ABSTRACT

CORRELATION STUDIES WITH CORN USING SEASONAL SOIL AND TISSUE TESTS

by Hari Mohan Singh

The objective of the study was to compare the usefulness of nutritional indices derived for corn from seasonal soil tests for nitrate, phosphate, and potassium, with those from seasonal tissue tests for the same nutrients, using recognized concepts for the interpretation of foliar analysis data. Samples of soil and corn midribs were collected periodically during the growing season from several field experiments. The time of appearance of visible nitrogen deficiency symptoms was noted, and final yields of corn were taken. Multiple regression analysis, employing two types of curvilinear equation, was used to correlate yields with soil tests or tissue tests for each sampling date.

Soil tests and tissue tests for all three nutrients were found, by analysis of variance, to be influenced by numerous management and soil factors, as well as by climatic conditions and time. Specific relationships, however, were frequently very different for soil tests than for tissue tests. Soil test variations during the growing season appeared to reflect changes in rates of release of nutrients from soil sources and removal by corn. Tissue test variations appeared to reflect variations in rate of uptake and rate of assimilation of nutrients by the corn.

Soil nitrate levels of 20 pounds per acre or less anticipated the development of visible nitrogen deficiency symptoms by one to three weeks. The corresponding "threshold" level for tissue nitrate was

200 ppm. N, on a green tissue basis.

Multiple regression analysis of unit observations (rather than treatment means) revealed distinct optimum levels of soil and tissue nitrate which were higher than the threshold levels (40 pounds per acre and 400 ppm., respectively for soil and tissue).

The "threshold" levels for development of visible nitrogen deficiency symptoms appear to correspond to "critical" levels in the zone of poverty adjustment, as defined in established schemes for interpretation of foliar analysis data. The "optimum" levels found appear to represent an upper limit of balanced nutrition, beyond which accumulations of soil or tissue nitrate reflect critical deficiencies of some other nutrient or of some other factor of growth.

The range between threshold and optimum levels may represent a zone where response is variable due to varying degrees of "nutrient substitution" -- in the sense used by production economists.

Similar relationships were observed for soil and tissue phosphate in one experiment.

Soil tests for nitrate were better correlated with yield, particularly during periods of rapid corn development, than were tissue tests for nitrate. The reverse was true for phosphorus tests. Essentially no significant correlations were found for soil or tissue tests for potassium in the experiments studied.

In general, the best multiple correlations with both soil and tissue tests were obtained at about silking time -- or, in other words, near the end of the grand period of growth and physiological development in corn.

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Useful soil test correlations were obtained where wide differences in nitrogen fertility had been established by previous treatments imposed over a period of years.

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by

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To My Parents

This thesis is dedicated to my parents, who encouraged me to come to the United States for advanced studies and who cared for my family during my absence from India.

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INTRODUCTION

Chemical methods for estimating fertilizer requirements of soil date from Liebig's discovery of the principles of plant nutrition. It has been established by many workers in the past that plants obtain nutrients from soils. It was found that only a fraction of the total nutrients in soil is available to plants. So attempts were made to get some measure of the rate at which these nutrients moved into the soil solution. Different methods were devised by different workers to measure the nutrients in solution. This led to the coining of such words as "active," "dormant," "available," "non-available," "exchangeable," "fixed," etc.

All these attempts were based on the idea that certain specific extractants would remove from soils those nutrients which are available to plants. Employing this concept, some success was had in predicting crop response to applied fertilizer from chemical tests of the soil.

During the last half century, rapid chemical tests of soils and plant tissue have been brought into practice. In the hands of experienced workers such tests are proving more valuable every day. Their use has been extended from laboratory and greenhouse to the field. Rapid tests are simple and inexpensive and afford a means of on-the-spot diagnosis. This has made possible nutritional surveys of relatively large areas in a short time at low cost. It has been possible to establish critical tissue concentrations for each nutrient for individual crops by making observations in which yields are compared to analytical values. Similarly, critical soil test levels for P, K and some of the secondary and minor nutrients have been established for specific soils and specific crops. Under intensive greenhouse culture, critical soil test levels have been determined with a high degree of precision. Under field conditions, correlations between crop yields and soil tests are much less exact; the soil tests provide general guides which must be augmented by specific information regarding soil type, cropping and management history and by skill and experience on the part of the prognosticator.

Soil tests for P and K provide a basis for arriving at reasonable rates of phosphate and potash to use on specific soils. No soil test for nitrogen has been found with any widely accepted usefulness in predicting in advance how much nitrogen might be released from the soil during a given growing season. Rough estimates can be made from a knowledge of soil type, organic matter content and soil management history. Release of nitrate during incubation has been used successfully for predicting fertilizer nitrogen needs of non-leguminous crops, except where these follow forage legumes.

The rate of release of soil nitrogen varies during the season and from one season to another. There is need for methods of estimating the current nitrogen status of corn during the growing season. To be most useful, such information should be timely and allow for correction of deficiencies during the current season and before potential yields have been irreversibly reduced.

In Japan, excessive fertilization is a problem, whereas in newly developed countries under-fertilization is the rule. In the United States, soil management practices present the whole spectrum between these extremes. The need for more accurate interpretation of soil and tissue tests is, therefore, of significant world-wide concern.

There is an increasing emphasis on the use of mathematical correlation, using functional models which can be readily transformed into economic terms. A large body of economic theory has evolved, based on such functional relationships. The concepts of production economics, however, have been refined far beyond the level of reliability yet realized by supporting agronomic data.

The objectives of the present study were the following:

(1) To investigate the extent to which tissue tests for nitrate used alone or in conjunction with tests for P and K may be employed to determine supplemental nitrogen needs of corn during the growing season.

(2) To investigate the relationships between soil levels of nitrate, P and K during the growing season and response of corn to supplemental nitrogen.

(3) To determine "threshold" values for nitrates in soil and tissue where actual nitrogen deficits develop prior to the appearance of visible deficiency symptoms in the corn plant.

(4) In approaching the above objectives, to use mathematical models of interest to production economists.

LITERATURE REVIEW

Fresh Tissue Tests

The correlation of mineral elements in fresh tissue with crop behavior was first undertaken in the U. S. A. Hoffer (48) made qualitative tests for Fe and K in fresh corn stalks and showed accumulation of Fe at the nodes when K was limiting.

In the beginning, sap was extracted either by crushing green tissues or extracting under heavy pressures. Later, simple extracting solutions were used for extracting soluble nutrients. Water was used by Nightingale (70, 71) for detection of calcium deficiency in sugarcane and pineapple, and by Marsh (56) for calcium and boron in tobacco and corn. Page and Burkhart (74) used boiling water for extraction of nutrients from fresh material for diagnosis of nitrogen, phosphorus and potassium deficiencies in peanuts and cotton. Emmert (30, 31, 32, 33, 34, 35) used two percent acetic acid for extracting nitrate, phosphate and potassium. Later Carolus (17, 18) extended the use of the same extractant to include calcium and magnesium in vegetable crops.

Thornton (93) et al., at Purdue, suspended finely chopped tissue directly in the chemical reagents used for detecting the nutrient; e.g. cobaltinitrite for K, ammonium molybdate for P and diphenylamine in sulfuric acid for NO_3^-N. This method has been used by Scarseth (85), Atkinson (4) and Wark (98) for the diagnosis of mineral deficiencies in small grains, tomatoes, potatoes and corn.

Carolus (17, 18), Hester (47), Peech and English (77) have used a Waring blendor for extraction of nutrients from fresh tissues. Carolus used two percent acetic acid, but Hester (47) adopted the acetate buffer solution (pH 4.8) developed by Morgan (66) for the latter's soil testing system.

Fresh tissue testing under field conditions has become prominent in all states of the U. S. A. and at many agricultural experiment stations of other countries.

Objectives of Tests

The immediate aim of fresh tissue testing is to assay the nutrient status of the plant sap. The principal objectives of such an assay have been cited to be:

(1) To aid in determining the nutrient supplying power of the soil.

(2) To aid in determining the effect of treatment on the nutrient supply in the plant.

(3) To study relationships between the nutrient status of the plant sap and crop performance as an aid in predicting fertilizer requirements.

Theory behind Fresh Tissue Tests

In tissue tests soluble tissue constituents are assayed to determine unassimilated N, P, K and other elements. Essentially all of the potassium in plant tissue is present in solution as the cation. The actual level of soluble N or P in the plant at a given time represents an equilibrium between rate of uptake from the soil and rate of metabolic assimilation within the plant. It has been assumed that imbalanced nutrition is reflected by low levels of one or more nutrients accompanied by abnormally high accumulations of one or more of the other nutrients. Thus, one obtains information regarding the factors of nutrition which may be limiting at any particular period. Since the nutritional status of the plant is not static, the demands of the plant change as it proceeds through its life cycle.

Role of Nitrate in the Plant

Nightingale and Eckerson (25, 70) have reported that NO_3^- does not directly affect the growth responses of plants. Environmental factors such as length of the day, light intensity, temperature or other external factors may affect the rate of assimilation of nitrate nitrogen. There occurs reduction of NO_3^- by a nitrate reducing enzyme system (reductase). The NH_4^+ produced combines with organic acids formed by oxidation of sugars, giving rise to amino acids which are then converted to complex proteins and other organic nitrogenous materials. Active synthesis of amino acids and proteins in many plants does not occur unless the tissues concerned contain a liberal reserve of NO_3^-.

According to Mehlich (61), NO_3^- ion is rapidly reduced in plants to NH_3, probably in the presence of a molybdenum-containing enzyme. In corn, the highest concentration of NO_3^- is found at the base of the stem. The concentration becomes progressively lower toward the top of the plant. Thus it seems reasonable to suppose that the reduction of nitrate and the assimilation of ammonium nitrogen occurs at least to some extent in all parts of the plant.

Nightingale (70) found in the pineapple, that soil temperatures of 68° F. or lower resulted in limitation of absorption of nitrate by roots.

Roles of P and K in the Plant

There are important interdependent relationships between nitrate, P and K in the nutrition of plants. Phosphorus functions as a carrier of energy, is required for respiration, and influences the synthesis of proteins. It plays an important role in plant metabolism as an accelerator of oxidative enzymes, as a promoter of root development and a regulator of maturity, and as a component of many vital compounds.

Potassium serves as a catalyst, condensing agent and translocation regulator, is necessary for the formation of carbohydrates, oils and proteins, stimulates enzyme activity, and is required for cell division, reduction of nitrates, and chlorophyll formation.

Correlation of Tissue Tests with Crop Response

Pettinger (82) extracted corn sap with a hydraulic press at a pressure of 6500 pounds per square inch from 15-inch sections of stalk immediately above ground and found that the concentration of nitrate nitrogen showed only a fair degree of correlation with nitrogen fertilization. It was well correlated, however, with the soil supply of NO_3^-N.

He suggested the following nutrient concentrations in corn sap as standards in diagnosing soils:

Very deficient NO_3^-N: Less than 100 ppm.

Moderately deficient NO_3^-N: 200 ppm.

Ample NO_3^-N: More than 300 ppm.

Lynd (53) found that tissue tests for N, P and K reflected soil fertilizer treatments on soil types varying widely in physical and chemical characteristics. Tissue tests throughout two growing seasons on rotation fertilizer experiments indicated that nitrogen was the limiting factor in plant growth and that a definite change took place in the nitrogen status of plants with the initiation of the flowering period.

Brock (16) tested soil and corn tissue at frequent intervals during the growing season in 1958 and 1959 in two of the rotations studied by Lynd. He found that levels of NO_3^- in both soil and tissue dropped sharply during a critical period beginning a week or two before tasseling and continuing through the pollination period. In Sims clay loam soil, corn yields were limited by nitrogen availability at levels of soil nitrate below 50 to 60 pounds N per acre during this period. In productive soils or where legumes or manure are plowed down, soil or tissue tests for nitrate may not reveal shortages until this critical period of nitrogen demand is reached. Usually this is too late to add supplemental nitrogen with conventional equipment. However, deficient tests during this period may be used in planning fertilizer and management programs for subsequent crops.

According to Magnitski (55), it is possible to outline rough indices of composition of corn midribs for obtaining high yields of green matter. The content of nitrate N in the earlier phases of corn development before appearance of bloom must be in the range of 800 to 1500 ppm., phosphorus content must be 40 to 100 ppm. and potassium content, 3000 to 4000 ppm. of fresh matter. In young plants showing deficiency symptoms, he found the content of various elements in fresh matter of midribs to be as follows: nitrate nitrogen, traces to none; phosphorus, 20 ppm. to traces; potassium, 600 to 1500 ppm.

Parts and Number of Plants to be Tested

Selection of the tissue to be tested in various crops and interpretation of the analyses under varying environmental conditions for any given crop require attention to a number of factors. It is essential to test that part of the plant which will give the best indication of the nutritional status. Certain principles have been fairly well established by many workers.

Many workers (21, 72) have suggested the following plant parts to use for a tissue test on a fully developed plant:

Crop	Nitrogen	Phosphorus	Potassium
Corn	Main stem or leaf midribs	Leaf midrib near ear	Blade tissue near ear

Thornton et al., (93) suggested sampling eight to ten plants from a single plot.

In later stages of growth, leaves for analysis are selected which have finished their growth and are physiologically active. These are located somewhat higher on the stem than in earlier periods.

Lynd (53) found that the third functioning basal leaf of corn plants is quite reliable as an indicator of plant nutrient status.

Time of Day for Tissue Tests

Welch (99) made hourly determinations from early morning until sunset and found that the nitrate status of corn plants was lowest in early morning. As the day advanced, the nitrate level increased, reaching its peak from about 11:00 a.m. to 3:00 p.m. after which it decreased to a level somewhat above that of the early morning.

Fallon (37) suggested that corn and small grain plants should not be tested in early morning hours since nitrate tends to accumulate over night. Testing during later forenoon and early afternoon was found to give accurate readings. According to him, nitrate tests should be avoided within 24 hours after a rain, since results may then be lower than normal. Further, he pointed out that lower leaves at the base and younger, immature leaves at the top should be avoided. Plants in the same field may vary in nutrient content, so several samples should be taken from the same field for average reading.

Stage of Growth for Tissue Tests

The most critical stage of growth for tissue tests of corn is from silking through early ear formation. To follow the nutritional trends of the plants more closely, Krantz et al., (50) suggested that tests be made at the following five stages of growth:

(1) Corn two to three feet high, about five weeks after planting.

(2) Tassels just emerging, about nine weeks after planting.

(3) Silking stage, about 11 weeks after planting.

(4) Late milk stage, about 13 weeks after planting.

(5) Husks beginning to dry, about 15 weeks after planting.

Soil Tests

Soil testing is currently the most popular diagnostic technique used in making fertilizer and lime recommendations. Routine soil testing services are offered by both public and private agencies in most states. The interpretation of soil tests, however, is still a matter for controversy. The precision with which fertilizer requirements can be predicted from soil tests falls far short of the precision possible in the tests themselves. This is because mathematical correlations with experimental data are frequently not good enough to justify using them except as a guide. Or, if good mathematical correlations are obtained, other soil or crop factors, or climatic factors, or economic considerations frequently make it advisable to use different fertilizer applications for a given soil test (10). A great deal of research activity in the area of soil fertility is directed towards the problem of correlating soil test results with crop response and economic fertilizer use.

Soil Tests in General Use

The essential difference between the various soil testing procedures currently in use is in the extracting solution which is employed. The actual chemical determinations for extracted nutrients range from qualitative "quick tests" suitable for use in the field to quantative laboratory determinations.

An early objective in soil testing was to find a selective solvent or extractant which would simulate the seasonal capacity of a crop to remove nutrients from the soil (24). This objective has been shown to be invalid, by and large. However, a high degree of selectivity is still recognized as an essential property of a useful soil extractant (13). The extractant must remove nutrient forms which are significant in crop nutrition.

Exchangeable potassium is considered to represent the major available form of this nutrient in soils. It is the form measured in a number of soil testing systems (12, 78). In general, however, potassium extractants have been selected with ionic strengths such as to give more or less relative estimates of exchangeable potassium in the major agricultural soils of a given region (52, 62, 66, 72, 91, 102).

Phosphorus occurs in soils in numerous forms (19). The availability to plants of various soil phosphorus fractions has been investigated by numerous workers (9, 13, 20, 29, 76).

Phosphorus uptake has been principally associated with acid-soluble and adsorbed phosphate in the range from pH 5.0 to 8.0. The availability of acid-soluble forms is sharply suppressed at soil pH's above 8.0. The availability of the phosphate ion decreases with decreasing pH below pH 6.0 -- due to the formation of iron and aluminum phosphates, which are only slightly soluble in acid extractants but are increasingly soluble as the pH of the extractant increases. Organic phosphorus fractions appear to contribute only indirectly to the available supply (27).

Accordingly, phosphorus extractants have been selected to give relative measures, (a) principally of acid-soluble phosphorus (8, 36, 47, 52, 62, 66, 72, 91, 93, 94, 102), (b) principally of adsorbed phosphorus (73), or (c) of acid-soluble plus adsorbed phosphorus (15).

Biological assays have been widely used to assess phosphorus availability in soils. These include vegetative tests such as the Neubauer tests (60) and the determination of "A" values, using P^{32} (42). Microbiological assays have been used for phosphorus, as well as for potassium and nitrogen (1, 81).

Nitrate, or forms of nitrogen which can be readily converted to nitrate by soil microbial processes, are generally accepted to be the available forms of this nutrient. Nitrate levels fluctuate rapidly with crop removal, organic amendments, leaching movement and with microbial release from organic matter. In humid regions, soil nitrate levels in the field frequently show little relationship to crop growth because the quantities of nitrate found usually are small relative to the potential for release of nitrate from organic forms during the growing season. Also, leaching results in movement of nitrate to horizons which are usually not sampled but which are reached by plant roots during the growing season. When nitrate in these deeper horizons has been taken into account, good correlations with crop yields have been obtained (100), particularly under semi-arid conditions (57). Under intensive greenhouse management, much higher levels of nitrate are maintained, and these are realistically related to crop response (58, 90).

Because early attempts to relate tests for soil nitrate with crop response were generally unsuccessful, investigators turned to methods for estimating the potential availability of soil nitrogen (2). No single test for soil nitrogen availability has been generally accepted. In some advisory programs, total nitrogen is determined chemically or estimated from organic matter determinations. Empirical availability factors are employed to calculate the soil nitrogen contribution to specific crops (87, 103).

"Available" nitrogen has been estimated chemically using mildly oxidative extractants (51, 81). Or available nitrogen may be estimated by a vegetative test, such as the Neubauer test (60). Production of nitrate during laboratory incubation of soil has been used to estimate soil delivery during the growing season, successfully in some areas (41, 67); unsuccessfully in others (3, 51). In some states, Michigan for one, no test for soil nitrogen is used. Nitrogen fertilizer recommendations are based on previous management and the needs of specific crops as determined by field experiments on groups of similar soils (Michigan Agr. Expt. Sta. Bul. E-159).

Soil Test Correlation

The basis for interpretation of soil tests in terms of fertilizer recommendations varies considerably from state to state. With vegetable crops on coastal plains soils in the eastern United States, soil tests are subtracted directly from known requirements for a desired production level, the balance being supplied as fertilizer, taking into account average availability coefficients for specific fertilizer materials (47). More frequently, soil tests are categorized as high, medium or low, or into responding and non-responding ranges. Fertilizer rates or ratios are then adjusted in accordance with experience gained through field fertilizer trials on the same or similar soils (66, 93, 94). In essence, these correlations between yield and soil test are based upon Liebig's law of the first limiting nutrient. Critical levels of specific nutrients and balance among the several nutrients are essential concepts employed.

Mathematical correlations of crop response with soil tests have been developed by a number of investigators. In general these have been based upon the Mitscherlich-Baule equation (7, 64) or some modification of it (10, 12, 13, 14, 44, 90). Some limitations on the application of these functions to prediction of fertilizer needs have been pointed out by Black (10).

In recent years, agronomists and economists have concerned themselves primarily with the functional analysis of crop response to applied nutrients, with little regard for soil tests (68). The percentage sufficiency concepts of Mitscherlich (64), Baule (7) and Spillman (88, 89) have been exploited by some investigators (28, 38, 101). Polynomial and square root functions have been employed by others because they permit simpler calculation of coefficients by least squares methods. These fertilizer response functions allow for diminishing returns but are not based on any logical concept of the nutritional behavior of the plant. Empirically, they have been found to fit experimental data rather well (22, 46, 92).

Some acceptable agronomic principles have been demonstrated by these procedures, such as, that the profitability of nitrogen fertilizer response is dependent upon the stand of corn (80). However, the concept of nutrient substitution, which has developed from such studies, has been difficult for agronomists to reconcile with long accepted principles of plant nutrition. According to this concept increases of one nutrient can substitute for decreasing supplies of another to maintain a constant yield. This would place qualifying restrictions on such long-accepted agronomic concepts as critical levels, nutrient balance and luxury consumption.

The physiological basis for nutrient substitution among the major elements has not been explained. However, recent studies involving correlation of corn yields with leaf composition have shown that wide fluctuations in the ratio of N to P in corn tissue can occur without affecting yield. Isoquant yield diagrams fitted to the leaf composition data were similar in form to those usually obtained for fertilizer input data (23).

Potentially, the functional analysis of fertilizer response data can be very useful. Well-developed concepts and computational procedures are available for incorporating cost-price variables and calculating optimum fertilizer rates and ratios for specific economic and management situations. However, practical application is hindered by the variability of supporting field experimental data. Variations in fertilizer response from field to field and from year to year are great. Yield equations need to be generalized by including additional variables, such as climatic factors and soil properties, including soil tests. Much current research is being directed toward this end (75, 79).

MATERIALS AND METHODS

Field Experiments

Experiments were carried out on three soil types. Six different field experiments were used for the studies on corn in 1960. Three of these were parts of previously established experiments involving systematic fertilization and management of four to twenty years' duration. One involved a comparison of current response with residual response to fertilizer applied one year previously. Two experiments were concerned only with response to the current year's fertilizer treatment. Results from the last three experiments were enigmatic and have not been fully evaluated. The present report deals only with data from the three long term experiments.

Rotation Experiment

This rotation experiment was established in 1941 by the Soil Science Department of Michigan State University on the Ferden Farm in Saginaw County. The soil at this location is Sims clay loam. The purpose of the experiment was to compare seven systems of farming at two fertility levels and two levels of supplemental nitrogen fertilization.

Out of seven rotations, three five-year rotations were selected for the present study:

(a) A rotation having two years of alfalfa-brome meadow (Rotation number 1)

(b) A cash crop rotation without green manure or forage legumes (Rotation number 6)

(c) A rotation having two leguminous green manure crops (Rotation number 7)

Rotation number 1 was comprised of alfalfa-brome, alfalfa-brome, corn, beets, and barley. Rotation number 6 had beans, wheat, corn, beets and barley, and rotation number 7 had beans, wheat (gm)*, soybeans, beets and corn (gm).

These rotations were replicated four times. A split-split plot field design was used. Rotations comprised the main plots, with fertility levels as sub-plots and supplemental nitrogen treatments as sub-sub-plots. Main plots were 28 feet by 90 feet and were subdivided longitudinally. High fertility sub-plots received 1600 pounds per acre of 5-20-10 over the five-year rotation period (400 pounds on corn); low fertility sub-plots received 800 pounds over five years (200 pounds on corn). One half of each fertility level sub-plot received no supplemental nitrogen, the other half received 100 pounds per acre of N sidedressed on corn and 50 pounds sidedressed on beets, beans and wheat.

The present study was concerned only with corn grown in 1960 -- during the fourth cycle of each rotation.

Residue Experiment

This rotation was begun in 1951 on the Ferden Farm on Sims clay loam. Its purpose was to determine if the alfalfa-brome hay that is normally removed could be replaced by sawdust or straw to maintain yields and soil building qualities in the rotation. The present study deals with the comparison of residual effects of the residue treatments and supplemental nitrogen on levels of NO_3^-, P and K in soil and corn tissue and on yield of corn in 1960. The corn in 1960 was planted at the beginning of the second cycle of a five-year rotation (corn, beans,

*gm = green manure (sweet clover planted as catch crop in wheat and corn).

barley, and two years of alfalfa-brome). This was six years after the initial residue treatments on a block of plots established in 1954.

Four residue treatments were involved as follows:

(1) Two years of alfalfa-brome hay cut and removed. This treatment repeated each cycle of the rotation.

(2) One year of alfalfa-brome hay cut and removed and the second year alfalfa cut, weighed and left on the plot. This treatment repeated each cycle of the rotation.

(3) Thirty-five tons per acre of sawdust was added after removing alfalfa-brome at the beginning of the experiment (six years before the 1960 corn crop which was used in this study).

(4) Three to four tons of wheat straw per acre applied after removal of the second year of alfalfa-brome. This treatment repeated each cycle of the rotation.

All treatments were replicated five times. A split-plot design was used. Residues comprised the main plots, with supplemental nitrogen treatments as sub-plots. Main plots were 14 feet by 90 feet and were subdivided longitudinally to give 7 feet by 90 feet sub-plots.

Fertilizer had been applied at rates of 100 pounds per acre of 5-20-10 for corn, 200 pounds 0-20-10 for beans and 240 pounds 5-20-10 for barley. No fertilizer had been used on the hay meadow. Supplemental nitrogen had been applied on one half of each residue plot at the rate of 100 pounds of nitrogen for corn and 40 pounds on beans and barley.

Nitrogen Source, Rate and Time of Application Experiment

This experiment was located on Hillsdale sandy loam at Michigan State University, Wilcox field. Corn had been grown continuously for the four years of the experiment.

Two nitrogen carriers were used -- calcium nitrate and ammonium sulfate. They were compared in fall, spring and summer applications at two rates, 40 and 80 pounds N per acre, the same treatments having been applied on the same plots over the four year period. Plot size was 14 feet by 50 feet with 42-inch row space between corn rows. Three hundred pounds 0-20-20 was plowed under and 200 pounds 0-20-20 was applied with the seed.

Field Procedures

Sampling

At each location, periodic soil and tissue samplings were made during the growing season. Twenty soil cores to an eight-inch depth were composited per plot. These were passed through a four-mesh screen, thoroughly mixed and extracted for the nitrate determination within 24 hours of sampling. The balance of the sample was rapidly air-dried and held for determination of available P and K at a later date. Leaf midribs opposite the basal ear were collected from eight plants per plot. Midrib samples were taken in the late forenoon or early afternoon. These were placed in plastic bags and quick-frozen for later determination of NO_3^--N and soluble P and K. At the time of removing the leaves, a quick test for nitrate was also made on the severed stub of each midrib. This was done to permit calibration of the quick test against the quantitative tissue nitrate determination. This calibration has not been completed.

Harvesting

Two rows of corn per plot were harvested mechanically. Moisture samples were taken, and final yields were calculated to bushels per acre at 15½ percent moisture content.

Laboratory Procedures

Frozen Tissue Tests

Five gms. of finely cut frozen tissue were placed with 50 ml. of two percent acetic acid in a Waring blendor, and a small amount of charcoal (Darco G 60) was added. This was macerated for five minutes and filtered to give a clear filtrate.

Nitrate in the filtrate was determined by the phenoldisulfonic acid method, adapted for photometric determination from Harper (45) and Prince (83).

Phosphorus was determined by the colorimetric method described by Fiske and Subbarow (40).

Potassium was determined with a flame photometer.

Soil Analysis

Field fresh soil was extracted for the nitrate determination with .02N $CuSO_4$. Calcium hydroxide was used to clarify the extracts (45, 49). Nitrate N was determined colorimetrically after reaction with brucine (86).

Soil phosphorus was determined colorimetrically in 0.025 N hydrochloric acid and 0.03 N ammonium fluoride (Bray P_1, adsorbed) (15).

Soil potassium was determined by flame photometer in Spurway reserve extracts (0.13 N hydrochloric acid) (91).

Soil pH was determined by glass electrode.

RESULTS

Effects of Treatment on Soil and Tissue Tests and Yields of Corn

Rotation Experiment

Tissue nitrate

Data presented in tables 1-a and 1-b show NO_3^- in tissue of corn grown on Sims clay loam at the Ferden Farm. Rotation 1, having two years of alfalfa-brome plus manure preceding corn, reflected the highest NO_3^- accumulation in tissue throughout the season. The lowest accumulation of NO_3^- early in the season was found in rotation 6, where corn was grown in rotation with other cash crops. Rotation 7, where two sweet clover catch crops were grown for green manure, occupied an intermediate position early in the season. There was a tendency for the relative rank of rotations 6 and 7 to change during the season. However, later differences were not significant and there was no significant date x rotation interaction. The rate of application of fertilizers did not have any effect on NO_3^- accumulation. Supplemental nitrogen favored increase in tissue NO_3^- in all rotations and also at both high and low levels of fertilizer application. There were no significant interactions between the treatment variables. Individual factors affected tissue nitrate in essentially the same way at each level or combination of the other factors (table 1-b).

Tissue phosphorus

Soluble phosphorus accumulated to higher levels in corn midribs in Rotation 6 than in Rotations 1 and 7 (tables 2-a and 2-b). High accumulations of phosphorus in Rotation 6 were associated with low

Table 1-a. -- PPM NO_3-N in tissue by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 7/18	7/29	8/11	9/14	Seasonal Average
Rotation 1	R_1	347	171	149	241	227
Rotation 6	R_6	146	85	137	206	144
Rotation 7	R_7	267	110	118	187	171
LSD_{05}		89	NS	NS	NS	37
800 lbs. 5-20-10*	F_1	261	127	146	207	185
1000 lbs. 5-20-10*	F_2	245	118	125	215	176
LSD_{05}		NS	NS	NS	NS	NS
No Suppl. N	N_1	228	116	121	215	170
Sidedressed N**	N_2	278	129	149	207	191
LSD_{05}		NS	NS	27	NS	NS
	R_1F_1	335	162	157	216	218
	R_1F_2	359	181	142	265	237
	R_6F_1	164	102	139	210	153
	R_6F_2	128	69	136	203	134
	R_7F_1	285	116	141	196	185
	R_7F_2	249	105	96	177	157
LSD_{05}	(R within F)	123	NS	NS	NS	50
LSD_{05}	(F within R)	NS	NS	NS	NS	NS
	R_1N_1	355	154	138	238	221
	R_1N_2	339	189	160	244	233
	R_6N_1	112	81	130	204	132
	R_6N_2	180	89	145	208	155
	R_7N_1	218	112	93	205	157
	R_7N_2	316	109	143	169	184
LSD_{05}	(R within N)	111	NS	NS	NS	47
LSD_{05}	(N within R)	NS	NS	47	NS	NS
	F_1N_1	227	111	122	221	170
	F_1N_2	296	142	169	194	200
	F_2N_1	230	120	120	210	170
	F_2N_2	261	116	130	220	181
LSD_{05}	(F within N)	NS	NS	NS	NS	NS
LSD_{05}	(N within F)	NS	NS	39	NS	NS

*Total over 5-year rotation.
**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 1-b. -- PPM NO_3-N in tissue by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Date 7/18	7/29	8/11	9/14	Seasonal Average
$R_1F_1N_1$	334 ab	127 abc	138 ab	222 a	205 ab
$R_1F_1N_2$	336 ab	198 a	177 a	210 a	230 a
$R_1F_2N_1$	375 a	181 ab	139 ab	253 a	237 a
$R_1F_2N_2$	343 ab	180 ab	144 ab	278 a	236 a
$R_6F_1N_1$	125 d	79 c	120 ab	207 a	133 c
$R_6F_1N_2$	203 bcd	125 abc	158 a	212 a	174 abc
$R_6F_2N_1$	99 d	84 bc	141 ab	202 a	132 c
$R_6F_2N_2$	157 cd	54 c	131 ab	205 a	137 c
$R_7F_1N_1$	221 abcd	129 abc	108 ab	232 a	172 abc
$R_7F_1N_2$	349 ab	104 abc	173 a	161 a	197 abc
$R_7F_2N_1$	215 bcd	96 bc	78 b	177 a	141 bc
$R_7F_2N_2$	283 abc	114 abc	114 ab	177 a	172 abc

a, b, c, d - Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

Table 2-a. -- PPM P in tissue by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 7/18	7/29	8/11	9/14	Seasonal Average
Rotation 1	R_1	106	106	103	73	97
Rotation 6	R_6	148	135	152	143	145
Rotation 7	R_7	68	73	61	59	65
LSD_{05}		23	NS	48	56	21
800 lbs. 5-20-10*	F_1	112	102	110	87	103
1600 lbs. 5-20-10*	F_2	103	108	101	96	102
LSD_{05}		NS	NS	NS	NS	NS
No Suppl. N	N_1	119	109	126	114	117
Sidedressed N**	N_2	96	100	85	69	87
LSD_{05}		13	NS	22	28	14
	R_1F_1	107	114	102	58	95
	R_1F_2	105	98	105	88	99
	R_6F_1	158	121	160	144	146
	R_6F_2	138	148	144	143	143
	R_7F_1	71	70	66	60	67
	R_7F_2	65	77	56	57	64
LSD_{05}	(R within F)	30	NS	51	63	23
LSD_{05}	(F within R)	NS	NS	NS	NS	NS
	R_1N_1	111	111	111	66	100
	R_1N_2	101	100	96	80	94
	R_6N_1	186	151	205	214	189
	R_6N_2	111	118	99	73	100
	R_7N_1	61	65	63	63	63
	R_7N_2	76	82	60	54	68
LSD_{05}	(R within N)	28	NS	54	66	23
LSD_{05}	(N within R)	23	NS	38	48	24
	F_1N_1	129	96	132	110	117
	F_1N_2	95	107	87	65	88
	F_2N_1	109	122	120	118	117
	F_2N_2	96	93	83	73	86
LSD_{05}	(F within N)	NS	NS	NS	NS	NS
LSD_{05}	(N within F)	19	NS	31	40	20

*Total over 5-year rotation.

**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 2-b. -- PPM P in tissue by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Date 7/18	7/29	8/11	9/14	Seasonal Average
$R_1F_1N_1$	123 b	123 bc	121 b	50 b	104 b
$R_1F_1N_2$	91 bcde	105 bcd	83 bc	67 b	86 bcd
$R_1F_2N_1$	98 bcd	100 cde	101 bc	82 b	95 bc
$R_1F_2N_2$	111 bc	96 cdef	108 bc	93 b	102 b
$R_6F_1N_1$	203 a	102 cde	210 a	211 a	181 a
$R_6F_1N_2$	113 bc	140 b	111 bc	77 b	110 b
$R_6F_2N_1$	168 a	201 a	201 a	217 a	197 a
$R_6F_2N_2$	108 bc	96 cdef	87 bc	68 b	90 bcd
$R_7F_1N_1$	61 e	62 f	67 bc	71 b	65 de
$R_7F_1N_2$	82 cde	77 def	66 bc	50 b	69 cde
$R_7F_2N_1$	61 e	67 ef	58 c	56 b	60 e
$R_7F_2N_2$	70 de	87 def	53 c	58 b	67 de

a, b, ... f -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

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levels of nitrate prior to and at tasseling time (tables 1-a and 1-b).

Rate of fertilizer application had no effect on tissue phosphorus. Supplemental nitrogen reduced the concentration of tissue phosphorus, particularly in the cash crop rotation (Rotation 6) and at the low level of fertility.

Growth and final yields of corn in this experiment increased with increasing nitrogen supply. Tissue phosphorus accumulated where growth was restricted by inadequate nitrogen in Rotation 6. Thus, inadequate nitrogen nutrition, reflected in low tissue nitrate tests, restricted the assimilation of phosphorus in the plant, allowing equilibrium levels of soluble, unassimilated phosphate to increase. Where no nitrogen was applied on Rotation 6, tissue phosphorus continued to increase through the last two samplings. Where supplemental nitrogen had been used on Rotation 6, tissue phosphorus declined during the last two samplings to levels similar to Rotations 1 and 7. These seasonal changes were associated with a statistical date x rotation x nitrogen interaction significant at five percent.

Tissue potassium

Potassium accumulation in the green tissue (table 3-a) was found to be greater in Rotation 7 than in Rotations 1 and 6. Low or high rates of application of fertilizer, as well as supplemental nitrogen treatment, had no consistent effect on potassium accumulation. However, about tasseling time, there was a highly significant rotation x fertilizer x nitrogen interaction. The data for the July 29 sampling in table 3-b show that the relative ranks of the three rotations were significantly altered by both fertility level and supplemental nitrogen treatments during this period of high nutrient requirement. As in the case of

Table 3-a. -- PPM K in tissue by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 7/18	7/29	8/11	9/14	Seasonal Average
Rotation 1	R_1	337	268	277	310	298
Rotation 6	R_6	383	297	274	320	318
Rotation 7	R_7	403	348	294	380	356
LSD_{05}		33	45	NS	21	17
800 lbs. 5-20-10*	F_1	381	296	276	342	324
1600 lbs. 5-20-10*	F_2	367	313	288	332	325
LSD_{05}		NS	NS	NS	NS	NS
No Suppl. N	N_1	393	303	285	326	327
Sidedressed N**	N_2	356	305	278	348	322
LSD_{05}		NS	NS	NS	NS	NS
	R_1F_1	346	255	269	321	298
	R_1F_2	327	281	286	299	298
	R_6F_1	391	283	280	318	318
	R_6F_2	374	311	267	323	319
	R_7F_1	406	350	278	386	355
	R_7F_2	401	346	310	375	358
LSD_{05}	(R within F)	62	55	NS	49	24
LSD_{05}	(F within R)	NS	NS	NS	NS	NS
	R_1N_1	348	275	280	299	300
	R_1N_2	326	261	275	321	296
	R_6N_1	405	298	279	316	324
	R_6N_2	361	295	268	325	312
	R_7N_1	426	338	296	364	356
	R_7N_2	380	358	291	396	357
LSD_{05}	(R within N)	59	56	NS	42	25
LSD_{05}	(N within R)	NS	NS	NS	NS	NS
	F_1N_1	408	292	291	333	331
	F_1N_2	355	300	260	350	316
	F_2N_1	378	315	280	319	323
	F_2N_2	357	310	296	345	327
LSD_{05}	(F within N)	NS	NS	NS	NS	NS
LSD_{05}	(N within F)	NS	NS	NS	NS	NS

*Total over 5-year rotation.

**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 3-b. -- PPM K in tissue by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Date 7/18	7/29	8/11	9/14	Seasonal Average
$R_1F_1N_1$	363 ab	288 abcd	288 a	301 cd	310 bcd
$R_1F_1N_2$	330 b	222 d	250 a	342 abcd	286 d
$R_1F_2N_1$	332 b	261 cd	272 a	297 d	290 cd
$R_1F_2N_2$	322 b	301 abc	300 a	301 cd	306 bcd
$R_6F_1N_1$	415 ab	250 cd	295 a	316 bcd	319 bcd
$R_6F_1N_2$	368 ab	316 abc	266 a	321 abcd	318 bcd
$R_6F_2N_1$	395 ab	347 ab	263 a	316 bcd	330 abc
$R_6F_2N_2$	353 ab	275 bcd	271 a	330 abcd	307 bcd
$R_7F_1N_1$	446 a	338 ab	290 a	383 abc	364 a
$R_7F_1N_2$	366 ab	361 a	266 a	288 ab	345 ab
$R_7F_2N_1$	407 ab	337 ab	303 a	345 abcd	348 ab
$R_7F_2N_2$	395 ab	356 a	317 a	405 a	368 a

a, b, c, d - Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

phosphorus, potassium levels tended to be lowest where corn was most vigorous (Rotation 1) and tissue nitrate levels were highest (table 1-b). Maximum potassium levels in Rotation 7 were associated with low tests for phosphorus (table 2-b). Thus potassium levels tended to be related inversely to both nitrogen and phosphorus.

Soil nitrate

Nitrate accumulations in soil were affected significantly by rotations and supplemental nitrogen treatments through most of the season (tables 4-a and 4-b). The high level of organic additions in the form of alfalfa residues and livestock manure in Rotation 1 resulted in the maintenance of relatively high nitrate concentrations through the last sampling date. The two sweet clover green manure crops in Rotation 7 contributed to significantly higher soil nitrate levels up until tasseling time in this rotation than in the cash crop rotation (Rotation 6). There was no evidence on June 21 of residual carryovers from previous years' nitrogen sidedressings, nor of any response to 50 pounds of nitrogen sidedressed on June 9 of the current season. A second 50-pound application of nitrogen was made with the last cultivation on June 30. Through the balance of the season, soil nitrate in sidedressed plots remained 6 to 13 pounds higher than in those which received no supplemental nitrogen. This compares with an 18 to 24-pound differential maintained by Rotation 1 over Rotation 6.

The level of fertility had no effect on soil nitrate levels in general. However, on July 29, a rotation x fertilizer interaction was encountered, such that nitrate levels were significantly reduced in Rotation 1 by the higher rate of fertilization. A similar relationship

Table 4-a. -- Pounds per acre NO_3-N in soil by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 6/21	7/2	7/18	7/29	8/11	9/14	Seasonal Average
Rotation 1	R_1	42	37	37	35	38	25	36
Rotation 6	R_6	19	13	14	16	16	7	14
Rotation 7	R_7	29	18	19	19	19	7	18
LSD_{05}		7	4	5	6	10	11	3
800 lbs. 5-20-10*	F_1	31	24	22	25	24	14	23
1600 lbs. 5-20-10*	F_2	29	21	25	22	25	12	22
LSD_{05}		NS	NS	NS	NS	NS	NS	NS
No Suppl. N	N_1	31	20	19	19	18	8	19
Sidedressed N**	N_2	29	26	28	28	31	18	27
LSD_{05}		NS	4	2	4	7	6	2
	R_1F_1	44	39	38	40	40	27	38
	R_1F_2	40	35	36	30	37	23	34
	R_6F_1	20	13	12	16	14	8	14
	R_6F_2	19	13	16	16	19	6	15
	R_7F_1	30	20	15	18	18	7	18
	R_7F_2	27	16	23	21	19	7	19
LSD_{05}	(R within F)	7	8	7	8	11	12	3
LSD_{05}	(F within R)	NS	NS	NS	7	NS	NS	NS
	R_1N_1	44	35	32	28	32	14	31
	R_1N_2	40	39	42	43	45	35	41
	R_6N_1	20	10	10	12	9	5	11
	R_6N_2	19	16	18	20	23	9	18
	R_7N_1	29	15	14	16	14	5	15
	R_7N_2	28	22	24	22	24	10	22
LSD_{05}	(R within N)	8	7	6	7	13	13	4
LSD_{05}	(N within R)	NS	NS	4	7	12	10	3
	F_1N_1	31	22	19	18	17	7	19
	F_1N_2	31	27	25	31	30	21	27
	F_2N_1	30	18	19	19	19	9	19
	F_2N_2	27	24	31	26	31	16	26
LSD_{05}	(F within N)	NS	NS	4	NS	NS	NS	NS
LSD_{05}	(N within F)	NS	6	3	6	10	8	1

*Total over 5-year rotation.

**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 4-b. -- Pounds per acre NO_3-N in soil by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Date 6/21	7/5	7/18	7/29	8/11	9/14	Seasonal Average
$R_1F_1N_1$	46 a	38 a	33 b	27 bcd	33 abc	13 c	32 bc
$R_1F_1N_2$	42 a	40 a	42 a	53 a	46 a	40 a	44 a
$R_1F_2N_1$	43 a	31 ab	31 b	28 bc	31 abc	16 bc	30 c
$R_1F_2N_2$	37 ab	38 a	41 a	33 b	44 ab	30 ab	37 b
$R_6F_1N_1$	19 cd	10 d	10 e	11 e	8 d	4 c	10 h
$R_6F_1N_2$	20 cd	17 cd	15 cde	21 cde	20 cd	12 c	17 defg
$R_6F_2N_1$	21 cd	11 d	10 e	13 e	11 d	5 c	12 gh
$R_6F_2N_2$	18 d	15 cd	21 c	20 cde	27 abcd	7 c	18 def
$R_7F_1N_1$	30 bc	17 cd	13 de	16 de	11 d	4 c	15 fg
$R_7F_1N_2$	30 bc	24 bc	18 cd	20 cde	25 bcd	11 c	21 de
$R_7F_2N_1$	28 bcd	13 cd	16 cde	17 cde	16 cd	5 c	16 efg
$R_7F_2N_2$	27 bcd	19 bcd	30 b	24 bcd	23 cd	10 c	22 d

a, b, ... h - Ranges of equivalence (Duncan, 1955). Within a column, numerical values with the same literal subscript are not different at 5 percent.

with fertilizer rate was maintained in all samplings, although the differences were smaller and not statistically significant. This suggests that more rapid growth of corn on the high fertility plots resulted in more rapid uptake of nitrogen, thereby lowering the equilibrium level of nitrate in the soil. A similar effect was observed during the first two samplings in Rotation 7. In both of these rotations there was a small yield response to fertility level (table 8-a).

It is of interest to note that relationships between soil nitrate and treatment were more distinct and differences attained a much higher order of statistical significance than was true for the tissue nitrate determinations.

Soil phosphorus

Available soil phosphorus values (tables 5-a and 5-b) reflect the heavy demand for phosphorus of the vigorously growing corn in Rotation 1. These low soil phosphorus values were associated with high soil and tissue NO_3^- and with moderately high tests for tissue phosphorus in this rotation. Final yields were also higher than in Rotations 6 and 7.

In the case of Rotation 7, relatively high soil tests for phosphorus were accompanied by the lowest levels of phosphorus in the tissue (table 2-a). Some unknown factors were obviously acting in Rotation 7 to enhance assimilation of phosphate in the crop or to retard its uptake from the soil.

Soil phosphorus was consistently four or five pounds higher at the high rate of fertilization than at the low, except right at tasseling time, when no significant effect was observed. The lack of significant differences at tasseling time may have been due to reduced rate of uptake

Table 5-a. -- Pounds per acre P in soil by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	6/21	7/5	7/18	7/29	8/11	9/14	Seasonal Average
Rotation 1	R_1	14	22	24	25	14	14	19
Rotation 6	R_6	22	28	30	28	21	21	25
Rotation 7	R_7	24	32	31	29	23	23	27
LSD_{05}		7	8	NS	NS	4	7	3
800 lbs. 5-20-10*	F_1	17	25	26	26	18	17	22
1600 lbs. 5-20-10*	F_2	22	29	31	28	21	22	25
LSD_{05}		3	3	4	NS	2	2	1
No Suppl. N	N_1	20	27	30	26	20	21	24
Sidedressed N**	N_2	19	27	26	28	19	18	23
LSD_{05}		NS	NS	4	NS	NS	2	1
	R_1F_1	12	22	21	24	11	11	17
	R_1F_2	15	22	27	25	16	16	20
	R_6F_1	18	27	29	26	20	20	23
	R_6F_2	25	29	31	30	23	23	27
	R_7F_1	22	28	27	29	22	21	25
	R_7F_2	26	36	35	29	25	25	29
LSD_{05}	(R within F)	7	8	NS	NS	5	8	3
LSD_{05}	(F within R)	5	5	7	NS	3	4	2
	R_1N_1	14	23	27	23	14	14	19
	R_1N_2	14	21	21	27	13	13	18
	R_6N_1	23	29	31	29	22	22	26
	R_6N_2	20	27	28	27	21	21	24
	R_7N_1	24	30	32	28	24	25	27
	R_7N_2	23	34	30	31	23	21	27
LSD_{05}	(R within N)	7	8	NS	NS	5	8	4
LSD_{05}	(N within R)	NS	4	6	NS	NS	3	2
	F_1N_1	17	25	26	25	18	18	21
	F_1N_2	18	26	25	28	18	17	22
	F_2N_1	23	29	34	28	22	23	27
	F_2N_2	20	29	27	29	20	20	24
LSD_{05}	(F within N)	3	4	5	NS	2	3	1
LSD_{05}	(N within F)	NS	NS	5	NS	NS	3	1

The dates 6/21 through 9/14 are grouped under the heading "Date".

*Total over 5-year rotation.

**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 5-b. -- Pounds per acre P in soil by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

	Date						Seasonal
Treatment	6/21	7/5	6/18	7/29	8/11	9/14	Average
$R_1F_1N_1$	12 h	24 de	23 bc	22 b	12 d	12 ef	17 e
$R_1F_1N_2$	13 gh	20 e	19 c	26 ab	11 d	11 f	16 e
$R_1F_2N_1$	16 efgh	22 de	31 ab	23 ab	16 c	17 de	21 cd
$R_1F_2N_2$	15 fgh	22 de	23 bc	28 ab	16 c	16 def	20 d
$R_6F_1N_1$	18 defg	26 cde	28 abc	25 ab	19 bc	19 cd	23 bc
$R_6F_1N_2$	19 def	27 cd	29 abc	27 ab	22 ab	20 bcd	24 b
$R_6F_2N_1$	28 a	32 abc	35 a	32 a	25 a	25 ab	29 a
$R_6F_2N_2$	22 bcd	27 cd	27 abc	28 ab	21 ab	21 bcd	24 b
$R_7F_1N_1$	21 cde	26 cde	28 abc	28 ab	23 ab	23 abc	25 b
$R_7F_1N_2$	22 bcd	31 bc	27 abc	31 ab	20 b	19 cd	25 b
$R_7F_2N_1$	27 ab	34 ab	37 a	28 ab	25 a	27 a	30 a
$R_7F_2N_2$	25 abc	38 a	32 ab	31 ab	25 a	23 abc	29 a

a, b, c....h - Ranges of equivalence (Duncan, 1955). Within a column, numerical values with the same literal subscript are not different at 5 percent.

or to more rapid mineralization of organic soil phosphorus, since soil phosphorus levels were at or near their seasonal high points.

Soil potassium

Soil tests for potassium (tables 6-a and 6-b) reflected the influence of treatment factors to a lesser degree than did the tissue tests for potassium (table 3-a). Main effects of rotation, fertility level and supplemental nitrogen treatment were generally non-significant.

On July 18, just before tasseling, there was a significant rotation x fertilizer interaction due to the fact that available soil potassium was augmented by the double rate of fertilization in Rotations 6 and 7 but not in Rotation 1. A direct relationship between soil potassium and rate of potash addition was maintained with moderate consistency only in Rotation 7, giving rise to a significant date x rotation x fertilizer interaction. The seasonal averages showed a significant difference for fertilizer only in Rotation 7. Low tissue phosphorus tests (table 2-a) suggest that low availability of phosphorus may have restricted growth in Rotation 7, thereby reducing crop demand for soil potassium and allowing it to increase.

A similar fertilizer x nitrogen interaction operated through most of the season to give a significantly higher seasonal average soil test for potassium at higher rates of fertilization only in plots which received no supplemental nitrogen. These results are consistent with the concept that seasonal levels of available potassium reflect the intensity of crop demand on the one hand and rate of release from unavailable soil sources on the other. The fact that treatment-associated variation in potassium soil tests at this location was generally much less than for soil NO_3^- and phosphorus indicates that potassium was not

Table 6-a. -- Pounds per acre K in soil by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 6/21	7/5	7/18	7/29	8/11	9/14	Seasonal Average
Rotation 1	R_1	174	180	175	174	167	159	171
Rotation 6	R_6	176	189	197	166	161	166	176
Rotation 7	R_7	182	187	188	182	172	166	179
LSD_{05}		NS	NS	NS	NS	NS	NS	NS
800 lbs. 5-20-10*	F_1	177	188	180	175	166	161	174
1600 lbs. 5-20-10*	F_2	178	183	193	173	167	166	177
LSD_{05}		NS	NS	10	NS	NS	NS	NS
No Suppl. N	N_1	178	185	184	174	165	167	175
Sidedressed N**	N_2	177	185	189	174	168	160	175
LSD_{05}		NS	NS	NS	NS	NS	NS	NS
	R_1F_1	177	176	180	171	172	164	173
	R_1F_2	171	184	170	178	162	154	170
	R_6F_1	177	198	189	170	160	160	175
	R_6F_2	176	181	204	162	163	172	176
	R_7F_1	177	190	170	184	166	159	174
	R_7F_2	187	184	206	180	178	174	184
LSD_{05}	(R within F)	NS	NS	NS	NS	NS	NS	13
LSD_{05}	(F within R)	NS	NS	17	NS	NS	NS	8
	R_1N_1	171	182	175	171	168	156	170
	R_1N_2	177	178	176	178	166	162	173
	R_6N_1	179	188	191	162	161	170	175
	R_6N_2	174	191	202	170	162	162	177
	R_7N_1	184	187	187	190	166	176	181
	R_7N_2	180	187	189	174	178	157	177
LSD_{05}	(R within N)	NS	NS	NS	NS	NS	NS	NS
LSD_{05}	(N within R)	NS	NS	NS	NS	NS	12	NS
	F_1N_1	176	185	173	175	162	162	172
	F_1N_2	178	190	187	175	169	160	176
	F_2N_1	180	186	196	174	167	172	179
	F_2N_2	176	180	191	173	168	160	174
LSD_{05}	(F within N)	NS	NS	16	NS	NS	NS	6
LSD_{05}	(N within F)	NS	NS	NS	NS	NS	NS	5

*Total over 5 year rotation.

**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 6-b. -- Pounds per acre K in soil by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Date 6/21	7/5	7/18	7/29	8/11	9/14	Seasonal Average
$R_1F_1N_1$	172 a	178 ab	182 bcd	168 a	170 ab	156 cd	171 bc
$R_1F_1N_2$	182 a	174 b	178 bcd	174 a	174 ab	172 abc	175 bc
$R_1F_2N_1$	170 a	186 ab	167 cd	173 a	166 b	156 cd	169 c
$R_1F_2N_2$	172 a	182 ab	173 bcd	183 a	158 b	152 cd	170 bc
$R_6F_1N_1$	178 a	190 ab	182 bcd	163 a	154 b	160 bcd	171 bc
$R_6F_1N_2$	176 a	206 a	197 abc	177 a	166 b	160 bcd	180 ab
$R_6F_2N_1$	180 a	186 ab	200 abc	162 a	168 ab	180 ab	179 abc
$R_6F_2N_2$	172 a	176 ab	208 ab	163 a	158 b	164 abcd	173 bc
$R_7F_1N_1$	178 a	188 ab	154 d	195 a	164 b	170 abc	174 bc
$R_7F_1N_2$	176 a	192 ab	186 abcd	174 a	168 ab	148 d	174 bc
$R_7F_2N_1$	190 a	186 ab	220 a	186 a	168 ab	182 a	188 a
$R_7F_2N_2$	184 a	182 ab	193 abc	174 a	188 a	166 abcd	181 ab

a, b, c, d - Ranges of equivalence (Duncan, 1955). Within a column, numerical values with the same literal subscripts are not different at 5 percent.

as critically limiting as the other two. This conclusion is supported by the extent to which variation in tissue tests for each of these three nutrients could be associated with treatment.

Soil reaction

Soil pH (tables 7-a and 7-b) did not show any remarkable variation during the growing season, although high fertilizer level and supplemental nitrogen occasionally lowered pH.

Corn yields

Data in table 8-a show that the principal yield responses were associated with rotations and supplemental nitrogen treatment. Yields were somewhat higher at the high level of fertilization than at the low, but differences were not significant. This would indicate that nitrogen was the nutrient which principally controlled yield. Responses ranged from a 41-bushel increase for supplemental nitrogen applied on Rotation 6 at the high level of fertility to a one-bushel decrease where nitrogen was applied on Rotation 1 at the low fertilizer rate (table 8-b). It is apparent that the response to nitrogen in this experiment followed a diminishing returns function of some sort.

Corn populations

Germination and survival of corn were influenced by fertility in this experiment. Total stalks at harvest time were increased significantly by the high level of fertilizer addition, particularly where supplemental nitrogen was also used (table 8-a).

Barrenness, on the other hand, was unaffected by rate of fertilization, but was strongly influenced by rotations and by supplemental nitrogen treatments. Comparison with table 1-a shows that barrenness was

Table 7-a. -- Soil pH by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 6/21	7/5	7/18	7/29	8/11	9/14	Seasonal Average
Rotation 1	R_1	6.5	6.5	6.6	6.2	6.5	6.6	6.5
Rotation 6	R_6	6.7	6.6	6.7	6.4	6.6	6.8	6.6
Rotation 7	R_7	6.5	6.4	6.6	6.1	6.5	6.6	6.4
LSD_{05}		NS	NS	NS	NS	NS	NS	NS
800 lbs. 5-20-10*	F_1	6.6	6.5	6.6	6.2	6.6	6.7	6.5
1600 lbs. 5-20-10*	F_2	6.5	6.5	6.6	6.2	6.4	6.6	6.5
LSD_{05}		NS	NS	NS	NS	.04	NS	NS
No Suppl. N	N_1	6.6	6.5	6.7	6.3	6.6	6.8	6.6
Sidedressed N**	N_2	6.6	6.5	6.6	6.2	6.4	6.6	6.5
LSD_{05}		NS	NS	0.06	NS	NS	0.09	0.03
	R_1F_1	6.5	6.5	6.5	6.2	6.5	6.6	6.5
	R_1F_2	6.5	6.5	6.6	6.2	6.4	6.7	6.5
	R_6F_1	6.7	6.6	6.8	6.4	6.7	6.8	6.7
	R_6F_2	6.7	6.6	6.7	6.3	6.5	6.8	6.6
	R_7F_1	6.5	6.4	6.7	6.1	6.5	6.6	6.5
	R_7F_2	6.5	6.4	6.6	6.2	6.4	6.5	6.4
LSD_{05}	(R within F)	NS	NS	NS	NS	NS	NS	NS
LSD_{05}	(F within R)	NS	NS	NS	NS	0.08	NS	NS
	R_1N_1	6.5	6.5	6.6	6.2	6.6	6.8	6.5
	R_1N_2	6.5	6.5	6.5	6.2	6.4	6.5	6.4
	R_6N_1	6.7	6.6	6.8	6.5	6.7	6.9	6.7
	R_6N_2	6.7	6.6	6.7	6.3	6.5	6.7	6.6
	R_7N_1	6.5	6.5	6.7	6.1	6.5	6.6	6.5
	R_7N_2	6.5	6.4	6.6	6.1	6.4	6.5	6.4
LSD_{05}	(R within N)	NS	NS	NS	NS	NS	NS	NS
LSD_{05}	(N within R)	NS	NS	0.11	NS	0.14	0.16	0.06
	F_1N_1	6.6	6.6	6.7	6.3	6.6	6.8	6.6
	F_1N_2	6.6	6.5	6.6	6.2	6.5	6.6	6.5
	F_2N_1	6.6	6.5	6.7	6.3	6.6	6.7	6.6
	F_2N_2	6.5	6.5	6.6	6.2	6.3	6.6	6.4
LSD_{05}	(F within N)	NS	NS	NS	NS	0.09	NS	NS
LSD_{05}	(N within F)	NS	NS	0.09	NS	0.11	0.13	0.05

*Total over 5 year rotation.

**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 7-b.- Soil pH by dates of sampling. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Date						Seasonal Average
	6/21	7/5	7/18	7/29	8/11	9/14	
$R_1F_1N_1$	6.5 a	6.6 ab	6.6 abc	6.2 ab	6.5 abc	6.8 a	6.5 bc
$R_1F_1N_2$	6.5 a	6.4 b	6.4 c	6.2 ab	6.4 bc	6.5 b	6.4 c
$R_1F_2N_1$	6.6 a	6.5 ab	6.7 ab	6.3 ab	6.6 ab	6.8 a	6.6 ab
$R_1F_2N_2$	6.5 a	6.5 ab	6.6 abc	6.2 ab	6.3 c	6.5 b	6.4 c
$R_6F_1N_1$	6.7 a	6.7 a	6.7 ab	6.5 a	6.7 a	6.9 a	6.7 a
$R_6F_1N_2$	6.7 a	6.6 ab	6.8 a	6.3 ab	6.6 ab	6.7 ab	6.6 ab
$R_6F_2N_1$	6.7 a	6.6 ab	6.8 a	6.5 a	6.7 a	6.9 a	6.7 a
$R_6F_2N_2$	6.7 a	6.6 ab	6.6 abc	6.2 ab	6.4 bc	6.7 ab	6.5 bc
$R_7F_1N_1$	6.5 a	6.5 ab	6.7 ab	6.0 b	6.6 ab	6.7 ab	6.5 bc
$R_7F_1N_2$	6.5 a	6.4 b	6.6 abc	6.1 b	6.4 bc	6.5 b	6.4 c
$R_7F_2N_1$	6.5 a	6.4 b	6.6 abc	6.2 ab	6.4 bc	6.5 b	6.4 c
$R_7F_2N_2$	6.5 a	6.4 b	6.5 bc	6.1 b	6.4 bc	6.5 b	6.4 c

a, b, c - Ranges of equivalence (Duncan, 1955). Within a column, numerical values with the same literal subscript are not different at 5 percent.

Table 8-a. -- Corn yields, fertile stalks, barren stalks and total stalks per acre. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Code	Corn yield per acre	Stalks per acre Fertile	Barren	Total
Rotation 1	R_1	98.4	14352	858	15210
Rotation 6	R_6	67.4	13869	1858	15727
Rotation 7	R_7	79.8	14748	1229	15977
LSD_{05}		16.3	NS	383	NS
800 lbs. 5-20-10*	F_1	80.2	13958	1262	15220
1600 lbs. 5-20-10*	F_2	83.5	14688	1368	16056
LSD_{05}		NS	699	NS	711
No Suppl. N	N_1	71.4	13808	1762	15571
Sidedressed N**	N_2	92.4	14837	868	15706
LSD_{05}		5.0	535	283	NS
	R_1F_1	96.2	13851	793	14645
	R_1F_2	100.7	14852	922	15775
	R_6F_1	67.8	13722	1750	15473
	R_6F_2	67.0	14015	1966	15982
	R_7F_1	76.6	14300	1242	15542
	R_7F_2	83.0	15197	1216	16413
LSD_{05}	(R within F)	17.9	NS	564	NS
LSD_{05}	(F within R)	NS	NS	NS	NS
	R_1N_1	96.1	14265	897	15162
	R_1N_2	100.8	14438	819	15257
	R_6N_1	50.3	12816	2785	15602
	R_6N_2	84.5	14921	931	15852
	R_7N_1	67.8	14343	1604	15947
	R_7N_2	91.8	15154	853	16008
LSD_{05}	(R within N)	17.4	1315	516	NS
LSD_{05}	(N within R)	8.6	927	491	NS
	F_1N_1	71.3	13777	1730	15507
	F_1N_2	89.2	14139	793	14932
	F_2N_1	71.5	13840	1794	15634
	F_2N_2	95.6	15536	943	16479
LSD_{05}	(F within N)	NS	880	NS	857
LSD_{05}	(N within F)	7.0	757	401	679

*Total over 5 year rotation.

**100 pounds N per acre on corn; 40 pounds on other row crops and wheat. 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

Table 8-b. -- Corn yields, fertile stalks, barren stalks and total stalks per acre. Ferden Farm rotations 1, 6 and 7. Sims clay loam. 1960. (Tasseling date: July 25.)

Treatment	Corn Yield Per Acre	Fertile Stalks Per Acre	Barren Stalks Per Acre	Total Stalks Per Acre
$R_1F_1N_1$	96.7 ab	14127 bc	845 bc	14973 cd
$R_1F_1N_2$	95.7 ab	13575 cd	741 c	14317 d
$R_1F_2N_1$	95.4 abc	14403 abc	948 bc	15352 bcd
$R_1F_2N_2$	105.9 a	15300 ab	897 bc	16197 abc
$R_6F_1N_1$	54.1 fg	13023 cd	2725 a	15749 abc
$R_6F_1N_2$	81.6 cd	14421 abc	776 c	15197 bcd
$R_6F_2N_1$	46.5 g	12609 d	2846 a	15456 abcd
$R_6F_2N_2$	87.5 bc	15421 ab	1086 bc	16508 ab
$R_7F_1N_1$	63.0 ef	14179 bc	1621 b	15801 abc
$R_7F_1N_2$	90.2 bc	14421 abc	862 bc	15283 bcd
$R_7F_2N_1$	72.5 de	14507 abc	1587 b	16094 abc
$R_7F_2N_2$	93.5 abc	15887 a	845 bc	16732 a

a, b, c....g - Ranges of equivalence (Duncan, 1955). Within a column, numerical values with the same literal subscript are not different at 5 percent.

inversely related to tissue nitrate prior to and at tasseling time.

The number of fertile stalks (stalks with ears) at harvest time was the net result of variations in survival (total stalks) and barrenness. As a result, fertile stalks were significantly influenced by rate of fertilization and supplemental nitrogen treatments, and, where no supplemental nitrogen was used, by rotations as well.

Residue Experiment

Tissue nitrate

Data presented in table 9 show the accumulation of nitrate in corn tissue on Sims clay loam as influenced by organic residues and supplemental nitrogen treatments. Leaf midrib samples were taken from only two of the five replications in the experiment. As a result, the level of statistical significance attained was low. Effects of residue treatments were not significant and no consistent relationships were maintained from one sampling to another. Tissue nitrate was consistently higher with supplemental nitrogen treatment than without. This effect was most pronounced just before tasseling (July 20 sampling) on the check and the sawdust plots.

High accumulations of tissue nitrate were found at early stages of growth. Nitrate was found to increase in the second sampling and then it dropped suddenly at about tasseling time. On July 20, the concentration of nitrate in corn tissue was still two to three times higher than for the corresponding July 18 sampling in the previous experiment (table 1-a). Nitrate levels in the last two samplings were similar in the two experiments. Changes from one sampling date to another were significant at the one percent level of probability.

Table 9. -- PPM NO_3-N in corn tissue by dates of sampling as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 6/28	7/7	7/20	8/11	9/16	Seasonal Average
Check**	R_1	1062	1333	636	94	225	670
Alfalfa-brome+	R_2	1207	2029	599	221	235	858
Sawdust++	R_3	1060	1755	643	107	275	768
Straw‡	R_4	1119	1600	545	155	204	724
LSD_{05}		NS	NS	NS	NS	NS	NS
No Suppl. N	N_1	970	1663	513	109	231	697
Ave. N Treatment*	N_2	1254	1695	698	180	238	813
LSD_{05}		NS	NS	128	NS	NS	117
	R_1N_1	1025	1415	483	84	223	646
	R_1N_2	1100	1251	790	104	227	694
	R_2N_1	1031	1760	515	146	227	736
	R_2N_2	1382	2298	683	296	244	980
	R_3N_1	1001	1760	479	65	300	721
	R_3N_2	1119	1751	806	150	250	815
	R_4N_1	823	1719	575	141	175	686
	R_4N_2	1415	1481	515	169	233	762
LSD_{05}	(R within N)	NS	NS	NS	NS	NS	NS
LSD_{05}	(N within R)	NS	NS	255	NS	NS	235

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5 year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

**All second-year hay removed.

+Second-year hay left and plowed down for corn.

++35 tons sawdust applied in 1954.

‡4 tons wheat straw plowed down for corn.

Tissue phosphorus

Tissue tests for phosphorus (table 10) were essentially unrelated to treatment. The actual test values for the period from just before tasseling to the end of the season were about the same as for Rotation 1 in the previous experiment (tables 2-a and b).

Tissue potassium

Potassium accumulation in plant sap (table 11) was found to behave seasonally like tissue NO_3^-. Potassium accumulation was high in the beginning, showed an increase on the second sampling date and then it dropped abruptly about tasseling time. Thereafter it showed a decline, except on the last sampling date. On the last sampling date there was a tendency for tissue potassium to increase again.

The lowest levels of potassium were invariably found where supplemental nitrogen was used without residue addition. Where alfalfa-brome hay or wheat straw were returned, tissue potassium was consistently higher than on the check, particularly where supplemental nitrogen was used. This residue x nitrogen interaction was significant at the five percent level on August 11 and in the seasonal averages. Potassium levels where sawdust had been applied were intermediate between those for the check plots and those for alfalfa-brome or wheat straw.

Soil nitrate

Nitrate accumulation in soil (table 12) was strongly influenced by residue treatment up until tasseling time. On plots which had received 35 tons of sawdust six years earlier, nitrate levels were significantly higher than the unamended check during the first two samplings. Nitrate was lower than the check through the third sampling on plots where four tons of wheat straw was plowed down for the 1960 corn crop.

Table 10. -- PPM soluble P in corn tissue by dates of sampling as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 6/28	7/7	7/20	8/11	9/16	Seasonal Average
Check**	R_1	113	56	108	70	83	86
Alfalfa-brome+	R_2	106	50	97	97	73	85
Sawdust++	R_3	133	47	105	76	65	85
Straw‡	R_4	108	45	75	82	76	77
LSD_{05}		17	NS	NS	NS	NS	NS
No Suppl. N	N_1	118	43	98	80	70	82
Ave. N Treatment*	N_2	113	55	94	82	79	85
LSD_{05}		NS	NS	NS	NS	NS	NS
	R_1N_1	115	55	107	80	77	87
	R_1N_2	112	57	110	60	90	86
	R_2N_1	102	50	107	110	80	90
	R_2N_2	110	50	87	85	67	80
	R_3N_1	145	42	105	65	62	84
	R_3N_2	122	52	105	87	67	87
	R_4N_1	110	27	75	67	60	68
	R_4N_2	107	62	75	97	92	87
LSD_{05}	(R within N)	NS	NS	NS	NS	NS	NS
LSD_{05}	(N within R)	NS	NS	NS	NS	NS	NS

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5-year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

**All second-year hay removed.

+Second-year hay left and plowed down on corn.

++35 tons sawdust applied in 1954.

‡4 tons wheat straw plowed down for corn.

Table 11. -- PPM K in corn tissue by dates of sampling as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 6/28	7/7	7/20	8/11	9/16	Seasonal Average
Check**	R_1	270	315	238	191	322	267
Alfalfa-brome+	R_2	337	451	276	253	318	327
Sawdust++	R_3	330	401	281	237	322	314
Straw‡	R_4	353	452	267	262	351	337
LSD_{05}		NS	31	NS	38	NS	24
No Suppl. N	N_1	310	398	265	228	316	304
Ave. N Treatment*	N_2	335	411	266	243	340	319
LSD_{05}		NS	NS	NS	NS	NS	NS
	R_1N_1	275	332	240	207	332	277
	R_1N_2	265	297	237	175	312	257
	R_2N_1	350	420	270	235	317	314
	R_2N_2	345	482	282	272	320	340
	R_3N_1	315	385	275	192	277	289
	R_3N_2	345	417	287	282	367	340
	R_4N_1	322	457	275	280	340	335
	R_4N_2	385	447	260	245	362	340
LSD_{05}	(R within N)	NS	62	NS	54	NS	37
LSD_{05}	(N within R)	NS	NS	NS	54	NS	40

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5-year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

**All second-year hay removed.

+Second-year hay left and plowed down on corn.

++35 tons sawdust applied in 1954.

‡4 tons wheat straw plowed down for corn.

Table 12. -- Pounds per acre soil NO_3^- by dates of sampling as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	Date 6/28	7/7	7/20	7/27	8/11	9/16	Seasonal Average
Check**	R_1	47	39	39	48	39	21	39
Alfalfa-brome+	R_2	43	44	36	48	36	21	38
Sawdust++	R_3	54	49	36	43	40	20	40
Straw‡	R_4	39	34	25	42	32	16	31
LSD_{05}		6	6	9	NS	NS	NS	3
No Suppl. N	N_1	41	40	31	38	28	12	32
Ave. N Treatment*	N_2	50	43	37	52	45	27	42
LSD_{05}		5	NS	NS	8	9	5	3
	R_1N_1	40	38	31	40	30	13	32
	R_1N_2	54	40	46	56	49	30	46
	R_2N_1	39	40	37	40	33	13	34
	R_2N_2	47	47	36	56	39	29	42
	R_3N_1	48	49	36	39	30	13	36
	R_3N_2	60	50	36	46	50	27	45
	R_4N_1	37	33	22	35	22	8	26
	R_4N_2	40	34	29	49	41	24	36
LSD_{05}	(R within N)	9	8	12	NS	NS	NS	5
LSD_{05}	(N within R)	10	NS	NS	NS	19	10	6

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5-year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.
**All second-year hay removed.
+Second-year hay left and plowed down on corn.
++35 tons sawdust applied in 1954.
‡ 4 tons wheat straw plowed down for corn.

This reflects the immobilizing effect of recently applied carbonaceous residues and is apparent in the seasonal averages at both levels of nitrogen addition.

Incubation data for this same experiment, reported by Mora (65) and Au (6), indicate that the immobilizing effect of the heavy sawdust application had been largely dissipated by the fourth year after incorporation of the sawdust.

The addition of supplemental nitrogen resulted in significant increases in the level of soil nitrate, except in the second and third samplings. There was a drop in level of nitrate during this period with all treatments, followed by a very temporary rise just at tasseling time. This would suggest that corn growth was such as to require large amounts of nitrogen during the two weeks prior to tasseling. The apparently reduced demand for nitrogen at tasseling time may have been related to climatic conditions. During the balance of the season, significantly higher levels of nitrate were maintained where supplemental nitrogen was used with all residue treatments.

The observed seasonal fluctuations in soil nitrate gave rise to interaction mean squares significant at five percent for the date x residue interaction and at one percent for date x nitrogen treatment.

Soil nitrate levels in this experiment were similar to those for Rotation 1 in the previous experiment (tables 4-a and 4-b).

Soil phosphorus

Available soil phosphorus (table 13) was unaffected by either residue or nitrogen treatments. There was a progressive decline in soil phosphorus through the season, giving rise to a highly significant mean square for date averages.

Table 13. -- Pounds per acre soil P by dates of sampling as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	Date						Seasonal
		6/28	7/7	7/20	7/27	8/11	9/16	Average
Check**	R_1	21	16	13	17	12	10	15
Alfalfa-brome+	R_2	26	15	14	17	13	11	16
Sawdust++	R_3	23	15	15	19	11	11	16
Straw‡	R_4	21	16	13	16	12	10	15
LSD_{05}		NS	NS	NS	NS	NS	NS	NS
No Suppl. N	N_1	24	16	13	17	12	10	15
Ave. N Treatment*	N_2	22	15	14	17	12	11	15
LSD_{05}		NS	NS	NS	NS	NS	NS	NS
	R_1N_1	21	17	13	17	14	10	15
	R_1N_2	21	15	13	17	11	11	15
	R_2N_1	28	15	15	17	12	10	16
	R_2N_2	25	14	13	16	13	12	15
	R_3N_1	23	15	15	18	11	10	15
	R_3N_2	24	16	15	19	11	11	16
	R_4N_1	24	17	12	16	12	10	15
	R_4N_2	19	15	14	17	13	10	14
LSD_{05}	(R within N)	NS	NS	NS	NS	NS	NS	NS
LSD_{05}	(N within R)	NS	NS	NS	NS	NS	NS	NS

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5-year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

**All second-year hay removed.

+Second-year hay left and plowed down on corn.

++35 tons sawdust applied in 1954.

‡ 4 tons wheat straw plowed down for corn.

Except for the first sampling date, soil phosphorus levels were lower than for the preceding experiment (tables 5-a and 5-b).

Soil potassium

The amount of available potassium in the soil (table 14) was not affected as much by the various treatments as was tissue potassium (table 11). In both cases, however, low levels of potassium were associated with the check treatment. The seasonal average for this treatment was found to differ from that for alfalfa-brome or sawdust at the one percent level of probability.

Supplemental nitrogen had no effect on soil potassium. The actual quantities found were similar to those in the previous experiment (tables 6-a and 6-b).

Soil reaction

Data on soil pH are presented in table 15. Variations in pH were not great (from 0.1 to 0.3 pH units). However, differences associated with nitrogen treatment were significant at the one percent level of probability during the last four samplings. The date x nitrogen interaction was also highly significant. This can be attributed to the fact that pH variations from date to date were larger where no supplemental nitrogen was used than where it was. The acidifying effect of the nitrogen fertilizer tended to counteract unknown factors which tended to raise the pH during the course of the season on plots which received no supplemental nitrogen. This behavior was similar to that observed in the previous experiment (tables 7-a and 7-b).

Corn yield

Corn yields shown in the first column of table 16 were very uni-

Table 14. -- Pounds per acre soil K by dates of sampling as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	6/28	7/7	7/20	7/27	8/11	9/16	Seasonal Average
		Date						
Check**	R_1	171	162	218	173	168	147	173
Alfalfa-brome+	R_2	177	184	224	172	185	161	184
Sawdust++	R_3	180	175	232	169	174	155	181
Straw‡	R_4	181	174	222	155	178	157	178
LSD_{05}		NS	NS	NS	NS	NS	9	6
No Suppl. N	N_1	177	174	225	166	180	155	180
Ave. N Treatment*	N_2	177	173	223	168	172	155	178
LSD_{05}		NS	NS	NS	NS	NS	NS	NS
	R_1N_1	169	164	222	168	174	147	174
	R_1N_2	173	160	214	178	163	147	172
	R_2N_1	177	184	226	166	190	156	183
	R_2N_2	177	184	222	178	180	166	184
	R_3N_1	184	176	226	178	176	156	183
	R_3N_2	176	174	239	160	171	153	179
	R_4N_1	180	174	226	152	180	161	179
	R_4N_2	183	175	219	158	176	153	177
LSD_{05}	(R within N)	NS	NS	NS	NS	NS	12	8
LSD_{05}	(N within R)	NS	NS	NS	NS	NS	NS	NS

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5-year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.
**All second-year hay removed.
+Second-year hay left and plowed down on corn.
++35 tons sawdust applied in 1954.
‡4 tons wheat straw plowed down for corn.

Table 15. -- Soil pH by dates of sampling as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	Date						Seasonal
		6/28	7/7	7/20	7/27	8/11	9/16	Average
Check**	R_1	6.2	6.3	6.1	6.1	6.3	6.2	6.3
Alfalfa-brome+	R_2	6.2	6.3	6.2	6.1	6.3	6.3	6.3
Sawdust++	R_3	6.1	6.3	6.1	6.0	6.2	6.3	6.2
Straw‡	R_4	6.2	6.3	6.2	6.1	6.3	6.3	6.3
LSD_{05}		.05	NS	NS	NS	NS	NS	.03
No Suppl. N	N_1	6.2	6.4	6.2	6.1	6.4	6.4	6.3
Ave. N Treatment*	N_2	6.2	6.3	6.1	6.0	6.2	6.1	6.1
LSD_{05}		NS	.06	.05	.08	.07	.08	.03
	R_1N_1	6.3	6.3	6.2	6.1	6.4	6.4	6.3
	R_1N_2	6.2	6.3	6.1	6.0	6.2	6.1	6.1
	R_2N_1	6.2	6.4	6.2	6.2	6.4	6.4	6.3
	R_2N_2	6.2	6.3	6.2	6.0	6.3	6.2	6.2
	R_3N_1	6.2	6.3	6.2	6.1	6.3	6.4	6.3
	R_3N_2	6.1	6.2	6.0	6.0	6.2	6.1	6.1
	R_4N_1	6.1	6.4	6.3	6.2	6.3	6.4	6.3
	R_4N_2	6.2	6.3	6.2	6.0	6.2	6.1	6.2
LSD_{05}	(R within N)	.12	NS	NS	NS	NS	NS	.05
LSD_{05}	(N within R)	NS	NS	.11	.17	.15	.16	.07

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5-year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.

**All second-year hay removed.

+Second-year hay left and plowed down on corn.

++35 tons sawdust applied in 1954.

‡ 4 tons wheat straw plowed for corn.

Table 16. -- Corn yields, fertile stalks, barren stalks and total stalks per acre as related to organic residues and nitrogen treatments. Sims clay loam. Ferden Farm. 1960. (Tasseling date: July 25.)

Treatment	Code	Yield Bu./A	Stalks per acre Fertile	Barren	Total
Check**	R_1	104	13737	552	14289
Alfalfa-brome+	R_2	108	14007	655	14662
Sawdust++	R_3	108	14634	669	15304
Straw‡	R_4	105	13613	538	14151
LSD_{05}		3	NS	NS	NS
No Suppl. N	N_1	105	13710	658	14369
Ave. N treatment*	N_2	107	14286	548	14835
LSD_{05}		NS	NS	NS	NS
	R_1N_1	104	13744	593	14338
	R_1N_2	104	13731	510	14241
	R_2N_1	106	13386	593	13979
	R_2N_2	109	14628	717	15345
	R_3N_1	108	14710	745	15456
	R_3N_2	108	14559	593	15152
	R_4N_1	103	12999	703	13703
	R_4N_2	108	14227	372	14600
LSD_{05}	(R within N)	NS	NS	NS	NS
LSD_{05}	(N within R)	NS	NS	NS	NS

*100 pounds N per acre on corn, 40 pounds on beans and barley in a 5-year rotation. No N on alfalfa-brome (2 years). 1960 N applications on corn: 50 pounds on June 9 plus 50 pounds on June 30.
**All second-year hay removed.
+Second-year hay left and plowed down for corn.
++35 tons sawdust applied in 1954.
‡ 4 tons wheat straw plowed down for corn.

form on these plots. Yields varied from 103 to 109 bushels per acre. The only significant differences were related to residue treatment.

The uniformly low phosphorus soil tests (table 13) suggest that phosphate availability was the factor which primarily controlled yields on these plots. There may have been some response to supplemental nitrogen in the case of the straw residue treatment. The five-bushel yield increase for nitrogen with straw was not significant, but it was associated with relatively low soil nitrate levels (table 12).

The significantly higher yields for the alfalfa-brome and sawdust treatments were very likely in response to phosphate released from organic sources. The rather high tissue test for phosphorus on the sawdust plots early in the season is consistent with this view (table 10).

Corn populations

Stand counts, shown in the last three columns of table 16 were not influenced significantly by treatment. Total stands were somewhat higher on alfalfa-brome and sawdust plots than on the other residue plots. There was also a tendency for supplemental nitrogen to reduce the proportion of barren stalks, particularly in combination with straw treatment.

Nitrogen Sources Experiment

This experiment involved a comparison of calcium nitrate and ammonium sulfate at two rates in fall, spring and summer applications for corn. The same treatments have been applied on the same plots over a four-year period. Treatments were replicated four times and all plots were sampled for soil and tissue tests.

Tissue nitrate

Data presented in tables 17-a and 17-b show NO_3^- in the tissue of corn grown on Hillsdale sandy loam. A statistical analysis combining all of the data showed significance at the one percent level for differences between means for sampling dates and for all main factor effects on seasonal averages. The interaction mean square for date x materials was significant at five percent. Mean squares significant at one percent were obtained for interactions between sampling date, on the one hand, and effects of rate and time of application and the average effect of nitrogen, on the other. The major changes associated with sampling date were a sharp drop in nitrate at tasseling time, followed by a further, less drastic decline during the last sampling interval. The highly significant interactions between treatment factors and date of sampling were due to the fact that rates of seasonal decline were different for different treatments. The most rapid seasonal declines were associated with high early levels of nitrate.

Main effects of treatment are strikingly apparent in the first two samplings and in the seasonal averages. The use of supplemental nitrogen enhanced nitrate accumulation in the first two tissue samplings, but this effect was significantly reversed in the last sampling. The enhancement in the first two samplings was greater at the 80-pound rate of nitrogen fertilization than at 40 pounds, and again there was a tendency towards reversal of the effect in the last sampling.

The fertilizer source of nitrogen was found to affect nitrate accumulation in the tissue. Ammonium sulfate maintained higher levels of tissue nitrate in the first two samplings at all rates and times of application than did calcium nitrate. Differences in the last sampling

Table 17-a. -- PPM NO_3-N in corn tissue by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1)

Treatment	Code	Date 7/14	Date 8/4	Date 9/12	Seasonal Average
No Suppl. N	N_1	361	107	92	177
Ave. N Treatment	N_2	725	259	57	309
LSD_{05}		188	103	30	84
Ammon. Sulf.	M_1	810	288	56	344
Calcium Nitr.	M_2	640	230	57	273
LSD_{05}		105	57	NS	46
40 lbs. N per A.	R_1	655	183	60	261
80 lbs. N per A.	R_2	795	335	54	356
LSD_{05}		105	57	NS	46
Late Fall*	T_1	608	214	62	247
Spring**	T_2	876	300	47	388
Summer***	T_3	691	264	61	291
LSD_{05}		128	NS	NS	57
	M_1R_1	754	195	62	290
	M_1R_2	866	381	50	398
	M_2R_1	556	171	57	231
	M_2R_2	725	289	57	315
LSD_{05}		148	81	NS	66
	M_1T_1	721	261	49	278
	M_1T_2	996	312	60	433
	M_1T_3	713	291	60	320
	M_2T_1	495	167	75	216
	M_2T_2	756	287	34	342
	M_2T_3	670	237	62	261
LSD_{05}		181	99	29	80
	R_1T_1	571	159	63	223
	R_1T_2	821	177	59	323
	R_1T_3	572	213	57	236
	R_2T_1	645	268	61	271
	R_2T_2	931	422	35	452
	R_2T_3	811	315	66	346
LSD_{05}		181	99	NS	80

*Broadcast on surface (soil temperature near freezing).

**Plowed down just before planting.

***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 17-b. -- PPM NO_3-N in corn tissue by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Date 7/14	8/4	9/12	Seasonal Average
$M_1R_1T_1$	721 bcd	188 de	55 abc	258 bcd
$M_1R_1T_2$	908 ab	185 de	71 ab	342 b
$M_1R_1T_3$	632 bcde	214 cde	60 abc	271 bcd
$M_1R_2T_1$	721 bcd	333 abcd	42 bc	299 bcd
$M_1R_2T_2$	1084 a	440 a	49 abc	524 a
$M_1R_2T_3$	793 abcd	369 abc	60 abc	370 b
$M_2R_1T_1$	422 e	131 e	71 ab	189 cd
$M_2R_1T_2$	734 bcd	170 de	47 abc	305 bcd
$M_2R_1T_3$	512 de	213 cde	53 abc	201 cd
$M_2R_2T_1$	568 cde	203 de	79 ab	243 bcd
$M_2R_2T_2$	778 bcd	403 ab	20 c	380 b
$M_2R_2T_3$	829 abc	261 bcde	71 ab	322 bc
No N	361 e	107 e	92 a	177 d

a, b, c, d, e -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

were not significant.

Spring application (at planting time) induced more NO_3^- accumulation in the tissue prior to tasseling than did fall or summer applications. This effect of spring application was most pronounced where the ammonium form of fertilizer nitrogen was used and at the higher rate of application (see also table 17-b).

Differences between fall and summer applications were not statistically significant. However, there was a marked tendency with calcium nitrate for summer sidedressing to promote higher tissue tests for nitrate prior to tasseling than fall application (table 17-b).

Except for the check treatment (no supplemental N), nitrate levels on July 14 were very similar to those for the comparable date in the residue experiment and two to three times higher than for Rotation 1 in the first experiment. Final levels in September were much lower than for either experiment conducted on heavier soil (cf. tables 1-a and 9).

Tissue phosphorus

There was a continuing increase in soluble tissue phosphorus over the sampled portion of the growing season (tables 18-a and 18-b). The mean square for sampling date was significant at the one percent level of probability.

The seasonal increase in tissue phosphorus was much less marked where supplemental nitrogen was used than where it was not. Ammonium sulfate was particularly effective in stabilizing phosphorus levels. Phosphorus tests were significantly lower with ammonium sulfate than with calcium nitrate.

High phosphorus levels late in the season were associated with treatments which had promoted relatively low nitrate tests in the first

Table 18-a.-- PPM soluble P in corn tissue by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment	Code	Date 7/14	8/4	9/12	Seasonal Average
No Suppl. N	N_1	64	109	157	111
Ave. N Treatment	N_2	66	91	111	89
LSD_{05}		NS	NS	NS	21
Ammon. Sulf.	M_1	61	85	92	79
Calcium Nitr.	M_2	72	97	130	99
LSD_{05}		10	NS	30	10
40 lbs. N per A.	R_1	68	90	117	90
80 lbs. N per A.	R_2	65	93	104	88
LSD_{05}		NS	NS	NS	NS
Late fall*	T_1	65	87	128	94
Spring**	T_2	68	92	90	81
Summer***	T_3	67	94	114	91
LSD_{05}		NS	NS	NS	NS
	M_1R_1	63	85	83	76
	M_1R_2	58	85	101	83
	M_2R_1	73	95	151	105
	M_2R_2	72	100	108	93
LSD_{05}		14	NS	42	16
	M_1T_1	63	72	98	79
	M_1T_2	57	88	74	70
	M_1T_3	63	96	103	88
	M_2T_1	67	103	158	109
	M_2T_2	78	97	107	93
	M_2T_3	72	93	125	95
LSD_{05}		17	NS	51	20
	R_1T_1	70	84	158	104
	R_1T_2	67	88	73	74
	R_1T_3	67	98	120	93
	R_2T_1	59	90	98	84
	R_2T_2	58	97	108	89
	R_2T_3	68	91	108	90
LSD_{05}		NS	NS	NS	NS

*Broadcast on surface (soil temperature near freezing).

**Plowed down just before planting.

***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 18-b. -- PPM Soluble P in corn tissue by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Date 7/14	Date 8/4	Date 9/12	Seasonal Average
$M_1R_1T_1$	66 a	69 a	95 bc	79 bcd
$M_1R_1T_2$	58 a	88 a	68 c	67 d
$M_1R_1T_3$	65 a	100 a	85 bc	81 bcd
$M_1R_2T_1$	59 a	75 a	100 bc	80 bcd
$M_1R_2T_2$	56 a	88 a	80 bc	73 cd
$M_1R_2T_3$	60 a	93 a	122 bc	95 abcd
$M_2R_1T_1$	74 a	100 a	220 a	129 a
$M_2R_1T_2$	76 a	88 a	78 bc	81 bcd
$M_2R_1T_3$	69 a	96 a	155 ab	104 abc
$M_2R_2T_1$	60 a	105 a	95 bc	88 bcd
$M_2R_2T_2$	80 a	106 a	135 bc	104 abc
$M_2R_2T_3$	75 a	89 a	95 bc	86 bcd
No N	64 a	109 a	157 ab	111 ab

a, b, c, d -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

sampling (cf. tables 17-a and 17-b). A similar inverse relationship between early season nitrate and late season phosphate was observed in the rotation experiment (cf. tables 1-a and 2-a). This suggests that the capacity for assimilating phosphate is influenced in the corn plant by nitrogen nutrition during early stages of growth.

This hypothesized relationship is most evident in the data which relate to the two nitrogen materials. Ammonium sulfate promoted much higher levels of tissue nitrate in the July 14 sampling than did calcium nitrate. This effect was most pronounced at the low rate of application and in the fall and spring applications. These are the treatments where the inverse relationship to late season phosphate was also most pronounced. The low rate of nitrogen fertilization was inadequate for maximum yields (table 24-a). The fall and spring applications would have influenced early stages of growth which would not have been influenced by the summer application. Therefore, it appears that high levels of unassimilated phosphate in the sap late in the season reflected restricted physiological development imposed by inadequate nitrogen nutrition at earlier stages of growth.

Tissue potassium

Changes in the level of tissue potassium from one sampling date to another (tables 19-a and 19-b) were highly significant. There was a sharp drop at tasseling time followed by a moderate rise at the end of the season.

There was no significant relationship with treatment, except in the September sampling. Here, tissue potassium was reduced by application of fertilizer nitrogen. The reduction was greater at the 80-pound

Ta

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Table 19-a. -- PPM K in corn tissue by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1)

Treatment	Code	Date 7/14	Date 8/4	Date 9/12	Seasonal Average
No Suppl. N	N_1	541	421	465	480
Ave. N Treatment	N_2	549	394	418	457
LSD_{05}		NS	NS	42	NS
Ammon. Sulf.	M_1	563	393	415	464
Calcium Nitr.	M_2	535	395	420	450
LSD_{05}		NS	NS	NS	NS
40 lbs. N per A.	R_1	547	390	431	460
80 lbs. N per A.	R_2	551	398	404	454
LSD_{05}		NS	NS	23	NS
Late Fall*	T_1	535	394	424	450
Spring**	T_2	561	385	406	455
Summer***	T_3	551	403	422	466
LSD_{05}		NS	NS	NS	NS
	M_1R_1	561	383	422	460
	M_1R_2	565	402	408	467
	M_2R_1	533	398	440	460
	M_2R_2	538	393	401	440
LSD_{05}		NS	NS	33	NS
	M_1T_1	549	388	423	454
	M_1T_2	574	394	393	459
	M_1T_3	566	396	428	478
	M_2T_1	521	400	426	446
	M_2T_2	549	376	419	451
	M_2T_3	536	410	416	453
LSD_{05}		NS	NS	NS	NS
	R_1T_1	536	386	448	453
	R_1T_2	552	381	414	455
	R_1T_3	552	404	430	473
	R_2T_1	533	402	400	447
	R_2T_2	571	389	398	455
	R_2T_3	550	402	414	459
LSD_{05}		NS	NS	40	NS

*Broadcast on surface (soil temperature near freezing).
**Plowed down just before planting.
***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 19-b. -- PPM - K in corn tissue by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Date 7/14	8/4	9/12	Seasonal Average
$M_1R_1T_1$	560 a	366 a	445 abc	455 a
$M_1R_1T_2$	547 a	401 a	385 c	445 a
$M_1R_1T_3$	575 a	383 a	435 abc	480 a
$M_1R_2T_1$	538 a	410 a	400 abc	453 a
$M_1R_2T_2$	600 a	388 a	402 abc	473 a
$M_1R_2T_3$	557 a	409 a	422 abc	476 a
$M_2R_1T_1$	513 a	406 a	452 ab	452 a
$M_2R_1T_2$	557 a	361 a	443 abc	464 a
$M_2R_1T_3$	529 a	425 a	425 abc	465 a
$M_2R_2T_1$	529 a	394 a	400 abc	440 a
$M_2R_2T_2$	541 a	391 a	395 bc	438 a
$M_2R_2T_3$	544 a	395 a	407 abc	442 a
No N	541 a	421 a	465 a	480 a

a, b, c -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

rate than at 40 pounds. This rate effect was greater with calcium nitrate than with ammonium sulfate, and greater with fall application than with applications made in spring or summer. In other words, potassium behaved with respect to nitrogen fertilization in a manner similar to phosphorus in this last sampling.

Soil nitrate

Nitrate accumulations in soil were increased significantly throughout the season by additions of nitrogen fertilizer (tables 20-a and 20-b). The higher rate of nitrogen application maintained higher NO_3^- levels in the soil. These main effects of nitrogen fertilizer were the same as their effects on tissue nitrate prior to and at tasseling time (cf. tables 17-a and 17-b). In September, tissue nitrate was inversely related to soil nitrate for these same treatment combinations.

Except for the July 14 sampling, the soil nitrate mean squares for time of application were highly significant. The highest levels of soil nitrate throughout the season were associated with the summer sidedressing. The spring application maintained higher soil nitrate tests than the fall application through the August 12 sampling. In contrast to this, tissue nitrate prior to tasseling was much higher where nitrogen was applied at planting time than where it was applied either in the fall or as a sidedressing in mid June.

There was no significant main effect of nitrogen source on soil nitrate levels. However, there was a significant to highly significant interaction between materials and time of application on most sampling dates and in the seasonal averages. This was due to the fact, with fall application, higher levels of nitrate were maintained in the soil by ammonium sulfate than by calcium nitrate, whereas the reverse was

Table 20-a. -- Pounds per acre NO_3-N in soil by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment	Code	Date 6/30	7/14	8/4	8/12	9/12	Seasonal Average
No Suppl. N	N_1	20	43	14	7	7	18
Ave. N Treatment	N_2	41	57	36	17	13	33
LSD_{05}		12	NS	13	8	NS	7
Ammon. Sulf.	M_1	38	58	36	18	14	33
Calcium Nitr.	M_2	43	57	36	17	12	33
LSD_{05}		NS	NS	NS	NS	NS	NS
40 lbs. N per A.	R_1	36	48	31	9	6	26
80 lbs. N per A.	R_2	46	66	41	25	19	39
LSD_{05}		6	14	7	4	6	4
Late fall*	T_1	32	47	27	10	8	25
Spring**	T_2	39	60	37	18	9	33
Summer***	T_3	51	64	44	24	21	41
LSD_{05}		8	NS	9	5	7	4
	M_1R_1	34	45	34	10	6	26
	M_1R_2	43	70	37	26	21	39
	M_2R_1	38	51	28	9	7	26
	M_2R_2	49	62	44	25	18	39
LSD_{05}		9	20	10	6	8	5
	M_1T_1	41	54	32	13	9	30
	M_1T_2	35	68	38	20	13	35
	M_1T_3	39	51	37	21	19	33
	M_2T_1	23	41	21	6	7	20
	M_2T_2	43	52	36	16	6	30
	M_2T_3	64	77	51	27	24	49
LSD_{05}		11	25	13	7	10	6
	R_1T_1	29	47	22	7	5	22
	R_1T_2	32	49	32	8	6	26
	R_1T_3	46	49	39	13	8	31
	R_2T_1	35	48	31	13	12	28
	R_2T_2	46	70	42	28	12	40
	R_2T_3	57	80	49	36	34	51
LSD_{05}		11	25	13	7	10	6

*Broadcast on surface (soil temperature near freezing).

**Plowed down just before planting.

***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 20-b. -- Pounds per acre NO_3-N in soil by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Date 6/30	7/14	8/4	8/12	9/12	Seasonal Average
$M_1R_1T_1$	34 cd	46 bc	29 bcd	9 d	4 c	24 e
$M_1R_1T_2$	34 cd	51 bc	38 b	9 d	8 c	28 cde
$M_1R_1T_3$	33 cd	40 c	35 bc	13 d	6 c	26 de
$M_1R_2T_1$	48 bc	63 abc	36 b	18 cd	15 bc	36 bcd
$M_1R_2T_2$	35 cd	85 ab	39 ab	31 ab	18 bc	42 b
$M_1R_2T_3$	44 bc	62 abc	38 b	30 abc	31 ab	41 b
$M_2R_1T_1$	24 d	48 bc	15 cd	6 d	6 c	20 e
$M_2R_1T_2$	31 cd	48 bc	27 bcd	7 d	5 c	23 e
$M_2R_1T_3$	59 ab	57 abc	42 ab	13 d	9 c	36 bcd
$M_2R_2T_1$	22 d	34 c	27 bcd	7 d	9 c	20 e
$M_2R_2T_2$	56 ab	56 bc	45 ab	25 bc	7 c	38 bc
$M_2R_2T_3$	69 a	98 a	60 a	42 a	38 a	61 a
No N	20 d	43 c	14 d	7 d	7 c	18 e

a, b, c, d, e -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

true with summer sidedressing. There was no difference between the two materials when they were applied at the time of spring planting.

In the case of tissue nitrate (table 17-a), on the other hand, higher levels were maintained through tasseling time by ammonium sulfate than by calcium nitrate, particularly with fall and spring applications. Since soil nitrate levels were unaffected, this suggests that the young corn crop was taking up nitrogen in both the ammonium and nitrate forms, but was preferentially assimilating the ammonium form. As a result, nitrate accumulated in the sap where the ammonium form was made available in fertilizer. This is consistent with accepted concepts of nitrogen nutrition (63, 69).[1]

Mean squares associated with sampling date were significant at the one percent level of probability. The seasonal decline in soil nitrate after tasseling in this sandy loam soil was, in general, more rapid than in the two earlier experiments conducted on Sims clay loam. Levels prior to tasseling tended to be higher, those at the end of the season lower. However, the 80-pound summer sidedressing with continuous corn on the sandy loam was equally as effective in maintaining soil nitrate through the period after tasseling as was 100 pounds sidedressed on corn in rotations including two years of alfalfa-brome on the heavier soil (cf. tables 4-a and 4-b).

Soil phosphorus

Addition of nitrogen tended to depress available soil phosphorus (tables 21-a and 21-b). This effect was rather consistent throughout

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[1]However, see also relation to soil pH, pp. 77.

Table 21-a. -- Pounds per acre P in soil by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment	Code	Date 6/30	7/14	8/4	8/12	9/12	Seasonal Average
No Suppl. N	N_1	127	126	123	121	123	124
Ave. N Treatment	N_2	115	116	117	128	112	118
LSD_{05}		12	NS	NS	NS	NS	6
Ammon. Sulf.	M_1	115	115	117	129	112	118
Calcium Nitr.	M_2	115	118	117	128	112	118
LSD_{05}		NS	NS	NS	NS	NS	NS
40 lbs. N per A.	R_1	114	117	118	129	115	119
80 lbs. N per A.	R_2	116	116	117	128	109	117
LSD_{05}		NS	NS	NS	NS	NS	NS
Late Fall*	T_1	116	116	121	135	116	121
Spring**	T_2	118	121	121	132	111	121
Summer***	T_3	111	112	110	118	108	112
LSD_{05}		NS	NS	7	13	NS	4
	M_1R_1	114	117	119	132	119	120
	M_1R_2	116	113	115	126	105	115
	M_2R_1	114	117	117	127	111	117
	M_2R_2	115	118	118	129	112	119
LSD_{05}		NS	NS	NS	NS	NS	5
	M_1T_1	115	113	119	134	113	119
	M_1T_2	123	124	123	136	112	124
	M_1T_3	108	108	110	117	111	111
	M_2T_1	118	120	122	137	119	123
	M_2T_2	113	117	119	127	111	118
	M_2T_3	113	116	110	120	105	113
LSD_{05}		12	NS	10	18	NS	6
	R_1T_1	113	121	120	142	121	123
	R_1T_2	116	116	119	129	112	118
	R_1T_3	114	115	115	118	112	115
	R_2T_1	119	112	121	129	112	119
	R_2T_2	121	126	124	135	111	123
	R_2T_3	107	110	105	119	104	109
LSD_{05}		12	NS	10	18	NS	6

*Broadcast on surface (soil temperature near freezing).
**Plowed down just before planting.
***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 21-b.-- Pounds per acre P in soil by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Date					Seasonal Average
	6/30	7/14	8/4	8/12	9/12	
$M_1R_1T_1$	108 ab	118 a	118 a	140 ab	122 a	121 ab
$M_1R_1T_2$	127 a	122 a	121 a	135 ab	114 a	123 a
$M_1R_1T_3$	109 ab	112 a	119 a	122 ab	121 a	116 ab
$M_1R_2T_1$	122 ab	107 a	120 a	128 ab	104 a	116 ab
$M_1R_2T_2$	120 ab	127 a	125 a	138 ab	111 a	124 a
$M_1R_2T_3$	108 ab	105 a	101 b	112 b	101 a	105 c
$M_2R_1T_1$	118 ab	124 a	122 a	143 a	119 a	125 a
$M_2R_1T_2$	105 b	111 a	117 ab	123 ab	111 a	113 bc
$M_2R_1T_3$	119 ab	117 a	111 ab	114 ab	103 a	113 bc
$M_2R_2T_1$	117 ab	117 a	123 a	130 ab	119 a	121 ab
$M_2R_2T_2$	122 ab	124 a	122 a	132 ab	111 a	122 ab
$M_2R_2T_3$	107 b	115 a	109 ab	126 ab	107 a	113 bc
No N	127 a	126 a	123 a	121 ab	123 a	124 a

a, b, c -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

the season. It was most evident in connection with summer sidedressing at the 80-pound rate of ammonium sulfate. As a result, highly significant mean squares were obtained in the seasonal averages for time of application; mean squares significant at five percent were obtained for the interactions between materials and rates, materials and time of application, and rates and time of application.

Comparison with tables 20-a and 20-b shows that soil phosphorus tests tended to be inversely related to soil tests for nitrate.

Mean yields for various treatments (table 24-a) were also inversely related to mean soil phosphorus tests. Thus it appears that the lower soil phosphorus levels reflected higher rates of removal associated with more vigorous growth of corn. Absolute levels of soil phosphorus in this experiment were of the order of five to ten times higher than in either of the two previous experiments (tables 5-a and 13).

Soil potassium

Soil tests for potassium (tables 22-a and 22-b) reflected the influence of treatment factors to a greater extent than tissue tests for potassium (table 19-a). However, there was no correspondence between soil and tissue tests.

A combined analysis of variance of all the soil potassium data showed that seasonal trends were highly significant. These included a gradual rise to maximum values at tasseling time, followed by a more rapid decline to seasonally low values in the last sampling.

The seasonal peak and levels after tasseling were lower with calcium nitrate than with ammonium sulfate. Highly significant materials x rates and materials x time interactions were obtained. High

Table 22-a. -- Pounds per acre K in soil by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment	Code	Date 6/30	7/14	8/4	8/12	9/12	Seasonal Average
No Suppl. N	N_1	196	204	224	159	198	196
Ave. N Treatment	N_2	202	208	229	183	154	195
LSD_{05}		NS	NS	NS	NS	27	NS
Ammon. Sulf.	M_1	202	212	241	198	159	202
Calcium Nitr.	M_2	203	203	217	168	148	188
LSD_{05}		NS	NS	21	18	NS	8
40 lbs. N per A.	R_1	196	217	230	179	158	196
80 lbs. N per A.	R_2	208	198	229	187	149	194
LSD_{05}		NS	NS	NS	NS	NS	NS
Late Fall*	T_1	200	209	226	179	161	195
Spring**	T_2	204	203	224	185	158	194
Summer***	T_3	203	212	238	184	142	196
LSD_{05}		NS	NS	NS	NS	NS	NS
	M_1R_1	210	226	250	199	169	211
	M_1R_2	193	197	232	197	148	194
	M_2R_1	183	207	209	159	146	181
	M_2R_2	223	199	225	177	151	195
LSD_{05}		27	NS	29	25	NS	11
	M_1T_1	194	203	225	199	166	197
	M_1T_2	203	197	229	191	151	194
	M_1T_3	208	235	271	204	159	215
	M_2T_1	206	214	227	159	156	193
	M_2T_2	204	208	219	180	164	195
	M_2T_3	198	188	205	164	125	176
LSD_{05}		NS	33	NS	31	26	14
	R_1T_1	186	223	231	177	166	197
	R_1T_2	189	202	210	182	155	188
	R_1T_3	214	225	248	177	152	203
	R_2T_1	214	194	221	182	156	193
	R_2T_2	218	203	238	188	160	201
	R_2T_3	192	198	227	191	132	188
LSD_{05}		NS	NS	NS	NS	NS	14

*Broadcast on surface (soil temperature near freezing).
**Plowed down just before planting.
***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 22-b.-- Pounds per acre K in soils by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Date 6/30	7/14	8/4	8/12	9/12	Seasonal Average
$M_1R_1T_1$	190 abc	222 ab	240 ab	200 ab	176 abc	206 b
$M_1R_1T_2$	210 abc	192 b	216 b	187 abc	148 bcde	191 bc
$M_1R_1T_3$	230 ab	264 a	295 a	209 a	184 ab	236 a
$M_1R_2T_1$	198 abc	184 b	210 b	198 ab	156 abcde	189 bc
$M_1R_2T_2$	196 abc	202 b	241 ab	194 abc	154 abcde	197 b
$M_1R_2T_3$	186 abc	206 b	246 ab	200 ab	134 cde	194 b
$M_2R_1T_1$	182 bc	224 ab	223 b	154 bc	156 abcde	188 bc
$M_2R_1T_2$	168 c	212 ab	203 b	178 abc	162 abcde	185 bc
$M_2R_1T_3$	198 abc	186 b	201 b	145 c	120 e	170 c
$M_2R_2T_1$	230 ab	204 b	232 b	165 abc	156 abcde	197 b
$M_2R_2T_2$	240 a	204 b	234 b	183 abc	166 abcd	205 b
$M_2R_2T_3$	198 abc	190 b	209 b	182 abc	130 de	182 bc
No N	196 abc	204 b	224 b	159 abc	198 a	196 b

a, b, c, d, e -- Ranges of equivalence (Duncan, 1955). Within columns numerical values with the same literal subscripts are not different at 5 percent.

soil tests for potassium were associated with the low rate of ammonium sulfate addition and with the high rate of calcium nitrate. The highest levels of potassium were generally associated with the summer sidedressing of ammonium sulfate, whereas calcium nitrate applied at this same time usually favored the lowest potassium tests. A rate x time interaction, significant at five percent, was also involved, such that low soil potassium most frequently followed spring application at the 40-pound rate, whereas, at the 80-pound rate, the lowest tests were found following the summer sidedressing.

This complicated response pattern in the soil potassium tests could not be related in any straightforward manner to soil or tissue tests for nitrate or phosphorus, nor to vigor of growth as reflected in final yields. Low tests were associated to some extent with high yields. However, the strong influence of nitrogen source on soil potassium levels suggests that cationic interactions involving ammonium and potassium or calcium and potassium were also involved.

Soil reaction

The range of soil reactions encountered during the season in this sandy loam soil (tables 23-a and 23-b) was greater than in the two experiments on Sims clay loam (pH 4.8 to 5.9 as against 6.0 to 6.9 in the rotation experiment and 6.0 to 6.4 in the residue experiment). Soil reaction was influenced to a greater degree by seasonal and treatment factors, reflecting the lower buffer capacity of the lighter soil.

Where no supplemental nitrogen was used or where calcium nitrate was used, pH rose sharply after tasseling. These late season increases were associated with depletion of soil nitrate and were highly significant. Where ammonium sulfate was used, pH was significantly lower all

Table 23-a.-- Soil pH by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1)

Treatment	Code	Date 6/30	7/14	8/4	8/12	9/12	Seasonal Average
No Suppl. N	N_1	5.5	5.6	5.5	5.7	5.8	5.6
Ave. N Treatment	N_2	5.3	5.2	5.2	5.4	5.5	5.3
LSD_{05}		NS	.20	.21	.16	.22	.10
Ammon. Sulf.	M_1	5.1	5.1	4.9	5.1	5.3	5.1
Calcium Nitr.	M_2	5.4	5.4	5.4	5.6	5.7	5.5
LSD_{05}		.17	.11	.12	.09	.12	.05
40 lbs. N per A.	R_1	5.3	5.3	5.2	5.5	5.6	5.4
80 lbs. N per A.	R_2	5.3	5.2	5.1	5.3	5.5	5.3
LSD_{05}		NS	.11	NS	.09	NS	.05
Late Fall*	T_1	5.2	5.2	5.2	5.4	5.5	5.3
Spring**	T_2	5.3	5.3	5.1	5.4	5.5	5.3
Summer***	T_3	5.4	5.3	5.2	5.4	5.5	5.3
LSD_{05}		NS	NS	NS	NS	NS	NS
	M_1R_1	5.2	5.2	5.0	5.3	5.4	5.2
	M_1R_2	5.1	5.0	4.9	5.0	5.2	5.0
	M_2R_1	5.4	5.4	5.4	5.6	5.7	5.5
	M_2R_2	5.4	5.3	5.4	5.6	5.8	5.5
LSD_{05}		.24	.16	.17	.12	.17	.08
	M_1T_1	5.0	5.0	4.9	5.2	5.4	5.1
	M_1T_2	5.1	5.1	4.9	5.1	5.3	5.1
	M_1T_3	5.3	5.2	5.0	5.1	5.2	5.2
	M_2T_1	5.4	5.4	5.4	5.6	5.7	5.5
	M_2T_2	5.5	5.5	5.4	5.6	5.7	5.5
	M_2T_3	5.4	5.3	5.3	5.6	5.8	5.5
LSD_{05}		.29	.19	.20	.15	.21	.09
	R_1T_1	5.1	5.2	5.2	5.5	5.6	5.3
	R_1T_2	5.3	5.4	5.1	5.4	5.5	5.3
	R_1T_3	5.5	5.3	5.3	5.5	5.6	5.4
	R_2T_1	5.3	5.2	5.1	5.3	5.5	5.3
	R_2T_2	5.3	5.2	5.2	5.3	5.5	5.3
	R_2T_3	5.3	5.2	5.1	5.2	5.4	5.2
LSD_{05}		NS	.19	NS	.15	NS	.09

*Broadcast on surface (soil temperature near freezing).
**Plowed down just before planting.
***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 23-b. -- Soil pH by dates of sampling as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Date 6/30	7/14	8/4	8/12	9/12	Seasonal Average
$M_1R_1T_1$	4.8 b	5.0 cd	5.1 cdef	5.3 bc	5.4 cd	5.1 cd
$M_1R_1T_2$	5.2 ab	5.4 ab	4.9 ef	5.3 bc	5.5 bcd	5.3 bc
$M_1R_1T_3$	5.5 a	5.3 abc	5.1 cdef	5.3 bc	5.4 cd	5.3 bc
$M_1R_2T_1$	5.2 ab	5.1 bcd	4.8 f	5.1 cd	5.4 cd	5.1 cd
$M_1R_2T_2$	5.0 b	4.9 d	4.8 f	4.9 d	5.2 de	5.0 d
$M_1R_2T_3$	5.2 ab	5.1 bcd	5.0 def	5.0 cd	5.0 e	5.1 cd
$M_2R_1T_1$	5.4 a	5.4 ab	5.4 abc	5.7 a	5.8 ab	5.5 ab
$M_2R_1T_2$	5.4 a	5.4 ab	5.3 abcd	5.6 ab	5.6 abc	5.4 ab
$M_2R_1T_3$	5.5 a	5.4 ab	5.4 abc	5.7 a	5.8 ab	5.6 a
$M_2R_2T_1$	5.4 a	5.3 abc	5.4 abc	5.6 ab	5.7 abc	5.4 ab
$M_2R_2T_2$	5.6 a	5.6 a	5.6 a	5.7 a	5.9 a	5.6 a
$M_2R_2T_3$	5.3 ab	5.2 bcd	5.2 bcde	5.5 ab	5.7 abc	5.4 ab
No N	5.5 a	5.6 a	5.5 ab	5.7 a	5.8 ab	5.6 a

a, b, c, d, e, f -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

through the season. The acidifying effect of ammonium sulfate was greater at the 80-pound rate than at 40 pounds, and the seasonal increase in the last two samplings was not significant at the higher rate.

Corn yield

Data in the first column of table 24-a show that supplemental nitrogen application increased corn yields, on an average, 45 percent over the check. There was an average increase of nine bushels per acre for 80 pounds of nitrogen over 40 pounds, regardless of material. However, the increase for rate was associated primarily with spring and summer application; the rate response with fall application was not significant at five percent probability.

Summer sidedressing gave a highly significant six to seven bushel increase over either fall or spring application. However, there was a significant materials x time interaction, such that yields were equally good with spring and summer applications of calcium nitrate, whereas, with ammonium sulfate, the spring application was significantly less efficient than the summer sidedressing.

The relatively low yield for the spring application of ammonium sulfate was associated with pH's of 4.9 to 5.1 during the period up through tasseling. At this low pH it is quite possible that the additional acidifying effect of the ammonium sulfate may have enhanced manganese availability to the point of toxicity during these earlier stages of growth (55)[2]. Extremely high tissue nitrate tests and significantly higher equilibrium levels of soil nitrate and phosphate during this period indicate that assimilation and uptake of these two nutrients were inter-

[2]See also relation to nitrogen nutrition, pp. 68.

Table 24-a. -- Corn yields, fertile stalks, barren stalks and total stalks as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment	Code	Yield Bu./A	Stalks per acre Fertile	Barren	Total
No Suppl. N	N_1	47	11563	4313	15875
Ave. N Treatment	N_2	68	14091	2589	16680
LSD_{05}		8	1384	1390	NS
Ammon. Sulf.	M_1	68	14156	2484	16641
Calcium Nitr.	M_2	68	14026	2693	16719
LSD_{05}		NS	NS	NS	NS
40 lbs. N per A.	R_1	64	13536	2964	16500
80 lbs. N per A.	R_2	73	14646	2214	16859
LSD_{05}		4	768	NS	NS
Late Fall*	T_1	65	13703	3070	16773
Spring**	T_2	66	13711	2570	16281
Summer***	T_3	73	14859	2125	16984
LSD_{05}		5	942	NS	NS
	M_1R_1	63	13448	3031	16479
	M_1R_2	74	14865	1938	16802
	M_2R_1	65	13625	2896	16521
	M_2R_2	72	14427	2490	16917
LSD_{05}		6	1087	NS	NS
	M_1T_1	68	13828	3094	16922
	M_1T_2	62	13703	2391	16094
	M_1T_3	74	14938	1969	16906
	M_2T_1	63	13578	3047	16625
	M_2T_2	70	13719	2750	16469
	M_2T_3	72	14781	2281	17062
LSD_{05}		7	1331	NS	NS
	R_1T_1	62	13125	3344	16469
	R_1T_2	61	13250	3234	16484
	R_1T_3	68	14234	2313	16547
	R_2T_1	68	14281	2797	17078
	R_2T_2	71	14172	1906	16078
	R_2T_3	79	15484	1938	17422
LSD_{05}		7	1331	NS	NS

*Broadcast on surface (soil temperature near freezing).
**Plowed down just before planting.
***Sidedressed in bands when corn was knee high. (1960 application made on June 15.)

Table 24-b. -- Corn yields, fertile stalks, barren stalks and total stalks as related to nitrogen materials, rates and times of application in the fourth year of annual treatment. Hillsdale sandy loam. East Lansing. 1960. (Tasseling date: August 1.)

Treatment Code	Yield Bu./A	Stalks Per Acre		
		Fertile	Barren	Total
$M_1R_1T_1$	64 bcd	13063 b	3813 a	16875 a
$M_1R_1T_2$	58 d	13094 b	3031 a	16125 a
$M_1R_1T_3$	67 bcd	14188 ab	2250 a	16438 a
$M_1R_2T_1$	72 abc	14594 ab	2375 a	16969 a
$M_1R_2T_2$	67 bcd	14313 ab	1750 a	16063 a
$M_1R_2T_3$	82 a	15688 a	1688 a	17375 a
$M_2R_1T_1$	61 cd	13188 b	2875 a	16063 a
$M_2R_1T_2$	65 bcd	13406 b	3438 a	16844 a
$M_2R_1T_3$	69 bcd	14281 ab	2375 a	16656 a
$M_2R_2T_1$	65 bcd	13969 ab	3219 a	17188 a
$M_2R_2T_2$	75 ab	14031 ab	2073 a	16094 a
$M_2R_2T_3$	76 ab	15281 ab	2188 a	17469 a
No N	47 e	13897 ab	2721 a	16618 a

a, b, c, d -- Ranges of equivalence (Duncan, 1955). Within columns, numerical values with the same literal subscripts are not different at 5 percent.

fered with by this treatment (cf. tables 17-a, 20-a and 21-a).

Corn populations

There were no significant differences in total stalks due to kind, rate, and time of nitrogen applications (table 24-a). The proportion of fertile stalks, however, was significantly increased by the use of supplemental nitrogen and by increasing rates. This effect of supplemental nitrogen was significantly greater with summer sidedressing than with either fall or spring application. These results are similar to those observed in the rotation experiment (table 8-a).

In the cash crop rotation (Rotation 6) a 68 percent increase in yield for sidedressed nitrogen was associated with a 16 percent increase in number of fertile stalks. In the present experiment, a 55 percent yield increase for summer sidedressing over no supplemental nitrogen was associated with a 28 percent increase in fertile stalks.

Since the summer sidedressing promoted a larger number of ears per acre than earlier applications while total stand was not affected, it appears that flowering and pollination processes in corn are critically influenced by nitrogen availability during the period just prior to and about tasseling time. It is known that peak seasonal uptake of nitrogen by corn occurs during this period (84).

Seasonal Distribution of Nutrients in Corn Tissue and in Soil

A number of relationships which were pointed out during the presentation of data in tables 1-a through 24-b may be seen more clearly in the graphical presentation of data for selected treatments in figures 1 through 6.

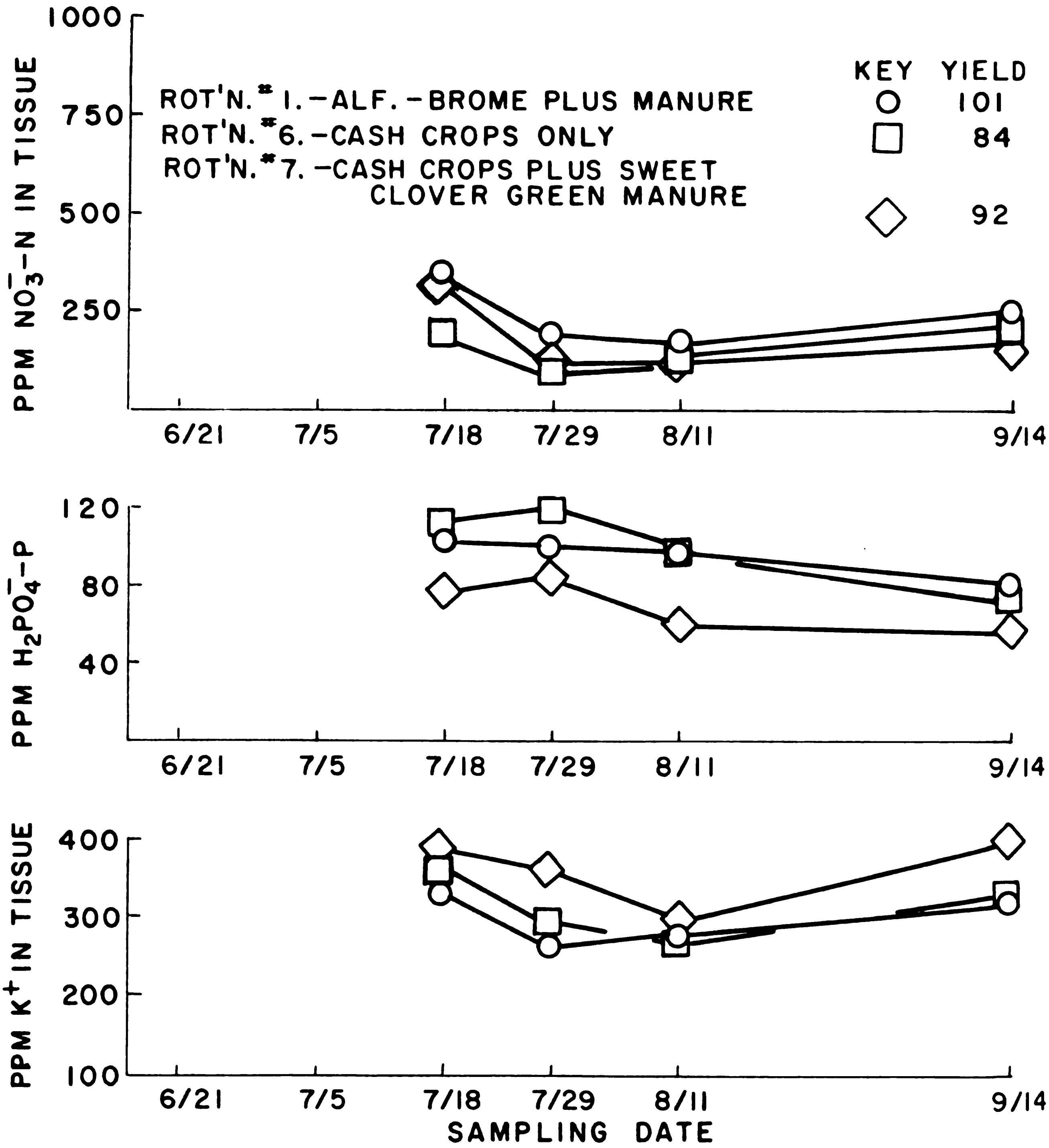

Figure 1. -- Soluble nutrients in midribs of corn in three rotations on Sims clay loam. Nitrogen sidedressed on June 9 and 30; total of 100 lbs. N. Tasseling Date: 7/25/60.

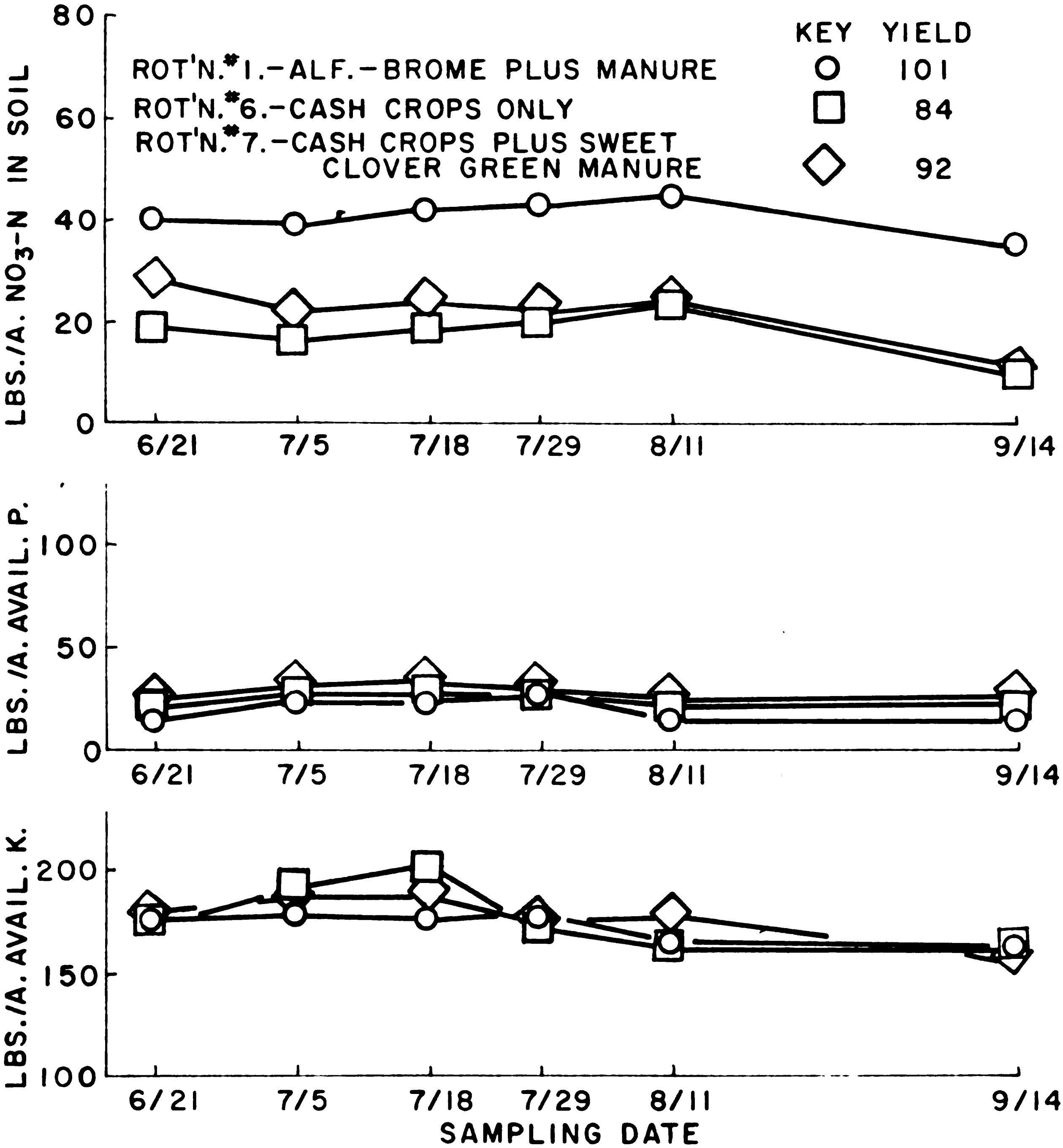

Figure 2. -- Available nutrients in Sims clay loam planted to corn in three rotations. Nitrogen sidedressed on June 9 and 30; total of 100 lbs. N. Tasseling date: 7/25/60.

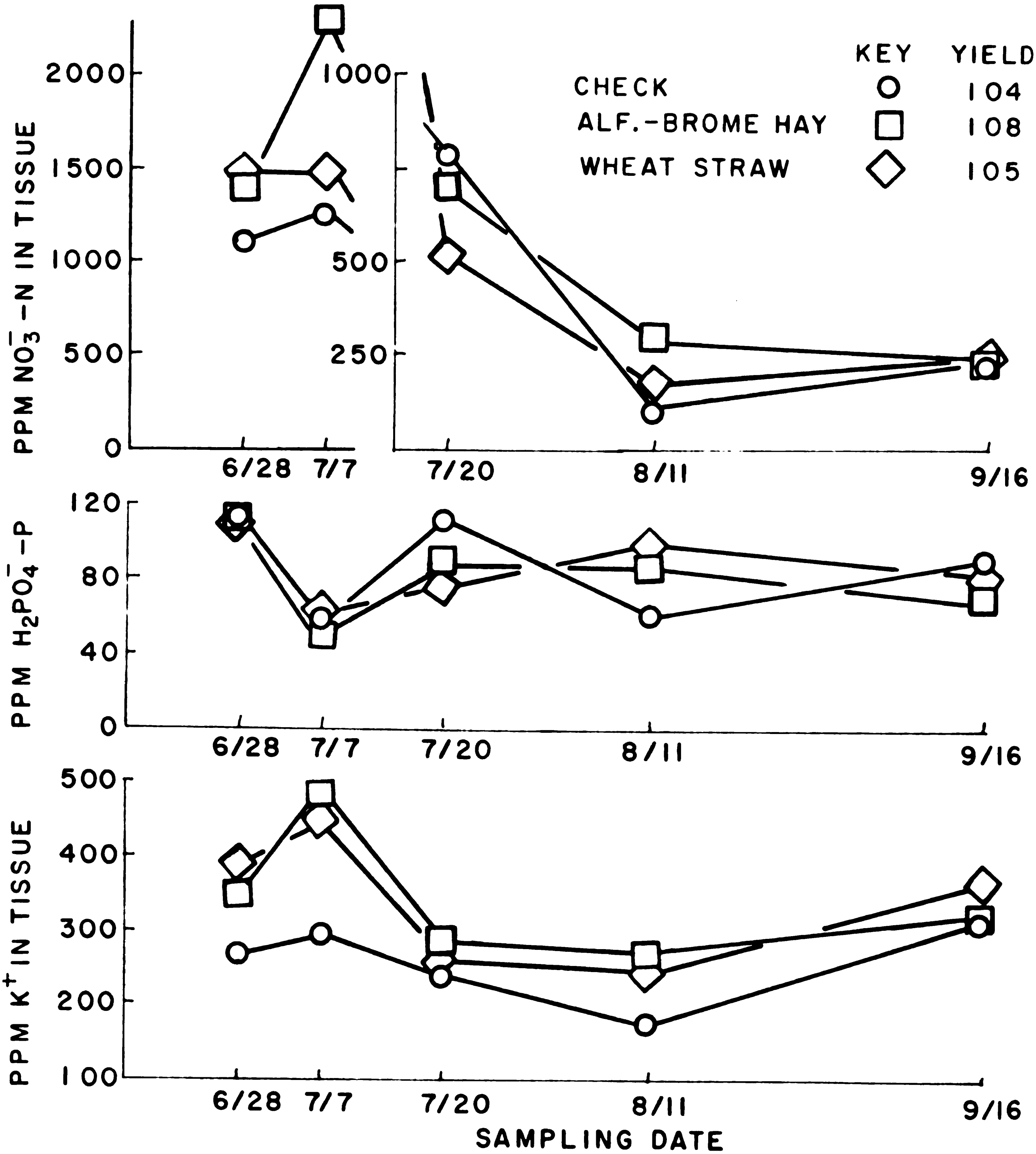

Figure 3. -- Soluble nutrients in midribs of corn following residue treatments on Sims clay loam. Nitrogen sidedressed on June 9 and 30; total of 100 lbs. N. Tasseling date: 7/25/60.

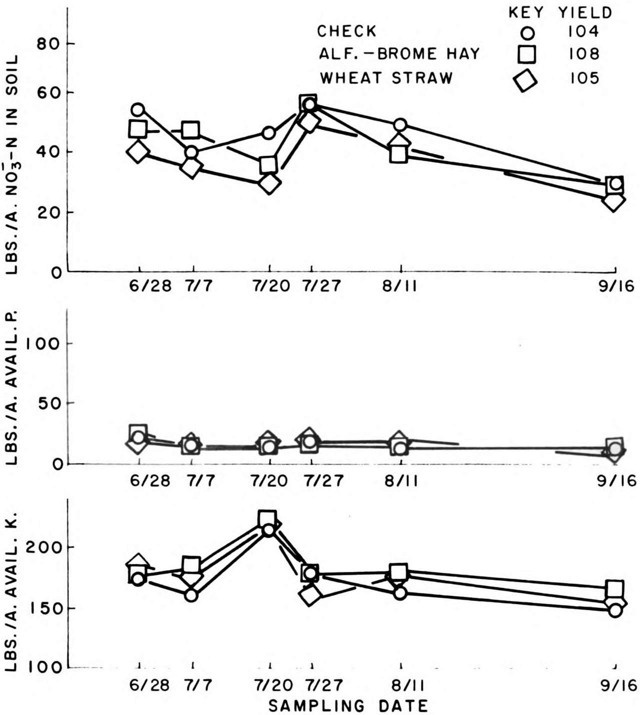

Figure 4. -- Available nutrients in Sims clay loam planted to corn following residue treatments. Nitrogen sidedressed on June 9 and 30; total of 100 lbs. N. Tasseling date: 7/25/60.

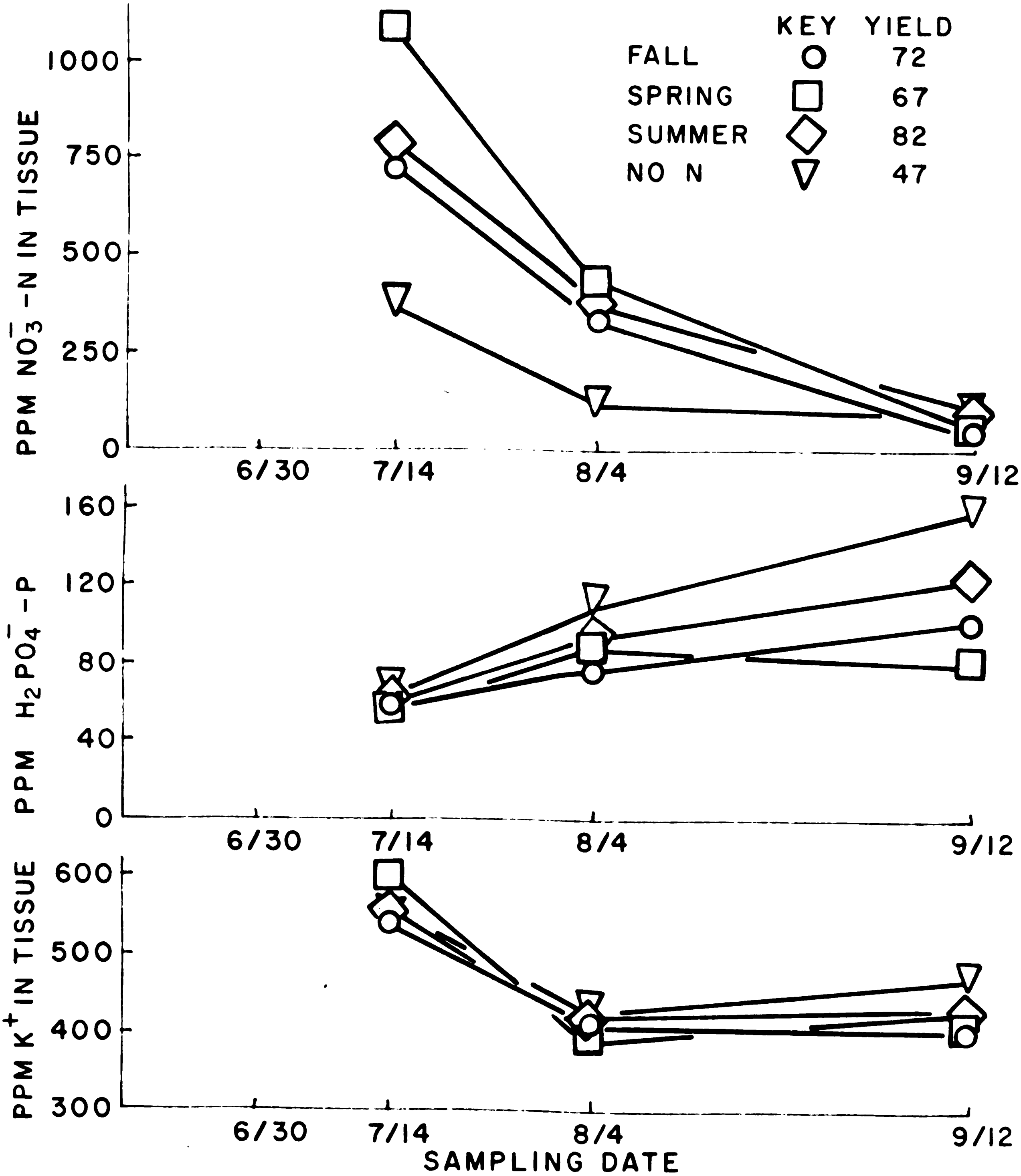

Figure 5. -- Soluble nutrients in midribs of corn on Hillsdale sandy loam as related to time of application of 80 lbs. N from ammonium sulfate. Tasseling date: 8/1/60.

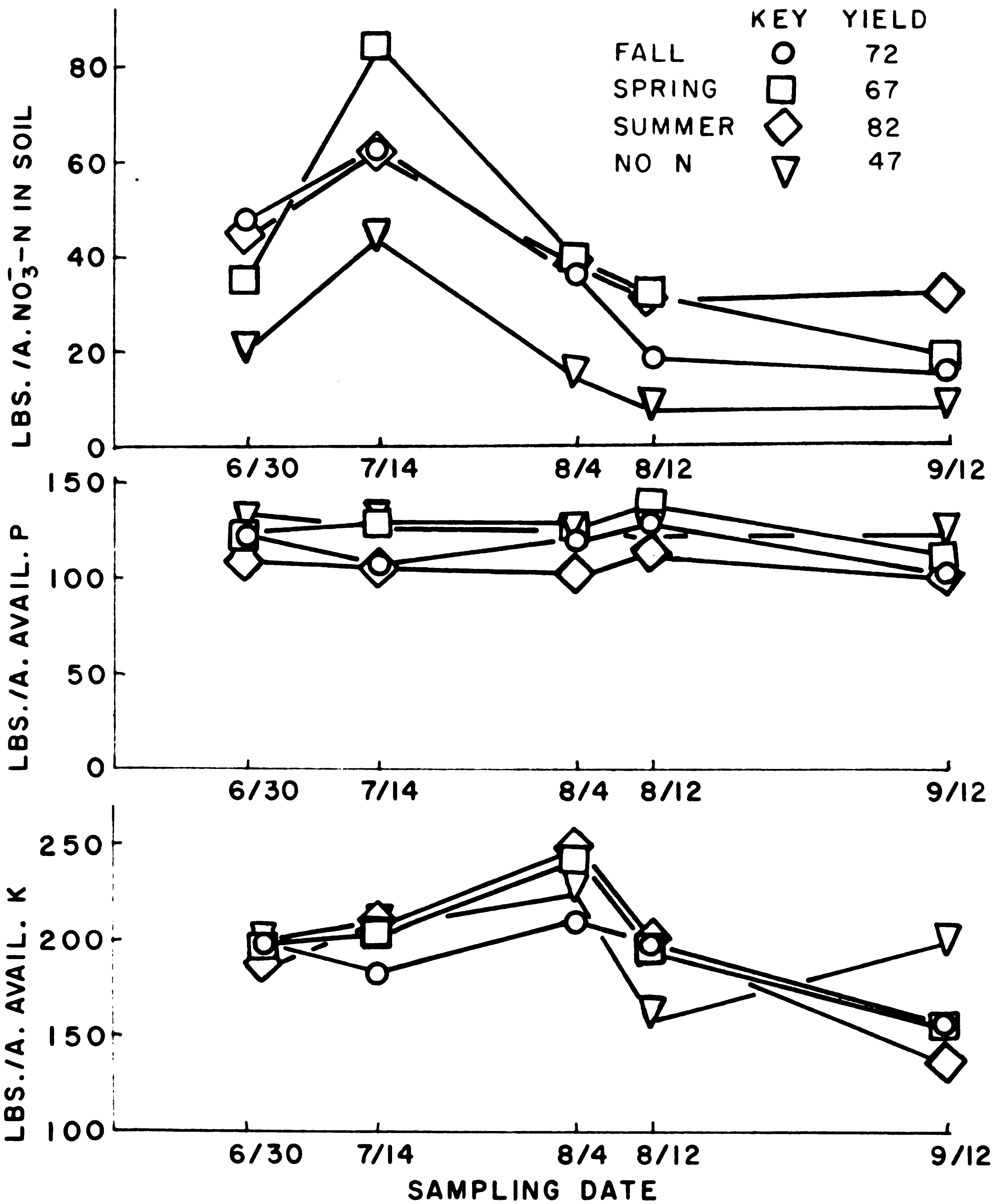

Figure 6. -- Available nutrients in Hillsdale sandy loam planted to corn as related to time of application of 80 lbs. N from ammonium sulfate. Tasseling date: 8/1/60.

For example, inverse relationships between tissue P and K are readily apparent within sampling dates in the data for Rotation 7 in figure 1. In figure 3, a sharp drop in tissue P on July 7 was associated with large accumulations of both N and K. This behavior in the rotation and residue experiments was associated with soil tests for P (figures 2 and 4) which were less than 36 pounds, or "low" according to criteria used in Michigan for evaluating the Bray P_1 soil test (Michigan Agr. Expt. Sta. Ext. Bul. E-159).

Soil P tests on the Hillsdale sandy loam were very high (figure 6). Here, tissue P (figure 5) accumulated during the season, and final levels were highest where tissue N was low during earlier periods of growth.

Similar reciprocal relationships between nutrients were apparent in the soil tests, although, generally, these were less marked than they were in the tissue tests. In the rotation experiment (figure 2), high soil nitrate levels in Rotation 1 were associated with relatively lower soil P throughout the season and lower soil K in the two samplings prior to tasseling. In the nitrogen sources experiment, there was a significant seasonal increase in soil K in the last sampling for the check treatment where soil nitrate was very low during the tasseling and post-tasseling periods (figure 6).

The principal reason for being concerned with seasonal changes in tissue or soil tests, however, is that these may give clues as to which of the three nutrients may have had a controlling influence on corn growth at specific stages of development.

In this connection, the seasonal changes in tissue test values were strikingly similar for N and K (figures 1, 3 and 5). Both reached seasonal highs two or three weeks before tasseling. Both declined sharply from this point on, but the major decline occurred prior to tasseling. The two or three weeks prior to tasseling is a period of rapid growth in plant size. Rapid assimilation of nitrate accounts for the rapid decline in tissue nitrate. The associated decline in tissue K is very likely due to dilution of previously absorbed K by the rapid increase in plant size and sap volume, since potassium is never "assimilated" by the plant in the same sense as N or P are. Essentially all of the potassium in the plant remains in solution as the cation (11, 97).

The rapid drop in tissue N and K associated with periods of rapid plant growth has pertinent significance for correlation studies. Deficiencies of either nutrient should be particularly critical during such periods. The likelihood of finding positive correlations with yield should be greater during or just after such periods of peak demand.

In the case of tissue P, the data for the residue and nitrogen source experiments (figures 3 and 5) show minimal levels two or three weeks prior to tasseling. Data for this earlier period for the rotation experiment were unreliable, but there is a suggestion in figure 1 that levels of P may have been lower if July 5 data were available. Low levels of P early in the season were associated with high tests for N and K in all three experiments. Thus, it would appear that positive correlations between yields and tissue P would be more likely during early stages of growth. However, differences in tissue P between treatment means were not great. Significant correlations with yield, if encountered, would be more likely associated with variation between replicates rather than between treatment means.

Late season accumulations of tissue P apparent in the data for the experiment on Hillsdale sandy loam (figure 5) appear to have been due to restricted assimilation and growth resulting from earlier deficiencies of nitrogen. Here, negative correlations with yield would be expected.

Such negative correlations between late season tissue P and yields must be interpreted with caution. It is not likely that levels of soluble P in the tissue were toxic. Rather, any strong negative correlation late in the season should be regarded as an artifact arising out of conditions of growth earlier in the season.

With regard to soil tests, the seasonal pattern for soil nitrate in the nitrogen source experiment (figure 6) was very similar to the pattern for tissue nitrate (figure 5). In the other two experiments (figures 2 and 4) there was no tendency for soil nitrate to reach a seasonal peak two or three weeks prior to tasseling. Such an early season peak, however, was very pronounced in 1958 and 1959 on the rotation experiment at the same location (16). The failure to reach a peak prior to tasseling in 1960 appears to have been due to cold, wet weather through July. Leaching and reduced mineralization of nitrogen from soil organic matter under these conditions apparently resulted in equilibrium nitrate levels which tended to be constant over the early periods of growth through tasseling time. Similar weather conditions at the location where the nitrogen source experiment was located in 1960 would not have interfered with mineralization to as great an extent because of the coarser texture of soil and generally better drainage and aeration conditions.

The relationship observed in figure 2 between treatment means for yield and soil nitrate suggests that strongly positive correlations could be expected through most of the season in this rotation experiment. The data in figure 6 leads to a similar expectation for the nitrogen sources experiment. In the residue experiment (figure 4), differences in soil nitrate between treatments were small and the general level was relatively high through most of the season. Yield differences were also small. The likelihood of significant correlations would be considerably less than in the other two experiments. There were no significant differences between replicates, so there would be no reason to expect better correlations associated with individual plot values than with treatment means.

Although treatments frequently resulted in significant differences in soil P and/or K, absolute differences were generally small. Strong correlations with yield among treatment means would not be expected, except for soil K, perhaps, in the last two samplings on the nitrogen sources experiment (figure 6). Here again, a strong negative component of response would be expected in the September 12 sampling. This would have to be regarded as an artifact arising out of earlier deficiencies of nitrogen.

Small differences in treatment means for soil P and K leave little room for significant correlation with mean yields. However, significant to highly significant differences between soil P and K tests for replicate blocks suggest that there might be greater likelihood of significant correlations if values for individual plots were used. The latter approach would also allow for a greater number of degrees of freedom for dilution of error in the correlation analysis.

General Relationships Between Nitrogen Deficiency Symptoms, Soil and Tissue Tests, and Corn Yields

Among the primary objectives of this investigation was the determination of "threshold" values for nitrates in soil or tissue where actual nitrogen deficits occur prior to the appearance of visible deficiency symptoms in corn. The experiments used were selected because previous yield data had shown a primary response to nitrogen.

Nitrogen deficiency symptoms observed included, a) a light, yellowish-green color, general to the whole plant, and b) yellowing of the midrib followed by necrosis beginning at the apex of the midribs of leaves in the lower half of the plant (21).

In the rotation experiment, nitrogen deficiency symptoms were observed by silking time (August 11) in all plots of the cash crop rotation (Rotation 6) and in those plots of the sweet clover rotation (Rotation 7) which had received no supplemental nitrogen. Yields with all these treatments were significantly reduced from the maximum yields developed on the alfalfa-brome rotation (Rotation 1) -- see tables 8-a and b. Nitrogen deficiency symptoms did develop later on in nitrogen sidedressed plots of Rotation 7, but yields were not significantly reduced from the corresponding plots of Rotation 1.

Mean yields for this experiment are plotted against mean nitrate values for tissue and soil in the scatter diagrams in figures 7 and 8. Significantly reduced yields and nitrogen deficiency symptoms prior to or at silking time were associated with treatments where tissue nitrate had dropped to about 200 ppm. or less and soil nitrate to 20 pounds per acre or less prior to the appearance of the first tassels on July 25.

Visible nitrogen deficiency symptoms appeared prior to tasseling

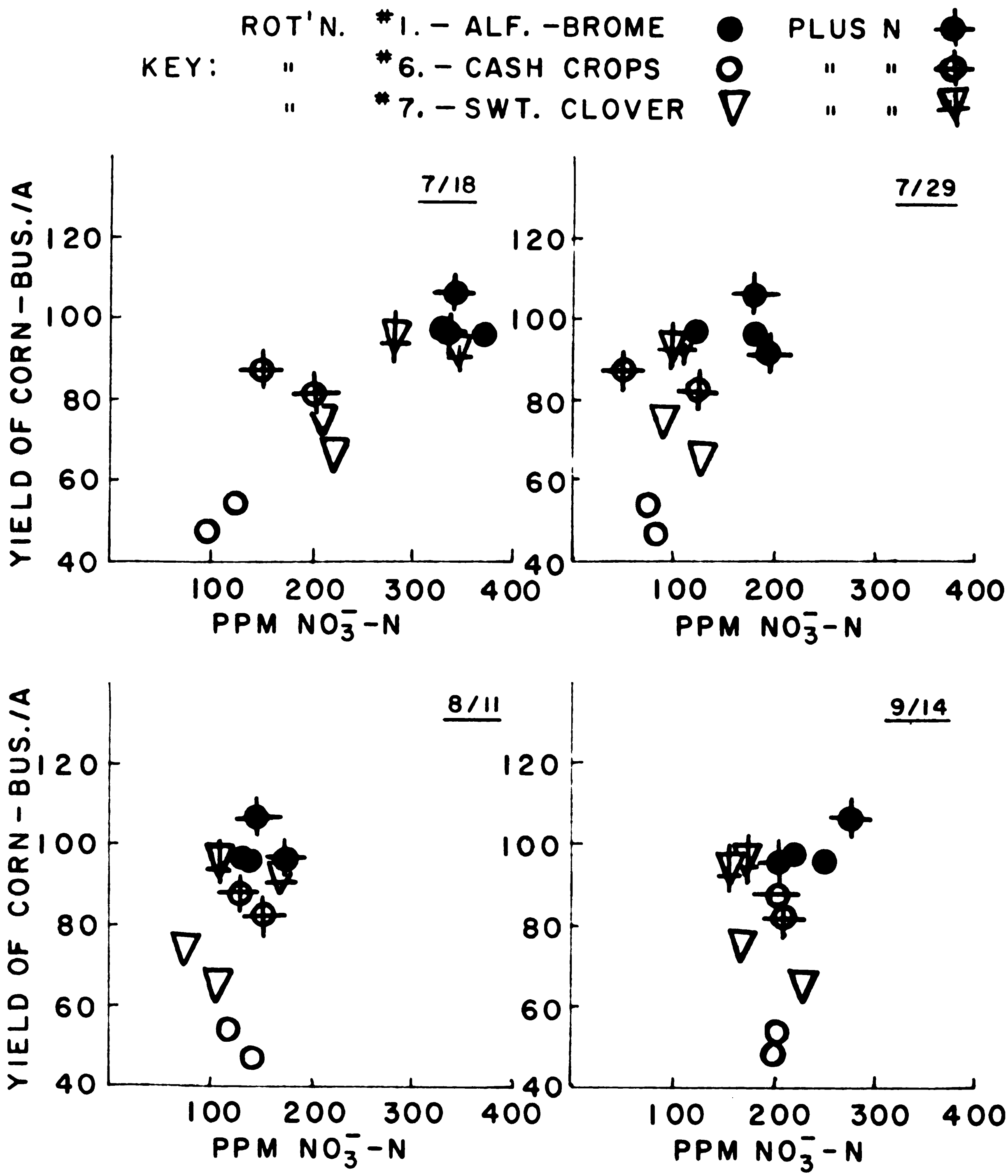

Figure 7. -- Corn yields vs. tissue nitrate in relation to sampling date, rotation and nitrogen treatment. Tasseling date: 7/25/60. (4-plot means.)

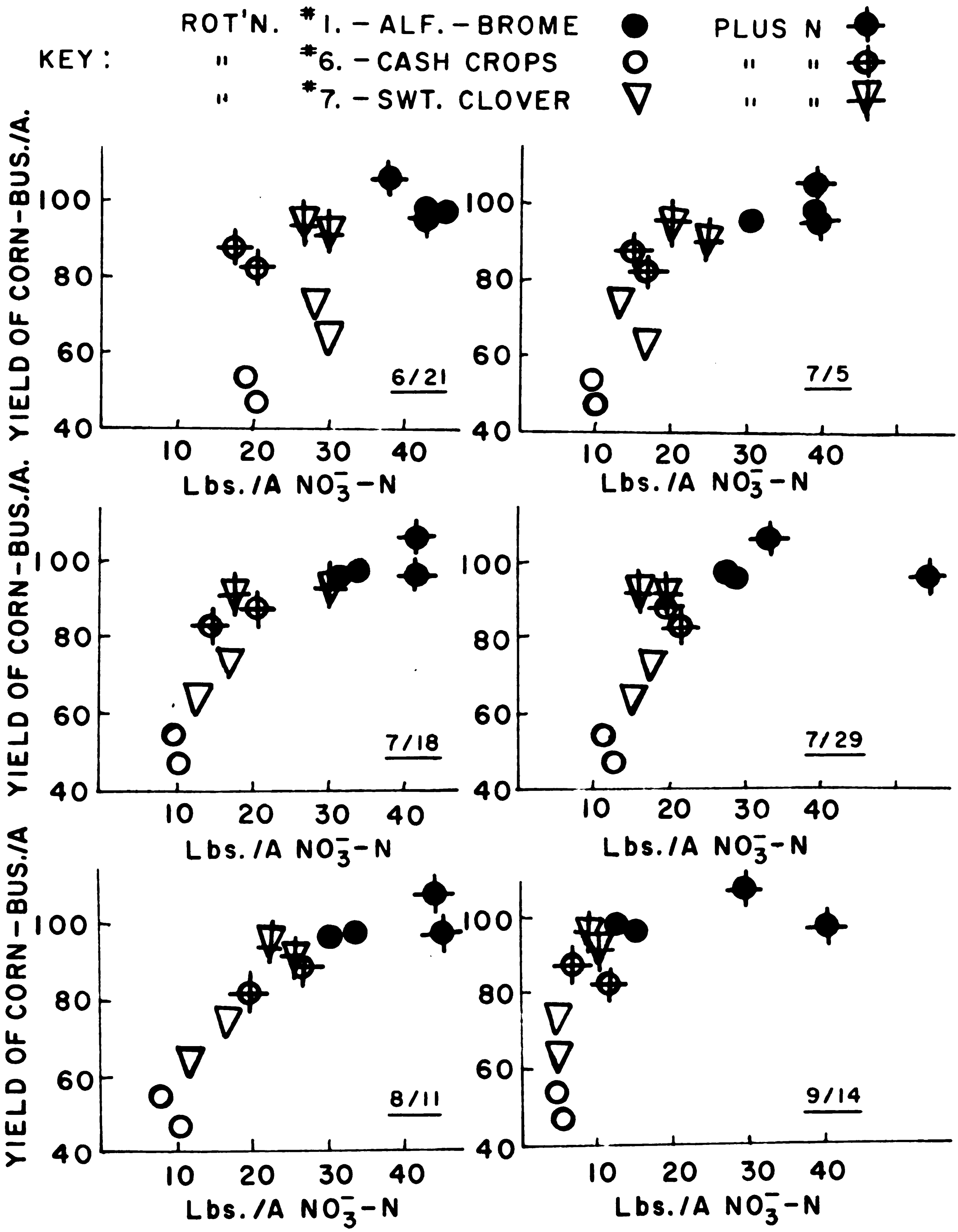

Figure 8. -- Corn yields vs. soil nitrate in relation to sampling date, rotation and nitrogen treatment. Tasseling date: 7/25/60. (4-plot means.)

time where no supplemental nitrogen was used on Rotation 6. Careful examination of the data revealed that, in all cases, soil tests of 20 pounds NO_3-N per acre or less were found one to three weeks prior to the appearance of nitrogen deficiency symptoms. Where soil nitrate levels of 30 pounds per acre or more were maintained through the silking stage (August 11), no nitrogen deficiency symptoms were observed at any time. No similar generalization could be made regarding the tissue tests.

In the nitrogen sources experiment, nitrogen deficiency symptoms developed during the period from tasseling (August 1) to completion of pollination (August 25) in all plots except those which had received 80 pounds of supplemental nitrogen. In general, yields for these treatments were significantly less than the maximum obtained where 80-pound rates were used (tables 24-a and b). These were treatments where tissue nitrate in the early tasseling period (August 4) was less than 240 ppm. (figure 9). Soil nitrate early in the season (June 30) and at tasseling time (August 1) for these same treatments was 40 pounds or less; at silking time (August 12), it was 20 pounds or less. Where soil nitrate remained above 30 pounds per acre through the silking stage, no deficiency symptoms developed until September and yields were not materially reduced from the maximum for this experiment. Again, soil tests of 20 pounds or less were encountered one to two weeks before visible deficiency symptoms appeared.

In the residue experiment, midrib firing was first observed the first of September and only on plots which received wheat straw without supplemental nitrogen. These were plots where tissue tests less than 200 ppm. of NO_3-N were found at silking time (August 11), and no subsequent recovery in nitrate level occurred in the September sampling

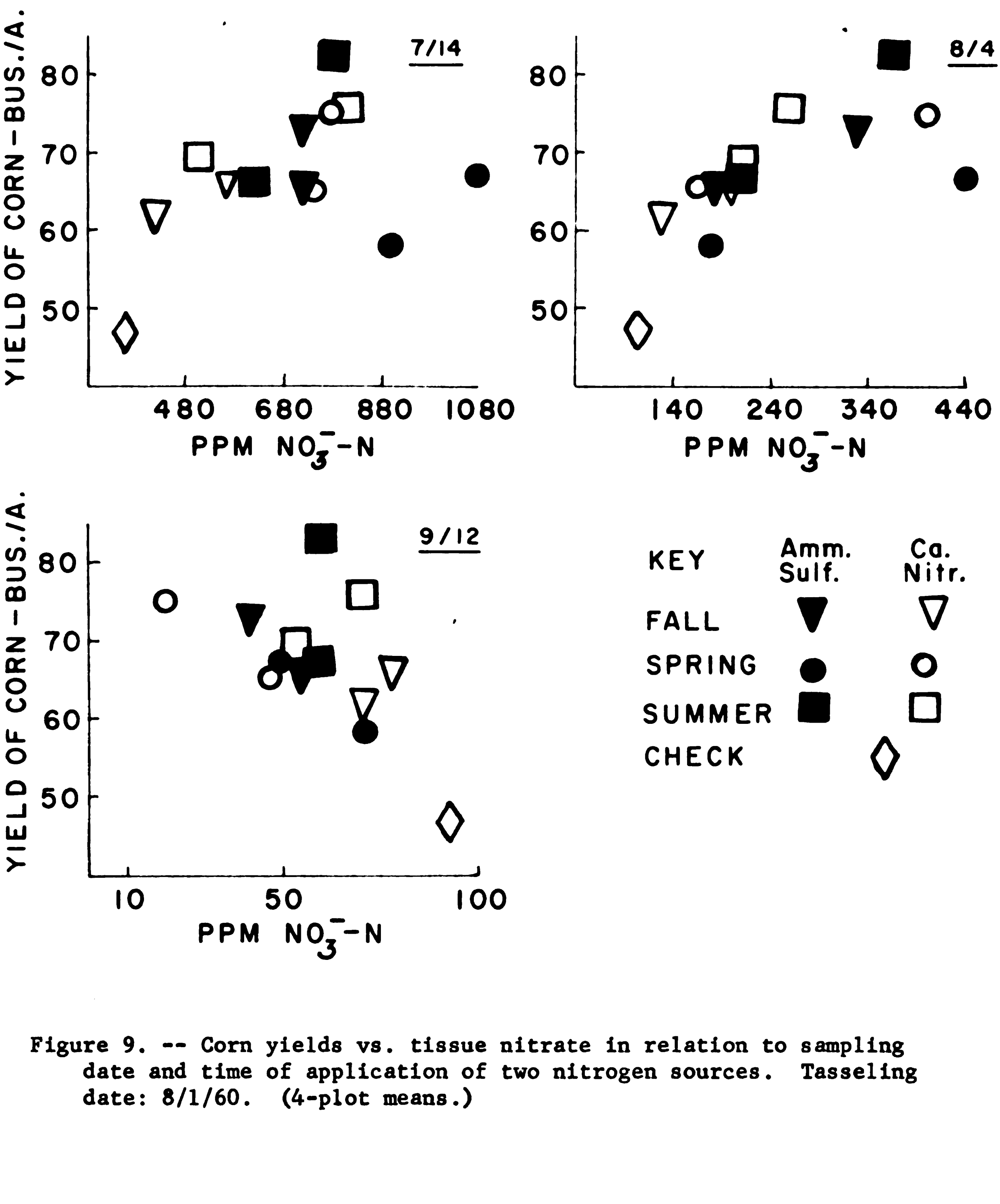

Figure 9. -- Corn yields vs. tissue nitrate in relation to sampling date and time of application of two nitrogen sources. Tasseling date: 8/1/60. (4-plot means.)

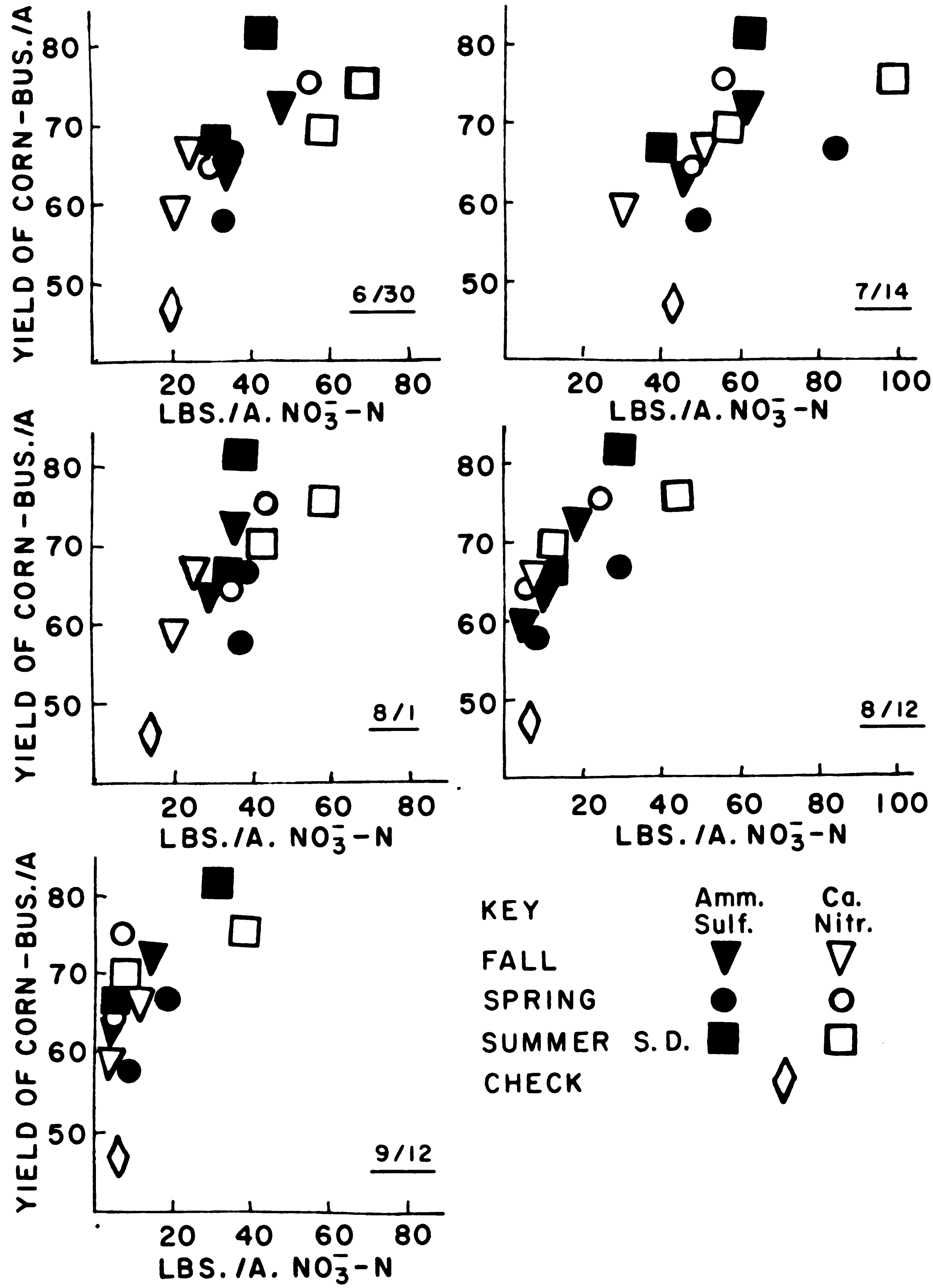

Figure 10. -- Corn yields vs. soil nitrate in relation to sampling date and time of application of two nitrogen sources. Tasseling date: 8/1/60. (4-plot means.)

(table 9). Also on these straw plots without supplemental nitrogen, soil tests approaching 20 pounds NO_3^--N were encountered twice prior to silking, and the September test was additionally sharply reduced (table 12).

The frequency of sampling in these experiments was inadequate for precise definition of the chronological relationship between critically low soil or tissue tests and the appearance of visible deficiency symptoms. It does appear that both tissue tests and soil tests revealed yield-limiting deficiencies of nitrogen prior to the development of external plant symptoms. However, soil tests were much more reliable.

As a first approximation, the "threshold" level for soil nitrate, below which deficiency symptoms may be expected in one to three weeks' time, is about 20 pounds per acre of nitrate-N. If soil tests fall below this threshold (and remain there) at any time prior to completion of pollination, it can be expected that yields will be adversely affected. The earlier this happens, the greater the expected yield reduction.

Fewer samplings of tissue were made than of soil. The seasonal distribution of tissue nitrate was, accordingly, less precisely defined. However, it is tentatively proposed that the corresponding "threshold" for tissue nitrate lies somewhere between 200 and 250 ppm., based on green weight of tissue.

It is apparent from the data that, only in cases of extreme nitrogen deficiency, do soil or tissue tests reveal shortages prior to about tasseling time. Present cultural techniques and equipment do not lend themselves to the application of supplemental nitrogen after corn has reached a height of two and one-half to three feet. Even if supplemental nitrogen were applied after this time, its availability would vary with the distribution of rainfall and soil moisture necessary to carry it down to the corn roots. Thus, soil or tissue tests would provide a guide for current season nitrogen applications only under conditions where shortages develop early in the season. Deficiencies revealed by later soil or tissue tests would, however, provide a basis for guiding management practices on the same field in future seasons.

Correlation Studies

In the following correlation studies, a preliminary attempt has been made to develop functional relationships between corn yields and soil and tissue tests for N, P and K. Corn populations were not considered because, in the experiments dealt with, stands were significantly related to treatment. No attempt has been made at this point to incorporate measurements of soil reaction and soil moisture, which were also made.

Two functional models have been used. One of these was a quadratic equation, including interaction terms. This type of function allows for diminishing returns and for declining yields at excessively high levels of a nutrient. It does not, however, allow for multiple inflections such as are found in the idealized sigmoid growth curve. The second model was an exponential-power function (Carter-Halter) which does allow for multiple inflections and also integrates interaction effects without sacrificing degrees of freedom.

These functions were applied only to data from the rotation experiment on Sims clay loam and the nitrogen source experiment on Hillsdale sandy loam. The available variance in the residue experiment was so small that it did not appear worthwhile to work with it at this time.

Tests made at different seasons of the year were used in order to determine whether correlations made at one stage of growth might be more informative than another. Individual observations rather than treatment means have been used in all calculations.

Rotation Experiment, Tissue Tests

Coefficients of linear correlation among tissue tests and corn yields for the rotation experiment are tabulated in table 25. Multiple regression statistics for the two functions are shown in table 26.

A highly significant, positive linear relationship between yield and tissue nitrogen in the July 18 sampling disappeared completely in the quadratic function and was broken down into non-significant positive and negative components in the Carter-Halter function.

Significant to highly significant negative linear correlations between yield and tissue P on all sampling dates were retained as non-significant negative components in the quadratic function. In the exponential function, they were resolved into significant to highly significant positive and negative components.

Yields were not significantly related to tissue K, except in combination with P in the quadratic function for July 18.

The proportion of total variance accounted for ($\bar{R}^2$) was generally higher for the Carter-Halter function than for the quadratic, and it was higher before tasseling (July 18), at silking time (August 11) and later (September 14) than in the early tasseling period (July 29).

The relationships expressed in the Carter-Halter function between yield and tissue P are depicted graphically in figure 11. The dominant negative segments of the observed portions of these curves are probably a carryover from the highly significant negative correlation between tissue N and tissue P which was established early in the season (table

Table 25. -- Coefficients of linear correlation among tissue tests and yield. Ferden Farm Rotations 1, 6 and 7. (Corn, 1960.)

Date	Tissue Nutrient	Coefficients of Correlation (r) P	K	Yield
7/18	N	-.418**	-.291	.606**
	P		-.129	-.510**
	K			-.223
7/29	N	.069	-.225	.027
	P		-.123	-.360*
	K			-.024
8/11	N	.062	-.167	.268
	P		-.174	-.543**
	K			.192
9/14	N	-.170	-.332*	.028
	P		-.211	-.627**
	K			.063

*Significant at 5 percent level of probability.
**Significant at 1 percent.

Table 26. -- Regression statistics for the multiple regressions of yield ($\hat{Y}$) on tissue tests for N, P and K on four dates. Ferden Farm Rotations 1, 6 and 7. (Corn, 1960.)

Model	Dates of sampling tissue			
	7/18	7/29	8/11	9/14
Quadratic function	Values of b in the equation $\hat{Y} = a + \Sigma b_i X_i$			
	+200.2 †	-13.75 †	+177.8 †	+324.8 †
	- .2326 N	+ .8369 N	- .2066 N	- .2612 N
	- .0000 N^2	- .0010 N^2	- .003 N^2	+ .0002 N^2
	- .4829 P	+ .3764 P	+ .0231 P	- 1.055 P
	- .0014 P^2	- .0024 P^2	- .0007 P^2	+ .0002 P^2
	- .3176 K	+ .2902 K	- .6784 K	- .9198 K
	- .0001 K^2	- .0003 K^2	+ .0008 K^2	+ .0009 K^2
	+ .0004 NP	- .0003 NP	- .0011 NP	+ .0002 NP
	+ .0008 NK	- .0016 NK	+ .0019 NK	+ .0004 NK
	+ .0017 PK*	+ .0002 PK	+ .0006 PK	+ .0024 PK
$\bar{R}^2$ ‡	.538	.209	.372	.362
Exponential-power function (Carter-Halter)	Values of b in the equation $\log \hat{Y} = a + \Sigma b_i X_i$			
	- 2.38899 †	- .23201 †	+ 3.79786 †	+ 1.68117 †
	- .00017 N	- .00035 N	+ .00048 N	+ .00004 N
	+ .35173 log N	+ .17777 log N	+ .08634 log N	- .03073 log N
	- .00184 P**	- .00466 P**	- .00339 P**	- .00239 P**
	+ .21999 log P*	+ .86348 log P*	+ .63390 log P**	+ .32316 log P*
	- .00214 K	- .00079 K	+ .00303 K	- .00006 K
	+ 1.58570 log K	+ .33712 log K	- 1.59369 log K	- .03799 log K
$\bar{R}^2$ ‡	.544	.272	.567	.545

†This is "a" in the equation.
*Value of b significant at 5 percent level of probability.
**Significant at 1 percent.
‡Coefficient of multiple determination.

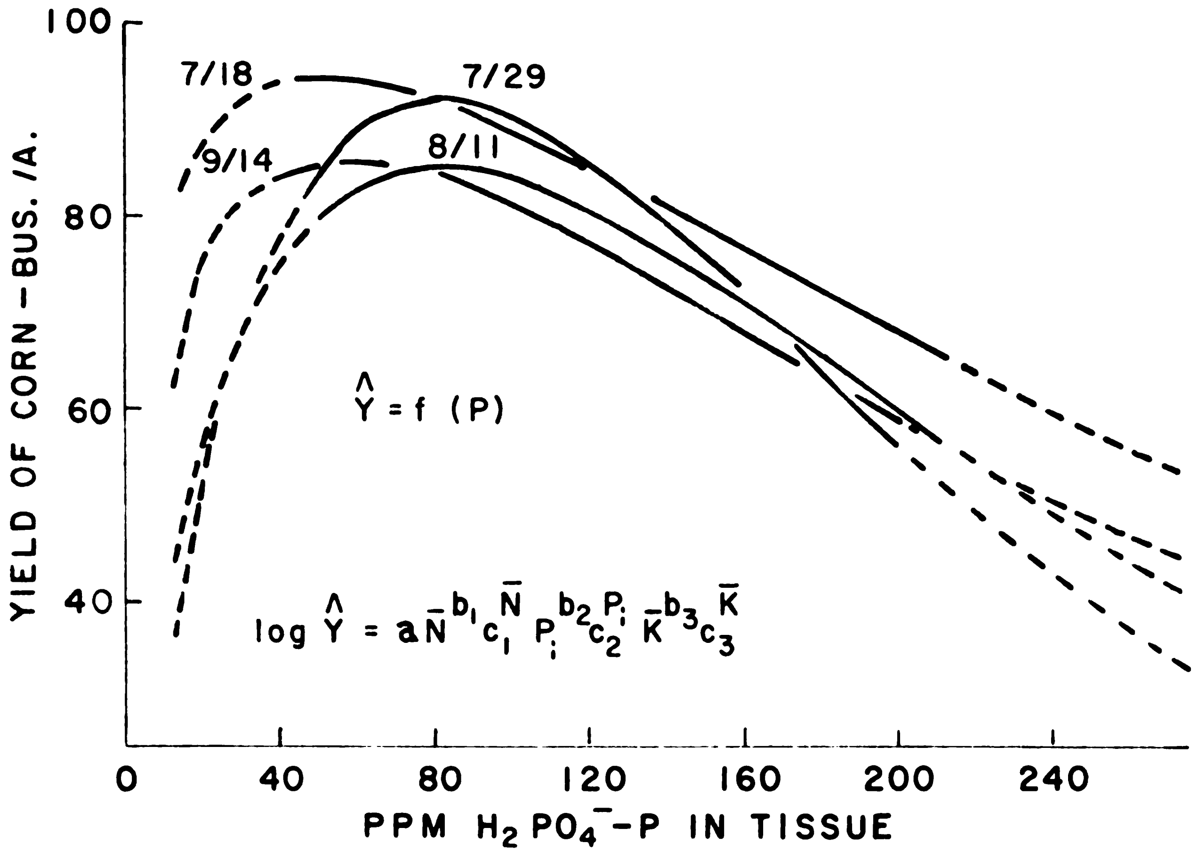

Figure 11. -- Corn yields calculated as a function of tissue P on four dates. Rotation experiment, Ferden Farm, 1960. Parameters b_2 and c_2 significant at 1 to 5 percent.

25, July 18). However, the fact that both the positive and the negative components of yield response to tissue P were significant to highly significant leads to the inference that the peaks of these curves correspond to valid estimates of the optimum level of tissue P necessary for maximum yields. These ranged from 50 to 85 ppm., and are consistent with levels of 40 to 100 ppm. reported by Magnitski (55).

Rotation Experiment, Soil Tests

Linear correlation coefficients among soil tests and yields for the rotation experiment are given in table 27. The corresponding multiple regression coefficients for the two functions are shown in table 28.

Yields were a highly significant, positive linear function of NO_3^--N on all sampling dates. In the quadratic function, on the other hand, the positive component of response to N reached significance at five percent on only one sampling date (July 18), whereas a highly significant negative component was expressed on four dates. A sizable portion of the positive relationship between yields and soil N was apparently distributed to the NP interaction term.

The positive linear response to N was reflected in the Carter-Halter function by significant to highly significant positive components. A negative N component became highly significant in the last two samplings.

There was a general tendency for yields to be negatively related to soil P, the linear correlation attaining significance in the last sampling. The relationship was resolved into positive and negative components in both functions, but significance was attained only in the Carter-Halter function for the sampling made at the time of silking (August 11). The NP cross product term in the quadratic was generally positive, and it was significant at one percent on July 5 and at five percent on September 14.

Table 27. -- Coefficients of linear correlation among soil tests and yield. Ferden Farm Rotations 1, 6 and 7. (Corn, 1960.)

Date	Soil Nutrient	Coefficients of Correlation (r) P	K	Yield
6/21	N	-.451**	-.055	.460**
	P		.514**	-.295
	K			.215
7/5	N	-.313	-.100	.656**
	P		.455**	-.035
	K			.141
7/18	N	-.190	-.034	.663**
	P		.455**	-.311
	K			.165
7/29	N	-.037	.129	.568**
	P		.400*	.111
	K			.197
8/11	N	-.383*	.099	.559**
	P		.262	-.253
	K			.265
9/14	N	-.356*	.131	.476**
	P		.428**	-.382*
	K			-.043

*Significant at 5 percent level of probability.
**Significant at 1 percent.

Table 28. -- Regression statistics for the multiple regressions of yield ($\hat{Y}$) on soil tests for N, P and K on six dates. Ferden Farm Rotations 1, 6 and 7. (Corn, 1960.)

Model	Dates of sampling soil		
	6/21	7/5	7/13
Quadratic function	Values of b in the equation $\hat{Y} = a + \leq b_i X_i$		
	$-71.791^{\dagger}$	$+61.635^{\dagger}$	$-23.948^{\dagger}$
	+ 1.4881 N	+ .8967 N	+ 3.2699 N
	- .0266 N^2	- .0321 N^{2**}	- .0486 N^{2**}
	+ 2.5711 P	- 4.6427 P	+ .0966 P
	- .0372 P^2	+ .0006 P^2	- .0602 P^2
	+ .9309 K	+ .5044 K	+ .6427 K*
	- .0022 K^2	- .0027 K^2	- .0022 K^2
	- .0142 NP	+ .0654 NP**	+ .0113 NP
	+ .0080 NK	+ .0024 NK	+ .0007 NK
	- .0078 PK	+ .0192 PK	+ .0115 PK
$\bar{R}^2$ †	.297	.571	.621
Exponential-power function (Carter-Halter)	Values of b in the equation $\log \hat{Y} = a + \leq b_i X_i$		
	$- 3.3754^{\dagger}$	$- 1.3530^{\dagger}$	$- .1300^{\dagger}$
	- .0061 N	- .0038 N	- .0064 N
	+ .7656 log N	+ .5771 log N**	+ .6579 log N*
	- .0172 P	- .0049 P	- .0168 P
	+ .5310 log P	+ .3841 log P	+ .7235 log P
	- .0037 K	- .0019 K	+ .0003 K
	+ 2.0803 log K	+ 1.1186 log K	+ .3116 log K
$\bar{R}^2$ †	.298	.481	.528

Table 28. -- Continued

Dates of sampling soil		
7/29	8/11	9/14
	Values of b in the equation $\hat{Y} = a + \Sigma b_i X_i$	
-9.3655 †	+101.04 †	+170.56 †
+2.0841 N	+ 2.0657 N	- 3.4262 N
- .0261 N^2**	- .0297 N^2**	- .0229 N^2*
-5.4525 P	+ 5.0826 P	- 6.8881 P
+ .0007 P^2	- .1031 P^2	+ .0980 P^2
+1.4143 K	- 1.2355 K	- .3148 K
- .0061 K^2	+ .0048 K^2	+ .0007 K^2
+ .0271 NP	+ .0433 NP	+ .1593 NP*
- .0013 NK	- .0003 NK	+ .0189 NK
+ .0287 PK	- .0144 PK	+ .0044 PK
.453	.592	.526
	Values of b in the equation $\log \hat{Y} = a + \Sigma b_i X_i$	
-1.3761 †	+ 6.8340 †	+ 4.3245 †
- .0053 N	- .0088 N**	- .0074 N**
+ .6105 log N**	+ .7938 log N**	+ .5201 log N**
+ .0105 P	- .0316 P**	+ .0038 P
- .6341 log P	+ 1.2252 log P**	- .2657 log P
- .0041 K	+ .0104 K	+ .0045 K
+1.7490 log K	- 3.8003 log K	- 1.4990 log K
.463	.683	.489

†This is "a" in the equation.
‡$\bar{R}^2$ = coefficient of multiple determination.
*Value of b significant at 5 percent level of probability.
**Significant at 1 percent.

There appeared to be little relationship between yields and soil K, although a significant positive parameter was obtained in the quadratic on July 18.

Neither function was consistently better than the other in explaining total variance. Both functions were notably uninformative in the June sampling, and both yielded more information just prior to tasseling and at silking time than during the early tasseling period (July 29).

The relationships defined by the Carter-Halter function for August 11 are shown graphically in figures 12 and 13. At average levels of soil K, predicted yields reached a maximum at 39 pounds N per acre and 18 pounds P. The highly significant positive and negative parameters for both N and P indicate that these values represent valid estimates of the optimum levels of these nutrients at this stage of growth.

The relationships in figure 13 suggest that there may have been some response to increasing levels of soil K. However, the K parameters were not significant. A point to be noted here is that the extrapolated negative slopes of these curves were determined by the curvature in observed positive segments. They are obviously misleading. This illustrates one of the pitfalls involved in the interpretation of multiple regression information of this sort. Inferences outside the observed range must be made with caution.

Nitrogen Sources Experiment

Linear correlation coefficients for the nitrogen sources experiment are given in tables 29 and 31. The corresponding multiple correlation coefficients appear in tables 30 and 32.

Significant linear correlations with yield were found only for tissue nitrate and soil nitrate. Significant parameters for tissue nitrate

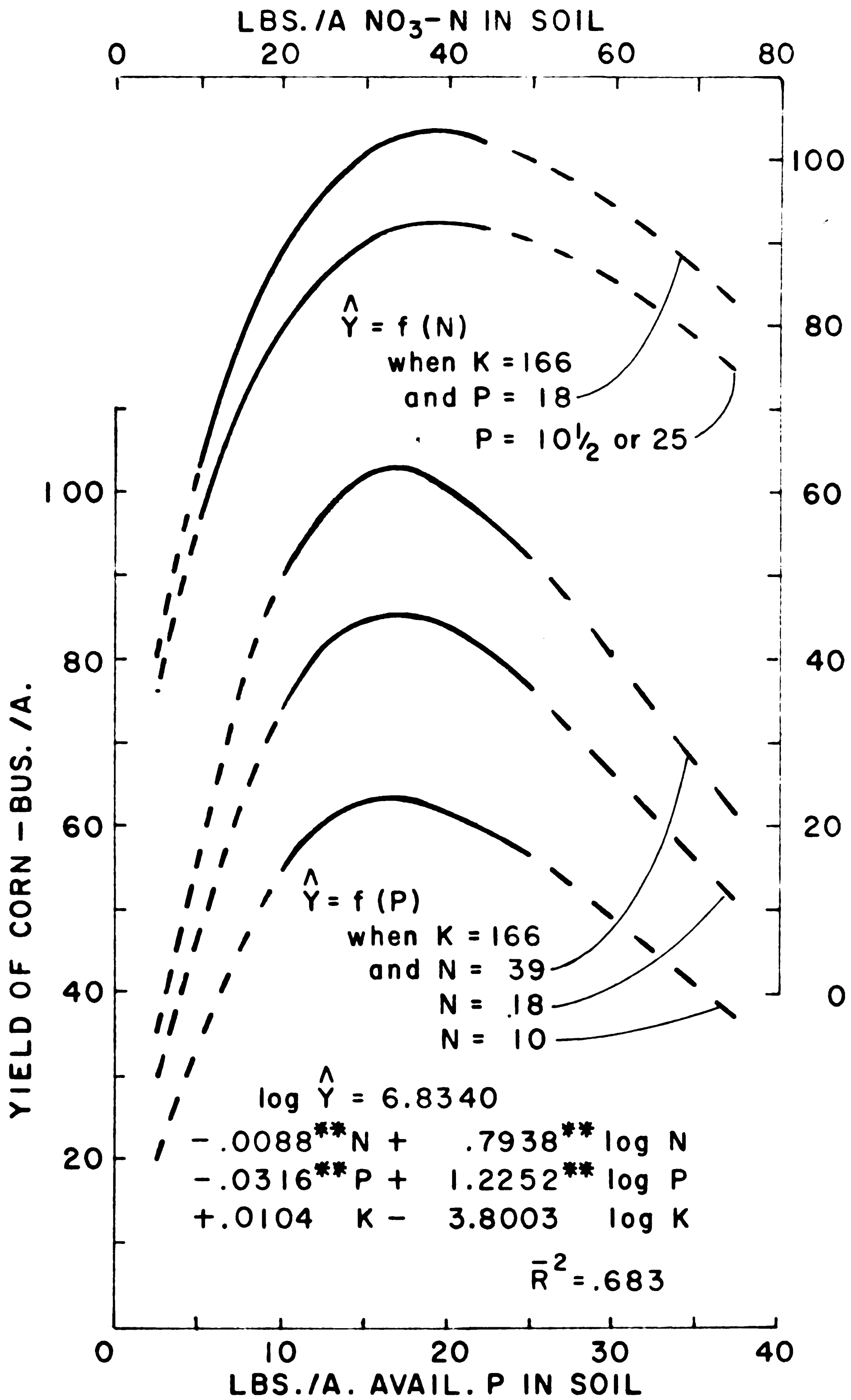

Figure 12. -- Corn yields calculated as a function of soil tests for N, P and K 17 days after tasseling. Rotation Experiment, Ferden Farm, 1960. Parameters for N and P significant at 1 percent.

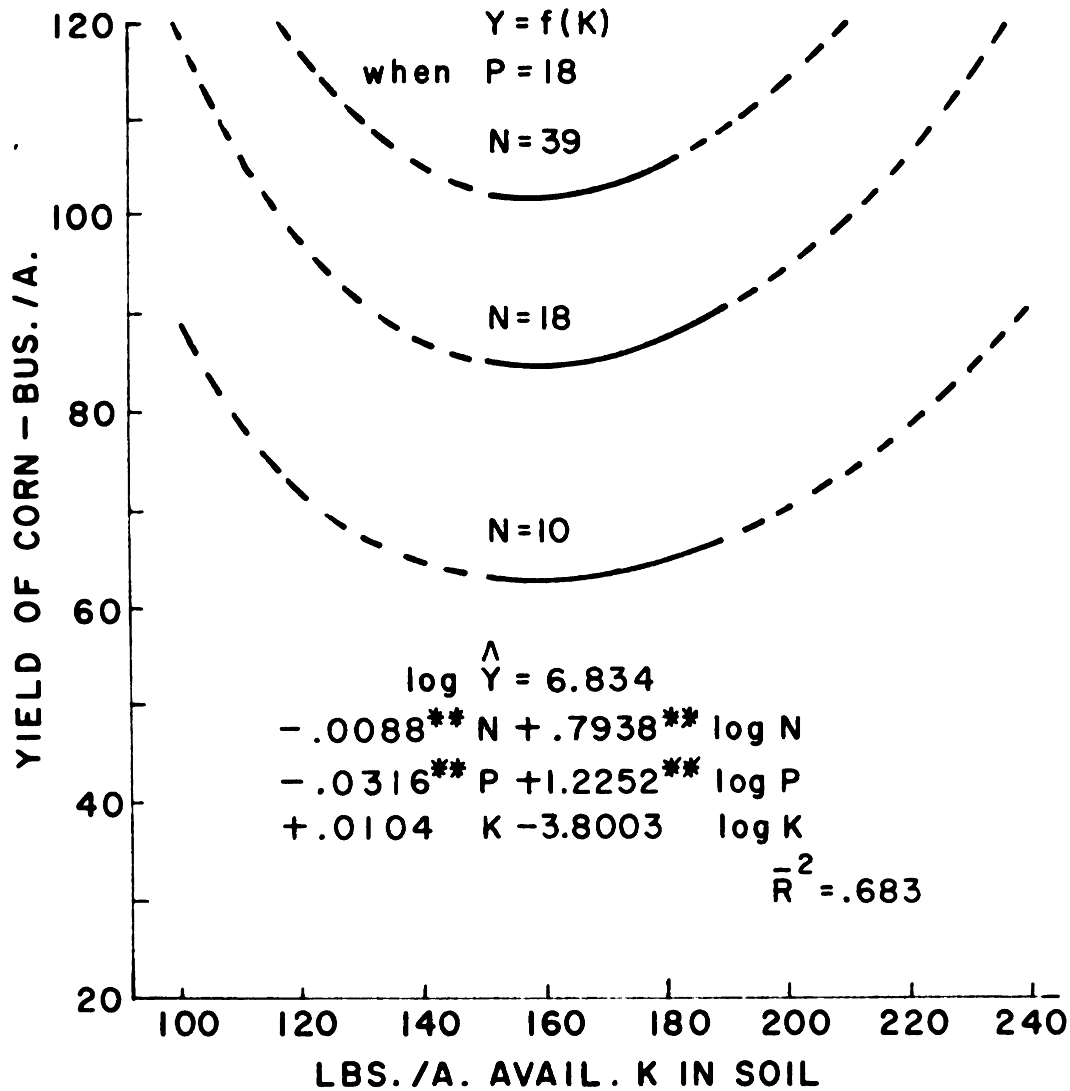

Figure 13. -- Corn yields calculated as a function of soil tests for N, P and K 17 days after tasseling. Rotation Experiment, Ferden Farm, 1960. Parameters for K not statistically significant.

Table 29. -- Coefficients of linear correlation among tissue tests and yield. Nitrogen sources, rates and times of application experiment, East Lansing. (Corn, 1960.)

Date	Tissue Nutrient	Coefficients of correlation (r) P	K	Yield
7/14	N	-.310*	+.595**	+.223
	P		+.019	+.184
	K			+.072
8/4	N	+.171	-.178	+.308*
	P		+.217	-.150
	K			+.081
9/12	N	+.093	+.368*	-.379*
	P		+.452**	-.154
	K			-.211

*Significant at 5 percent level of probability.
**Significant at 1 percent.

Table 30. -- Regression statistics for the multiple regression of yields ($\hat{Y}$) on tissue tests for N, P and K on three dates. Nitrogen sources, times and rates of application experiment. East Lansing. (Corn, 1960.)

Model	Dates of sampling tissue		
	7/14	8/4	9/12
Quadratic function	Values of b in the equation $\hat{Y} = a + \Sigma b_i X_i$		
	-233.2 †	-70.34 †	+361.6 †
	- .0162 N	+ 5.0952 N	- 5.9511 N
	- .0000 N^2	- .0069 N^2	+ .0025 N^2
	- .1157 P	+ 1.1401 P	- 2.1766 P
	+ .0006 P^2	+ .0009 P^2	+ .0017 P^2 (*-)
	+ 1.2529 K	+ .3068 K	- .6710 K
	- .0013 K^2	+ .0012 K^2	- .0000 K^2
	- .0013 NP	- .0290 NP	+ .0397 NP
	+ .0001 NK	- .0191 NK	+ .0143 NK (*-)
	+ .0002 PK	- .0063 PK	+ .0048 PK
	+ .0000 NPK	+ .0001 NPK	- .0001 NPK
$\bar{R}^2$ ‡	- .009	.254	.234
Exponential-power function (Carter-Halter)	Values of b in the equation $\log \hat{Y} = a + \Sigma b_i X_i$		
	- 7.035 †	- 1.925 †	+ 2.551 †
	+ .0001 N	- .0003 N*	- .0004 N
	- .0457 log N	+ .2762 log N**	- .0695 log N
	+ .0010 P	- .0001 P	- .0006 P
	+ .0167 log P	- .1447 log P	+ .1221 log P
	- .0035 K	- .0016 K	+ .0003 K
	+ 3.9052 log K	+ 1.5915 log K	- .3377 log K
$\bar{R}^2$ ‡	.039	.265	.018

†This is "a" in the equation.
Value of b significant at 5 percent level of probability or closely approaching significance (-).
**Value of b significant at 1 percent.
‡Coefficient of multiple determination.

Table 31. -- Coefficients of linear correlation among soil tests and yield. Nitrogen sources, times and rates of application experiment, East Lansing. (Corn, 1960.)

Date	Soil Nutrient	Coefficients of correlation (r) P	K	Yield
6/30	N	-.012	+.139	+.519**
	P		+.223	-.048
	K			-.119
7/14	N	+.110	-.142	+.238
	P		+.067	-.037
	K			-.064
8/4	N	-.219	+.023	+.417**
	P		+.158	-.136
	K			+.127
8/12	N	-.038	+.241	+.465**
	P		+.007	+.017
	K			+.214
9/12	N	-.318*	-.276*	+.411**
	P		+.288*	-.102
	K			-.216

*Significant at 5 percent level of probability.
**Significant at 1 percent.

Table 32. -- Regression statistics for the multiple regressions of yields ($\hat{Y}$) on soil tests for N, P and K on five dates. Nitrogen sources, rates and times of application experiment. East Lansing. (Corn, 1960.)

Model	Dates of sampling soil	
	6/30	7/14
Quadratic function	Values of b for the equation $\hat{Y} = a + \Sigma b_i X_i$	
	-70.34 †	-37.05 †
	+ 5.0952 N	- .1189 N
	- .0069 N^2	- .0017 N^2
	+ 1.1401 P	+ 1.1772 P
	+ .0009 P^2	- .0035 P^2
	+ .3068 K	+ .3461 K
	+ .0012 K^2	- .0002 K^2
	- .0290 NP	+ .0027 NP
	- .0191 NK	+ .0010 NK
	- .0063 PK	- .0025 PK
	+ .0001 NPK	- .0000 NPK
$\bar{R}^2$ ‡	.285	- .052
Exponential-power function (Carter-Halter)	Values of b in the equation $\log \hat{Y} = a + \Sigma b_i X_i$	
	+ 4.108 †	- 1.257 †
	- .0019 N	- .0012 N
	+ .4172 log N	+ .2711 log N
	+ .0006 P	- .0036 P
	- .1454 log P	+ .7734 log P
	+ .0026 K	- .0015 K
	- 1.3792 log K	+ .7891 log K
$\bar{R}^2$ ‡	.286	- .007

Table 32. -- Continued

Dates of sampling soil		
8/4	8/12	9/12
	Values of b for the equation $\hat{Y} = a + \Sigma b_i X_i$	
+497.8 †	-57.54 †	-36.92 †
- 15.5116 N	+ 8.4212 N*	+ 1.2044 N
- .0090 N^2	- .0257 N^2**	- .0079 N^2
- 2.2275 P	+ 1.0103 P	+ 1.3177 P
- .0118 P^2	+ .0008 P^2	- .0033 P^2
- 3.0997 K	+ .4978 K	+ .2825 K
+ .0004 K^2	+ .0008 K^2	- .0001 K^2
+ .1396 NP	- .0565 NP*	- .0061 NP
+ .0827 NK	- .0339 NK*	+ .0034 NK
+ .0246 PK	- .0065 PK*	- .0028 PK
- .0007 NPK	+ .0003 NPK*	- .0000 NPK
.163	.325	.110
	Values of b in the equation $\log \hat{Y} = a + \Sigma b_i X_i$	
- .4231 †	+ 3.090 †	- .3517 †
- .0034 N	- .0028 N	+ .0006 N
+ .4086 log N*	+ .2262 log N*	+ .0688 log N
- .0061 P	- .0002 P	- .0010 P
+ 1.4619 log P	+ .0640 log P	+ .3107 log P
+ .0008 K	+ .0021 K	- .0030 K
- .3102 log K	- .8782 log K	+ .9343 log K
.209	.251	.118

†This is "a" in the equation.
‡R^2= coefficient of multiple determination.
*Value of b significant at 5 percent level of probability.
**Significant at 1 percent.

were encountered only in the Carter-Halter function early in the tasseling period (table 30, August 4). Significant positive parameters for soil nitrate (table 32) appeared about tasseling time (August 4) and at silking time (August 12) in the Carter-Halter function. In the quadratic model, significant positive and negative components of response to nitrate appeared at silking time. These were distributed among the linear and squared N terms and the various interactions involving N. A significant negative parameter for the PK interaction was also found.

A high degree of intercorrelation among the tissue nutrients themselves (table 29) may have contributed to the low level of significance among functional parameters on July 14 and September 12 (table 30). Intercorrelation among independent variables may have been an undesirable feature of the soil test data for September, also (table 31). Even where significant multiple regression coefficients were found, however, coefficients of multiple determination ($\bar{R}^2$) were low. Neither the tissue tests nor the soil tests contributed sufficient information to account for more than 25 to 30 percent of the total yield variance of this experiment.

This indicates that factors other than N, P or K were dominantly controlling corn yields. The soil pH on these plots ranged from 4.9 to 5.8 (table 23-a). In this range, it would be expected that soil reaction would have a very strong influence on nutrient uptake by corn. Notably, the availability of manganese may have been enhanced at the lower pH's to the point where toxic accumulations occurred in the tissue. No attempt was made in this preliminary study to incorporate available soil pH data into the functional analyses, but this should be done. Future studies on acid soils such as this should take into consideration the effects of lime, and should also include the measurement of manganese in the tissue.

In spite of the low $\bar{R}^2$ values for the overall equations, significant parameters should be examined for possibly useful agronomic information. In figure 14, the relationships between yields and tissue and soil nitrate levels on August 4 are plotted as calculated from the Carter-Halter equation. Both positive and negative components of response to tissue N were significant, leading to the conclusion that a concentration of 400 ppm. NO_3^--N in green tissue was optimum for maximum yields. The apex of the curve was broad, however, and there was little difference in expected yield between 250 and 600 ppm.

Only the positive parameter for soil N attained significance at five percent. However, the negative coefficient of N was significant at the ten percent level of probability. The point on the abscissa below the peak of the curve may be taken as a reasonable estimate of the optimum level of soil nitrate. The absolute optimum appears to have been 50 pounds N per acre, although there was little difference between 40 and 60 pounds.

The exponential relationship between yields and soil nitrate at silking time (August 11) is shown in the upper half of figure 15. The optimum level of soil NO_3^--N appeared to have been about 37 pounds, although there was little difference between 25 and 50 pounds per acre. The corresponding quadratic function is plotted in the lower half of figure 15. A very similar optimum is indicated -- about 39 pounds NO_3^--N per acre.

The predicted maximum yield for the quadratic is 20 bushels greater than for the Carter-Halter function, the peak of the curve is narrower, and the extrapolated decline at higher levels of N is essentially a mirror image of the observed positive leg of the curve. The form of the Carter-Halter function is more reasonable in terms of actual experience with patterns of crop response in the field.

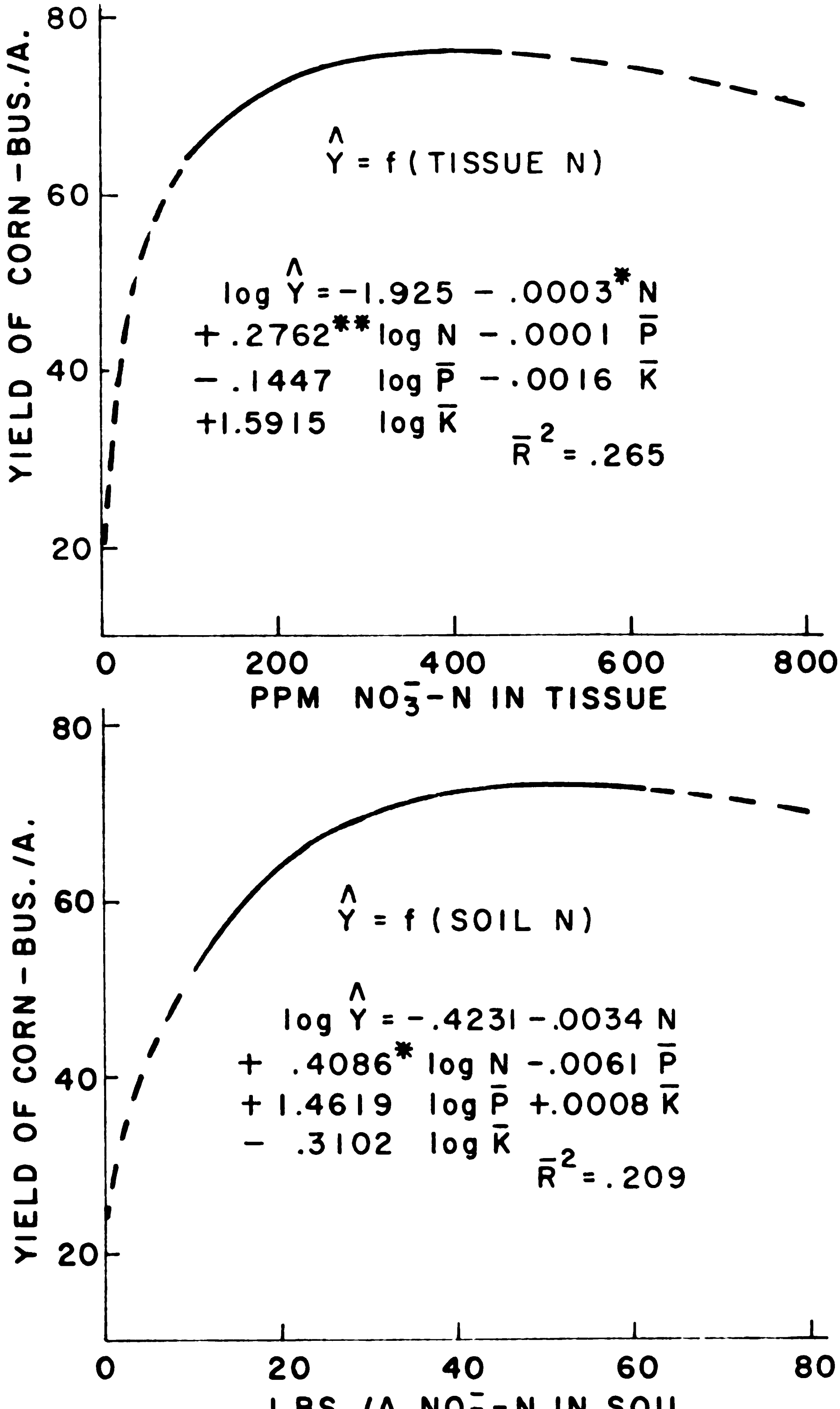

Figure 14. -- Corn yields as calculated functions of tissue tests and soil tests (variable N, average P and K), at tasseling time. Nitrogen sources experiment, East Lansing, 1960.

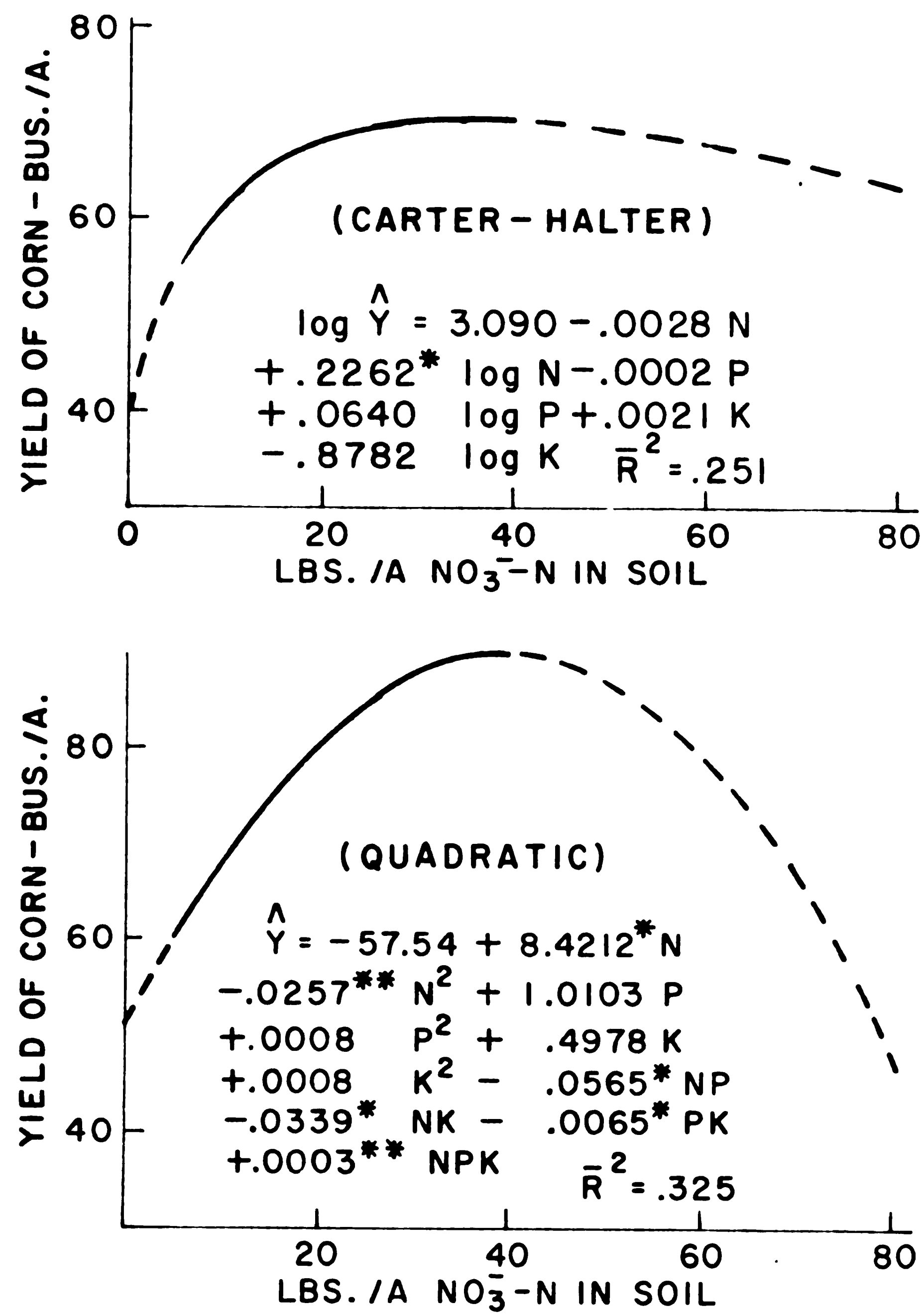

Figure 15. -- Corn yields as calculated functions of soil tests (variable N, average P and K), 11 days after tasseling. Nitrogen sources experiment, East Lansing, 1960.

DISCUSSION

In the three experiments for which data have been presented here, treatments represent management inputs for which costs can be calculated. In a broad sense, several different types of "output" were measured. These included soil pH, soil nutrient levels, tissue nutrient levels, corn populations and corn yields. Only the last has an economic value that can be determined, at least at the present time.

Actually, economic inputs (management practices and fertilizer) and economic output (yield) are separated by a whole chain of intermediate "input-output" relationships. Fertilizers, for example, are applied to the soil. To the extent that soil tests are affected, changes in soil nutrient levels represent the most immediate "outputs" resulting from application of the fertilizer. Soil tests do not change linearly with the addition of fertilizer nutrients. Some sort of functional relationship, undoubtedly, does exist, involving numerous factors such as soil type, organic matter, rainfall, crop removal, extracting procedure, etc.

Soil nutrient levels, in turn, bear some sort of relationship to plant intake. This relationship again is not simple. It is affected by factors both of the external and internal environment of the plant.

Within the plant, nutrients taken up by the roots represent inputs into the internal pool of soluble raw materials. Outputs from this pool represent inputs into the assimilative apparatus. There they are combined with inputs from the photosynthetic process to produce growth and finally storage materials in grain or other plant parts. These are outputs to which the farmer can again assign economic value.

Economists and farmers are primarily concerned with relationships between the first input and the last output in this chain. This is also an ultimate concern of the agronomist. However, the latter is more immediately concerned with relationships in the intervening sequence. The agronomist's contribution must be through defining these intermediate relationships. The ultimate objective will be better served if specialists in different fields can come to common agreement on conceptual schemes for formalizing their findings. The economists have taken the lead in developing mathematical framework for the overall problem. If the piecemeal findings of other specialists can be defined according to similar functional concepts, the development of more generalized production functions will be easier.

Soil tests and tissue tests represent attempts to measure intermediate inputs or outputs in the chain. Theoretically, the closer the sequential relationship between one measured input or output and the next, the easier it should be to establish some sort of predictable relationship between them.

In traditional agronomic terms, numerous workers have shown that limiting and critical levels of nutrients in plant tissue are rather constant for a given crop at varying stages of growth and under a wide range of soil and climatic conditions (96, 97). In the present study, data from two widely different soil types provided remarkably similar estimates of deficient and optimum levels of nitrate in corn tissue. The accumulation of similar data from field and laboratory experiments over a period of years should establish reliable nutritional indices for this crop (corn). These would be immediately useful to the farmer in modifying his management practices from year to year in accordance with accepted agronomic concepts. If the observed functional relationships can be formalized mathematically and reliable parameters found, these may eventually find a place in a more generalized production equation.

Soil nutrient levels are further removed in the sequence of intermediate inputs and outputs leading to final yield. As a result, soil tests have been found to be generally less reliable than foliar analyses in diagnosing nutritional deficiencies. Frequently soils are sampled and tested in off-seasons of the year. This introduces an additional chronological separation between the tests and the period of crop demand. This may not be a serious factor with nutrients such as P and K where slow release from unmeasured forms tends to maintain test values at moderately uniform levels. Significant seasonal fluctuations in P and K were observed in this study, but they were small, relatively speaking, to those observed for nitrate.

Large seasonal fluctuations in soil nitrate reflected variations in rate of release from soil organic matter and rates of crop removal or leaching loss. Data from three experiments on two soil types showed that soil tests for nitrate were even more useful than tissue tests in anticipating deficiencies and identifying optimum levels of nitrogen for corn. The proposed deficient level of about 20 pounds NO_3^--N per acre requires further verification. The optimum level of about 40 pounds NO_3^--N per acre was in exact agreement with that found during two previous seasons at one of the same locations. The optimum value, therefore, appears to be valid over a fairly wide range of soil and climatic conditions. Its usefulness for diagnostic purposes will depend on the development of routines which will minimize changes in nitrate content of moist soil samples between the time of sampling and the time of testing.

The agronomic significance of discrete limiting and optimum (or critical) levels of soil nitrate is clear. If a continuous functional relationship to yield can be defined and shown to have general applicability, a rational basis may appear at a later date for introducing it into a generalized production function with economic significance.

The mathematical functions employed were useful in verifying and providing statistical support for the optimum nitrate levels arrived at by inspection of treatment means for yields and soil or tissue tests. In addition they revealed functional relationships with soil and tissue phosphorus which were not expected and would not have been found by comparing treatment means.

There were disappointingly few significant coefficients for multiple regression. This was due, in part at least, to the relatively small number of plots in individual experiments. In this regard, the Carter-Halter function had somewhat of an advantage, because fewer degrees of freedom were taken up by independent terms in the equation.

Numerous coefficients significant at 10 to 20 percent probability levels were encountered. These were not examined. However, it is likely that all parameters, regardless of statistical significance, may be relevant to the observed range of measurements and should be retained. It may be possible at a later date to compare these with coefficients from other experiments covering different ranges of observation. In this way, more generalized parameters may be derived.

In the rotation experiment, up to 68 percent of total variance was accounted for by the Carter-Halter regression. Preliminary examination of the residuals indicated that these were still related to treatment. More careful study of these residual variations may make it possible to distinguish between response to the current year's fertilizer applications and response to residual effects of previous treatment on soil factors.

In the case of the nitrogen sources experiment, residuals appeared to be related rather strongly to soil pH. The low $\bar{R}^2$ values for this experiment are very likely due to the fact that soil pH was not included in the equations for the soil tests. Manganese toxicity was very likely a controlling physiological factor. If manganese determinations had been available for inclusion in the equations for tissue nutrients, larger $\bar{R}^2$ values might have been obtained.

In spite of the low level of total information provided by these functions, parameters for nitrate appeared to be valid and led to estimates of optimum levels which were consistent with those for other experiments and from previous work.

Thus, useful information can be extracted from multiple regression analyses of agronomic data, even when the overall predictability of a given group of data may be low. The "hidden" replication associated with regression points lends additional statistical support for inferences which are made. The conceptual format of the regression equations used here are such that they may be readily integrated into more generalized production functions as their relationship to other stages of the "input-output" sequence are better understood.

SUMMARY

Soil tests for nitrate and available P and K were found, by analysis of variance, to be significantly influenced by numerous management and soil factors, as well as by climatic conditions and time. Soil test variations during the growing season appeared to reflect changes in rates of release from soil sources and removal by corn.

Tissue tests for nitrate, phosphate and potassium in corn midribs were found to be influenced by the same factors as were soil tests. Specific effects were frequently very different, however. Tissue test variations during the season appeared to reflect variations in rate of uptake and rate of assimilation of nutrients by the corn.

Soil tests of 20 pounds per acre of nitrate nitrogen or less anticipated the development of visible nitrogen deficiency symptoms by one to three weeks. The corresponding "threshold level" for tissue nitrate was 200 ppm. N, on a green tissue basis.

The earlier these threshold levels were breached, the greater was the yield depression at the end of the season. Only in situations of relatively low nitrogen fertility were deficient levels observed early enough in the season to correct them by nitrogen sidedressings, using conventional equipment. Deficient levels which developed after completion of pollination did not reduce yields significantly, even when visible deficiency symptoms did develop in September prior to maturity.

Multiple regression analysis of unit observations (rather than treatment means) revealed distinct optimum levels of soil and tissue nitrate which were higher than the threshold levels (40 pounds per acre and 400 ppm., respectively for soil and green tissue). The optimum soil nitrate level coincided exactly with values obtained by inspection

of treatment means from three experiments on two different soil types in 1960 and from one of these experiments over a three-year period.

Multiple regression analysis also revealed significant to highly significant relationships between yield and both soil and tissue phosphorus in one experiment. These were not expected and were not obvious in the treatment means.

Multiple regression curves displayed distinct optima for soil and tissue phosphorus. These were 18 pounds per acre of P in the soil by the Bray P_1 test and 50 to 85 ppm. of P extractable with acetic acid in the tissue.

Soil tests for nitrate were better correlated with yield, particularly during periods of rapid corn development, than were tissue tests for nitrate. The reverse was true for the phosphorus tests. Essentially no significant correlation was observed between yields and soil or tissue tests for potassium in the experiments studied.

In general, the best multiple correlations, with both soil and tissue tests, were obtained at silking time -- or, in other words, near the end of the grand period of growth and physiological development in corn.

CONCLUSIONS

It appears that reliable "threshold" values can be established for nitrates in soil and tissue where actual N deficits develop prior to the appearance of visible deficiency symptoms in corn. These threshold values appear to correspond to the "critical" level in the zone of poverty adjustment, as defined in established schemes for interpretation of foliar analysis data (97).

Multiple regression analysis of yields and soil or tissue tests made during the growing season revealed distinct optimum levels of nitrate for maximum yields of corn. These optimum levels were higher than the threshold levels. They may represent an upper limit of balanced nutrition, beyond which accumulations of nitrate reflect critical deficiencies of some other nutrient or some other factor of growth.

The range between the threshold and optimum levels may represent a zone where variable response may be expected due to varying degrees of "nutrient substitution," in the sense used by production economists.

Multiple regression analysis using appropriate curvilinear models promises to be equally useful in uncovering functional relationships between crop yields and soil or tissue tests for nutrients other than N.

LIST OF REFERENCES

1. Allen, O. N. Experiments in Soil Bacteriology. Burgess Publishing Co., Minneapolis. Pp. 64-73. 1957.

2. Allison, L. E. Estimating the ability of soil to supply nitrogen. Agr. Chem. 11 (4):46-48, 139. 1956.

3. Anderson, G. R. An economic evaluation of three soil nitrogen tests. Unpub. M.S. Thesis, Michigan State University, East Lansing, Michigan. 1958.

4. Atkinson, H. J., Patry, L. M., and Wright, L. E. Plant tissue testing. Sci. Agr. 24:437-442. 1944.

5. ______________, ____________, and Levick, R. Plant tissue testing III. Effects of fertilizer applications. Sci. Agr. 28:223-228. 1948.

6. Au, F. Mineralization of soil organic nitrogen as influenced by organic amendments, nitrogen fertilizer, crop sequence and time. Unpub. M.S. Thesis, Michigan State University, East Lansing, Michigan. 1958.

7. Baule, B. Landwirtsch. Jahrb. 51:363-385. 1918.

8. Baver, L. D., and Bruner, F. H. Rapid soil tests for estimating the fertility needs of Missouri soils. Missouri Agr. Exp. Sta. Bul. 404. 1939.

9. Bishop, W. D., and Barber, S. A. The effect of soil phosphorus compounds on soil test correlation. Soil Sci. Soc. Amer. Proc. 22:435-439. 1958.

10. Black, C. A. Evaluation of nutrient availability in soils, and prediction of yield response to fertilization. Iowa State College Jour. of Sci. 30:1-11. 1955.

11. Bonner, J. Plant Biochemistry. Academic Press Inc., New York. 537 pp. 1952.

12. Bray, R. H. Soil-plant relations: I. The quantitative relation of exchangeable potassium to crop yields and to crop response to potash additions. Soil Sci. 58:305-324. 1944.

13. __________. Soil-plant relations: II. Balanced fertilizer use through soil tests for potassium and phosphorus. Soil Sci. 60:463-473. 1945.

14. __________. Correlation of soil tests with crop response to added fertilizer and with fertilizer requirement. In H. B. Kitchen, ed. Diagnostic Techniques for Soils and Crops. Amer. Potash Inst. Washington, D. C. Pp. 53-86. 1948.

15. __________., and Kurtz, L. T. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59:39-45. 1945.

16. Brock, W. Unpublished data. Mich. Agr. Exp. Sta. (Soil Sci.). 1958-59.

17. Carolus, R. L. Experiences with rapid chemical tests for the determination of nutrient deficiencies in vegetable crops. Proc. Amer. Soc. Hort. Sci. 33:479-583. 1936.

18. ____________. The use of rapid chemical plant nutrient tests in fertilizer deficiency diagnoses and vegetable crop research. Virginia Truck Exp. Sta. Bul. 98:1531-1556. 1938.

19. Chang, S. C., and Jackson, M. L. Fractionation of soil phosphorus. Soil Sci. 84:133-144. 1957.

20. Cho, C. M., and Caldwell, A. C. Forms of phosphorus and fixation in soils. Soil Sci. Soc. Amer. Proc. 23:458-460. 1959.

21. Cook, R. L., and Millar, C. E. Plant nutrient deficiencies. Michigan Agr. Exp. Sta. Spec. Bul. 353. 1953.

22. Doll, J. P., Heady, E. O., and Pesek, J. T. Fertilizer production functions for corn and oats; including an analysis of irrigated and residual response. Iowa. Agr. Exp. Sta. Res. Bul. 463:363-394. 1958.

23. Dumenil, L. Nitrogen and phosphorus composition of corn leaves and corn yields in relation to critical levels and nutrient balance. Soil Sci. Soc. Amer. Proc. 25:295-298. 1961.

24. Dyer, B. The analytical determination of probable available mineral plant food in soils. Jour. Chem. Soc. 65:115-167. 1894.

25. Eckerson, S. H. Protein synthesis by plants. I. Nitrate reduction. Bot. Gaz. 77:377-390. 1924.

26. _____________. Influence of phosphorus deficiency on the metabolism of tomato plants. Amer. Jour. Bot. 16:852. 1929.

27. Eid, M. T., Black, C. A., and Kempthorne, O. Importance of soil organic and inorganic phosphorus to plant growth at low and high soil temperatures. Soil Sci. 71:361-370. 1951.

28. ________, __________, ______________, and Zoellner, J. A. Significance of soil organic phosphorus to plant growth. Iowa Agr. Exp. Sta. Res. Bul. 406. 1954.

29. Eik, K., Webb, J. R., Black, C. A., Smith, C. M., and Pesek, J. T. Evaluation of residual effects of phosphate fertilization by laboratory and plant-response methods. Soil Sci. Soc. Amer. Proc. 25:21-24. 1961.

30. Emmert, E. M. The determination of nitrate in green tomato and lettuce tissues. Plant Physiol. 4:519-528. 1929.

31. ___________. The effect of soil reaction on the growth of tomatoes and lettuce and on the nitrogen, phosphorus and manganese content of the soil and plant. Kentucky Agr. Exp. Sta. Bul. 314. 1931.

32. ___________. Field method for estimating nitrate, phosphate and potassium in plants. Plant Physiol. 7:315-321. 1932.

33. ___________. Tests for phosphate, nitrate and soluble nitrogen in conducting tissue of tomato and lettuce plants as indicators of availability and yield. Kentucky Agr. Exp. Sta. Cir. 43. 1934.

34. ___________. Plant tests as a guide to fertilizer treatment of tomatoes. Proc. Amer. Soc. Hort. Sci. 38:621-622. 1941.

35. ___________. Plant tests as a guide to fertilizer treatment of tomatoes. Kentucky Agr. Exp. Sta. Bul. 430. 1942.

36. Emerson, P. Principles of Soil Technology. The Macmillan Co., New York. Pp. 402. 1930.

37. Fallon, J. Field testing reveals the story of the plant nutrients. Crops and Soils 11 (10):9-10. 1959.

38. Farden, C. A., and Magistad, O. C. Use of the yield equation in pineapple culture. Jour. Amer. Soc. Agron. 24:964-975. 1932.

39. Fertilizer recommendations for Michigan crops. Michigan Coop. Ext. Serv. Bul. E-159.

40. Fiske, C. H. and Subbarow, Y. The colorimetric determination of phosphorus. Jour. Biol. Chem. 66:375-400. 1925.

41. Fitts, J. W., Bartholomew, W. V. and Heidel, H. Correlation between nitrifiable nitrogen and yield response of corn to nitrogen fertilization on Iowa soils. Soil Sci. Soc. Amer. Proc. 17:119-122. 1953.

42. Fried, M., and Dean, L. A. A concept concerning the measurement of available soil nutrients. Soil Sci. 73:263-271. 1952.

43. Fujimoto, C. K., and Sherman, G. D. Behavior of manganese in soil and the manganese cycle. Soil Sci. 66:131-145. 1948.

44. Hanway, J., and Dumenil, L. Predicting nitrogen fertilizer needs of Iowa soils: III. Use of nitrate production together with other information as a basis for making nitrogen fertilizer recommendations for corn in Iowa soils. Soil Sci. Soc. Amer. Proc. 19:77-80. 1955.

45. Harper, H. J. The accurate determination of nitrates in soils. Phenoldisulfonic acid method. Ind. Eng. Chem. 16:180-183. 1924.

46. Heady, E. O., Pesek, J. T. and Brown, W. G. Crop response surfaces and economic optima in fertilizer use. Iowa Agr. Exp. Sta. Res. Bul. 424. 1955.

47. Hester, J. B. Soil and plant tests as aids in soil fertility programs. Comm. Fert. 63 (5):10-16, 18, 29. 1940.

48. Hoffer, G. N. Testing corn stalks chemically to aid in determining their plant food needs. Indiana Agr. Exp. Sta. Bul. 298. 1928.

49. Jackson, M. L. Soil Chemical Analysis. Prentice-Hall, Inc., Englewood Cliffs, N. J. Pp. 197-201. 1958.

50. Krantz, B. A., Nelson, W. L., and Burkhart, L. F. Plant-tissue tests as a tool in agronomic research. In H. B. Kitchen, ed. Diagnostic Techniques for Soils and Crops. Amer. Potash Inst., Washington, D. C. Pp. 137-155. 1948.

51. Kresge, C. B., and Merkle, F. G. A study of the validity of laboratory techniques in appraising the available nitrogen producing capacity of soils. Soil Sci. Soc. Amer. Proc. 21:516-521. 1958.

52. Lunt, H. A., Swanson, C. L. W., and Jacobson, H. G. M. The Morgan soil testing system. Connecticut Agr. Exp. Sta. Bul. 541. 1950.

53. Lynd, J. Q. Diagnosis of plant nutrient deficiencies by means of soil tests, plant tissue tests and foliar analysis. Unpub. Ph.D. Thesis, Mich. State. Univ., East Lansing. 1948.

54. __________, Turk, L. M., and Cook, R. L. Application of soil tests, tissue tests and foliar analysis to field experiments. Soil Sci. Soc. Amer. Proc. (1948) 14:236-241. 1949.

55. Magnitski, K. P. The diagnosis of mineral nutrition of plants according to chemical composition of leaves. In W. Reuther, ed. Plant Analysis and Fertilizer Problems. American Institute of Biological Sciences, Washington, D. C. Pp. 159-179. 1961.

56. Marsh, R. P. Comparative study of the calcium-boron metabolism of representative dicots and monocots. Soil Sci. 53:75-78. 1942.

57. Mathers, A. C., Vietz, F. G., Jr., Jensen, M. E. and Sletten, W. H. Relationship of nitrogen and grain sorghum yield under three moisture regimes. Agron. Jour. 52:443-446. 1960.

58. Matkin, O. A., and Chandler, P. A. Nitrogen in nursery soils. In K. F. Baker, ed. The U. C. system for producing healthy container-grown plants. California Agr. Exp. Sta. Ext. Ser. Man. 23:108-122. 1957.

59. McCool, M. M., and Weldon, M. D. The effect of soil type and fertilization on the composition of expressed sap of plants. Jour. Amer. Soc. Agron. 20:778-792. 1928.

60. McGeorge, W. T. Modified Neubauer method for soil cultures. Soil Sci. 62:61-70. 1946.

61. Mehlich, A., and Drake, M. Soil chemistry and plant nutrition. In F. E. Bear, ed. Chemistry of the Soil. Reinhold Publishing Corp., New York. Pp. 286-327. 1958.

62. Merkle, F. G. Soil testing operation, interpretation and application. Pennsylvania Agr. Exp. Sta. Bul. 398. 1940.

63. Millar. C. E. Soil Fertility. John Wiley & Sons, Inc., New York. Pp. 132-134. 1955.

64. Mitscherlich, E. A. Landwirtsch. Jahrb. 38:537-552. 1909.

65. Mora R., J. A. Effects of organic amendments, fertilizer nitrogen, time and cropping sequence on the mineralization of soil organic nitrogen. Unpub. M.S. Thesis, Michigan State University, East Lansing, Mich. 1957.

66. Morgan, M. F. Chemical soil diagnosis by the universal soil testing system. Connecticut Agr. Exp. Sta. Bul. 450. 1941.

67. Munson, R. D., and Stanford, G. Predicting nitrogen fertilizer needs of Iowa soils: IV. Evaluation of nitrate production as a criterion of nitrogen availability. Soil Sci. Soc. Amer. Proc. 19:464-468. 1955.

68. ___________, and Doll, J. P. The economics of fertilizer use in crop production. In A. G. Norman, ed. Advances in Agronomy XI. Academic Press, Inc., New York. Pp. 133-169. 1959.

69. Nightingale, G. T. The nitrogen nutrition of green plants. Bot. Rev. 3:85-174. 1937.

70. _______________. Nitrate and carbohydrate reserves in relation to nitrogen nutrition of pineapple. Bot. Gaz. 103:409-456. 1942.

71 _______________. Potassium and phosphate nutrition of pineapple in relation to nitrate and carbohydrate reserves. Bot. Gaz., 104:191-223. 1942.

72. Ohlrogge, A. J. The Purdue soil and tissue tests. Indiana Agr. Exp. Sta. Bul. 584. 1952.

73. Olsen, S. R., Cole, C. V., Watanabe, F. S., and Dean, L. A. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U. S. D. A. Cir. 939. 1954.

74. Page, N. R., and Burkhart, L. Mineral nutrient extraction and distribution in the peanut plant. Jour. Amer. Soc. Agron. 33:743-755. 1941.

75. Parks, W. L., and Knetsch, J. L. Corn yields as influenced by nitrogen level and drouth intensity. Agron. Jour. 51:363-364. 1959.

76. Patel, J. M., and Mehta, B. V. Soil phosphorus fractionation studies. Soil Sci. Soc. Amer. Proc. 25:190-192. 1961.

77. Peech, M., and English, L. Rapid microchemical soil tests. Soil Sci. 57:167-195. 1944.

78. ________, Alexander, L. T., Dean, L. A., and Reed, J. F. Methods of soil analysis for soil fertility investigations. U. S. D. A. Cir. 757. 1947.

79. Pesek, J. T. Agronomic problems in securing fertilizer response data desirable for economic analysis. In E. L. Baum, E. D. Heady, and J. Blackmore, ed. Methodological Procedures in the Economic Analysis of Fertilizer Use Data. Iowa State College Press, Ames. Pp. 101-112. 1956.

80. __________, and Heady, E. O. Derivation and application of a method for determining minimum recommended rates of fertilization. Soil Sci. Soc. Amer. Proc. 22:419-423. 1958.

81. Peterson, L. A., Attoe, O. J., and Ogden, W. B. Correlation of nitrogen soil tests with nitrogen uptake by the tobacco plant. Soil Sci. Soc. Amer. Proc. 24:205-209. 1960.

82. Pettinger, N. A. The expressed sap of corn plants as an indicator of nutrient needs. Jour. Agr. Res. 43:95-119. 1931.

83. Prince, A. L. Determination of total nitrogen, ammonia, nitrates and nitrites in soils. Soil Sci. 59:47-52. 1945.

84. Sayre, J. D. Mineral accumulation in corn. Plant Physiol. 23: 267-281. 1948.

85. Scarseth, G. D. Plant tissue testing in diagnosis of the nutritional status of growing plants. Soil Sci. 55:113-120. 1943.

86. Shickluna, J. C. Chemical procedures for the analysis of soil. Michigan State University Soil Sci. Mimeograph. Pp. 7-9. 1957.

87. Smith, G. E. Soil fertility and corn production. Missouri Agr. Exp. Sta. Bul. 583. 1952.

88. Spillman, W. J., and Lang, E. The Law of Diminishing Returns. World Book, New York. Pp. 1-77. 1924.

89. ______________. Use of the exponential yield curve in fertilizer experiments. U. S. D. A. Tech. Bul. 348. 1933.

90. Spurway, C. H. Soil Fertility Diagnosis and Control for Field, Garden, and Greenhouse Soils. Edwards Bros., Inc., Ann Arbor, Mich. 176 pp. 1948.

91. ____________, and Lawton, K. Soil testing -- a practical system of soil fertility diagnosis. Mich. Agr. Exp. Sta. Tech. Bul. 132. 1949.

92. Sundquist, W. B., and Robertson, L. S., Jr. An economic analysis of some controlled fertilizer input-output experiments in Michigan. Mich. Agr. Exp. Sta. Tech. Bul. 269:1-57. 1959.

93. Thornton, S. F., Conner, S. D. and Fraser, R. R. The use of rapid chemical tests on soils and plants as aids in determining fertilizer needs. Indiana Agr. Exp. Sta. Cir. 204. 1939.

94. Truog, E. Present status and future of soil testing and soil analysis. Soil Sci. Soc. Amer. Proc. (1936) 2:181-183. 1937.

95. ________. Test for available soil nitrogen. Comm. Fert. 88:72. 1954.

96. Ulrich, A. Plant analysis methods and interpretation of results. In H. B. Kitchen, ed. Diagnostic Techniques for Soils and Crops. Amer. Potash Inst., Washington, D. C. Pp. 157-198. 1948.

97. ________, Ririe, D., Hills, F. J., George, A. G., and Morse, M. D. (1) Plant analysis, a guide for sugar beet fertilization. California Agr. Exp. Sta. Bul. 766. 1959.

98. Wark, D. C. Tests on plant tissue as a guide to the soil's available nutrients. Jour. Australian Inst. Agr. Sci. 5:224-227. 1939.

99. Welch, C. D. Unpub. M.S. Thesis, North Carolina State College, Raleigh, N. C. 1947. (Cited in Krantz, et al., p. 146, 1948.)

100. White, W. C., and Pesek, J. Nature of residual nitrogen in Iowa soils. Soil Sci. Soc. Amer. Proc. 23:39-42. 1959.

101. Wilcox, O. W. Meaning of the great German soil fertility survey. Soil Sci. 79:123-132. 1955.

102. Wolf, B., and Ichisaka, V. Rapid chemical soil and plant tests. Soil Sci. 64:227-244. 1947.

103. Woodruff, C. M. Estimating the nitrogen delivery of soil from the organic matter determination as reflected by Sanborn Field. Soil Sci. Soc. Amer. Proc. 14:208-212. 1949.