming, 1958), barley and sugar beets (Penman, 1956), pears (Hendrickson and Veihmeyer, 1942), and many other crops show little or no increase in crop yields when the soil moisture level is increased above the fifty percent level. Similarly, several investigators have demonstrated that production of particular crops decreases as the soil moisture is increased to excessive levels. Viets (1962) and Chang (1968) have presented two summary articles, discussing the information presently available regarding crop production and soil moisture.

As the demand for crop production expands, increased importance will be placed upon efficient water use in agriculture. Efficiency in the broadest sense may mean growing as much crop as possible with limited water supplies. Consequently, it is necessary that continued consideration be given to the subject of crop production as it is affected by soil moisture availability particularly under conditions of limited water.

A related subject of crop production that has received considerable attention is the relationship between actual evapotranspiration and crop yields. Several experiments with crops grown in containers have indicated that the relationship between dry matter production and transpiration is linear (Chang, 1968). However, this may not be the case when considering evapotranspiration and production. While Viets (1962) and Allison et al., (1958) have found a linear relationship between evapotranspiration and production, Staple and Lehane (1954), working with spring wheat grown in field plots, found that yields increased curvilinearly with increasing evapotranspiration.

The specific soil moisture level required for maximum production varies with different crops. For many reasons the determination of such optimum levels has received considerable attention. The information relating to this aspect of crop growth has proven most valuable in the development of efficient irrigation programs for many crops. Prediction equations based on soil moisture availability have been developed to describe the influence of soil moisture on yields. As a result it has been possible to develop efficient cropping practices based on existing soil moisture and irrigation conditions.

### Nitrogen and crop growth

A considerable amount of research has demonstrated that soil fertility also influences crop growth. Tisdale and Nelson (1966) have indicated that yields often do not reach the genetic limit of crop plants because of nutrient deficiencies. Under low-fertility conditions a given crop variety may not be allowed to develop the full potential of its yielding capacity. An adequate supply of plant-nutrient elements is a prerequisite to maximum agricultural production.

Sixteen elements are required for crop growth (Bear, 1964; Tisdale and Nelson, 1966 ; Buckman and Brady, 1960). Each of the elements plays a specific role in the growth and development of a plant, and when present in an insufficient quantity, growth and crop yields may be significantly reduced. Nitrogen is one of the necessary nutrient elements. As Millar, Turk, and Foth (1958) have stated, perhaps no element has received so much attention as has nitrogen in studies relative to plant nutrition.

Soil nitrogen is important in several aspects of crop growth. Its presence affects both color and over-all growth. Plants deficient in nitrogen usually experience a gradual loss of chlorophyll, which results in a light green to yellow color. The supply of nitrogen also influences the time of crop maturity. Evidence also indicates that the crop quality and disease resistance is partially a function of the amount of nitrogen available (Millar et al., 1958).

Several studies have considered corn responses to soil nitrogen. Included among these are studies by Carlson, Alessi, and Mickelson (1959); Fox (1973); Huszar, Skold, and Danielsen (1970); Linscott, Fox, and Lipps (1962); Nunez and Kamprath (1960); Parks and Knetsch (1959); and several others. The results of these studies indicate that the several growth stages of corn production can be influenced by soil nitrogen. Consequently, the rate of development and over-all growth is strongly dependent on the soil nitrogen status throughout the growing season.

Soil moisture-nitrogen interactions

Extensive research has been concerned with the subject of the interactions of soil moisture with fertility. Viets (1962) has presented a summary of research dealing with this subject. A similar review has been prepared by Pierre et al., (1965). Soil moisture can significantly influence the fertility status within the crop root zone. Soil moisture acts as a transport mechanism, a dissolving agent, and a leaching agent for various fertilizers, while at the same time being involved in plant transpiration.

The interaction of soil moisture and nitrogen has been studied extensively. The relatively high solubility of most nitrogen compounds makes most nitrogen subject to extensive leaching. Consequently, it becomes unavailable for plant use. Denitrification losses are commonly associated with high soil moisture conditions (Mahendrappa and Smith, 1967; Myers and McGarity, 1971; Patrick and Wyatt, 1964).

Several studies have considered the specific relationships of soil moisture-nitrogen interactions to corn production. Among these are studies by Carlson et al. (1959), Huszar et al. (1970), Knetsch (1959), Parks and Knetsch (1959), and Viets (1965). Their findings were quite variable. However, in most studies it was concluded that the soil moisture-nitrogen interaction was of considerable importance to corn production. Studies by Huszar et al. (1970) and Stanford (1973) and Black (1966) indicated that maximum crop production was not always associated with maximum soil moisture and nitrogen levels because of the interaction effects.

## Production functions describing crop responses

The increasing need for efficient crop production has caused an increasing concern for the methods used to investigate crop responses to various growth factors. At the same time increased attention has been directed toward the methods of describing crop responses to soil moisture and fertilizer conditions.

Crop responses to various combinations of soil moisture and fertilizer have been used to determine ideal response surfaces, or production functions, for many crops (Black, 1966; French, 1956; Heady and Pesek, 1954; Huszar et al, 1970; Jensen and Pesek, 1959b; Knetsch, 1959; Parks and Knetsch, 1959). Box and Hunter (1958) have indicated that the production function approach of describing crop responses is used for two reasons: (1) to find the conditions of the variables under consideration, which give the best yield, and (2) to determine the characteristics of the response surface in the neighborhood of the optimum operating conditions to indicate how operations should be modified if conditions change in order to best control management.

Several production function forms have been used to describe corn responses to various combinations of soil moisture and fertilizer. Heady and Dillon (1961), Baum et al. (1956), and French (1956) have described as many as five forms including the Spillman exponential function, the Heady, Pesek, Johnson quadratic, the Heady transformed quadratic, the Cobb-Douglas power function, and the Gompertz curve. The form that has been most successfully used to describe the response surface of corn to soil moisture and nitrogen fertilizer is a second degree form of the Heady, Pesek, Johnson quadratic function (Huszar, 1970; Jensen and Pesek, 1959a; Heady and Dillon, 1961).

The general form of the second degree quadratic production function is represented by equation (1):

$$\hat{Y} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 + \varepsilon$$

where:

$\hat{Y}$ = dependent variable, here yield

$X_1, X_2, \ldots$ = independent variables, here soil moisture and nitrogen fertilizer

$\varepsilon$ = error due to the fact that the postulated independent variables do not completely explain Y

$\beta_i$ = population regression coefficients

The response data is used to derive an estimate of equation (1). Heady and Dillon (1961) have presented a thorough discussion of production function forms and their use.

Several researchers have described field designs for obtaining response data sufficient to derive estimated response surfaces (Box, 1954; Cochran and Cox, 1957; Halcrow, 1955; Heady and Dillon, 1961; Ostle, 1963). Box (1954) demonstrated the use of a two level factorial or fractional factorial which would allow for the estimation of all linear and two factor interaction terms. This design, augmented with additional points, would also allow the quadratic effects to be determined. Such composite designs have been quite successful. Cochran and Cox (1957) have also suggested the use of a central composite design with fractional replication to strengthen the weakness in the second order terms. They also suggested the use of a rotatable second order design, with replication of points at the center. Heady and Dillon (1961) and Huszar et al. (1970) have described the use of complete factorial, split plot designs. The split plot design has also been successfully used with incomplete factorial experiments (French, 1956; Huszar et al., 1970). Another field design that has received only limited use is the continuous function experimental design. Fox (1973) has used this design to obtain data describing the response of sweet corn to nitrogen fertilizer.

Cochran and Cox (1957) have indicated that polynomial response surfaces are relatively easy to fit but are notoriously untrustworthy when extrapolated. Therefore, a polynomial surface should be regarded only as an approximation to the response surface within the region covered by an experiment. They also suggest that any predictions made from the polynomial about the response outside the region should be verified by experiments. French (1956) has stated that the fault of most factorial experiments is the number of treatments from which a response is determined is usually insufficient to permit accurate estimation of the yield response function. Estimated functions based on observations over the complete range of treatments closely approximate the over-all function. Similarly, Halcrow (1955) has indicated that adequate production functions are not available because of poor research techniques. Only fragments of input-output curves have been developed. He goes on to state that few researchers have analyzed the output response associated with a wide range of input variables.

Fox (1973) has successfully used the continuous function experimental design to measure the response to inputs over a very wide range of treatments. The continuous function design is one in which a variable is increased in many small increments across an experimental area. By treating only a few plants as a plot, and using small treatment level increments, many treatment rates can be established. Using this method a second variable can be examined by arranging the small increments at right angles to the first variable. "Border effects" can be ignored because the incremental change in the variable is very small and the treatment is increased in one direction and decreased in the other direction from each plot. Fox (1973) has indicated that if a second factor is varied at right angles to the first, a well defined response surface can be obtained.

# EXPERIMENTAL PROCEDURE

The 1972 trials were carried out on Millville silt loam soil at the Utah State University Greenville Farm near Logan. This soil was well drained. The experimental site was located on a nearly level tract, with a 0 to 2 percent slope. The 1973 plots were established on a Kidman fine sandy loam soil at the Utah State University Farm, near Farmington, Utah. This soil was well drained, deep, and coarse textured.

## Conventional split plot design

In 1972 and 1973 a complete factorial split plot design was laid out (Figures 1 and 2). The soil moisture and nitrogen treatments were arranged so that soil moisture levels served as whole plots and nitrogen levels were considered as subplots. This split plot design has been the conventional method of field layout used to collect data suitable for production functions (Box and Hunter, 1958; Heady and Dillon, 1961; Mason, 1956; Cochran and Cox, 1957).

The 1972 plots consisted of four rows of field corn (Utahybrid 544A) for each treatment combination. Plots were 10.67 meters long with a 1.52 meter alley at the end of each plot. All 20 treatment combinations were replicated four times. Whole plots and subplots were completely randomized and arranged as in Figure 1. The same procedure was used to arrange the treatments in 1973. However, the record rows were only 6.10 meters long. Again, each block was replicated four times. Figure 2 is the layout of the 1973 trials. Both years the corn was planted at a rate of 65,200 plants/ha.

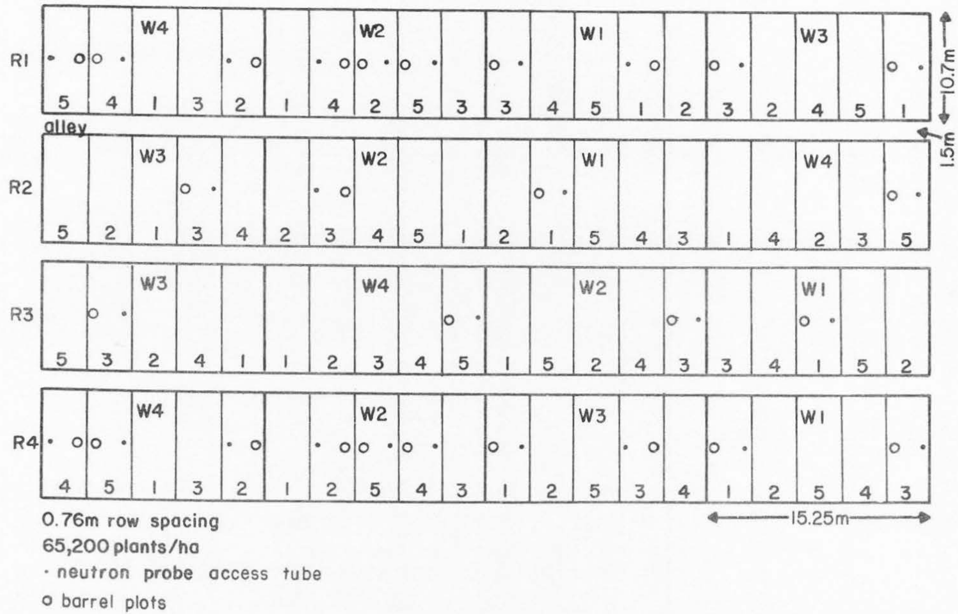



Figure 1. 1972 conventional split plot design, complete factorial. 4 reps x 4 water levels x 5 fertilizer levels. Greenville Farm.

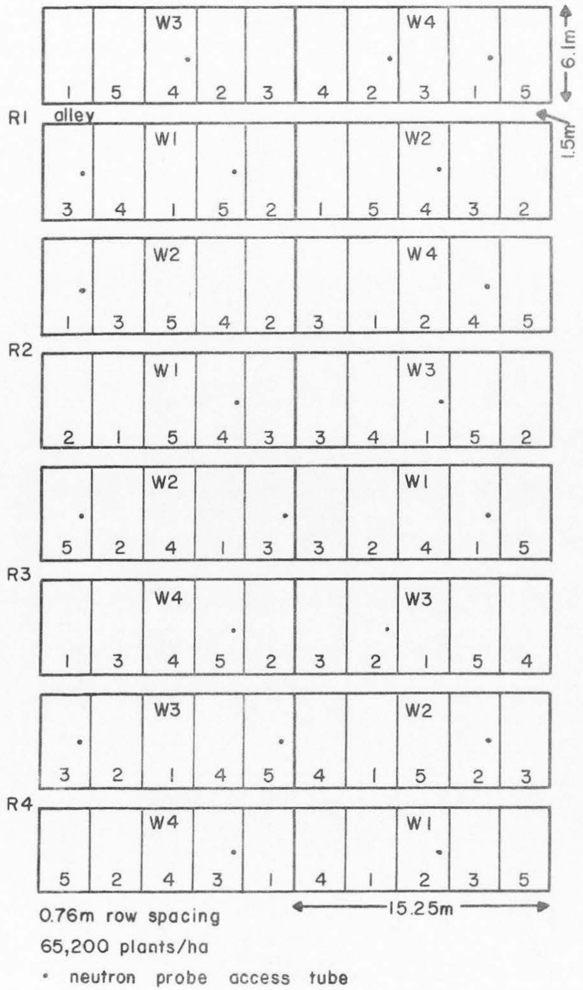



Figure 2. 1973 conventional split plot design, complete factorial, 4 reps x 4 water levels x 5 fertilizer levels, Farmington Farm.

The irrigation system for Greenville consisted of gated aluminum pipe and furrow irrigation. Each whole plot in each block was irrigated separately. First year experience with a furrow system demonstrated the need for greater control over the irrigation treatments. Consequently, a drip irrigation system with emitters spaced every 0.61 meter was installed in Farmington in 1973. Prior to setting up the field plots, four irrigation levels were established both in 1972 and 1973. Using the soil moisture characteristic curve for each of the soils (see Appendix) minimum matric potential values were selected for each of the irrigation levels to be considered. Throughout the growing season, soil moisture measurements were made, using a neutron probe to 1.22 meters and commercial tensiometers to 0.46 meter. When moisture measurements indicated that the matric potential of a particular whole plot was equal to or below the previously established ideal minimum for that water level, the whole plot was irrigated back to field capacity or as close to that soil moisture level as practical.

Nitrogen fertilizer was banded to a depth of approximately 0.20 meter on each plot. The source of nitrogen was ammonium nitrate, 34-0-0. Five rates were established with the intent of providing for levels that would be both excessive and deficient. Although the N fertilizer treatment levels for the plots were the same in 1972 and 1973, the initial soil nitrogen levels were different between locations. The Greenville Farm site had previously been cropped to dry beans, while the Farmington Farm site had been fallowed for two years prior to establishing the plots there. The difference in past history of the two sites suggested that differences in initial soil fertility conditions existed.

The fallow practice at Farmington was used to eliminate most soil N prior to the 1973 planting. The levels established are shown in Table 1. All of the plots were fertilized with a uniform application of phosphorous at a rate of approximately 18 kg P/ha to insure that P did not become a limiting factor during the growing season. This rate was based on soil test phosphorous measurements made in 1972 and 1973.

Table 1. 1972-1973 conventional split plot design, nitrogen fertilizer treatment levels.

| N-fertilizer level | N applied, kg/ha |
|---|---|
| 1 | 0 |
| 2 | 56 |
| 3 | 112 |
| 4 | 225 |
| 5 | 449 |

The experimental units for both years were four row plots. The two inside rows from each plot were used as record rows, while the outside row on each edge served as a buffer. Using this technique, each recorded plot was separated from adjacent plots by two buffer rows. Little lateral water or fertilizer movement occurred in these soils. Therefore, the two row buffer was adequate. The reduction in row length from 10.67 to 6.1 meters in 1973 was undertaken in an attempt to reduce the field plot size. The Farmington site was considerably more uniform than the Logan site due to the past history and soil type.

The harvesting operations were similar in 1972 and 1973. Within the conventional split plot field design, the plots were harvested using a single row mechanical chopper. One record row in each plot was harvested and weighed. A silage sample from each plot was collected and used for plant moisture content determinations. All yields were then adjusted to oven dry weights. Grain yield was also determined for each treatment. The ears from the second record row in each plot were harvested and dried prior to shelling. The grain yields were determined and then adjusted to standard water percentage weights and reported as kg/ha. The 1973 dry matter yields were also sampled for nitrogen analysis.

A split plot analysis of variance was performed for both the 1972 and 1973 conventional plot data prior to any data manipulation. The procedure used was that described by Steel and Torrie (1960). The same kind of analysis was performed for the dry matter yields, shelled corn yields, and nitrogen analysis results.

Continuous variable plot design

As a means of examining many levels of each of the two parameters, soil moisture and nitrogen fertilizer, a second field design was developed. The field layout involved a systematic positioning of controlled parameters at right angles to each other within a field. The treatment level of each parameter was progressively increased from plot to plot going across the experimental area. In order to do this, it was necessary to position relatively small experimental units adjacent to each other and eliminate buffer zones between plots. Using this method each of ten rows of corn, planted at a rate of approximately 65,200 plants/ha, was treated as a different soil moisture level. Within each row, each successive 1.0 meter (Logan) or 1.22 meter (Farmington) strip was fertilized at a slightly higher rate than the adjacent strip. The incremental treatment level in 1972 was approximately 25 kg/ha and in 1973 it was 24 kg/ha. Twenty-two levels of fertilization were established in 1972 and 24 levels were established in 1973.

Ammonium nitrate fertilizer was spread with a small hand fertilizer spreader. The fertilizer was then disked to a depth of approximately 0.15 meter. The fertilizer treatments, presented in Table 2, were placed at right angles to the soil mositure levels, across the rows.

Table 2. 1972-1973 continuous variable plot design, nitrogen fertilizer treatment levels.

| N-fertilizer level | N applied, kg/ha 1972 | 1973 | N-fertilizer level | N applied, kg/ha 1972 | 1973 |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 13 | 235 | 288 |
| 2 | 26 | 24 | 14 | 262 | 312 |
| 3 | 39 | 48 | 15 | 274 | 336 |
| 4 | 65 | 72 | 16 | 301 | 360 |
| 5 | 79 | 96 | 17 | 313 | 384 |
| 6 | 105 | 120 | 18 | 339 | 408 |
| 7 | 118 | 144 | 19 | 353 | 432 |
| 8 | 144 | 168 | 20 | 379 | 456 |
| 9 | 157 | 192 | 21 | 392 | 480 |
| 10 | 183 | 216 | 22 | 421 | 504 |
| 11 | 196 | 240 | 23 | - | 528 |
| 12 | 222 | 264 | 24 | - | 552 |

The incremental increase in treatment level from plot to plot was assumed to be small enough so that each plot functioned essentially as a buffer plot for the adjacent plots, thus justifying the elimination of specific buffer zones between treatments.

This particular field design required good control of the variables being studied. The relatively small plot size and the slight increase in treatment level from one plot to the next could be achieved only with good control of the variables. Prior to planting, ten soil moisture levels were selected, ranging from a level slightly higher than field capacity to permanent wilting. Based on the soil characteristic curves (see Appendix) the corresponding matric potential values were determined. The levels selected in 1972 and 1973 are presented in the Results. Irrigation scheduling was determined using the same method as the conventional split plot design. Irrigation was done using a drip irrigation system. The daily irrigation schedule is in the Appendix. The need for control made it necessary to equip each row of emitters with its own shut off valve. This made it possible to irrigate each row separately, just as each whole plot in the split plot design was irrigated independently of the other whole plots. The field plot layout for 1972, in Figure 3, shows the system used to locate the rows and fertilization rates within each row. The same pattern was used in 1973, with only slight modifications. In 1973 the length of each plot was increased from 1.0 to 1.22 meters and the number of fertilizer treatments was increased from 22 to 24 levels. Figure 4 shows the positioning of the four 1972 replicates with respect to each other. Replication of treatments was attained by replicating the entire block four times. In 1973 the blocks were positioned so that the outside row of each block was bordered by a similar treatment level of an adjacent block. By positioning the blocks in such a manner, the highest water level of one block served as a border row to the highest water level of the adjacent block.

The continuous variable design plots were harvested by hand in both years. The entire production from each plot was collected and weighed on a spring balance. From every fifth plot in each row a plant sample was also collected to determine the moisture percentage of the plant material. The moisture percentage values were then used to

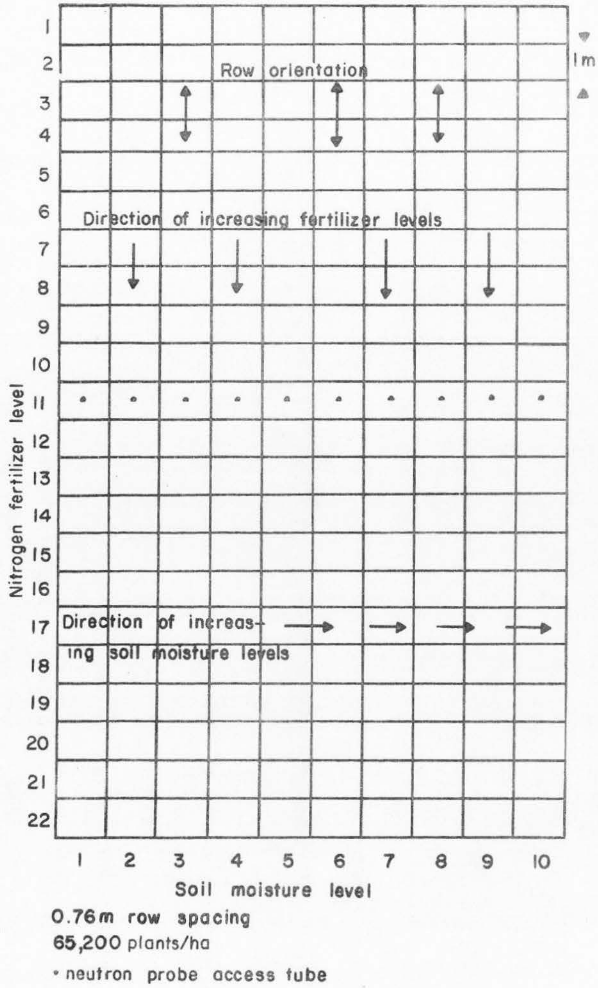



Figure 3. 1972 continuous variable plot design, block layout. 10 water levels x 22 fertilizer levels, Greenville Farm.

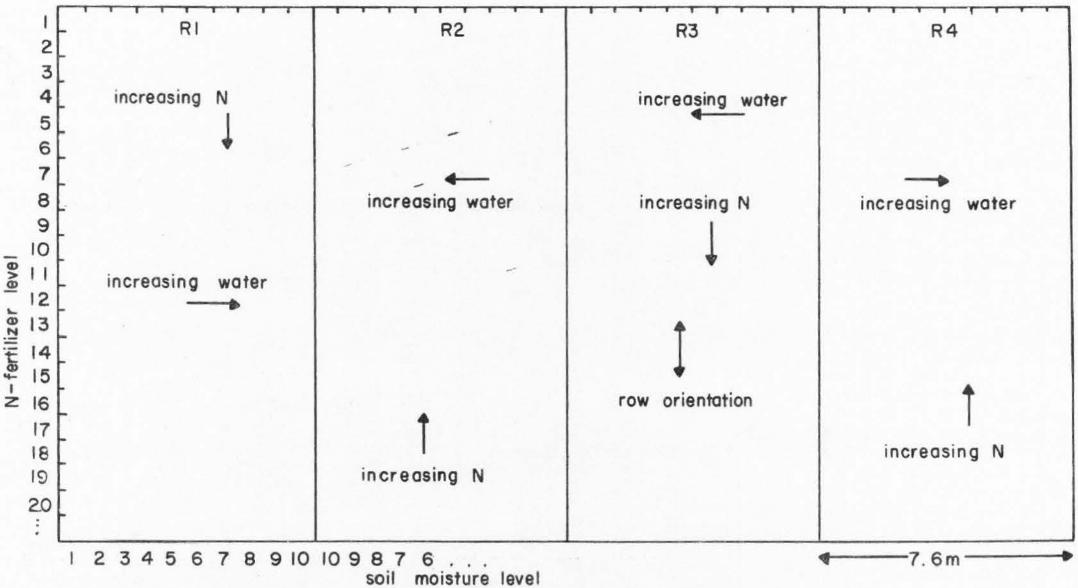



Figure 4. 1972 continuous variable plot design, block orientation. 4 reps x 10 water levels x 22 fertilizer levels. 1973: 4 reps x 10 water levels x 24 fertilizer levels.

determine the dry weight yield from each plot. The same procedure was used in 1972 and 1973.

Prior to performing an analysis of variance of the yield data from the continuous variable design plots, it was necessary to decide upon the proper procedure to use. The method used to establish the various fertilizer treatment levels was such that any variability in the yields due to errors associated with the establishment of the fertilizer levels would not be significant. That is, by initially calibrating the hand spreader at one application rate and then using that single setting to establish all the treatment levels, any error associated with one treatment would be spread over all treatments. The experimental design was such that each row within a ten row block was treated as a soil moisture level and within each row each successive sample was treated as an N-fertilizer level. Although the treatments were not randomly arranged, each soil moisture level, or row, was considered a whole plot while the fertilizer treatments were considered as subplots. Based on these assumptions, the analysis of variance was performed as a split plot analysis, using the procedure described by Steel and Torrie (1960).

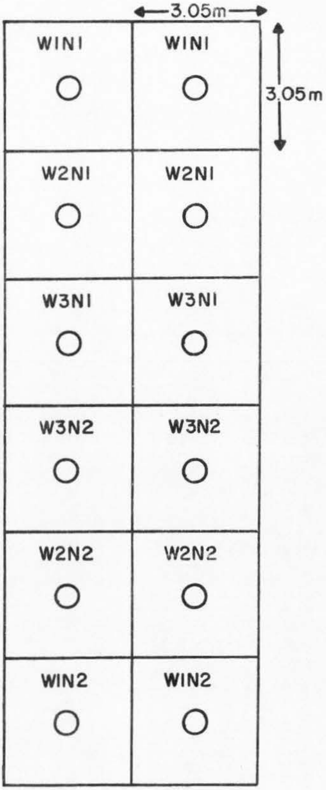
### Barrel lysimeters

In an attempt to evalute the possibility of developing a simple method of determining reliable water use data for response surfaces for field corn, several of the treatment combinations of the conventional split plot design were applied to corn grown in 208.2 liter barrels of soil. The barrels were also used to provide additional information on crop water use.

The barrels were installed in such a way as to provide a means of controlling the soil mositure status of the plots. The barrels eliminated the problems associated with upward soil water flow into the root zone and downward flow of water out of the root zone. The barrels also provided a relatively small plot, which could be easily installed to obtain data for the determination of crop response surfaces.

In 1972 ten of the 20 treatments in the split plot design were replicated twice within the barrels. The location of the barrels within the experimental area is shown in Figure 1. In order to subject the crop grown in barrels to conditions similar to those of the field plots, the soil cores used in the barrels were undisturbed. The procedure used to obtain the cores has been presented in the Appendix. The barrels were placed in the ground within the inside buffer row of the field plots they represented. Soil moisture measurements were collected from each barrel using a neutron probe. The soil moisture level of each barrel was maintained so as to be representative of the field plot within which the barrel was located. Water was applied to the surface of each barrel by hand when necessary. Fertilizer was applied by hand to each barrel and then raked into the soil to approximately 20 cm depth prior to planting. The fertilization rate of each barrel was the same as the field plot within which each barrel was located.

The barrel plots used in 1973 in Farmington were not located within the plots they represented. In a separate block twelve barrels were installed prior to planting. Each of these undisturbed cores was located in the center of a 3.05 meters square plot. Each plot and barrel was planted, fertilized and irrigated separately by hand. The borders around each barrel were irrigated using the drip system. The field plot layout of the barrels used in 1973 is shown in Figure 5.




○ Barrel plot - 0.27 $m^2$ area, 0.21 $m^3$ volume

W1: $\psi m = -10$ bars (proposed)

W2: $\psi m = -0.6$ bar "

W3: $\psi m = -0.1$ bar "

N1 = 0 kg N/ha

N2 = 300 kg N/ha

Figure 5. 1973 barrel plot field layout. 2 reps x 3 water levels x 2 fertilizer levels. Farmington Farm.

In 1972 and 1973 all the barrel plot yields were harvested when the field plots were harvested. The entire yield from each barrel was weighed and then dried to determine the moisture percentage of the plants. The yields were reported as kg/ha of oven dry matter. The yield data and the water use data, determined from the irrigation schedule and the change in soil moisture storage, were used to determine the water-use efficiency of corn grown under various soil moisture conditions. The information is included in the Results and Appendix.

# RESULTS AND DISCUSSION

## Soil moisture levels

Initially the objective of the irrigation scheduling was to maintain the soil water content of each treatment at such a level that the matric potential never became less than the proposed ideal minimum level. Within the 1972 conventional split plot design four proposed soil moisture levels were established as in Table 3. The actual minimum matric potential values were quite different from those proposed, for several reasons. The matric potential and the water content within the profile with actively growing roots was not uniform. The shape of the characteristic curve in this range was such that a slight change in the water content was accompanied by a large change in the matric potential. Furthermore, the changing crop demands for water made it quite difficult to maintain a particular soil water level for any length of time, as evidenced by the changing soil water contents in the root zone (Figures 6 and 7). Consequently, rather than maintain the ideal levels, an attempt was made to keep the soil moisture for the various treatments between two extreme levels, those being a level of maximum irrigation, level 4, and a level of irrigation by natural precipitation only, level 1.

The actual minimum matric potential values for the 1972 conventional plots were not determined. The soil water content was determined on approximately a weekly basis. Initially the minimum water content measured for each soil water level was above the proposed minimum. However, as the season progressed and the crop demand for water increased, the min-

Table 3. 1972 conventional split plot design[1] soil moisture treatment levels.

| Soil moisture level | Matric potential proposed minimum | Soil water cm applied | Change in soil moisture storage in top 120 cm | Total cm used[2] |
|---|---|---|---|---|
| 1 | -9.0 bars | 7.15 | +7.11 | 14.26 |
| 2 | -2.4 | 24.57 | -0.45 | 24.12 |
| 3 | -0.67 | 37.98 | +3.25 | 41.23 |
| 4 | -0.27 | 51.05 | -1.30 | 49.75 |

[1]Greenville Experiment Station
[2]This does not include possible upward flow or depletion below 120 cm.

imum water content began to decrease. Although the plots were irrigated in an attempt to recharge the profiles to field capacity when the minimum levels were reached, sufficient water was not always added during the irrigations to recharge the profiles. The length of time the plots were irrigated with the furrow system was not always long enough to provide adequate recharge to the profile. With the drip system irrigation water was available only two days per week, and the emitters were not able to supply the amount of water needed to recharge the profile during this limited time period. Slow infiltration rates also reduced the effectiveness of the irrigations in Farmington. Consequently, the minimum water content decreased with each successive measurement throughout the season. Therefore, the actual minimum matric potential value obtained by any method of averaging the matric potentials at several times did not adequately describe the dynamic situation that actually existed in the field plots. Although other investigations have not emphasized this problem, almost all soil moisture experiments conducted in the field have similar problems.

Similar discussion could be applied to the volumetric water content determined for each soil moisture level. Here again the average water content, determined on approximately a weekly schedule, decreased during the growing season. The dynamic situation encountered in the 1972 conventional plots was also true for 1973 at Farmington. Table 4 includes the soil moisture levels proposed for the Farmington conventional split plot design, along with the cumulative irrigation rate for each level.

Table 4. 1973 conventional split plot design[1].

| | | Soil water | | |
|---|---|---|---|---|
| Soil moisture level | Matric potential proposed minimum | cm applied | Change in soil moisture storage in top 120 cm | Total cm used[2] |
| 1 | -15.0 bars | 10.78 | +15.6 | +26.4 |
| 2 | - 2.0 | 30.55 | +11.4 | +42.0 |
| 3 | - 0.8 | 44.91 | +11.0 | +55.9 |
| 4 | - 0.3 | 57.77 | +6.8 | +64.6 |

[1]Farmington Experiment Station
[2]This does not include possible upward flow or depletion below 120 cm.

The changing soil moisture levels are shown in Figure 6. This shows the volumetric water content measured from 0.3 to 0.6 meter depth throughout the study period. These data are from the 1972 Logan experiments. The same data for the 1973 plots are shown in Figure 7. Soil moisture measurements from 0.9 to 1.20 meters depth have also been plotted and included in the Appendix (Figures 19 and 20) to demonstrate the changing

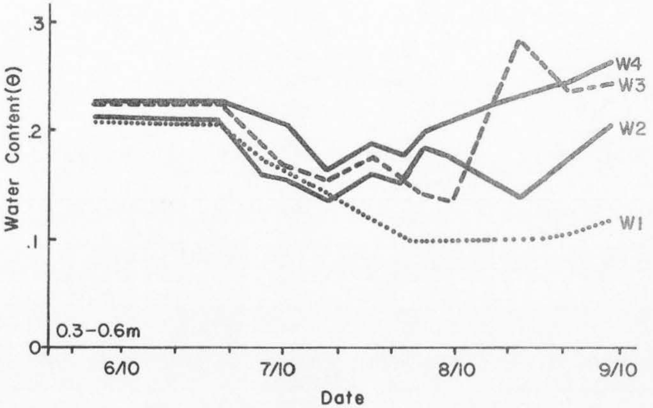



Figure 6. 1972 conventional split plot design, volumetric water content in the root zone during the growing season. 0.3 - 0.6m depth.

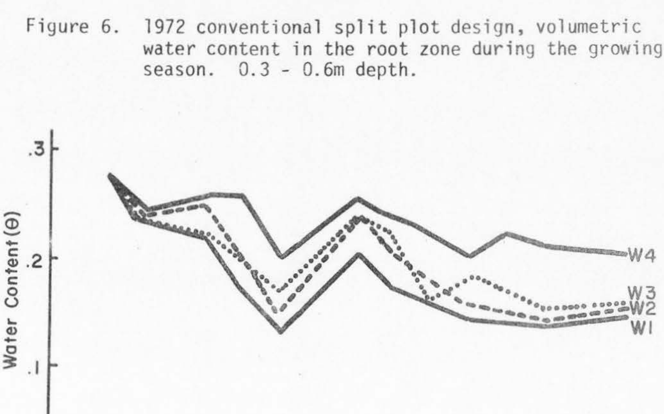



Figure 7. 1973 conventional split plot design, volumetric water content in the root zone during the growing season. 0.3 - 0.6m depth.

soil moisture levels that were experienced during the 1972 and 1973 crop growing seasons.

A climatic summary of the conditions for the two study years is included in the Appendix (Table 28 and 29).

Results from the continuous variable design plots were treated similar to the conventional plots in analyzing the yield data. The initial ideal matric potentials were again not maintained. The changing matric potential and the decreasing water content within each profile made it difficult to apply a quantitative value to each soil moisture level. The method of scheduling irrigations was such that the ideal levels were not maintained. The soil moisture levels were actually maintained in the following manner: the lowest soil moisture level was determined as the naturally occurring level, supported by natural precipitation and moisture stored within the soil profile, while the highest level was achieved by irrigating at the highest feasible rate as determined by the availability of irrigation water, the capacity of the trickler irrigation system to deliver water to the plots, and the ability of the soils to absorb water. The intermediate levels were maintained at levels which would provide a continuous gradation in soil moisture levels from the field capacity level to the wilting point level.

In 1972 and 1973 ten soil moisture levels were initially selected from the matric potential-water content curves. However, only seven levels were achieved in 1972 and eight in 1973. In 1972 levels 1, 2, and 3 were all equal to the minimum level. One other row was treated as a border and not harvested. Natural precipitation was such that the ideal lower levels could not be achieved. Table 5 shows the soil moisture treatment levels for the 1972 plots. The eight soil moisture levels

Table 5. 1972 continuous variable plot design[1] soil moisture treatment levels.

| Soil moisture level | Matric potential proposed minimum | cm applied | Soil water: Change in soil moisture storage[2] | Total cm used[3] |
|---|---|---|---|---|
| 0 (border) | -25.0 | 4.09 | +7.77 | 11.86 |
| 1 | -25.0 | 4.09 | +7.77 | 11.86 |
| 2 | - 5.5 | 4.09 | +7.61 | 11.70 |
| 3* | - 2.4 | 4.09 | +7.31 | 11.40 |
| 4* | - 1.2 | 14.06 | +7.01 | 21.07 |
| 5* | - 0.67 | 19.74 | +6.09 | 25.83 |
| 6* | - 0.41 | 43.34 | +2.82 | 46.16 |
| 7* | - 0.27 | 53.71 | -0.45 | 53.26 |
| 8* | - 0.18 | 63.79 | -1.06 | 62.73 |
| 9* | - 0.10 | 72.38 | -1.67 | 70.71 |

[1] Logan
[2] Change in storage measured in the top 120 cm of the profile.
[3] This does not include possible upward flow or depletion below 120 cm.
*Yield data collected from this plot.

Table 6. 1973 continuous variable plot design[1] soil moisture treatment levels.

| Soil moisture level | Matric potential proposed minimum | cm applied | Soil water: Change in soil moisture storage[2] | Total cm used[3] |
|---|---|---|---|---|
| 1 | -15.0 bars | 10.99 | +19.6 | 30.6 |
| 2* | -10.0 | 10.99 | +18.5 | 29.5 |
| 3* | - 2.0 | 17.20 | +16.7 | 33.9 |
| 4* | - 1.0 | 25.99 | +18.7 | 44.7 |
| 5* | - 0.6 | 28.93 | +17.9 | 46.8 |
| 6* | - 0.4 | 29.97 | +19.5 | 49.5 |
| 7* | - 0.2 | 33.39 | +14.9 | 48.3 |
| 8* | - 0.1 | 39.96 | +12.8 | 52.8 |
| 9* | - 0.05 | 49.59 | +10.3 | 59.9 |
| 10 | - 0.05 | 64.65 | +9.3 | 74.0 |

[1] Farmington
[2] Change in storage measured in the top 120 cm of the profile.
[3] This does not include possible upward flow or depletion below 120 cm.
*Yield data collected from this plot.

established in 1973 are shown in Table 6. Here levels 1 and 10 were used as border rows; the effective levels from which yield data were collected were 2 through 9.

The problem of a changing soil moisture level during the growing season was experienced within the continuous variable plots also. Some of the soil water contents as measured during the growing season are shown for the 0.3 to 0.60 meter depth here in Figures 8. and 9, for the 1972 and 1973 plots respectively. Additional curves have been included in the Appendix (Figure 24 and 25). It is quite clear from these curves that the soil moisture levels were not maintained at some constant minimum levels, but decreased with time during the growing season. Again, this was the result of several factors, including the fact that irrigation water was available on a limited time schedule, making it necessary to irrigate when water was available. Another factor contributing to the failure to irrigate the plots to field capacity at each irrigation was the capacity of the tricklers to supply water to the plots. The slow delivery rate became a major drawback. However, the total water use was considerably different for the various water levels, so the levels may have been more distinct than suggested by the soil water content data. Moreover, since water was applied frequently at low rates, the surface water contents were probably much different than shown by the neutron probe data which was limited to 30 cm and deeper.

In order to compare the results of the conventional split plot designs with the results of the continuous variable plot designs, it was necessary to describe the treatments in a similar manner for both experiments. When selecting the treatment levels to be established

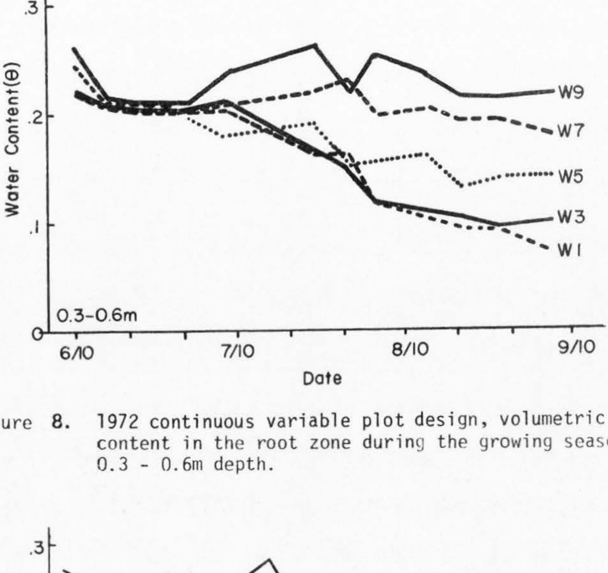



Figure 8. 1972 continuous variable plot design, volumetric water content in the root zone during the growing season, 0.3 - 0.6m depth.

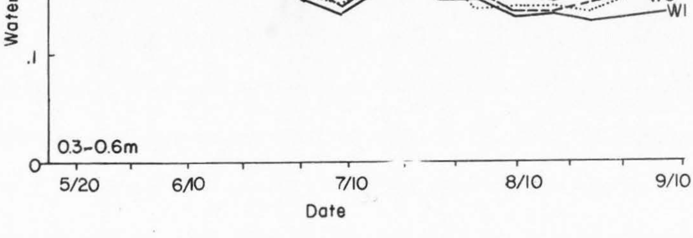



Figure 9. 1973 continuous variable plot design, volumetric water content in the root zone during the growing season, 0.3 - 0.6m depth.

in the field, it was intended that the several soil moisture levels assigned to the continuous variable plots would include the soil moisture levels assigned to the conventional split plots. That is, the lowest and highest soil moisture levels within the conventional split plot experiments were to be equivalent to the lowest and highest soil moisture levels within the continuous variable plots. As previously mentioned, it was particularly difficult to maintain discrete soil moisture levels within the field. Consequently, the comparison of the soil moisture levels from the two designs was different than that initially intended. Based on a comparison of the amount of water applied to each treatment level, the frequency of irrigation, the change in soil moisture storage, and the volumetric soil moisture content in the root zone throughout the growing season, the following relationships were selected to describe the soil moisture levels of the conventional split plot designs in terms of the continuous variable plot soil moisture treatment levels for the two years.

1972 Logan Experiments

| Conventional split plot soil moisture level | equivalent to | continuous variable plot soil moisture level |
|---|---|---|
| 1 | | 3.0 |
| 2 | | 5.0 |
| 3 | | 6.5 |
| 4 | | 8.0 |

1973 Farmington Experiments

| Conventional split plot soil moisture level | equivalent to | continuous variable plot soil moisture level |
|---|---|---|
| 1 | | 2 |
| 2 | | 4 |
| 3 | | 7 |
| 4 | | 9 |

In all subsequent calculations the split plot soil moisture treatment levels were expressed on a scale comparable to the continuous variable plot soil moisture levels, as indicated above.

Yield data

The yield data from the 1972 conventional plots from each replicate are presented in the Appendix (Table 30.) The oven dry matter yields were used in plotting the yield curves in Figure 10. The curves indicate that increases in both nitrogen fertilizer and the soil moisture level caused increases in the dry matter yields. The increase in yields from soil moisture level 3 to level 5 is rather large. The additional responses to increased soil moisture above level 5 are significant, although not as great as from level 3 to level 5. Similarly, the relative response to the lower rates of fertilization are much higher than to the higher fertilization rates. Above the level of approximately 112 kg N/ha the yield curve for each soil moisture level approaches a zero slope, suggesting that the response to fertilization above this level is slight. Similar curves for shelled corn are shown in the Appendix (Figure 21).

The dry matter yields obtained in 1973 at Farmington were used to plot Figure 11. The data from each replicate as well as the data on shelled corn yields, the results of the nitrogen analysis performed on the dried matter samples, and the corresponding yield curves are included in the Appendix.

The yield curves plotted from the 1973 data are similar to those of 1972. Production was significantly increased by increasing the soil moisture level. Significant yield increases occurred between the lowest and highest soil moisture levels. Yields also increased as the fertilizer

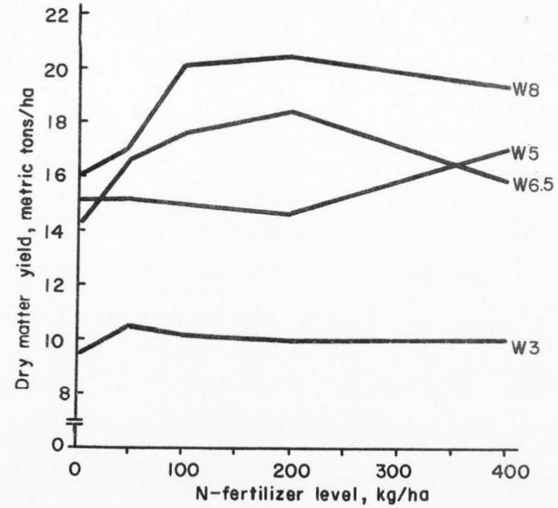



Figure 10. 1972 conventional split plot design, oven dry matter yields. Four replicate averages.

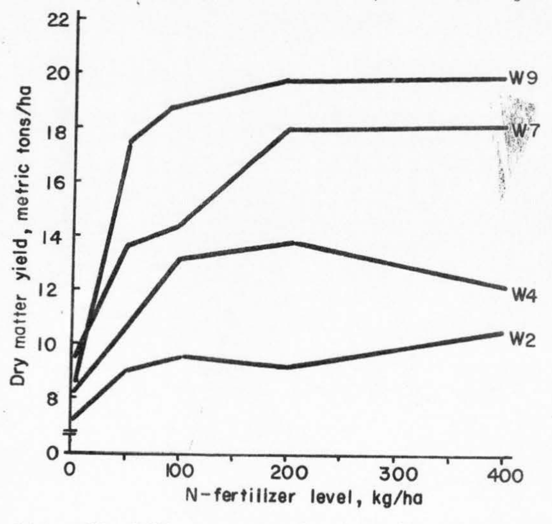



Figure 11. 1973 conventional split plot design, oven dry matter yields. Four replicate averages.

level was increased. The response to low levels of fertilizer was large, but as the fertilizer level was increased, the response diminished. Above approximately 224 kg N/ha there was little response to additional fertilizer.

The results of the split plot analysis of variance, performed for both the 1972 and 1973 conventional plot dry weight yields are presented

Table 7. Analysis of variance for oven dry matter yields from the 1972 conventional split plots.

| Source of variation | Degrees of freedom | Sum of squares | Mean sum of squares | F-ratio |
|---|---|---|---|---|
| Replicates | 3 | 156.7 | 52.2 | |
| Soil moisture | 3 | 2569.6 | 856.5 | 39.1* |
| Error (A) | 9 | 197.1 | 21.9 | |
| Fertilizer | 4 | 185.0 | 46.3 | 3.2* |
| Interaction | 12 | 222.4 | 18.5 | 1.3 |
| Error (B) | 48 | 693.5 | 14.5 | |

* Significant at the 95 percent level.

Table 8. Analysis of variance for oven dry matter yields from the 1973 conventional split plots.

| Source of variation | degrees of freedom | Sum of squares | Mean sum of squares | F-ratio |
|---|---|---|---|---|
| Replicates | 3 | 10.3 | 3.4 | |
| Soil moisture | 3 | 2200.2 | 733.4 | 80.6* |
| Error (A) | 9 | 81.5 | 9.1 | |
| Fertilizer | 4 | 1711.7 | 427.9 | 27.1* |
| Interaction | 12 | 520.3 | 43.4 | 2.7* |
| Error (B) | 48 | 757.7 | 15.8 | |

*Significant at the 95 percent level.

in Tables 7 and 8, respectively. Similar results were obtained for the shelled corn yields and nitrogen analysis and are included in the Appendix (Table 35, 36, 37).

The analysis of variance of the 1972 conventional split plot data indicates that the yield values differed significantly with respect to both the soil moisture levels and the nitrogen fertilizer levels. However, the interaction between soil moisture and fertilizer was not significant. For the 1973 conventional plots the interaction term proved to be significant along with the soil moisture and fertilizer terms.

The 1972 variable plot data consisted of yields measured on four replicates of each of 154 different plots. The averages of these four replicates are included in Table 9. The yields from each replicate are included in the Appendix. Only the dry matter yield was measured on the continuous variable design plots. Initially the data were plotted as they appear in Table 9. However, the variability of the data due to the small sample size made it difficult to detect the trends in the yield responses. Therefore, the data in Table 9 were smoothed by determining a three plot running average down each column. This was done twice. The smoothed data were used to plot the curves of Figure 12.

The averaging operations were quite successful in smoothing the data and helping to reduce the variability previously mentioned. The large number of points were valuable in plotting the yield curves. The many treatments make it possible to plot the entire yield curve for each soil moisture level. The yield curves indicate a positive response to increasing fertilizer levels up to approximately 280 kg N/ha. Above this level the yields begin to decrease. The corn also responded

Table 9. 1972 continuous variable plot design oven dry matter yield.[1]

| N-fertilizer level kg/ha | | | Soil moisture level | | | | |
|---|---|---|---|---|---|---|---|
| | 1,2,3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 0 | 9.1 | 10.4 | 11.6 | 12.4 | 13.2 | 14.3 | 15.1 |
| 26 | 12.3 | 7.1 | 13.7 | 14.4 | 22.0 | 13.9 | 13.3 |
| 39 | 6.9 | 10.6 | 10.6 | 12.7 | 11.2 | 19.3 | 17.5 |
| 65 | 10.7 | 9.4 | 13.4 | 17.8 | 13.7 | 17.1 | 15.0 |
| 79 | 7.4 | 9.8 | 12.7 | 19.7 | 20.1 | 20.5 | 15.1 |
| 105 | 10.9 | 11.0 | 11.7 | 11.9 | 16.6 | 16.9 | 13.9 |
| 118 | 11.9 | 12.4 | 18.6 | 16.0 | 17.1 | 14.5 | 23.6 |
| 144 | 7.2 | 8.9 | 13.2 | 20.1 | 18.9 | 23.7 | 21.5 |
| 157 | 9.6 | 12.4 | 13.9 | 13.6 | 14.0 | 19.2 | 19.1 |
| 183 | 10.5 | 9.7 | 10.1 | 19.5 | 14.4 | 18.9 | 21.5 |
| 196 | 11.6 | 14.2 | 14.9 | 15.6 | 22.1 | 21.6 | 18.7 |
| 222 | 12.5 | 10.6 | 15.8 | 19.0 | 16.7 | 22.9 | 19.7 |
| 235 | 8.7 | 12.1 | 14.1 | 21.1 | 15.8 | 19.9 | 21.3 |
| 262 | 13.4 | 12.6 | 14.0 | 16.9 | 25.2 | 27.9 | 22.3 |
| 274 | 11.6 | 13.9 | 12.1 | 21.3 | 21.4 | 25.2 | 21.4 |
| 301 | 11.1 | 13.8 | 13.1 | 17.9 | 21.2 | 18.6 | 22.4 |
| 313 | 10.3 | 15.1 | 16.9 | 19.5 | 17.6 | 23.5 | 14.9 |
| 339 | 8.3 | 11.7 | 12.6 | 15.8 | 18.3 | 21.9 | 20.8 |
| 353 | 13.4 | 15.1 | 13.4 | 24.1 | 18.1 | 19.4 | 22.8 |
| 379 | 10.3 | 12.7 | 14.9 | 20.2 | 17.7 | 16.7 | 16.5 |
| 392 | 9.9 | 11.1 | 10.9 | 20.8 | 22.4 | 15,8 | 19.6 |
| 421 | 11.4 | 15.2 | 12.5 | 19.6 | 14.1 | 19.1 | 18.4 |

[1]Each value is the average of four replicates in metric tons dry matter/ha.

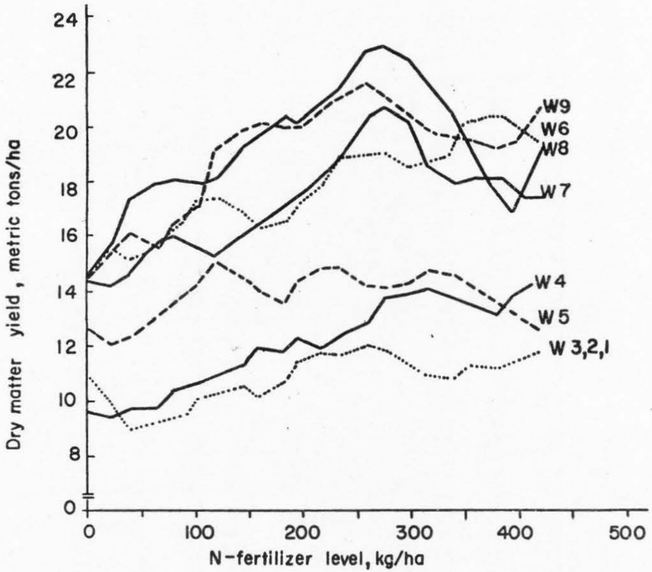



Figure 12. 1972 continuous variable plot design, oven dry matter yields, four replicate averages, smoothed twice.

positively to the increase in soil moisture levels from level 3 to level 9. The largest single increase due to soil moisture occurred between levels 5 and 6.

The data from the 1973 continuous variable design plots were averaged to obtain the data of Table 10. This average block data was then used in determining the running average values, used in plotting the yield curves of Figure 13. The original data from the Farmington plots have been included in the Appendix. As in 1972, the corn responded positively to the fertilizer treatments; as the treatment level was increased to approximately 300 kg N/ha, the yield increased. Above that level, additional fertilizer caused a reduction in dry matter production. The response to the increasing soil moisture levels was also positive. The largest single response again occurred between soil moisture levels 5 and 6.

The analysis of variance for the 1972 data is presented in Table 11.

Significant F-ratios were found for soil moisture and N-fertilizer. Yield differences associated with the interaction of the two treatments and with the various replicates were found to be non-significant.

A similar analysis was performed with the yield data of 1973 (Table 12).

As with the 1972 analysis, the 1973 analysis indicated that significant differences in yield were associated with the soil moisture levels and the N-fertilizer levels. The interaction between soil moisture and N-fertilizer was also significant. Replicates were also significant.

The barrel plots were treated similar to the field plots for purpose of analysis. The 1972 barrel water use data and corresponding yield data

Table 10. 1973 continuous variable plot design oven dry matter yield.[1]

| N-fertilizer level kg/ha | 1,2 | 3 | 4 | Soil moisture level 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| 0 | 6.4 | 5.1 | 8.5 | 8.9 | 9.6 | 10.2 | 10.5 | 10.7 |
| 24 | 6.4 | 4.1 | 8.1 | 5.6 | 7.7 | 10.7 | 10.7 | 14.1 |
| 48 | 6.4 | 7.5 | 10.1 | 7.9 | 11.6 | 11.2 | 11.5 | 13.8 |
| 72 | 6.3 | 7.1 | 8.6 | 8.8 | 11.0 | 13.4 | 12.1 | 13.9 |
| 96 | 6.5 | 6.8 | 8.7 | 8.9 | 14.4 | 13.6 | 15.1 | 14.3 |
| 120 | 8.5 | 8.5 | 9.2 | 10.3 | 14.0 | 13.7 | 14.3 | 15.1 |
| 144 | 7.2 | 8.1 | 11.2 | 10.5 | 12.7 | 16.5 | 14.2 | 17.0 |
| 168 | 7.7 | 9.2 | 10.4 | 10.6 | 17.1 | 14.0 | 14.6 | 16.2 |
| 192 | 7.7 | 9.2 | 9.8 | 9.6 | 13.5 | 15.8 | 17.5 | 14.3 |
| 216 | 7.6 | 8.9 | 12.7 | 9.7 | 15.1 | 15.6 | 14.8 | 19.3 |
| 240 | 9.0 | 9.8 | 9.6 | 11.0 | 18.5 | 16.3 | 18.0 | 18.3 |
| 264 | 6.8 | 9.6 | 11.8 | 11.2 | 15.2 | 16.8 | 13.9 | 14.7 |
| 288 | 8.9 | 9.6 | 9.5 | 13.4 | 13.3 | 15.3 | 18.2 | 18.3 |
| 312 | 7.7 | 7.8 | 11.1 | 12.5 | 13.9 | 14.9 | 17.7 | 16.6 |
| 336 | 6.9 | 8.8 | 10.0 | 10.8 | 15.4 | 14.2 | 16.1 | 17.3 |
| 360 | 6.6 | 8.6 | 11.2 | 11.1 | 17.1 | 15.5 | 17.7 | 20.7 |
| 384 | 10.4 | 9.1 | 10.6 | 10.7 | 14.6 | 16.8 | 18.1 | 16.7 |
| 408 | 7.0 | 10.0 | 11.7 | 11.4 | 14.7 | 12.4 | 12.5 | 17.7 |
| 432 | 8.8 | 8.7 | 11.2 | 11.2 | 14.7 | 15.7 | 16.5 | 19.2 |
| 456 | 7.0 | 8.6 | 9.9 | 10.1 | 14.4 | 14.4 | 13.6 | 18.7 |
| 480 | 7.3 | 9.4 | 9.4 | 11.9 | 13.5 | 15.0 | 18.1 | 14.7 |
| 504 | 8.4 | 8.2 | 10.1 | 10.2 | 14.9 | 12.2 | 13.5 | 17.1 |
| 528 | 7.7 | 9.2 | 11.1 | 9.2 | 14.0 | 13.5 | 13.6 | 15.8 |
| 552 | 5.7 | 7.1 | 8.3 | 8.5 | 9.5 | 13.3 | 12.9 | 15.7 |

[1]Each value is the average of four replicates in metric tons dry silage/ha.

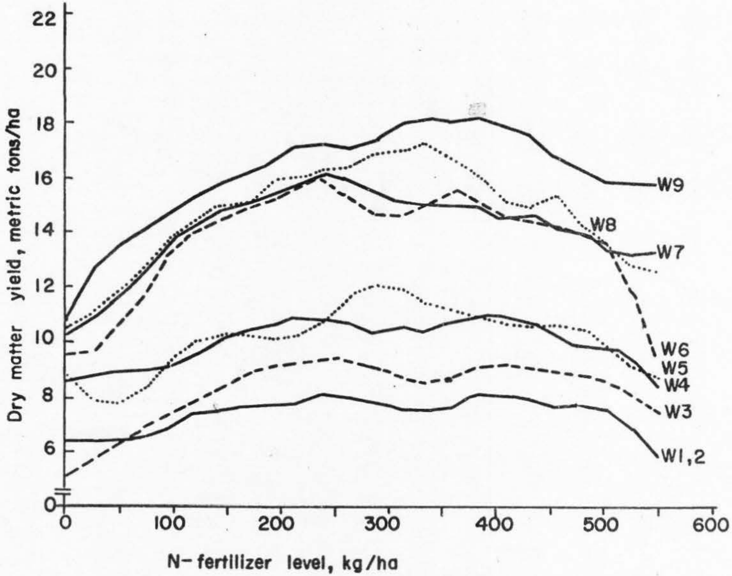



Figure 13. 1973 continuous variable plot design, oven dry matter yields, four replicate averages, smoothed twice.

Table 11. Analysis of variance for oven dry matter yields from the 1972 continuous variable plots.

| Source of variation | Degrees of freedom | Sum of squares | Mean sum of squares | F-ratio |
|---|---|---|---|---|
| Replicates | 3 | 0.72 | 0.24 | |
| Soil moisture | 6 | 209.13 | 34.86 | 30.34* |
| Error (A) | 18 | 20.68 | 1.15 | |
| Fertilizer | 21 | 51.39 | 2.45 | 3.26* |
| Interaction | 126 | 93.95 | 0.75 | 1.00 |
| Error (B) | 441 | 330.76 | 0.75 | |

*Significant at the 95 percent level.

Table 12. Analysis of variance for oven dry matter yields from the 1973 continuous variable plots.

| Source of variation | Degrees of freedom | Sum of squares | Mean sum of squares | F-ratio |
|---|---|---|---|---|
| Replicates | 3 | 8.53 | 2.84 | 17.51* |
| Soil moisture | 7 | 62.46 | 8.92 | 53.82* |
| Error (A) | 21 | 3.48 | 0.17 | |
| Fertilizer | 23 | 13.32 | 0.58 | 10.65* |
| Interaction | 161 | 9.14 | 0.057 | 1.04* |
| Error (B) | 552 | 30.06 | 0.057 | |

*Significant at the 95 percent level.

was grouped and averaged (Table 13). Both the small sample size within each barrel, and the uncertainty of water use (due to poor control of irrigation) were responsible for the variability in yield within soil moisture levels. The barrels were situated within the plot rows such that several of the barrels were mistakenly irrigated when the surrounding plots were furrow irrigated. The yield data were averaged by soil moisture levels.

Table 13. 1972 barrel plot water use and dry matter yield.

| Soil moisture level | cm $H_2O$ applied | cm $H_2O$ used[1] | kg dry matter / ha | kg/ha / cm |
|---|---|---|---|---|
| 1 | 22.18(6)[2] | 39.94 | 14099 | 353 |
| 2 | 32.87(8) | 49.21 | 15944 | 324 |
| 3 | 40.25(6) | 55.98 | 15087 | 270 |
| 4 | 43.31(8) | 56.15 | 15423 | 274 |

[1] cm $H_2O$ used equals cm $H_2O$ applied plus the change in soil moisture storage within the barrel during the season.
[2] Numbers in parenthesis indicate the number of barrel plots included in the average.

The plots established in 1972 provided some useful guidelines for installing similar plots in Farmington. Although the cores within the barrels were undisturbed, the conditions for crop growth in the field were not duplicated in the barrels. The barrels created a confined root zone for the corn and, consequently, the soil within the barrels was depleted of soil moisture at a faster rate than in the field. Each barrel supported only a small number of plants, making it necessary for good control of the treatment levels.

In 1973 the barrel plots included two N-fertilizer levels. The rates of application were no fertilization and approximately 340 kg N/ha. The soil moisture levels are shown in Table 14, along with the yields. The data was grouped by water levels and averaged, so that each value presented is the average of four barrel plots. Inspection of the yield data indicated that the yields were not significantly affected by the fertilizer treatments, and could be averaged.

Table 14. 1973 barrel plot water use and dry matter yield.

| Soil moisture level | cm $H_2O$ applied | cm $H_2O$ used[1] | kg dry matter / ha | kg/ha / cm |
|---|---|---|---|---|
| 1 | 10.79 | 20.61 | 3210 | 156 |
| 2 | 42.45 | 50.72 | 9874 | 195 |
| 3 | 45.86 | 52.70 | 12666 | 240 |

[1] cm $H_2O$ used equals cm $H_2O$ applied plus the change in soil moisture storage within the barrel during the season.

## Absolute production functions

The data collected in 1972 and 1973 were used to describe the response of field corn to combinations of various levels of soil moisture and N-fertilization. The response surfaces were described in terms of second degree quadratic production functions. The second degree quadratic form provided the best fit, which was consistent with other findings (Huszar, 1970; Heady and Dillon, 1961; Jensen and Pesek, 1959a).

The procedure used to estimate the regression coefficients was that of multiple regression by least squares analysis. A Burroughs B6700 computer system was used to implement the necessary programs from the Statistical Program Package (STATPAC) developed by Hurst (1973). The programs used included the Multivariate Data Collection (MDCR), Stepwise Multiple Regression (SMRR) and Stepwise Multiple Regression Upward (SMRU). Initially the yield data collected from all treatments of each design were used in the least squares analysis. The production function determined from the 1972 conventional split plot design is represented by equation (2). Equation (3) was obtained using the data from the 1972 continuous variable plot design:

$$\hat{Y} = 4552 + 2813W + 13.9N - 165.9W^2 - 0.03N^2 + 0.6WN \qquad (2)$$

$R^2 = 0.64 \qquad F = 29.08$

$P(Y \pm 5.9\%) = 0.95$

$$\hat{Y} = -3595 + 4053W + 29.8N - 216.4W^2 - 0.06N^2 + 0.7WN \qquad (3)$$

$R^2 = 0.33 \qquad F = 59.83$

$P(Y \pm 3.2\%) = 0.95$

where Y = yield of oven dry matter measured in kg/ha

W = soil moisture level, expressed as a qualitative level, i.e., 3, 4, 5, 6, 7, 8, 9.

N = amount of N fertilizer applied, measured in kg/ha, i.e., 0 to 448 kg N/ha.

The 1972 data demonstrate quite clearly that production functions can be easily developed, using data collected in both the conventional split plot design and the continuous variable design.

The negative regression coefficients associated with the second degree N-fertilizer term suggest diminishing returns to high levels of nitrogen. The diminishing returns to high levels of N-fertilizer are consistent with other findings (Stanford and Hunter, 1973; Heady and Pesek, 1954; Huszar et al., 1970).

The multiple correlation coefficients, or $R^2$ values, for the two production functions indicate different degrees of goodness of fit. The percent of variation in dry silage yield that was explained by the variation in levels of soil moisture and N-fertilizer applied ranged from 33 to 64 percent. The low $R^2$ associated with the continuous variable design was the result of considerable variation within the limited number of replications and the small plot size. The F ratio for each production function indicated a high degree of statistical significance. Analyses of variance for the regressions were performed to determine the significance of the subsets of each production function. Simple correlation matrices were also determined for each of the terms in the quadratic production function. The correlations of yield with each subset are included in Table 15, along with the regression analyses of variance for the 1972 designs.

Table 15. Regression analysis of variance and simple correlation coefficients for the 1972 designs.

| Source of variation | Degrees of freedom | Mean sum of squares | F-ratio | Simple correlation with yield |
|---|---|---|---|---|
| | | Conventional split plot design | | |
| Soil moisture | 1 | .1290E + 09 | 22.50* | 0.879 |
| Fertilizer | 1 | .1836E + 08 | 3.20 | 0.164 |
| Second order soil moisture | 1 | .5507E + 08 | 9.60* | 0.822 |
| Second order fertilizer | 1 | .2831E + 08 | 4.94* | 0.113 |
| Soil moisture x fertilizer | 1 | .6364E + 07 | 1.11 | 0.518 |
| Model | 5 | .1668E + 09 | 29.08* | |
| Error | 74 | .5735E + 07 | | |
| | | Continuous variable plot design | | |
| Soil moisture | 1 | .7813E + 09 | 29.16* | 0.726 |
| Fertilizer | 1 | .3566E + 09 | 13.31* | 0.249 |
| Second order soil moisture | 1 | .3462E + 09 | 12.92* | 0.694 |
| Second order fertilizer | 1 | .4502E + 09 | 16.80 | 0.191 |
| Soil moisture x fertilizer | 1 | .2255E + 08 | 0.84 | 0.561 |
| Model | 5 | .1603E + 10 | 59.83* | |
| Error | 610 | .2679E + 08 | | |

*Significant at the 95 percent level.

In both designs the dry matter yield correlated highest with the soil moisture. The correlation indicated that as the soil moisture level increased, the yield increased. The F-ratios were also significant. The correlation between yield and fertilizer levels was relatively low in both designs, suggesting that the initial soil fertilizer level was relatively high. Only the F-ratio from the continuous plots was significant.

The production functions were used to predict the yield curves presented in Figures 14 and 15. The estimated yield curves represent the smoothed response surface. The yield curves for the two designs are quite similar. The greatest positive response to the N fertilizer treatments occurred at nitrogen levels below the maximum application rate. A positive response occurred up to approximately 250 kg/ha of N. Above this rate the slope of the yield curve became negative, indicating a diminishing response to higher N fertilizer levels. Within the conventional design the greatest response to soil moisture occurred between levels 1 and 2. Each subsequent increase in the soil moisture level resulted in a smaller positive response.

The predicted yield curves for the 1972 continuous variable design plots (Figure 15) also demonstrated the diminishing response to increasing soil moisture. The diminishing returns to soil moisture and fertilizer inputs were also evident from the actual yield curves. The actual data showed the greatest response to soil moisture between levels W5 and W6 (cf. Fig. 12). Ideally the treatment levels considered were to include soil moisture treatment levels that would result in negative returns. However, because of the problems previously mentioned, excessive irrigation was not possible. Any negative returns predicted from the production functions would be beyond the range of the data used to determine the functions.

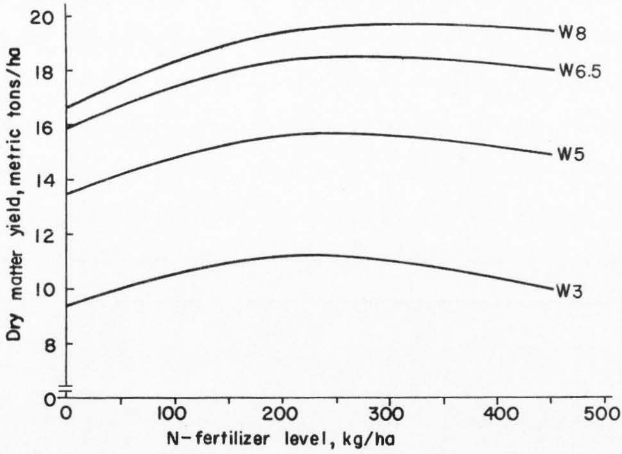



Figure 14. 1972 conventional split plot design, predicted dry matter yields, metric tons dry matter/ha.

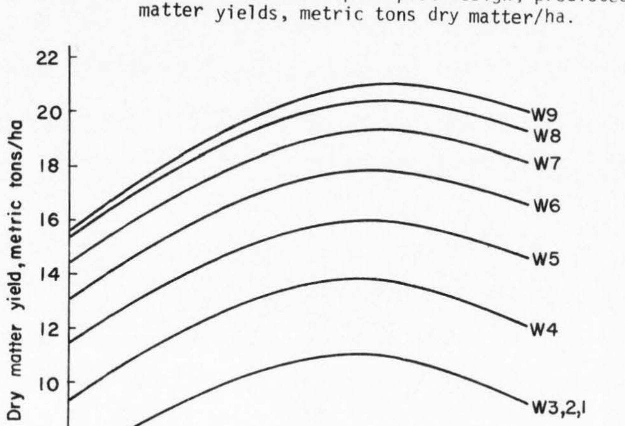



Figure 15. 1972 continuous variable plot design, predicted dry matter yields, metric tons dry matter/ha.

A similar procedure was applied to the 1973 data as was used in 1972. The yield data from all the conventional design plots were used to obtain equation (4) and all the continuous variable design plot data were used to obtain equation (5). The dimensions of the input data were approximately the same in 1972 and 1973.

$$\hat{Y} = 4373 + 498W + 31.7N - 54.6W^2 - 0.08N^2 + 2.9WN \qquad (4)$$

$$R^2 = 0.74 \qquad F = 43.07$$

$$P(Y \pm 7.9\%) = 0.95$$

$$\hat{Y} = 1547 + 1405W + 26.8N - 22.1W^2 - 0.05N^2 + 0.5WN \qquad (5)$$

$$R^2 = 0.49 \qquad F = 199.37$$

$$P(Y \pm 2.6\%) = 0.95$$

The production functions developed are similar to those obtained with the 1972 data.

The coefficients of determination are quite similar to those obtained with the 1972 data. The better goodness of fit of the conventional design data compared with the continuous design data was partially due to the smaller number of data points used to determine the conventional design production function. The F ratio for each production function indicates a high degree of statistical significance (Table 16).

The simple correlations of dry silage yield with the subset of the 1973 designs are quite similar to those for the 1972 data as shown in Table 16. As with the 1972 data the dry matter yield was correlated highest with the soil moisture variable. Yields were relatively highly correlated with the soil moisture-N fertilizer interaction. The correlation between yield and N fertilizer was relatively low. Analyses of variance for the regressions are included in Table 16, along with the simple correlation coefficients for dry silage yield.

Table 16. Regression analyses of variance and simple correlation coefficients for 1973 designs

| Source of variation | Degrees of freedom | Mean sum of squares | F-ratio | Simple correlation with yield |
|---|---|---|---|---|
| | | Conventional split plot design | | |
| Soil moisture | 1 | .1369E + 08 | 2.40* | 0.703 |
| Fertilizer | 1 | .1322E + 09 | 23.16* | 0.461 |
| Second order soil moisture | 1 | .3449E + 06 | 0.06 | 0.690 |
| Second order fertilizer | 1 | .1902E + 09 | 33.31* | 0.348 |
| Soil moisture x fertilizer | 1 | .5833E + 08 | 10.22* | 0.743 |
| Model | 5 | .2459E + 09 | 43.07* | |
| Error | 74 | .5709E + 07 | | |
| | | Continuous variable plot design | | |
| Soil moisture | 1 | .2222E + 09 | 26.55* | 0.841 |
| Fertilizer | 1 | .7519E + 09 | 89.87* | 0.188 |
| Second order soil moisture | 1 | .5366E + 07 | 0.64 | 0.822 |
| Second order fertilizer | 1 | .1013E + 10 | 121.03* | 0.097 |
| Soil moisture x fertilizer | 1 | .2858E + 08 | 3.42* | 0.620 |
| Model | 5 | .1668E + 10 | 199.37* | |
| Error | 762 | .8366E + 07 | | |

[1]Significant at the 95 percent level.

The yield curves presented in Figures 16 and 17 were determined from the production functions. The predicted yield curves represent the complete response surfaces for field corn grown in the 1973 conditions. Here again, the predicted yield curves for the two field designs are quite similar. The maximum response to N fertilizer occurred at approximately 350 kg N/ha. Above this level diminishing yields were predicted. Within the conventional plot design, the greatest response to increasing soil moisture levels occurred between levels 2 and 4. Each additional

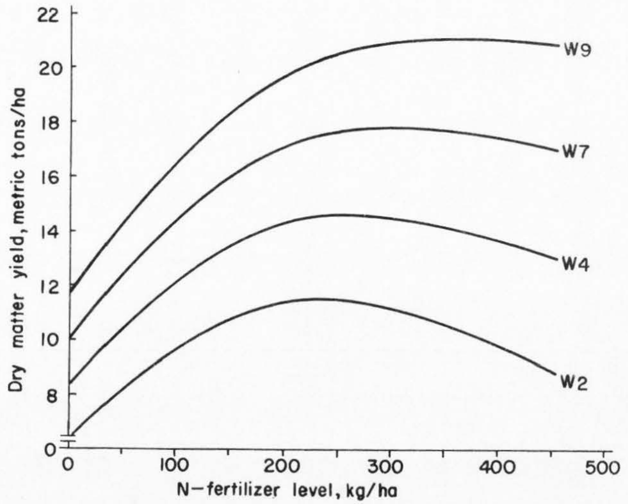



Figure 16. 1973 conventional split plot design, predicted dry matter yields, metric ton dry matter/ha.

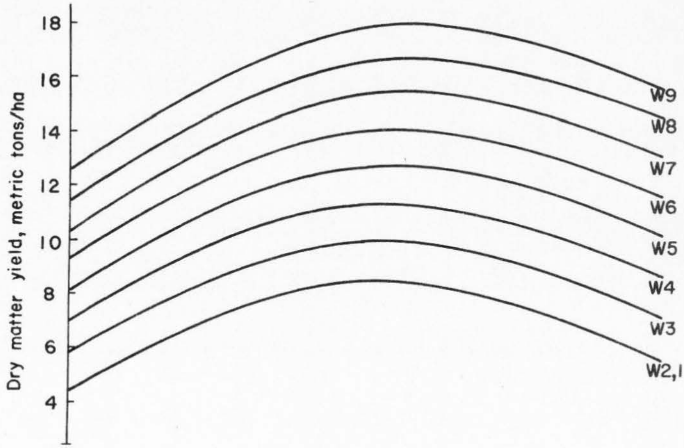



Figure 17. 1973 continuous variable plot design, predicted dry matter yields, metric tons dry matter/ha.

increase in soil moisture resulted in a smaller increase in yield. The continuous variable design predicted yield curves indicated that there was little difference in fertilizer response from level to level. The predicted curves smoothed the actual data. The yield data indicated that the greatest response to soil moisture within the continuous variable design plots occurred between soil moisture levels W5 and W6 (cf. Figure 12.)

Using the production functions developed for each design of 1972 and 1973, yields were predicted for each of the treatment combinations established in the field plots. The predicted yield values were then used to perform an analysis of variance between the populations described by the production functions (Table 17). Initially the analyses were

Table 17. F ratios of analyses of variance of dry matter yields predicted by the 1972 and 1973 production functions.

| Source of variation | F-ratio |
|---|---|
| Between 1972 designs | |
| conventional vs. continuous | 3.48 |
| Between 1973 designs | |
| conventional vs. continuous | 1.59 |
| Between conventional designs | |
| 1972 vs. 1973 | 56.07* |
| Between continuous designs | |
| 1972 vs. 1973 | 21.76* |

*Significant at the 95 percent level.

performed to compare the populations described by each of the two functions obtained in 1972 and 1973. The F ratio determined was non-significant at the 95 percent level, indicating that the predicted populations did not differ significantly. A similar analysis was used to compare the 1972 and 1973 conventional split plot design production functions and the 1972 and 1973 continuous variable plot design production functions. The results of the several comparison are presented in Table 17.

The comparison of the yields predicted by the production functions from both designs of 1972 and 1973 indicated that the two production functions did not predict the same population.

Several factors could account for the fact that one field design, used in two different years, resulted in significantly different production functions. The Logan site was different from the Farmington site in both soil and climatic conditions. The differences in soil characteristics included texture, water holding capacity, and initial soil nitrogen. The residual soil N of the Kidman soil at Farmington was very low, while the residual N was considerably higher for the Millville soil. The important climatic factors that were different were the potential evapotranspirational demand and the length of the growing season. All these factors most likely contributed to the differences in yields from 1972 to 1973.

Relative production functions

The production functions determined from the dry matter yields provided estimates of the yield as influenced by soil moisture and N fertilizer. However, the magnitude and variation in the levels of the input variables make it difficult to realize the contribution of each of the components of the total production function to the predicted yield values. In order to demonstrate the contribution of each component to the predicted yield, relative production functions were determined. For each design the maximum soil moisture level and N fertilizer level was determined.

The treatment levels associated with each plot were transformed to relative values by expressing them as fractions of the maximum level of each variable. The yields were also changed to relative yields as fractions of the maximum measured yield. A least squares analysis was then performed using these relative treatment and yield values.

The sample regression coefficients obtained using the relative levels demonstrated the magnitude of the contribution of each component in the production function to the predicted yields. This is evident from the relative production functions determined from the 1972 data. The 1972 relative production functions for the conventional split plot design and the continuous variable plot design, respectively, are:

$$\frac{\hat{Y}}{Ymax} = 0.178 + 1.285\frac{W}{Wmax} + 0.294\frac{N}{Nmax} - 0.65\left(\frac{W}{Wmax}\right)^2 - 0.294\left(\frac{N}{Nmax}\right)^2 + 0.14\frac{W}{Wmax}\frac{N}{Nmax} \qquad (6)$$

and

$$\frac{\hat{Y}}{Ymax} = -0.127 + 1.301\frac{W}{Wmax} + 0.449\frac{N}{Nmax} - 0.62\left(\frac{W}{Wmax}\right)^2 - 0.39\left(\frac{N}{Nmax}\right)^2 + 0.11\frac{W}{Wmax}\frac{N}{Nmax} \qquad (7)$$

Using the same procedure with the 1973 data, the relative production functions were determined for the two designs. They are for the conventional split plot design and the continuous variable design, respectively,

$$\frac{\hat{Y}}{Ymax} = 0.213 + 0.428\frac{W}{Wmax} + 0.81\frac{N}{Nmax} - 0.05\left(\frac{W}{Wmax}\right)^2 - 0.78\left(\frac{N}{Nmax}\right)^2 + 0.43\frac{W}{Wmax}\frac{N}{Nmax} \qquad (8)$$

ıd

$$\frac{\hat{Y}}{Y} = 0.075 + 0.61W_{Wmax} + 0.72N_{Nmax} - 0.085(W_{Wmax})^2 - 0.69(N_{Nmax})^2 + 0.13W_{Wmax}N_{Nmax} \quad (9)$$

The relative contribution of each of the components in the production function to the predicted yields varies with each production function. The most significant regression coefficients were those associated with the relative soil moisture level and the relative N fertilizer level. The diminishing returns to increasing input levels were responsible for the significant second order terms (cf. Table 15, 16).

The relative yields predicted by each of the relative production functions were used to compare the four sets of results. As with the previously determined functions, an analysis of variance was performed on the populations predicted by these relative functions. The results of those analyses are shown in Table 18, the F ratios of the analyses.

Table 18. F ratios of analyses of variance of the relative yields predicted by the 1972 and 1973 relative production functions.

| Source of variation | F ratio |
|---|---|
| 1972 designs | |
| conventional vs. continuous | 2.11 n.s. |
| 1973 designs | |
| conventional vs. continuous | 1.93 n.s. |
| 1972 vs. 1973 | |
| conventional designs | 1.43 n.s. |
| 1972 vs. 1973 | |
| continuous designs | 0.70 n.s. |

n.s. = Non-significant at the 95 percent level.

The analyses indicate that the differences in the sample populations predicted by the relative production functions were not significant. This suggests that when the data from the 1972 and 1973 conventional split plot designs are expressed in relative terms, the corresponding response surfaces did not differ for the two designs. The analyses indicated the same for the 1972 and 1973 continuous variable designs. The similarity of the relative response surfaces among years, locations, and designs supports the possible use of some form of relative response surface in describing a transferable production function.

Reduced designs

An objective of this research was to determine the extent to which the field plots could be reduced, with regard to both the plot size and the number of treatments established in the field, and still obtain data sufficient to develop reliable production functions. The analysis of the dry matter yields predicted by the continuous variable design and the conventional split plot design in either 1972 or 1973 indicated that the predicted yields did not differ significantly. Consequently, either design appeared suitable for determining the production function. Also, the 1972 and 1973 conventional split plot design functions were determined from different plot sizes. The coefficients of determination for the two conventional plot experiments indicated approximately the same reliability of the 1973 as the 1972 data, even though the former plots were reduced in size by approximately 50 percent. The improved control of the irrigation practices used in 1973 may be responsible for maintaining the $R^2$ at a level comparable to that of the 1972 data.

The complete factorial split plot designs of the Logan and Farmington sites were used as the basis for evaluating the feasibility of reducing the number of treatments necessary to determine production functions.

In order to evaluate the possibility of using an incomplete factorial design, several different incomplete factorial designs were constructed from the data collected from the 1972 complete factorial split plot design. After eliminating the data from selected treatments, a least squares analysis was performed, using the remaining data. The resultant production function was compared to the function obtained from the complete factorial design. Using this approach the 1972 conventional plot design was reduced from 4 replicates of 20 treatment combinations to 4 replicates of 10 treatment combinations, without significantly changing the production function. One incomplete factorial design that predicted the same response surface as that described by the complete factorial is shown in Table 19. Several other studies have demonstrated the need for replication of the treatment plots (Heady and Dillon, 1961; Viets, 1965; and French, 1956).

Table 19. Treatment combinations included in incomplete factorial split plot design used to determine the 1972 and 1973 production functions.

| Soil moisture levels | | N fertilizer level, kg/ha | | | | |
|---|---|---|---|---|---|---|
| 1972 | 1973 | 0 | 56 | 112 | 225 | 449 |
| 3 | 2 | X | | X | | X |
| 5 | 4 | X | | X | | |
| 6.5 | 7 | | | X | | X |
| 8.0 | 9 | X | | X | | X |

The 1973 split plot design data were treated the same way. The maximum reduction in the number of treatments was approximately the same as that of the 1972 data. The production functions determined with the data from the incomplete factorial designs were essentially the same as those from the complete factorial designs. The production functions for the incomplete factorial conventional split plot designs are presented below for the 1972 and 1973 data.

$$\hat{Y} = 4301 + 1295W + 23.8N + 4.16W^2 - 0.06N^2 + 1.4WN \quad (10)$$

$$R^2 = 0.76$$

$$P(Y \pm 8.8\%) = 0.95$$

$$\hat{Y} = 4950 + 611.2W + 41.7N + 11.6W^2 - 0.09N^2 + 2.1WN \quad (11)$$

$$R^2 = 0.79$$

$$P(Y \pm 12.2\%) = 0.95$$

The coefficients of determination for the incomplete factorial designs are substantially higher than those of the complete factorial designs, because of the fewer points and the better fit to the quadratic form. All of the $R^2$ values were significant at the 95 percent level.

Several other reduced designs were considered in incomplete factorials of the 1972 conventional split plot data. Within two of these reduced designs an entire whole plot was eliminated by omitting all yield responses from water level 5. The production function obtained from the data from the treatment combinations shown in Table 20 is presented in Equation 12.

$$\hat{Y} = 6725 + 21.4W + 31.4N + 120.8W^2 - 0.07N^2 + 1.59WN \quad (12)$$

$$R^2 + 0.70$$

$$P(Y \pm 8.7\%) = 0.95$$

Table 20. Treatment combinations included in an incomplete factorial split plot design used to determine the 1972 and 1973 production functions.

| Soil moisture levels | | N fertilizer level, kg/ha | | | | |
|---|---|---|---|---|---|---|
| 1972 | 1973 | 0 | 56 | 112 | 225 | 449 |
| 3 | 2 | X | X | X | | X |
| 5 | 4 | | | | | |
| 6.5 | 7 | | X | X | X | X |
| 8.0 | 9 | X | | X | X | X |

The population predicted by Equation 12 did not differ significantly from that predicted by the production function obtained from the complete factorial split plot design (Equation 2).

Another design tested was that shown in Table 21 below.

Table 21. Treatment combinations included in an incomplete factorial split plot design used to determine the 1972 and 1973 production functions.

| Soil moisture levels | | N fertilizer level, kg/ha | | | | |
|---|---|---|---|---|---|---|
| 1972 | 1973 | 0 | 56 | 112 | 224 | 449 |
| 3 | 2 | X | X | | X | |
| 5 | 4 | | | | | |
| 6.5 | 7 | | X | X | X | |
| 8.0 | 9 | | | X | X | X |

The population described by the production function obtained from this incomplete factorial design did not differ significantly from that described by the complete factorial production function. The production function (Equation 13) was quite similar to the complete factorial function.

$$\hat{Y} = 3328 + 1762W = 24.1N - 65.5W^2 - 0.07N^2 + 2.6WN \qquad (13)$$

$$R^2 = 0.68$$

$$P(Y \pm 8.9\%) = 0.95$$

The same incomplete factorial designs were considered with the 1973 conventional split plot design as were tested with the 1972 data (Tables 20 and 21). The respective production functions are presented in Equations 14 and 15. As in the case of the 1972 data, the populations described by the production functions from the incomplete designs were not significantly different from that described by the 1973 complete factorial design production function (Equation 4). The production functions determined were for the two designs.

$$\hat{Y} = 5268 + 531.7W + 39.7N + 17.5W^2 - 0.08N^2 + 2.1WN \qquad (14)$$

$$R^2 = 0.74$$

$$P(Y \pm 10.5\%) = 0.95$$

$$\hat{Y} = 4960 + 799.6W + 26.2N + 14.4W^2 - 0.06N^2 + 2.1WN \qquad (15)$$

$$R^2 = 0.76$$

$$P(Y \pm 10.0\%) = 0.95$$

Within the continuous variable plots, consideration was given to grouping the treatment levels and yields rather than eliminating treatment levels. All grouping of the continuous variable plots was designed to create larger plots that would facilitate the harvesting operations, without changing the continuous variable design in such a manner that buffer zones were needed between plots. Initially the 1972 yields were grouped by two treatments within each row. The resultant design consisted of four replicates of 11 fertilizer levels within 7 soil moisture levels. Therefore, each yield was the average yield of two adjacent fertilizer treatments within a row. The production function determined from these grouped data was essentially the same as that obtained using all replicates of the 154 treatment combinations (cf. Table 40, Appendix).

The production functions obtained from several other grouping schemes were compared with the overall production function. The maximum number of plots grouped together was twelve. The yields from all plots in one group were averaged along with the soil moisture and fertilizer levels. Table 22 represents the treatment combinations included in each group. The corresponding production function is presented in Equation 16. The maximum grouping created a 4 x 4 complete factorial design with four replicates of each group.

Table 22. 1972 continuous variable plot design grouped dry matter yields.

| Grouped soil moisture levels | Grouped N fertilizer levels, kg/ha |
|---|---|
| 3 + 4 | 0 + 25 + 39 + 65 + 78 + 104 |
| 5 + 6 | 117 + 143 + 157 + 183 + 195 + 222 |
| 7 + 8 | 234 + 261 + 274 + 301 + 313 + 339 |
| 9 | 352 + 378 + 392 + 421 |

$$\hat{Y} = -6188 + 4354W + 46.1N - 234.3W^2 - 0.08N^2 + 0.13WN \qquad (16)$$

$$R^2 = 0.73$$

$$P(Y \pm 6.5\%) = 0.95$$

The 1973 continuous variable plot design data was also grouped. The 192 treatment combinations were reduced to 16 treatment combinations without a significant change in the production function. The F ratio for the comparison was 0.577. The 4 x 4 complete factorial was obtained by grouping 12 plots together and averaging the yields. Each grouping was the average of the yields from 6 consecutive N fertilizer levels within two adjacent rows. The treatment combinations comprising the groups are shown in Table 23.

Table 23. 1973 continuous variable plot grouped dry silage yields.

| Grouped soil moisture levels | Grouped N fertilizer levels, kg/ha |
|---|---|
| 2 + 3 | 0 + 24 + 48 + 72 + 96 + 120 |
| 4 + 5 | 144 + 168 + 192 + 216 + 240 + 264 |
| 6 + 7 | 228 + 312 + 336 + 360 + 384 + 408 |
| 8 + 9 | 432 + 456 + 480 + 504 + 528 + 552 |

The production function for the reduced design is shown below (Equation 17).

$$\hat{Y} = 880 + 1667W = 25.5N - 43.9W^2 - 0.04N^2 + 0.6WN \quad (17)$$

$$R^2 = 0.81$$

$$P(Y \pm 7.6\%) = 0.95$$

The multiple correlation coefficient was significantly increased by the grouping process. The improved goodness of fit is the result of both the twelve-fold reduction in the number of data points and the smoothing caused by the averaging of plots to obtain the grouped yield. The grouped plot $R^2$ for the continuous variable plots is considerably higher than that for the conventional split plot design.

The confidence interval for the estimated mean yield from each production function varied considerably with the designs. The 95 percent confidence interval, expressed as a percentage of the estimated mean yield, varied from 2.6 to 7.9 percent. In both 1972 and 1973 the continuous variable design data was associated with a smaller confidence interval than the conventional split plot design data.

The production functions obtained with the data from the field designs may be somewhat misleading. The regression coefficients obtained by the least squares method of fit, when used to estimate yield responses, tend to smooth the data. The smoothing tends to "dampen" the crop responses to the different soil moisture levels. Consequently, the W levels are not distinguished in the estimated response surfaces as significantly as the raw data show. A comparison of Figures 12 and 15 clearly demonstrates this point. The data of Figure 12 show that the most significant yield increase occurred between soil moisture levels 5 and 6. However, the estimated response curves in Figure 15 indicate that the most significant yield response occurred between soil moisture levels 3 and 4. The same can be seen from the 1973 continuous variable plot data (Figures 13 and 17). The production functions also tend to over-emphasize the decreasing returns to high fertilizer levels. This is especially true for the lower soil moisture levels. Within the 1972 and 1973 conventional split plot designs the response to increasing fertilizer levels within the lowest soil moisture level was either non significant or positive (Figures 8 and 9). The predicted yield curves of Figures 14 and 16 indicate that a decreasing response occurred above a fertilizer rate of approximately 250 kg/ha within the lowest soil moisture level. Consequently, the predicted yield curves should be considered with some caution, outside of the region from which the experimental data was obtained.

Although the estimated populations from the incomplete factorial designs do not differ significantly from those of the complete factorial designs, considerable resolution is sacrificed for the incomplete design. The reduced designs contained approximately 50 percent of the treatment combinations of the complete factorial designs. The confidence intervals associated with the estimated mean yields of the incomplete designs are considerably larger than those for the complete designs. The increase in the $R^2$ with the reduced designs indicates a greater degree of closeness with which the predicted response surface fits the observed points. The reduction in fertilizer levels from five to four or three levels causes the data to approach the ideal number of data points to which a second degree quadratic function can be fitted.

The grouping procedure used to reduce the continuous variable designs increases the $R^2$ by reducing the number of data points through which the regression plane must fit and by smoothing the data before fitting the production function. The reduction in the number of observation points also causes an increase in the confidence interval for the estimated mean yield of each function.

Transferability of production functions

The transferability of the production functions to another location was considered with the functions obtained from the 1972 and 1973 data. The production functions were transformed into several different forms and the resultant populations were compared. The procedure was to select the 1973 continuous variable design production function as a base against which all other production functions were compared. The 1973 function was used as a base because of the low residual soil N associated with the Farmington site.

The comparison of the absolute production functions, as previously discussed, indicated that the production functions determined by the two designs did not differ significantly within the study years, but they did differ significantly between years. The yields predicted from the 1972 functions from Logan were considerably higher than the yields measured at Farmington. Consequently, the transferability of an absolute production function was disregarded. The absolute production function for any particular study is site specific. When considering the yield responses in a second location no consideration was given to the site differences such as soil characteristics and climatic conditions.

Consideration was also given to the possible transferability of a relative production function (Equations 6, 7, 8, and 9). The relative production functions determined for the 1972 data were considered (Table 18). These production functions had been determined by expressing all input data relative to the maximum level of the variables. The relative production functions for the 1972 designs were not significantly different. If the relative production function was transferable, it would be possible to predict the yield response to inputs at any site, knowing only the transferable relative production function and the maximum input levels at another site.

The comparison of the 1972 and 1973 relative production functions indicated that the predicted populations did not differ significantly. However, with the treatment levels expressed as fractions of the maximum level of each variable, the magnitude of the relative values is dependent on the maximum treatment level. This may be quite misleading because the maximum treatment level is not necessarily associated with the maximum yield response.

The yields and treatment levels were also expressed relative to the treatment levels associated with the maximum yield rather than the maximum treatment levels for each design. Production functions were then determined and compared for the two designs of 1972 and 1973. (The production functions are included in the Appendix, Table 41).

The populations predicted by the relative production functions of the 1972 and 1973 conventional split plot designs were significantly different. The 1972 plots were presumably high in soil N, which was not accounted for when determining the prediction equations. The conventional plot yield curves indicated that the relative yield at zero fertilizer in Logan was approximately equal to the relative yield at a treatment level of 75 kg N/ha in Farmington. Therefore, each N fertilizer treatment for Logan was adjusted upward by 75 kg/ha and the resultant production function determined. The population predicted by the adjusted relative production function did not differ significantly from the 1973 Farmington conventional split plot design relative production function. The results of the comparison are presented below.

Analysis of variance for populations estimated by the conventional split plot design relative (of optimum) production functions.

| source of variation | df | F ratio |
|---|---|---|
| 1973 vs. 1972 | 1 | 2.28* |
| 1973 vs. 1972 adjusted[1] | 1 | 0.17 |

*significant at the 95 percent level.
[1]all fertilizer levels increased by 75 kg N/ha.

For the continuous variable designs, the production functions determined with the ratios of the treatments and yields to the optimum levels of the 1972 and 1973 data predicted significantly different populations. Several methods were used to adjust the 1972 data in an attempt to obtain a production function that predicted populations that did not differ significantly from the 1973 data. The maximum yield obtained in 1972 was associated with a much lower N fertilizer level than that for the maxmimum yield of 1973.

To account for the contribution of the high residual soil N to the 1972 yields, each 1972 N fertilizer treatment level was increased by 75 kg/ha and a new relative production function was determined, using ratios of the optimum levels. The same procedure was used with the continuous variable designs as was used with the conventional split plot data. A comparison of this function with the 1973 function showed that the predicted populations differed significantly.

This same procedure was repeated several times, changing the N fertilizer level by which the treatments were increased before determining the adjusted 1972 production function. The 1972 treatment levels were shifted upward by as much as 200 kg N/ha. This implied that the initial residual soil N was equivalent to a N fertilizer level of 200 kg N/ha. The population described by the 1972 production function, adjusted by 200 kg N/ha did not differ significantly from that described by the 1973 continuous variable design function. Below that level of adjustment the populations differed. This supports the idea that a relative production function can be adjusted or manipulated to the degree that it may be transferable to several locations. However, since a shift of 200 kg N/ha was needed with one design and a shift of 75 kg N/ha was needed with another design there is some question of the validity of this method of adjustment.

Barrel lysimeters

The effectiveness of the barrel lysimeters, which were intended to provide useful information regarding the crop water use efficiency at Logan and Farmington, was limited by several problems in 1972 and 1973. As previously mentioned, several of the plots at Logan were mistakenly irrigated on several occasions. Consequently, the actual water use was somewhat in question. Another problem with the 1972 data was the variability in yield. Because of the small plots the variability was as great within the treatments as between treatments.

Although the 1973 barrel plots were handled with much more control, the data was as variable within the treatments as between the treatments.

In determining the water use data of 1972 (Table 13) all the fertilizer treatments within each soil moisture level were averaged. The 1972 data indicated that the water use efficiency of field corn within the barrel plots decreased with increasing soil moisture levels. The 1973 barrel plot data (Table 14) indicated that the water use efficiency increased with increasing soil moisture. The barrel data indicated that the small plots with the limited plant populations were not suitable to obtain reliable data for production functions. Because of the variability of the data collected during the two years, the barrel plots were not used to determine production functions for the two sites.

A second objective of the barrel plots was to assist in estimating the water use in the field plots. The field plot yields were, in most cases, considerably larger than the yields within the barrel plots. This was especially true within the highest soil moisture levels. If a situation had been attained within the highest soil moisture levels of both the field plots and barrels, where soil moisture was not limiting, and if the barrels were representative of the field plots, then the yields from the two plots should have been comparable. The significant difference in yield between the highest soil moisture level of the barrel plots and field plots suggested that the corn within the barrels did not behave the same as that in the field. The variability of the data within treatments and the lack of agreement with the field plots indicated that the barrel plot data were not reliable enough to be used to assist in estimating the water use in the field plots.

# SUMMARY AND CONCLUSIONS

An objective of this study was to determine if crop production functions could be developed in the field. Two of the three field designs studied provided crop response data that was suitable for generating reliable production functions. Production functions describing field corn production as related to soil moisture and nitrogen fertilizer were determined from data collected from the conventional split plot design and from the continuous variable plot design. The multiple correlation coefficients for the production functions determined in 1972 and 1973 ranged from 0.33 to 0.74. The higher $R^2$ values were associated with the conventional split plot design, although all coefficients were significant at the 95 percent level.

The production functions determined from the two designs did not differ significantly within years, but they did differ significantly between years. The between year variation was most likely due to the changes in growing conditions from 1972 and 1973 and from Logan to Farmington, Utah.

Relative production functions were also determined by expressing yields and treatment levels as fractions of either the maximum level of each variable or the optimum level of each variable (that associated with maximum yield was not necessarily the maximum treatment level). The relative (of the maximum level) production functions did not differ significantly within years or between years. Those determined relative to the optimum input levels did not differ significantly within years but they did differ significantly between years.

Another objective was to determine the maximum degree of treatment elimination and/or treatment grouping possible while not significantly reducing the reliability of the resultant production functions. Several incomplete factorial split plot designs were created in reduced designs of the conventional split plot designs. The production functions obtained did not differ significantly from the complete factorial designs, and the confidence interval was increased only slightly by reducing the number of treatments. The most reduced design was an incomplete factorial, split plot of three soil moisture levels and five fertilizer levels in nine treatment combinations.

The continuous variable plot designs were reduced by grouping similar treatment plots together and averaging the yields before determining the production functions. Both the 1972 and 1973 continuous variable designs were reduced to complete factorial designs of four soil moisture levels and four fertilizer levels. The resultant production functions did not differ significantly from those of the complete designs, although the confidence limits were considerably larger with the reduced designs.

The ability to group several similar treatment combinations within the continuous variable design improves the usefulness of this design. The grouping process is particularly valuable when harvesting the plots. Rather than harvest many small plots, it is possible to increase the plot size and improve the reliability of the yield data by grouping. Certainly the grouping process does facilitate harvesting. However, a compromise must be made in order not to defeat the purpose of the continuous variable plot design. The major fault of most conventional designs is that the number of points used to describe the production function is too few to adequately describe the complete response surface.

One compromise which seems to offer a solution to the problem is that of fewer treatment combinations, while using them in a continuous variable design. In this particular study a continuous variable design of approximately eight fertilizer treatment levels and eight soil moisture treatment levels would have probably provided sufficient data to develop a reliable production function.

The transferability of the production functions was considered. The similarity of the relative production functions within designs and between years suggested the possible transferability of a relative production function. The relative (of the optimum levels) production functions were adjusted by several methods in an attempt to account for site specific conditions, such as residual soil nitrogen, which influence crop production. The conclusions were that the production functions as they were determined here could not be readily transferred to a second location without first making additional consideration for site specific soil fertility conditions.

When considering the use of any particular design for obtaining production function data, consideration should be given to the adaptability of the design to the physical situation and to the information desired. Although the continuous variable design is quite well-suited to locations where field space is limiting and/or many treatment variables and combinations are to be considered, this design should be used only on relatively uniform sites. The systematic location of treatments with respect to each other, rather than randomization, is based on the assumption that field variability (with respect to soil properties) is at a minimum. The completely randomized, conventional split plot design is, conversely, well-suited to situations of significant site variability. Consequently, each site and experiment should be treated with the most appropriate design.

## SUGGESTIONS FOR FURTHER RESEARCH

This study, like most others of a scientific nature, has been successful at answering some questions and raising some new ones. Certainly our understanding of production functions and the field designs necessary to obtain data suitable for generating reliable production functions has increased. At the same time several questions have been raised, suggesting the need for additional research. Some of those questions and areas of further investigation are:

1. How well will the reduced designs function in the field? What amount of incomplete replication can be used to obtain reliable data for production functions?

2. What other means are available to express the changing soil moisture conditions in the field?

3. Is it possible to maintain a somewhat constant soil moisture level? If so how could it apply to a practical condition?

4. What is the largest treatment increase that is possible while still maintaining the continuous variable design?

5. What are the economic considerations of corn production, based on the information provided from the production functions?

6. Can transferable production functions be determined for other controlling factors?

7. What is the most useful field design to use in a particular location, the complete or incomplete, the conventional split plot or the continuous variable plot design?

8. Can the continuous variable design be modified to be used with a sprinkler irrigation system?

9. Is the continuous variable design practical with more than two variables and with other crops?

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# APPENDIXES

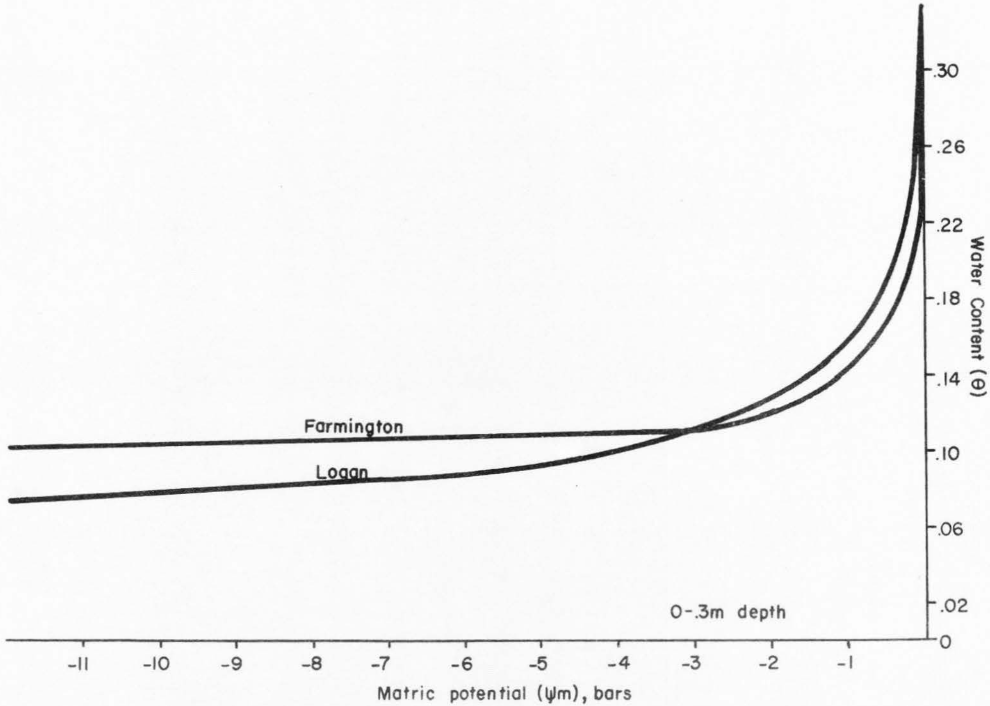


Figure 18. Moisture characteristic curves. Millville silt loam and Kidman sandy loam (Farmington) soils.

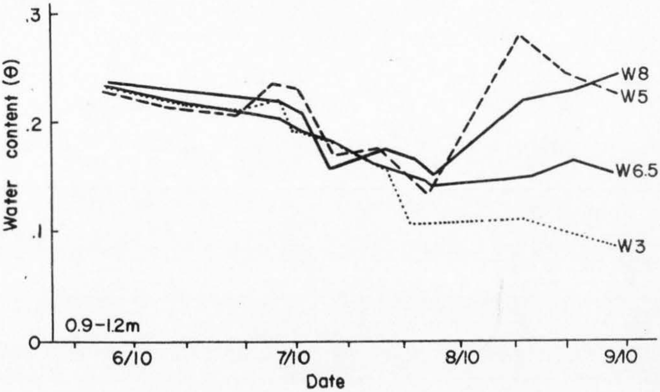


Figure 19. 1972 conventional split plot design, volumetric water content in the root zone during the growing season. 0.9 - 1.2m depth.

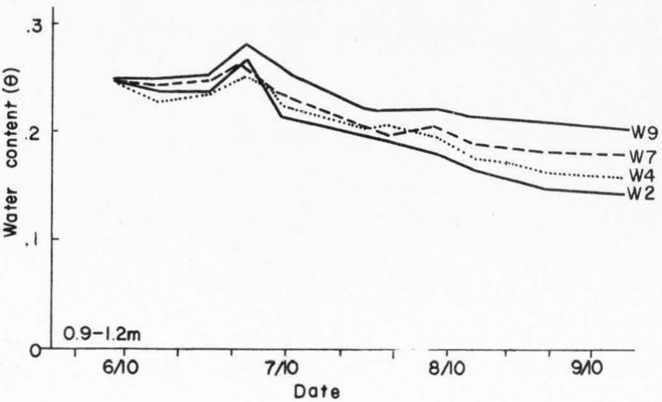


Figure 20. 1973 conventional split plot design, volumetric water content in the root zone during the growing season. 0.9 - 1.2m depth.

Table 24. Irrigation schedule of 1972 conventional split plot design plots. Greenville Farm (centimeters of water.).

| | Soil moisture level | | | |
|---|---|---|---|---|
| Date | W1 | W2 | W3 | W4 |
| 6/14/72 | | | | 1.54 |
| 20 | | | | 1.54 |
| 23 | 1.27 | 1.27 | 1.27 | 1.27 |
| 24 | .50 | .50 | .50 | .50 |
| 26 | 1.50 | 1.50 | 1.50 | 1.50 |
| 29 | | | | 2.54 |
| 7/7/72 | | | 2.54 | 1.54 |
| 12 | | | 3.81 | 1.54 |
| 18 | | 1.90 | | |
| 20 | | 5.30 | | • |
| 21 | | | 3.81 | 2.54 |
| 26 | | | 1.81 | 2.54 |
| 8/1/72 | | | 7.62 | 5.82 |
| 7 | | | | 7.82 |
| 9 | | 5.62 | | |
| 11 | | | 5.62 | |
| 13 | .96 | .96 | .96 | .96 |
| 16 | | | | 13.24 |
| 21 | | 5.60 | | |
| 23 | | | 5.62 | |
| 24 | | | | 3.24 |
| 29 | .20 | .20 | .20 | .20 |
| 30 | .28 | .28 | .28 | .28 |
| 9/5/72 | 1.55 | 1.55 | 1.55 | 1.55 |
| 6 | .89 | .89 | .89 | .89 |
| TOTAL | 7.15 | 24.57 | 37.98 | 51.05 |

Table 25. Irrigation schedule of 1972 continuous variable design plots. Greenville Farm (centimeters of water).

| Date | Soil moisture level | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 |
| 6/2/72 | .42 | .42 | .42 | .42 | .42 | .42 | .42 | .42 | .77 |
| 5 | | | | | | | | | .69 |
| 6 | | | | | | | | | .69 |
| 7 | | | | | | | | | .69 |
| 8 | | | | | | | | | .65 |
| 9 | | | | | | | .86 | 1.48 | .74 |
| 10 | | | | | | | .63 | .63 | .63 |
| 12 | | | | | | .62 | .62 | .83 | .83 |
| 13 | | | | | | | .62 | .62 | .62 |
| 14 | | | | | | | .62 | .62 | 1.25 |
| 15 | | | | | | .62 | | .62 | .62 |
| 16 | | | | | | .32 | .31 | .64 | .64 |
| 17 | | | | | | | .73 | .73 | .73 |
| 19 | | | | | | .71 | .63 | .63 | 1.34 |
| 20 | | | | | | .59 | .59 | .62 | .62 |
| 21 | | | | | | .81 | .81 | .81 | .81 |
| 22 | | | | | | | .73 | .73 | .73 |
| 23 | 1.27 | 1.27 | 1.27 | 1.27 | 1.27 | 1.27 | 1.27 | 1.27 | 1.27 |
| 26 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| 27 | | | | | | | | | .65 |
| 28 | | | | | | | | | .82 |
| 29 | | | | | | | | 1.00 | 1.00 |
| 30 | | | | | | | | | 1.00 |
| 7/1/72 | | | | | | 1.33 | 1.33 | 1.33 | 1.33 |
| 3 | | | | | | .82 | .82 | .82 | .82 |
| 4 | | | | | | .52 | .52 | .96 | .96 |
| 6 | | | | | .36 | .36 | .36 | .64 | .64 |
| 7 | | | | | | 1.09 | 1.09 | 1.09 | 1.09 |
| 8 | | | | | | 1.04 | 1.04 | | 1.04 |
| 10 | | | | 1.39 | 1.39 | 1.39 | 1.52 | 1.52 | 1.52 |
| 11 | | | | | | 1.32 | 1.32 | | 1.32 |
| 12 | | | | | | 1.14 | 1.14 | 1.14 | 1.14 |
| 13 | | | | .88 | | | .88 | .88 | .88 |
| 14 | | | | | | 1.84 | 1.84 | 1.84 | 1.84 |
| 17 | | | | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 | 1.06 |
| 18 | | | | | | .99 | .99 | .99 | .99 |
| 19 | | | | | | | | | .05 |
| 20 | | | | | | | 1.56 | 1.56 | 1.56 |
| 21 | | | | | 1.58 | | | | 1.58 |
| 22 | | | | | | | | | .62 |
| 24 | | | | | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 |
| 25 | | | | | | .75 | .75 | .75 | .75 |
| 26 | | | | | | | .81 | .81 | .81 |

Table 25. Continued.

| Date | Soil moisture level | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 |
| 7/27/72 | | | | | | .52 | .52 | .52 | .52 |
| 28 | | | | | | 1.10 | 1.10 | 1.10 | 1.10 |
| 31 | | | | | | | | | 1.07 |
| 8/1/72 | | | | 1.51 | | | 1.51 | 1.51 | 1.51 |
| 2 | | | | | 1.19 | 1.19 | | | 1.19 |
| 3 | | | | | | 1.10 | 1.10 | 1.10 | 1.10 |
| 4 | | | | | | 1.04 | 1.04 | 1.04 | 1.04 |
| 5 | | | | | | .95 | .95 | .95 | .95 |
| 7 | | | | | 1.32 | 1.32 | 1.32 | 1.32 | 1.32 |
| 8 | | | | 1.50 | | 1.50 | 1.50 | | 1.50 |
| 9 | | | | | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 |
| 10 | | | | | 1.36 | | 1.36 | 2.90 | 2.90 |
| 11 | | | | .49 | | .49 | .49 | .49 | .49 |
| 12 | | | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 14 | | | | 1.14 | | 1.14 | 1.14 | | 1.14 |
| 16 | | | | | | .91 | .91 | .91 | .91 |
| 17 | | | | 1.00 | | | 1.00 | | 1.00 |
| 18 | | | | | | | | 1.19 | 1.19 |
| 21 | | | | | | 1.65 | 1.65 | 1.65 | 1.65 |
| 22 | | | | | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 |
| 23 | | | | | 1.44 | | 1.44 | | 1.44 |
| 24 | | | | | | 1.26 | | 1.26 | 1.26 |
| 25 | | | | | | | | | .73 |
| 28 | | | | | .75 | .75 | .75 | .75 | .75 |
| 29 | .41 | .41 | .41 | .41 | .41 | .41 | .41 | .41 | .41 |
| 31 | | | | | | 1.56 | 1.56 | 1.56 | 1.56 |
| 9/7/72 | | | | | | | | | .88 |
| 11 | | | | | | .88 | .88 | .88 | .88 |
| TOTAL | 4.10 | 4.10 | 4.10 | 14.07 | 18.77 | 41.80 | 52.20 | 63.70 | 72.40 |

Table 26. Irrigation schedule of 1973 conventional split plot design plots. Farmington Farm (centimeters of water).

| | Soil moisture level | | | |
|---|---|---|---|---|
| Date | W1 | W2 | W3 | W4 |
| 6/7/73 | | 0.09 | 0.09 | 0.09 |
| 11 | | 1.08 | 1.08 | 1.08 |
| 19 | | | 5.38 | 5.38 |
| 26 | | | | 4.30 |
| 29 | | | 2.69 | 2.69 |
| 7/3/73 | | 2.30 | | 2.30 |
| 6 | | | 3.36 | 3.36 |
| 10 | | 5.53 | | 2.84 |
| 12 | | | 1.34 | 1.34 |
| 12-15 | 3.60 | 3.60 | 3.60 | 3.60 |
| 17 | | | | 1.34 |
| 19 | 2.50 | 2.50 | 2.50 | 2.50 |
| 20 | | 2.69 | 1.34 | |
| 21 | 2.18 | 2.18 | 2.18 | 2.18 |
| 25 | | | | 2.07 |
| 27 | | | | 1.34 |
| 8/1/73 | | | 2.69 | 1.34 |
| 3 | | | | 2.69 |
| 7 | | | 4.04 | 1.34 |
| 10 | | | 4.04 | 1.34 |
| 14 | | | 2.69 | 2.69 |
| 17 | | | | 4.04 |
| 21 | | | | 2.69 |
| 24 | | | 2.69 | 1.34 |
| 28 | | 8.07 | 2.69 | 1.34 |
| 9/2/73 | 2.50 | 2.50 | 2.50 | 2.50 |
| TOTAL | 10.78 | 30.55 | 44.91 | 57.77 |

Table 27. Irrigation schedule of 1973 continuous variable design plots, Farmington Farm (centimeters of water).

| | Soil moisture level | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | W1 | W2 | W3 | W4 | W5 | W6 | W7 | W8 | W9 | W10 |
| 6/7/73 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 |
| 8 | | | | | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 |
| 11 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 | 1.04 |
| 19 | | | | 4.14 | 4.14 | 4.14 | 4.14 | 4.14 | 4.14 | 4.14 |
| 21 | | | | | | | | | | 3.15 |
| 26 | | | | | | | | 0.68 | 0.68 | 3.79 |
| 29 | | | | | | | | | 4.14 | 4.14 |
| 7/3/73 | | | | 1.81 | | 1.81 | | 1.81 | | 1.81 |
| 6 | | | | | | | 3.42 | | 3.42 | 3.42 |
| 10 | | | | 4.40 | 2.07 | 4.40 | | 2.33 | | 2.33 |
| 13 | | | | | | | | | | 2.07 |
| 12-15 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 | 3.60 |
| 17 | | | | | | | | | 3.10 | 2.07 |
| 19 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 |
| 20 | | | | | | | | 2.07 | | |
| 21 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 |
| 25 | | | | | | | 5.17 | | 3.10 | 2.07 |
| 27 | | | | | 5.17 | | | | | 2.07 |
| 8/1/73 | | | | | | | | | | 3.10 |
| 3 | | | | | | | | | 2.07 | 2.07 |
| 7 | | | | | | | | 4.14 | 3.10 | 2.07 |
| 10 | | | | | | 4.14 | 4.14 | | | 4.14 |
| 13 | | | | | 4.14 | | | | 4.14 | 3.10 |
| 16 | | | | 4.65 | | | | 4.14 | | 2.58 |
| 21 | | | | | | | | | 6.21 | |
| 24 | | | 6.21 | | 1.03 | 3.10 | 4.14 | 5.17 | | 2.07 |
| 28 | | | | | | | | 3.10 | 3.10 | 2.07 |
| 9/2/73 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 |
| TOTAL | 10.99 | 10.99 | 17.20 | 25.99 | 28.93 | 29.97 | 33.39 | 39.96 | 49.59 | 64.65 |

Table 28. Weather data for Logan, Utah, at the Greenville Farm, 1972.

| Date | Air temperature Max F | Min F | Wet F | Dry F | Wind mi/ day | Prec. cm | Epan. cm |
|---|---|---|---|---|---|---|---|
| 5/17 | 83 | 45 | 54 | 79 | 103 | | 1.14 |
| 18 | 78 | 45 | 57 | 74 | 38 | | .38 |
| 19 | 75 | 55 | 52 | 75 | 60 | | .71 |
| 20 | 75 | 49 | 51 | 62 | 56 | | .69 |
| 21 | 64 | 48 | 46 | 60 | 118 | .18 | .41 |
| 22 | 60 | 35 | 50 | 51 | 5 | | .23 |
| 23 | 70 | 37 | 55 | 64 | 35 | .13 | .56 |
| 24 | 76 | 41 | 57 | 76 | 48 | .03 | .56 |
| 25 | 75 | 42 | 45 | 72 | 19 | | .46 |
| 26 | 75 | 37 | 56 | 73 | 25 | | .74 |
| 27 | 78 | 39 | 58 | 78 | 18 | | .56 |
| 28 | 80 | 46 | 61 | 78 | 22 | | .61 |
| 29 | 82 | 48 | 63 | 80 | 41 | | .81 |
| 30 | 83 | 63 | 60 | 80 | 117 | | 1.09 |
| 31 | 87 | 47 | 63 | 86 | 30 | | .63 |
| 6/1 | 87 | 50 | 64 | 78 | 8 | | .79 |
| 2 | 79 | 54 | 63 | 75 | 36 | | .41 |
| 3 | 83 | 56 | 68 | 80 | 57 | | .71 |
| 4 | 80 | 54 | 61 | 72 | 47 | 1.24 | 1.12 |
| 5 | 81 | 55 | 62 | 71 | 50 | | .84 |
| 6 | 82 | 55 | 66 | 82 | 38 | | .25 |
| 7 | 83 | 56 | 65 | 74 | 49 | | .64 |
| 8 | 80 | 59 | 60 | 69 | 57 | | .64 |
| 9 | 82 | 52 | 63 | 80 | 47 | | .64 |
| 10 | 84 | 55 | 62 | 84 | 43 | | .58 |
| 11 | 83 | 49 | 61 | 77 | 54 | | 1.07 |
| 12 | 79 | 45 | 65 | 80 | 13 | | .33 |
| 13 | 79 | 45 | 59 | 75 | 24 | | .61 |
| 14 | 84 | 46 | 64 | 82 | 22 | | .38 |
| 15 | 87 | 56 | 64 | 84 | 35 | | .94 |
| 16 | 88 | 60 | 62 | 75 | 33 | | 1.14 |
| 17 | 85 | 64 | 59 | 68 | 58 | | .79 |
| 18 | 81 | 54 | 59 | 65 | 24 | .20 | .61 |
| 19 | 71 | 41 | 57 | 71 | 21 | | .38 |
| 20 | 77 | 43 | 59 | 77 | 20 | | .66 |
| 21 | 82 | 50 | 63 | 80 | 39 | | .66 |
| 22 | 82 | 50 | 63 | 68 | 35 | .84 | .51 |
| 23 | 77 | 55 | 59 | 67 | 24 | .86 | .53 |
| 24 | 70 | 50 | 55 | 55 | 43 | 1.04 | .33 |
| 25 | 71 | 45 | 59 | 65 | 53 | .79 | .28 |
| 26 | 74 | 43 | 59 | 70 | 12 | | .41 |
| 27 | 77 | 47 | 61 | 69 | 20 | | .76 |
| 28 | 83 | 48 | 67 | 82 | 14 | | .53 |

Table 28. Continued.

| Date | Max F | Air temperature Min F | Wet F | Dry F | Wind mi/day | Prec. cm | Epan. cm |
|---|---|---|---|---|---|---|---|
| 6/29 | 89 | 50 | 64 | 86 | 13 | | .64 |
| 30 | 91 | 54 | 65 | 88 | 14 | | .79 |
| 7/1 | 91 | 51 | 67 | 86 | 8 | | |
| 2 | 86 | 47 | 61 | 73 | 25 | | .84 |
| 3 | 81 | 47 | 62 | 80 | 20 | | .53 |
| 4 | 83 | 51 | 62 | 80 | 58 | | .86 |
| 5 | 89 | 47 | 63 | 83 | 13 | | .66 |
| 6 | 91 | 57 | 66 | 86 | 22 | | .76 |
| 7 | 90 | 58 | 62 | 83 | 26 | | .89 |
| 8 | 90 | 50 | 65 | 82 | 22 | | .61 |
| 9 | 89 | 53 | 64 | 89 | 19 | | .69 |
| 10 | 89 | 52 | 63 | 85 | 18 | | .66 |
| 11 | 91 | 50 | 67 | 91 | 12 | | .51 |
| 12 | 91 | 53 | 67 | 90 | 15 | | .76 |
| 13 | 93 | 58 | 69 | 91 | 11 | | .89 |
| 14 | 93 | 58 | 66 | 86 | 27 | | .84 |
| 15 | 87 | 52 | 85 | 85 | 17 | | .58 |
| 16 | 85 | 51 | 66 | 85 | 12 | | .64 |
| 17 | 85 | 51 | 63 | 83 | 8 | | .58 |
| 18 | 84 | 52 | 62 | 84 | 26 | | .81 |
| 19 | 84 | 54 | 64 | 82 | 30 | | .84 |
| 20 | 85 | 53 | 53 | 72 | 35 | .08 | .79 |
| 21 | 79 | 49 | 60 | 72 | 35 | | .48 |
| 22 | 78 | 46 | 61 | 78 | 20 | | .46 |
| 23 | 89 | 45 | 64 | 88 | 13 | | .69 |
| 24 | 91 | 54 | 67 | 89 | 33 | | .81 |
| 25 | 90 | 55 | 67 | 90 | 31 | .08 | .71 |
| 26 | 90 | 59 | 66 | 87 | 8 | | .48 |
| 27 | 91 | 55 | 63 | 81 | 16 | | .66 |
| 28 | 90 | 52 | 65 | 87 | 10 | | .53 |
| 29 | 96 | 51 | 68 | 94 | 9 | | 1.02 |
| 30 | 96 | 57 | 63 | 78 | 25 | | .53 |
| 31 | 87 | 63 | 70 | 86 | 10 | | .51 |
| 8/1 | 92 | 58 | 67 | 87 | 22 | | .53 |
| 2 | 89 | 54 | 65 | 85 | 20 | | .66 |
| 3 | 89 | 48 | 68 | 87 | 4 | | .94 |
| 4 | 91 | 57 | 66 | 90 | 36 | | .76 |
| 5 | 91 | 52 | 65 | 89 | 2 | | .51 |
| 6 | 93 | 52 | 64 | 92 | 11 | | .74 |
| 7 | 95 | 51 | 66 | 93 | 5 | | .69 |
| 8 | 95 | 52 | 64 | 92 | 8 | | .76 |
| 9 | 96 | 55 | 65 | 59 | 9 | | .76 |
| 10 | 96 | 55 | 65 | 94 | 11 | | .71 |

Table 28. Continued.

| | | Air temperature | | | Wind | | |
|---|---|---|---|---|---|---|---|
| Date | Max F | Min F | Wet F | Dry F | mi/ day | Prec. cm | Epan. cm |
| 8/11 | 96 | 60 | 68 | 94 | 17 | | .89 |
| 12 | 96 | 71 | 73 | 94 | 41 | | .51 |
| 13 | 95 | 58 | 67 | 84 | 13 | | .89 |
| 14 | 85 | 55 | 65 | 73 | 25 | 1.09 | .66 |
| 15 | 84 | 54 | 65 | 80 | 20 | | .38 |
| 16 | 87 | 59 | 66 | 84 | 27 | | .66 |
| 17 | 87 | 54 | 62 | 86 | 25 | | .58 |
| 18 | 87 | 51 | 62 | 81 | 11 | | .56 |
| 19 | 83 | 60 | 67 | 83 | 30 | | .51 |
| 20 | 84 | 49 | 60 | 84 | 8 | | .61 |
| 21 | 86 | 50 | 65 | 82 | 14 | | .66 |
| 22 | 88 | 50 | 63 | 84 | 23 | | .56 |
| 23 | 87 | 52 | 53 | 63 | 6 | | .43 |
| 24 | 75 | 43 | 55 | 75 | 13 | | .38 |
| 25 | 82 | 52 | 62 | 78 | 47 | | .61 |
| 26 | 85 | 57 | 65 | 80 | 16 | | .53 |
| 27 | 87 | 51 | 64 | 85 | 20 | | |
| 28 | 87 | 55 | 65 | 76 | 21 | | 1.27 |
| 29 | 81 | 48 | 60 | 80 | 15 | .53 | .15 |
| 30 | 83 | 49 | 66 | 83 | 18 | .08 | .56 |
| 31 | 84 | 54 | 63 | 76 | 17 | | .43 |
| 9/1 | 80 | 48 | 63 | 58 | 19 | | .43 |
| 2 | 80 | 47 | 60 | 70 | 25 | | .41 |
| 3 | 84 | 50 | 62 | 82 | 25 | | .46 |
| 4 | 85 | 50 | 60 | 80 | 38 | | .66 |
| 5 | 81 | 56 | 58 | 58 | 23 | 1.83 | .38 |
| 6 | 69 | 50 | 55 | 57 | 44 | .64 | .23 |
| 7 | 75 | 47 | 62 | 73 | 12 | | .25 |
| 8 | 81 | 47 | 60 | 76 | 13 | | .56 |
| 9 | 80 | 63 | 61 | 78 | 83 | | .74 |
| 10 | 80 | 50 | 59 | 79 | 47 | | .53 |

Table 29. Weather data for Farmington, Utah, at the Farmington Experiment Station, 1973.

| | Air temperature | | | | Air temperature | | |
|---|---|---|---|---|---|---|---|
| Date | Max F | Min F | Prec. cm | Date | Max F | Min F | Prec. cm |
| 5/11 | 73 | 37 | | 6/22 | 92 | 52 | |
| 12 | 80 | 44 | | 23 | 92 | 67 | |
| 13 | 81 | 58 | | 24 | 86 | 56 | |
| 14 | 81 | 57 | | 25 | 88 | 53 | |
| 15 | 79 | 44 | | 26 | 90 | 57 | |
| 16 | 82 | 44 | | 27 | 95 | 58 | |
| 17 | 83 | 49 | | 28 | 92 | 68 | |
| 18 | 86 | 51 | .20 | 29 | 92 | 63 | |
| 19 | 86 | 51 | | 30 | 94 | 61 | |
| 20 | 72 | 51 | | | | | |
| 21 | 70 | 50 | | 7/1 | 93 | 58 | |
| 22 | 75 | 41 | | 2 | 91 | 51 | |
| 23 | 80 | 44 | | 3 | 94 | 56 | |
| 24 | 80 | 57 | | 4 | 96 | 57 | |
| 25 | 77 | 48 | 1.27 | 5 | 99 | 56 | |
| 26 | 59 | 35 | .15 | 6 | 98 | 70 | |
| 27 | 64 | 36 | | 7 | 94 | 59 | |
| 28 | 71 | 40 | | 8 | 95 | 71 | |
| 29 | 74 | 42 | | 9 | 97 | 59 | |
| 30 | 76 | 51 | | 10 | 99 | 70 | |
| 31 | 82 | 46 | | 11 | 99 | 63 | |
| | | | | 12 | 90 | 68 | |
| 6/1 | 82 | 50 | .79 | 13 | 84 | 61 | 3.07 |
| 2 | 67 | 46 | .08 | 14 | 84 | 64 | .03 |
| 3 | 67 | 39 | | 15 | 82 | 55 | .58 |
| 4 | 66 | 45 | | 16 | 86 | 59 | |
| 5 | 76 | 41 | | 17 | 92 | 56 | |
| 6 | 85 | 45 | | 18 | 92 | 62 | |
| 7 | 87 | 53 | | 19 | 83 | 61 | 1.91 |
| 8 | 87 | 50 | | 20 | 84 | 55 | .10 |
| 9 | 96 | 56 | | 21 | 85 | 44 | 1.32 |
| 10 | 95 | 61 | | 22 | 77 | 55 | .46 |
| 11 | 94 | 55 | | 23 | 81 | 47 | .53 |
| 12 | 87 | 50 | | 24 | 82 | 53 | .28 |
| 13 | 89 | 56 | | 25 | 85 | 61 | |
| 14 | 86 | 59 | .41 | 26 | 87 | 56 | |
| 15 | 64 | 48 | .46 | 27 | 89 | 57 | |
| 16 | 75 | 40 | | 28 | 91 | 57 | |
| 17 | 75 | 48 | | 29 | 91 | 59 | |
| 18 | 60 | 38 | | 30 | 89 | 56 | |
| 19 | 69 | 35 | | 31 | 90 | 57 | |
| 20 | 79 | 40 | | | | | |
| 21 | 86 | 48 | | 8/1 | 92 | 55 | |

Table 29. Continued.

| Date | Air temperature Max F | Min F | Prec. cm | Date | Air temperature Max F | Min F | Prec. cm |
|---|---|---|---|---|---|---|---|
| 8/2 | 93 | 56 | | 9/1 | 70 | 42 | 1.63 |
| 3 | 93 | 61 | | 2 | 61 | 41 | 2.06 |
| 4 | 93 | 64 | .13 | 3 | 74 | 40 | |
| 5 | 84 | 56 | | 4 | 80 | 42 | |
| 6 | 88 | 58 | | 5 | 88 | 52 | |
| 7 | 87 | 58 | | 6 | 88 | 59 | |
| 8 | 91 | 54 | | 7 | 87 | 53 | |
| 9 | 96 | 55 | | 8 | 80 | 46 | 1.04 |
| 10 | 93 | 55 | | 9 | 70 | 47 | .08 |
| 11 | 91 | 56 | | 10 | 78 | 51 | .06 |
| 12 | 95 | 55 | | | | | |
| 13 | 89 | 58 | | | | | |
| 14 | 90 | 60 | | | | | |
| 15 | 94 | 56 | | | | | |
| 16 | 95 | 65 | | | | | |
| 17 | 90 | 57 | | | | | |
| 18 | 90 | 57 | .46 | | | | |
| 19 | 92 | 63 | | | | | |
| 20 | 96 | 66 | | | | | |
| 21 | 94 | 66 | .03 | | | | |
| 22 | 86 | 57 | .18 | | | | |
| 23 | 90 | 57 | | | | | |
| 24 | 88 | 50 | | | | | |
| 25 | 87 | 49 | | | | | |
| 26 | 89 | 50 | | | | | |
| 27 | 89 | 57 | | | | | |
| 28 | 80 | 47 | | | | | |
| 29 | 82 | 47 | | | | | |
| 30 | 89 | 48 | | | | | |
| 31 | 88 | 54 | | | | | |

Table 30. 1972 conventional split plot design oven dry matter yield, metric tons dry matter/ha.

| Soil moisture level | Block | N-fertilizer level kg/ha[1] 0 | 56 | 112 | 225 | 449 |
|---|---|---|---|---|---|---|
| 1 | 1 | 9.9 | 12.6 | 8.6 | 8.8 | 13.0 |
| | 2 | 8.1 | 10.0 | 11.0 | 8.2 | 8.1 |
| | 3 | 11.6 | 9.0 | 11.2 | 11.8 | 9.7 |
| | 4 | 7.8 | 10.4 | 9.6 | 11.0 | 9.7 |
| 2 | 1 | 17.6 | 13.6 | 15.4 | 12.0 | 18.0 |
| | 2 | 13.7 | 15.4 | 13.5 | 12.7 | 15.3 |
| | 3 | 16.8 | 17.3 | 15.9 | 17.1 | 18.9 |
| | 4 | 12.3 | 14.3 | 15.0 | 17.2 | 16.6 |
| 3 | 1 | 11.3 | 15.9 | 17.3 | 17.6 | 17.7 |
| | 2 | 11.9 | 15.9 | 17.9 | 18.3 | 11.0 |
| | 3 | 16.2 | 15.1 | 16.9 | 18.2 | 18.6 |
| | 4 | 16.8 | 19.2 | 18.3 | 19.7 | 16.0 |
| 4 | 1 | 16.8 | 14.7 | 22.2 | 26.9 | 21.1 |
| | 2 | 14.5 | 20.0 | 18.5 | 20.5 | 17.2 |
| | 3 | 16.8 | 16.8 | 21.5 | 21.3 | 22.3 |
| | 4 | 15.3 | 17.3 | 18.5 | 12.9 | 16.8 |

[1]N applied as $NH_4NO_3$, 34%N.

Table 31. 1972 conventional plot design, shelled corn yield, metric tons grain[1]/ha.

| Soil moisture level | Block | N-fertilizer level kg/ha[2] 0 | 56 | 112 | 225 | 449 |
|---|---|---|---|---|---|---|
| 1 | 1 | 2.7 | 4.2 | 3.1 | 2.7 | 3.0 |
| | 2 | 3.9 | 2.8 | 4.5 | 3.6 | 4.0 |
| | 3 | 3.8 | 2.1 | 5.4 | 4.9 | 3.5 |
| | 4 | 4.3 | 3.4 | 3.9 | 4.5 | 4.3 |
| 2 | 1 | 9.9 | 6.4 | 6.7 | 7.0 | 6.8 |
| | 2 | 7.1 | 7.8 | 7.2 | 7.6 | 8.5 |
| | 3 | 7.0 | 8.1 | 7.8 | 7.3 | 8.2 |
| | 4 | 7.6 | 7.0 | 8.5 | 7.8 | 7.3 |
| 3 | 1 | 5.8 | 6.8 | 7.5 | 8.0 | 7.8 |
| | 2 | 5.2 | 7.2 | 7.7 | 7.5 | 6.6 |
| | 3 | 7.9 | 8.8 | 7.5 | 8.3 | 7.4 |
| | 4 | 6.2 | 7.5 | 9.1 | 7.5 | 7.7 |
| 4 | 1 | 7.3 | 5.4 | 8.2 | 9.3 | 7.0 |
| | 2 | 5.7 | 6.6 | 5.7 | 9.4 | 9.2 |
| | 3 | 8.1 | 9.5 | 8.7 | 9.8 | 8.9 |
| | 4 | 7.0 | 7.6 | 7.1 | 6.4 | 7.3 |

[1]grain yield is reported at 15.5% moisture content.
[2]N applied as $NH_4NO_3$, 34% N.

Table 32. 1973 conventional split plot design oven dry matter yield, metric ton dry matter/ha.

| Soil moisture level | Block | N-fertilizer level kg/ha[1] 0 | 56 | 112 | 225 | 449 |
|---|---|---|---|---|---|---|
| 1 | 1 | 6.9 | 11.8 | 8.3 | 7.3 | 10.1 |
| | 2 | 8.4 | 5.8 | 11.4 | 8.4 | 10.5 |
| | 3 | 5.1 | 10.0 | 10.9 | 10.3 | 12.4 |
| | 4 | 8.4 | 8.6 | 7.6 | 10.6 | 9.2 |
| 2 | 1 | 7.8 | 8.4 | 12.9 | 12.1 | 12.7 |
| | 2 | 6.4 | 14.9 | 12.5 | 14.2 | 14.3 |
| | 3 | 8.7 | 9.7 | 16.4 | 15.2 | 8.7 |
| | 4 | 9.5 | 9.9 | 10.5 | 13.7 | 12.4 |
| 3 | 1 | 7.6 | 13.5 | 19.5 | 21.0 | 17.7 |
| | 2 | 10.2 | 11.0 | 14.9 | 17.1 | 16.9 |
| | 3 | 9.1 | 16.3 | 11.2 | 15.9 | 17.1 |
| | 4 | 9.0 | 13.7 | 11.9 | 17.6 | 21.1 |
| 4 | 1 | 7.5 | 16.5 | 20.2 | 18.9 | 21.6 |
| | 2 | 8.1 | 16.2 | 18.02 | 18.2 | 21.7 |
| | 3 | 6.6 | 20.3 | 19.6 | 21.3 | 20.4 |
| | 4 | 11.4 | 16.4 | 17.2 | 20.0 | 15.8 |

[1]N applied as $NH_4NO_3$, 34% N.

Table 33. 1973 conventional split plot design shelled corn yield, metric tons grain[1] /ha.

| Soil moisture level | Block | N-fertilizer level, kg/ha[2] 0 | 56 | 112 | 225 | 449 |
|---|---|---|---|---|---|---|
| 1 | 1 | 2.0 | 3.4 | 3.1 | 4.7 | 4.5 |
| | 2 | 2.3 | 3.6 | 2.3 | 4.3 | 2.2 |
| | 3 | 1.8 | 3.3 | 4.6 | 3.8 | 4.3 |
| | 4 | 2.3 | 6.8 | 3.6 | 3.9 | 4.1 |
| 2 | 1 | 2.8 | 4.1 | 6.9 | 5.9 | 7.0 |
| | 2 | 1.9 | 4.7 | 5.2 | 5.7 | 3.8 |
| | 3 | 2.9 | 4.6 | 3.4 | 3.0 | 5.7 |
| | 4 | 2.2 | 4.6 | 5.0 | 6.4 | 5.2 |
| 3 | 1 | 3.6 | 5.8 | 5.8 | 9.3 | 9.0 |
| | 2 | 2.6 | 7.2 | 5.6 | 8.6 | 8.4 |
| | 3 | 3.1 | 6.3 | 8.8 | 9.1 | 8.3 |
| | 4 | 2.1 | 5.3 | 9.3 | 9.3 | 8.1 |
| 4 | 1 | 3.1 | 6.1 | 7.7 | 11.2 | 10.1 |
| | 2 | 2.7 | 5.3 | 8.2 | 10.6 | 10.9 |
| | 3 | 3.6 | 4.2 | 9.0 | 8.1 | 11.4 |
| | 4 | 2.2 | 5.1 | 8.3 | 8.8 | 9.9 |

[1] grain yield is reported at 15.5% moisture content.
[2] N applied as $NH_4NO_3$, 34% N.

Table 34. 1973 conventional split plot design per cent nitrogen in dry matter.

| Soil moisture level | Block | N-fertilizer level kg/ha[1] 0 | 56 | 112 | 225 | 449 |
|---|---|---|---|---|---|---|
| 1 | 1 | 0.16 | 0.87 | 1.07 | 1.03 | 1.22 |
| | 2 | 0.83 | 1.03 | 1.04 | 1.00 | 1.18 |
| | 3 | 0.65 | 1.02 | 0.99 | 1.31 | 1.26 |
| | 4 | 0.74 | 1.09 | 1.06 | 1.25 | 1.17 |
| 2 | 1 | 0.63 | 0.84 | 0.73 | 1.20 | 1.30 |
| | 2 | 0.69 | 0.79 | 1.15 | 1.11 | 1.10 |
| | 3 | 0.62 | 0.84 | 1.01 | 1.05 | 1.36 |
| | 4 | 0.57 | 0.75 | 1.02 | 1.19 | 1.26 |
| 3 | 1 | 0.57 | 0.77 | 0.78 | 0.98 | 1.32 |
| | 2 | 0.77 | 0.63 | 0.77 | 1.07 | 1.13 |
| | 3 | 0.68 | 0.79 | 0.83 | 1.14 | 1.08 |
| | 4 | 0.60 | 0.82 | 0.76 | 1.05 | 1.23 |
| 4 | 1 | 0.54 | 0.70 | 0.67 | 1.10 | 1.08 |
| | 2 | 0.76 | 0.68 | 0.66 | 0.72 | 1.12 |
| | 3 | 0.55 | 0.66 | 0.94 | 1.07 | 1.12 |
| | 4 | 0.58 | 0.61 | 0.72 | 0.87 | 1.01 |

[1] N applied as $NH_4NO_3$, 34% N.

Table 35. Analysis of variance for shelled corn yields from the 1972 conventional split plots.

| Source of variation | Degrees of freedom | Sum of squares | Mean sum of squares | F-ratio |
|---|---|---|---|---|
| Replicates | 3 | 34.03 | 11.34 | |
| Soil moisture | 3 | 686.11 | 228.70 | 57.15* |
| Error (A) | 9 | 36.01 | 4.00 | |
| Fertilizer | 4 | 18.72 | 4.60 | 1.27 |
| Interaction | 12 | 50.61 | 4.22 | 1.14 |
| Error (B) | 48 | 177.47 | 3.70 | |

*Significant at the 95 percent level.

Table 36. Analysis of variance for shelled corn yields from the 1973 conventional split plots.

| Source of variation | Degrees of freedom | Sum of squares | Mean sum of squares | F-ratio |
|---|---|---|---|---|
| Replicates | 3 | 0.59 | 0.20 | |
| Soil moisture | 3 | 41.79 | 13.93 | 61.92* |
| Error (A) | 9 | 2.03 | 0.23 | |
| Fertilizer | 4 | 48.09 | 12.02 | 54.15* |
| Interaction | 12 | 16.40 | 1.37 | 6.15* |
| Error (B) | 48 | 10.66 | 0.22 | |

*Significant at the 95 percent level.

Table 37. Analysis of variance for percent nitrogen in dry matter yields from the 1973 conventional split plots.

| Source of variation | Degrees of freedom | Sum of squares | Mean sum of squares | F-ratio |
|---|---|---|---|---|
| Replicates | 3 | 0.025 | 0.0083 | |
| Soil moisture | 3 | 0.505 | 0.1683 | 33.66* |
| Error (A) | 9 | 0.045 | 0.005 | |
| Fertilizer | 4 | 2.880 | 0.720 | 67.29* |
| Interaction | 12 | 0.183 | 0.015 | 1.42 |
| Error (B) | 48 | 0.516 | 0.011 | |

*Significant at the 95 percent level.

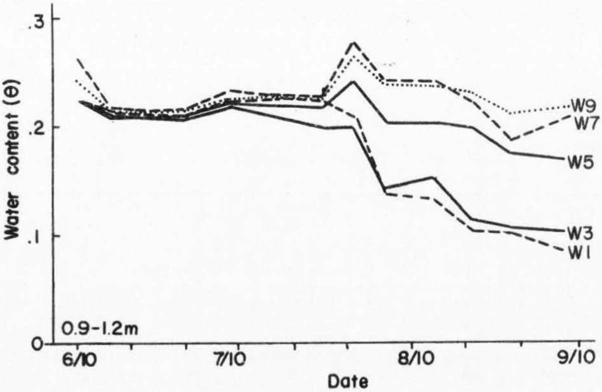


Figure 21. 1972 continuous variable plot design, volumetric water content in the root zone during the growing season, 0.9 - 1.2m depth.

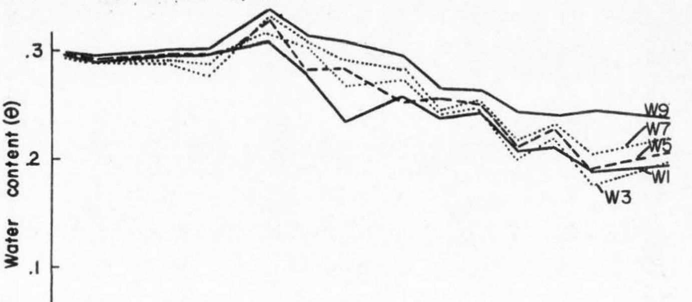


Figure 22. 1973 continuous variable plot design, volumetric water content in the root zone during the growing season, 0.9 - 1.2 m depth.

Table 38. 1972 continuous variable plot design, oven dry matter yield, metric tons dry matter/ha.

| N-fertilizer level kg/ha | Soil moisture level 1,2,3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| | | | Block 1 | | | | |
| 0 | 5.4 | 7.4 | 10.5 | 11.6 | 13.5 | 17.2 | 12.9 |
| 26 | 9.0 | 10.0 | 12.6 | 17.7 | 11.8 | 14.7 | 17.9 |
| 39 | 9.0 | 10.3 | 8.0 | 15.4 | 13.8 | 17.9 | 21.3 |
| 65 | 9.4 | 5.2 | 16.3 | 16.6 | 16.1 | 19.8 | 12.2 |
| 79 | 6.4 | 10.3 | 8.6 | 17.2 | 17.2 | 19.0 | 18.2 |
| 105 | 9.0 | 14.2 | 15.0 | 15.2 | 17.2 | 19.3 | 17.9 |
| 118 | 12.0 | 11.6 | 22.8 | 21.3 | 14.1 | 17.3 | 18.4 |
| 144 | 5.4 | 14.8 | 15.4 | 21.0 | 17.2 | 21.9 | 21.8 |
| 157 | 9.4 | 7.1 | 13.3 | 9.5 | 16.7 | 17.6 | 12.0 |
| 183 | 8.1 | 8.4 | 10.8 | 20.7 | 8.6 | 19.9 | 26.0 |
| 196 | 15.5 | 17.4 | 15.7 | 11.3 | 30.4 | 21.6 | 18.4 |
| 222 | 9.1 | 14.2 | 20.3 | 16.6 | 14.1 | 45.8 | 24.0 |
| 235 | 15.5 | 11.0 | 11.0 | 28.4 | 11.5 | 10.2 | 19.0 |
| 262 | 18.2 | 19.3 | 17.2 | 24.0 | 33.8 | 22.4 | 21.0 |
| 274 | 11.8 | 16.8 | 14.5 | 19.0 | 17.2 | 19.6 | 25.4 |
| 301 | 15.2 | 18.7 | 17.2 | 15.2 | 23.8 | 21.6 | 23.1 |
| 313 | 15.5 | 11.6 | 14.8 | 16.6 | 14.1 | 19.3 | 17.6 |
| 339 | 7.8 | 18.0 | 14.2 | 24.6 | 16.7 | 18.2 | 19.2 |
| 353 | 13.5 | 16.1 | 17.8 | 17.5 | 14.9 | 19.0 | 26.2 |
| 379 | 3.7 | 9.3 | 12.3 | 14.5 | 20.1 | 18.7 | 15.6 |
| 392 | 12.1 | 15.1 | 15.0 | 26.7 | 29.5 | 13.3 | 23.8 |
| 421 | 5.4 | 11.6 | 15.0 | 12.7 | 14.1 | 21.6 | 12.0 |
| | | | Block 2 | | | | |
| 0 | 6.2 | 5.2 | 8.2 | 11.9 | 10.3 | 11.0 | 14.5 |
| 26 | 15.9 | 2.6 | 17.2 | 10.6 | 21.3 | 11.3 | 15.9 |
| 39 | 4.7 | 8.0 | 8.7 | 15.4 | 14.9 | 14.4 | 18.1 |
| 65 | 9.0 | 7.8 | 16.0 | 23.4 | 13.7 | 23.5 | 17.9 |
| 79 | 8.1 | 7.1 | 11.7 | 20.4 | 22.4 | 19.8 | 12.3 |
| 105 | 8.4 | 10.3 | 7.3 | 13.6 | 13.2 | 18.1 | 15.6 |
| 118 | 13.8 | 11.0 | 13.5 | 17.6 | 14.9 | 22.1 | 27.9 |
| 144 | 6.0 | 4.5 | 10.1 | 21.6 | 18.1 | 25.0 | 20.7 |
| 157 | 12.5 | 11.3 | 11.4 | 13.0 | 16.9 | 15.9 | 20.4 |
| 183 | 6.8 | 7.4 | 7.0 | 20.1 | 18.4 | 17.6 | 17.3 |
| 196 | 9.4 | 11.6 | 14.4 | 18.1 | 12.3 | 22.7 | 18.4 |
| 222 | 11.5 | 9.0 | 10.7 | 16.0 | 20.9 | 19.0 | 21.0 |
| 235 | 3.1 | 5.8 | 17.2 | 23.7 | 16.9 | 34.1 | 20.4 |
| 262 | 12.5 | 15.2 | 8.6 | 22.2 | 25.8 | 49.3 | 18.4 |
| 274 | 11.1 | 11.6 | 12.3 | 21.3 | 19.6 | 45.3 | 21.3 |
| 301 | 1.7 | 9.7 | 11.0 | 17.1 | 26.4 | 17.0 | 17.0 |
| 313 | 7.0 | 18.4 | 17.9 | 19.3 | 20.1 | 26.1 | 11.7 |

Table 38. Continued.

| N-fertilizer level kg/ha | Soil moisture level 1,2,3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| | | | Block 2 | | | | |
| 339 | 7.0 | 9.0 | 9.5 | 16.6 | 21.3 | 28.1 | 19.6 |
| 353 | 11.5 | 10.3 | 15.0 | 24.5 | 25.3 | 12.2 | 16.8 |
| 379 | 14.8 | 9.7 | 12.0 | 15.1 | 14.1 | 19.6 | 16.2 |
| 392 | 8.1 | 9.7 | 7.3 | 18.4 | 22.4 | 15.9 | 23.4 |
| 421 | 5.4 | 17.9 | 11.0 | 28.1 | 15.5 | 16.2 | 22.6 |
| | | | Block 3 | | | | |
| 0 | 10.0 | 10.6 | 12.2 | 10.5 | 12.0 | 12.0 | 13.0 |
| 26 | 17.5 | 8.4 | 9.8 | 13.3 | 27.5 | 18.1 | 15.9 |
| 39 | 6.0 | 12.6 | 17.8 | 12.5 | 11.5 | 24.4 | 12.6 |
| 65 | 9.5 | 10.6 | 12.6 | 10.0 | 14.9 | 11.3 | 12.3 |
| 79 | 7.8 | 10.9 | 13.5 | 22.5 | 27.0 | 27.5 | 12.0 |
| 105 | 10.5 | 11.3 | 12.9 | 9.7 | 8.3 | 23.6 | 14.5 |
| 118 | 9.7 | 12.9 | 17.8 | 10.7 | 23.5 | 11.6 | 19.0 |
| 144 | 6.4 | 8.0 | 16.3 | 21.0 | 17.2 | 18.4 | 23.4 |
| 157 | 8.7 | 14.2 | 17.2 | 16.6 | 10.9 | 22.7 | 17.3 |
| 183 | 12.5 | 6.8 | 11.0 | 24.5 | 10.9 | 22.1 | 18.1 |
| 196 | 9.5 | 12.6 | 20.0 | 13.0 | 26.1 | 21.6 | 18.7 |
| 222 | 13.4 | 13.2 | 17.8 | 34.2 | 8.6 | 20.1 | 13.7 |
| 235 | 8.4 | 16.4 | 18.1 | 10.0 | 11.7 | 12.5 | 16.7 |
| 262 | 8.7 | 4.5 | 12.0 | 10.7 | 29.8 | 24.1 | 23.2 |
| 274 | 12.1 | 19.6 | 16.6 | 27.2 | 18.9 | 11.0 | 21.0 |
| 301 | 8.7 | 12.9 | 11.0 | 18.7 | 11.5 | 15.3 | 29.3 |
| 313 | 12.8 | 10.6 | 16.9 | 23.1 | 16.0 | 19.3 | 12.3 |
| 339 | 9.5 | 14.5 | 16.6 | 13.0 | 12.5 | 2.3 | 13.4 |
| 353 | 16.2 | 13.2 | 12.3 | 32.5 | 9.2 | 17.0 | 17.0 |
| 379 | 9.6 | 17.7 | 17.5 | 25.5 | 23.0 | 17.0 | 25.4 |
| 392 | 10.5 | 8.0 | 7.4 | 20.1 | 12.3 | 18.1 | 22.3 |
| 421 | 12.1 | 20.6 | 12.9 | 25.1 | 17.5 | 22.7 | 26.8 |
| | | | Block 4 | | | | |
| 0 | 15.0 | 18.4 | 15.7 | 15.6 | 17.1 | 17.0 | 20.1 |
| 26 | 6.8 | 7.4 | 15.4 | 16.0 | 27.5 | 11.3 | 3.7 |
| 39 | 7.8 | 11.5 | 8.0 | 7.4 | 4.6 | 20.4 | 17.9 |
| 65 | 15.0 | 14.2 | 8.9 | 21.3 | 10.0 | 13.6 | 17.9 |
| 79 | 7.4 | 10.9 | 17.2 | 18.7 | 13.7 | 15.9 | 17.9 |
| 105 | 15.9 | 8.2 | 11.7 | 9.2 | 27.5 | 6.8 | 7.8 |
| 118 | 12.1 | 14.2 | 19.4 | 14.5 | 16.0 | 6.8 | 29.0 |
| 144 | 10.8 | 8.0 | 11.0 | 16.9 | 23.0 | 29.5 | 20.1 |
| 157 | 7.8 | 16.9 | 13.5 | 15.4 | 11.5 | 20.4 | 26.8 |
| 183 | 14.5 | 16.1 | 11.7 | 12.7 | 19.5 | 15.9 | 24.5 |

Table 38. Continued.

| N-fertilizer level kg/ha | 1.2.3 | 4 | Soil moisture level 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|
| | | | Block 4 | | | | |
| 196 | 12.1 | 15.4 | 9.5 | 19.8 | 19.5 | 20.4 | 19.3 |
| 222 | 16.2 | 5.8 | 14.2 | 9.5 | 23.3 | 6.8 | 20.1 |
| 235 | 7.8 | 15.2 | 9.8 | 22.2 | 23.0 | 22.7 | 29.0 |
| 262 | 14.2 | 11.6 | 18.1 | 10.7 | 11.5 | 15.9 | 26.8 |
| 274 | 11.5 | 7.8 | 4.9 | 17.7 | 29.8 | 25.0 | 17.9 |
| 301 | 11.8 | 14.2 | 12.9 | 20.4 | 23.0 | 20.4 | 20.1 |
| 313 | 5.8 | 20.0 | 18.1 | 19.0 | 20.1 | 29.5 | 18.1 |
| 339 | 7.8 | 5.2 | 10.2 | 9.2 | 23.0 | 18.1 | 31.2 |
| 353 | 12.5 | 20.6 | 8.6 | 21.9 | 23.0 | 29.5 | 31.2 |
| 379 | 13.2 | 13.9 | 17.5 | 25.8 | 13.7 | 11.3 | 8.9 |
| 392 | 9.1 | 11.6 | 13.8 | 18.1 | 25.3 | 15.9 | 8.9 |
| 421 | 22.6 | 10.6 | 11.0 | 12.5 | 9.2 | 15.9 | |

Table 39. 1973 continuous variable plot design, oven dry matter yield, metric tons dry matter/ha.

| N-fertilizer level kg/ha | 1,2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| | | | | Soil moisture level | | | | |
| | | | | **Block 1** | | | | |
| 0 | 6.4 | 10.0 | 14.0 | 10.2 | 13.6 | 17.0 | 12.9 | 10.6 |
| 24 | 6.6 | 4.3 | 8.7 | 4.1 | 9.3 | 12.8 | 7.5 | 11.2 |
| 48 | 8.7 | 6.8 | 10.8 | 9.0 | 11.4 | 11.9 | 10.8 | 15.1 |
| 72 | 7.6 | 8.3 | 11.4 | 9.4 | 8.9 | 14.8 | 10.4 | 11.9 |
| 96 | 6.2 | 7.3 | 10.6 | 10.2 | 14.7 | 11.7 | 8.5 | 14.7 |
| 120 | 7.4 | 10.9 | 8.7 | 7.8 | 14.9 | 12.8 | 11.4 | 14.3 |
| 144 | 6.2 | 4.3 | 10.6 | 9.0 | 11.4 | 16.6 | 10.2 | 14.9 |
| 168 | 6.4 | 10.1 | 10.6 | 10.9 | 15.4 | 10.6 | 12.9 | 17.9 |
| 192 | 7.4 | 8.8 | 8.3 | 7.8 | 12.0 | 15.5 | -1.0 | 17.9 |
| 216 | 7.0 | 7.9 | 12.6 | 6.6 | 11.8 | 18.8 | 12.0 | 18.8 |
| 240 | 6.7 | 8.2 | 10.6 | 9.8 | 13.1 | 15.7 | 16.6 | 15.3 |
| 264 | 6.4 | 9.4 | 8.3 | 11.5 | 16.2 | 16.8 | 12.9 | 14.7 |
| 288 | 9.3 | 7.5 | 9.9 | 13.3 | 14.7 | 14.8 | 19.3 | 16.6 |
| 312 | 9.5 | 6.4 | 12.8 | 10.9 | 14.2 | 12.8 | 17.8 | 16.2 |
| 336 | 6.8 | 8.5 | 12.6 | 11.7 | 17.4 | 11.9 | 13.7 | 12.7 |
| 360 | 6.8 | 9.2 | 10.6 | 12.3 | 12.2 | 13.7 | 17.0 | 19.2 |
| 384 | 8.9 | 9.0 | 10.8 | 10.2 | 15.8 | 17.2 | 11.0 | 17.5 |
| 408 | 8.3 | 6.8 | 11.6 | 11.9 | 12.2 | 10.8 | 15.5 | 17.3 |
| 432 | 10.0 | 7.9 | 9.3 | 8.4 | 12.5 | 14.8 | 13.1 | 17.5 |
| 456 | 4.5 | 10.7 | 11.6 | 13.1 | 12.5 | 12.4 | 10.2 | 15.5 |
| 480 | 7.2 | 7.1 | 7.5 | 9.4 | 13.8 | 14.4 | 17.8 | 10.8 |
| 504 | 4.9 | 8.6 | 9.5 | 11.7 | 11.4 | 10.8 | 13.3 | 13.2 |
| 528 | 5.7 | 9.4 | 9.5 | 9.2 | 11.6 | 14.6 | 13.3 | 13.6 |
| 552 | 5.7 | 8.8 | 8.9 | 6.1 | 9.6 | 14.6 | 11.0 | 13.2 |
| | | | | **Block 2** | | | | |
| 0 | 6.8 | 3.4 | 5.7 | 7.4 | 7.6 | 6.4 | 9.5 | 10.8 |
| 24 | 5.9 | 4.7 | 7.7 | 8.0 | 2.7 | 9.3 | 11.0 | 12.1 |
| 48 | 5.7 | 6.0 | 10.2 | 7.6 | 11.4 | 11.0 | 12.2 | 11.7 |
| 72 | 5.3 | 4.7 | 4.9 | 5.7 | 12.0 | 9.7 | 12.6 | 13.2 |
| 96 | 4.7 | 5.3 | 5.7 | 8.2 | 10.7 | 8.8 | 20.5 | 11.2 |
| 120 | 8.3 | 3.6 | 9.5 | 7.2 | 10.5 | 10.8 | 14.7 | 10.6 |
| 144 | 7.2 | 7.3 | 9.5 | 8.0 | 8.0 | 14.1 | 16.0 | 12.5 |
| 168 | 8.1 | 9.4 | 9.5 | 8.6 | 18.2 | 13.5 | 16.0 | 16.8 |
| 192 | 10.6 | 8.1 | 7.3 | 8.4 | 11.6 | 10.4 | 17.2 | 15.8 |
| 216 | 8.3 | 8.6 | 11.0 | 9.2 | 12.9 | 13.5 | 13.7 | 19.0 |
| 240 | 6.4 | 9.0 | 6.5 | 9.4 | 19.1 | 12.4 | 17.4 | 16.2 |
| 264 | 4.0 | 7.1 | 11.8 | 7.8 | 13.1 | 16.1 | 15.8 | 15.8 |
| 288 | 7.6 | 8.3 | 11.8 | 9.0 | 11.1 | 12.6 | 18.0 | 14.9 |
| 312 | 6.6 | 7.7 | 10.2 | 11.3 | 11.4 | 9.7 | 17.6 | 12.1 |
| 336 | 5.1 | 9.2 | 8.9 | 8.6 | 7.6 | 13.0 | 15.1 | 16.8 |

Table 39. Continued.

| N-fertilizer level kg/ha | Soil moisture level 1,2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| | | | | Block 2 | | | | |
| 360 | 5.9 | 5.8 | 7.7 | 6.6 | 14.2 | 8.2 | 10.2 | 15.3 |
| 384 | 8.3 | 8.6 | 9.8 | 7.8 | 14.0 | 11.3 | 16.0 | 9.1 |
| 408 | 4.9 | 12.6 | 9.9 | 8.8 | 8.9 | 8.2 | 12.6 | 10.8 |
| 432 | 8.7 | 6.6 | 12.0 | 7.4 | 14.0 | 13.0 | 13.7 | 14.7 |
| 456 | 6.8 | 7.1 | 7.7 | 4.9 | 12.7 | 12.6 | 11.6 | 13.8 |
| 480 | 6.2 | 6.6 | 8.3 | 10.2 | 11.4 | 11.9 | 16.8 | 10.4 |
| 504 | 9.1 | 9.0 | 11.6 | 8.4 | 15.8 | 9.5 | 12.4 | 11.7 |
| 528 | 11.0 | 8.5 | 10.4 | 6.4 | 10.7 | 12.8 | 16.4 | 12.1 |
| 552 | 5.7 | 7.1 | 10.4 | 8.2 | 9.1 | 17.2 | 10.8 | 18.4 |
| | | | | Block 3 | | | | |
| 0 | 6.8 | 3.4 | 7.7 | 9.2 | 9.3 | 2.6 | 10.2 | 11.0 |
| 24 | 6.8 | 3.4 | 9.5 | 4.5 | 10.9 | 10.2 | 14.1 | 12.3 |
| 48 | 5.9 | 8.3 | 10.2 | 7.0 | 13.1 | 9.9 | 12.9 | 14.5 |
| 72 | 5.7 | 6.6 | 10.4 | 10.7 | 8.2 | 16.1 | 13.1 | 15.5 |
| 96 | 10.2 | 5.6 | 9.5 | 11.1 | 15.1 | 16.3 | 15.5 | 17.1 |
| 120 | 8.5 | 9.8 | 9.5 | 14.3 | 14.2 | 17.0 | 15.8 | 19.0 |
| 144 | 7.9 | 9.8 | 13.2 | 14.7 | 15.6 | 16.8 | 15.1 | 19.0 |
| 168 | 9.3 | 7.9 | 8.5 | 8.2 | 16.7 | 14.8 | 13.7 | 15.8 |
| 192 | 7.4 | 7.7 | 11.2 | 12.9 | 16.5 | 19.0 | 17.8 | 15.8 |
| 216 | 10.0 | 10.0 | 14.2 | 10.2 | 18.0 | 16.8 | 13.3 | 21.0 |
| 240 | 17.6 | 10.1 | 11.6 | 12.7 | 18.5 | 19.0 | 17.4 | 19.0 |
| 264 | 9.3 | 13.1 | 14.0 | 10.4 | 13.6 | 14.6 | 11.2 | 14.9 |
| 288 | 9.8 | 9.0 | 8.1 | 16.4 | 16.2 | 17.4 | 17.2 | 19.0 |
| 312 | 6.8 | 9.2 | 12.6 | 16.2 | 12.9 | 19.4 | 17.0 | 15.3 |
| 336 | 8.3 | 9.6 | 8.9 | 11.8 | 18.0 | 14.4 | 21.8 | 20.1 |
| 360 | 8.3 | 9.8 | 12.0 | 13.9 | 21.4 | 23.4 | 21.6 | 22.9 |
| 384 | 16.6 | 7.5 | 13.8 | 12.8 | 13.8 | 19.0 | 23.0 | 24.2 |
| 408 | 5.9 | 10.9 | 10.4 | 12.9 | 20.0 | 16.8 | 10.6 | 20.1 |
| 432 | 5.9 | 8.3 | 14.6 | 12.5 | 14.7 | 15.7 | 19.5 | 18.4 |
| 456 | 9.8 | 7.7 | 9.9 | 12.7 | 18.2 | 16.1 | 16.2 | 21.2 |
| 480 | 8.1 | 10.1 | 11.8 | 10.4 | 10.5 | 16.1 | 14.1 | 19.9 |
| 504 | 5.1 | 5.8 | 8.3 | 10.9 | 17.4 | 14.8 | 17.6 | 17.7 |
| 528 | 5.5 | 11.1 | 14.0 | 11.9 | 15.4 | 11.3 | 14.3 | 19.4 |
| 552 | 5.7 | 5.6 | 4.9 | 9.2 | 4.9 | 12.6 | 20.3 | 17.5 |
| | | | | Block 4 | | | | |
| 0 | 5.5 | 3.8 | 6.7 | 8.6 | 8.0 | 14.8 | 9.3 | 10.6 |
| 24 | 6.4 | 4.1 | 6.5 | 5.9 | 7.8 | 10.6 | 10.4 | 21.0 |
| 48 | 5.1 | 9.0 | 9.3 | 8.0 | 10.5 | 11.7 | 10.2 | 13.8 |

Table 39. Continued.

| N-fertilizer level kg/ha | 1,2 | 3 | 4 | Soil moisture level 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| | | | | Block 4 | | | | |
| 72 | 6.4 | 9.0 | 7.7 | 9.4 | 14.9 | 13.0 | 12.4 | 15.1 |
| 96 | 4.9 | 9.0 | 9.1 | 5.9 | 16.9 | 17.4 | 16.0 | 14.3 |
| 120 | 10.0 | 9.8 | 8.9 | 12.0 | 16.5 | 14.4 | 15.1 | 16.6 |
| 144 | 7.4 | 11.1 | 11.5 | 10.2 | 15.8 | 18.3 | 15.6 | 21.6 |
| 168 | 7.0 | 9.2 | 12.8 | 14.7 | 18.2 | 17.0 | 16.0 | 14.3 |
| 192 | 5.3 | 12.4 | 12.4 | 9.4 | 14.0 | 18.3 | 24.0 | 7.6 |
| 216 | 5.3 | 9.0 | 13.0 | 12.9 | 17.6 | 13.5 | 20.1 | 18.6 |
| 240 | 5.3 | 11.7 | 9,7 | 12.1 | 23.1 | 18.3 | 20.7 | 22.7 |
| 264 | 7.4 | 8.6 | 13.2 | 14.9 | 17.8 | 19.9 | 16.0 | 13.5 |
| 288 | 8.7 | 13.6 | 8.1 | 14.7 | 11.1 | 16.6 | 18.5 | 22.7 |
| 312 | 8.1 | 7.9 | 8.9 | 11.7 | 16.9 | 17.7 | 18.5 | 22.9 |
| 336 | 7.4 | 7.9 | 9.5 | 11.1 | 18.5 | 17.7 | 13.7 | 1916 |
| 360 | 5.3 | 9,6 | 14.4 | 11.5 | 20.7 | 16.6 | 22.0 | 25.5 |
| 384 | 7.6 | 11.1 | 8.1 | 11.9 | 14.7 | 19.6 | 22.6 | 16.0 |
| 408 | 8.7 | 9.6 | 15.0 | 12.1 | 18.0 | 13.7 | 11.2 | 22.7 |
| 432 | 10.4 | 12.0 | 8.7 | 16.6 | 17.8 | 19.2 | 19.9 | 26,1 |
| 456 | 7.0 | 9,0 | 10.4 | 9,6 | 14.2 | 16.3 | 16.6 | 24.2 |
| 480 | 7.9 | 13.7 | 9.9 | 17.4 | 18.5 | 17.4 | 23.8 | 17.9 |
| 504 | 14.4 | 9.4 | 11.0 | 10.0 | 14.9 | 13.7 | 10.6 | 25.9 |
| 528 | 8.5 | 8.1 | 10.4 | 9.2 | 18.2 | 15.2 | 10.6 | 17.9 |
| 552 | 5.5 | 7.0 | 9.2 | 10.7 | 14.5 | 8.8 | 9.6 | |

Table 40. Production functions determined with two plot grouping of continuous variable design plot yields.

1972 continuous variable design plots

$$Y = -3627 + 4107W + 29.2N - 227.3W^2 - 0.05N^2 + 0.76\ WN$$

$$R^2 = 0.47$$

1973 continuous variable design plots

$$Y = 1563 + 1387W + 26.9N - 20.6W^2 - 0.05N^2 + 0.55WN$$

$$R^2 = 0.56$$

Table 41. Production functions determined with treatment levels and yields transformed to a fraction of the optimum treatment and yield levels.

1972 conventional split plot design

$\hat{Y}$ max = 20400 kg/ha, Wopt = W4, Nopt = 224 kg/ha

$$\frac{\hat{Y}}{Ymax} = 0.18 + \frac{1.29W}{Wopt} + \frac{0.15N}{Nopt} - \frac{0.65W^2}{Wopt^2} - \frac{0.07N^2}{Nopt^2} + \frac{0.07WN}{Wopt\ Nopt}$$

$R^2 = 0.66$

1972 continuous variable plot design

$\hat{Y}$ max = 27900 kg/ha, Wopt = W8, Nopt = 261 kg/ha

$$\frac{\hat{Y}}{Ymax} = -.13 + \frac{1.16W}{Wopt} + \frac{0.28N}{Nopt} - \frac{0.50W^2}{Wopt^2} - \frac{0.15N^2}{Nopt^2} + \frac{0.06WN}{Wopt\ Nopt}$$

$R^2 = 0.33$

1973 conventional split plot design

$\hat{Y}$ max = 19890 kg/ha, Wopt = W4, Nopt = 448 kg/ha

$$\frac{\hat{Y}}{Ymax} = 0.21 + \frac{0.43W}{Wopt} + \frac{0.81N}{Nopt} - \frac{0.05W^2}{Wopt^2} - \frac{0.78N^2}{Nopt^2} + \frac{0.43WN}{Wopt\ Nopt}$$

$R^2 = 0.74$

1973 continuous variable plot design

$\hat{Y}$ max = 20730 kg/ha, Wopt = W9, Nopt = 360 kg/ha

$$\frac{\hat{Y}}{Ymax} = 0.08 + \frac{0.59W}{Wopt} + \frac{0.47N}{Nopt} - \frac{0.07W^2}{Wopt^2} - \frac{0.29N^2}{Nopt^2} + \frac{0.08WN}{Wopt\ Nopt}$$

$R^2 = 0.57$

## Procedure for using the apparatus for obtaining undisturbed soil cores

The following materials and procedure was used to obtain undisturbed soil cores within the barrel plots in the field:

Materials: two or more working bodies, two long-handle, 8" spades, 8 pound maul, access tube (6'), digger equipment, including frame, winch, cable and hook, triangular lifter, digger, bottom slats, center rod, and allen wrenches.
2" - 4" plank (6" wide x 3' long), two screwdrivers, 55 gallon barrel with top cut off, top of barrel, to the center of which a 1" nut has been welded, claw hammer, access tube triangle.

Procedure:

1. Place the digger, cutting edge down, in position. Dig around the outside of the digger to a depth of approximately 1 foot. Place the plank on top of the digger and, using human "lard", push the digger down. Continue this process in about 1 foot increments to a depth of approximately 30 inches.

2. Using the shovels as levers, wedge the bottom slats into the digger to hold the core in place. The maul or a hammer may be used to force the slats in.

3. Place the access tube triangle on top of the digger and make an access tube hole in the center of the core. This should be more than 30" deep, and directly in the center of the core.

4. Remove the access tube triangle and place the triangular lifter on the digger. Position the frame directly over the core, and using the winch, lift the core and digger apparatus out of the ground. It should be lifted about 3 feet.

5. Put a barrel upside down into the hole, below the core. Place the barrel top plate under the core and then put the threaded center rod down through the core. Thread the center rod to the nut on the barrel top and lower the core down on to the barrel.

6. Remove the triangular lifter and attach the cable to the center rod. Lift up the core and digger and remove the barrel from the hole. Eye-ball level the hole and put the barrel in the hole, right side up. The barrel should be directly under the core.

7. Lower the core down to the top of the barrel and remove the bottom slats. With the digger centered directly over the barrel, spring open the digger with the allen wrench and a screw driver.

8. *Slowly* lower the core down into the barrel, while resting the digger on the top of the barrel. Hold the digger directly over the barrel as the core is lowered down. Two people can center the digger well, using screw drivers. Once the core is completely down, remove the digger.

9. Position the barrel by lifting it with the center rod. If the core is completely down and the barrel is in place, unthread the center rod and fill in the hole.

10. If the core will not slide into the barrel, pull it up and lower it again. Also, the digger must be directly over the barrel and vertical. If it is tilted off line from the barrel, the core will bind. The person keeping the barrel and digger in line can also help by shaking the digger slightly as the core is lowered into the barrel.

11. If all goes well, the barrel lysimeters can be installed at a rate of approximately 1 per hour, with two or three graduate students earning their pay.

# VITA

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Doctor of Philosophy

Dissertation: Determination of Crop Production Functions as Related to Soil Moisture and Nitrogen

Major Field: Soils

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