EFFECTS OF ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE ON THE MINERALIZATION OF SOIL ORGANIC NITROGEN

By

JOSE ANTONIO MORA R

A THESIS

Submitted to the College of Agriculture of Michigan
State University of Agriculture and Applied
Science in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

Department of Soil Science

1957

ABSTRACT

Soil samples were taken in the fall from a field rotation experiment on Sims clay loam. The samples represented soil to which various organic amendments had been applied one, two, three, four, and five years previously. A massive application of sawdust (35 tons per acre) was compared with more normal residue treatments: four tons per acre of wheat straw, two cuttings of second-year alfalfa-brome hay, and the check treatment wherein both cuttings of second-year alfalfa-brome hay were removed. The residue treatments were initiated the season preceding corn in a five-year rotation of corn, white pea beans, barley, alfalfa-brome, and alfalfa-brome. Supplemental nitrogen was used with corn, beans, and barley on one-half of each residue-treated plot.

The depletive nature of the first three crops in the rotation was reflected by a decline in total carbon and in the ratio of carbon to nitrogen in the soil. The loss of carbon was initially more rapid where supplemental nitrogen was used in conjunction with the check, straw, and sawdust treatments. Minimum C:N ratios were reached during the second or third years of the rotation, except after the

heavy sawdust application, when there was a progressive decline through the fourth or fifth year.

The "soil-building" influence of the alfalfa-brome grown during the last two years of the rotation was reflected by rapid increases in total nitrogen. Carbon accumulated more rapidly than nitrogen. The resultant increase in soil C:N ratio was enhanced by residual effects of supplemental nitrogen applied during the first three years, except where alfalfa-brome hay had been the original organic amendment. Supplemental nitrogen had no effect on soil C:N ratio following the initial application of alfalfa-brome hay.

The soils following all treatments tended to stabilize at a C:N ratio of 9:1 during the last two years of the rotation. During the first three years of the rotation, soil C:N ratios greater than 9:1 were associated with the presence of an excess of carbonaceous residues from the first year's corn crop or from the heavy sawdust application. Soil C:N ratios less than 9:1 reflected low levels of carbonaceous energy materials. This was shown by the low level of microbial activity which was supported during a fourteen-day incubation period and measured by carbon dioxide evolution.

The mineralization of nitrogen during a fourteen-day incubation period was sharply reduced in soil samples taken one year after addition of sawdust. This was due to microbial immobilization. The extent of microbial immobilization was directly related to activity of the microbial population, as was shown by the fact that both carbon dioxide evolution and the suppression of nitrogen mineralization during incubation were enhanced in sawdust-treated plots to which supplemental nitrogen had been applied.

The availability to microbial attack of the products of decomposition of all residues tended rapidly to approach the same low level, as reflected by carbon dioxide evolution. The ratio of carbon mineralized to nitrogen mineralized also tended to fall rapidly during decomposition to the same ratio as the ratio of carbon to nitrogen in the residual organic materials undergoing decomposition in the soil.

In soil sample with narrow C:N ratios (10:1 or less), the rate of nitrogen mineralization tended to be directly related to total soil nitrogen. In soils with C:N ratios greater than 10:1 there was an inverse relationship between total soil nitrogen and nitrogen mineralization rate. The inverse relationship in soils with wide C:N ratio appeared to result from the nitrogen immobilizing potential of excess carbonaceous energy materials, the presence of which was reflected by the wider soil C:N ratio.

The depression of nitrogen mineralization during incubation in soils of wide C:N ratio was reflected in depressed crop yields. In soils of narrow C:N ratio there was no relationship between incubation nitrification or mineralization rate and crop yields.

It is suggested that further studies be directed toward relating total carbon and nitrogen determinations to nitrogen mineralization rate and to crop response to fertilizer nitrogen.

ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude and thanks to his major professor, Dr. A. Wolcott. Without his great interest, constant advice, and patient counseling many aspects of the study would have been immeasurably more difficult.

Special thanks are expressed by the author to Dr. S. L. Litzenberger for providing much of the incentive and inspiration to undertake advanced studies, and to the Rockefeller Foundation for the financial assistance which made it possible to complete them.

He is also grateful to Dr. R. L. Cook, who was instrumental in the author's coming to Michigan State University, and to Dr. J. F. Davis for his valuable suggestions and criticisms during preparation of the manuscript.

TABLE OF CONTENTS

LIST OF TABLES

TABLE		Page

LIST OF FIGURES

FIGURE | Page

INTRODUCTION

In recent years there has been a resurgence of interest in the transformations which nitrogen undergoes in soils. This has been stimulated, in part, by changing economic conditions which have caused marked changes in types of farming, notably a shift away from livestock toward a predominance of cash crops in many commercial enterprises. This has resulted in a decrease in the importance of livestock manures and legumes as a source of nitrogen in fertility programs and an increased reliance on commercial nitrogen fertilizers. Revolutionary changes in fertilizer technology have abetted these changes by providing cheap, high-analysis nitrogen materials and time- and labor-saving methods of transport, handling, and application.

Nitrogen used in commercial fertilizers has increased phenomenally without the parallel development of fundamental concepts for assessing the efficiency or economy of increasing rates of nitrogen application. For example, no soil test for nitrogen is available that approaches the reliability of soil tests for phosphorus and potassium in predicting the fertilizer requirements of specific crops on specific soils.

Nitrogen availability in soils is intimately related to its dynamic transformation from mineral forms to organic combinations with carbon and the reversal of these processes. New techniques in organic chemistry and biochemistry are throwing increasing light on the identity of soil organic compounds and the nature of their complex associations in the soil. This new knowledge of the fundamental composition and chemical behavior of soil organic matter provides a new background for interpreting the results from field studies directed toward an empirical correlation of soil tests for nitrogen with crop response. The present report represents an initial phase in the accumulation of field and laboratory data which can be used as a partial basis for developing such interpretations.

OBJECTIVES

The primary objective of the present study was the accumulation of chemical and biological data that might be used in future studies directed toward correlating various soil tests for estimating nitrogen-supplying power of a soil with crop yields. Initially these studies were restricted to an attempt to evaluate the effects of residue treatment, crop sequence, time, and supplemental nitrogen fertilization on crop yields. Data were obtained from a field experiment on Sims clay loam, which represents an important agricultural group of soils in Michigan. The fulfillment of this first objective must await the accumulation of similar chemical data and crop yields over a period of years so as to adequately measure rotational effects.

A secondary objective, although of primary importance at this stage of the study, was to evaluate tentatively the effects of field treatments and time on the chemical and biological tests themselves.

REVIEW OF LITERATURE

For many years, in the scientific and popular literature, soil organic matter has been regarded as one of the best criteria of good soil management or soil productivity. Between the years 1850 and 1890 it was established that nitrogen released by decomposition from organic compounds in the soil was a principal source of available nitrogen for plant nutrition. It was accepted that, normally, nitrogen was first released as ammonia, which was converted via nitrite to nitrate, and that most plants preferentially used nitrate. The same belief seems to prevail up to the present day, though some modern investigations have demonstrated the possible uptake of soluble organic substances by higher plants.

In 1877, Schloesing and Muntz (42) showed that the oxidation of ammonia to nitrate in sewage was a biological process. Warrington (53) in 1878 found that nitrate formation in soil was a biological process, and that ammonia was the starting point for nitrification. In 1891 (54) he described two kinds of bacteria obtained by inoculating liquid media with soil. One kind oxidized ammonium salt to nitrite; the other kind oxidized nitrite to nitrate and did not oxidize ammonia.

Marchal (32) in 1893 pointed out that ammonia was the first form of mineral nitrogen to appear in any breakdown of nitrogen-containing organic substances. The fundamental interpretation of the process of oxidation of ammonia to nitrate via nitrite had been given in the nineteenth century, and the general outline still accepted is as follows:

$$\underbrace{\overbrace{\text{Organic N} \rightarrow \text{Ammonia}}^{\text{Ammonification}}}_{\text{"Nitrifiable N"}} \overbrace{\rightarrow \text{Nitrite} \rightarrow \underbrace{\text{Nitrate}}_{\text{"Available N"}}}^{\text{Nitrification}}$$

It was found very early that the level of nitrate in the soil at any given time could provide no basis for estimating the amount of nitrogen that might be released for crop use from organic sources in the soil. For this reason, numerous investigators have attempted to show a parallelism between total soil nitrogen, its nitrifiability, and the availability of nitrogen for crops and soil productivity.

Studying the problem of ammonifiability versus nitrifiability as tests for the relative availability of nitrogenous fertilizers, Lipman and Burgess (31) concluded in 1917 that the nitrate form of nitrogen was of paramount importance for the nutrition of most plants.

In 1918 Burgess (9), while experimenting on Hawaiian soils, attempted to determine the possibility of predicting crop yields

from microbiological data. Ammonification, nitrification, and nitrogen fixation were used as bases for prediction in a routine and comparative test. The nitrification process was shown to be by far the most accurate biological measure for evaluating soil fertility conditions and predicting future crop yields.

Gainey (20) asserted that it is not unreasonable to find a correlation between nitrifying capacity of a soil and its ability to support vigorous plant growth. He concluded that those conditions which tend to promote rapid nitrification are closely related to those which result in maximum crop yields, though active nitrification may not be the cause of high fertility.

Using as indexes the cellulose decomposing power and nitrifying capacity, White *et al*. (55) found highly significant correlations between both tests and crop yields at the Jordan soil fertility plots in Pennsylvania.

On the other hand, Fraps *et al*. (16), studying the relation between total and mineral nitrogen in soils of uniform type, found that the higher the total nitrogen in the soil the more mineral nitrogen is produced in incubation experiments and under field conditions. Fraps and Sterges (17, 18), in later work with different soil types, realized that entirely different mineralization powers can be brought about by the same total nitrogen content in fundamentally

different soils. However, they maintained that the mineralization of nitrogen depends primarily on the amount of total nitrogen in the soil if some individual impediments are first removed. They adjusted widely different soils to uniform structure, moisture content, pH, mineral supply, and microbial population by grinding, sifting, liming, fertilizing, and innoculating the samples, and by maintaining strictly standardized conditions of temperature, aeration, and moisture content during incubation. When these precautions were taken, the mineralization of nitrogen was closely related to the total nitrogen content of the soil. Carpenter et al. (10) arrived at the same conclusion. They also found very close correlation (significant at the 1 per cent level) between the total nitrogen content of the upper 12-inch layer of soil and the yield of wheat in a cumulative rotation experiment.

Gainey et al. (21, 22), using for their work samples derived from the same soil type but from spots known to be very different in their power to form mineral nitrogen, arrived at the reverse conclusion. Gainey (21) formulated the opinion that nitrogen mineralization and the fertility of a soil are more intimately associated with the characteristic properties of a small part of the total nitrogen than with all of it. A small part is active; the rest is stable and therefore relatively inert. He found that, when the nitrogen content and the nitrate accumulating power of a large number of soils are determined and the data thus obtained are grouped on the basis of the nitrogen content of the soils and averaged, an almost perfect direct relationship may appear to exist between the total nitrogen content and the nitrate accumulating ability. On the other hand, if the original data are used as a basis for calculating the coefficient of correlation, the relationship between the two factors may be found to be very slight or even nil. Using plots in a long-term fertilization and crop-rotation experiment on uniform soil, Allison and Sterling (1) again checked this point. They found a close relation between nitrogen mineralization and the total nitrogen content (correlation coefficient of 0.7 to 0.8), fully supporting the opinions of Fraps and Carpenter. Nevertheless, they understood that this conclusion would hold true only for one soil type.

The activities of various organisms which bring about the transformation of the complex plant and animal organic materials into simple inorganic elements or compounds are known collectively as mineralization. The mineralization of nitrogen includes its initial release as ammonia (ammonification) and the subsequent oxidation of ammonia through nitrite to nitrate (nitrification). Failure to distinguish clearly between ammonification and nitrification has given rise to considerable confusion in the literature. In most normal soils the oxidation of ammonia proceeds so rapidly that the formation of ammonia from organic matter may be obscured, as the only end product of the mineralization seems to be nitrate. As a result, nitrification has received much attention, whereas ammonification often has been neglected. Many workers up to the present time, for a matter of convenience, designate not only the oxidation of ammonia to nitrate, but also the whole process of mineralization of organic matter, as "nitrification."

Since mineralization is mainly biochemical in nature, many interacting and complex factors have an influence on the processes of ammonification and nitrification. The amount of ammonia or nitrate formed from the decomposition of organic matter depends upon the following important factors: the presence of the organisms concerned in decomposition and nitrification, carbon-nitrogen ratio and chemical composition of the organic materials, moisture and temperature, aeration, soil reaction, mineral nutrient status, and other chemical, physical, and biotic properties of soils.

One of the most important factors which influences mineralization of organic matter is the presence of organisms responsible for the processes of ammonification and nitrification. Gainey (20) and others found that all cultivated soils, under conditions approximating normal, contain active nitrifying organisms. Waksman (49),

studying bacterial numbers in soils at different depths and seasons of the year, found that the greatest number of bacteria were found at a depth of one inch. There was a regular decrease in the number of organisms from a depth of one inch down to a depth of thirty inches. The maximum bacterial numbers during the year varied with different soils according to the time of the year. Quantitative investigation of bacterial and protozoan populations by Cutler et al. (13) indicated further that the number of bacteria in the soil varies considerably with the season of the year. They found the general level of numbers to be highest in spring and autumn.

It is apparent that organic nitrogenous compounds which may find their way into soils are exceedingly numerous and vary greatly in composition. Consequently, it is not surprising to find a great number of types of heterotrophic organisms active in the formation of ammonia. In fact, a large percentage of all microbes in soils may be able to produce ammonia from organic materials. These include large numbers of different bacteria (spore-formers and non-sporulating species), filamentous fungi, and actinomycetes. These vary greatly in their nutritional requirements, in their efficiency of carbon assimilation, and in the nitrogen content of their tissues. According to Waksman and Starky (52), the average per cent of nitrogen in microbial tissues for fungi is 5; streptomycetes, 8; and bacteria, 10. The average efficiency of carbon assimilation in per cent of substrate carbon consumed for fungi is 40; streptomycetes, 8; and bacteria, 10. Because of these differences in the efficiency of assimilation of carbon into microbial cell material and the differences in C:N ratio of the resulting microbial tissues, the extent of immobilization or mineralization of nitrogen during decomposition of plant residues is profoundly influenced by the nature of the decay population. Because of differences in nutritional requirements, the nature and size of the heterotrophic soil population varies rapidly with the quantity, nature, and stage of decomposition of plant or animal residues returned to the soil.

The organisms responsible for nitrification are autotrophic bacteria. They utilize energy from the chemical oxidation of ammonia or nitrite and assimilate carbon directly from carbon dioxide. Those which oxidize ammonia to nitrite include a limited number of species in two genera: Nitrosomonas and Nitrosococcus. An even smaller number of species of Nitrobacter are responsible for the conversion of nitrite to nitrate.

The groups of microorganisms concerned with the process of ammonification include aerobic and anaerobic forms, but the bacteria involved in the process of nitrification are strictly aerobic. Thus the relative amounts of ammonia and nitrate produced are affected in part by the amount of oxygen available in soil air. Plummer (39) investigated the influence of oxygen on ammonification and nitrification by incubating soils in sealed flasks containing different mixtures of oxygen, carbon dioxide, and nitrogen. He concluded that there is no optimum content of oxygen for the production of ammonia. The results for all gas mixtures, except the very high concentrations of oxygen, were practically the same. Under purely anaerobic conditions, caused by an atmosphere of pure carbon dioxide, there was somewhat less ammonia produced than when oxygen was present at the beginning. On the other hand, oxygen was the limiting atmospheric constituent for nitrification, and there was an optimum mixture of this gas (one containing from 35 to 60 per cent oxygen).

Studies of Fathi and Bartholomew (14) indicated that the minimum oxygen concentration for nitrification was below 0.4 per cent and the optimum concentration of oxygen for nitrification in the soil systems studied was about that contained in ordinary air. Approximately half as much nitrate was produced when the oxygen concentration was maintained at 2.1 per cent as at 20 per cent. Reducing the oxygen concentration from about 20 to 11 per cent had only a negligible influence upon the rate of nitrification. Harmsen and Van Schreven (29), in regard to the effect of aeration on the process of mineralization, stated that the oxygenation of soil is a complex of processes, depending not only on the water content and the compactness of the soil, but also on its content of decomposable organic matter and other reduction-oxidation systems.

Soil moisture is another major factor effecting the number and activities of organisms responsible for mineralization. Greaves and Carter (24), studying the influence of moisture upon the bacterial activities of twenty-two soils ranging from light sand to clay and from soils nearly devoid of organic matter, found that every soil gave a maximum ammonification when it contained 60 per cent of its water-holding capacity. Nitrification was at its maximum at 50 per cent or 60 per cent of its water-holding capacity and varied with specific soils to near water saturation. According to Bhaumick (4), the moisture tension at which the maximum amount of carbon dioxide was evolved during fifteen days differed for several soils. For all the soils studied the peak rate of carbon dioxide production was observed at or very near to the moisture tension at the aeration porosity limit, taken by convention at a tension of 50 cm of water. Microbial analysis revealed differences in the abundance of microbial groups both at different tensions and for soils differing in texture. It appeared that such differences in microbial populations were at least partly responsible for differences in the amount of carbon dioxide evolved from several soils. Fitts, Bartholomew, and

Heidel (15) found that 100 cm of water tension provided optimum moisture for the production of nitrate under laboratory conditions. Depending on the texture of the soil, this tension resulted in 25 to 35 per cent moisture.

The process of mineralization is also greatly influenced by temperature variation. Marchal (32) found that only traces of ammonia were produced at temperatures from 0° to 5° C, with maximum production at 30° C. Studies of the effect of constant and alternating temperatures in connection with ammonification and nitrification conducted by Panganiban (36) indicated that ammonification took place between 15° and 60° C, and that at higher temperatures the rate was faster. There was no difference in ammonification at 5° or 15° C; little or no ammonia was formed when samples were maintained at constant temperature or alternated between 5° and 15° C. Studies with nitrification at constant temperature showed that the process took place between 15° C and 40° C, and that the optimum temperature in soil culture was 35° C, or slightly higher. Alternating temperatures depressed the process greatly.

Greaves et al. (24) found that the ammonifying power of the soil tested was modified by storing for 24 months at various temperatures. The accumulation of ammonia was greater in soils

which were stored at 10° C and least in those stored at 40° C. The storage of sils at 10°, 20°, and 30° C for 24 months produced rather permanent changes in their nitrifying microflora. In two out of four soils stored at 40° C, the ability to produce nitrate had been lost completely.

According to Waksman (50), nitrification was noticeable at 5° C, became prominent at 12° C, and reached a maximum at 37° C. Higher temperatures, such as 45° C, exerted an injurious effect. Ammonification temperatures ranged from 4° to 80° C, and reached the optimum from 30° to 45° C. The studies of Frederic (19) on formation of nitrate from ammonium nitrogen in soils indicated that differences in the population of nitrifiers in the original soil were responsible for differences in the temperature range for nitrification. The low rate of nitrification in certain soils at low temperatures appeared to be due to a paucity of nitrifying microorganisms and a slow rate of development rather than on inactivation of the nitrification process itself.

The influence of soil reaction on the process of mineralization was recognized long ago. Waksman (50) concluded that the limiting acidity for the process of nitrification is pH 3.7 to 4.0, whereas the optimum reaction for ammonification is at pH 6.0 to 7.0. Allison and Sterling (1), using in their work mineral soil with pH ranging between 6.1 and 7.3, with and without calcium carbonate, observed that liming had in all cases a stimulating effect on mineralization, continuing for a long time. Cornfield (12) studied the effect of artificially acidifying a clay soil from an initial pH of 6.65 to a pH of about 4.0 by the addition of $AlSO_4$ or $FeSO_4$. They found that the over-all mineralization of nitrogen was significantly reduced and nitrification was almost completely suppressed, while ammonification decreased only slightly. Consequently, ammonia accumulated in the acidified samples. However, Halvorson and Caldwell (27), studying the factors affecting nitrate-producing power, found that the presence of large amounts of calcium carbonate inhibited nitrification.

Investigating ammonification and nitrification in soils over a wide range of conditions (reaction, moisture content, aeration, temperature), Hwang and Frank (30) formulated the important general rule that nitrification is more restricted to optimal conditions than is ammonification. Since ammonification is still significant in all extreme cases, the result is an accumulation of ammonia both at too low and too high pH, too low and too high temperature, and so on.

Fraps and Sterges (17), studying the effect of phosphate on the nitrifying capacity of 171 soils, observed that phosphorus treatments, especially when calcium carbonate was also present, stimulated materially the oxidation of ammonia in a large proportion of those soils. Brown and Gawda (8) came to the conclusion that rock phosphate and acid phosphate increased the nitrate content and the nitrifying power of the soil. Addition of phosphate and potash, according to Balwing, Walters, and Smith (2), stimulated the nitrification process.

Theron (45), studying the influence of plants on the mineralization of nitrogen, found that nitrification was entirely repressed under grass from the second season after its establishment onward, and did not take place when grass was dormant in winter. Under an annual crop, suppression of nitrification could be detected only as the crop approached maturity. During the period that nitrification was depressed, replaceable ammonia made its appearance in the soil in more than normal quantities. Goring and Clark (23), investigating the influence of crop growth on mineralization of nitrogen in the soil, concluded that less mineral nitrogen accumulates in cropped soils than in fallow soils, even though an accounting is made of the nitrogen removed by cropping, and the extent of the nitrogen deficit encountered is correlated to total weight of roots, to the nitrogen content of crop grown, and to the increase in number of microorganisms that accompanies plant growth. It

was believed that nitrogen unaccounted for in cropped soils is immobilized in the soil rather than lost to the air.

Periodic additions of fresh plant materials in the form of crop residues and green manures have long been accepted as fundamental to good soil management and the maintenance of soil organic matter. However, Broadbent (7), using isotopically tagged plant materials, concluded that fresh organic matter sometimes can bring about a net decrease in soil organic matter, especially if small amounts of readily decomposable material are added frequently to the soil. This conclusion was confirmed by Hallam and Bartholomew (26), who also found that the rate of residue addition of beans, straw, or other organic matter resulted in pronounced differences in the mineralization of native soil organic matter. Small amounts of fresh organic matter destroyed more of the stable humus than they added through the synthesis of new stable humus, whereas large additions of fresh material brought about a net gain in stable organic matter in the soil. The conclusions of Pink and Allison (38) are opposed to the general findings of this study.

Numerous studies have been made in relation to the limits of nitrogen content of organic materials below which no immediate mineralization of nitrogen may be expected. A generally accepted rule of thumb is that this point is reached in materials with a C:N

ratio of 20:1 to 25:1. Turk and Millar (48), studying the effects of different plant materials on the accumulation of soil organic matter, observed a generally inverse relationship between C:N ratio of organic amendments and the rate of nitrate accumulation in soils. Recently Barnes (3) arrived at the same conclusion. Owen and Winsor (35) carefully investigated the mineralization of nitrogen from organic matter using amino acids for this purpose. They observed a close inverse correlation between the rates of nitrogen mineralization and the C:N ratios of the acids when added to the soil. Bear (41) criticized the general attitude toward the C:N ratio and its frequent employment in the evaluation of materials for use as nitrogenous fertilizers. He pointed out the great differences in resistance to microbial attack of the different carbon and nitrogen compounds which occur in different relative amounts in different natural materials. Recently Bremner and Shaw (6), studying the mineralization of some nitrogenous materials, confirmed the results of similar studies by Rubins and Bear (41). They showed that casein and formalized casein had similar C:N ratios but their rates of mineralization were quite different, and cellulose nitrate with a C:N ratio of 2.3:1 was very resistant to decomposition, whereas crab shell meal with a C:N ratio of 5.1:1 was mineralized fairly rapidly.

Several types of procedures for determining nitrogen availability in soils have been advocated. The method Woodruff (56) has described is based on the amount of soil organic matter as determined by wet combustion. He assumed that each percentage of organic matter in the surface plow depth of soil corresponded to about 1,000 pounds of total nitrogen per acre. If all organic matter were alike, Woodruff concluded that the liberation of nitrogen from organic matter in a form available to plants would be proportional to the amount of organic matter in the soil. In criticism of this concept, it may be said that the fraction of soil organic matter that decomposes to liberate nitrogen for a particular crop depends upon such factors as the season of the year in which the crop grows, the temperature and moisture conditions of the soil throughout the growing period of the crop, soil texture, and the structural condition of the soil. Thus, it is necessary to know how much nitrogen is released from the organic matter in a given soil or group of similar soils under specific environmental conditions.

Another group of methods involves the chemical extraction of a fraction of the soil nitrogen. Truog (47) proposed a procedure involving partial alkaline oxidation of soil organic material.

A third procedure, which has received recent widespread attention, is that of biological mineralization of nitrogen from soil during a controlled incubation period (28, 44).

Harmsen and Van Schreven (29), reviewing methods for estimating the nitrogen mineralizing capacity of soils, concluded that the determination of the momentary amount of mineral nitrogen in the soil has a very dubious value. Referring to the value and limitations of the incubation method, they pointed out that the incubated soil samples are kept under entirely artificial conditions. The results of such experiments are in no way comparable with the mineralization process under field conditions. Such incubation experiments provide information about the short-term potential of the soil for mineralizing nitrogen, whereas under field conditions the real mineralization capacity is influenced by variable factors related to crop, management practices, and climate, acting over the relatively long period of the growing season. It is not advisable intentionally to make incubation conditions less favorable for mineralization, because only by creating optimal conditions can the method be more or less standardized. This is certainly necessary to obtain comparable results.

Some characteristics of data obtainable with incubation mineralization procedures which place serious limitations on their usefulness in predicting crop response should be mentioned:

1. In cultivated virgin soils and in soils with a poor structure the rate of mineralization under optimum conditions of incubation is stimulated to a level that is much above the natural rate of mineralization under field conditions. In samples of uncultivated acid, forest, or heath soils, more nitrogen may be liberated than in samples of productive cultivated soils, whereas under field conditions the reverse situation prevails.

2. The liberation of mineral nitrogen during incubation has been proved to be significantly influenced by conditions which prevailed in the field before sampling: cultivation, cropping, fertilization, and meteorological and seasonal factors.

3. Under variable climatic conditions, the mineralization capacity of soils is influenced not only by treatment of the soil prior to sampling and by seasonal factors, but also by difference in climatic conditions between consecutive years.

4. Whereas most workers have found straight or regularly curved, smooth lines when plotting the mineralized nitrogen against time, others have reported an irregular increase of the mineral nitrogen with sharp fluctuations. This fact tends to invalidate the

use of an arbitrarily standardized length of incubation period, particularly when for convenience a short incubation period is selected.

Harmsen and Van Schreven (29) summarized the difficulties and shortcomings of incubation techniques by stating that reliable results sufficiently correlated with nitrogen requirement of field crops can be expected only when the incubation technique is restricted to one soil type, one climatic zone, and one farming system, and when all samples are collected within one season, preferably during the early spring. For each set of conditions the interpretation of the results obtained must be developed separately, and their interpretation certainly will vary from one year to another, owing to uncontrollable and unpredictable variations in weather conditions. Consequently the determination of the nitrogen requirement of soils presumably will not reach the same degree of accuracy as the determination of P and K requirements. The most feasible approach appears to be the derivation, by elaborate empirical comparisons, of approximate correlations with crop response for each soil type or each group of closely similar soils.

MATERIALS AND METHODS

Field Treatments and Cropping History

Forty soil samples, composited by treatment and by year of establishment from the "Michigan rotation" plots at the Ferden farm in Saginaw County were used for this experiment. The soil is classified as Sims clay loam.

The "Michigan rotation" was originally established to determine the effect on crop yields of a large amount of sawdust in comparison with more normal quantities and types of residues. The five-year crop sequence for the rotation was corn, beans, barley, alfalfa-brome, and alfalfa-brome.

Fertilizer treatments were as follows:

Corn: 100 pounds 5-20-10 per acre;

Beans: 200 pounds 0-20-10 per acre;

Barley: 240 pounds 5-20-10 per acre;

Alfalfa-brome: no fertilizer either year.

Residue treatments were as follows:

1. Two-year-old alfalfa-brome (two cuttings of hay removed), followed by corn, beans, barley, alfalfa-brome, and alfalfa-brome.

2. Same as treatment one, except that neither cutting of the second year of alfalfa-brome was removed.
3. Same as treatment one, except that 35 tons of sawdust per acre was applied after removal of the second cutting of hay on the second year of alfalfa-brome.
4. Same as treatment three, except that four tons of wheat straw was applied instead of sawdust.

One-half of each plot received 40 pounds of nitrogen supplemental to the regular fertilizer treatments on corn and beans, except that corn following the sawdust treatment received 120 pounds instead of 40 pounds of supplemental nitrogen. One-half of each plot was topdressed with 20 pounds of extra nitrogen on barley, except in 1952, when 40 pounds was used, and again in 1956, when the use of supplemental nitrogen on barley was discontinued because of lodging difficulties which attended a change in variety planted.

The treatments were replicated five times and the residue treatments were initiated on a complete block of plots in each of the following years: 1951, 1952, 1953, 1954, and 1955. The five-year sequence of corn, beans, barley, alfalfa-brome, and alfalfa-brome had been in effect for three complete turns of the rotation before the residue treatments were initiated.

Soil samples were taken September 25, 1956. The five replications of each treatment were composited. The treatments for each year of establishment were sampled. Thus the samples represented plots to which the first residue treatments had been applied one, two, three, four, and five years previously.

Laboratory Determinations

Laboratory determinations were made as follows:

A. pH, with a glass electrode, using a 1:1 soil-to-water suspension.

B. Water-holding capacity, by Bouyoucos (5) suction method.

C. Ammonia, nitrite, and nitrate, following the Peech and English (37) procedure for extraction with Morgan's extracting solution (10 per cent sodium acetate buffered with acetic acid to pH 4.8). Ammonia determinations were made by direct nesslerization, using sodium silicate to protect against turbidity. The phenol-disulfonic acid method for determining nitrate plus nitrite after oxidizing nitrite with H_2O_2 according to Chase (11) was used. Nitrite was determined by difference between determinations with and without H_2O_2.

D. "Available organic soil nitrogen," including ammoniacal soil nitrogen, was determined, using alkaline permanganate as described by Truog (47). A Hellige nitrogen comparator was used for selecting the closest match of the test solution with the nitrogen standard.

E. Nitrifiable nitrogen. Nitrate formed during a two-week incubation under standardized conditions was determined, following the procedure developed by Hanway and Stanford (44) at Iowa State College. Ten-gram samples were used. The soil was mixed with an equal volume of vermiculite. The mixture was placed on another layer of vermiculite over a glass wool pad in a carbon filter tube. A covering layer of vermiculite was placed on top. Nine milliliters of 0.2 per cent water solution of Krillium was added to each tube and allowed to remain in contact for 15 minutes before the initial leaching in order to obtain clear leachates. Moisture was adjusted in each sample individually by applying suction. The tubes were stoppered with one-hole rubber stoppers. Samples were incubated for a period of two weeks at 35° C in an incubator maintained at constant 98 per cent relative humidity by keeping shallow pans full of 2 per cent sulphuric acid in the bottom of the incubator. Nitrate was measured by the phenoldisulfonic acid method.

F. Total carbon. Estimates were obtained by the wet combustion method as modified by Prince (40). In order to obtain a homogeneous sample, five grams of each soil sample were ground and thoroughly mixed, and a 0.5 gram portion was used for the actual determination. Orthophenanthroline was used as the indicator.

G. Total nitrogen. A modification by Prince (40) of the Kjeldahl procedure was followed. A mixture consisting of $CuSO_4$, HgO, and K_2SO_4 was used as a catalyst. The indicator selected consisted of a mixture of 10 ml of 0.1 per cent bromocresol green in 95 per cent alcohol and 2 ml of 0.1 per cent methyl red in 95 per cent alcohol.

H. Rate of respiration was measured by the simultaneous CO_2 absorption method of Norman and Newman (34). One-hundred-gram soil samples were placed in Mason jars and moisture was adjusted to 70 per cent of water-holding capacity. The jars were incubated for a period of two weeks, maintaining the temperature at 35° C. The soils were aerated every four days to supply sufficient oxygen for maximum CO_2 production. Vials containing sodium hydroxide were placed in each Mason jar for collecting the CO_2 evolved. Determinations of CO_2 were made by titrating the contents of each vial with HCl of known normality in the presence of an excess of $BaCl_2$. Phenolphthalein was used to determine the end point.

Except for CO_2 evolution, all determinations were made in duplicate.

EXPERIMENTAL RESULTS

Laboratory Determinations

Water-holding capacity

The water-holding capacity of the samples was determined for the purpose of adjusting the soil moisture of the samples used in respiration studies. The data are presented in Table 4 (Appendix). It can be noted that there were no differences for treatments or for years.

Soil reaction

The results of determinations for soil reaction are given in Table 5 (Appendix). The pH in the first year's samples was a half-unit lower in all treatments than in those taken the second and third years. There was a tendency for fourth- and fifth-year samples to be still higher in pH. No effect of treatment seemed to exist. The differences between years most probably reflect soil variations between the blocks of plots which were established in different years.

Soil phosphorus

The analyses for active phosphorus are given in Table 6 (Appendix). No differences between years or treatments were found.

The results of reserve phosphorus determinations are presented in Table 1. In general, reserve phosphorus in the soil increased with time. The only differences in reserve phosphorus which can be related to treatment are the reduction in phosphorus during the first year after sawdust and nitrogen were added, and a tendency for reserve phosphorus to remain low over the entire period on those plots which received straw. The increase in phosphorus with time may have been due in part to soil variation, althought progressive mineralization of organic phosphorus can be postulated.

Forms of soil nitrogen

Table 7 (Appendix) shows the results of ammonia determination. It can be noted that ammonia production was low in the first year (14 to 20 pounds per acre), increasing about 70 per cent in the second year, with no additional changes over the rest of the period. There were no differences that could be ascribed to treatment at any time.

Determinations for nitrite were negative in all samples.

TABLE 1

RESERVE PHOSPHORUS, SOLUBLE IN 0.13 N HCl, IN SIMS CLAY LOAM AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
	Phosphorus (pounds per acre)[a]					
Check	34	38	58	56	70	51
Check + N	27	46	50	48	64	47
Alfalfa	28	49	52	48	57	47
Alfalfa + N	30	49	48	54	53	46
Sawdust	29	46	50	36	66	45
Sawdust + N	20	49	61	46	66	48
Straw	31	60	59	33	52	47
Straw + N	37	35	63	39	37	42
Average for no N	31	48	55	43	61	48
Average for + N	28	45	55	47	55	46
Average for years	29	46	55	45	58	47

[a] Average of duplicate determinations.

Results of nitrate analyses are given in Table 2. Nitrate nitrogen was recovered from all treatments in the first two years and only from the checks in the third year. Addition of nitrogen increased nitrates in the soil the first and second years, with the exception in the second year of those samples to which sawdust or straw had been added.

The results for permanganate-soluble nitrogen are presented in Table 8 (Appendix). Values ranged from 75 to 200 pounds per acre. No relation to treatment or time existed.

Total nitrogen

Total nitrogen in pounds per acre is shown in Figure 1 for treatments and for years after treatment. The lowest total nitrogen regardless of treatment occurred in the first year. Plots where sawdust was applied had the highest amount of total nitrogen at this time. Total nitrogen increased with time, except for slight depressions in the third year after treatment in the check, alfalfa, and straw plots. The highest total nitrogen content each year was found following sawdust treatment. This reflects the role of carbon in immobilizing nitrogen in organic combinations in the soil.

The low total nitrogen content in the first year can not be explained in terms of nitrogen removed by the corn crop. Nor can

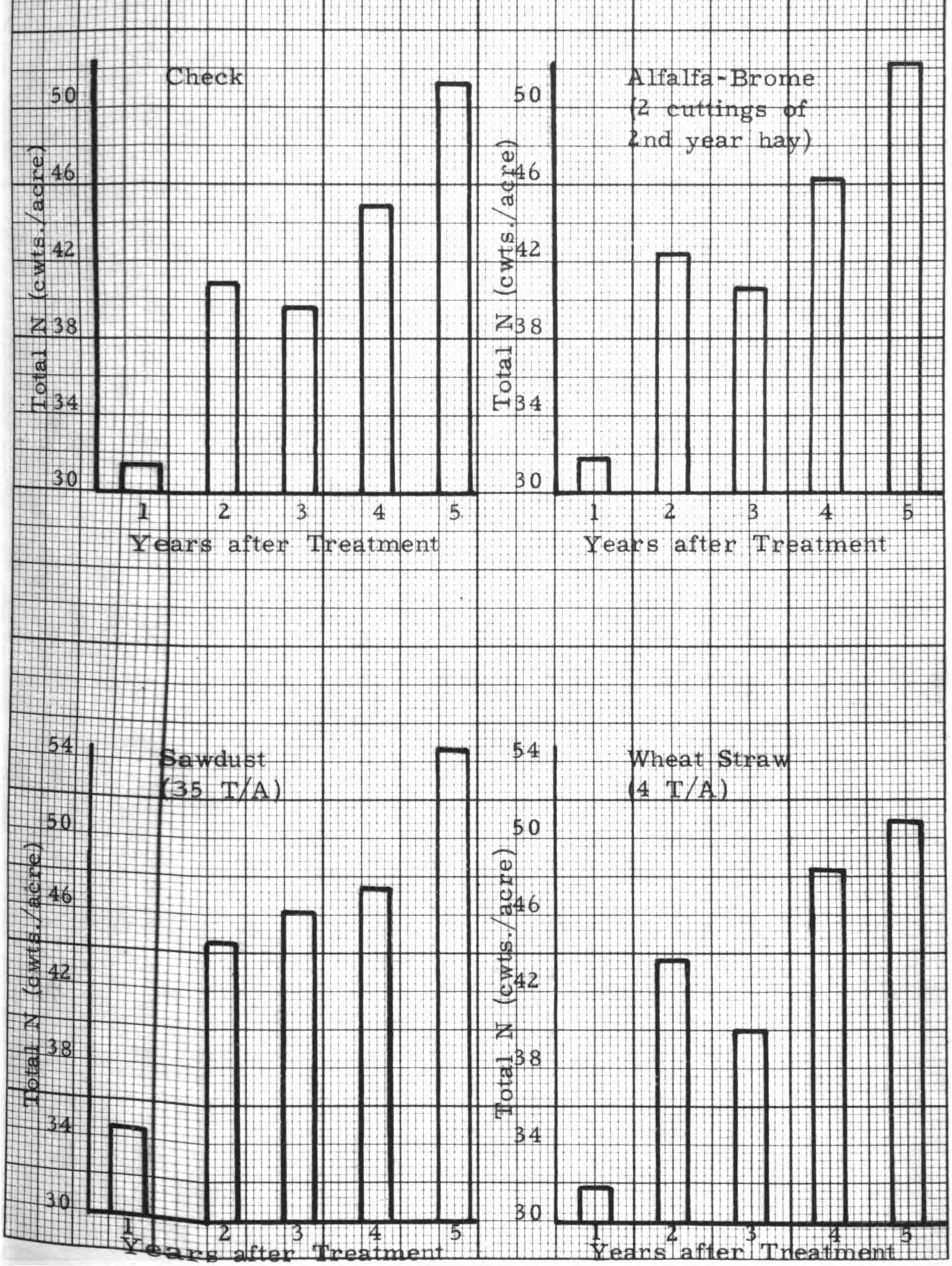
TABLE 2

NITRATE NITROGEN EXTRACTED WITH MORGAN'S SOLUTION FROM SIMS CLAY LOAM AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment				
	1	2	3	4	5
	NO_3-N (pounds per acre)				
Check	5	15	10	-	-
Check + N	10	20	80	-	-
Alfalfa	5	20	-	-	-
Alfalfa + N	10	55	-	-	-
Sawdust	5	10	-	-	-
Sawdust + N	10	11	-	-	-
Straw	11	20	-	-	-
Straw + N	38	16	-	-	-

Figure 1. Total nitrogen in Sims clay loam at yearly intervals after addition of various organic amendments.

FIGURE 1


Check
Total N (cwts./acre)
30
34
38
42
46
50
1
2
3
4
5
Years after Treatment
Alfalfa-Brome
(2 cuttings of
2nd year hay)
Total N (cwts./acre)
30
34
38
42
46
50
1
2
3
4
5
Years after Treatment
Sawdust
(35 T/A)
Total N (cwts./acre)
30
34
38
42
46
50
54
1
2
3
4
5
Years after Treatment
Wheat Straw
(4 T/A)
Total N (cwts./acre)
30
34
38
42
46
50
54
1
2
3
4
5
Years after Treatment

the 700 to 1,200 pounds increase the second year be explained in terms of fertilizer nitrogen applied or fixation of atmospheric nitrogen by the bean crop. Soil differences are most probably responsible for this variation in total nitrogen, although survey studies in 1955 showed that the soil covered by this experiment was uniform. Soil tests for ammonia nitrogen and reserve phosphorus indicated a marked difference in the soil in the block of plots established one year before soil samples were taken, as compared with the other four blocks (Table 7 [Appendix] and Table 1 [p. 32]).

The large increases of nitrogen in the fourth and fifth years correspond to similar increases in total carbon in the case of the check and the soils treated with alfalfa hay and straw. These increases could reasonably represent contributions from the alfalfa-brome grown during these years.

The use of supplemental nitrogen during the first three years resulted in both substantial increases and substantial decreases in total nitrogen with individual treatments during individual years (Table 9 [Appendix]). There was no apparent explanation for these anomalous fluctuations, so the effect of nitrogen was ignored in Figure 1.

Total carbon

The determinations for total carbon by wet combustion are recorded in Table 10 (Appendix). Figure 2 shows the trend of total carbon in pounds per acre for treatments and for years after treatment. There was little consistency in the effect of nitrogen treatment. Therefore, the values for plots with and without supplemental nitrogen were combined and only the averages for materials are shown in the histogram, as was done for total nitrogen in Figure 1. A relatively uniform amount of total carbon was found during the first year in the check, alfalfa, and straw treatments. The plots which received these three treatments showed a yearly decreasing trend in total carbon up to the third year. From then on there was an increase in carbon, reaching the maximum in the fifth year after treatment. The least accumulation in the fifth year among these treatments was found in the check and the maximum in plots to which the hay from the second-year alfalfa-brome had been returned to the soil as an organic amendment. The decline in carbon during the first three years with these treatments reflects the depletive nature of the crops grown (corn, beans, barley). The rapid increase during the fourth and fifth years appears to have been due to the alfalfa-brome grown during those years.

Figure 2. Total carbon in Sims clay loam at yearly intervals after addition of various organic amendments.

The sawdust treatment, which contained a relatively large amount of carbon (originally about 17 tons), provided the exception. The amount of total carbon was quite similar to the other treatments in the first year, but from then on up to the third year a substantial increase in total carbon resulted, decreasing in the fourth year and increasing again in the fifth. The low amount of carbon in the first year and the large increase of carbon in the third year may be explained either as the result of inadequate sampling technique or to incomplete determination of carbon. It is possible, however, that the wet-combustion technique failed to detect relatively unaltered lignin materials in the sawdust during early stages of decomposition. This point should be investigated further.

Soil C:N ratio

Although the effects of supplemental nitrogen on total nitrogen and total carbon, considered individually, appeared to be erratic, the effects on soil C:N ratios presented graphically in Figure 3 suggest that the differences observed may have been real and not the result of random errors in sampling or chemical determination. The original data are recorded in Table 11 (Appendix).

In Figure 3, plots which received no supplemental nitrogen are represented by a bar with a superscript "0"; those which

Figure 3. Soil C:N ratios in Sims clay loam at yearly intervals after addition of various organic amendments with and without supplemental nitrogen fertilizer.

received topdressed nitrogen on corn, beans, and barley during the first three years, by a superscript "N." In the check and in the sawdust-treated soil, the effect of nitrogen was inconsistent, sometimes narrowing and sometimes widening the C:N ratio. With the straw treatment, there was no effect of nitrogen the first or fourth years after addition, but during the second, third, and fifth years the C:N ratio was narrowed on the plots which received supplemental nitrogen during the first three years.

In contrast to these results are those on plots where alfalfa hay was the initial organic amendment. Here the yearly fluctuations in C:N ratio were unaffected by the supplemental nitrogen which was used on the first three crops in the rotation.

Theoretically, these results can be explained, in part, in terms of differential immobilization and mineralization of carbon and nitrogen as influenced by the chemical nature and the relative amounts of active carbon and nitrogen present in the soil or added in the form of fertilizers, organic amendments, or the residues from successive crops.

In the case of low-nitrogen materials such as straw or sawdust, extensive immobilization of soil and fertilizer nitrogen would be expected to accompany the early stages of decomposition. This would be followed by mineralization of previously immobilized

nitrogen as the more carbonaceous energy materials were dissipated. The proportion of nitrogen to carbon immobilized is profoundly influenced by the nature of the microbial population, as has been shown by Waksman (50). The predominant microbial population at any time is in turn greatly influenced by the specific origin of plant residues and their stage decomposition. Decomposition rate is further influenced by the proportion of available nitrogen to available energy sources. Thus, the dynamic alternation of immobilization and mineralization of nitrogen would be expected to follow a different chronological pattern where supplemental fertilizer nitrogen was used than where it was not. Reinforcement or interference with the cycle of immobilization and mineralization by the alternating succession of residues from leguminous and nonleguminous crops grown in the rotation would be expected to aggravate or minimize fluctuations in relative composition of organic materials left in the soil, depending on the degree of synchrony achieved. The inconsistent effects of nitrogen on soil C:N ratios observed in Figure 3 for low-nitrogen materials are at least understandable in this light, even if they can not be explained in detail from the data at hand.

By parallel reasoning, the lack of any apparent nitrogen effect on C:N ratios following the initial alfalfa hay treatment can be explained by considering that this high-nitrogen material did not set up any strong immobilizing impetus in the soil. Nitrogen mineralized during its decomposition was adequate to balance the immobilizing influence of the succeeding corn crop. The residues from the second-year bean crop performed a similar function during decomposition of residues from the succeeding barley. In this they were augmented by the presence of the growing alfalfa which was seeded with the barley. The internal nitrogen-carbon balance of the soil was thus poised by a preponderance of leguminous residues so that supplemental fertilizer nitrogen had no additional influence that could be detected.

The marked effects on the C:N ratios of time and cropping sequence remain to be explained. Any explanation at this time must be considered provisional until later annual samplings make it possible to differentiate between these effects and those due to soil variation. It can be pointed out that, in the check and in the plots treated with alfalfa-brome and wheat straw, the C:N ratio narrowed rapidly, reaching a minimum in the third year. Narrowing of soil C:N ratio is typical of the weathering of soil organic matter (46). The increased C:N ratios during the fourth and fifth years quite probably reflect the "soil-building" influence of the alfalfa-brome grown during those years.

Significantly, the narrowing of C:N ratio in the check plots was not as great where nitrogen was used and recovery occurred earlier (in the third year). Where wheat straw was added in the beginning, nitrogen had the reverse effect. This suggests that the rapid decomposition of the straw promoted more active weathering of soil humic materials. This is in accord with the reported ''priming'' action of fresh plant materials on the decomposition of soil organic matter (7, 23). A similar effect was observed with the sawdust during the second, fourth, and fifth years, when legumes were grown. The wider C:N ratio in the third year when barley was grown following supplemental nitrogen on the sawdust and check plots is an apparent discrepancy. However, the fact that no supplemental nitrogen was used in 1956 with barley may have influenced this result.

A further point to be noted in Figure 3 is the distinct tendency for all treatments to stabilize at a C:N ratio of about 9:1. Presumably this ratio represents the composition of soil organic matter characteristic for this soil, cropping program, and climatic situation. Ratios wider than this reflect the presence of a surplus of available energy materials. Ratios narrower than 9:1 represent stages of decomposition wherein the soil organic matter itself is the principle energy source and the influence of amendments or crop residues is at a minimum.

Mineralization of nitrogen

Nitrogen released as nitrate during a 14-day incubation period, using the Iowa incubation nitrification technique, is tabulated for treatments and years after treatment in Table 12 (Appendix).

Figure 4 shows the trends in incubation nitrification or mineralization rates as influenced by treatment, and by time or crop succession. Two principal effects are noted. The first of these is the marked suppression of nitrogen mineralization the first year in the presence of sawdust, due to the large excess of energy materials contributing to microbial immobilization. This initial suppression was enhanced by the supplemental nitrogen treatment. In samples from subsequent years, the release of nitrate-N increased uniformly year by year, and this recovery was more rapid where extra nitrogen was used.

The second striking result depicted in Figure 4 is the marked suppression of mineralization rate by nitrogen treatment during the first three years on the check plots. This was followed by a much more rapid recovery with nitrogen treatment in the fourth and fifth years. Similar effects of nitrogen are to be noted in the soil treated with alfalfa and straw, although the chronological sequence of suppression and stimulation was different.

Figure 4. Nitrifiable nitrogen released as nitrate during a 14-day incubation period in soil samples taken at yearly intervals after addition of various organic amendments with and without supplemental nitrogen fertilizer (Sims clay loam).

It should be emphasized that the supplemental nitrogen was applied during the first three years only. Stimulatory effects of nitrogen treatment during the fourth and fifth years were residual effects. Increased mineralization of nitrogen in these two years must be attributed to the presence of larger quantities of nitrogen immobilized during preceding periods of suppressed nitrate-producing capacity.

Alternate immobilization and mineralization of nitrogen is clearly apparent in the five-year period represented in Figure 4. The principal factors controlling this cyclic immobilization and mineralization appear to have been the relative proportions of nitrogen and energy carbon available to the soil population. Both the magnitude of the fluctuations in nitrifiability and their time sequence were strongly influenced by the amount of fertilizer nitrogen used, and by the amounts and plant origin of organic amendments and of residues from the crops grown in the rotation. The extent to which soil variation contributed to these results remains to be seen from data to be collected from these plots in future years.

Mineralization of carbon

The immobilization of nitrogen by microbial assimilation in the presence of plant materials low in nitrogen involves the respiratory loss of carbon as carbon dioxide from readily available energy sources, such as sugars, starches, and cellulose. The carbon retained in microbial cells and in the form of resistant or low-energy constituents of the original plant materials (lignin, resins, et cetera) may be considered to have been "immobilized" in the same sense as the nitrogen which these residual materials contain. The relative immobility or inactivity of both carbon and nitrogen in these residual combinations is a function of their availability to microbial attack.

Subsequent mineralization of "immobilized" nitrogen can not occur extensively without the concurrent mineralization or release of carbon as carbon dioxide. The rate of release of carbon dioxide and mineral nitrogen during incubation have both been used interchangeably as indexes of decomposability or availability of organic materials to microbial attack (6, 34). Since an excess of available energy materials promotes net assimilation of nitrogen by the decay organisms, the release of mineral nitrogen is not always a valid criterion of decomposability. Under normal conditions of aeration, however, carbon dioxide evolution is quite generally accepted as a valid index of microbial activity, hence of the availability of energy carbon in the nutritional environment of the microbial population (52).

In the present study, the evolution of carbon as carbon dioxide during a 14-day incubation period was used as a measure of decomposability of residual materials left in the soil. These data are recorded in Table 13 (Appendix) and are presented in graph form in Figure 5.

In the sawdust-treated soil, carbon dioxide was evolved at an extremely rapid rate one year after application. This coincides with the maximum suppression of nitrogen mineralization (Fig. 4). The supplemental nitrogen treatment greatly enhanced microbial activity (Fig. 5) and intensified the immobilization of nitrogen by microbial assimilation (Fig. 4).

From the fact that decomposition in the laboratory was more rapid in the nitrogen-treated soils, it may be inferred that this was also true the first two years in the field (Fig. 5). This more rapid dissipation of readily available energy materials in the presence of extra nitrogen is reflected in the more rapid recovery of the capacity for releasing nitrogen in subsequent years (Fig. 4). The dynamic mineralization and reutilization of nitrogen initially immobilized in microbial cells would have further contributed to the consistently higher nitrogen release with nitrogen treatment after the first year.

Figure 5. Carbon evolved as CO_2 during a 14-day incubation period from soil samples taken at yearly intervals after addition of various organic amendments with and without supplemental nitrogen fertilizer (Sims clay loam).

The most readily available energy materials in the sawdust were apparently largely dissipated by the end of the second year (Fig. 5), although the level of carbon dioxide production remained distinctly higher than with any other treatment through the fifth year. Differences in carbon dioxide production among other treatments were minor, which indicates a rather close similarity in availability to microbial attack of the products of advanced decomposition of different plant materials.

In this connection, increasing resistance to decomposition of sawdust residues was directly related to increasing nitrogen content, as is shown by the generally parallel decline of both carbon dioxide evolution and C:N ratio (Fig. 3). Moderate increases in carbon dioxide evolution the fourth and fifth years from check soils and from those treated with alfalfa and straw were also associated with increases in C:N ratio relative to the second and third years.

This emphasizes the very different role played by nitrogen in the decomposition of fresh plant materials from that which it plays in the decomposition of residual products of advanced decomposition, including soil humic materials. In the first case, the nitrogen content of fresh plant materials frequently limits the size of microbial population which can develop to attack the excess energy materials present. In the second case, the nature of the chemical bonds by which nitrogen is linked to carbon in the resistant residual compounds is one of the factors which limits the availability of the combined carbon as an energy source for microorganisms (6, 33, 51).

Relation of Laboratory Data to Crop Yields

The soil samples used in this study were taken in September, 1956. Crop yields for 1957 were not available at the time this report was written. Any attempt to relate the laboratory findings to previous yield history would have to be made on the assumption that the chemical differences found to be related to the different treatments in 1956 were similarly related in previous years. In the case of certain large differences, some such assumptions may be tentatively made at this time.

The yields for all crops since the experiment was begun in 1951 are presented in Table 3.

The strongly immobilizing effect of sawdust on nitrogen noted in Figure 4 has been reflected, in part, in the yields of corn, beans, and barley (Table 3). The nitrogen mineralization data show a large net release during the fourth year of nitrogen previously immobilized by sawdust. This has apparently been reflected in increased yields of first-year alfalfa-brome hay. A maximum release of nitrogen

TABLE 3

CROP YIELDS OVER A FIVE-YEAR PERIOD ON SIMS CLAY LOAM FOLLOWING THE ADDITION OF VARIOUS ORGANIC AMENDMENTS WITH AND WITHOUT SUPPLEMENTAL NITROGEN FERTILIZER[a]

Treatment	1952	1953	1954	1955	1956	Avg.	2d Yr. Hay 1956
			Corn (bushels per acre)				
Check	59.2	92.9	83.5	96.3	79.6	82.3	
Check + N	61.4	96.7	90.6	101.0	102.7	90.5	
Alfalfa	64.9	94.1	87.0	102.6	75.3	84.8	
Alfalfa + N . . .	64.8	98.0	93.6	101.1	84.1	88.3	
Sawdust	47.1	39.8	26.9	52.7	15.3	36.4	
Sawdust + N . . .	48.6	64.6	30.3	79.7	35.9	51.8	
Straw	61.2	87.6	82.2	101.0	71.2	80.6	
Straw + N	60.6	95.7	83.4	97.9	78.0	83.1	
			Beans (bushels per acre)				
Check		45.2	27.9	28.1	37.8	34.8	
Check + N		44.1	28.8	27.2	40.6	35.2	
Alfalfa		45.3	27.7	22.4	35.9	32.8	
Alfalfa + N . . .		42.9	30.1	26.0	41.1	35.0	
Sawdust		38.6	22.1	24.1	23.1	27.0	
Sawdust + N . . .		42.8	25.1	29.4	31.2	32.1	
Straw		44.2	28.5	25.4	36.4	33.6	
Straw + N		43.7	30.1	26.1	41.5	35.4	
			Barley (bushels per acre)				
Check			53.4	51.5	47.2	52.5	
Check + N			56.1	54.5	-	55.3	
Alfalfa			52.0	50.7	47.7	51.4	
Alfalfa + N . . .			54.7	55.5	-	55.1	
Sawdust			45.6	41.1	39.9	43.4	
Sawdust + N . . .			48.1	54.5	-	51.3	
Straw			51.7	54.5	48.1	53.1	
Straw + N			52.2	53.1	-	52.6	
			Alfalfa-Brome Hay (tons per acre)				
Check				2.26	3.53	2.89	4.54
Alfalfa				2.09	3.66	2.87	2.12[b]
Sawdust				2.36	3.67	3.01	4.40
Straw				2.08	3.59	2.83	4.53

[a]Unpublished data, presented by courtesy of J. R. Guttay, Michigan Agricultural Experiment Station, Department of Soil Science.

[b]First cutting only.

occurred in all samples from the fifth year. The release for all treatments was of approximately the same order of magnitude. This result is consistent with the uniformly high yields of second-year hay in 1956.

Corn, bean, and barley yields responded quite consistently to supplemental nitrogen. Presumably increased harvest yields were associated with increased production of top and root residues by these crops. The increased rate of return of crop residues where extra nitrogen was applied may well have promoted increased microbial assimilation of nitrogen. This would account in part for the marked immobilizing effect of nitrogen treatment observed during the first three years in the check plots in Figure 4. Similar effects of fertilizer nitrogen on nitrogen mineralization with organic amendments follow a different time pattern. These must be interpreted as reflecting the modulation by initial residue treatment of the cycles of immobilization and mineralization imposed by the sequence of crops in the rotation.

DISCUSSION

Insufficient data have been collected to date to permit an evaluation of the various methods used for estimating the nitrogen-supplying capacity of soils in terms of predictable relationships with crop yield. Some tentative estimation may be made, however.

Ammonia nitrogen is one of the intermediates in the mineralization of organic nitrogen, but its level in normal soils shows little tendency to fluctuate with treatments which drastically alter the availability of soil nitrogen to plants (Table 7). Although the level of nitrate nitrogen in the soil at any given time may reflect recent additions of fertilizer nitrogen (Table 2), or accumulations over periods when mineralized nitrogen is not being removed by leaching or crop removal, it has little bearing on the potential rate of release during the cropping season.

Nitrate released during standardized incubation, as in the Iowa nitrification procedure, did appear to reflect differences in nitrogen mineralization capacity which were significant to crop growth. However, this was true only when the principal factor controlling mineralization was the presence in the soil of a surplus of available energy materials in the form of low-nitrogen residues such as sawdust. Incubation nitrification rates failed to reflect the potential nitrogen-supplying capacity of residues high in nitrogen, such as alfalfa hay or alfalfa sod. (Compare corn yields in Table 3 with nitrifiable nitrogen in Figure 3.)

Another limitation is the marked effect of time and cropping sequence on the release of nitrogen during incubation (Figure 3). The point in the rotation where the soil is sampled may greatly alter the test and its significance in terms of crop response.

The time consumed by incubation procedures has led many people to favor strictly chemical measurements as a basis for guiding nitrogen fertilizer practices. Some thought has been given to procedures which may extract a labile fraction of soil nitrogen which may represent the portion more readily attacked by soil microorganisms. The concept has theoretical merit. However, the Truog permanganate procedure (47) failed to show any significantly large differences in these labile forms of nitrogen in the samples used in this study (Table 8). Obviously, the method can not evaluate the immobilizing influence of varying quantities of recently added crop residues. Accurate predictions based on measurement of relatively available forms of nitrogen can not be made without giving due allowance to this factor.

For the same reason, determinations of total carbon or total nitrogen considered individually can not be expected to reveal anything more than gross differences in organic matter content between rather widely different soils or cropping programs.

The ratio of carbon to nitrogen, on the other hand, may offer the possibility of evaluating the relative quantities of excess carbon present and its nitrogen-immobilizing potential. It also provides a criterion for characterizing soils where net depletion of soil organic matter is going on. (See discussion of Figure 3, pages 46-47.)

The use of total carbon or total nitrogen as a measure of quantity of organic matter, together with the C:N ratio as an index to its net immobilizing or mineralizing potential for nitrogen, offers possibilities. The nature of the relationships which may be found to exist between mineralizability of soil nitrogen, soil C:N ratio, and total nitrogen is suggested by the data plotted in Figure 6.

A generally inverse relationship between nitrifiable nitrogen and soil C:N ratios was found in samples from the sawdust-treated plots. No such relationship was found in samples following any of the other treatments. Therefore, only the points for sawdust have been identified by year and nitrogen treatment.

Total soil nitrogen in each sample is shown adjacent to each point. The inverse relationship between nitrifiable nitrogen and C:N

Figure 6. Nitrifiable nitrogen as related to soil C:N ratio and total soil nitrogen in Sims clay loam.

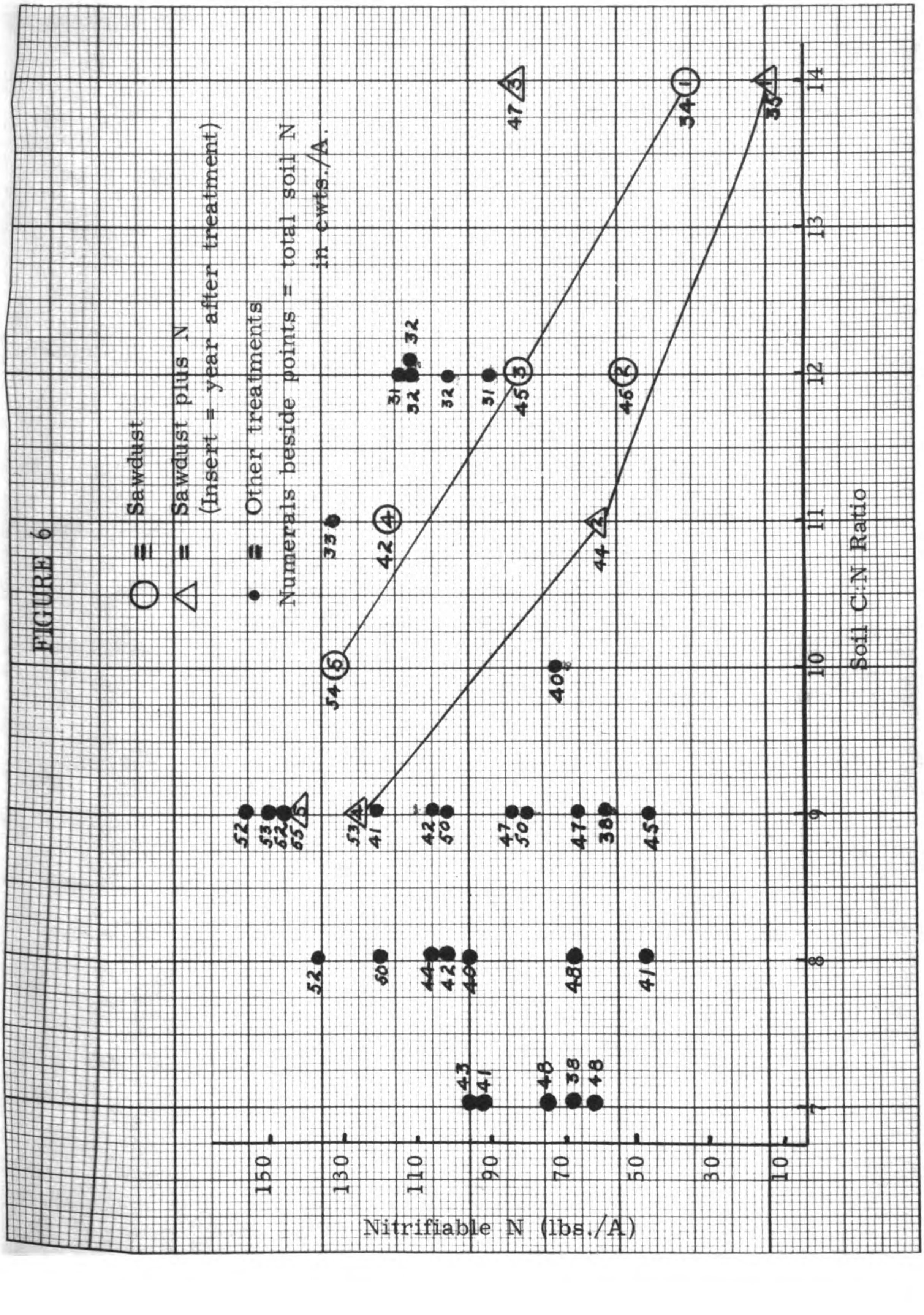

○ = Sawdust
△ = Sawdust plus N
(Insert = year after treatment)
● = Other treatments
Numerals beside points = total soil N
in cwts./A.
Nitrifiable N (lbs./A)
Soil C:N Ratio

FIGURE 6

ratio in the sawdust-treated soils was principally due to the increased nitrate production following an increase in total nitrogen. When lines were drawn through salient points representing sawdust with nitrogen and sawdust without nitrogen, it was found that most sawdust-treated samples gave values falling within this functional zone. The one large discrepancy was the third-year sample which had received extra nitrogen.

The general effects of nitrogen treatment with sawdust were to narrow the C:N ratio and to depress the release of nitrogen at any given C:N ratio. The two discrepancies from this general pattern are significantly related to the nature of residues supplied from the crop grown during the 1956 season just preceding the taking of the samples in September. The second-year samples reflect an additional suppressing effect of the nitrogen contained in leguminous residues from the bean crop on net mineralization of nitrogen in the soil. In the third-year samples, C:N ratio was widened by nitrogen treatment, presumably by reason of the increased production of carbonaceous straw and root residues by the barley crop where extra fertilizer nitrogen was used (cf. barley yields in Table 3). The fact that nitrifiability was not lowered accordingly is due to the predominating influence of the large quantities of residual products of sawdust decomposition in the soil.

If all points plotted in Figure 6 are now considered, without regard to treatment, a distinct tendency will be seen at C:N ratios of 11 and 12 for nitrate production to decline with increasing total nitrogen in the soil. At narrower C:N ratios of 8 to 10, the reverse is generally true: higher mineralization rates are associated with higher total nitrogen. Here again discrepancies exist which can be rationalized in terms of current crop effects or soil variation.

However, general principles appear to account for the general trends observed. As has been pointed out (pages 46-47), all treatments showed a tendency to stabilize at C:N ratios of about 9:1. Ratios higher than this would then reflect the presence of excess energy materials, ratios less than 9:1 would reflect the absence of significant quantities of relatively undecomposed plant materials in the soil.

It was further pointed out (page 56) that the amount of available nitrogen present during the decomposition of fresh plant materials frequently determines the size of the microbial population which can develop and the consequent rate of decomposition.

This point is graphically illustrated in Figure 7, where carbon evolved as carbon dioxide is plotted against soil C:N ratio. The points for sawdust treatment are again identified by year after

Figure 7. Microbial activity measured as CO_2 evolved in a 14-day incubation period, and its relation to soil C:N ratio and sawdust treatment in Sims clay loam.

addition and nitrogen treatment. A much more rapid decomposition of sawdust was maintained by supplemental nitrogen treatment through the second year than where no nitrogen was applied. The reason for the discrepancy of the third-year nitrogen-treated sawdust sample is here apparent in the wide C:N ratio attributable to soil variation and/or increased production of barley residues low in nitrogen. Apparently decomposition rate at this wide C:N ratio was limited by a shortage of nitrogen in forms available for microbial assimilation, even though total nitrogen was relatively high.

The extremely high level of microbial activity stimulated by nitrogen with sawdust treatment the first year resulted in greater suppression of nitrate release during incubation than where no extra nitrogen was used (cf. Figure 4). Obviously, the larger and more active microbial population stimulated by the addition of nitrogen in available form intensified the assimilative immobilization of all forms of nitrogen in the soil.

This more intense microbial immobilization of nitrogen at higher levels of microbial activity was not expressed the second year, even though the carbon dioxide evolved from sawdust with supplemental nitrogen was still considerably higher than with sawdust without supplemental nitrogen. The reason for this can be deduced from the data plotted in Figure 8.

Figure 8. The ratio of mineralization of carbon to the mineralization of nitrogen as related to soil C:N ratio and sawdust treatment in Sims clay loam.

In Figure 8 the ratio of release of carbon as carbon dioxide to release of nitrogen as nitrate during a 14-day incubation period is plotted against the C:N ratio of the soil. The points for sawdust are again identified. The extremely divergent mineralization ratios for sawdust with and without nitrogen the first year reflects the dominance of carbonaceous materials in the energy substrates which were being attacked by decay organisms at this time. The sharply narrowing ratios of carbon to nitrogen released in subsequent years reflect an increasing dependence for energy on compounds containing both carbon and nitrogen. The greater microbial activity the second year in sawdust plots with additional nitrogen reflects the greater availability of previously immobilized proteinaceous residues from the declining microbial population than of the resistant soil materials which were being relied on for nitrogen by the organisms which were attacking the unamended sawdust.

Carbonaceous substrates supplied in the sawdust were dissipated much more rapidly in the presence of extra nitrogen. This is shown by the extremely rapid narrowing of the mineralization ratio, as well as by the more rapid narrowing of the soil C:N ratio. Significantly, the mineralization ratio had declined by the third year to the same value as the ratio of carbon to nitrogen in the soil itself.

With all other treatments, the mineralization ratios also tended to closely approximate the C:N ratio of the soil.

The fact that it was possible to detect these large differences in microbial activity and in the ratio of mineralization of carbon to nitrogen by samples representing yearly time intervals was due to the extremely large quantities of sawdust added and its relatively great resistance to microbial attack. Similar sequences of intensified microbial assimilation followed by rapidly narrowing mineralization ratio would have attended the addition of the other amendments and of residues from the successive crops. However, because of their greater decomposability and the much lower quantities used, the changes observed here in the pattern of sawdust decomposition over a five-year period would have been completed more quickly, probably within periods of three months to a year, depending on the material itself, the availability of nitrogen, and environmental factors such as moisture, aeration, tillage, and temperature (14, 15).

The transient nature of the residual effects of organic matter addition is well illustrated by the rapidity with which residues from all materials approached a common level of decomposability in the soil (Figure 7) and a similar pattern of decomposition as reflected in their tendency to release carbon and nitrogen in the same ratio as they occur in the organic substrates remaining in the soil for microbial attack (Figure 8). From the relationships observed in Figure 6 between nitrifiability of nitrogen, total soil nitrogen, and C:N ratio, it would appear that a fair degree of correlation between nitrogen availability and total nitrogen might be expected in soils where a characteristic ratio of carbon to nitrogen had been established (in this case 9:1). However, in soils where recent management practices had resulted in soil C:N ratios wider than this, no such correlation could be expected. The validity of any test for nitrogen-supplying power of soils depends, therefore, on the accuracy with which it can reflect the immobilizing potential of excess energy materials resulting from recent additions of organic residues.

The value of the Iowa incubation test for nitrifiable nitrogen apparently lies in its ability to reflect differences in immobilizing potential of excess energy materials in the soil. Its failure to reveal differences in mineralizing potential of high-nitrogen residues is most probably due to the fact that the length of the incubation period is too short.

Determinations of total carbon and nitrogen in the soil are suggested for further study as a basis for predicting nitrogen requirements of crops.

CONCLUSIONS

The following conclusions are tentatively deduced from the data that have been presented. They are consistent with concepts that appear in the extensive literature on nitrogen transformations in soils and organic composts. Their significance in the development of reliable schemes for predicting crop response from chemical and biological soil tests can only be established by further studies conducted with a view to substantiating or revising the general principles outlined.

1. The depression of incubation mineralization rate in soil samples taken after recent additions of plant materials low in nitrogen is due principally to its immobilization in the form of microbial cells. The extent of this immobilization is a function of the size and activity of the microbial population. This was shown by the fact that the initial depressing effect of carbonaceous residues was actually intensified by the addition of supplemental fertilizer nitrogen.

2. The suppression of nitrogen mineralization by carbonaceous amendments or crop residues is transient. The effective period of suppression was found to be influenced by the quantity and specific

origin of the plant materials themselves, as well as by the rotational sequence of leguminous and nonleguminous crops, and by the level of nitrogen fertilization.

3. Although an increased level of nitrogen fertilization intensified the initial microbial immobilization of nitrogen, it also markedly reduced the period of time during which nitrogen mineralization was depressed by fresh additions of plant materials low in nitrogen.

4. As microbial activity declined, the residual availability of the nitrogen previously immobilized in microbial proteins was apparently high. This was shown by the large recovery of nitrifiable nitrogen in samples taken during the later years of the Michigan rotation at the Ferden farm, following strong suppression during the early years in the presence of low-nitrogen amendments and carbonaceous residues from crops such as corn and barley. It was further revealed in the relatively high capacity for concurrent mineralization of both carbon and nitrogen displayed by sawdust with supplemental nitrogen at intermediate stages of decomposition.

5. The residual high availability of proteinaceous nitrogen previously immobilized in microbial tissues also appeared to be transient and was associated with periods of rapidly declining microbial activity.

6. With all materials there was a rapid narrowing of soil C:N ratio during decomposition. Soils from all plots, regardless of treatment, tended to approach a ratio of 9:1 of carbon to nitrogen in the soil at the end of the five-year period.

7. The residues from all treatments at low C:N ratios were characterized by being about equally resistant to microbial attack and by the fact that carbon and nitrogen were mineralized in about the same ratio as they were contained in the soil organic materials which were undergoing decomposition.

8. In consequence of item 7 above, there was a distinct tendency for nitrogen to be mineralized at low C:N ratios in quantities directly proportional to the total nitrogen present in the soil.

9. In consequence of item 1 above, nitrogen mineralized at higher C:N ratios tended to be inversely proportional to the total nitrogen present in the soil.

10. It is proposed that the determination of both total carbon and total nitrogen in soils may offer the following advantages as a basis for estimating crop response to nitrogen: (a) The establishment of characteristic C:N ratios for specific soils and cropping programs in a given climatic region may permit the identification of situations where a direct proportionality coefficient may apply between total soil nitrogen and crop yields or crop response to

fertilizer nitrogen. (b) Where C:N ratios wider than the ratio characteristic for the soil and cropping program are found, microbial immobilization of nitrogen may be expected to be a dominant factor in availability. It is possible that the intensity of this immobilization potential may be estimated from the C:N ratio and a knowledge of the immediately preceding cropping history.

11. With reference to item 10, the relative significance of wet- and dry-combustion procedures for determining total carbon needs to be investigated.

LIST OF REFERENCES

1. Allison, P. L., and L. D. Sterling. Nitrate formation from soil organic matter in relation to total nitrogen and cropping practices. Soil Sci. 67:239-252, 1949.

2. Balwing, I. L., W. E. Walters, and F. K. Smith. Fertilizer treatments as affecting nitrate production. Proc. Indiana Acad. of Sci. 295-309, 1921.

3. Barnes, T. W. The behaviour of nitrogenous materials buried in the soil. Jour. Agr. Sci. 40:191-197, 1950.

4. Bhaumick, H. D., and F. Clark. Soil moisture tension and microbiological activity. Soil Sci. Soc. Amer. Proc. 12: 234-238, 1947.

5. Bouyoucos, G. J. A comparison between the suction method and the centrifuge method for determining moisture equivalent of soils. Soil Sci. 40:165-171, 1935.

6. Bremner, J. M., and K. Shaw. The mineralization of some nitrogenous materials in soil. Jour. Sci. Food Agr. 8: 341-347, 1957.

7. Broadbent, F. E. Nitrogen release and carbon loss from soil organic matter during decomposition of added plant residues. Soil Sci. Soc. Amer. Proc. 12:246-249, 1947.

8. Brown, P. E., and N. R. Gawda. The effect of certain fertilizers on nitrification. Jour. Amer. Soc. Agron. 16:137-146, 1924.

9. Burgess, P. S. Can we predict probable fertility from soil biological data? Soil Sci. 6:449-462, 1918.

10. Carpenter, R. W., H. J. Haas, and E. F. Miles. Nitrogen uptake by wheat in relation to nitrogen content of soil. Agron. Jour. 44:420-423, 1952.

11. Chase, F. E. A preliminary report on the use of the Lees and Quastel soil perfusion technique in determining the nitrifying capacity of field soils. Sci. Agr. 28:315-320, 1948.

12. Cornfield, A. H. The mineralization of nitrogen in a soil acidified with sulfur, aluminum sulphate and ferrous sulphate. Jour. Sci. Food Agr. 4:298-301, 1953.

13. Cutler, D. W., L. M. Crump, and H. Sadan. Quantitative investigation of bacterial and protozoan population of soil with an account of the protozoan fauna. Roy. Soc. Phil. Trans. (London) 211B:317-350, 1922.

14. Fathi, O. M., and W. V. Bartholomew. Influence of oxygen concentration in soil air on nitrification. Soil Sci. 71:215-219, 1951.

15. Fitts, J. W., W. V. Bartholomew, and H. Heidel. Predicting nitrogen fertilizer needs of Iowa soils: evaluation and control of factors in nitrate production and analysis. Soil Sci. Soc. Amer. Proc. 19:69-73, 1955.

16. Fraps, G. S. Relation of soil nitrogen, nitrification and ammonification to pot experiments. Texas Agr. Exp. Sta. Bul. 283: 1-51, 1921.

17. Fraps, G. S., and A. J. Sterges. Effect of phosphates on nitrifying capacity of soils. Soil Sci. 47:115-121, 1939.

18. Fraps, G. S., and A. J. Sterges. Nitrification capacities of Texas soil types and factors which affect nitrification. Texas Agr. Exp. Sta. Bul. 693, 1947.

19. Frederic, L. R. Formation of nitrate from ammonium nitrogen in soils: effect of population of nitrifiers. Soil Sci. 83: 481-485, 1957.

20. Gainey, P. L. The significance of nitrification as a factor in soil fertility. Soil Sci. 3:399-415, 1917.

21. Gainey, P. L. Total nitrogen as a factor influencing nitrate accumulation in soils. Soil Sci. 42:157-163, 1936.

22. Gainey, P. L., M. C. Sewell, and H. C. Myers. Nitrogen. The major cause in the production of spotted wheat fields. Kansas Agr. Exp. Sta. Bul. 43:1-58, 1937.

23. Goring, C. A., and F. Clark. Influence of crop growth on mineralization of nitrogen in the soil. Soil Sci. Soc. Amer. Proc. 13:261-267, 1948.

24. Greaves, J. E., and E. G. Carter. Influence of moisture on the bacterial activity of the soil. Soil Sci. 10:361-387, 1920.

25. Greaves, J. E., and L. J. Jones. The influence of temperature on the microflora of the soil. Soil Sci. 58:377-387, 1944.

26. Hallam, M. J., W. V. Bartholomew. Influence of rate of plant residue addition in accelerating the decomposition of soil organic matter. Soil Sci. Soc. Amer. Proc. 17:365-368, 1953.

27. Halvorson, A. R., and A. C. Caldwell. Factors affecting the nitrate producing power of some Minnesota soils. Soil Sci. Soc. Amer. Proc. 13:258-260, 1948.

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

29. Harmsen, G. W., and D. A. Van Schreven. Advances in agronomy. Vol. VII. Edited by A. G. Norman. Academic Press, Inc. Pp. 299-398, 1955.

30. Hwang, Y., and M. Frank. Mikrobiologische und biochemische Untersuchungen über das Auftreten von zwei Maxima der Ammoniakanhäufung in Boden. Arch. Microbiol. 9:469-476, 1938. (Cited by Harmsen, G. W., and D. A. Van Schreven Adv. in Agron. 7:344, 1955.)

31. Lipman, C. B., and P. S. Burgess. Ammonifiability versus nitrifiability as a test for the relative availability of nitrogenous fertilizers. Soil Sci. 3:63-75, 1917.

32. Marchal, E. The production of ammonia in the soil by microbes. Acad. Roy. Belge, Bul. Ser. 3,25:727-771, 1893. (Cited by Harmsen, G. W., and D. A. Van Schreven, Adv. in Agron. 7:299, 1955.)

33. Mattson, S., and E. Kouttler-Andersson. Ammonia fixation and humus nitrogen. (The acid base condition in vegetation, litter and humus.) Annals Agr. College of Sweden 11:107-134, 1943.

34. Norman, A. G., and A. S. Newman. Some effects of sheet erosion on soil microbial activity. Soil Sci. 52:31-46, 1941.

35. Owen, O., and G. W. Winsor. The nitrogen status of soils. II. The effect of levels of application on nitrification of some nitrogenous fertilizers. Jour. Agr. Sci. 40:191-197, 1950.

36. Panganiban, E. H. Temperature as a factor in nitrogen changes in the soil. Jour. Amer. Soc. Agron. 17:1-31, 1925.

37. Peech, M., and L. English. Rapid microchemical soil tests. Soil Sci. 57:167-196, 1944.

38. Pinck, L. A., and F. E. Allison. Maintenance of soil organic matter: III. Influence of green manures on the release of native soil carbon. Soil Sci. 71:67-75, 1951.

39. Plummer, J. K. Some effects of oxygen and CO_2 on nitrification and ammonification. N.Y. (Cornell) Agr. Exp. Sta. Bul. 384: 305-330, 1916.

40. Prince, A. L. Methods in soil analysis. Chemistry of the soil. Edited by Bear, F. E. ACS Mon. No. 126:328-362, 1955.

41. Rubins, E. J., and F. E. Bear. C/N ratio of organic fertilizer materials in relation to the availability of their nitrogen. Soil. Sci. 54:411-423, 1942.

42. Schloesing, T., and A. Muntz. Sur la nitrification per les ferments organises. C.R. Acad. Sci. Paris 84:301, 1877. (Cited by Meiklejohn, J., Jour. Soil Sci. 4:59-68, 1953.)

43. Spurway, C. H., and K. Lawton. Soil testing. Mich. Agr. Exp. Sta. Tech. Bul. 132, 1949.

44. Stanford, G., and J. Hanway. Predicting nitrogen fertilizer needs of Iowa soils: a simplified technique for determining relative nitrate production in soils. Soil Sci. Soc. Amer. Proc. 19:74-77, 1955.

45. Theron, J. J. The influence of plants on the mineralization of nitrogen and the maintenance of organic matter in the soil. Jour. Agr. Sci. 41:289-296, 1951.

46. Thompson, L. M., and C. A. Black. The mineralization of organic phosphorus, nitrogen and carbon in Clarion and Webster soils. Soil Sci. Soc. Amer. Proc. 14:147-151, 1950.

47. Truog, E. Technical Information Directions No. 697-18 for the Hellige-Truog Combination Soil Tester. Hellige, Inc., N.Y.

48. Turk, L. M., and C. E. Millar. The effects of different plants, materials, lime and fertilizers on the accumulation of soil organic matter. Jour. Amer. Soc. Agron. 28:310-324, 1936.

49. Waksman, S. A. Bacterial numbers at different depths and in different seasons of the year. Soil Sci. 1:363-380, 1916.

50. Waksman, S. A. Soil Microbiology. John Wiley and Sons, Inc. Pp. 61-66, 1952.

51. Waksman, S., and K. Iyer. Fixation of proteins by lignins and formation of complexes resistant to microbial decomposition. Soil Sci. 36:69-82, 1933.

52. Waksman, S. A., and R. L. Starkey. Soil and the Microbe. John Wiley and Sons, Inc. Pp. 94-99, 1949.

53. Warington, R. On nitrification. Jour. Chem. Soc. 33:44-51, 1877.

54. Warington, R. On nitrification. Jour. Chem. Soc. 59:484-529, 1891.

55. White, J. W., F. J. Holben, C. D. Jeffries, and A. C. Richer. Correlation of microbiological and chemical soil data with crop yields of the Jordan soil fertility plots. Soil Sci. 67:279-285, 1949.

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

APPENDIX

TABLE 4

WATER-HOLDING CAPACITY OF SIMS CLAY LOAM AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE--BOUYOUCOS SUCTION METHOD

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
	Per Cent Moisture (oven-dry basis)[a]					
Check	36	42	42	33	42	39
Check + N	36	41	45	43	49	42
Alfalfa	29	43	40	43	36	38
Alfalfa + N	38	46	41	32	44	40
Sawdust	43	34	48	41	44	42
Sawdust + N	44	47	44	38	39	42
Straw	47	39	40	35	46	42
Straw + N	41	42	43	40	37	41
Average for no N	39	40	43	38	42	40
Average for + N	40	44	43	38	42	42
Average for years	39	42	43	38	42	41

[a]Average of duplicate determinations.

TABLE 5

SOIL REACTION OF SIMS CLAY LOAM AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE--SOIL pH BY GLASS ELECTRODE USING 1:1 SOIL-TO-WATER RATIO

Treatment	Years after Treatment				
	1	2	3	4	5
	Soil pH				
Check	6.3	6.9	6.8	6.7	6.6
Check + N	6.2	6.9	6.8	6.7	6.7
Alfalfa	6.3	6.9	6.9	6.7	6.6
Alfalfa + N	6.3	6.8	6.7	6.7	6.6
Sawdust	6.3	6.8	6.7	6.7	6.5
Sawdust + N	6.3	6.9	6.7	6.7	6.6
Straw	6.3	6.8	6.8	6.6	6.6
Straw + N	6.2	6.9	6.8	6.8	6.7

TABLE 6

"ACTIVE" PHOSPHORUS, SOLUBLE IN 0.018 ACETIC ACID, AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE IN SIMS CLAY LOAM

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
	Phosphorus (pounds per acre)[a]					
Check	7.2	8.0	6.4	6.4	8.0	7.2
Check + N	8.4	7.2	6.4	6.4	8.0	7.3
Alfalfa	7.2	8.0	7.2	8.0	8.0	7.7
Alfalfa + N	7.6	7.2	6.4	7.2	9.6	7.6
Sawdust	7.2	8.0	9.6	6.4	8.0	7.8
Sawdust + N	6.4	7.2	7.2	9.6	7.2	7.5
Straw	8.0	7.2	8.0	9.6	8.0	8.2
Straw + N	7.2	8.0	6.4	8.0	8.0	7.5
Average for no N	7.4	7.8	7.8	7.6	8.0	7.7
Average for + N	7.4	7.4	6.6	7.8	8.2	7.5
Average for years	7.4	7.6	7.2	7.7	8.1	7.6

[a]Average of duplicate determinations.

TABLE 7

AMMONIA EXTRACTED WITH MORGAN'S SOLUTION FROM SIMS CLAY LOAM, AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
	NH_3-N (pounds per acre)[a]					
Check	15	32	32	22	26	25
Check + N	18	28	26	30	24	25
Alfalfa	14	25	30	23	29	24
Alfalfa + N	14	24	26	34	31	26
Sawdust	17	33	33	35	33	30
Sawdust + N	18	30	33	33	33	29
Straw	18	26	30	35	29	27
Straw + N	20	26	28	24	28	25
Average for no N	16	29	31	29	29	27
Average for + N	18	27	28	30	29	26
Average for years	17	28	30	29	29	26

[a]Average of duplicate determinations.

TABLE 8

PERMANGANATE-SOLUBLE NITROGEN IN SIMS CLAY LOAM, AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment 1	2	3	4	5	Avg.
	Permanganate-soluble N (pounds per acre)[a]					
Check	150	75	150	150	150	135
Check + N	213	150	150	150	150	163
Alfalfa	150	200	150	75	75	130
Alfalfa + N	150	150	150	150	150	150
Sawdust	175	150	75	75	150	125
Sawdust + N	150	150	150	150	150	150
Straw	150	75	75	150	150	120
Straw + N	150	113	150	150	150	143
Average for no N	156	125	113	113	131	128
Average for + N	166	141	150	150	150	151
Average for years	161	133	131	131	141	139

[a]Average of duplicate determinations.

TABLE 9

TOTAL NITROGEN (KJELDAHL) IN SIMS CLAY LOAM, AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment 1	2	3	4	5	Avg.
	Total N (pounds per acre)[a]					
Check	3304	4076	4043	4781	5018	4244
Check + N	3069	4087	3873	4200	5218	4089
Alfalfa	3172	4341	4317	4512	5144	4297
Alfalfa + N	3201	4152	3818	4749	5321	4248
Sawdust	3406	4500	4532	4182	5405	4405
Sawdust + N	3502	4422	4684	5278	5489	4675
Straw	3228	3990	3950	4691	4959	4164
Straw + N	3126	4751	4066	4996	5208	4429
Average for no N	3278	4227	4211	4542	5132	4278
Average for + N	3225	4353	4110	4806	5309	4361
Average for years	3252	4290	4161	4674	5221	4320

[a]Average of duplicate determinations.

TABLE 10

TOTAL CARBON BY WET COMBUSTION IN SIMS CLAY LOAM, AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
	Total Carbon (pounds per acre)[a]					
Check	37700	35500	28900	40300	37900	36060
Check + N	36900	34400	34500	35900	44900	37320
Alfalfa	37700	33100	31900	39000	47200	37780
Alfalfa + N . . .	39800	34100	28100	43100	48200	38660
Sawdust	47100	55300	55100	46700	53100	51460
Sawdust + N . . .	47400	46800	64100	49900	49400	51520
Straw	37300	38200	32200	40000	45700	38680
Straw + N	37800	31800	29600	45600	39200	36800
Average for no N	39950	40525	37025	41500	45975	40995
Average for + N	40475	36775	39075	43625	45425	41075
Average for years	40213	38650	38050	42563	45700	41035

[a]Average of duplicate determinations.

TABLE 11

C:N RATIO OF SIMS CLAY LOAM AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
	Soil C:N Ratio					
Check	11	9	7	8	8	9
Check + N	12	8	9	9	9	9
Alfalfa	12	8	7	9	9	9
Alfalfa + N	12	8	7	9	9	9
Sawdust	14	12	12	11	10	12
Sawdust + N	14	11	14	9	9	11
Straw	12	10	8	9	9	9
Straw + N	12	7	7	9	8	9
Average for no N	12	10	8	9	9	10
Average for + N	13	8	9	9	9	10
Average for years	12	9	9	9	9	10

TABLE 12

PRODUCTION OF NITRATE NITROGEN DURING A 14-DAY INCUBATION PERIOD, AS AFFECTED BY ORGANIC AMENDMENTS, FERTILIZER NITROGEN, TIME, AND CROPPING SEQUENCE

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
Nitrifiable Nitrogen as NO_3-N (pounds per acre)[a]						
Check	132	122	93	68	120	107
Check + N	114	48	59	101	147	93
Alfalfa	111	107	93	47	156	103
Alfalfa + N	111	105	68	66	152	100
Sawdust	36	53	81	117	131	83
Sawdust + N	14	60	84	125	144	110
Straw	101	72	96	84	102	91
Straw + N	90	75	62	81	137	89
Average for no N	95	88	91	79	127	96
Average for + N	82	72	68	93	145	92
Average for years	89	80	79	86	136	94

[a] Average of duplicate determinations.

TABLE 13

CARBON EVOLVED AS CARBON DIOXIDE DURING A 14-DAY INCUBATION PERIOD FROM SIMS CLAY LOAM, AS AFFECTED BY THE PREVIOUS HISTORY OF ORGANIC AMENDMENTS, NITROGEN FERTILIZATION, AND CROPPING SEQUENCE

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
Carbon Dioxide Evolution (pounds of carbon per acre)[a]						
Check	679	458	384	685	757	592
Check + N	718	453	594	567	704	607
Alfalfa	433	451	496	674	718	554
Alfalfa + N	542	568	494	722	774	620
Sawdust	2834	1128	1026	937	889	1363
Sawdust + N	4360	1942	1013	1130	799	1849
Straw	552	541	583	658	643	595
Straw + N	544	449	534	722	622	574
Average for no N	1225	645	622	739	752	797
Average for + N	1541	853	659	785	725	913
Average for years	1333	749	641	762	738	845

[a]Average of duplicate determinations.

TABLE 14

RATIO OF CARBON TO NITROGEN MINERALIZED DURING A 14-DAY INCUBATION PERIOD IN SIMS CLAY LOAM, AS AFFECTED BY PREVIOUS HISTORY OF ORGANIC AMENDMENTS, NITROGEN FERTILIZATION, AND CROPPING SEQUENCE

Treatment	Years after Treatment					Avg.
	1	2	3	4	5	
C:N Mineralized in 14 Days						
Check	5	4	4	10	6	6
Check + N	6	9	10	6	5	7
Alfalfa	4	4	5	14	5	7
Alfalfa + N	5	5	7	11	5	7
Sawdust	79	21	13	8	7	26
Sawdust + N	323	32	12	9	6	76
Straw	5	8	6	8	6	7
Straw + N	6	6	9	9	5	7
Average for no N	23	9	7	10	6	11
Average for + N	85	13	10	9	5	24
Average for years	54	11	8	9	6	18

Date Due
