Reactions of Nitrogenous Fertilizers in Calcareous Soils

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The influence of the environmental factors peculiar to arid and semiarid calcareous soils on the reactions and movement of nitrogenous fertilizers is reviewed. The movement of ammonium nitrogen in soil is dependent on the nature of the ammonium source, the cation exchange capacity, the kind of cations on the exchange complex, and the rate of nitrification. Volatilization of ammonia is markedly influenced by placement. Loss from surface-applied NH_4 increases as the pH increases above neutral. Nitrates form readily in calcareous soils up to pH 9.0 if NH_4 concentration is favorable and the pO_2 is not limiting. Nitrite will accumulate at almost any pH value above neutral, depending upon the concentration of NH_4 as it interacts with pH levels. Gaseous loss of nitrogen from nitrite and nitrate salts occurs as oxides of nitrogen, nitrogen gas by chemical reaction, and nitrogen gas by bacterial denitrification. All nitrogen fertilizer sources do not nitrify at the same rate in calcareous soils and do not react alike from a standpoint of availability to plants.

CALCAREOUS SOILS are characteristically located in arid and semiarid climatic zones. About 25% of the earth's land surface is arid, and 30% is semiarid. Calcareous soils contain calcium carbonate throughout the plant-root zone in quantities ranging from a trace to over 50% by weight. The cation-exchange positions are almost wholly saturated with calcium ions. Interspersed with calcareous soils are found sodic and potassic soils of relatively high pH values. Accumulations of soluble salts of various cation and anion combinations also occur in arid and semiarid regions where calcareous soils predominate. Some of these salts are sufficiently abundant to affect adversely nitrogen transformations as well as absorption of nitrogen by plants.

Arid and semiarid lands are characterized by low levels of organic matter and consequently low nitrogen reserves since the soil organic matter is the nitrogen carrier. Vegatation is sparse and moisture is limiting. Downward leaching of nitrogen is at a minimum compared with that of humid regions. Summer temperatures usually are hot; winter temperatures may be either cold as in the higher plateaus and inlands or mild as in basins of southwest United States and coastal areas. All of these environmental factors influence the reactions and movement of nitrogenous fertilizers in calcareous soils.

Reactions of Ammonia and Ammonium Fertilizers

Although inorganic nitrogen salts have been used as fertilizers for more than 120 years, the technical production of an inexpensive nitrogen source is a recent development. The demand for greater use of nitrogen for maximum economic crop production also has only recently been demonstrated experimentally. New high-concentration nitrogen sources such as urea and anhydrous and aqueous ammonia are used widely. Rates of application not only are high, but increased use of band and injection placement, compared with broadcast, concentrates the fertilizer in a small zone of the soil.

Residual Effect. All changes involving the biological use of ammonia end with an acid residual effect. When an anion is associated with the ammonia nitrogen, the residual effect will be different from that if the urea, anhydrous or aqueous form, is used. Ammonium sulfate and nitrate are salts of strong acids. Urea, on the other hand, hydrolyzes to ammonium carbonate which is a salt of a weak acid. Ammonium carbonate decomposes to form ammonia. Although urea initially acts as a nonpolar substance, it often is transformed so rapidly in soils of agricultural value that it may be considered almost as ammonia (9, 17, 18) from a practical standpoint.

It still remains to be proved that long-time residual effect on the physical properties of calcareous soils, by continued use of the ammonium ion, is different as compared with that of the nitrate ion. Martin and Richards (26) and Pratt et al. (32) report that in soils which were very poorly buffered and contained only traces of lime and where long-time use of $(NH_4)_2SO_4$ reduced the pH to a strongly acid condition (pH 4), the ammonium ion was oxidized only very slowly to nitrate. The persistence of the ammonium ions on the soil exchange complex reduced the rate of water infiltration and encouraged soil aggregate deterioration (27). Such soils, however, are not typical of calcareous soils as originally defined in this article.

Rarely is it possible to change appreciably the pH value of the root zone of calcareous soils by continued long-time use of ammonium fertilizers to the extent that biological nitrification is inhibited by strongly acid conditions.

A high amount of exchangeable NH_4, concentrated on a thin layer of the surface soil after heavy applications of certain ammonium fertilizers, has been suggested as temporarily reducing water infiltration rate in some calcareous soils. Evidence that this is of practical significance for crop production under field conditions is lacking. In general, the ammonium ion does not remain unchanged long in calcareous soils.

Distribution in Soils. Ammonium seldom is distributed uniformly throughout the soil from the viewpoint of the nitrifying organism, regardless of the method of application. Both ammonium and ammonia are absorbed readily by the soil. Thus, the soil organisms are confronted with a concentration gradient. The distribution about the maximum depends upon kind of fertilizer applied, method of placement, soil texture, and soil moisture. Aqua ammonia and ammonia gas form a more diffuse pattern than ammonium sulfate when banded in a calcareous alkaline sandy soil according to Lorenz et al. (24). More upward movement was observed with the former two forms than with ammonium sulfate.

Rate of Nitrification. Most calcareous soils have nitrifying flora with a great capacity to convert large quantities of ammonium nitrogen to nitrate in a relatively short time. Two calcareous soils, Salinas clay and Imperial clay, for example, exhibited conversion rates above 40 p.p.m. per day, according to Broadbent et al. (11). Conversion rates higher than this presumably have not

been recorded. The pH values of the two soils range from 8.0 to 8.1.

Band placement of ammonia fertilizers poses a different environment for nitrification than broadcast. At the edge of the band where ammonium concentrations are low, nitrification occurs rapidly and completely. The environment in this area more closely resembles that of broadcast placement than any other area. Near the center of the band where higher concentrations occur, nitrification is inhibited if the soil is poorly buffered. Where aqueous and anhydrous ammonia are added to a sandy soil, the tendency to produce a high pH value is partly compensated for by greater diffusion. Where inhibition of nitrification takes place, it may be caused by one or more of several factors:—high concentration of any type of ammonium fertilizer associated with a soil reaction on the alkaline side of neutrality; salt effect producing an osmotic concentration too high for optimal activity of the nitrifying bacteria; and excessively high pH value. A specific threshold value is not suggested by this last factor since nitrification has been shown to take place without inhibition up to about 9.0 in calcareous soils (11, 17).

Movement. Movement of ammonium by leaching in calcareous soils is not great (5, 7, 14, 18, 19, 31), since it is readily attached to the soil colloid in the cation-exchange position and held firmly. A large portion of nitrogen applied as ammonia, under usual conditions, may be expected to be retained within 6 inches of the point of application until such time as it may be oxidized to nitrate (5, 9, 11). Tyler et al. (38) report that the ammonium from NH_4OH, NH_4NO_3, and urea moved but very little downward in four calcareous soils as a result of wetting to the field capacity. Some upward movement of ammonium nitrogen was common with all materials but greatest where NH_4OH was applied. The movement of applied ammonium nitrogen in soil is dependent on the nature of the ammonium source, soil type–cation exchange capacity, rate of nitrification, and kind of cations on exchange complex.

Fixation. Fixation of ammonia by clay minerals in a position unavailable to plants occurs in some soils (4, 7, 23). Fixation is primarily controlled by the nature of the clay minerals in the soil and not the presence or absence of $CaCO_3$ or a high or low pH value. Vermiculite and weathered illite (hydrous mica) fix ammonia to a greater extent than other clay minerals. Montmorillonite-like clays fix small quantities of NH_4-N under certain desiccation conditions and kaolinite clays do not fix ammonia. Illite and vermiculite are capable of fixing ammonia under moist conditions; montmorillonite is not. Montmorillonite clays dominate in calcareous soils of

arid and semiarid climates. Thus it appears that calcareous soils may be expected to fix some ammonia. However, further study is needed to determine whether the amounts are of practical significance. The ready availability of potassium in most calcareous soils, on the other hand, may be expected to counteract fixation by preventing ammonia from entering the fixation positions (3, 6), since both ions are competitive for the same sites.

Because of the low organic matter content—0.1 to 1.0%—of most arid and semiarid calcareous soils, fixation of ammonia by organic constituents, as explained by Broadbent (8), may be considered to be less in these soils than in soils of higher organic matter content. For the most part, fixation of ammonia by organic matter in calcareous soils can be considered of little appreciable practical importance.

Volatilization. Volatilization of ammonia from surface applications can reach economic importance (25, 35). The pH value of a soil has a marked influence on ammonia loss. The amount of loss in neutral or acid soils is small. In calcareous soils of pH values of about 7.2 or above, volatilization loss increases as the alkalinity increases. Losses as high as 51% have been observed by Martin and Chapman (25) in a soil of pH 8 when certain ammonium fertilizers were applied to the surface. They report a greater loss from ammonium hydroxide than from ammonium sulfate and ammonium nitrate. Loss from urea and dried blood was comparatively small except in the poorly buffered soils. It should be noted, however, that appreciable loss occurs only when there is simultaneous loss of moisture. Furthermore, the higher the temperature, the greater the loss. Thus losses in the summer are higher than during the winter.

Loss of ammonia from irrigation water is well known. Losses may be economically significant (33). Losses may be minimized by applying ammoniated irrigation water on a cool, calm, overcast day, with a minimum of flowing-surface turbulence.

Volatilization losses are greatly reduced or eliminated by placing the ammonium fertilizer below the surface of the soil. A depth of a few inches may completely reduce losses by volatilization. Greater losses have been reported from calcareous than from neutral or acid soils. However, loss by volatilization need not be a serious economic problem if care and attention are given to proper placement in the soil (5, 19).

Absorption. Ammonia (NH_4OH, NH_3) reacts differently in some instances in calcareous soils than ammonium from ammonium salts. For example, Jenny et al. (20) found that more nitrogen was absorbed from $(NH_4)_2SO_4$ than from NH_4OH in alkaline soils; whereas the

reverse was true for acid soils. The process of nitrogen absorption is governed by base-exchange reactions. Exchange is equivalent for $(NH_4)_2SO_4$; i.e., for every NH_4 ion absorbed, a corresponding cation is released. In contrast to this, the amount of NH_4 absorbed from NH_4OH greatly exceeds the cations liberated. In laboratory-prepared soil columns, the effect of NH_4 ion on water penetration is so variable it is not possible to generalize. It should be noted, however, that ammonium does not necessarily retard penetration in all soils. Data indicate $(NH_4)_2SO_4$ salts as well as NH_4OH increased, as often as decreased, penetration in laboratory-prepared soil columns.

Microbiological Transformations of Fertilizer Nitrogen

A brief review of the nitrifying characteristics of nitrogenous fertilizers of possible use in fertilizer combinations in calcareous soils is important for at least three reasons. First, considerable attention continues to be focused on the effectiveness of the ammonium form vs. the nitrate form in the nutrition of plants. Second, a threshold soil paste pH value of 7.7 ± 0.1 has been suggested above which nitrification—the conversion of nitrite to nitrate—will not proceed normally. Third, claims are made of unusual loss of nitrogen from ammonium containing or forming fertilizers applied to soils having pH values above 7.0.

Effectiveness of Nitrogen Sources. Considerable attention regarding the effectiveness of the ammonium form vs. the nitrate form in the nutrition of plants took place between the period of 1889 and 1930. It was established that some plants grow equally well with either nitrates or ammonium salts as a source of nitrogen, and that others, although assimilating ammonium salts in the absence of nitrate, seem to grow better when nitrates are applied. From a standpoint of the assimilation of these two ions, the ammonium form requires a lower expenditure of energy by the plant in its conversion to protein.

Since 1930, the different factors that influence the relative value of the nitrate and ammonium ions in the nutrition of plants have been studied. The effectiveness of one form as compared with the other appears to depend upon the type and age of the plant and the pH value of the root medium. Young sugar cane, for example, cannot survive without some nitrate ions present. Young rice plants, on the other hand, cannot use this form but grow well with ammonium nitrogen. Cotton and corn, as well as many other plants, grow equally well with both forms. In experiments with cotton, the reaction of the root medium influenced the uptake of these two ions. The absorption of ammonium nitrogen de-

creased as the pH increased up to a certain level, whereas the absorption of nitrate nitrogen was only slightly affected by changes in reaction. Evidence also has been presented indicating that in root medium where the oxygen tension is low the nitrate ion gives better growth than ammonium nitrogen. The practical significance of this, under field conditions, is difficult to ascertain. Regardless of the form utilized to the greatest extent by plants, it has been well established that the nitrate form will predominate in normal, well-aerated soils.

Nitrite Oxidation. Plants will absorb the nitrite ion as readily as the nitrate. Nitrite can be tolerated by plants only in low concentrations. Nitrite oxidation has been recognized as the second of two principal steps in the nitrification process for over 80 years. Nitrite accumulation has been emphasized as being associated with neutral or alkaline soils. Nitrite accumulations in considerable amounts in soils having pH values above neutral and where fairly large amounts of ammonium fertilizers were added have been reported (13, 16, 25). Although Martin et al. (27) suggested a threshold pH value of 7.7 ± 0.1 above which the complete oxidation of ammonia to nitrate will not occur and to which the pH value of such soil must first be reduced before nitrates will accumulate in appreciable amounts, Meyerhof (29, 30) in his classic research of 1916 and 1917 considered the optimum pH value for nitrite oxidation to nitrate to be between 8.3 and 9.2.

Fuller et al. (18) reported in 1950 that under field conditions nitrates formed readily in calcareous soils well above the pH value of 7.8. The absence of nitrite accumulation indicated that the pH value was not unfavorable for nitrification in soils having a pH value above the suggested threshold. The apparent discrepancy between the threshold hypothesis established under laboratory conditions and the lack of a similar threshold value under field conditions appears to be resolved after consideration of the greater sensitivity of the *Nitrobacter* compared with the *Nitrosomonas* for ammonium ions.

The two principal steps in nitrification involve first the formation of nitrite,

$$NH_4^+ + 3/_2 O_2 \xrightarrow{Nitrosomonas} NO_2^- + 2H + H_2O$$
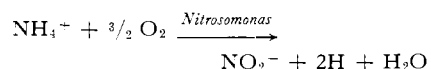
followed by oxidation of nitrite to nitrate,

$$NO_2^- + 1/_2 O_2 \xrightarrow{Nitrobacter} NO_3^-$$
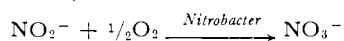
Ammonia ion has a greater inhibitory effect on the respiratory activity of *Nitrobacter* than *Nitrosomonas*. This is also true for nitrite ions. Thus, it is possible to establish a pseudothreshold value for complete oxidation to nitrate at almost any pH value that will permit plant growth, depending on the concentration of ammonia or nitrite level present in the biological oxidation system. Inhibition of oxidation of nitrite to nitrate can be readily demonstrated in glass tumblers of soil in the laboratory incubator; whereas in the less confining conditions of the field it does not occur as readily.

Tyler and Broadbent (37) recently showed that very low concentrations of nitrite are inhibitory to the oxidative process in acid soils. In calcareous soils, however, they showed that more than a 100-fold increase in nitrite concentration is required to produce the same magnitude of respiratory inhibition. Meyerhof (29), as early as 1916, suggested that nitrite reacts with free amino groups of the cell protein. Thus, the toxic effect would be expected to be most pronounced under acid conditions and least under alkaline.

Reactions of Nitrate Fertilizers

Mobility. The ready mobility of the nitrate ion in soils is one of its most outstanding characteristics. Nitrogen in the nitrate form moves with the wetting front in irrigated calcareous soils. It may be readily lost by leaching below the root area. A second important characteristic that differentiates nitrate nitrogen from ammonia is its susceptibility to reduction to nitrous oxide with subsequent gaseous loss under a wide variety of conditions.

Gaseous Loss. Nitrous oxide in the earth's atmosphere was discovered in 1946 by the astronomer Adel (1), who suggested that the gas originated from the decomposition of nitrogen compounds in soil. This assumption was based on N_2O concentration in the lower layers of the atmosphere and its observed presence in the gases of the soil (36). Adel (2) further suggested that ultraviolet radiation photochemically decomposed nitrous oxide into nitrogen and oxygen in the upper atmosphere. Thus the complete nitrogen cycle, that begins with nitrogen fixation in the soil, can be postulated.
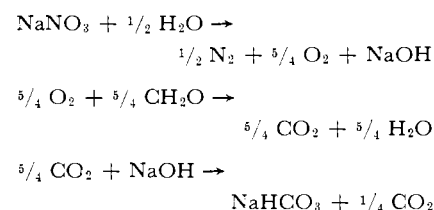
Denitrification of nitrate nitrogen in soils to yield nitrous oxides as well as free nitrogen has been shown by Broadbent (8) to occur at all oxygen levels. Finding that it takes place under aerobic as well as anaerobic conditions led him to suggest that it probably is of widespread occurrence in soil. He estimated that the quantities of nitrogen returned to the atmosphere by these processes may equal that removed from the air by biological fixation.

Nitrite decomposition appears to take place in acid soils to a greater extent than in alkaline calcareous soils according to Tyler and Broadbent (37). Nitrites are more stable in calcareous than acid soils.

Rather large losses of nitrogen are reported from certain California soils contained in a long-term lysimeter experiment, according to Chapman et al. (12, 13). The losses could not be accounted for in leachings or harvested crop. The greatest loss was from the soils receiving calcium nitrate plus annual additions of straw or a nonlegume cover crop. Reasoning that there is a biological mechanism that is able to effect aerobic losses of nitrogen in the presence of carbonaceous material together with nitrate, as suggested by Corbet and Wooldridge (15), Broadbent et al. (8, 10) found that nitrogen losses occurred at all oxygen levels when both nitrate and ground clover were added to soils. The experimental soils ranged in pH values from acid to alkaline. Broadbent (8) concluded that: "Denitrification may occur even though fresh additions of organic matter have not been made," "Low oxygen concentration in the soil atmosphere is not a necessary condition for the denitrification process," and "denitrification rate is affected more by quantities of nitrate and oxidizable carbon in the soil than by partial pressure of oxygen."

At low oxygen level (0.14% O_2), nitrate may be used for the required energy-releasing reaction of the oxidation of carbon in accordance with the following reactions:

$$NaNO_3 + 1/_2 H_2O \rightarrow$$
$$1/_2 N_2 + 5/_4 O_2 + NaOH$$
$$5/_4 O_2 + 5/_4 CH_2O \rightarrow$$
$$5/_4 CO_2 + 5/_4 H_2O$$
$$5/_4 CO_2 + NaOH \rightarrow$$
$$NaHCO_3 + 1/_4 CO_2$$

The concept that denitrification of nitrate and nitrite is influenced more by the amount of organic matter in the medium than the oxygen concentration is shared also by Meiklejohn (28) and Korsakova (22), who isolated several species of *Pseudomonas* capable of reducing nitrate at all levels of oxygen.

Although it has been demonstrated conclusively that denitrification is not exclusively an anaerobic process, soil microbiologists generally agree that most of the losses of nitrogen, other than ammonia, are brought about by denitrifying bacteria under anaerobic conditions. The rapid loss of nitrogen as free nitrogen gas and nitrous oxide from nitrate salts applied to a soil and incubated anaerobically has been demonstrated so often it has become a classroom exercise. Where oxygen is present, the rate of evolution of nitrogen gas is markedly retarded.

Reactions of Some Organic Nitrogen Sources

The development of nitrogenous fertilizer combinations of organic and inorganic materials of varying nitrifying characteristics, once they are understood
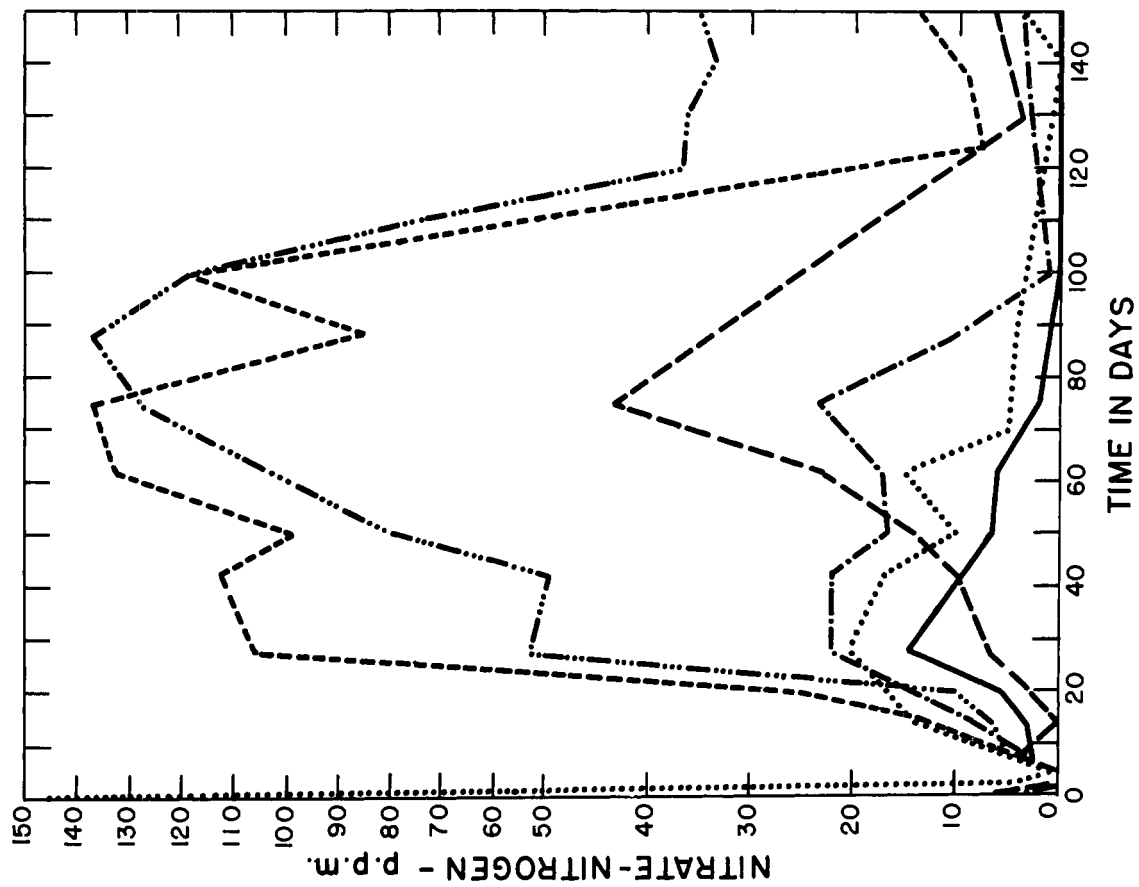
Figure 2. Change with time of nitrate-nitrogen in Mohave sandy loam treated with various nitrogen fertilizers

(- - - -) (NH₄)₂SO₄; (· · · · ·) NH₄OH; (— — —) CaNCN; (— - —) CO(NH₂)₂; (· · · · · ·) Ca(NO₃)₂; (————) untreated
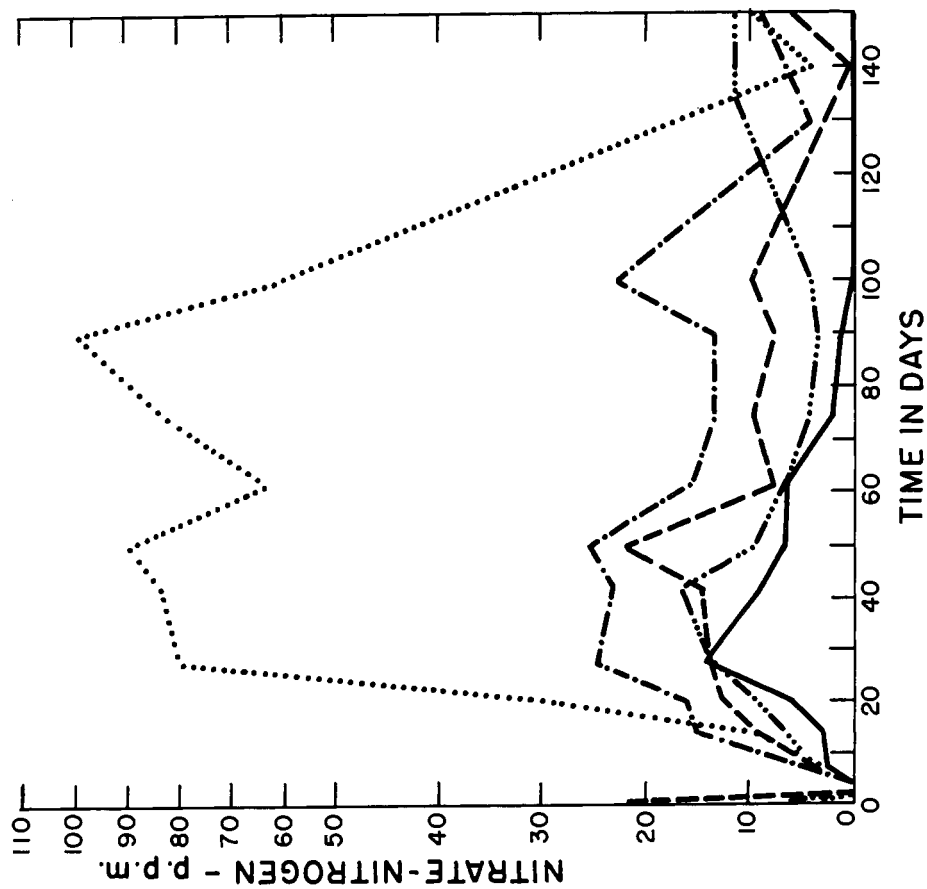

Figure 1. Change with time of nitrate-nitrogen in Mohave sandy loam treated with various nitrogen fertilizers

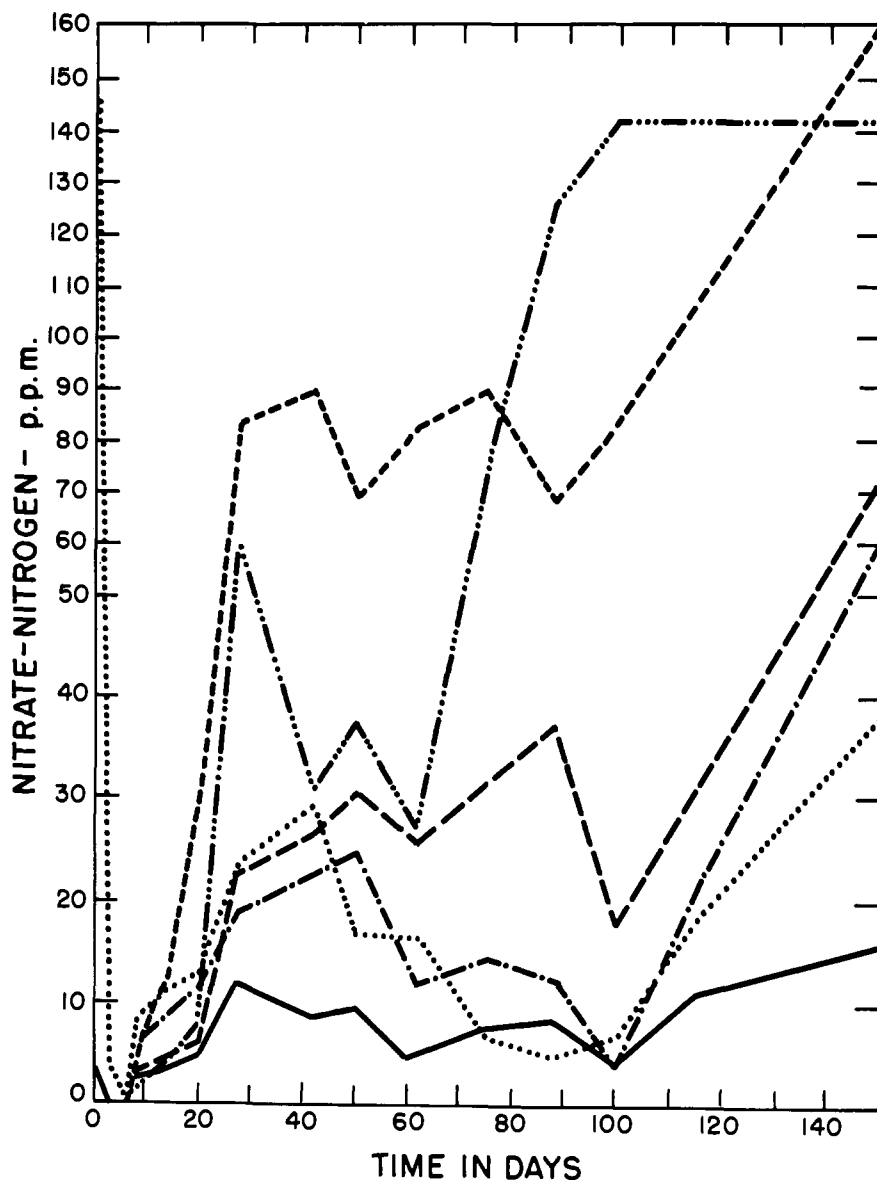(· · · · ·) activated sewage; (— · —) steer manure; (- - - -) goat manure; (— — —) commercial mix; (————) untreated

Figure 3. Changes with time of nitrate-nitrogen in Adelanto clay loam treated with various nitrogen fertilizers

(- - - - -) (NH₄)₂SO₄; (—— · · ·) NH₄OH; (— —) CaNCN; (— · —) CO(NH₂)₂; (. . . . . .) Ca(NO₃)₂; (———) untreated

Table I. The Influence of Some Organic Nitrogen Fertilizers on Barley Yields from Two Calcareous Soils

Material Added	Increase in Barley Grain Due to Nitrogen Application	
	Laveen clay loam, %	Super-stition sand, %
None	. . .	. . .
Dicyanodiamid	3.1	. . .
Guanylurea sulfate	7.5	. . .
Guanidine nitrate	27.8ᵃ	0.5
Ureaform N-20	30.6ᵃ	8.0
Ammonium sulfate	32.6ᵃ	38.8ᵃ
Ureaform N-40	40.3ᵃ	20.8ᵃ
Cyanamid	45.3ᵃ	52.4ᵃ
Thiourea	62.3ᵃ	62.4ᵃ

ᵃ Highly significant increase, 1% level.

and phosphorus nitride at this concentration and under these particular laboratory conditions.

Cyanamid and thiourea exhibited similar nitrification characteristics. When applied at the 200 p.p.m. rate, considerable ammonia was noted but no nitrate formation. When applied at a lower rate of 100 p.p.m. N, cyanamid nitrified slowly, and thiourea showed appreciable oxidation.

When the organic N sources were added to (NH₄)₂SO₄, the nitrification of the components of the mixtures appeared to be additive—i.e., each component appeared to nitrify as if present alone, except in mixtures containing cyanamid and dicyanodiamid. These latter mixtures reflected nitrification characteristics of the cyanamid and dicyanodiamid.

Field Investigations. COMPARISONS OF NITRIFICATION. Steer manure, goat manure, urea plus manure, activated sewage, urea, calcium cyanamid, calcium nitrate, ammonium sulfate, and aqua ammonia were compared at a rate of 250 p.p.m. N with respect to nitrification rate and level of nitrogen retained in a field experiment on uncropped calcareous Mohave sandy loam and Adelanto clay loam (Figures 1, 2, and 3) (18). The steer and goat manure liberated NO₃-N at about equal rates (Figure 1). The commercial mix of urea plus manure, calcium nitrate, and urea alone liberated NO₃-N at about the same rate as the two manures alone. Activated sewage in the Mohave soil produced NO₃-N at a rate considerably above the aforementioned fertilizers (Figure 1). Cyanamid in both soils maintained a notably higher level of nitrate concentration than the manures, but less than activated sewage. Nitrates of calcium nitrate were leached quickly from the 12-inch sampling depth. Urea also exhibited the same tendency but movement was more delayed. Ammonium sulfate and aqueous ammonia

fully, might be projected easily into a solution of several problems, such as increasing the nitrogen supply for plant use during periods when nitrifying activity of the soil is slow, regulating the available nitrogen to correspond more closely throughout the growing season with the demand of the plant, and providing a uniform supply of nitrogen over a long growing period for plants such as grasses and fruit trees. Since a long growing season is one of the characteristics of most calcareous areas, the development of any fertilizer in combination with one or more others would necessarily have to take into consideration the retention of the nitrogenous materials within the root zone of soils. The nitrifying characteristics of some organic nitrogenous materials of possible use in long-time fertilizer combinations were investigated by Fuller et al. (17, 18) under laboratory and field conditions in an

attempt to obtain a better knowledge of the behavior of nitrogenous fertilizers in calcareous soils.

Laboratory Investigations. The nitrifying characteristics of cyanamid, dicyanodiamid, guanidine nitrate, guanylurea sulfate, thiourea, melamine, and ureaform N-40 and N-20, when applied to several calcareous soils, were compared with ammonium sulfate and urea as rate controls under laboratory conditions (17).

Nitrification appeared to proceed normally and satisfactorily with ammonium sulfate, urea, guanylurea sulfate, and ureaform N-40 and N-20 when added at a rate of 200 p.p.m. N to Gila fine sandy loam, a calcareous soil of pH 8.0. The nitrifying characteristics varied widely, however. They are named above in the order of decreasing rate of nitrification. Nitrification did not proceed normally with dicyanodiamid, melamine,

yielded rather large amounts of nitrate over a long period of time in both soils (Figures 2 and 3).

COMPARISONS FOR BARLEY PRODUCTION. The same nitrogen fertilizers were applied at a rate of 50 pounds of N per acre to Laveen clay loam and Superstition sand to evaluate them as sources of nitrogen fertilizer for barley grain production. The nitrogenous materials increased grain yields significantly above that of unfertilized plots except for dicyanodiamid and guanylurea sulfate (Table I). Thiourea appeared significantly better than the other sources on both soils. A second crop of barley planted to the same plots on both soils demonstrated a distinct residual effect due to the previous year's application of thiourea. The other nitrogen sources failed to show residual effects for a second barley crop. Thiourea has an inhibitory effect on the rate of biological nitrification, thus slowing down nitrogen loss through reactions characteristic of nitrate or nitrite (18).

Ammonium sulfate was found to support significantly higher winter barley yields than calcium nitrate when compared in Yuma, Arizona, on Superstition sand, according to Stanberry (34). This is in agreement with the nitrification data which show that ammonium sulfate maintained a higher level of nitrogen in this calcareous soil over a period of a year than did calcium nitrate.

Enigma of Soil Nitrogen Balance Sheets

The failure of nitrogen balance sheets to balance soil nitrogen gains and losses constitutes an enigma that continues to resist complete solution.

In 1954, Allison (3) discussed "the enigma of soil nitrogen balance sheets" in detail. Little has transpired during the

last 8 years to change the situation. Also, after balance sheets are made for calcareous soils, income and outgo do not completely balance even though apparent account has been made of all known soil-nitrogen gains and losses. Thus calcareous soils do not differ from neutral and acid soils in the enigma.

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Movement of Applied Potassium in Soils

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MOVEMENT or mobility of potassium (K) in soils, as well as movement of other elements essential to plant growth, has been a subject of much investigation, particularly during the past three decades. After gaining some understanding of soil K and its disdistribution in soil profiles, information was needed as to the fate of K applied as crop residues, manures and chemical fertilizers. Van Alstine (69) prepared an early review that included some information on movement of K, but data at that time were limited. Many experiments involving additions of materials to soils and subsequent leaching with applied water or rainfall have been conducted since that time. Potassium determinations have been made on the leachate percolating through the soil and/or on various depth increments of the soil profile.

While exchangeable K has been the fraction usually determined, nonexchangeable K has also been studied. Experiments have been conducted in laboratory, greenhouse and field lysimeters of various types (28) and in field trials with various treatments.

Needless to say, the literature on K movement in soils and factors affecting it is voluminous, but space does not permit coverage of all material which could be appropriately cited. The objectives in this review are to discuss the factors influencing movement of