MINERAL AND ORGANIC FORMS OF NITROGEN IN SOME MICHIGAN SOILS AND AN AGRO-ECONOMIC EVALUATION OF THEIR POTENTIAL USEFULNESS FOR ADVISORY PURPOSES

Thesis for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

Bhubneshwar Narain Singh

1960

This is to certify that the

thesis entitled

Mineral and Organic Forms of Nitrogen in Some Michigan Soils and an Agro-Economic Evaluation of Their Potential Usefulness for Advisory Purposes

presented by

Bhubneshwar Narain Singh

has been accepted towards fulfillment of the requirements for

Doctorate degree in Soil Science

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Date September 12, 1960

O-169

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By

Bhubneshwar Narain Singh

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies
of Michigan State University of Agriculture and
Applied Science in partial fulfillment of
the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Soil Science
Field of Agronomic Extension

1960

Approved A R Wolcott

Bhubneshwar Narain Singh

ABSTRACT

Air-dry soil samples from five established field experiments were analyzed for exchangeable ammonium, nitrate, and two organic nitrogen fractions. These two organic fractions included the portion hydrolyzed by digestion with strong sulfuric acid and the portion resistant to acid hydrolysis. Attempts were made to correlate these measured forms of nitrogen with crop yields.

Ammonium levels in air-dry soils were several times higher than would be expected in field fresh soils, indicating release by breakdown of soil organic materials during storage. The quantities found were higher in soils high in total organic nitrogen than in soils low in organic nitrogen. There was no relationship to crop yields or to residual yield variance not explained by current fertilizer treatments.

Nitrate levels in soils sampled in the fall of the year reflected rotational differences and levels of previous nitrogen application. In soil samples taken in the spring, nitrate was low and unrelated to prior treatment. No correlation with crop yields or yield residuals was observed.

The two organic fractions and their total showed a tendency to increase with increasing level of nitrogen applied one year previously. However, these increases were not statistically significant. Where supplemental nitrogen had been applied on corn, beans and barley in a rotation including two years of alfalfa-brome, significant increases in each fraction and in their total were observed at the end of the first five-year rotational cycle. The increases in total organic nitrogen ranged from 352 to 648 pounds per acre, exceeding by a factor of 3 to 5

the 120 pounds total supplemental nitrogen which had been applied on the three crops preceding alfalfa. In a second experiment on the same soil type (Sims clay loam) where supplemental nitrogen had been applied on row crops and cereal grains over four cycles of two 5-year rotations, no significant increases in soil organic nitrogen were found. Residual organic nitrogen was significantly higher, by 400 pounds, in the livestock rotation which included manure and two years of alfalfa than in the cash crop rotation.

The ratio of nonhydrolyzable to hydrolyzable nitrogen varied under different systems of management. The proportion of nonhydrolyzable nitrogen was higher where alfalfa was included in the rotation, or where supplemental nitrogen was used. This effect of supplemental nitrogen was enhanced when combined with a high rate of application of other fertilizer nutrients.

In one experiment a maximum of 61 percent of yield variance was found to be associated with regression in a five-variable polynomial equation involving either total organic nitrogen or hydrolyzable nitrogen. However, most of the variance was associated with rotation or supplemental nitrogen treatments. A maximum of 26 percent of yield variance was associated linearly with total soil organic nitrogen when rotation, fertility level and supplemental nitrogen treatments were ignored. Only 15 percent and 5 percent of yield variance were similarly associated with hydrolyzable and nonhydrolyzable nitrogen, respectively.

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ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Dr. A. R. Wolcott for patient counsel and assistance throughout the course of this study. He is particularly indebted to Dr. R. L. Cook who made arrangements for financial assistance and who was instrumental in arranging the author's return for a second period of graduate study at Michigan State University. Special thanks are due Dr. O. Ulrey, US-TCM Expert, located at Ranchi Agricultural College, Bihar, India, for his interest and aid in securing a travel fellowship from the Council on Economic and Cultural Affairs, Inc. The financial assistance from the council is gratefully acknowledged.

He is also grateful to Dr. Glenn L. Johnson for his valuable suggestions and criticisms during preparation of the manuscript, and to Mr. B. Hoffnar for his help in the statistical computations.

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INTRODUCTION

Decisions that farmers make regarding the use of fertilizers are based primarily upon the economic returns they hope to realize from the investment. Estimates of fertilizer costs and expected returns must be weighed against similar estimates for alternative production factors. Decisions resulting from such weighting of alternatives may be qualitative, resulting in total rejection or adoption of a given practice. Or they may be quantitative and expressed in terms of how much of one factor should be substituted for how much of another.

Agronomic research and farmers' experience have built up compelling evidence for the qualitative affirmative decision to use fertilizer. They have also established broad quantitative limits to the range of pounds-per-acre inputs over which the decision is valid. These limits have been established with some degree of refinement for different crops, soil management groups and systems of management. Soil tests for P, K, and pH have contributed additional refinement by providing a basis for assessing the probability that fertilizer applied to a given field will result in increased yields of a given crop.

However, the opportunities for quantitative interpretation of available agronomic data fall short of the requirements for quantitative decision making. Over what range of nutrient combinations can a cheaper nutrient be substituted for a dearer? What part of the cost of fertilizer nutrients may be credited to residual benefits to succeeding crops? At what level of fertilizer input do expected net returns approach marginal equivalence to expected returns from equivalent expenditures for alternative production factors? Deductive economic principles for maximizing returns from combinations of production factors involve manipulation of clearly delineated functional relationships. Currently available agronomic data does not lend itself to effective functional analysis.

In recent years, cooperative activities of agronomists and agricultural economists have been directed towards the design of experiments for obtaining fertility and yield data appropriate for functional analysis. These have been concerned primarily with defining fertilizer input and crop yield output relationships. However, the degree of unexplained yield variation encountered has led to the attempted use of soil tests and other measured soil or climatic variables as independent variables in various formulated functions.

Several difficulties have appeared as regards the use of soil test data for additional control over variance unexplained by input-output functions. Among these are the lack of agreement among agronomists as to the scientific validity of available soil tests. Reservations are particularly strong as regards tests for availability of soil nitrogen, although it is agreed that tests for P and K are far from being as informative as might be desired. A further difficulty is the lack of precise theoretical concepts which might be used to deduce appropriate mathematical formulations for specifying functional relationships between crop yields, applied nutrients, and residual soil nutrients as estimated by soil tests.

A principal objective of the present study was to evaluate several chemically derived fractions of soil nitrogen in terms of their sensitivity as measures of residual nitrogen from previous treatment. A secondary objective was the application of functional analysis as a statistical tool for evaluating the significance of measured nitrogen fractions to crop performance. These investigations must be considered preliminary in scope. However, they were motivated by the ultimate objective of providing appropriate agronomic information for economic optima studies leading towards efficient fertilizer use.

LITERATURE REVIEW

Nature of Soil Organic Nitrogen

Present knowledge about the nature of soil organic nitrogen is based on the studies of nitrogen compounds released by extraction or hydrolysis of soil by chemical agents, usually strong acids or bases. Practically all the nitrogen present in surface soil is in combination with organic compounds. Gortner and Morrow (29) fractionated the nitrogen present in mineral and organic soils and showed that a large part of organic nitrogen was in the form of protein and proteinaceous compounds.

Hobson and Page (34) performed numerous studies on soil organic matter and concluded that the humic materials contain a complex of non-nitrogenous humic acids and protein. A smaller portion of the total nitrogen extracted from soils with cold soda was found to be in the amino form than in protein of animal or vegetable origin. From this they concluded that the protein was of a different source than plant or animal protein.

At about the same time Waksman and Iyer (80, 81, 82) postulated that protein existed in the soil in the form of a resistant ligno-protein complex, and this accounted for its apparent low availability to micro-organisms and plants.

Kojima (40) and Bremner (10) showed that 30-40 percent of total nitrogen was in the form of amino acid in soil organic matter hydrolysates. Bremner, et al. (13), and Sowden (69), estimated that 5-10 percent was in the form of hexosamines. Numerous amino acids and hexosamines have been identified by Bremner (11, 14), but their modes of linkage in soil have not been established. Adams et al. (1), and Anderson (5), indicated that of the order of 2 percent of the total nitrogen in surface soil occurs in the forms of adenine, cystein, thymine. The proportion in which these nitrogen bases occurred indicated that they came previously from microbial nucleic acids. Bremner (12) has estimated that not more than 10 percent of total soil nitrogen is present as nucleic acid.

Allison (2) pointed out that nitrogen in humus is very hetrogeneous in nature and is believed to consist of protein, amino-sugars, nucleic acid, chitin, heterocyclic compounds and ligno-protein complexes. Rodrigues (63) and Bremner (15) have shown that some of the nitrogen in soil previously considered to be organically combined is in the form of ammonium trapped in the lattice of clay minerals. Allison (2) pointed out that these nitrogen compounds are so intimately bound with clays that they are largely free from biological attack. However, present evidence indicates that more than 95 percent of the total nitrogen in the surface soil is organically combined. It must be mineralized (converted to inorganic form) before it is available for plant absorption.

Availability of Organic Nitrogen

An abundant literature exists on the availability of organic nitrogen to plants. There is much that is ambiguous or contradictory in this literature. However, it is a universally accepted concept that organic nitrogen must be mineralized before it is available for plant uptake. The process by which this is carried out is called "mineralization" and is the result of microbial activity. The stages in mineralization of organic nitrogen have been outlined as follows:

Ammonification (Organic N → Ammonia); Nitrification (Ammonia → Nitrite → Nitrate)

Organic N ⟶ Ammonia ⟶ Nitrite ⟶ Nitrate

Nitrifiable N (Organic N → Ammonia); Available N (Nitrite → Nitrate)

In a normal soil, nitrate is the end product of nitrogen mineralization. Marchall (45) pointed out that ammonia was the first form of mineral nitrogen to appear in the break-down of nitrogenous organic materials. This is oxidized to nitrate via nitrite. Nitrate formed by ammonification and nitrification during some finite period, such as a growing season in the field or the period of an incubation in the laboratory, is referred to as "nitrifiable" nitrogen. Organisms involved in the decomposition process use organic substances as food. Part of the materials entering the metabolic processes of decomposition is used in the synthesis of microbial cell tissue and part is converted to inorganic (mineral) form. The nitrogen mineralized in excess of the needs of the microorganisms represents nitrogen "available" for higher plants.

Harmsen and Van Schreven (32) have summarized the areas of major agreement in the literature dealing with mineralization of organic nitrogen in soil as follows:

(a) In ordinary soil, the rate of oxidation to nitrate is greater than the formation of nitrite. Nitrite formation, in turn, is faster than the rate of ammonification. As a result, ammonium and nitrite do not accumulate in soils except under abnormal conditions.

(b) In fallow soils, the mineral nitrogen content is lowest in winter, rises in spring, is highest in summer, and goes down in autumn.

(c) In cropped soils, the minimum mineral nitrogen content is accompanied by maximum plant growth, and maximum mineral nitrogen content occurs after harvest.

(d) The winter minimum is due to heavy leaching in humid climates. The rise in spring is probably due to a "partial sterilization effect" as a result of frost, giving rise to an enhanced activity of the surviving population as the soil warms up in the spring.

(e) The mineral nitrogen content of soil under perennial crops remains very low at all times.

(f) The nitrogen content of organic materials below which no mineralization occurs corresponds to a C:N ratio of 20 to 25 : 1.

Nitrate is considered the form primarily used by most crop plants. Mehlich (48) has stated that NO_3 ion is rapidly reduced in plants to NH_3, probably in the presence of a molybdenum-containing enzyme. The NH_3, in combination with organic acids, forms amino acids, which are the building stones of proteins. Lyon, Buckman and Brady (44) have pointed out that young plants of almost all kinds are capable of using nitrogen in the form of ammonia, although they seem to grow better if some nitrate nitrogen is also available. They pointed out that plants such as lowland rice even prefer ammoniacal nitrogen instead of nitrate. Wallace and Mueller (78) found an average ratio of ammonia to nitrate absorption of 1.84; ammonia absorption increased with rising pH, but nitrate absorption decreased with increasing pH. Burris (20), discussing the relative effectiveness of nitrate and ammonia in plant nutrition, observed that his own experimental data indicate that plants usually assimilate ammonia more readily than nitrate.

Chapman and Liebig (21) have concluded that whenever two conditions occur, namely, fairly high ammonium concentrations and neutral to alkaline soil conditions, more or less accumulation of nitrite in plants may be expected. Nightingale (54) has reported that nitrate is reduced rapidly to the ammonia form after absorption by plants and is then converted into organic nitrogen compounds in the same manner as ammonia nitrogen. Mevius and Dikussar (49) reported that sweet corn can utilize nitrogen of nitrites in either neutral or alkaline solution. The optimum concentration is approximately 50 mg of nitrite nitrogen per litre, but at a pH of 7.0 as much as 200 mg per litre is not injurious. An increase in the amount of nitrite in a medium is followed by a rapid increase in assimilation and in the total amount of nitrogen in plants.

Thus the toxicity of nitrite and ammonia nitrogen is probably dependent upon the relative rates of absorption and utilization or detoxification within the plant. Grogan and Zink (30) and Tiedjens and Robbins (75) have concluded that if assimilation or detoxification of ammonia or nitrite nitrogen within the plant keeps pace with absorption so that no accumulation occurs, injury to the plant is prevented.

Bremner (19), Salter and Green (66), and Woodruff (89) have estimated that nitrogen is released from soil organic matter to the extent of 1 to 3 percent during each growing season. Allison (2) listed factors which affect the rate of release of nitrogen from soil organic matter. These are: (a) nature of the soil organic matter itself, (b) temperature, (c) moisture, (d) aeration, (e) reaction, (f) supply of inorganic nutrients, and (g) nature of the soil microflora.

Millar *et al.* (51) in studying the effect of decomposing plant residues on accumulation of nitrate in soil, found a significant correlation between accumulation of nitrates in the soil and the carbon and nitrogen contents of the materials added. Materials with a wide C:N ratio depressed the accumulation of nitrates in soil to a greater extent than materials having a narrow C:N ratio. Waksman and Hutchings (79) concluded that the source and chemical nature of organic materials added to the soil strongly influence the retention of nitrogen in organic forms in the soil.

Waksman and Tenney (84) suggested that 1.7 percent nitrogen in decomposing rye was sufficient for microbial need, and that a nitrogen content in excess of this value was rapidly mineralized. Waksman and

Tenney (83), Pinck et al. (59), and Norman (55) have reported that, at a critical nitrogen content of 1.2 to 1.7 percent, neither tie-up (immobilization) or release (mineralization) of nitrogen takes place.

Broadbent (16), Jansson and Clark (36), and Broadbent and Bartholomew (17) have pointed out that different kinds of organic matter incorporated in the soil either alone or together with an inorganic nitrogen source, will influence net mineralization differently. Millar et al. (51) reported that materials high in nitrogen tend to decompose faster at first than materials low in nitrogen. After prolonged decomposition, Turk (77) found that plant materials high in nitrogen gave a greater retention of carbon than did materials lower in nitrogen.

The rate of residue addition is also a factor affecting the availability of nitrogen in soil. Wright (90), Millar et al. (52), Lohnis et al. (42), Allison and Sterling (3), Patrick (57), Dunn and Wheeting (22), and Pinck et al. (59) have noted that the rate of tie-up or release of nitrogen from organic materials tended to decrease with increasing rate of addition or concentration of the plant residues or manures in soils. Bartholomew (7) has pointed out that where the addition rates have been either high (5 to 20 tons per acre) or low (0.5 to 2 tons per acre) or where the range in the rate has not been wide, the influence of concentration of residues on nitrogen tie-up has not always been evident. However, the influence of concentration of residues on rate of decomposition and nitrogen tie-up had been most evident where low rates of nitrogen were compared to high rates.

Periodic addition of fresh plant materials in the form of crop residues and green manures has long been accepted as fundamental to good soil management. Their influence upon the soil nitrogen supply within a very few weeks after application is often marked. Very little carryover or delayed influence has been noted in crops succeeding the initial one.

The application of inorganic nitrogen to low nitrogen residues has been reported both to hasten and to retard decomposition of these materials. Starkey (70), Tenney and Waksman (74), McCalla (47), Jansson and Clark (36) have found that the addition of inorganic nitrogen both in and apart from soil tended to speed up decomposition. However, Chapman and Liebig (21) found that additional nitrogen did not influence the level of carbonaceous material retained in the soil after prolonged decomposition.

Since mineralization is mainly biochemical in nature, environmental factors which affect the number and activity of microorganisms, also influence the processes of ammonification and nitrification. The microorganisms connected with ammonification include aerobic and anaerobic forms, but the bacteria involved in nitrification are strictly aerobic. Thus the relative amounts of soil nitrogen in the form of ammonia nitrogen and nitrate nitrogen are affected by the amount of oxygen available in soil air. Plummer (60) observed under strictly anaerobic condition that there was somewhat less ammonia produced than when oxygen was present at the beginning. Oxygen was found to be the limiting atmospheric constituent for nitrification. Fathi and Bartholomew (24) indicated that the minimum oxygen concentration for nitrification was below 0.4 but greater than 0.2 percent, and the optimum concentration was about that contained in ordinary air.

Soil moisture is another factor affecting the number and activities of the organisms connected with mineralization. Gainey (27) found that nitrate accumulation was directly proportional to moisture content of soils. Bollen (9) found that 60 percent moisture saturation capacity was optimum for ammonification and nitrification. However, 75 per cent of saturation capacity was found to be the optimum content for carbon dioxide evolution in prolonged respiration experiments. Fitts *et al.* (25) found that 100 cm of water tension was optimum for the production of nitrate under laboratory conditions. Depending on the texture of the soil, this tension resulted in 25 to 35 percent moisture.

Mineralization is also greatly affected by temperature. Ensminger and Pearson (23) have summarized the effects of temperature as follows: "It is a generally accepted fact that the greatest accumulation of nitrate takes place during the summer months and the least during winter months." Panganiban (56) found that ammonification took place between 15 and 60 degrees C, the rate increasing with rise in temperature. Nitrification took place at 15 and 40 degrees C. The optimum temperature for nitrification was 35 degrees C or slightly higher. Rothwell and Frederick (64) have found that nitrification proceeds at a low but significant rate at temperatures as low as 5 degrees C. Sabey *et al*. (65) reported that nitrification rate decreased with diminution in soil temperature. However, the relationship was not linear over the entire temperature range and was dissimilar in different soils.

In dealing with environmental conditions the role of soil reaction cannot be overlooked. Allison and Sterling (3) found that lime produced a greater increase in nitrification in a low nitrogen soil than in a high nitrogen soil. In all cases, lime had a stimulating effect on mineralization, continuing for a long time. Halvorson and Caldwell (31) reported that the presence of large amounts of calcium carbonate inhibited nitrification. Stojanovic and Alexander (71) observed the inhibition of *Nitrobactor* by free NH_3 at alkaline pH. They found that concentrations of ammonia greater than 250 mg/ml reduced nitrate formation proportionally to the concentration of NH_4. Oxidation of ammonium to nitrite was unaffected. Harmsen and Van Schreven (32) stated that in most normal soils nitrite seldom accumulates to a measurable level, but the formation of nitrite is enhanced by a high pH level to a greater degree than the transformation of nitrite to nitrate.

An adequate supply of nutrients, notably phosphorus, is also needed for rapid decomposition. Kaila (38) noted that 0.2 percent phosphorus was an average level below which decomposition was retarded and immobilization of mineral phosphates occurred. Ensminger and Pearson (23) have concluded that soil treatment such as the addition of limestone, phosphorus, and potassium affects the production of nitrates in the field, as do tillage operations such as plowing, cultivation, fallowing, and mulching. McCalla (47) found more nitrate nitrogen liberated from sweetclover residues which were plowed under than from the same residues left on the surface of the soil as mulch.

The presence in the soil of roots of growing crops and the sequence of crops in a rotation have been observed to affect mineralization of nitrogen. Goring and Clark (28) concluded that less net mineralization of nitrogen occurred in cropped soils than in fallow soils. They believed that nitrogen unaccounted for in cropped soil was immobilized in the soil rather than lost to the air. Brown (19) observed that the rotation of crops resulted in greater numbers of soil organisms as well as greater ammonifying and nitrifying powers in soil than continuous cropping to corn or clover. Brown suggested that carbonaceous matter exuded from roots favours development of nitrate consuming organisms in soil with a consequent transformation of nitrates to insoluble organic forms. Lyons *et al.* (43) presented data in support of the postulation that certain plants differ in their ability to take up nitrogen from the soil because of characteristic differences in the amount and composition of the organic compounds liberated by their roots.

Procedures for Determining Nitrogen Availability

Several types of procedures for determining nitrogen availability in soils have been advocated. Allison (2) has classified them into four general categories:

1. Vegetative tests
2. Nitrification tests
3. Soil nitrogen released by chemical reagents
4. Determination of total nitrogen either directly or by measuring total organic matter.

Vegetative tests: Field plot experiments or greenhouse experiments are conducted and nitrogen uptake by crops or test plants are determined. Different rates of nitrogen addition are needed to provide a basis for the interpretation of values obtained. Allison (2) points out that because of time and expense involved the vegetative test can only be used to a limited extent. Lyon et al. (43) and Bartholomew (7) have observed that this test does not give a measure of total available nitrogen as it is normally influenced by the previous crop residues.

Nitrification tests: Release of nitrate during incubation has been widely used as a measure of availability of nitrogen in soils. It has been based on incubation techniques of which the Iowa test is representative. Fitts et al. (25) demonstrated that nitrate produced during incubation under standardized conditions provided a basis for predicting the nitrogen requirement of corn under Iowa conditions. They obtained a highly significant negative correlation between nitrifiable nitrogen and yield response of corn to nitrogen fertilization. Harmsen and Van Schreven (32), in reviewing methods for estimating the nitrogen mineralization capacity of soils, pointed out that the determination of the momentary amount of mineral nitrogen (ammonium or nitrate) in the soil has a very dubious value. They expressed the concensus of numerous investigators that the results from incubated samples are in no way comparable to the mineralization process under field conditions. Under field condition variable factors related to crop, management practices, and climate are involved, whereas incubation experiments provide information on the short term potential of the soil for mineralizing nitrogen. Saunder *et al.* (67) found that the nitrogen mineralized in laboratory incubated soil, sampled towards the end of the dry season, gave a good index of the nitrogen likely to be available for crops grown under field conditions during the subsequent growing season. It was necessary to determine the time when nitrification began for reliable estimates of mineralization or nitrification rates.

Allison (2), discussing the incubation tests, has suggested three factors to be considered: (1) A standardized system of treatment of soil samples following removal from the field, (2) optimum incubation conditions with respect to moisture and aeration, and (3) the increase of nitrification rate by addition of lime.

Chemical extraction of nitrogen: A third type of procedure involves the chemical extraction of a fraction of the soil nitrogen. Truog (76) proposed a procedure involving partial oxidation of soil organic materials with alkaline permanganate. It was assumed that the permanganate attacked the readily oxidizable portion of the soil organic matter. Nitrogen is released as ammonia and measured together with exchangeable ammonia. Kresge and Merkle (41) investigated the alkaline permanganate distillation procedure in laboratory and field studies. Their studies showed that a good correlation existed between this determination and incubation nitrification rates. The amounts of nitrogen released by nitrification or by alkaline permanganate oxidation were useful in evaluating soils and soil management practices. Peterson *et al.* (58) found highly significant correlation coefficients between total soil nitrogen and each of the following: Alkaline permanganate nitrogen (0.95), percentage organic matter (0.99), nitrification rate (0.65) and the amount of ammonia nitrogen extracted by various concentrations of sulfuric and hydrochloric acids (0.59 to 0.71). However, they found that the tests were not significantly correlated with nitrogen uptake by a second crop.

Kamerman and Klintworth (39) made chemical determinations on soil for total and hydrolyzable nitrogen and for total and non-hydrolyzable carbon. Nonhydrolyzable nitrogen and hydrolyzable carbon were calculated by difference. They observed that nitrifiable nitrogen was inversely related to the ratio of hydrolyzable carbon/hydrolyzable nitrogen and also inversely related to the ratio of total nitrogen/hydrolyzable nitrogen.

Estimation of total nitrogen: The fourth type of procedure involves the direct or indirect measurement of total nitrogen. Gainey (27) observed a very close and direct relationship between nitrogen content of soils and their nitrate accumulating ability. He obtained a correlation of 0.990 ± 0.012 for a "non-fertile" series of soils and 0.988 ± 0.0006 for a "fertile" series. Allison et al. (3) showed that a positive correlation existed between total soil nitrogen and nitrate formed at all incubation periods in limed and unlimed soils.

Woodruff (89) estimated the rate of nitrogen delivery to crops from a chemical determination of soil organic matter. If all organic matter were alike, he concluded that the liberation of nitrogen from organic matter in a form available to plants would be proportional to the amount of organic matter present in the soil.

Bartholomew (7) has expressed the relationship in mathematical terms as follows:

$$\frac{dx}{dt} = kx$$

Where x = the organic nitrogen content

k = a constant for a particular soil under specific management

$\frac{dx}{dt}$ = the rate of liberation of nitrogen.

If "t" is in yearly unit, k is a measure of the annual net mineralization of nitrogen.

In criticism of this concept, Bartholomew pointed out that the fraction of soil organic matter that decomposes to liberate nitrogen for a particular crop depends upon other factors also such as cropping pattern, texture, structure and moisture condition during the growing period of the crop. Woodruff (89) found that the delivery of nitrogen from soil to crop was a function of crops. He showed that on the average the annual rate of delivery of nitrogen was 2 percent for corn, 1 percent for small grain, and 3/4 percent for a crop of leguminous nature such as soybeans.

Smith (68) observed that the amount of nitrogen that a soil will deliver will depend very much on texture. A clay or clay loam will release 1 1/4 to 2 1/2 percent of its total nitrogen in one season, a silt loam 1 1/2 to 3 percent and a sand or a sandy loam 4 to 6 percent. He also emphasized the importance of temperature and moisture conditions during the growing season, as well as the nature of any organic matter recently turned under. Thus, it is necessary to know how much nitrogen is released from the organic matter in a given soil under specific environmental conditions. Allison (2), discussing the merits and limitations of the various procedures, has stressed the need for further research to evolve a method that is simple, rapid and inexpensive.

MATERIALS AND METHODS

Field Treatments and Cropping Histories

Soil samples for this study were collected from five established field experiments.* Three of these were fertilizer experiments where widely divergent levels of N, P and K had been applied for one crop prior to the taking of soil samples. These experiments provided an opportunity for measuring the accumulation of nitrogen during a single cropping season in various fractions following applications of nitrogen ranging from 20 to 320 pounds per acre. In a fourth experiment, various residues had been applied with and without supplemental nitrogen at the beginning of a five-year rotation; and soil samples were taken at the end of the first cycle of the rotation. A fifth experiment involved widely divergent cropping systems, fertility levels and supplemental nitrogen treatments imposed for four cycles of a five year rotation prior to sampling.

Fertilizer experiments:

A group of three extensive field experiments were established in 1955 to provide data for economic optima studies on fertilizer usage (Sundquist and Robertson). Numerous levels and combinations of N, P and K were employed with minimal replication, the original objective being to establish response surfaces rather than discrete incremental response points. From each of these experiments soil samples for the present study were taken from selected treatments covering the full range of nitrogen treatments at each of several combinations of P and K. This was done to compensate for the fact that only two field replications

*Locations of field experiments and soil types are described in Appendix III.

were available for each treatment. Assuming no interaction between N levels and P K combinations in their effects on soil nitrogen levels, the P K combinations would provide additional replication for evaluating the effects of applied nitrogen levels on soil nitrogen.

The Fick farm and the Campbell farm experiments were both located on Kalamazoo sandy loam. At the Fick farm, the first applications of fertilizer were made in 1955 for corn. Soil samples were taken in the spring of 1956, just before the same fertilizer treatments were repeated on the same plots for oats.

At the Campbell farm, the fertilizer treatments were applied for oats in the spring of 1955 and again for winter wheat in September, 1955. Soil samples were taken just prior to fertilizing for wheat.

The experiment at the Thompson farm was located on Sims loam. Here the fertilizer treatments were first applied for corn in 1955 and again in the spring of 1956 for white pea beans. Soil samples for analysis were taken during the winter of 1955-56.

The actual levels of N, P, and K used in the treatments selected for this study are shown in Tables 1 to 6.* Ammonium nitrate, superphosphate and muriate of potash were the carriers used. All of the fertilizer was broadcast before plowing, with the exception of 40 pounds P_2O_5 which was applied as a starter fertilizer at planting time on all plots which received superphosphate.

Residue experiment:

Beginning in 1951, an experiment was set up at the Ferden farm to determine the effects on crop yields of the addition of large amounts of sawdust in comparison with more normal quantities and types of residues. The objective was to determine if alfalfa-brome that is removed from the rotation as hay could be replaced by sawdust or straw to

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*Pp. 24-29.

maintain yields and soil building qualities in the rotation. The present study deals with the comparison of residual effects of residue treatment and supplemental nitrogen on mineral and organic forms of nitrogen and on yields of corn in plots establised in 1953.

The cropping sequence was corn, beans, barley, followed by two years of alfalfa-brome. Four residue treatments were employed:

1. Two cuttings of alfalfa-brome hay removed each year.
2. Same as treatment one, except that neither cutting of the second year of alfalfa-brome was removed. This treatment is repeated each cycle of the rotation, the second repetition of the treatment having been made during the summer of 1958, prior to the taking of soil samples in September.
3. Same as treatment one, except that 35 tons of sawdust per acre was applied after the removal of the second cutting of hay on the second year of alfalfa-brome, at the beginning of the experiment only. This application was made in the fall of 1953, five years prior to the taking of soil samples for this investigation.
4. Same as treatment one, except that 3 to 4 tons of wheat straw was applied after the removal of the second cutting of hay during the second year of alfalfa-brome. This treatment is repeated each cycle of the rotation. The second application of straw was made in the fall of 1958 at about the time soil samples were taken.

Fertilizer has been applied at the rate 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 has been applied during either hay year.

Supplemental nitrogen has been applied on one half of each residue plot at the rate of 40 pounds per acre of nitrogen for corn, beans, and barley.

All treatments were replicated five times and composite soil samples were collected from each replicate in September, 1958. Chemical determinations on these soil samples were compared with yields of corn on the same plots in 1959.

Rotation experiment:

A series of rotation experiments was initiated in 1941 by the Soil Science Department of the Michigan Agricultural Experiment Station on the Ferden Farm in Saginaw County. These rotations were established to study the effects of cropping sequence, fertility level and supplemental nitrogen on crop yields and soil properties.

For the present study, two rotations were selected which represented extremes of crop response to supplemental nitrogen. Rotation No. 1 was a livestock rotation with corn, sugar beets, barley and two years of alfalfa-brome. Ten tons of livestock manure has been applied for corn during each of four completed cycles of the rotation. No significant response to supplemental nitrogen has been obtained with any of the crops in this rotation.

Rotation No. 6 was a cash crop rotation comprised of corn, sugar beets, barley, beans and wheat. Yields of corn on this rotation have averaged less than half those on Rotation 1, and there have been consistently large increases in yields of corn, barley and wheat for applied supplemental nitrogen (61, 62).

Two levels of fertilization have been maintained on each rotation. The low fertilizer rate from 1940 to 1950 was 400 pounds per acre 2-16-8 applied over the five-year rotation period. In 1951, it was raised to 800 pounds 4-16-8. The high fertilizer rate from 1940 to 1950 was 800 pounds 2-16-8, in 1951 it was raised to 1600 pounds 4-16-8. Half of the five-year rate was applied to sugar beets and half to the rest of the crops in the rotation other than hay.

Supplemental nitrogen was applied on one half of each fertilizer level plot on corn, beets and small grains, at the rate of 40 pounds per acre.

The soil is classified as Sims clay loam. Soil samples were taken from each of the four replicate plots of each treatment at the time of planting corn in May 1959 and were analyzed in the laboratory. The laboratory data were correlated with corn yields taken in the fall of 1959.

Laboratory Determinations

Analytical procedures which were employed in these experiments involved the determination of exchangeable ammonium, nitrate, and hydrolyzable and nonhydrolyzable forms of nitrogen on the same air dry soil sample.

Exchangeable ammonium:

Twenty-five gram air-dry soil samples screened through a 40-mesh sieve were shaken for 30 minutes in 100 ml of N-K_2SO_4 in N/10 H_2SO_4 (13). The samples were filtered with suction and washed twice with distilled water. The filtrate and washings were transferred quantitatively into 800 ml Kjeldahl flasks. Eighty ml of 40 percent NaOH was added to each flask to make the filtrate alkaline, and the ammonia nitrogen was distilled into 25 ml of 4 percent boric acid containing bromocresel green-methyl red as indicator. The distillates were titrated with 0.025 N HCl.

Nitrate:

The residues remaining in the distillation flasks after the determination of exchangeable ammonia were diluted until the volume was 300 ml. One teaspoon of Devarda's alloy (Cu, 50 percent, Al, 45 percent and Zn, 5 percent) was added to bring about the reduction of the nitrate.

The flasks were then immediately connected to the distillation apparatus and distillation was continued into 25 ml of 4 percent boric acid containing bromocresol green-methyl red as indicator. The distillate was titrated with 0.025 HCl.

Hydrolyzable and nonhydrolyzable nitrogen:

Hydrolysis of extracted soil: The extracted soil left on the Buchner funnel was transferred with the filter paper into the original 500 ml Erlenmeyer flask. Eighty ml of 80 percent H_2SO_4 (this amount contains 35 ml of concentrated H_2SO_4) was added to the soil and filter paper in the flask. The flask was shaken at intervals for two hours at room temperature. The volume was made to 350 ml by adding distilled water. The flask was then stoppered with a one-hole rubber stopper fitted with a Bunsen valve and was autoclaved at 15 lbs. pressure for four hours. The flask was allowed to cool to room temperature. The supernatant was decanted through a Coors No. '0' Buchner funnel and washed twice with distilled water. The filtrate and washings were transferred quantitatively into an 800 ml Kjeldahl flask for the determination of hydrolyzable nitrogen. The residue after hydrolysis was transferred into a second 800 ml Kjeldahl flask for the determination of nonhydrolyzable nitrogen.

Hydrolyzable nitrogen: To the first Kjeldahl flask which contained 350 ml of hydrolysate (35 ml of concentrated H_2SO_4), were added a few glass beads, 19.8 g of K_2SO_4, 0.82 g of HgO and 0.16 g of $CuSO_4$. The flask was then placed on the digestion rack. Surplus water was driven off by slow heating. Heating was increased gradually to maintain a temperature above 360 degrees C but below 410 degrees C. The heating was continued for one hour after the solution cleared. After digestion the flask was allowed to cool to the point where crystals started to form. Then 300 ml of distilled water was added cautiously with constant swirling, after which 150 ml of 40 percent NaOH plus 24 percent sodium thiosulphate solution was added down the side of the flask without mixing. The flask was connected to the distillation apparatus and swirled. Ammonia was then distilled into 50 ml of 4 percent boric acid with bromocresol green-methyl red as indicator. The distillate was titrated with 0.1 N HCl.

Nonhydrolyzable nitrogen: To the Kjeldahl flask containing the residue after hydrolysis were added 35 ml of concentrated H_2SO_4, 19.8 g of K_2SO_4, 0.82 g of HgO and 0.16 g of $CuSO_4$. The rest of the procedure for digestion was the same as described for hydrolyzable nitrogen. After digestion was complete the flask was cooled. Ammonia was taken up in four 100 ml aliquots of distilled water and transferred quantitatively by decanting into a second Kjeldahl flask. Distillation and titration of ammonia were the same as for hydrolyzable nitrogen.

Calculations: The amount of exchangeable ammonium, nitrate, and hydrolyzable and nonhydrolyzable nitrogen was expressed in pounds per acre according to the following expression:

$$\frac{(T-B) \times N \times 0.014 \times 2 \times 10^6}{S}$$

Where:

T = ml standard acid in sample titration

B = ml standard acid in blank titration

N = normality of acid

S = weight of soil sample in grams.

EXPERIMENTAL RESULTS

Fertilizer Experiments

The three nutrient level experiments all involved differential rates of N, $P2O_5$ and K_2O applied to one crop preceding sampling. Thus any differences in measured nitrogen fractions would represent one year's residual accumulation from applied fertilizer. The individual plot values for inorganic and organic forms of nitrogen, together with crop yields, are presented in Tables 13 to 21 in the Appendix. Treatment means are given in Tables 1 to 6.

Residual effects of fertilizer on ammonium and nitrate levels:

On Sims clay at the Thompson farm (Tables 5 and 6) there were no significant differences in NH_3-N or NO_3-N following application of nitrogen from zero to 320 pounds per acre. There were no apparent trends in quantities of either form of nitrogen recovered in their relation to treatment.

On Kalamazoo sandy loam at two locations (Tables 1 to 4), both NH_3-N and NO_3-N increased with increasing levels of nitrogen applied one year prior to sampling. On the Fick farm NH_3-N was higher at the three higher levels of P_2O_5 and K_2O application than where X-40-80 was used.

The values for NH_3-N encountered were 5 to 10 times greater than levels normally found in field fresh soils. It would appear that much of this nitrogen was released from organic combination during air drying. These soils were stored in air dry condition for three to four years. The levels of NH_3-N were considerably higher in soils from the Fick and Thompson farms (Tables 1, 2, 5, and 6) where the preceding crop had been corn than on the Campbell farm (Tables 3 and 4) where the preceding crop was oats. This suggests that the larger quantities of root residues

... Effects of one annual application of N, P and K on residual forms of soil nitrogen ...
yields of oats following a second annual application ...

Table 1. -- Effects of one annual application of N, P and K on residual forms of soil nitrogen and yields of oats following a second annual application of the same fertilizer treatments. Fick farm. Kalamazoo sandy loam. 1955-56.

Treatment* $N-P_2O_5-K_2O$	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Org. N Lbs/A	Oats Bus/A
			No Fertilizer vs Fertilizer				
0 - 0 - 0	48	26	74	890	310	1200	23.5
N - P - K	43	30	73	978	324	1302	66.7
LSD_{05}	NS	NS	NS	NS	NS	NS	25.9
			Nitrogen Level				
20 - X - X	40	29	69	954	297	1251	59.4
80 - X - X	37	27	64	963	289	1252	69.4
240 - X - X	57	35	92	1031	406	1437	73.0
LSD_{05}	6.7	NS	8.9	100	NS	NS	NS
			Combinations of Phosphate and Potash				
X - 40 - 80	36	26	62	915	323	1238	63.5
X - 160 - 80	50	33	83	1010	343	1353	62.0
X - 480 - 80	45	24	69	934	320	1254	65.2
X - 480 - 240	41	35	76	1031	305	1336	75.2
LSD_{05}	7.7	NS	10.3	NS	NS	NS	NS

* - Fertilizer treatment applied in spring of 1955 for corn and again in spring of 1956 for oats. Soil samples were taken prior to applying fertilizers for oats.

Table 2.--Effects of N, P and K on residual forms of soil nitrogen, observed
residuals not

Table 2.--Effects of N, P and K on residual forms of soil nitrogen, observed yields of oats, and oat yield residuals not functionally associated with current nutrient inputs. Fick farm. Kalamazoo sandy loam. 1955-56.

Treatment $N - P_2O_5 - K_2O$	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Organic N Lbs/A	Observed Yield Oats Bus/A	Residual[(a)] $Y_i - \hat{Y}_i$ Exp.	Residual[(a)] $Y_i - \hat{Y}_i$ Poly.
20 - 40 - 80	39	29	68	890	320	1210	55.0	- 3.8	0.2
80 - 40 - 80	33	24	57	940	325	1265	72.0	3.7	1.5
240 - 40 - 80	-	-	-	-	-	-	-	0.1	0.4
20 -160 - 80	43	42	85	970	307	1217	70.5	11.9	15.5
80 -160 - 80	40	26	66	860	280	1140	49.5	-18.5	-21.3
240 -160 - 80	66	32	98	1200	455	1655	66.0	0.4	-0.4
20 -480 - 80	44	22	66	925	275	1200	51.0	-1.1	5.1
80 -480 - 80	38	21	59	1005	320	1325	72.0	1.4	0.6
240 -480 - 80	53	30	83	873	365	1238	72.5	3.6	4.7
20 -480 -240	36	23	59	1028	286	1314	61.0	-6.1	-5.4
80 -480 -240	36	38	74	1045	231	1276	84.0	6.9	3.7
240 -480 -240	51	44	95	1020	397	1417	80.5	5.6	6.9
LSD_{05}	13.4	7.5	17.8	NS	NS	NS	NS	-	-

(a) From Sundquist and Robertson, Mich. Agr. Sta. Tech. Bull. 269, Table 4, p. 26, 1959. Residuals obtained by subtracting from observed yields the predicted yields obtained from two production functions fitted to the observed yields and added increments of N, P and K:

Exponential function: $\text{Log } \hat{Y}_0 = 1.57315152 + .16475028 \log N + .00057687\, N - .02441092 \log P + .00009610\, P - .00634345 \log K + .00021757\, K$

Polynomial function: $\hat{Y}_0 = 43.326378 + .40112190\, N - .00130761\, N^2 - .00650205\, P + .00000534\, P^2 + .06186818\, K - .00010387\, K^2 + .00000068\, NP - .00010905\, NK + .00007542\, PK.$

Table 3.--Effects of one annual application of N, P and K on residual f

Table 3.--Effects of one annual application of N, P and K on residual forms of soil nitrogen, and yield of wheat following a second annual application of the same fertilizer nutrients. Campbell farm. Kalamazoo sandy loam. 1955-56.

Treatment* $N-P_2O_5-K_2O$	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Organic N Lbs/A	Wheat Bus/A
			No Fertilizer vs Fertilizer				
0 - 0 - 0	19.5	6.0	25.5	850	201	1051	30.5
N - P - K	30.4	25.5	55.9	878	240	1118	35.5
LSD_{05}...	NS	19.2	NS	NS	NS	NS	NS
			Nitrogen Level				
20- X - X	32.6	23.0	55.6	879	229	1108	31.6
80 - X - X	26.9	23.0	49.9	856	253	1110	37.2
240- X - X	31.8	31.0	62.8	899	238	1137	37.6
LSD_{05}...	NS	NS	NS	NS	NS	NS	3.7
			Combinations of Phosphate and Potash				
X - 40 - 80	24.5	20.0	44.5	868	232	1101	33.2
X -160 - 80	29.2	21.0	50.2	893	256	1149	35.2
X -480 - 80	37.2	29.0	66.2	873	229	1102	36.3
X -480 - 240	30.8	32.0	62.8	877	244	1121	37.3
LSD_{05}...	NS	NS	20.1	NS	NS	NS	NS

* - Fertilizer applied in Spring of 1955 for oats and again in fall of 1955 for wheat. Soil samples were taken prior to application of fertilizers for wheat.

Table 4.--Effects of N, P and K on residual f

Table 4.--Effects of N, P and K on residual forms of soil nitrogen, observed yields of wheat and wheat yield residuals not functionally associated with current nutrient inputs. Campbell farm. Kalamazoo sandy loam. 1955-56.

Treatment	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Organic N Lbs/A	Observed Yield Wheat Bus/A	Residual[a] $Y_i - \hat{Y}_i$ Exp.	Poly.
20 - 40 - 80	30.5	12.0	42.0	870	203	1073	29.5	-3.4	-2.2
80 - 40 - 80	25.0	21.0	46.0	805	249	1054	35.0	0.3	-0.1
240 - 40 - 80	18.0	28.0	46.0	930	245	1175	35.0	-2.7	-1.5
20 -160- 80	23.0	5.0	27.5	825	213	1038	30.0	-2.9	-2.4
80 -160- 80	22.5	13.0	35.0	945	285	1230	36.2	1.5	0.2
240 -160- 80	42.0	46.0	88.0	910	269	1179	39.0	0.8	0.9
20 -480- 80	39.0	35.0	74.0	870	234	1104	32.0	-1.6	0.5
80 -480- 80	33.5	24.0	57.0	855	240	1095	39,0	3.6	3.6
240 -480- 80	39.0	30.0	68.5	895	212	1107	38.0	-0.5	-0.1
20 -480-240	38.0	41.0	78.5	950	265	1215	35.0	0.0	0.1
80 -480-240	26.5	33.0	59.5	820	239	1059	38.5	1.7	0.6
240 -480-240	28.0	22.0	50.0	860	227	1087	38.5	-1.5	0.0
LSD_{05}...	15.4	26.2	34.8	NS	NS	NS	NS		

(a) From Sundquist and Robertson, Michigan Agricultural Experiment Station Tech. Bull. 269. Table 7, p. 32, 1959. Residuals obtained by subtracting from observed yields the predicted yields obtained from two production functions fitted to the observed yields and added increments of N, P and K:

Polynomial function: $\hat{Y}_w = 28.53873032 + .08598469N - .00022084\ N^2 + .01637506\ P - .00003511\ P^2 + .00857080\ K + .00002132\ K^2 + 00001902\ NP - .00007994\ NK + .00001512\ PK.$

Exponential function: $\text{Log}\ \hat{Y}_w = 1.44504717 + .02263580 \log N + .00017268\ N + .01657636 \log P - .00001727\ P + .00127968 \log K + .00010823\ K$

Table 5.--Effects of one annual application of N, P and K on residual forms of soil nit

Table 5.--Effects of one annual application of N, P and K on residual forms of soil nitrogen, and yields of beans following a second annual application of the same fertilizer nutrients. Thompson farm. Sims loam. 1955-56.

Treatment* $N - P_2O_5 - K_2O$	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Org. N Lbs/A	Beans Bus/A
			No Fertilizer vs Fertilizer				
0 - 0 - 0	46	22	68	2805	1125	3930	11.5
N - P - K	55	29	84	2762	1300	4062	25.1
LSD_{05}...	NS	NS	NS	NS	NS	NS	8.7
			Nitrogen Level				
20 - X - X	58	27	85	2657	1257	3913	19.3
160 - X - X	60	26	86	2785	1355	4140	26.0
320 - X - X	48	34	82	2852	1307	4159	30.2
LSD_{05}...	NS	NS	NS	NS	NS	NS	7.6
			Combinations of Phosphate and Potash				
X - 40 - 20	61	32	93	2540	1228	3768	26.8
X - 40 - 320	53	31	84	2875	1402	4277	24.7
X - 640 - 320	48	23	71	2925	1255	4180	23.0
LSD_{05}...	NS	NS	NS	NS	NS	NS	NS

* - Fertilizer treatment applied in Spring of 1955 for corn and again for white pea beans in the Spring of 1956. Soil samples were taken during the winter of 1955-56.

Table 6.--Effects of N, P and K on residual forms of soil nitrogen, observed yields of beans, and bean yield residuals not functionally associated with current nutrient inputs. Thompson farm. Sims loam. 1955-56.

Treatment $N - P_2O_5 - K_2O$	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Organic N Lbs/A	Observed Yield Beans Bus/A	Residual[a] $Y_i - \hat{Y}_i$ Poly.	Exp.
20 - 40 - 20	67	29	96	2405	1140	3545	24.0	6.1	5.8
160 - 40 - 20	62	30	92	2425	1265	3690	24.0	-1.8	0.0
320 - 40 - 20	51	38	88	2790	1280	4070	33.0	4.8	4.2
20 - 40 -320	55	29	83	2645	1420	4065	20.0	0.3	-0.8
160 - 40 -320	58	22	79	3145	1445	4590	28.0	2.2	3.0
320 - 40 -320	46	42	88	2835	1340	4175	27.0	-1.2	-3.0
20 -640 -320	49	24	73	2920	1210	4130	15.0	-7.9	-8.6
160 -640 -320	-	-	-	-	-	-	-	-0.2	0.8
320 -640 -320	46	23	69	2930	1300	4230	32.0	-1.6	-3.2
LSD_{05}...	NS	NS	NS	NS	NS	NS	11.7	-	-

(a) From Sundquist and Robertson, Michigan Agr. Expt. Sta. Tech. Bull. 269, Table 12, p. 43, 1959. Residuals obtained by subtracting from observed yields the predicted yields obtained from two production functions fitted to the observed yields and added increments of N, P and K:

Exponential function: $\text{Log}\ \hat{Y}_b = 1.20741357 + .03473935 \log N + .00039659\ N + .02146077 \log P + .00005973\ P$

Polynomial function: $\hat{Y}_b = 17.6023144 + .06268789\ N - .00010708\ N^2 + .01274996\ P - .00001056\ P^2 + .00000634\ NP$

from corn may have been the source of NH_3-N released during air drying. The quantities of residues from oats would have been less, due to the nature of crop itself and to the fact that a longer period of time intervened between harvesting of crop and sampling of soil.

By analysis of variance, these differences in inorganic forms of nitrogen attained only a low order of significance, since only two replications were employed. More effective use of the number of observations available might have been possible through use of regression analysis, and some of the observed trends might have been shown to be significant. Regression analysis was not employed, however.

Residual effects on organic forms of nitrogen:

No significant differences in the organic forms of nitrogen were obtained in the three fertilizer experiments. This again may have been due to inadequate replication for analysis of variance. There was a consistent tendency at all three locations for total organic nitrogen to increase with increasing level of nitrogen application. Although there was a tendency for hydrolyzable and nonhydrolyzable nitrogen to vary directly with total nitrogen, this was not consistently true.

Relation of treatment and nitrogen fractions to yield:

The 1956 crop yields from these experiments were subjected to functional analysis by Sundquist (72, 73). He formulated an exponential production function involving inputs of N, P and K which accounted for 37 percent of the variation in mean yield of beans at the Sims loam location. A five-variable polynomial function fitted to the same data accounted for 42 percent of the variability. These two functions are presented at the bottom of the Tables 2 and 6. In the last two columns of these tables the differences between predicted and observed yields (residuals) are shown.

Graphical analysis failed to show any relationship between these residual unaccounted-for variations in yield and any of the nitrogen fractions measured, individually or in various combinations.

In the case of oat yields on Kalamazoo sandy loam, Sundquist (73) was able to account for 48 percent of the variation with a nine-variable polynomial fitted to the data and 58 percent by an exponential function. These functions and the unexplained residuals are presented in Table 2. Similar polynomial and exponential functions fitted to wheat yields on Kalamazoo sandy loam accounted for 44 and 43 percent of the variance, respectively. These functions and corresponding residuals are given in Table 4. Again no relationship could be established between the residuals and any of the forms of soil nitrogen measured.

In all three experiments the factors of major significance to yield in both types of production function was the input of nitrogen. As noted above, there was a tendency for the various forms of nitrogen to increase with nitrogen applied. To the extent that this occurred, the current year's input of nitrogen and the residual effects of the previous year's equivalent inputs were confounded. The failure to find any relationship between the forms of nitrogen measured and yield residuals not explained by nutrient input functions was probably due, in part, to relatively large errors in sampling and chemical determination, and, in part, to the inappropriateness of the experimental design.

Organic Residue Experiment

In this experiment soil samples were taken at the end of the first cycle of a five-year rotation in which various types of residue had been applied with and without supplemental nitrogen. There were five replications of each treatment in this experiment. Individual plot determinations for nitrogen and corn yields are given in Tables 22 to 28 in the

Appendix. Mean values for residues, supplemental nitrogen and individual treatments are given in Table 7.

Inorganic forms of nitrogen:

Ammonium levels found in these soils were high. Much of this ammonia was probably released from organic combination during air drying and storing. The highest amount of ammonium was found where the last two cuttings of alfalfa-brome hay were left as the residue treatment and where supplemental nitrogen had been used. These two treatments also gave rise to significantly higher levels of nitrate nitrogen. Total inorganic nitrogen (ammonia plus nitrate) was, of course, significantly greater with the alfalfa-brome treatment and where supplemental nitrogen was used.

Organic forms of nitrogen:

All residue treatments tended to increase both hydrolyzable and nonhydrolyzable nitrogen over the check. The increase in hydrolyzable nitrogen was significant for the sawdust treatment and the increase in nonhydrolyzable nitrogen was significant for alfalfa-brome. Total organic nitrogen was significantly higher than the check for both of these treatments.

As an average for all residue treatments the addition of supplemental nitrogen had resulted in a 470-pound increase in total organic nitrogen. This is of the order of 3 to 4 times the total supplemental nitrogen applied during the first three years of the rotation (40 pounds each on corn, beans and barley). It is also 3 times greater than the expected variation between treatments (LSD_{05} = 165 pounds per acre). Sixty-three percent of this increase in total organic nitrogen was due to a 300-pound increase in nonhydrolyzable nitrogen.

forms of nitrogen and yields of corn. Ferden farm. Sims clay loam. 1959.

Table 7.--Residual effects of residue and supplemental nitrogen treatments on mineral and organic forms of nitrogen and yields of corn. Ferden farm. Sims clay loam. 1959.

Treatment	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Organic N Lbs/A	Corn Bus/A
				Residue			
Check	96	55	151	3194	856	4050	114.5
Alfalfa-brome	102	72	174	3281	1057	4338	114.8
Sawdust	91	60	151	3504	906	4410	116.1
Straw	94	58	152	3262	917	4178	110.9
LSD_{05}	6.0	4.6	6.2	104.7	127.1	164.5	NS
				Nitrogen Level			
No N	91	56	147	3223	786	4009	111.9
Supplemental N	101	66	167	3397	1082	4479	116.2
LSD_{05}	3.0	8.0	3.3	79.1	75.4	83.3	3.58
				Residue vs Nitrogen			
Check	91	52	143	3087	638	3725	113.4
Check + N	101	58	159	3300	1073	4373	115.4
Alfalfa-brome	96	67	163	3221	941	4162	114.4
Alfalfa-brome + N	108	76	184	3341	1174	4514	115.1
Sawdust	87	51	138	3394	773	4167	113.4
Sawdust + N	96	68	164	3614	1039	4653	118.8
Straw	90	55	145	3192	792	3984	106.5
Straw + N	97	61	158	3331	1042	4373	115.4
LSD_{05}	7.0	5.4	7.8	153	166	201	7.2

The effects of supplemental nitrogen on the residual level of total organic nitrogen was greater on the check plot to which no residue was applied. Here the increase was 648 pounds of nitrogen per acre as compared with 352, 488, and 389 pounds where supplemental nitrogen was applied following alfalfa-brome, sawdust and straw respectively. Again 60 percent or more of the increase in total nitrogen occurred in the nonhydrolyzable fraction.

All of the above increases in total organic nitrogen were significantly greater at one percent than the 120 pounds total supplemental nitrogen applied during the first three years of the rotation. This would imply that the fixation of atmospheric nitrogen by two years' growth of alfalfa was materially enhanced where supplemental nitrogen was used on preceding crops.

Corn yields:

Corn yield in 1955 was not influenced significantly by residue treatment. The addition of 100 pounds of supplemental nitrogen resulted in a significant average increase of 4.3 bushels per acre. Within residue treatments, the increase for supplemental nitrogen was significant only in the case of the straw, where yields were depressed in the absence of nitrogen. This reflects the immobilizing influence of straw applied in the fall of 1958

Graphical analysis revealed only a slight overall tendency for yields to be higher at the higher levels of total nitrogen. Within residue treatments there was great variation in the relation between yields and total nitrogen, ranging from a distinct positive relationship for the check where no supplemental nitrogen was used to a negative relationship where supplemental nitrogen was applied on the check treatment. The scattered points for other residue treatments reflected varying degrees of ambiguity and there appeared to be no basis for attempting a regression analysis of yields and total nitrogen. Graphical analysis also failed to show any useful relationship between corn yields and any of the nitrogen fractions measured.

Ferden Farm Rotation Experiment

In this experiment soil samples were taken at the beginning of the fifth cycle of two five-year rotations in which two fertility levels had been maintained and in which half of the area had received no nitrogen other than that applied at planting time and one half had received supplemental nitrogen applied on corn, sugar beets and small grain. The fertility and supplemental nitrogen treatments were imposed on a split plot basis on all five replications of each rotation. The individual plot values for the various nitrogen determination and corn yields are presented in Tables 29 to 32 in the Appendix. Mean values for the different treatments are given in Table 8.

Inorganic forms of nitrogen:

As was true in the case of the residue experiment, ammonium nitrogen was several times higher than normal for fresh mineral soils in the field, indicating that some conversion of organic nitrogen to ammonium nitrogen may have occurred during drying and storage. The levels of ammonium, nitrate, and total inorganic nitrogen were completely unrelated to treatment.

Organic forms of nitrogen:

In Table 8 it appears that the only significant effect on total organic nitrogen was that of rotation. Twenty years after establishment there was a difference of 422 pounds in favour of Rotation 1. Only 24 percent of

... organic forms of nitrogen. Ferden farm. Sims clay loam. 1958. ... on mineral

Table 8.--Residual effects of rotation, fertility level and supplemental nitrogen treatments on mineral and organic forms of nitrogen. Ferden farm. Sims clay loam. 1958.

Treatment	NH_3-N Lbs/A	NO_3-N Lbs/A	Total Mineral N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Total Organic N Lbs/A	Corn Bus/A
Rotation 1 vs 6							
Rotation 1	74	43	117	3252	874	4126	103.6
Rotation 6	75	43	118	2933	772	3705	69.0
LSD_{05}	NS	NS	NS	NS	NS	302.3	16.6
Low vs High Fertility							
Low fertility	70	47	117	3150	779	3929	82.3
High fertility	78	38	116	3035	868	3903	90.3
LSD_{05}	7.6	NS	NS	NS	NS	NS	NS
No Nitrogen vs Nitrogen							
No nitrogen	73	43	116	3156	738	3894	78.1
Suppl. N	75	43	118	3029	909	3938	94.5
LSD_{05}	Ns	NS	NS	NS	NS	NS	8.2
Rotation vs Fertility Level							
Rotation 1 L F	71	49	120	3285	789	4074	97.0
Rotation 1 H F	76	37	113	3220	960	4180	110.0
Rotation 6 L F	69	45	114	3015	770	3785	68.0
Rotation 6 H F	80	40	120	2850	775	3625	70.0
LSD_{05}	NS	NS	NS	NS	NS	NS	31.2
Rotation vs Nitrogen							
Rotation 1	73	40	113	3365	778	4143	101.0
Rotation 1 + N	75	43	118	3140	971	4111	106.0
Rotation 6	73	43	116	2948	698	3645	55.0
Rotation 6 + N	76	43	119	2918	847	3765	83.0
LSD_{05}	NS	NS	NS	NS	NS	NS	11.5
Fertilizer vs Nitrogen							
Low F	65	50	115	3198	760	3958	78.0
Low F + N	75	44	119	3103	798	3901	87.0
High F	81	36	117	3115	716	3831	79.0
High F + N	75	41	116	2955	1019	3974	102.0
LSD_{05}	NS	NS	NS	NS	NS	NS	11.5
Rotation vs Fertilizer vs Nitrogen							
Rotation 1 L F N_0	67	52	119	3400	782	4182	96.0
Rotation 1 L F N_1	76	47	123	3170	795	3965	97.4
Rotation 1 H F N_0	80	36	116	3330	774	4104	106.4
Rotation 1 H F N_1	73	38	111	3109	1146	4255	114.4
Rotation 6 L F N_0	65	49	114	2995	738	3733	59.0
Rotation 6 L F N_1	73	41	114	3035	801	3836	76.9
Rotation 6 H F N_0	82	36	118	2900	657	3557	50.9
Rotation 6 H F N_1	77	44	121	2800	893	3693	89.3
LSD_{05}	NS	NS	NS	NS	NS	NS	16.3

this difference could be attributed to the nonhydrolyzable fraction. This is in contrast to the residue experiment where nonhydrolyzable nitrogen accounted for 60 percent or more of the observed increase in the total nitrogen.

Fertility level and supplemental nitrogen had no significant effect on either organic fractions or their total. However, there was a marked tendency for a reciprocal variation in the hydrolyzable and nonhydrolyzable fractions. Quite consistently hydrolyzable nitrogen was lower at the high fertility level than at the low and it was lower where supplemental nitrogen had been added than where it had not. Nonhydrolyzable nitrogen, on the other hand, was higher at the high fertility level and with supplemental nitrogen. The highest levels of nonhydrolyzable nitrogen were found where high fertility level and supplemental nitrogen were combined. This effect was greatest in Rotation 1. Conversely the lowest level of nonhydrolyzable nitrogen was found at the low fertility level without supplemental nitrogen.

These trends, although not statistically significant by analysis of variance, appear to be significantly related to the observation of Mattson and Kouttler-Anderson (46), that the proportion of acid resistant nitrogen in decomposing litter and humus increased with base status and nitrogen content of the original material. To determine whether a similar disproportionate rate of increase in nonhydrolyzable nitrogen with total organic nitrogen existed in the soils studied here, linear regression analysis was resorted to. Table 9 presents the results of such analyses for these two rotations (Rotation 1 and Rotation 6) and for the residue experiment (Michigan rotation).

Highly significant correlations ranging from 0.632 to 0.741 were obtained between hydrolyzable and total organic nitrogen for the three rotations. In the case of the nonhydrolyzable nitrogen, a relatively low though significant correlation of 0.400 was obtained for the cash crop rotation (Rotation 6). This rotation contained no forage legume.

Table 9.--Correlation and regression of hydrolyzable and nonhydrolyzable forms of nitrogen on total organic nitrogen in Sims clay loam under three systems of management.

Rotation	Dependent variable (Y)	Correlation with total organic nitrogen (r)	Prediction equation X = Total organic nitrogen
Rotation 1	Hydrolyzable N	0.632**	$\hat{Y} = 1405 + 0.448\ X$
	Nonhydrolyzable N	0.714**	$\hat{Y} = 1405 + 0.552\ X$
Rotation 6	Hydrolyzable N	0.741**	$\hat{Y} = 263 + 0.721\ X$
	Nonhydrolyzable N	0.400**	$\hat{Y} = -263 + 0.279\ X$
Residue experiment	Hydrolyzable N	0.720**	$\hat{Y} = 1483 + 0.431\ X$
	Nonhydrolyzable N	0.812**	$\hat{Y} = -1483 + 0.569\ X$
Average	Hydrolyzable N	0.720**	$\hat{Y} = 1142 + 0.507\ X$
	Nonhydrolyzable N	0.670**	$\hat{Y} = 1132 + 0.493\ X$

Both Rotation 1 and the Michigan rotation included two years of alfalfa-brome. In these two rotations highly significant correlations of 0.714 and 0.812 were obtained between nonhydrolyzable and total nitrogen. In these rotations there was a larger regression coefficient (0.552 and 0.569) for nonhydrolyzable nitrogen than for hydrolyzable nitrogen (0.448 and 0.431). In other words, over the range of values included in these rotations more than half of the increase in total nitrogen occurred in the nonhydrolyzable fraction. On the other hand, in the cash crop rotation only about one-fourth of each incremental increase in total nitrogen occurred in the nonhydrolyzable fraction ($b = 0.279$).

Johnston (37) found that the decomposibility of organic residues in soil decreased sharply with increasing content of nonhydrolyzable nitrogen. The relationships observed in Table 9 suggest that there is a qualitative difference in the nature of soil organic matter formed under forage-legumes such as alfalfa (Rotation 1 and the Michigan rotation) than under non-legumes (Rotation 6). Organic matter formed under alfalfa would appear to be more resistant in nature because of its higher nonhydrolyzable nitrogen content. Millar *et al.* (51) showed a greater residual accumulation of organic carbon and nitrogen after prolonged decomposition of leguminous materials than of nonlegumes.

The marked tendency for nonhydrolyzable nitrogen to accumulate at a more rapid rate than hydrolyzable nitrogen in the two legume rotations is shown graphically in Figure 1. The ratio of nonhydrolyzable to hydrolyzable nitrogen increased from 0.16 to 0.36 as total nitrogen increased from 3300 to 4900 pounds per acre.

Corn yields:

Corn yields for the livestock rotation and the cash crop rotation (Rotations 1 and 6) are shown in the last column of Table 8. Analysis of

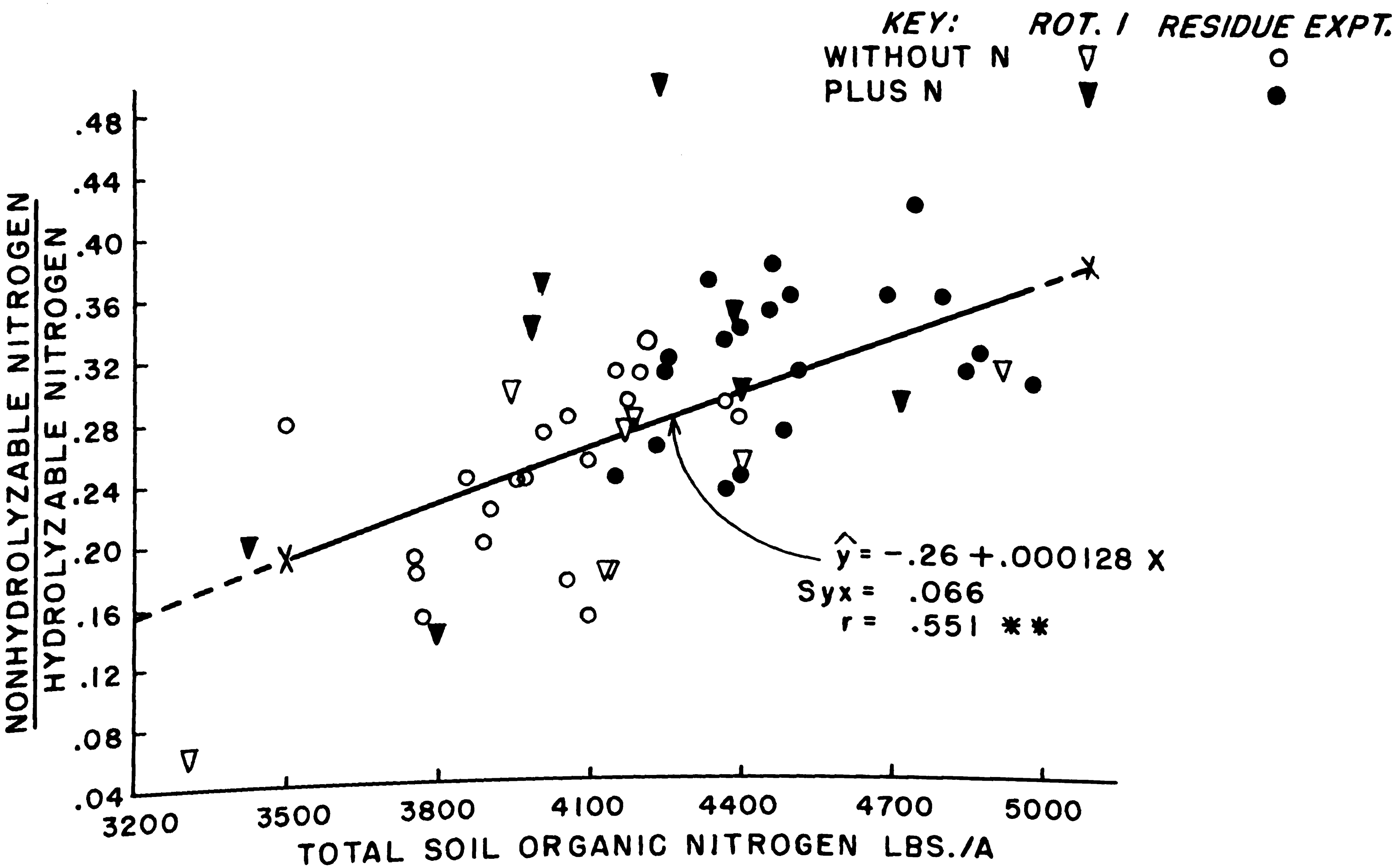


Figure 1.--Correlation and regression of the ratio of nonhydrolyzable nitrogen to hydrolyzable nitrogen on total organic nitrogen in Sims clay loam under two 5-year rotations containing alfalfa-brome.

variance revealed that the significant main effects on yields were those of rotation and supplemental nitrogen. The average increase for the high fertility level was not significant. Significant interactions occurred such that there was a 20-bushel increase for supplemental nitrogen on the cash crop rotation (Rotation 6) and a nonsignificant 5-bushel increase on the livestock rotation (Rotation 1). There was also a significant 23-bushel increase for supplemental nitrogen at the high level of fertility, but a 9-bushel increase at the low level of fertility was not significant at 5 percent. These differences observed in 1958 were similar to the long term yield results reported by Robertson (61, 62).

Scatter diagrams of all observations revealed nothing but a very general trend between corn yields and hydrolyzable nitrogen, nonhydrolyzable nitrogen or total soil nitrogen. Graphical analysis of treatment means showed that consistently higher yields for Rotation 1 were associated with consistently higher levels of total organic nitrogen (Figure 2-A). The effect of supplemental nitrogen was to raise the level of yield at a given level of soil organic nitrogen. There was a similar effect of high fertility level at each level of nitrogen. These effects of supplemental nitrogen and fertility level on the level of response to rotation were even more striking when corn yields were plotted against hydrolyzable nitrogen (Figure 2-B). In the case of nonhydrolyzable nitrogen, on the other hand, the effect of supplemental nitrogen was to displace the level of yield response to rotation horizontally in the direction of higher values for nonhydrolyzable nitrogen (Figure 2-C). In other words yield increases for Rotation 1 over Rotation 6 were smaller as the level of nonhydrolyzable nitrogen increased. Where supplemental nitrogen was used this effect was exaggerated at the high fertility level. Thus there was a tendency for treatment means to approach a diminishing returns pattern.

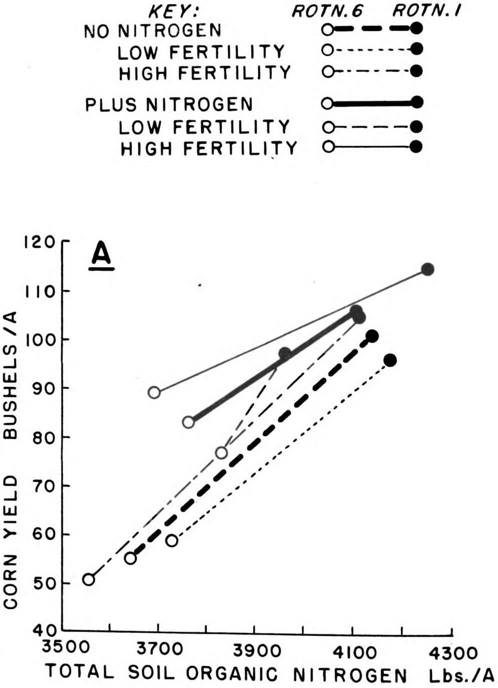
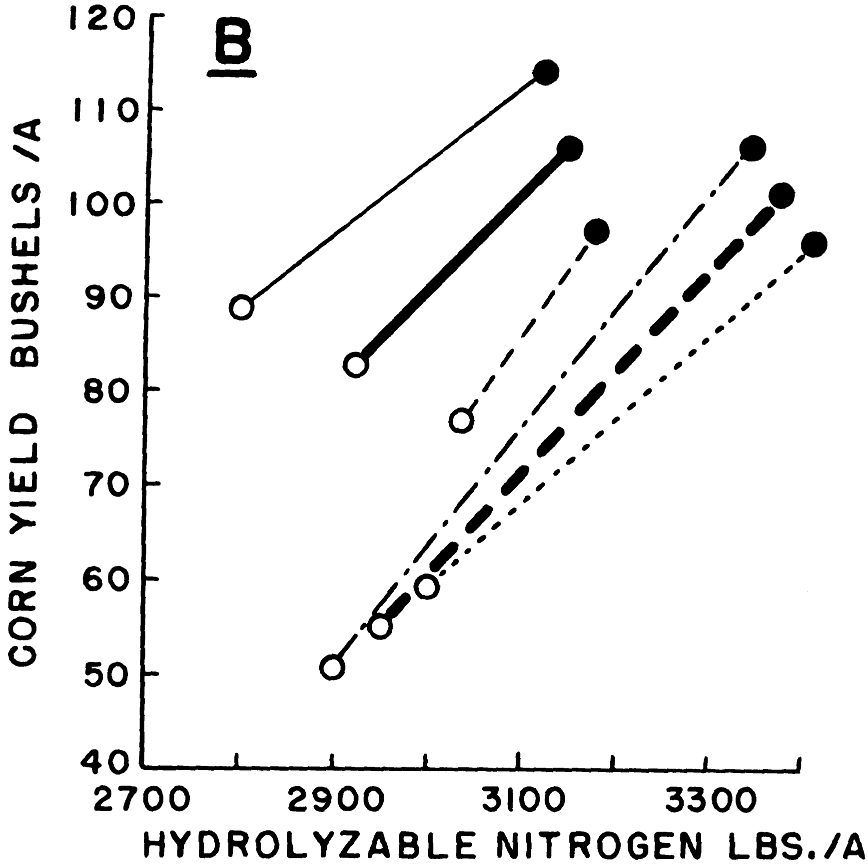
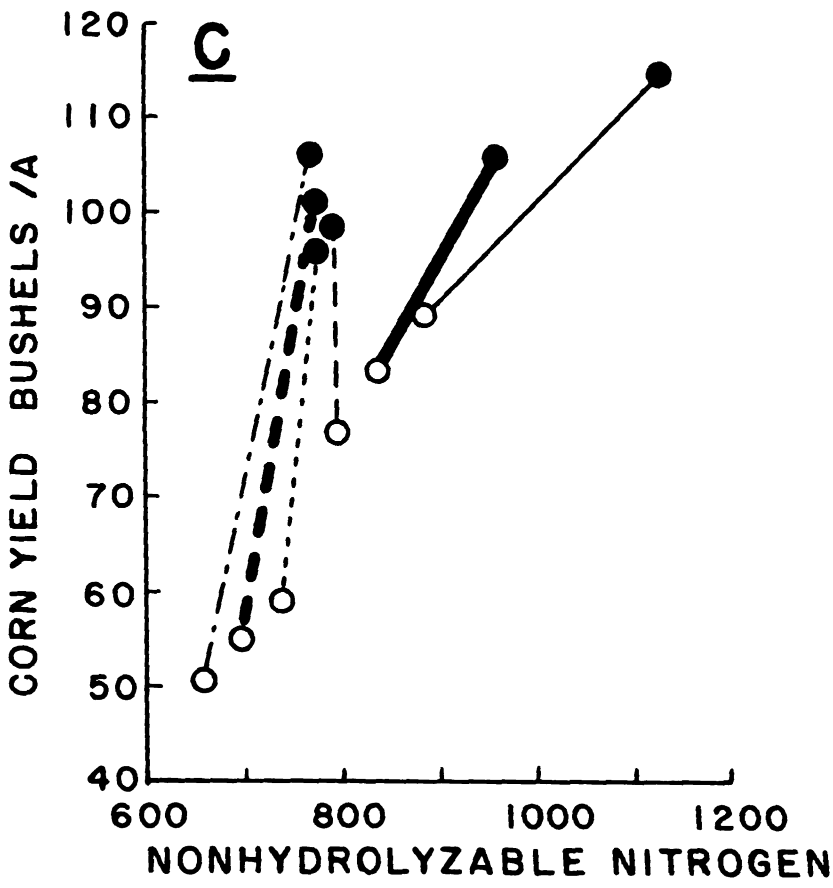


Figure 2.--Basic response of corn to rotation treatments as related to supplemental nitrogen treatment, fertility level, and total organic nitrogen (A), hydrolyzable nitrogen (B), and nonhydrolyzable nitrogen (C) in Sims clay loam as reflected in treatment means.


B
CORN YIELD BUSHELS /A
120
110
100
90
80
70
60
50
40
2700
2900
3100
3300
HYDROLYZABLE NITROGEN LBS./A


C
CORN YIELD BUSHELS /A
120
110
100
90
80
70
60
50
40
600
800
1000
1200
NONHYDROLYZABLE NITROGEN

Production Function Analysis of Corn Yields for Rotations 1 and 6

Graphical analysis of treatment means described above suggested that it might be possible to fit a multifactor production function to the individual observations which would associate significant portions of the corn yield variance with known variables. A polynomial equation of the following type was formulated and fitted to the unit observations.*

$$\hat{Y} = a + b_1X_1 + b_2X_1^2 + b_3X_2 + b_4X_3 + b_5X_4$$

Where:

X_1 = Soil nitrogen fraction

X_2 = Fertility level (low = -1, high = + 1)

X_3 = Rotation (Rotation 1 involving a forage legume = +1, and Rotation 6 involving no legume = -1)

X_4 = Applied nitrogen (No nitrogen = -1, and supplemental nitrogen = +1).

In fitting the above function to the data, observed quantitative values for yield and soil nitrogen fractions were used. Due to the qualitative nature of the rotation variable it was necessary to assign to the two rotations arbitrary numerical values the means of which would be zero. Because of the unknown cumulative residual effects of fertility treatments and supplemental nitrogen treatments over a period of four rotations, it appeared feasible to treat these also as qualitative variables. A numerical index of -1 was assigned to the low fertility level, the cash crop rotation which contained no forage legume and to the no-nitrogen treatment. An index of +1 was assigned to the complementary level of each of these variables.

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*Computational formulae used in these analyses are given in Appendix II.

Rotations 1 and 6:

Total nitrogen as soil nitrogen variable: The formulated production function was first applied to the total nitrogen data for Rotations 1 and 6 combined. Equation I shows the fitted function. The standard errors of the estimated factor coefficients are shown in parentheses below each estimated value. Additional statistical measures shown include R^2, the coefficient of multiple determination, and R, the coefficient of multiple correlation. Adjustment of R for the number of variables gives the adjusted coefficient of multiple correlation, $\bar{R}$, the square of which, $\bar{R}^2$, is the adjusted coefficient of multiple determination. This last statistic provides an estimate of the percentage of total yield variance which was associated with the regression. Also shown is the standard error, S, of the predicted yield.

Equation I:
$$\hat{Y} = \underset{}{2365.569728} + \underset{(1.153748)}{1.554255\ X_1} - \underset{(.000148)}{.000184\ X_1^2} + \underset{(2.9093221)}{3.012541\ X_2}$$

$$+ \underset{**\ (3.198854)}{15.076648\ X_3} + \underset{(2.784790)\ **}{7.601438\ X_4}$$

$R^2 = .674$ $\quad$ $R = .821$

$\bar{R}^2 = .611$ $\quad$ $\bar{R} = .782$

$S = 156.499$

The adjusted coefficient of multiple correlation $\bar{R}$, for this regression was .782. The coefficient of multiple determination, $\bar{R}^2$, was .611. This indicates that 61 percent of the variance in corn yield was explained by the relationship expressed in the regression equation. In this equation the estimated regression coefficients for rotation and applied nitrogen were significant at the one percent level, which indicates that corn yield was highly related to rotation and applied nitrogen.

None of the coefficients for other variables were significant at the 10 percent level of probability.

The yields and independent variables were intercorrelated as follows:

$$r_{yx_1} = .512$$

$$r_{yx_2} = .461$$

$$r_{yx_3} = .698$$

$$r_{yx_4} = .332$$

Coefficients of determination estimated from these values indicate that approximately 48 percent of yield variance was associated linearly with rotation (X_3), 26 percent with total soil nitrogen (X_1), and 10 percent with supplemental nitrogen treatment (X_4); less than 2 percent was associated with fertility level (X_2). Analysis of variance had shown that differences in total soil nitrogen were mainly due to rotation. The above calculations suggest that as much as one-half of the rotational effect on corn yields may have been associated with differences in quantities of residual organic nitrogen remaining in the two rotations.

The individual coefficients of determination estimated in the last paragraph assume a linear relationship between independent and dependent variables. If it could be assumed that, in fact, the relationship between yield and total soil nitrogen were curvilinear, then it might be inferred that an even larger proportion of the variance associated with rotation might have been due to differences in the soil nitrogen. The non-significant coefficients for nitrogen in Equation I do not provide any strong evidence for such a curvilinear relationship, although the negative sign for the coefficient of X_1^2 does reveal a tendency towards curvilinearity.

Hydrolyzable nitrogen as soil nitrogen variable: The substitution of hydrolyzable nitrogen values for X_1 in the formulated function produced Equation II as follows:

Equation II: $\hat{Y} = -43.163556 + .069063\, X_1 - .000009\, X_1^2 + 4.673082\, X_2$

$\qquad\qquad (.121159) \qquad (.000020) \qquad (2.928480)$

$+ 14.600104\, X_3 + 9.057379\, X_4$

$**(3.185036) \qquad (2.916283)**$

$R^2 = .671 \qquad R = .819$

$\bar{R}^2 = .607 \qquad \bar{R} = .779$

$S = 15.734$

The adjusted coefficient of correlation for the equation was .779. The percentage variance in corn yield associated with regression was the same as in Equation I (61 percent). The standard error of estimate was less, however, by a factor of 10. Rotations and applied nitrogen were again found to be highly correlated with yield. The negative sign for the coefficient of X_1^2 suggests a basic curvilinear relationship. However, neither of the coefficients for nitrogen were significant at 10 percent.

The simple correlation between yields and hydrolyzable nitrogen accounted for somewhat less of the total yield variance (15 percent) than did the simple correlation between yields and total nitrogen (26 percent).

Nonhydrolyzable nitrogen as soil nitrogen variable: A third equation was calculated by using the nonhydrolyzable fraction as the soil nitrogen variable. The result of this fit is shown in Equation III:

Equation III: $\hat{Y} = 81.289131 + .014340\, X_1 - .000009\, X_1^2 + 3.988935\, X_2$

$\qquad\qquad (.046781) \qquad (.000030) \qquad (3.019390)$

$+ 17.390515\, X_3 + 8.180587\, X_4$

$**(3.985495) \qquad (3.134721)*$

$R^2 = .625$ $\qquad$ $R = .790$

$\bar{R}^2 = .553$ $\qquad$ $\bar{R} = .743$

$S = 16.798$

The adjusted coefficient of multiple correlation was .743. The adjusted coefficient of multiple determination pointed out that 55 percent of the variance in corn yield was associated with regression. The coefficient for rotation (X_3) was significant at the one percent probability level, that for applied nitrogen (X_4) at five percent. The rest of the coefficients were not statistically significant. Only about 5 percent of the total yield variance was accounted for by the simple correlation between yield and nonhydrolyzable nitrogen.

Rotation 1

In fitting the above equations to the data for both Rotations 1 and 6, it was observed that the major portion of the variance in corn yields was associated with rotation, and that at least a portion of the rotation-associated variance may have been due to differences in soil nitrogen which were inseparably associated with rotation. In point of fact, about 25 percent of the variation in total nitrogen was associated linearly with rotation and about 20 percent of the variation in hydrolyzable nitrogen was associated with rotation. Only about 3 percent of the variance in nonhydrolyzable nitrogen was associated with rotation. In order to eliminate the possible confounding of rotational and soil nitrogen effects in the fitted function, the formulated function was modified by eliminating the rotation variable. The modified function was fitted to the data for each rotation separately.

Total nitrogen as soil nitrogen variable: In Equation IV yield is expressed as a function of total nitrogen (X_1), fertility level (X_2) and applied nitrogen (X_4) for Rotation 1 only.

$$\text{Equation IV:}\quad \hat{Y} = -350.996089 + \underset{(.192736)}{.225023\,X_1} - \underset{(.000024)}{.000028\,X_1^2} + \underset{(4.722668)}{3.737259\,X_2} + \underset{(3.899593)}{1.858591\,X_4}$$

$$R^2 = .308,\ R = .555,\ \bar{R}^2 = .0558,\ \bar{R} = .236,\ S = 15.486.$$

The adjusted coefficient of multiple correlation for this equation was .236, and only about 5 percent of the yield variance was associated with regression. None of the individual coefficients was significant at 10 percent. It is apparent that none of the measured variables were associated significantly with yield in accordance with the postulated function.

Hydrolyzable nitrogen as soil nitrogen variable: Hydrolyzable nitrogen values for Rotation 1 when substituted in the modified expression produced Equation V:

$$\text{Equation V:}\quad \hat{Y} = 1159.352782 + \underset{(.364969)}{.777978\,X_1} - \underset{(.000056)}{.000119\,X_1^2} + \underset{(3.526206)}{5.673704\,X_2} + \underset{(3.808620)}{4.266871\,X_4}$$

$$R^2 = .458,\ R = .677,\ \bar{R}^2 = .261,\ \bar{R} = .511,\ S = 13.700.$$

Here both the coefficients for nitrogen were significant at the 10 percent level of probability. However, the $\bar{R}^2$ indicated that only about 26 percent of the variance in yield was associated with the regression. There was a slight reduction in the standard error of estimate as compared with Equation IV. The larger negative coefficient for X_1^2 provides more evidence of a curvilinear relationship between yields and this nitrogen fraction than was apparent in any of the previous equations. This does suggest an approach towards a postulated diminishing returns type of relation between yield and hydrolyzable nitrogen. However, the low proportion of total variance associated with the over-all regression makes this observed relationship with hydrolyzable nitrogen of little practical significance.

The lack of statistical significance in the applied nitrogen variable would have been expected in this rotation where no significant response to applied nitrogen was revealed by the analysis of variance.

Rotation 6

Total nitrogen as soil nitrogen variable: In Equation VI are shown the results of fitting the modified function to the data for Rotation 6, with total nitrogen as the soil nitrogen variable.

Equation VI:

$$\hat{Y} = 431.373400 - \underset{(.249506)}{.216364\, X_1} + \underset{(.000034)}{.000032\, X_1^2} + \underset{(4.049600)}{4.354247\, X_2} + \underset{(3.569171)^{**}}{12.635942\, X_4}$$

$$R^2 = .652 \qquad R = .807$$

$$\bar{R}^2 = .525 \qquad \bar{R} = .725, \quad S = 14.024.$$

The adjusted coefficient of multiple correlation was .725 and about 52 percent of the total variance in yield was associated with the regression. However, only the coefficient for applied nitrogen (X_4) was significant at 1 percent. Coefficients of determination calculated from simple correlation coefficients indicated that about 50 percent of the yield variance was associated linearly with applied nitrogen, about 17 percent with the soil nitrogen variable and essentially none with fertility level.

Hydrolyzable nitrogen as nitrogen variable: When hydrolyzable nitrogen was substituted in this equation for Rotation 6 the estimated parameters were quantitatively similar to those in Equation VI (compare Equation VII).

Equation VII:
$$\hat{Y} = 321.668840 - \underset{(.342295)}{.202849\, X_1} + \underset{(.000061)}{.000039\, X_1^2} + \underset{(5.624063)}{5.131337\, X_2} + \underset{(3.796944)}{14.828507\, X_4}$$

$$R^2 = .611 \qquad R = .782$$
$$\bar{R}^2 = .469 \qquad \bar{R} = .685, \quad S = 14.822$$

The percentage variance associated with regression in Equations VI and VII was quantitatively of the same order (52 percent vs 47 percent). The quantitative similarities in form and effectiveness of Equations VI and VII would have been expected since there was little evidence of a change in the proportion of hydrolyzable nitrogen to total nitrogen with increasing total nitrogen in this rotation. This is in contrast with Rotation 1 where the proportion of hydrolyzable nitrogen was found to decrease with increasing total nitrogen. As a result the form and effectiveness of Equations IV and V were rather dissimilar.

No attempt was made to fit production functions involving nonhydrolyzable nitrogen to the individual rotations.

DISCUSSION

Significance of Mineral Forms of Nitrogen

Nitrate:

Nitrate may be considered the most available form of nitrogen for many crop plants. The levels of nitrate found in the soil at any given time will reflect a balance between rate of mineralization of organic nitrogen and rate of removal by crop uptake, leaching or denitrification.

Quantities of nitrate present at the time a crop is planted will reflect the initial supply and may show some relation to final crop yield (53, 85). In the case of nutrient level experiments on the Campbell farm (Table 3) nitrate levels were significantly related to previous treatments. The quantitative differences would have been enough to influence yields of the following wheat crop. Such effects were masked to a large extent by the current application of fertilizer. However, Sundquist (73), using data from the same experiment, found an increase in the correlation between wheat yield residuals from plant nutrient input-output functions and the nitrogen variable when nitrate present at planting time was added to nitrifiable nitrogen determined by an incubation procedure. Anderson (6) had found very little correlation with nitrifiable nitrogen alone.

Sundquist's experience may have arisen from fortuitous circumstances related to the time when soil samples were taken. In the absence of leaching rains during the period between oat harvest and the time of soil sampling, it was possible for large differences in accumulated nitrate to develop. These differences existed at the time the wheat was planted, and it would be reasonable to expect that they might have influenced wheat yields. In humid areas leaching rains during the fall, winter and spring tend to erase any differences in nitrate accumulating capacity between soils by planting in the spring time. This effect may be observed in the nonsignificant differences in nitrate which were found at locations where soil samples were taken in spring (Tables 1, 5, and 8). For the same reason, significant differences in nitrate found in fall samples from the residue experiment (Table 7) would have had little bearing on the yields of corn planted the following spring.

Research completed and in progress at the Michigan Agricultural Experiment Station indicates that soil nitrate level during the period of peak nitrogen requirement (about tasseling time) may be very significantly related to corn yields (18, 88).

Ammonium:

The normal range of exchangeable ammonium nitrogen expected in mineral soils in the field is from 3 to 30 pounds per acre (35). The quantities of ammonium found in the soils used in this investigation were of the order of 3 to 4 times greater than would have been expected in the same soils in the field. It is safe to assume that breakdown of organic compounds during air-drying and storage over a 3 to 4 year period contributed to the high levels of ammonium encountered. The effect of air-drying would be similar to that of steam sterilization (86), and probably accounts for the increasing nitrifying capacities associated with prolonged air dry storage, as reported by Harpstead and Brage (33).

The quantities of ammonium recorded were related in a general way to total organic nitrogen, in that both were considerably higher in the heavy Sims soil (Tables 5, 7, 8) than in the Kalamazoo sandy loam (Tables 1, 3). To the extent that ammonium was released from organic combination during air dry storage, it might be assumed to represent a more labile, hence more readily available, fraction of soil organic nitrogen. However, no consistent trends were observed between this fraction and yields in any of the experiments.

Significance of Organic Forms of Nitrogen

A technical problem involved in studies of soil nitrogen derives from the fact that yearly or rotational changes are small relative to the total quantity present. Errors inherent in the chemical determination are of the order of 1 to 2 percent of the total. This is in addition to sampling errors. Thus errors in the determination of total soil nitrogen are of the same order of magnitude as the annual increments of fertilizer nitrogen used in normal management. Annual changes in total organic nitrogen due to residual from applied nitrogen would be even less.

For these reasons, rather extensive replication is necessary to establish the reliability by analysis of variance of differences in total soil nitrogen associated with treatment at a given location on a given soil type. Differences which can be shown, even with adequate replication, will normally be greater than year to year changes. Accumulative residual effects from several years of treatment are necessary to give differences that can be detected with any degree of reliability.

Kamerman and Klintworth (39) found that, while total organic nitrogen remained unchanged for annual periods after addition of fertilizer nitrogen, the proportion of hydrolyzable nitrogen varied over a considerable range. Similarly Johnston (37) found more extreme variation in the hydrolyzable and nonhydrolyzable fractions than in their total following the addition of various residues with and without supplemental nitrogen. These considerations led to the hope at the outset of the present studies that changes in one or the other of these fractions might be detected with greater precision than changes in total organic nitrogen. These hopes were not justified by the data.

In the rotation and residue experiments there was evidence that nonhydrolyzable nitrogen increased with total nitrogen at a more rapid rate than did the hydrolyzable fraction. However, this behavior could not be related to crop performance. Attempts to correlate these two fractions with crop yields were plagued by two major difficulties:

1. Inadequate knowledge of the normal range or the effect of soil and management factors on distribution of nitrogen between these two fractions.

2. The lack of anything more than fragmentary data regarding the significance of nitrogen in these two fractions to mineralizability or crop availability.

Factors affecting the proportion of nonhydrolyzable to total nitrogen: Mattson and Kouttler-Anderson (46) and Johnston (37) found that the acid resistant nitrogen fraction in decomposing plant residues and humus increased with nitrogen content of the original residues or with the level of supplemental nitrogen. Proximate analyses of composting plant materials reported by Tenney and Waksman (74) reflect increasing levels of residual acid-resistant nitrogen with increasing original nitrogen content or added mineral nutrients. The effect of added nutrients reported by Tenney and Waksman parallel the observation by Mattson and Kouttler-Anderson (46) that acid-resistant nitrogen increased with the base status (cation content) of the soil or of the original litter. Johnston (37) and Tenney and Waksman (74) also associated high levels of acid-resistant nitrogen at advanced stages of decomposition with high original lignin content of plant residues.

Trends observed in the present studies were consistent with the experience of these investigators. In the rotation experiment (Table 10), supplemental nitrogen applied to corn, sugar beets and cereal grains over four rotational cycles increased the proportion of nitrogen not hydrolyzable by sulfuric acid in both rotations and at both fertility levels. The effect of nitrogen was greater in the legume rotation than in the cash crop rotation, and it was strikingly enhanced when combined with a high level of addition of fertilizer salts.

In the residue experiment (Table 11), the return of high nitrogen residues in the form of two cuttings of alfalfa-brome hay increased the proportion of nonhydrolyzable nitrogen from 17 percent of total soil nitrogen to 23 percent. The use of supplemental nitrogen on the first three crops in the rotation raised the proportion to 26 percent when combined with alfalfa-brome residues. The effect of sawdust and straw treatments were less marked, but supplemental nitrogen had a similar effect with these two materials as with the alfalfa-brome hay.

Trends following a single year's fertilization in the nutrient level experiments were somewhat erratic. However, the combination of large applications of nitrogen with large additions of phosphate and potash at the Fick farm resulted in large increases in the proportion of non-hydrolyzable nitrogen in Kalamazoo sandy loam (Table 12). At the other two locations, the overall effect of added N, P and K was in the same direction. At the Campbell farm on Kalamazoo sandy loam the proportion of nonhydrolyzable nitrogen was 19 percent where no fertilizer was used and 22 percent as an average for all fertilized plots. Corresponding figures for Sims clay at the Thompson farm were 29 percent for unfertilized soil and 32 for fertilized.

An unexpected phenomenon encountered in these studies was an apparent synergistic effect of fertilizer nitrogen applied for preceding crops on nitrogen fixation by alfalfa in the residue experiment (Table 7). Increases in total organic nitrogen recovered exceeded by three or four times the sum of the supplemental nitrogen added on the first three crops of the rotation. By statistical criteria, the net gain in nitrogen would

Table 10.--Percentage nonhydrolyzable nitrogen as related to supplemental nitrogen treatment and levels of applied nutrients. Sims loam. Ferden farm.

Treatment	Nonhydrolyzable N Percent of total	Treatment *	Nonhydrolyzable N Percent of total
Cash crop rotation	19	Low fertility	19
Cash crop rotation + N	22	Low fertility + N	20
Legume rotation	19	High fertility	19
Legume rotation + N	24	High fertility + N	26

*Low fertility = 800 pounds of 5-20-10 over 5-year period.
High fertility = 1600 pounds of 5-20-10 over 5-year period.

Table 11.--Percentage nonhydrolyzable nitrogen as related to supplemental nitrogen and residue treatment. Sims loam. Ferden farm.

Treatment	Nonhydrolyzable N Percent of total	Treatment	Nonhydrolyzable N Percent of total
No residue	17	Sawdust	19
No residue + N	24	Sawdust + N	22
Alfalfa-brome	23	Straw	20
Alfalfa-brome + N	26	Straw + N	24

Table 12.--Percentage nonhydrolyzable nitrogen as related to level of applied nutrients. Kalamazoo sandy loam. Fick farm.

Treatment	Nonhydrolyzable N Percent of total	Treatment	Nonhydrolyzable N Percent of total
0 - 0 - 0	26	20 - 240 - 80	23
20 -- 40 - 80	26	240 - 240 - 80	30
20 -160 - 80	25	20 - 240 -240	22
240 -160 - 80	27	240 - 240 -240	28

appear to have been real. However, a similar effect was not observed in the legume rotation (Rotation 1) of the rotation experiment.

Significance of nonhydrolyzable nitrogen to nitrogen availability: Very few investigators have concerned themselves with the relationship between the acid-hydrolyzable or acid-resistent nitrogen fractions and the mineralizability or availability to crops of soil organic nitrogen. In respiration experiments, Johnston (37) found that resistance to microbial decomposition of organic matter in soil increased with increasing nonhydrolyzable content. Data by Waksman and Iyer (82) for their "ligno-protein" complexes may be similarly interpreted. This would suggest that changes in the resistant fraction may reflect qualitative changes in the total organic complex. These changes in turn may affect the mineralizability of nitrogen combined in the organic complex and its availability to plants.

On the other hand, Johnston found that the proportion of nonhydrolyzable nitrogen was drastically reduced in the presence of a growing nonleguminous crop, wheat. This would indicate that the organic combinations reflected in this fraction are not completely resistant to decomposition. Rather, it would appear that a reduced rate of release might result in continued release over a longer period of time. This is further suggested by seasonal patterns of nitrate release obtained by Brock (18) for the cash crop and livestock rotations studied here (Rotations 1 and 6). Soil nitrate levels were much higher all season in the livestock rotation than in the cash crop rotation. This was related primarily to the higher total nitrogen in the soil (Table 8). During the period of peak nitrogen requirement for corn, soil nitrate levels declined sharply on both rotations, both where supplemental nitrogen was used and where it was not. After the period of maximum uptake by corn, nitrate tended to accumulate again only on plots with a history of supplemental nitrogen fertilization. This sustained capacity for nitrate release was associated with the high proportion of nonhydrolyzable nitrogen in soil from plots receiving supplemental nitrogen (Table 10).

Significance of hydrolyzable nitrogen to nitrogen availability: Investigators elsewhere have attempted to measure labile portions of soil organic nitrogen on the premise that organic nitrogen combinations with a low degree of stability to mild chemical reagents would also be those most readily attacked by soil microorganisms. The nitrogen in such fractions would be expected to be more closely related to seasonal availability to crops than would the total nitrogen present. The alkaline permanganate distillation procedure is representative of this approach (76). Correlation studies involving this measurement have not given any strong support for the basic premise (6, 53).

The acid-hydrolyzable nitrogen measured in the present study represents an analogous "labile" fraction. However, the chemical treatment was drastic, and 2/3 to 4/5 of total soil nitrogen was involved. Organic nitrogen compounds and complexes reflected in this fraction would represent a wide range of biological activity in terms of decomposibility. Also, carbonaceous constituents (sugars, uronic acids, etc.) present in labile combination would provide readily available energy for microbial synthesis and immobilization of associated nitrogen.

These factors tend to undermine any theoretical postulation that crop performance might be directly related to the quantity of nitrogen released by acid hydrolysis. Johnston (37) found no relationship between the hydrolyzable fraction and mineralizability of soil organic nitrogen or its availability to wheat. On the other hand, Kamerman and Klintworth (39) found that nitrate released during 30 days' incubation varied inversely with C:N ratio of the hydrolyzable fraction of soil organic matter. Their results would suggest that both carbon and nitrogen contents should be taken into account in attempts to correlate any labile fraction of soil organic matter with net mineralization or crop availability.

A further noteworthy observation of Kamerman and Klintworth was their finding that the C:N ratio of the hydrolyzable fraction was very sensitive to recent additions of fertilizer nitrogen. Seasonal patterns appeared which covered a wide range of C:N ratios, and these patterns were related to treatment. In the present work, lack of sensitivity to recent fertilizer treatment in the nutrient level experiments was found to be a major liability of the chemical nitrogen determinations. Unless such sensitivity can be achieved, there can be little hope that chemical determinations can be used to explain the residual benefits which experience has shown do accrue to applied fertilizer nitrogen. The relationship between C:N ratio of fresh plant materials and the balance between net mineralization or net immobilization of nitrogen during decomposition is well known. Theoretically the C:N ratio of recently returned crop residues should be reflected in the labile fractions of soil organic matter. A fruitful course for future fundamental research would appear to involve investigation of the relationship between mineralizability of soil nitrogen and the C:N ratio of various "labile" fractions. Such fundamental research is essential before mathematical models for functional correlation of soil organic nitrogen with crop response can be postulated with any approximation to reality.

Evaluation of Experimental Design

The field experiments used in this investigation were not designed specifically for the correlation studies which were attempted. The three nutrient level experiments were designed for continuous function analysis of fertilizer input-crop yield output data. Minimal replication was employed with a large number of treatments to facilitate delineation of a yield response surface. Precise determination of discrete yield points or residual nutrient levels as affected by treatment were irrelevant to this objective.

Inadequate replication made it impossible to establish by the methods of analysis of variance whether significant variations in soil nitrogen had been achieved. In these three experiments, observed increases in residual soil organic nitrogen resulting from one year's application of nitrogen fertilizer ranged from 10 to 220 pounds per acre in the nonhydrolyzable fraction and from net losses to an increase of 140 pounds in the hydrolyzable fraction. A maximum variation between duplicate chemical determinations of 40 pounds per acre was allowed in the nonhydrolyzable fraction and 80 pounds in the hydrolyzable. This variability inherent in the chemical determinations is large relative to the variance encountered in the soils studied. The additional replication afforded by sampling the applied nitrogen variable at several levels of P and K application proved inaffective because of apparent interactions between applied nitrogen and the P K combination. The two replications available at this level of subdivision were inadequate to establish the statistical validity of the apparent interactions or of the differences between treatment means. These difficulties might have been overcome to a degree by taking advantage of the internal replication available in regression analysis. This was not done. It would appear that future studies should make provision in experimental design for effective use of regression analysis to relate measured soil parameters with soil treatment variables.

The failure to establish the reliability of specific soil nitrogen levels seriously weakened any inferences to be drawn regarding relationships between fertilizer treatment and changes in level or quality of soil nitrogen.

An intercorrelation of soil tests and fertilizer inputs was inherent in the experimental designs used in this study. The historical treatments which were expected to produce the required variance in soil nitrogen level were repeated as current inputs for the crop with which correlation was attempted. To an indeterminate degree, yield variance associated with differences in soil test arising from prior treatment would have been included in the variance associated with current treatment, since prior and current treatments were the same on any given plot. In effect, the portion of yield variance available for segregating the effects of soil test from those of current treatment was reduced to that portion associated with the differential availability or effectiveness of soil forms of nitrogen as compared with fertilizer forms. Considering the relatively large errors involved in sampling and chemical analysis, this loss of available yield variance would appear to be prohibitive.

Similar criticisms may be directed to the rotation and residue experiments. Here more extensive replication and longer periods of prior treatment gave rise to statistically significant differences in the level of total soil nitrogen and, in the residue experiment, of the two individual fractions. However, current treatments and treatments prior to sampling were the same, so that the soil nitrogen variable and the treatment variables tended to be intercorrelated. Also, the total number of measured points in each experiment was small relative to the requirements for effective functional analysis.

Evaluation of Functional Analyses

The prediction functions formulated here represented an empirical incorporation of variables, some of which were in themselves hybrid combinations of input factors and levels of management. Rotation and supplemental nitrogen treatments were significantly reflected in the soil test values themselves. Rotational levels of applied nutrients (N, P and K) tended to influence the soil nitrogen values in a way which was consistent with theoretical expectation, even though the observed effects were not significant statistically.

When the data for the cash crop and livestock rotations were combined, a maximum of 61 per cent of yield variance was associated with regression when total nitrogen or the hydrolyzable fraction was used as the soil nitrogen variable. Only 55 percent was associated with regression when nonhydrolyzable nitrogen was used. However, the major portion of the explained variance was associated with rotations and supplemental nitrogen. Since these two variables were responsible for significant variations in soil nitrogen, significant portions of yield variance associated with them would have accrued to the soil nitrogen variable had rotation and supplemental nitrogen treatment been left out of the formulated function.

It would have been logically invalid to eliminate the supplemental nitrogen variable from the function, since a major part of the corn response would have been to the current year's input rather than to residual accumulation from prior treatment. Some argument might be offered for eliminating the rotation variable from the function and allowing intercorrelated variance to associate itself solely with the soil nitrogen variable. Rotations represent management levels, and, as such, are not subject to direct quantitation. To the extent that management levels give rise to measurable increments of identificable soil parameters, these parameters may be used to characterize management level quantitatively and may be substituted for it in production functions of the form used here.

Conceivably, not all the chemical or physical changes associated with management level will be identifiable. In the combined analysis for Rotations 1 and 6, about 26 percent of yield variance was associated with total soil nitrogen and 48 percent with rotation. Thus, it might be estimated that of the order of one-half of the effect of rotations on yield was due to total soil nitrogen and half to other unidentified factors associated with rotation.

Elimination of rotation from the function might have increased the significance of the regression coefficients for soil nitrogen, but it would also have increased the portion of variance unaccounted for. Due to shortage of time and logical reservations regarding the suitability of the data and the essential validity of the formulated functions, no attempt was made to fit such a function or other alternative functions to the combined data for both rotations.

The attempts made here to eliminate rotation by restricting analysis to within-rotation variance was not very informative. In the livestock rotation (Rotation 1), coefficients approaching significance for hydrolyzable nitrogen were obtained. However, the overall effectiveness of the regression was low; only about 26 percent of the yield variance was accounted for. This was not unexpected, since the available yield variance was small and analysis of variance had revealed no significant differences in yield for the nitrogen and fertility subtreatments in this rotation.

In the cash crop rotation (Rotation 6), greater yield variance was available for analysis. Functions involving either total or hydrolyzable nitrogen accounted for approximately 50 percent of the variance in yield. Intercorrelations with supplemental nitrogen and fertility level may have contributed to lack of significance of the soil nitrogen coefficients. Highly significant coefficients for applied nitrogen were consistent with the results of analysis of variance.

The degree of intercorrelation of independent variables inherent in the experimental designs would have reduced the effectiveness of any production function that might have been employed. However, a major difficulty was the lack of any logical or theoretical concepts to use as a basis for formulating a regression expression.

Two fractions of organic nitrogen were measured directly, a third might have been estimated from the ammonium nitrogen found in air dry soil. Attempts to postulate appropriate production functions based on these measurements at once raised a number of questions. Does any measured fraction by itself represent an independent estimate of the potential availability of total soil nitrogen to the crop? Or does each represent a distinct level of chemical stability or resistance to microbial decomposition, making it necessary to include all measured fractions as separate variables in the same production function?

Beyond these were even more fundamental questions. Is this fractionation potentially as useful as some others that might have been used? Few comparative studies of the significance of various nitrogen fractionation schemes to availability or mineralizability of soil organic nitrogen have been made. To what extent do carbonaceous materials associated with each fraction promote net immobilization or net mineralization? How might these be estimated and expressed in quantitative terms relevant to functional analysis?

These problems can be investigated most effectively by fundamental studies at the laboratory and greenhouse level. Until such studies have been made and tentative working hypotheses established, any attempt, such as that made here, to apply functional analysis to field data must be considered premature.

On the other hand, the requirements of functional production analysis should be kept clearly in mind in fundamental studies. The results of agronomic research are translated by agricultural economists into farm management terms by application of formal deductive principles which rely on the manipulation of functional relationships. For this reason, fundamental agronomic research should be concerned with uncovering functional relationships between soil parameters and plant response. For this purpose, continuity of measurement along the surface of the function is of greater utility than precise measurement of discrete points. Functional mathematical analysis together with appropriate measures of reliability should be included among the statistical tools for evaluating fundamental agronomic data.

Agro-Economic Considerations

Some of the more obvious relationships in the data are of interest. In the case of the rotation experiments it was found that corn responded to supplemental nitrogen with significant yield increases in the cash crop rotation (Rotation 6) but not in the livestock rotation (Rotation 1). According to Michigan Extension Bulletin E-159, Fertilizer Recommendations for Michigan Crops (49), no response to nitrogen in addition to that in the starter fertilizer would be expected where 8 tons of manure and a legume sod are plowed down for corn. Ten tons of manure and a legume sod had been plowed down for corn in Rotation 1 over four cycles of the rotation. Thus the general validity of the current basis for fertilizer recommendations was borne out by these data.

On the other hand, 100 pounds of supplemental nitrogen on the cash crop rotation failed by a significant increment to achieve the 100-bushel yields which might have been expected on this soil type. Obviously, the fundamental relationship between corn yields and supplemental nitrogen is different under these two systems of management. However, the data provide no clues as to the differences in form between these two functions. Speaking in general terms, available agronomic data is characterized by a large proportion of unexplained variance. The field experiments from which such data are derived are frequently not designed to facilitate the exposition of functional relationships. Where there is a large amount of unexplained variance it becomes difficult to select appropriate mathematical functions. The combination of fair to poor agronomic data with empirically selected mathematical functions which may or may not express real relationships contributes to relatively low precision in making fertilizer recommendations.

The chemical data for these two rotations show that significant differences in residual organic nitrogen have resulted from the two systems of management. The reduced response to supplemental nitrogen in the livestock rotation was associated with a residual supply of organic nitrogen which was 420 pounds greater than in the cash crop rotation. There was no obvious basis for evaluating this difference in terms of its contribution to yield differences. Independent estimates made at different fertility levels and supplemental nitrogen treatments ranged from 6 to 22 pounds increase in soil nitrogen per bushel increase in yield in the livestock rotation as compared with the cash crop rotation. Such variations cannot be interpreted in terms of a uniform seasonal rate of decomposition and release of nitrogen in soils of varying organic nitrogen contents. If a uniform seasonal rate of decomposition equal to 2 percent of total soil nitrogen were assumed, the difference in total nitrogen between the two rotations would represent a difference in nitrogen released to corn of only 8 to 10 pounds per acre. This is hardly enough to account for the 46 bushel difference in yield where no supplemental nitrogen was used.

These observations strongly suggest that differences in quality as well as quantity of soil nitrogen were involved. The need for significant measures of quality which will reflect both durability and the immobilization potential of associated carbonaceous material is apparent. The search for such measures should involve experimental designs which will permit functional interpretation.

In the case of the residue experiments, the return of two cuttings of alfalfa hay resulted in a significant 300 pound increase in total soil nitrogen after five years. There was, however, no effect on yields of corn. There is no basis for placing a value on the residual nitrogen increment in terms of capital gain or of estimating its recovery in succeeding crops over a period of years. Collateral effects on soil physical properties which may influence yields in later years are also unknown. For the farm manager these data present the alternatives of a tangible loss in feed and income from two unharvested cuttings of hay against a measurable increase in soil organic matter the benefits of which are intangible. Of course, it is possible that a psychic satisfaction might be derived, based on the traditional conviction that soil organic matter is a good thing and every effort should be made to build it up.

Similar significant increases in total soil nitrogen were obtained five years after a 35-ton application of sawdust. Corn yields were not affected in 1959. In two previous seasons, corn yields planted six years after similar sawdust applications were significantly higher than for any other treatment. However, these residual benefits must be weighed against the high cost of transportation and application of such large amounts of sawdust, as well as large reductions in yield of crops planted during the first three years after application. Large investments in supplemental nitrogen during these first three years would have reduced the injurious effects of the sawdust and would probably have enhanced the residual accumulation of organic nitrogen. Here again the value of this residual nitrogen could not be assessed at the present state of our knowledge.

The chemical data and yield results reported here are of agronomic interest. The nitrogen fractions studied did not reflect previous treatment with the hoped for degree of sensitivity. However, the differences in total nitrogen between rotations, residue treatments and supplemental nitrogen treatments do help to characterize the effects of these treatments on soils in a general way. It is obvious that more sensitive measures are needed. Also that the observed relationships must be defined with much more specificity before soil nitrogen determinations can provide information useful for purposes of farm management.

SUMMARY AND CONCLUSION

The principal objective of the present study was to evaluate several chemically derived fractions of soil nitrogen in terms of their sensitivity as measures of residual nitrogen from previous treatment. In this regard, the findings may be summarized as follows:

1. The level of ammonium nitrogen in air dried samples was higher than expected in field fresh soils. Ammonium was probably released by breakdown of organic compounds during air drying and storage. The quantities of ammonium found were related in a general way to the content of organic nitrogen but were not closely related to treatment.

2. Nitrate nitrogen was related to treatment in soil samples taken in the fall of the year. Leaching during the fall and winter apparently obliterated any significant differences in soil samples taken in the winter or spring.

3. The two organic fractions measured were not measured precisely enough to reflect significant differences in residual nitrogen from a single year's application ranging up to 320 pounds of N per acre. Cumulative effects of rotation, residue treatment and supplemental nitrogen treatments over a period of years were reflected in the hydrolyzable fraction, the nonhydrolyzable fraction or in the sum of the two. There was a relatively more rapid increase in the nonhydrolyzable fraction than in the hydrolyzable fraction where alfalfa was included in the rotation. Supplemental nitrogen treatment and the level of application of other fertilizer nutrients also promoted a disproportionately

rapid increase in the nonhydrolyzable fraction. These results are consistent with those reported by other investigators who have studied similar nitrogen fractions in composting organic residues.

A secondary objective in this investigation was the application of functional analysis as a statistical tool for evaluating the significance of the measured nitrogen fractions to crop performance. The attempts made here to formulate and fit prediction equations to field data appear to have been premature. Two principal obstacles were encountered:

1. The lack of fundamental data bearing on the mineralizability or availability of nitrogen in the two organic fractions. Two aspects of this problem need investigation: (a) the relationship between the proportion of labile to resistant nitrogenous fractions and their mineralizability, and (b) the effect of associated carbonaceous constituents on net mineralization.

2. The experimental design of field experiments were inappropriate for correlating soil tests with crop performance. In all experiments there was excessive intercorrelation between treatment variables and soil tests. In the rotation and residue experiments, the number of levels of any treatment factor was inadequate to permit the application of regression analysis.

Future research in this area should consider the use of experimental designs which will permit the application of regression analysis to uncover functional relationships between treatment variables and measured nitrogen fractions on the one hand, and between the measured fractions and crop response to fertilization on the other. Increased precision in defining such functional relationships is essential if soil tests are to contribute to increased precision of fertilizer recommendations based on current principles of economic analysis.

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APPENDIX I

Individual Observations

Table 13.--Residual ammonia and nitrate nitrogen one year after fertilizer treatment and yield following a repeated application of N, P and K. Fick farm, Kalamazoo sandy loam, 1955-56.

Treatment			Replication I		Replication II		Yield of Oats	
N	P_2O_5	K_2O	NH_3-N Lbs/A	NO_3-N Lbs/A	NH_3-N Lbs/A	NO_3-N Lbs/A	Rep. I Bus/A	Rep. II Bus/A
0	0	0	54	26	42	25	30.0	17.3
20	40	80	43	38	35	20	44.3	65.9
80	40	80	31	24	35	23	65.4	78.8
320	40	80	-	-	-	-	-	-
20	160	80	42	45	44	39	75.2	65.6
80	160	80	43	31	37	20	47.5	51.3
320	160	80	81	36	51	28	59.2	73.1
20	640	80	42	25	45	19	42.8	59.1
80	640	80	40	22	36	20	68.3	76.2
320	640	80	57	31	49	28	78.6	66.0
20	640	320	33	26	38	19	65.6	55.6
80	640	320	36	40	35	36	86.4	82.2
320	640	320	51	45	51	42	81.2	80.0

Table 14.--Residual hydrolyzable and nonhydrolyzable nitrogen one year after fertilizer treatment. Fick farm, Kalamazoo sandy loam, 1955-56.

Treatment			Replication I		Replication II	
N	P_2O_5	K_2O	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A
0	0	0	920	330	860	290
20	40	80	950	330	830	310
80	40	80	870	300	1010	350
320	40	80	-	-	-	-
20	160	80	950	334	990	280
80	160	80	850	300	870	260
320	160	80	1620	640	780	270
20	640	80	880	280	970	270
80	640	80	1010	330	1000	310
320	640	80	810	470	936	260
20	640	320	1136	344	920	228
80	640	320	940	288	1150	234
320	640	320	990	320	1050	474

Table 15.--Residual inorganic and organic nitrogen one year after fertilizer treatment. Fick farm, Kalamazoo sandy loam, 1955-56.

Treatment			Replication I		Replication II	
N	P_2O_5	K_2O	Inorganic N Lbs/A	Organic N Lbs/A	Inorganic N Lbs/A	Organic N Lbs/A
0	0	0	80	1250	68	1150
20	40	80	81	1280	56	1140
80	40	80	55	1170	58	1360
320	40	80	-	-	-	-
20	160	80	87	1284	83	1270
80	160	80	73	1150	58	1130
320	160	80	117	2260	79	1050
20	640	80	68	1160	64	1240
80	640	80	62	1340	57	1310
320	640	80	87	1280	77	1196
20	640	320	60	1480	57	1148
80	640	320	76	1168	71	1384
320	640	320	96	1310	94	1524

Table 16.--Residual ammonia and nitrate nitrogen one year after fertilizer treatment and yield following a repeated application of N, P and K. Campbell farm, Kalamazoo sandy loam, 1955-56.

Treatment			Replication I		Replication II		Yield of Wheat	
N	P_2O_5	K_2O	NH_3-N Lbs/A	NO_3-N Lbs/A	NH_3-N Lbs/A	NO_3-N Lbs/A	Rep. I Bus/A	Rep. II Bus/A
0	0	0	14	6	25	6	28.5	31.8
20	40	80	36	6	25	17	32.9	25.7
80	40	80	25	25	25	17	38.0	31.8
320	40	80	22	28	14	28	35.0	35.2
20	160	80	29	8	17	1	29.4	31.4
80	160	80	25	8	20	17	36.9	36.4
320	160	80	34	56	50	36	36.4	42.2
20	640	80	39	25	39	45	37.1	26.6
80	640	80	36	25	31	22	39.6	38.4
320	640	80	39	20	39	39	40.4	35.9
20	640	320	48	59	28	22	33.3	36.5
80	640	320	22	20	31	45	37.4	39.8
320	640	320	20	22	36	22	40.4	37.1

Table 17.--Residual hydrolyzable and nonhydrolyzable nitrogen one year after fertilizer treatment. Campbell farm, Kalamazoo sandy loam, 1955-56.

Treatment			Replication I		Replication II	
N	P_2O_5	K_2O	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A
0	0	0	730	196	970	206
20	40	80	850	186	890	220
80	40	80	900	270	710	228
320	40	80	870	230	990	260
20	160	80	800	206	850	220
80	160	80	1000	310	890	260
320	160	80	870	228	950	310
20	640	80	950	248	790	220
80	640	80	780	260	930	220
320	640	80	930	218	860	206
20	640	320	900	230	1000	300
80	640	320	720	228	920	250
320	640	320	740	206	980	248

Table 18.--Residual total inorganic and organic nitrogen one year after fertilizer treatment. Campbell farm, Kalamazoo sandy loam, 1955-56.

Treatment			Replication I		Replication II	
N	P_2O_5	K_2O	Inorganic N Lbs/A	Organic N Lbs/A	Inorganic N Lbs/A	Organic N Lbs/A
0	0	0	20	926	31	1176
20	40	80	42	1036	42	1110
80	40	80	50	1170	42	938
320	40	80	50	1100	42	1250
20	160	80	37	1006	18	1070
80	160	80	33	1310	37	1150
320	160	80	90	1098	86	1260
20	640	80	64	1198	84	1010
80	640	80	61	1040	53	1150
320	640	80	59	1148	78	1066
20	640	320	107	1130	50	1300
80	640	320	42	948	76	1170
320	640	320	42	946	58	1228

Table 19.--Residual ammonia and nitrate nitrogen one year after fertilizer treatment and yield following a repeated application of N, P and K. Thompson farm, Sims loam, 1955-56.

Treatment			Replication I		Replication II		Yield of Beans	
N	P_2O_5	K_2O	NH_3-N Lbs/A	NO_3-N Lbs/A	NH_3-N Lbs/A	NO_3-N Lbs/A	Rep. I Bus/A	Rep. II Bus/A
0	0	0	2	12	89	32	7.2	16.3
20	40	20	73	31	70	26	18.6	29.3
160	40	20	67	31	57	29	20.0	27.5
320	40	20	50	34	51	41	34.0	30.7
20	40	320	57	31	52	26	24.1	15.0
160	40	320	55	24	60	19	23.6	32.0
320	40	320	47	58	45	26	20.0	32.8
20	640	320	55	21	43	26	15.3	14.3
160	640	320	-	-	-	-	-	-
320	640	320	22	33	70	12	29.4	34.0

Table 20.--Residual hydrolyzable and nonhydrolyzable nitrogen one year after fertilizer treatment. Thompson farm, Sims loam, 1955-56.

Treatment			Replication I		Replication II	
N	P_2O_5	K_2O	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A	Hydrolyzable N Lbs/A	Nonhydrolyzable N Lbs/A
0	0	0	3190	1070	2420	1180
20	40	20	2290	960	2520	1320
160	40	20	2320	1280	2530	1250
320	40	20	3210	1510	2370	1050
20	40	320	2960	1440	2330	1400
160	40	320	2940	1380	3350	1510
320	40	320	2690	1280	2980	1400
20	640	320	2620	1130	3220	1290
160	640	320	-	-	-	-
320	640	320	2760	1190	3100	1410

Table 21.--Residual inorganic and organic nitrogen one year after fertilizer treatment. Thompson farm, Sims loam, 1955-56.

Treatment			Replication I		Replication II		Yield of Beans	
N	P_2O_5	K_2O	Inorganic N Lbs/A	Organic N Lbs/A	Inorganic N Lbs/A	Organic N Lbs/A	Rep. I Bus/A	Rep. II Bus/A
0	0	0	14	4260	121	3600	7.2	16.3
20	40	20	103	3250	96	3840	18.6	29.3
160	40	20	98	3600	86	3780	20.0	27.5
320	40	20	83	4720	92	3420	34.0	30.7
20	40	320	87	4400	78	3730	24.1	15.0
160	40	320	78	4320	79	4860	23.6	32.0
320	40	320	105	3970	70	4380	19.9	32.8
20	640	320	76	3750	69	4510	15.3	14.3
160	640	320	-	-	-	-	-	-
320	640	320	55	3950	82	4510	29.4	34.0

Table 22.--Ammonia nitrogen in Sims clay loam as affected by organic amendments, and fertilizer nitrogen.

Treatment	Replication 1	2	3	4	5	Average
	Pounds of NH_3-N per acre					
Check	83	95	89	92	98	91
Check plus N	98	106	94	103	104	101
Alfalfa-brome . . .	100	100	91	98	92	96
Alfalfa-brome + N .	115	109	112	100	103	108
Sawdust	89	80	89	86	89	87
Sawdust plus N . . .	92	100	103	92	94	96
Straw	92	92	92	81	92	90
Straw plus N	98	100	101	89	98	97

Main effects of residues:

Check	96
Alfalfa-brome	102
Sawdust	91
Straw	94

Main effects of nitrogen:

No nitrogen	91
Supplemental nitrogen	101

Table 23.--Nitrate nitrogen in Sims clay loam as affected by organic amendments, and fertilizer nitrogen.

Treatment	Replication					Average
	1	2	3	4	5	
	Pounds of NO_3-N per acre					
Check	51	48	63	51	45	52
Check plus N	54	54	74	55	55	58
Alfalfa-brome. . . .	68	68	71	63	66	67
Alfalfa-brome + N .	74	77	79	73	76	76
Sawdust.	49	51	42	57	57	51
Sawdust plus N . . .	71	71	66	71	63	68
Straw	57	54	48	60	54	55
Straw plus N	61	61	57	66	60	61

Main effects of residues:

Check	55
Alfalfa-brome.	72
Sawdust	60
Straw	58

Main effects of nitrogen:

No nitrogen	56
Supplemental nitrogen	66

Table 24.--Inorganic nitrogen in Sims clay loam as affected by organic amendments, and fertilizer nitrogen.

Treatment	Replication					Average
	1	2	3	4	5	
	Pounds of inorganic nitrogen per acre					
Check	134	143	152	143	143	143
Check plus N . .	152	160	168	158	159	159
Alfalfa-brome . .	168	160	162	161	158	173
Alfalfa-brome + N	189	186	191	173	179	184
Sawdust	138	131	131	143	146	138
Sawdust + N . . .	163	171	169	163	157	165
Straw	149	146	140	141	146	144
Straw plus N . .	159	161	158	155	158	158
Main effects of residues:						
Check						151
Alfalfa-brome						173
Sawdust						151
Straw						151
Main effects of nitrogen:						
No nitrogen						147
Supplemental nitrogen						166

Table 25.--Hydrolyzable nitrogen in Sims clay loam as affected by organic amendments, and fertilizer nitrogen.

Treatment	Replication 1	2	3	4	5	Average
	Pounds of hydrolyzable nitrogen per acre					
Check	3100	3156	2712	3276	3192	3087
Check plus N	3348	3456	3312	3216	3168	3300
Alfalfa-brome . . .	3144	3216	3168	3184	3192	3221
Alfalfa-brome + N .	3384	3240	3288	3456	3336	3341
Sawdust.	3456	3288	3216	3432	3576	3394
Sawdust plus N . . .	3552	3528	3624	3744	3624	3614
Straw	3192	3144	3168	3216	3240	3192
Straw plus N	3240	3264	3288	3312	3552	3331
Main effects of residues:						
	Check					3194
	Alfalfa-brome					3281
	Sawdust					3504
	Straw					3262
Main effects of nitrogen:						
	No nitrogen					3223
	Supplemental nitrogen					3397

Table 26.--Nonhydrolyzable nitrogen in Sims clay loam as affected by organic amendments, and fertilizer nitrogen.

Treatment	Replication 1	2	3	4	5	Average
	Pounds of nonhydrolyzable nitrogen per acre					
Check	756	600	780	492	565	638
Check plus N . . .	888	1068	1188	1044	1176	1073
Alfalfa-brome. . .	888	996	1056	984	780	941
Alfalfa-brome + N	1212	1224	1368	1248	816	1174
Sawdust.	600	816	960	960	528	773
Sawdust + N . . .	816	960	1152	1140	1128	1039
Straw	768	864	984	696	648	792
Straw + N.	1008	1128	1080	1152	840	1042

Main effects of residues:	
Check	856
Alfalfa-brome.	1057
Sawdust	906
Straw	917
Main effects of nitrogen:	
No nitrogen	786
Supplemental nitrogen	1082

Table 27.--Organic nitrogen in Sims clay loam as affected by organic amendments, and fertilizer nitrogen.

Treatment	Replication 1	2	3	4	5	Average
	Pounds of organic nitrogen per acre					
Check	3856	3756	3492	3768	3756	3726
Check + N. . . .	4236	4524	4500	4260	4344	4373
Alfalfa-brome. .	4032	4212	4224	4368	3972	4162
Alfalfa-brome+N	4596	4464	4656	4704	4152	4514
Sawdust.	4056	4104	4176	4392	4104	4166
Sawdust + N. . .	4368	4488	4776	4884	4752	4654
Straw	3960	4008	4152	3912	3888	3984
Straw + N. . . .	4248	4392	4368	4464	4392	4392

Main effects of residue:

Check	4049
Alfalfa-brome.	4338
Sawdust.	4410
Straw	4178

Main effects of nitrogen:

No nitrogen.	4009
Supplemental nitrogen	4478

Table 28.--Corn yields in Sims clay loam as influenced by organic amendments, and fertilizer nitrogen.

Treatment	Replication I Bus./A	Replication II Bus./A	Replication III Bus./A	Replication IV Bus./A	Replication V Bus./A
Check	119.9	119.3	107.0	116.8	111.9
Check plus N	113.2	113.2	110.7	123.0	118.1
Alfalfa-brome	120.5	118.1	107.0	114.4	111.9
Alfalfa-brome plus N	110.7	116.8	115.6	114.4	118.1
Sawdust	110.7	113.2	111.9	115.6	115.6
Sawdust plus N	119.3	114.4	119.3	124.2	116.8
Straw	113.2	111.9	107.9	113.2	86.1
Straw plus N	115.6	114.4	119.3	113.2	114.4

Table 29.--Ammonia and nitrate nitrogen in Sims clay loam as influenced by cropping sequence, fertility level and supplemental nitrogen treatment.

Rotation	Treatment		Replication I		Replication II		Replication III		Replication IV	
	Fertility	Nitrogen	NH_3-N Lbs/A	NO_3-N Lbs/A	NH_3-N Lbs/A	NO_3-N Lbs/A	NH_3-N Lbs/A	NO_3-N Lbs/A	NH_3-N Lbs/A	NO_3-N Lbs/A
1	Low	0	51	77	71	42	68	51	76	36
1	Low	N	54	74	77	28	100	36	71	51
1	High	0	57	36	87	22	86	36	89	48
1	High	N	65	27	64	28	82	52	81	45
6	Low	0	63	51	64	68	44	36	86	42
6	Low	N	74	44	66	60	77	33	77	27
6	High	0	83	41	76	35	86	33	83	36
6	High	N	74	55	62	22	89	60	84	39

Table 30.--Hydrolyzable and nonhydrolyzable nitrogen in Sims clay loam as influenced by cropping sequence, fertility level and supplemental nitrogen treatment.

Rotation	Treatment		Replication I		Replication II		Replication III		Replication IV	
	Fertility	Nitrogen	HN Lbs/A	NHN Lbs/A	HN Lbs/A	NHN Lbs/A	HN Lbs/A	NHN Lbs/A	HN Lbs/A	NHN Lbs/A
1	Low	0	3540	872	3280	900	3680	1152	3100	204
1	Low	N	3580	1044	2920	1092	2860	564	3320	480
1	High	0	3520	624	3020	924	3500	636	3280	912
1	High	N	2800	1440	2980	1008	3260	1128	3396	1008
6	Low	0	3220	600	3320	1044	3140	324	2300	984
6	Low	N	3120	984	3280	636	3360	840	2380	744
6	High	0	2900	768	3140	696	3140	228	2420	936
6	High	N	2780	1052	2860	504	3060	1008	2500	1008

Table 31.--Mineral and organic nitrogen in Sims clay loam as influenced by cropping sequence, fertility level and supplemental nitrogen treatment.

Rotation	Treatment		Replication I		Replication II		Replication III		Replication IV	
	Fertility	Nitrogen	Mineral N Lbs/A	Organic N Lbs/A	Mineral N Lbs/A	Organic N Lbs/A	Mineral N Lbs/A	Organic N Lbs/A	Mineral N Lbs/A	Organic N Lbs/A
1	Low	0	128	4412	113	4180	119	4832	112	3304
1	Low	N	128	4624	105	4012	136	3424	122	3800
1	High	0	93	4144	109	3944	122	4136	137	4192
1	High	N	92	4240	92	3988	134	4388	126	4404
6	Low	0	114	3820	132	4364	80	3464	128	3284
6	Low	N	118	4104	126	3916	110	4200	104	3124
6	High	0	124	3668	111	3836	119	3368	119	3356
6	High	N	129	3832	84	3364	149	4068	123	3508

Table 32.--Corn yields in Sims clay loam as influenced by cropping sequence, fertility level and supplemental nitrogen treatment.

Rotation	Treatment		Replication I	Replication II	Replication III	Replication IV
	Fertility	Nitrogen	Bus./A	Bus./A	Bus./A	Bus./A
1	Low	0	100.8	107.7	73.3	102.2
1	Low	N	110.3	96.8	74.6	107.7
1	High	0	98.2	112.5	121.6	93.3
1	High	N	105.3	112.7	139.4	100.4
6	Low	0	42.0	71.5	68.3	54.4
6	Low	N	77.4	74.6	100.6	55.0
6	High	0	52.1	45.7	50.3	55.6
6	High	N	75.0	95.0	112.1	75.0

APPENDIX II

Computational Formulae Used in Functional Analyses

Computational Formulae Used in Functional Analyses

N = Number of observations

ΣX = Arithmetic sum of observations x

ΣX^2 = Sum of squares of x

$\bar{X}$ = Mean of x's

$\bar{X}^2$ = Mean of x^2

σ^2 = Variance = $(\bar{X}^2 - \bar{X} \cdot \bar{X})$

σ = Standard deviation = $\sqrt{\sigma^2}$

$\Sigma X_1 X_2$ = Sum of products of $x_1 x_2$ (cross products)

$\overline{X_1 X_2}$ = Mean of cross products

N' = Number of observations = number of variables or M-M (where M = number of variables)

R = Coefficient of multiple correlation

$\bar{R}$ = Corrected R (also $_c R$)

r_{12} = Correlation coefficient = $\dfrac{\overline{X_1 X_2} - \bar{X}_1 \bar{X}_2}{\sigma_1 \quad \sigma_2}$ or $\dfrac{N\Sigma X_1 X_2 - \Sigma X_1 \Sigma X_2}{\sqrt{[N\Sigma X_1^2 - (\Sigma X_1)^2][N\Sigma X_2^2 - (\Sigma X_2)^2]}}$

Formulae for simple correlation (2 variables)

$\hat{Y} = a + bx$ y = dependent variable x = independent variable

$b = \dfrac{\Sigma XY - N\bar{X}\bar{Y}}{\Sigma X^2 - N(\bar{X})^2}$ $a = \bar{y} - \bar{x}b$ $r = \dfrac{\overline{xy} - \bar{x}\,\bar{y}}{\sigma_x \cdot \sigma_y}$

S = standard error of estimate = $\sigma_y \sqrt{1 - r^2}$

σ_b = standard error of b = $\dfrac{\sigma_y}{\sigma_x} \sqrt{\dfrac{1 - r^2}{N}}$ $t_r = \dfrac{r}{\sigma_r}$ or $\dfrac{r\sqrt{N-2}}{\sqrt{1 - r^2}}$

σ_r = standard error of r = $\dfrac{\sqrt{1 - r^2}}{\sqrt{N - 2}}$ $t_b = \dfrac{b}{\sigma_b}$

Multiple correlation by formulae (3 variables - with x_1 dependent)

Beta (β) coefficients

$$\beta_2 = \frac{r_{12} - (r_{13} r_{23})}{1 - r_{23}^2} \qquad \beta_3 = \frac{r_{13} - (r_{12} r_{23})}{1 - r_{23}^2}$$

b coefficients

$$b_2 = \beta_2 \left(\frac{\sigma_1}{\sigma_2}\right) \qquad b_3 = \beta_3 \left(\frac{\sigma_1}{\sigma_3}\right)$$

$$a = \bar{X}_1 - b_2 \bar{x}_2 - b_3 \bar{x}_3$$

$$R^2 = \beta_2 r_{12} + \beta_3 r_{13} \qquad R = \sqrt{R^2} \qquad \bar{R}^2 = 1 - (1 - R^2)\left(\frac{N-1}{N-M}\right)$$

$$\sigma_{\beta_2} = \sigma_{\beta_3} = \text{stan. error of } \beta \text{ coeff.} = \sqrt{\frac{1 - R^2}{(1 - r_{23}^2)(N-M)}}$$

$$\sigma_{b_2} = \text{stan. error of b} = \sigma_{\beta_2}\left(\frac{\sigma_1}{\sigma_2}\right); \quad \sigma_{b_3} = \sigma_{\beta_3}\left(\frac{\sigma_1}{\sigma_3}\right); \quad t_b = \text{same as above}$$

Residuals (after computing $\hat{y} = a + b_1 x_1 + b_2 x_2$)

Substitute computed values of a, b_1 and b_2 in equation along with original x_1, x_2 for each sample observation and get the predicted value of y, say $\hat{y}$. Subtract this from original y for that observation, to get residual. Suggested form below --

Predic. equa: $\hat{y} = 5.0260 + .0738\, x_1 + 1.2867\, x_2$, $y - \hat{y}$ = Residual

X_1	X_2	Sample No.	A	bx_1	b X_2	$\hat{y}$	y	Residual*
3	10	1	5.0260	.2214	12.8670	18.1144	16.7345	-1.3799
5	8	2	5.0260	.3690	10.2936	15.6886	17.4497	1.7611
1	5	3	5.0260	.0738	6.4335	11.5333	11.1521	- .3812

*Residuals should total 0. If logs were used, antilog of y must be found before getting residuals.

Computation of Prediction Equation by "Least Squares"

The inverse is computed <u>omitting</u> the dependent variable from the Identity and from the Inversion.

The Raw Moments are first Augmented and Adjusted.

X_i = Independent variables

Y = Dependent variable

K_i = Adjustment factor

K_i' (Deadjustment factor) is $\frac{K_i}{K_y}$

$\overline{X}_i$ Mean of X_i

$\overline{Y}$ Mean of Y

c_{ii} are the diagonal elements of the inverse.

$b_i = (M_{ix})^{-1} M_{iy}$ Where $(M_{ix})^{-1}$ is inverse of the i row of the moments of all the x's.

$a = \overline{y} - \Sigma\, b_i\, \overline{x}_i$

$R^2 = \frac{\Sigma\, b_i\, m_{iy}}{\Sigma\, y^2}$ Where m_{iy} are the moments of all the x_i on y_i.

$R = \sqrt{R^2}$

$\overline{R} = 1 - (1 - R^2)\left(\frac{N - 1}{N - M}\right)$ Where N is the number of observations and M the total number of variables.

$\overline{R} = \sqrt{\overline{R}^2}$

$\overline{S}^2 = \frac{\Sigma\, y^2 - \Sigma b_i m_{iy}}{N - M}$

$\overline{S} = \sqrt{\overline{S}^2}$

In computing R^2, either adjusted or deadjusted figures may be used as long as both the Equation and the b's are either adjusted or deadjusted.

For $\overline{S}^2$ the adjusted figures must be used.

For "a" the deadjusted figures are used with the means, which have not been adjusted.

σb_i (Standard error of b_i) = $(\sqrt{c_{ii}})\ (\overline{S})$

Prediction Equation: $y = a + bx_2 + bx_3 + bx_4 + bx_5$

$t_i\ \frac{b_i}{\sigma b_i}$

Example

$\hat{y} = 86.618252576 + 9.87479703x_2 + 6.7076962x_3 - 14.2685815x_4 - 13.7574111x_5$

	(6.86534778)	(12.0923398)	(12.2988143)	(8.3785081)
t =	1.438353503	.554706228	1.160159113	1.641988160

APPENDIX III

Locations of Field Experiments and Soil Type Descriptions

Locations of Field Experiments

Fertilizer experiments:

Ewald Fick farm: Section 34, T 2 S, R 7 W; Calhoun County. (Kalamazoo sandy loam).

John Campbell farm: Section 4, T 2 S, R 10 W; Kalamazoo County. (Kalamazoo sandy loam).

Kenneth Thompson farm: Section 4, T 10 N, R 2 W; Gratiot County. (Sims loam).

Residue and rotation experiments:

Lee Ferden farm: Section 33, T 9 N, R 3 E; Saginaw County. (Sims clay loam).

Soil Type Descriptions

Kalamazoo soils:

The Kalamazoo series includes well-drained Grey-Brown Podzolic soils developed on acid loam, sandy loam, and loamy sand materials over calcareous or neutral sands and gravel at depths of 42 to 66 inches. They have a sandy clay loam to clay loam subsoil between 10 and 20 inches thick.

Sims soils:

The Sims series includes naturally poorly drained soils developed in calcareous clay loam or silty clay loam till. They need tile drainage for crop production.