



Studies of nitrogen losses from fertilized Bowdoin clay soil
by Gilbert Schumaker

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree
of Master of Science in Soils

Montana State University

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Abstract:

Nitrogen losses from Bowdoin clay were studied in the greenhouse. Nitrogen uptake in barley was used as an indicator of nitrogen loss in ammonium and nitrate forms by applying these sources to the clay soil and allowing the barley to mature.

Two greenhouse experiments were conducted applying nitrogen sources to Bowdoin clay. Nitrogen materials were applied on the soil surface at four rates with two levels of moisture in the first experiment. More than 50% of the applied nitrogen was recovered from the nitrate source treatment. Nitrogen recovery from the ammonium-treated pots was much less—15 to 20%. Differences were noted in the application of nitrogen at different rates; no differences were noted between moisture treatments.

The nitrogen materials were mixed with the soil in a second experiment to observe the effect of placement on nitrogen uptake, again assuming nitrogen uptake to be an indicator of nitrogen loss. Results showed a recovery of 80 to 90% of the applied nitrogen.

Nitrogen loss in the ammoniacal form was measured from Bowdoin clay in the laboratory. The clay soil has the ammonium-fixing capacity of 8 meq. per 100 gm. of soil, much larger than in most soils. Some volatilization of ammonia was measured; however, the amounts measured were small, with the largest loss being 7% of the nitrogen applied.

These determinations do not necessarily account for all the ammonium source loss measured in the greenhouse experiment with nitrogen application on the soil surface. It is possible that some of the ammonium nitrogen became positionally unavailable.

It was shown in these studies that losses from the surface application of the ammonia source of nitrogen can be overcome by the surface application of the nitrate source or by deeper placement of any of the fertilizer materials studied.

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FERTILIZED BOWDOIN CLAY SOIL

by

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ABSTRACT

Nitrogen losses from Bowdoin clay were studied in the greenhouse. Nitrogen uptake in barley was used as an indicator of nitrogen loss in ammonium and nitrate forms by applying these sources to the clay soil and allowing the barley to mature.

Two greenhouse experiments were conducted applying nitrogen sources to Bowdoin clay. Nitrogen materials were applied on the soil surface at four rates with two levels of moisture in the first experiment. More than 50% of the applied nitrogen was recovered from the nitrate source treatment. Nitrogen recovery from the ammonium-treated pots was much less--15 to 20%. Differences were noted in the application of nitrogen at different rates; no differences were noted between moisture treatments.

The nitrogen materials were mixed with the soil in a second experiment to observe the effect of placement on nitrogen uptake, again assuming nitrogen uptake to be an indicator of nitrogen loss. Results showed a recovery of 80 to 90% of the applied nitrogen.

Nitrogen loss in the ammoniacal form was measured from Bowdoin clay in the laboratory. The clay soil has the ammonium-fixing capacity of 8 meq. per 100 gm. of soil, much larger than in most soils. Some volatilization of ammonia was measured; however, the amounts measured were small, with the largest loss being 7% of the nitrogen applied.

These determinations do not necessarily account for all the ammonium source loss measured in the greenhouse experiment with nitrogen application on the soil surface. It is possible that some of the ammonium nitrogen became positionally unavailable.

It was shown in these studies that losses from the surface application of the ammonia source of nitrogen can be overcome by the surface application of the nitrate source or by deeper placement of any of the fertilizer materials studied.

INTRODUCTION

The purpose of this dissertation is to discuss the type of nitrogen loss or losses which occur in Bowdoin clay as investigated in the laboratory and greenhouse.

Nitrogen recovery data from native hay experiments on Bowdoin clay¹ have indicated that only a small portion of the nitrogen applied is recovered by the hay crop. While crops respond very favorably to nitrogen application on the Bowdoin clay soil, not more than 30% of the nitrogen applied is recovered the year of application. Experiments have shown that only a small percentage of the nitrogen not utilized the year of application is taken up by the crop in following years. Thus it appears that the nitrogen not recovered in plant material is lost or becomes unavailable for crop use. Losses of volatile forms of nitrogen and the fixation of ammonium are possible causes.

With the increased use of nitrogen fertilizers and with applications at higher rates becoming more common, attention must be given to the factors responsible for these losses which impair the efficiency of nitrogen use.

Since nitrogen losses, believed to occur here, are either in the form of ammoniacal or nitrate nitrogen, one approach used in this investigation was to measure the nitrogen uptake by plants treated with these sources of nitrogen under greenhouse conditions. The form of nitrogen loss occurring could then be determined, since a reduction of the nitrogen supply

¹U. S. Department of Agriculture, Agricultural Research Service, Western Soil and Water Management Research Branch, Milk River Annual Report, 1957.

in the soil due to loss would be reflected in a reduction of nitrogen uptake by the plant.

Greenhouse experiments with barley were conducted in two phases. Nitrogen applications were on the surface in the first greenhouse experiment. Following this experiment, a comparison of nitrogen uptake by barley was made when various sources of nitrogen were mixed with the soil.

In order to verify conclusions drawn from greenhouse experiments, quantitative measurements of nitrogen loss by ammonia volatilization and ammonium fixation were then made in the laboratory to determine the importance of these forms of nitrogen losses.

Studies of the types of nitrogen losses which occur from Bowdoin clay will be helpful in finding a means of reducing nitrogen loss, resulting in greater nitrogen economy and increased productivity.

REVIEW OF LITERATURE

From the reservoir of soil nitrogen, there is a continual removal and return of nitrogen during the course of the nitrogen cycle. Black (1957) has explained the addition and removal of nitrogen from this reservoir quite fittingly: "Over each annual cycle, some nitrogen is mineralized, and some is immobilized. Some is removed by plants, and some is returned in the form of plant residues. Some is lost to the atmosphere, and some is returned. Some may be lost by leaching and some added by fertilization. Some may be lost by erosion or added by deposition."

This addition and removal of nitrogen from the soil has been discussed by Allison (1955). He refers to the nitrogen balance sheets of a number of long-term experiments and shows the total nitrogen additions and losses during the course of these experiments. Even when an account was made of nitrogen lost by leaching and erosion, all the nitrogen added could not be accounted for. It appears that the only adequate explanation of these negative balances is nitrogen loss by the volatilization of various forms of nitrogen and by the fixation of the ammonium ion, rendering it unavailable in the soil.

Early investigations indicated that some of the nitrogen applied to the soil was lost in some form; however, nitrogen fertilizers were not applied in large quantities. At that time, refined methods of measuring small losses occurring at slow rates had not been developed. Since these losses, which were believed to occur, could not be measured, it was concluded that they did not reach significant proportions.

It is, however, recognized today that these previously unexplored losses can reach significant proportions, particularly where nitrogen is applied in large quantities.

It is not likely that nitrogen is leached from Bowdoin clay since the depth of water penetration in this soil is about 30 inches. This form of loss will not be reviewed.

Forms of nitrogen loss which will be reviewed are: the fixation of ammonium, the volatilization of ammonia, and the loss of elemental nitrogen through denitrification. While the fixation of ammonium is not a loss in a strict sense, it is difficult to reclaim and is not immediately available for crop growth.

Nitrogen Loss by Ammonium Fixation

The property of certain soils to change added ammonium into a non-exchangeable state is termed ammonium fixation. Leggett² describes fixed ammonium as "ammonium which is entrapped between two adjacent mineral plates, presumably in the voids formed by the hexagonal oxygen rings in the oxygen layers of some silicate minerals. The entrapment results from a decrease in the basal spacing of the mineral to the extent that the distance between the adjacent mineral plates is not sufficient to allow exchange reactions to occur. It is assumed that fixed NH_4 is present in minerals in a position similar to that of K in micas."

McBeth (1917) was one of the earlier workers who noted the occurrence of ammonium fixation. He observed that ammonium salts added to soils could

²Leggett, Glen E. Ammonium fixation in soils and minerals. Doctor of Philosophy thesis, State College of Washington, Pullman, p. 2. 1958.

not always be reclaimed from the soil in the same quantity that had been added. In studies reported in 1917, he treated several soils with ammonium salts but was able to reclaim no more than 95% of the amount added. He described this loss as ammonium fixation.

Allison et al. (1953a and 1953b), in their work on ammonium fixation, reported values of less than 1.0 meq. per 100 gm. of soil for non-kaolinitic soils. Kaolinitic soils do not have the capacity to fix ammonium. It was also shown that, on drying the ammonium treated soils, the amount of ammonium fixed was almost doubled. Leggett³ determined the ammonium-fixing capacities of 30 surface soils and found that eight of these soils had ammonium-fixing capacities greater than 0.5 meq. per 100 gm. of soil under moist conditions. Ammonium fixation in New York soils was studied by Sohn and Peech (1958). They found the capacity of most of these soils to fix ammonium to be below 1.0 meq. per 100 gm. However, values as high as 5.0 meq. per 100 gm. of soil were measured in some soils containing average amounts of organic matter. It was also noted that about half of the ammonium fixed was due to soil organic matter. They investigated the ammonium-fixing capacity of several soils high in organic matter and found considerably larger ammonium-fixing capacities in these soils. They suggest that the ammonium combines chemically with certain organic fractions in the soil. Allison et al. (1953b), on the other hand, estimate that subsoils fix about four times as much ammonium as do surface soils. This would indicate that subsoils contain a larger

³Ibid., p. 52.

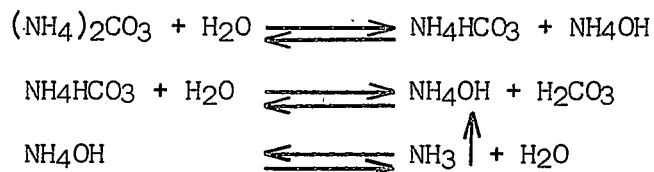
quantity of ammonium-fixing clay minerals or the ammonium-fixing capacity of the soil surface has been neutralized as a result of ammonium release by decomposing organic matter. They also compared ammonium fixation of soils high in certain clay minerals under both moist and dry treatments. Their data shows that both illite and vermiculite clay minerals fix ammonium under moist conditions, while montmorillonite fixes ammonium upon drying. This explains the increased ammonium fixation following the drying of some ammonium-treated soils.

The findings of these workers can be summarized. The ammonium ion is fixed by certain clay minerals present in soils. The amount of ammonium fixed depends on the amount of clay minerals present in the soil that have the ability to fix ammonium ions. The amount of fixation is also dependent on the moisture condition to which the soil is subjected when montmorillonitic clay minerals are present. Some of the ammonium added to soils also becomes unavailable due to its combination with certain organic substances in the soil.

Volatilization of Ammonia

Loss of ammonia through the volatilization of this gas is another type of nitrogen loss from the soil.

Wahhab (1957) proposes that the loss occurs as a result of the evaporation of ammonia and water vapor together. It is known that, in an alkaline soil, ammonia is present in the following forms which are readily changed to free ammonia which is subject to loss as a gas:



He proposes that the above equilibrium exists in the soil solution between these compounds as shown. Ammonium ions continue to exist in the soil solution as long as there are ammonium ions on the exchange complex. Then the ammonium ion supplied to the soil solution by the exchange complex becomes a part of these equilibrium reactions, and free ammonia can be evolved as long as there are ammonium ions on the exchange complex. Wahhab (1957) explains that ammonia and water vapor exert their own partial pressures and evaporate together in proportions which depend upon their molar concentrations. As the concentration of ammonia is increased, larger amounts of ammonia will be volatilized.

Work by Jewitt (1942) gives evidence that the cation exchange capacity is also a factor influencing the loss of ammonia into the air. Loss of ammonia occurs more rapidly in soils low in exchange capacity. He explains the relation of cation exchange to ammonia loss: "The base exchange tends to maintain the concentration of ammonia in solution at a constant level". Soils high in cation exchange can build up a high reserve of ammonium ions and maintain a constant concentration in the soil solution for a considerable length of time. Soils low in cation exchange capacity cannot hold a large reserve of ammonium ions and the rate of loss is not maintained at a constant level. Such soils would be comparable to a dilute solution of ammonium hydroxide, in which the ammonium content declines progressively as evaporation occurs.

Jewitt (1942) and Wahhab (1957) have reported volatile losses of ammonia from ammonium sulfate applications. Losses were found to vary with the soil pH. Both observed considerable losses from alkaline soils. Wahhab (1957) showed that a reduction of the soil pH from 8.4 to 7.3 greatly reduced the ammonia volatilized, while a further lowering of the soil pH to 5.4 resulted in no loss of ammonia.

Martin and Chapman (1951) also measured substantial losses of ammonia from alkaline soils. In this connection, they found that nitrogen applications which raised the soil pH permitted volatile losses of ammonia to occur. They concluded that losses from alkaline soils could be reduced by the use of neutral or acid ammonium fertilizers. A solution of ammonium sulfate has an acid pH. The alkaline forms of ammonia are anhydrous ammonia, aqueous ammonia, and ammonium carbonate, a product of the hydrolysis of urea. This occurs by the reaction of urea and water in the presence of urease, an enzyme produced by soil bacteria. This is discussed by Conrad (1940).

Gibson (1930) investigated the decomposition of urea in soils of a wide range of characteristics. Since none of the soils was slow to transform urea into ammonium, it was concluded that the hydrolysis was due to the enzyme activity of urease.

Jewitt (1942) and Wahhab (1957) both showed that nitrogen loss, as ammonia, increases with an increase in the concentration of ammonium salts. Wahhab (1957) found that 6.8% of a 25-mgm. application to a sandy loam soil was lost as ammonia, while 13.4% of a 100-mgm. application was lost.

Measurements of ammonia loss by volatilization on Putman silt loam were conducted by Wagner and Smith (1958). They found that the loss of ammonia from urea applications was most rapid at the time when the ammonium ion was at its maximum concentration. The rate of loss increased as more urea was transformed into ammoniacal nitrogen, then decreased as more of the ammonium was nitrified into nitrate nitrogen.

Wahhab (1957) demonstrated that larger losses of ammonia occurred from a sandy soil than from a sandy loam. This emphasizes the effect of texture on losses by volatilization of ammonia.

Wahhab (1957) and Jackson and Chang (1947) both report that ammonia losses can be reduced or eliminated by the placement of the ammonium salt below the soil surface.

The relationship of ammonia loss to moisture loss was investigated by Jewitt (1942). He found that ammonia continued to be volatilized as long as evaporation occurred.

Losses by Denitrification

The loss of nitrogen in the elemental form from the soil through the reduction of nitrate nitrogen is termed denitrification. Bremner and Shaw (1958) define denitrification as "the microbial process whereby nitrate is reduced to gaseous compounds such as nitrous oxide and nitrogen".

Denitrification has not been considered a serious loss or thought to be responsible for the loss of significant amounts of nitrogen in well-drained soils, since denitrification is usually thought to occur only under anaerobic conditions. However, Broadbent (1951) published results which showed serious nitrogen losses under aerobic conditions. He found

that a sandy loam soil containing 1,290 p.p.m. of total nitrogen and 64 p.p.m. of nitrate nitrogen lost 250 p.p.m. of nitrogen in 7 days under incubation.

The work of Lowenstein et al. (1957) showed that denitrification takes place in soils under conditions similar to those found in the field. Their greenhouse studies with cropped and uncropped soils resulted in large losses under different nitrogen source treatments. The possibility of denitrification occurring under anaerobic conditions was not ruled out, however. It was pointed out that, despite the fact that these experiments were carried out under good aeration, a soil may possess oxygen-poor areas which could result in denitrification.

In a study of the denitrification in eight Missouri soils, Wagner and Smith (1958) found that the largest losses occurred in the Weldon silt loam, while the Sharkey clay showed losses most consistently from the different nitrogen sources applied. They attributed these losses to denitrification.

Regarding the effect of soil pH on denitrification, the work of Bremner and Shaw (1958) showed that pH does have an effect. Significant losses of nitrogen occurred in soils above pH 5.0. They also showed that soil temperature was a factor affecting denitrification. The results showed that denitrification increased rapidly with a rise in temperature up to 25° C. It was found that nitrogen loss occurred most rapidly at 60° C. but that denitrification was inhibited at a temperature of 70° C.

Losses from Nitrite Nitrogen

In addition to the loss of nitrogen gas by means of denitrification, Wahhab and Uddin (1954) studied the possible occurrence of nitrogen loss

as a result of the interaction of the ammonium (NH_4^+) ion with the nitrite (NO_2^-) ion. An interaction was found at higher concentrations of these two ions under desiccation with the resulting loss of nitrogen gas. Without high concentrations, loss occurred through the volatilization of the individual compounds of these two ions. Loss through the interaction of these two ions was significant in highly alkaline soils of pH 10; however, the direct loss of ammonia gas and the loss from spontaneous decomposition of the nitrous ion were of greater significance in the lower alkaline range than was the interaction of the two compounds.

Nitrogen loss measured from the decomposition of the nitrite ion on desiccation is of interest, however. Madhok and Uddin (1946) also report this type of loss. It may be of significance in some soils. Caster et al. (1942) report that ammoniacal nitrogen applied to certain alkaline desert soils was oxidized only to the nitrite stage. Waksman (1952), in his discussion of nitrification, lists the oxidation of ammonium to nitrite as the first link in the formation of nitrate by certain autotrophic bacteria. With incomplete nitrification, losses could occur from the nitrite formed if conditions were ideal for the spontaneous decomposition of nitrite. Wahhab and Uddin (1954) felt that loss through this mechanism might be important in some soils. Morrill and Dawson⁴ studied the nitrification pattern when soils were perfused with ammonium sulfate. Above pH 7.2, it was found that Nitrobacter, the

⁴Morrill, L. G., and Dawson, J. E. An explanation of the nitrification patterns observed when soils are perfused with ammonium sulfate. *Agronomy Abstracts*, 1958, p. 15.

organism which completes the nitrification of ammonia to nitrate, goes through a lag phase, while Nitrosomonas, the nitrite-producing bacteria, proliferate rapidly. The lag was attributed to soil pH.

The discussion of the work of others presented in the foregoing review gives evidence that nitrogen losses can occur in soils in a significant proportion to warrant steps which will reduce losses.

MATERIALS AND METHODS

Greenhouse Experiments

A bulk sample of Bowdoin clay was taken from the surface at a selected site and brought into the greenhouse, where it was crushed finely enough to pass through a 4-mm. sieve. After thoroughly mixing the sieved soil, pots measuring $6\frac{1}{2}$ inches in diameter and $9\frac{1}{2}$ inches in height were filled with 4 kgm. of air-dry soil.

A treatment of 570 mgm. of treble superphosphate was mixed with the soil. This was equivalent to 100 pounds of P_2O_5 per acre based on the surface area of the pot.

Each pot was seeded with 20 kernels of barley, the pots being thinned to 10 plants per pot on emergence of the seedlings. The pots were seeded previous to the application of the nitrogen and watering of the pots since the clay soil is very difficult to handle when it is wet. One-half of the water required to bring the soil to field capacity was then added. The various concentrations of nitrogen sources were added at the soil surface in solution form as measured by a 25-cc. volumetric pipette. These treatments are listed in table I. Following the nitrogen treatment, the remaining water required to bring the soil to field capacity was added. Urea was used as the ammonium source since ammonia would not be lost into the air during application.

Two moisture levels were maintained--the minimum moisture contents being 50 and 75% of the total available moisture. Each pot was weighed individually during the period of growth, and when the minimum moisture level was reached, sufficient water was added to bring the soil back to

Table I. Nitrogen rates and sources used for greenhouse experiment on Bowdoin clay.

Nitrogen source	Gm. of fertilizer added for each rate			Equivalent mgm. of nitrogen added		
	100 lbs./A	200 lbs./A	300 lbs./A	100 lbs./A	200 lbs./A	300 lbs./A
Check	0	0	0	0	0	0
CaNO ₃ (hydrate)	1.98	3.96	5.94	265	530	795
NH ₄ NO ₃	.72	1.44	2.15	241	481	722
Urea (NH ₄)	.52	1.04	1.56	234	469	703

field capacity.

The pots were arranged in a completely randomized block design. A system of pot rotation within each replication was established so that none of the pots was on the outer edges of the bench during the full course of the experiment.

Plant height measurements were made at maturity. The heads were then removed, and the remaining plant material was clipped. The heads and straw were dried at 70° C. and weighed to determine the total plant material weight. The heads were then threshed and, after cleaning, the weight of the grain was determined. The barley grain was ground in a laboratory mill for the determination of nitrogen content, as was the straw to which the chaff had been added. Nitrogen was determined by the Kjeldahl method.

The second greenhouse experiment was conducted in the same manner as the previous experiment except that potassium nitrate was included as a nitrate source. Applications at the rate of 300 pounds of nitrogen per acre were omitted, as was the 75% moisture treatment. The minimum moisture was maintained at 50% of the total available moisture. This experiment was cared for and harvested as discussed previously. After threshing and weighing the grain, it was combined with the straw and chaff, then ground. Nitrogen content was then determined on the total plant.

Aggregation Measurements

Since the addition of calcium nitrate to the Bowdoin clay caused an apparent change in soil structure, a measurement of the dispersion

ratio of the soil taken from the surface inch of the 300 pounds N per acre calcium nitrate pots, 300 pounds N per acre urea pots, and the corresponding check pots was made. Dispersion ratio was measured by determining the amount of silt plus clay in the nondispersed sample compared to the total silt plus clay in the sample when dispersed. The grams of silt plus clay in the dispersed and nondispersed samples were measured by the pipette method as described by Middleton (1930).

Ammonia Volatilization

Measurement of the ammonia volatilized from Bowdoin clay was determined by placing 100 gm. of the soil in 500-cc. erlenmeyer suction flasks. After bringing the sample to a moisture content approximating field capacity, a urea or ammonium nitrate solution was distributed over the surface of the soil. Ammonia-free air, dried with calcium chloride, was then drawn by means of a vacuum over the soil surface through gas dispersion tubes, and any volatile ammonia was collected in a .02 N sulphuric acid solution. At the end of 1 week of incubation, the sulphuric acid was titrated with standard sodium hydroxide. The amount of ammonia volatilized was determined by the difference in milliequivalents of acid remaining after ammonia collection and that present at the start of the experiment. The suction flasks containing the soil and the acid traps were connected in a train; treatments were run in duplicate and included a blank soil treatment.

The amount and sources of nitrogen applied to Bowdoin clay are listed in table II.

Table II. Nitrogen salts applied to Bowdoin clay for the measurement of ammonia volatilization (milligrams applied to 100 gm. of soil).

	Source	
	Urea	Ammonium nitrate*
Nitrogen equivalent in milligrams	88	176
Milligrams of material	196	526

*These rates should provide the same amount of ammonium as the urea application.

Fixation of Ammonium

The procedure followed for the determination of ammonium fixation was that outlined by Leggett⁵ with adaptations for the measurement of ammonium fixed under air-dry conditions. Both ammonium-chloride-treated soil samples and blank soil samples treated with a volume of water equivalent to the ammonium chloride solution were aerated until the soil was air dry. Ammonia evolved during the aeration and drying was collected in acid traps. The procedure of Leggett⁶ was then followed with the addition of potassium carbonate and collection of ammonia in the acid traps for 16 hours by the aeration recovery method he describes. Samples were run in duplicate.

Soil Analyses

The procedure of Jackson (1958) was followed in the determination of the cation exchange capacity of Bowdoin clay, using a centrifuge washing procedure with calcium as the replacing ion. The calcium was then replaced by the ammonium ion. Calcium was determined by the versene titration.

The particle size distribution of the clay soil was determined by the pipette procedure outlined in USDA Handbook No. 60 (1954) after dispersing the soil in 2% calcium meta-phosphate solution.

Internal and external surface area of Bowdoin clay was determined by the total and external ethylene glycol retention method described in USDA Handbook No. 60 (1954).

⁵Leggett, op. cit., p. 23.

⁶Ibid.

Extractable sodium, potassium, and calcium plus magnesium as well as conductivity were determined from the saturation extract. These procedures and the determination of soil pH from the saturation paste were followed as described in the section, "Methods for Soil Characterization" of USDA Handbook No. 60 (1954).

The determination of soil organic matter was by the Walkley-Black method (Jackson, 1958). Nitrifiable nitrogen was determined after incubation of the soil-vermiculite mixture for 2 weeks as described by Stanford and Hanway (1955).

Procedures of Richards (USDA Handbook No. 60, 1954) were followed in obtaining the 1/10- to 15-atmospheres moisture extraction data. The pressure plate was used at tensions of 1/10 to 1 atmosphere. The pressure membrane was used for tensions of 5 and 15 atmospheres.

Statistical Procedures

The analysis of the data collected from the greenhouse experiments was by the method outlined by Kempthorne (1952) for partially factorial experiments. The multiple range test of Duncan was used for mean separation as described by LeClerc (1957) where more than three means were involved. The L.S.D. was used where three means were being compared.

EXPERIMENTAL RESULTS

Soil Analyses

The results of the measurement of particle size distribution show that the texture is a clay (table III).

A measurement of specific surface differentiates between expanding and nonexpanding types of clay minerals. The results reported in table IV show a large internal surface area, indicating the presence of a large proportion of expanding-type clay minerals.

Various saline and alkali characteristics of Bowdoin clay and other soil characteristics are shown in table V.

The measurement of pH shows that this surface soil is slightly alkaline. The percent exchangeable sodium is above 15%, commonly given as the lower limit of the alkali classification. The conductivity is not high enough to produce saline effects detrimental to most plants. While the conductivity and pH of this soil are low, it might be classed as a degraded alkali soil due to its high percent exchangeable sodium. These results are in agreement with Frahm (1948).

The cation exchange capacity is high. This is to be expected in view of the high clay content and the presence of a large internal surface area. This gives evidence that this soil is high in montmorillonitic clay. The organic matter is quite low for a surface soil. The nitrifiable nitrogen is correspondingly low.

Moisture retention data at various tensions are shown in table VI, while figure 1 gives the moisture retention curve for the Bowdoin clay. The ability of this soil to retain a large amount of moisture at low

Table III. Particle size distribution of Bowdoin clay surface soil as determined by the pipette method.

Sample	% Sand	% Silt	% Clay
1	3.9	21.5	74.5
2	0.6	24.3	75.0
Average	2.2	22.9	74.7

Table IV. Specific surface of Bowdoin clay as measured by the ethylene glycol retention method.

Sample No.	Surface area--square meters per gm. of soil		
	Total external + internal	External	Internal
1	368	155	213
2	363	138	224
3	375	139	236
Average	369	144	224

Table V. Measurement of various soil characteristics of Bowdoin clay.

Characteristic	Value determined	
pH	7.7	
Cation exchange capacity	48.25	meq./100 gm. of soil
Electrical conductivity	3.0	mmhos/cm.
Organic matter	1.75	percent
Nitrifiable nitrogen	33.2	parts per million
Soluble cations		
Sodium	2.9	meq./100 gm. of soil
Potassium	0.03	meq./100 gm. of soil
Calcium + magnesium	0.43	meq./100 gm. of soil
Exchangeable cations		
Sodium	12.5	meq./100 gm. of soil
Potassium	2.3	meq./100 gm. of soil
Exchangeable sodium percentage	20.0	percent

Table VI. Percent moisture retained by Bowdoin clay under various tensions.

Tension-- atmospheres	Percent moisture
1/10	89.2
1/3	62.2
1	53.6
5	38.2
15	32.4

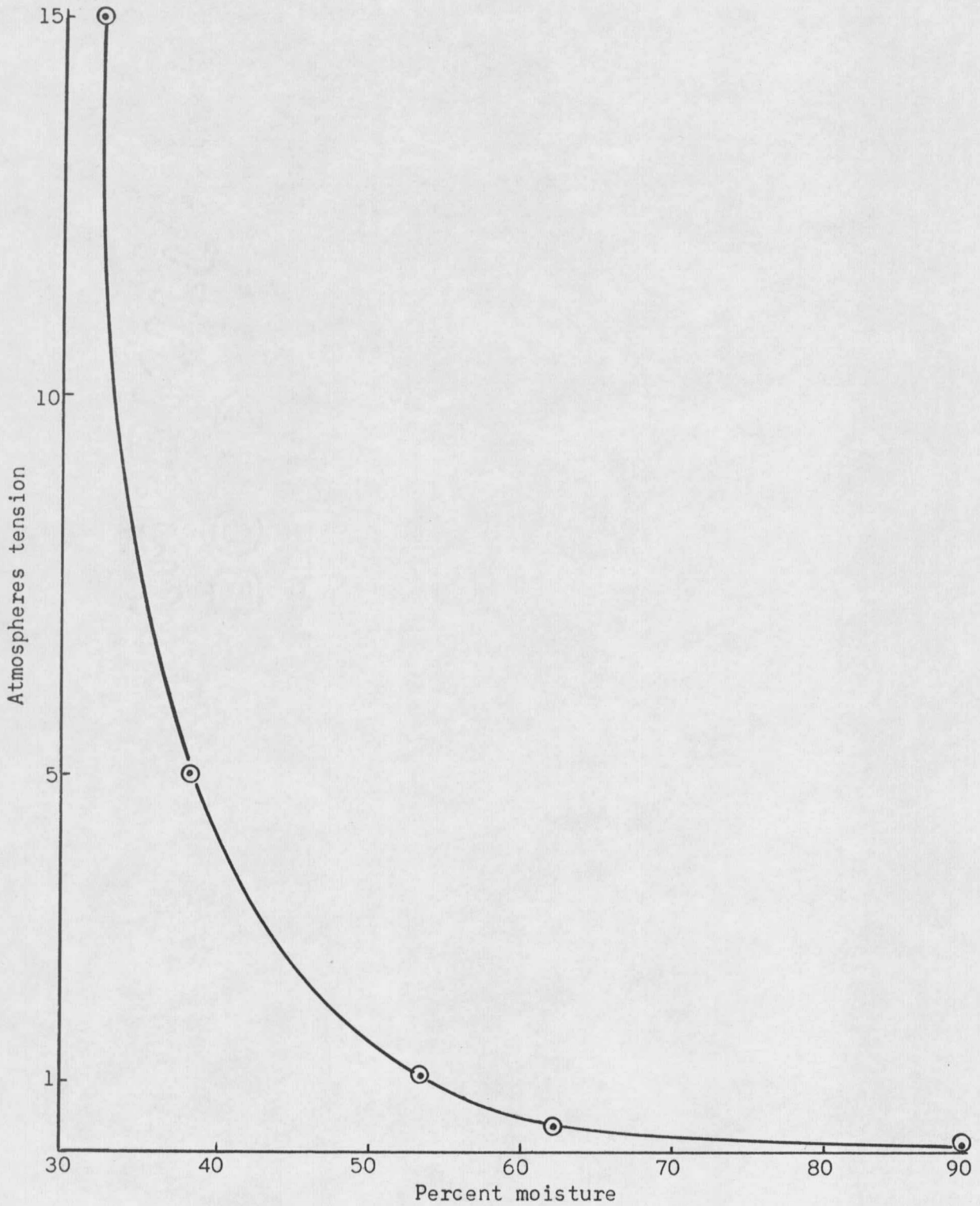


Figure 1. Moisture retention curve for Bowdoin clay surface soil.

tensions is illustrated in this curve.

Greenhouse Experiments

Emergence of the barley from the experiment where the nitrogen materials were applied on the soil surface was uniform, and good stands resulted. All treatments showed good color and made good growth during the early stages of the experiment. Yellowing of the leaves, a sign of nitrogen deficiency, became apparent in the check treatments 4 to 5 weeks following emergence. Color differences due to nitrogen rate were also apparent. Height differences due to nitrogen source were not marked until the plants began to head. These plant height measurements are reported in table VII. The higher rates of nitrogen application produced taller plants. Plant height where urea was applied was definitely shorter than other treatments receiving nitrogen. The tallest plants measured were where the nitrate source was applied. This is illustrated in figure 2. During the course of this experiment, better aggregation and an increased infiltration rate were observed where calcium nitrate fertilizer was applied. This effect was investigated further and is reported in the section on soil aggregation.

Good emergence was also observed on the second greenhouse experiment where the nitrogen materials were mixed with the soil. Differences in the check and the other treatments became apparent in about 5 weeks following emergence when yellowing of the leaves on the check treatments was noted. At this time, a slight difference in plant height was noted between the 100 and 200 pounds of nitrogen per acre pots. No differences in height were observed between the four sources applied.



Figure 2. Comparison of barley height when nitrogen sources were applied on the soil surface; (left) 100 pounds nitrogen per acre, (right) 300 pounds nitrogen per acre.

Table VII. Average plant height of mature barley treated with surface applications of nitrogen and moisture maintained at two levels.

Rate (lbs. N/A)	Treatment Nitrogen source	Minimum	Minimum
		moisture-- 50% cm.	moisture-- 75% cm.
0	CaNO ₃	69.3	64.3
0	NH ₄ NO ₃	59.7	62.3
0	Urea (NH ₄)	65.3	66.3
100	CaNO ₃	93.3	90.7
100	NH ₄ NO ₃	82.3	87.7
100	Urea (NH ₄)	79.3	73.0
200	CaNO ₃	96.7	95.0
200	NH ₄ NO ₃	88.3	93.7
200	Urea (NH ₄)	78.7	84.3
300	CaNO ₃	97.0	98.0
300	NH ₄ NO ₃	94.0	94.0
300	Urea (NH ₄)	90.7	89.7
Moisture treatment mean		82.9	83.3
Nitrogen source means:			
	Check	64.8	64.3
	CaNO ₃	95.7	94.6
	NH ₄ NO ₃	88.2	91.8
	Urea (NH ₄)	82.9	82.3

Increases in the number of tillers due to calcium nitrate were noted in the experiment where nitrogen was applied on the soil surface. These results are shown in appendix table XIX. An increase in the number of tillers was noted at the higher rates of application of both calcium nitrate and ammonium nitrate. Appendix table XX shows the tillering data from the greenhouse experiment where the nitrogen materials were mixed with the soil. There was no apparent difference in tillering between the nitrogen sources applied; however, differences in nitrogen rate are evident.

The weight of plant material produced where the nitrogen was applied to the soil surface is reported in table VIII. A highly significant difference between nitrogen source means and a highly significant difference in rate means were found in the analysis of variance (appendix table XXI). There was no significant difference between the two moisture treatments. An interaction between nitrogen source and nitrogen rate was also highly significant. Table IX, multiple comparison tests, shows that each nitrogen source is significantly different from the other source. The differences due to nitrogen rate are illustrated in figure 3, which shows the plant material increased with increasing amounts of nitrogen. A linear relationship was found on this data. A comparison of the weight of plant material produced by the three nitrogen sources where the nitrogen was applied on the surface is shown in figure 4.

Figure 5 shows the relative yield of the three nitrogen sources at the four rates of nitrogen applied. The calcium nitrate treatment produced the most plant material at all rates.

Table VIII. Average weight of plant material harvested with surface applications of nitrogen.

Nitrogen rate (lbs. N/A)	Nitrogen source			Mean nitrogen rate gm.
	CaNO ₃ gm.	NH ₄ NO ₃ gm.	Urea (NH ₄) gm.	
0	12.2	10.9	12.3	11.8
100	28.7	22.6	17.1	22.6
200	36.6	30.1	20.8	29.2
300	49.3	31.4	26.9	35.9
Nitrogen source mean	31.7	23.6	19.3	24.9

Moisture treatment average

Minimum moisture, 50%	24.3
Minimum moisture, 75%	25.4

Table IX. Multiple comparison tests for mean separation of total barley plant material weights.

Nitrogen source x rate interaction--SSR mean separation, 5% level			
Rank	Rate (lbs. N/A)	Nitrogen source	Mean weight plant material* gm.
A	0	NH ₄ NO ₃	10.9
B	0	NO ₃	12.2
C	0	NH ₄	12.3
D	100	NH ₄	17.1
E	200	NH ₄	20.8
F	100	NH ₄ NO ₃	22.6
G	300	NH ₄	26.9
H	100	NO ₃	28.7
I	200	NH ₄ NO ₃	30.1
J	300	NH ₄ NO ₃	31.4
K	200	NO ₃	36.6
L	300	NO ₃	49.3

*Treatment comparisons above each bracket versus those below the bracket are significant at the 5% level.

Nitrogen source means:

	Nitrogen source		
	CaNO ₃	NH ₄ NO ₃	Urea (NH ₄)
Mean weight	31.7	23.6	19.3

L.S.D. .01 = 3.74
.05 = 2.80

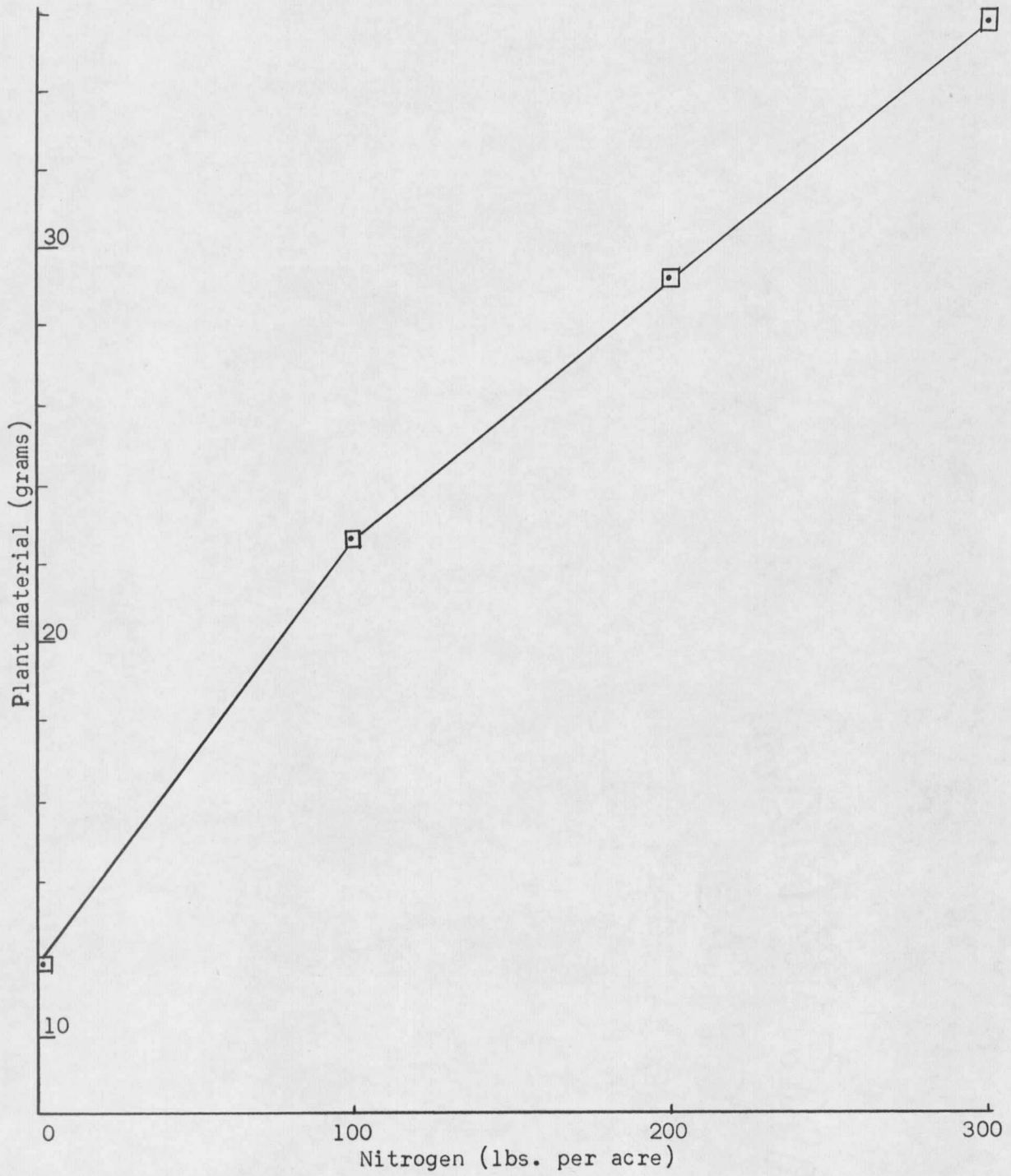


Figure 3. Total barley plant material weight produced from four rates of nitrogen (application on the soil surface).

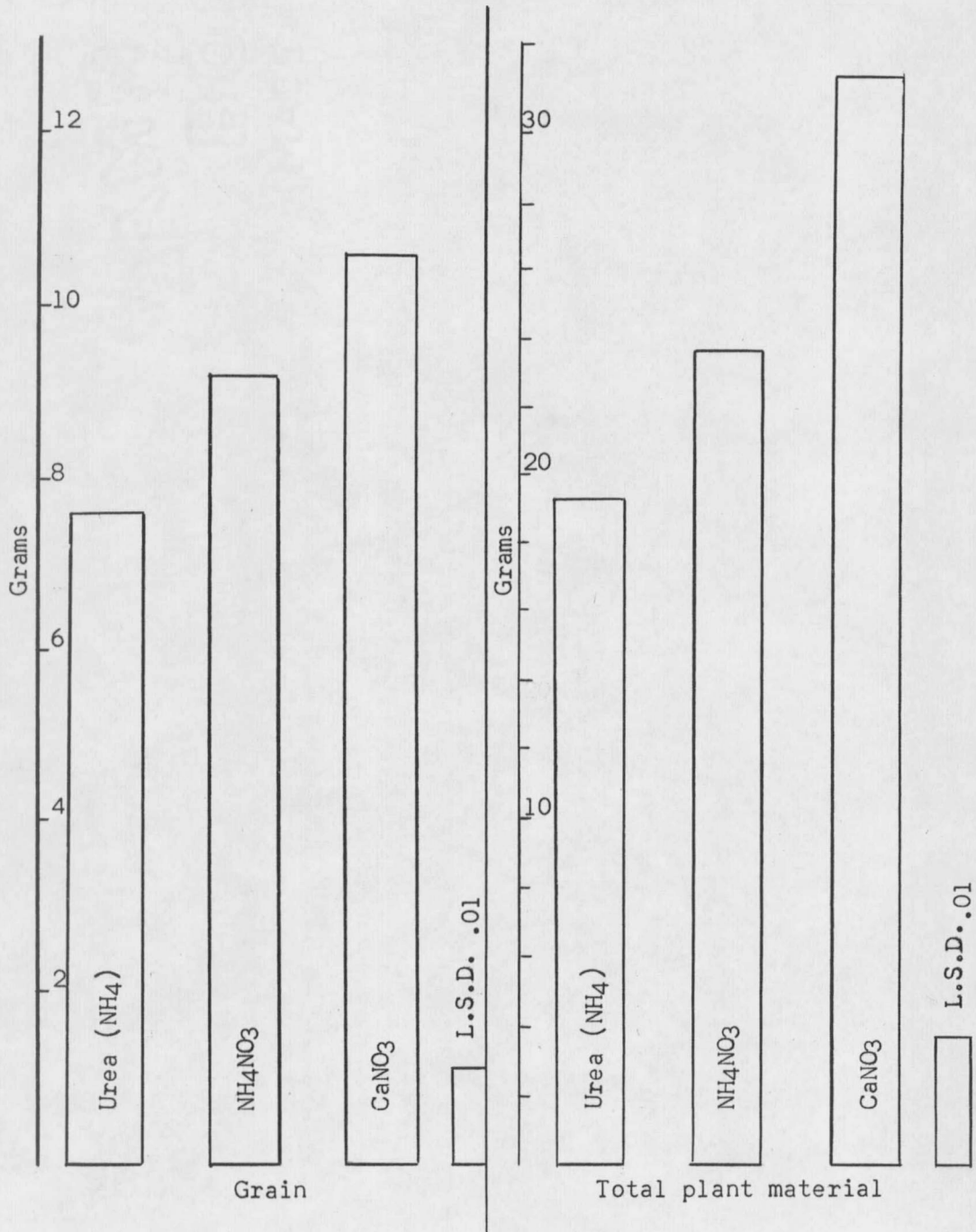


Figure 4. The effect of nitrogen source treatments on barley grain weight and total plant material weight (average of four rates with nitrogen application on the soil surface).

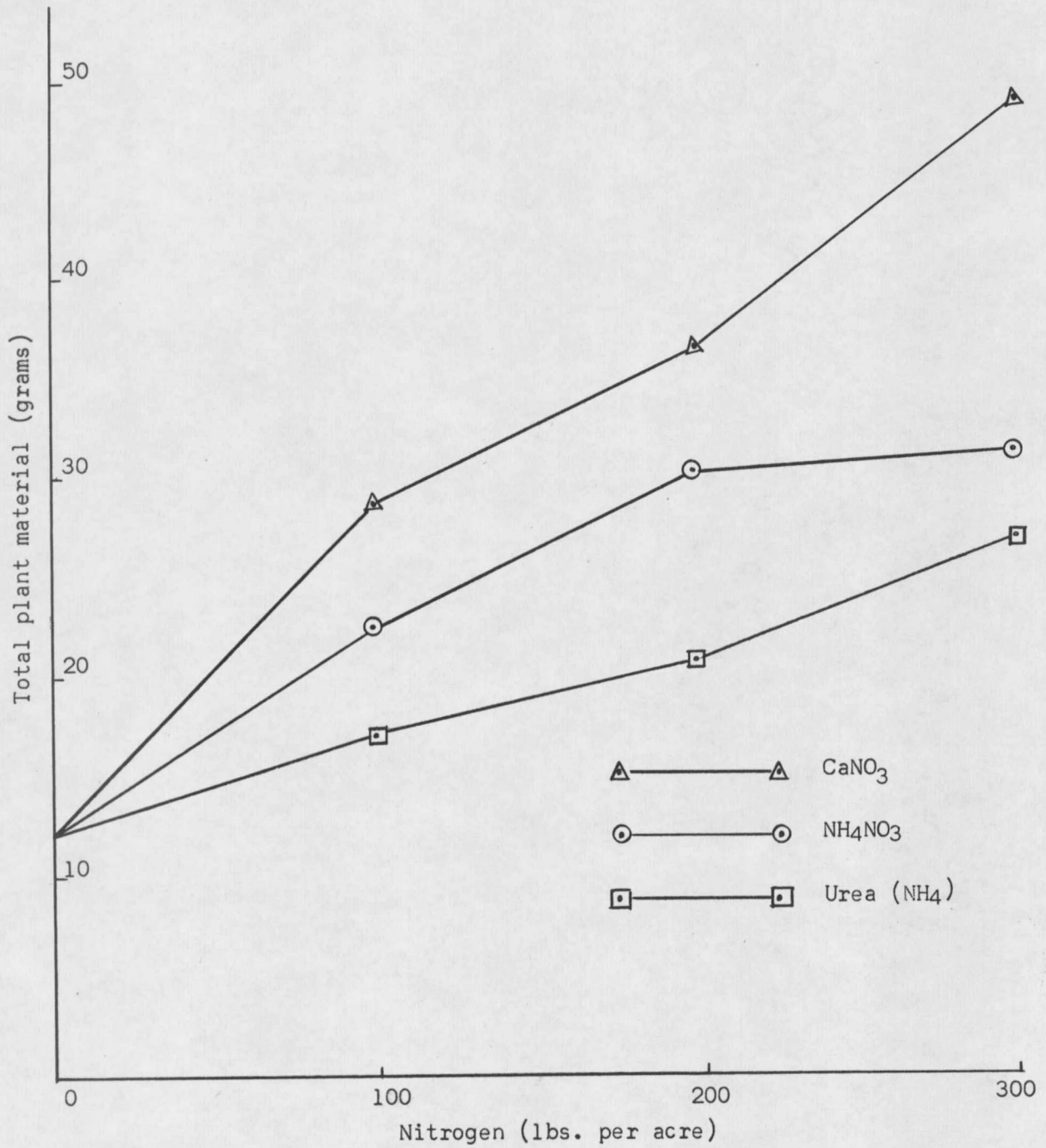


Figure 5. Comparison of barley total plant material weights when three nitrogen sources were applied at four rates on the soil surface.

The weight of grain harvested in the greenhouse experiment is reported in appendix table XXII. The analysis of variance (appendix table XXIII) of the grain data shows that the nitrogen source and nitrogen rate effects are highly significant. The nitrogen source by rate interaction was also highly significant. Figure 6 shows how grain weight increased when nitrogen rate was increased. Trend regression analysis on this data shows both a linear and a quadratic relationship (appendix table XXIII). Figure 7 gives a comparison of the three nitrogen sources at the four rates of nitrogen. A comparison of the grain weight produced from the three nitrogen sources is shown in figure 4.

The nitrogen uptake was determined from the nitrogen analysis of the grain and straw. The nitrogen analysis data is reported in appendix table XXV, while the nitrogen uptake data is reported in table X. Differences in nitrogen uptake were similar to differences in the grain and plant material weights. That is, the effects of nitrogen rate and nitrogen source were highly significant (appendix table XXVIII). The interaction of nitrogen source by rate was also highly significant. The comparison of nitrogen sources, using the L.S.D., shows that the amount of nitrogen uptake from one nitrogen material is distinctly different from that taken up by each of the other materials.

Figure 8 shows how nitrogen uptake from the three nitrogen sources compares when applied at the four rates. The nitrogen uptake from calcium nitrate at the 300 pounds of nitrogen per acre rate is distinctly different from the other sources and rates of application. This is also evident in table XI.

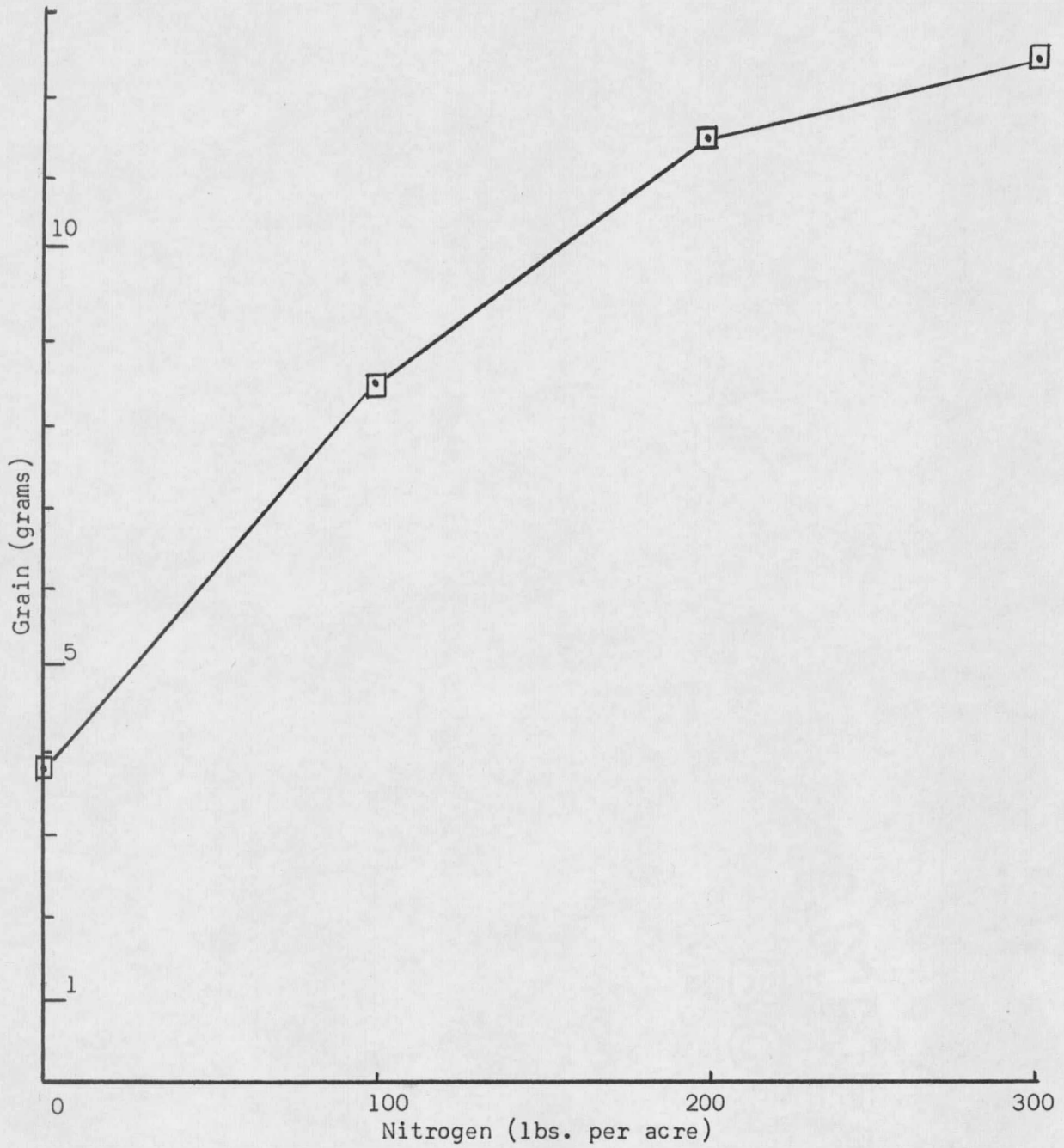


Figure 6. Barley grain produced from four rates of nitrogen (application on the soil surface).

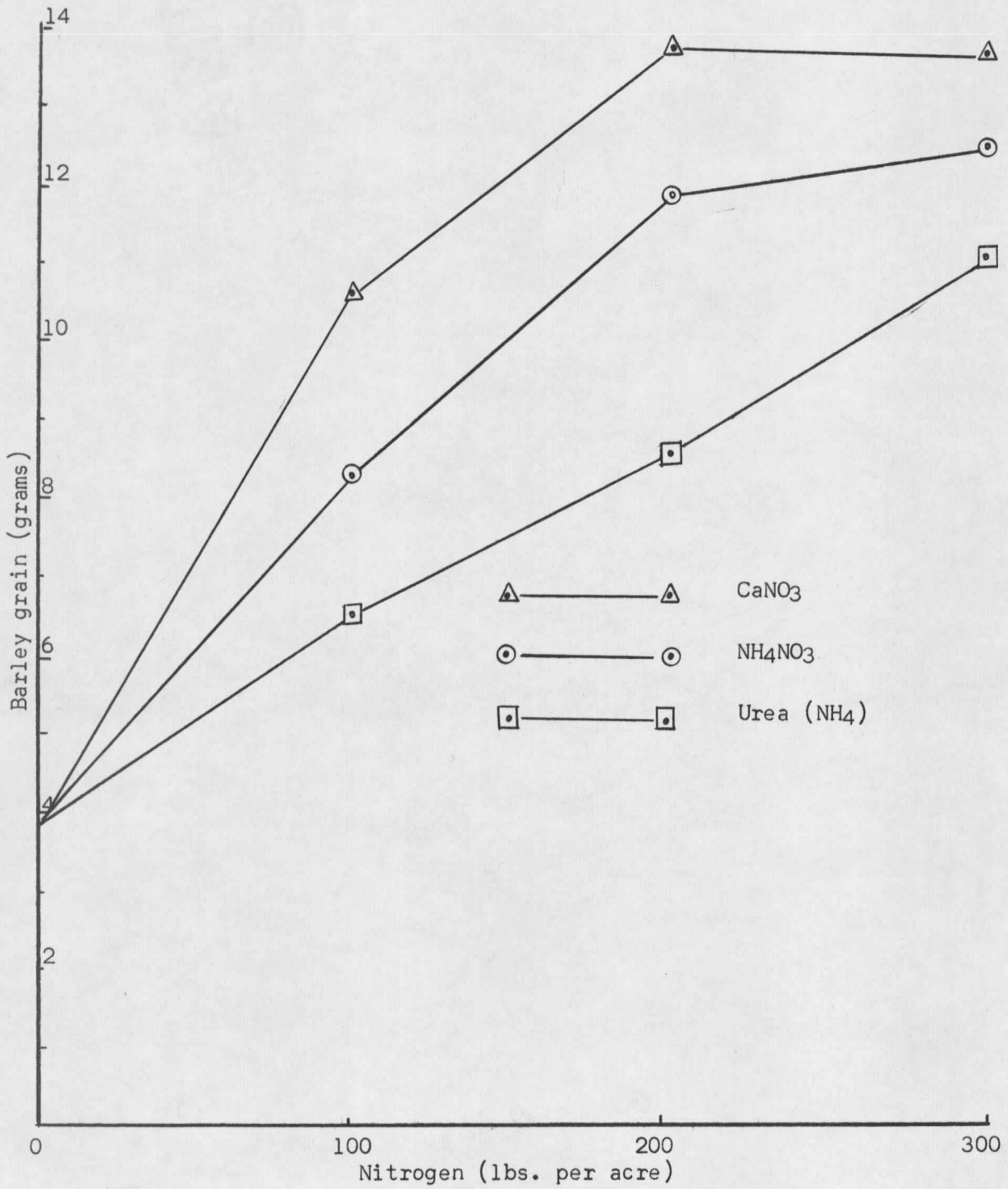


Figure 7. Comparison of barley grain weights when three nitrogen sources were applied at four rates on the soil surface.

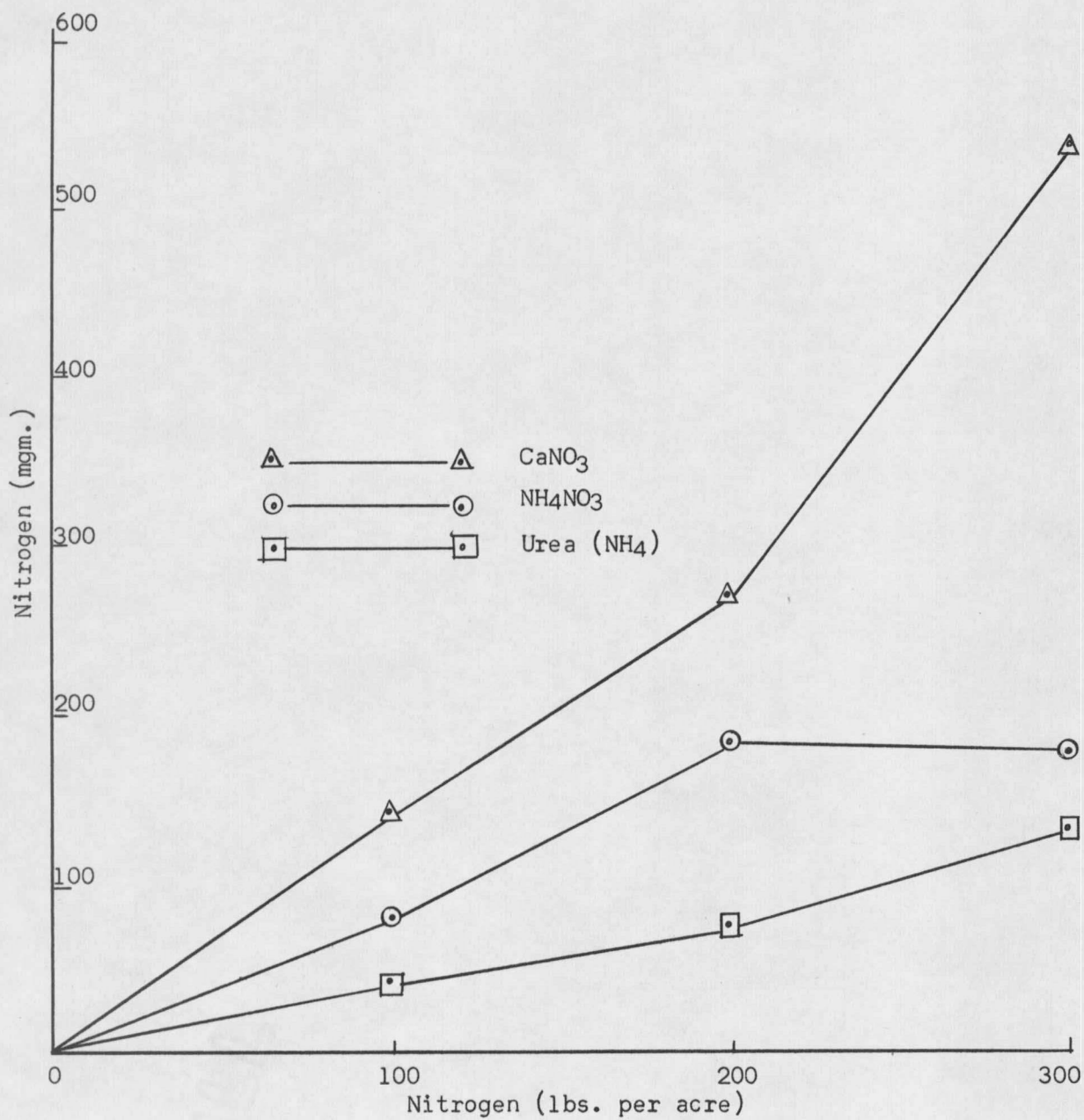


Figure 8. Comparison of milligrams of nitrogen recovered when three nitrogen sources were applied at three rates on the soil surface.

Table X. Average milligrams of nitrogen uptake in barley plant material with surface applications of nitrogen.

Treatment		Minimum moisture, 50% mgm.	Minimum moisture, 75% mgm.	Means	
Rate (lbs. N/A)	Nitrogen source			Moisture level mgm.	Nitrogen rate mgm.
0	CaNO ₃	103	106	105	
0	NH ₄ NO ₃	104	94	99	
0	Urea (NH ₄)	103	106	105	103
100	CaNO ₃	246	243	245	
100	NH ₄ NO ₃	189	178	183	
100	Urea (NH ₄)	138	151	144	191
200	CaNO ₃	394	356	375	
200	NH ₄ NO ₃	276	291	283	
200	Urea (NH ₄)	186	181	184	281
300	CaNO ₃	580	703	642	
300	NH ₄ NO ₃	326	328	327	
300	Urea (NH ₄)	241	235	238	402
Moisture treatment means		241	248		

Table XI. Multiple comparison tests for mean separation of nitrogen content data from greenhouse experiment.

Nitrogen source x rate interaction--SSR mean separation, 5% level			
Rank	Rate (lbs. N/A)	Nitrogen source	Mean weight. plant material* mgm.
A	0	NH ₄ NO ₃	99
B	0	Urea (NH ₄)	105
C	0	CaNO ₃	105
D	100	Urea (NH ₄)	144
E	100	NH ₄ NO ₃	183
F	200	Urea (NH ₄)	184
G	300	Urea (NH ₄)	238
H	100	CaNO ₃	245
I	200	NH ₄ NO ₃	283
J	300	NH ₄ NO ₃	327
K	200	CaNO ₃	375
L	300	CaNO ₃	642

Nitrogen source means:

	Nitrogen source		
	CaNO ₃	NH ₄ NO ₃	Urea (NH ₄)
Milligrams	341	223	168
L.S.D. .01 = 31			
.05 = 24			

The average milligrams of nitrogen recovered above the check treatments and the percent nitrogen recovered from the different treatments are reported in table XII. The application of the nitrate source on the soil surface as calcium nitrate resulted in the highest amount of nitrogen recovered, while urea gave the lowest nitrogen uptake.

The weight of barley plant material produced in the second greenhouse experiment is shown in table XIII. Fertilizer materials were thoroughly mixed in the soil in this experiment. The analysis of variance shows a significant difference due to nitrogen rate. However, none of the other treatments showed a significant difference. The weight of grain produced in this experiment is given in appendix table XXIX, showing a significant increase in grain yield due to the increased rates of nitrogen. The percent nitrogen contained in the total plant material appears in appendix table XXX. The average milligrams of nitrogen uptake as determined from the plant material weight and nitrogen percentage data are given in table XIV. The analysis of variance of this data shows significant differences in the milligrams of nitrogen uptake at the different rates of nitrogen application. Figure 9 shows very little difference in plant material weight among the four nitrogen sources at the two nitrogen rates excluding the check. The average milligrams of nitrogen recovered above the check treatments and the percent nitrogen recovered are given in table XV. Nitrogen source differences were not evident in this experiment, while the amount of nitrogen recovered was good from all the sources at the two rates of application.

Table XII. Average milligrams of nitrogen recovered above check treatments and percent nitrogen recovered of added nitrogen (surface applications of nitrogen).

Treatment Nitrogen source	Mgm. of nitrogen applied	Minimum moisture, 50%		Minimum moisture, 75%	
		Mgm. recovered	% Nitrogen recovered	Mgm. recovered	% Nitrogen recovered
CaNO ₃	265	143	54.0	137	51.7
NH ₄ NO ₃	241	85	35.3	84	34.9
Urea (NH ₄)	234	35	15.0	45	19.2
CaNO ₃	530	290	54.7	249	47.0
NH ₄ NO ₃	481	172	35.6	197	41.0
Urea (NH ₄)	469	73	15.6	75	16.0
CaNO ₃	795	476	59.9	597	75.1
NH ₄ NO ₃	722	121	16.8	234	32.4
Urea (NH ₄)	703	138	19.6	129	18.3
Moisture treatment average		170	34.1	194	37.3

Table XIII. Average weight of plant material when nitrogen materials were mixed with the soil.

Nitrogen source	Nitrogen rate (lbs. N/A)			Mean nitrogen source
	0	100	200	
	gm.	gm.	gm.	gm.
CaNO ₃	18.7	34.2	45.2	32.7
KNO ₃	18.3	35.9	45.6	33.3
NH ₄ NO ₃	18.8	34.8	45.6	33.0
Urea (NH ₄)	18.8	33.5	41.5	31.3
Nitrogen rate mean	18.6	34.6	44.5	32.6

Analysis of variance of barley plant material weight

Variance	df	SS	MS	F
Replication	2	25.7	12.9	4.16*
Rate	2	4,074.6	2,037.3	657.2**
Source	3	22.1	7.4	2.4
Source x rate	6	22.3	3.7	1.2
Error	22	69.0	3.1	
Total	35	4,213.7		

* Significant at the 5% level.

**Significant at the 1% level.

Table XIV. Average milligrams of nitrogen uptake when nitrogen materials were mixed with the soil.

Nitrogen source	Nitrogen rate (lbs. N/A)			Mean nitrogen source
	0	100	200	
	mgm.	mgm.	mgm.	
CaNO ₃	182	377	557	372
KNO ₃	172	392	557	374
NH ₄ NO ₃	188	400	571	387
Urea (NH ₄)	172	375	552	366
Nitrogen rate mean	179	386	559	375

Analysis of variance of nitrogen uptake in barley plant material

Variance	df	SS	MS	F
Replication	2	0	0	
Nitrogen rate	2	.872	.436	121.1 *
Source	3	.002	.0007	1.94
Source x rate	6	0	0	
Error	22	.008	.0036	
Total	35	.882		

*Significant at the 5% level.

Table XV. Average milligrams of nitrogen recovered above check treatments and percent recovered of added nitrogen (nitrogen mixed with the soil).

Treatment	Nitrogen rate (lbs. N/A)					
	100			200		
	Mgm. N added	Mgm. N recovered	% N recovered	Mgm. N added	Mgm. N recovered	% N recovered
CaNO ₃	209	195	81.6	417	375	78.5
KNO ₃	195	220	91.7	389	385	80.2
NH ₄ NO ₃	197	209	86.7	393	383	79.5
Urea (NH ₄)	198	202	86.3	395	380	81.2

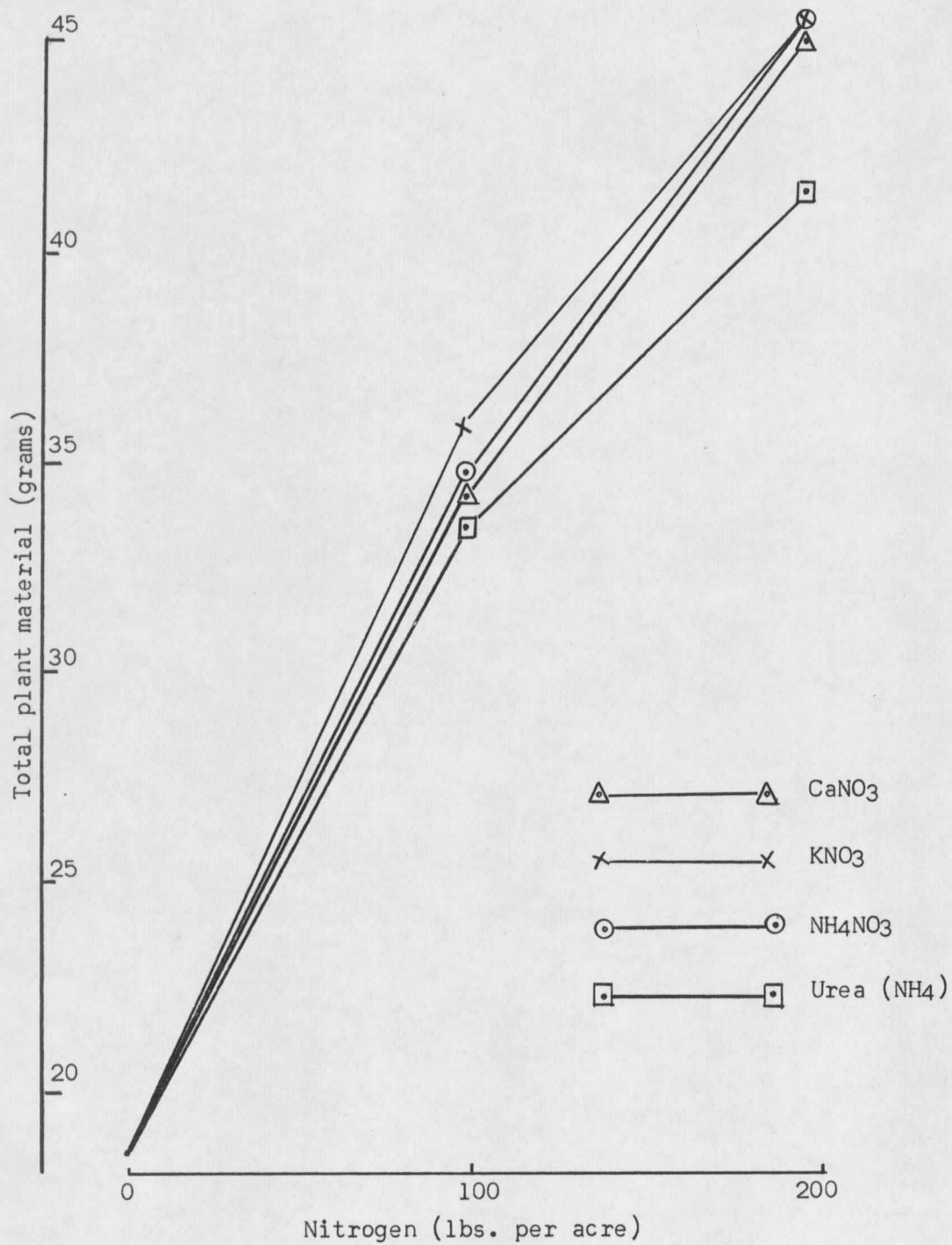


Figure 9. Comparison of total plant material weights when four nitrogen sources were applied at three rates by mixing the fertilizer with the soil.

Aggregation Analyses

Dispersion ratio was measured on the surface inch of the pots from the experiment where nitrogen application was on the surface. Treatments analyzed were urea and calcium nitrate at the rate of 300 pounds of nitrogen per acre and the check pots of three replications. Results are given in table XVI. The check and urea-treated soils contained significantly larger amounts of silt plus clay in suspension in the non-dispersed sample. Treatment with calcium nitrate produced a more stable aggregate.

Ammonium Fixation

Table XVII shows the milliequivalents of ammonium fixed by the Bowdoin clay soil. The value reported is about eight times the value of 1.0 meq. per 100 gm. of soil, frequently reported to be a maximum for most soils.

Ammonia Volatilization Measurement

Milliequivalents of ammonia volatilized from the clay soil following treatment and the equivalent milligrams of ammonia are reported in table XVIII. These results show that only a small percent of the nitrogen applied to the soil was volatilized in the form of ammonia. Although the two materials produced the same amount of ammonia, less was volatilized from ammonium nitrate.

Table XVI. Measurement of dispersion ratio of untreated Bowdoin clay and soil treated with nitrogen materials (grams of silt plus clay in a liter suspension of a 50-gm. soil sample).

Treatment		Rep.	Gm. per liter		Gm. silt + clay aggregated	Dispersion ratio	Average dispersion ratio
Rate	Nitrogen source		silt + clay in suspension				
(lbs. N/A)			Undispersed	Dispersed			
0	Check	1	31.6	46.4	14.8	.68	.63
		2	28.5	46.9	18.4	.61	
		3	28.9	47.3	18.4	.61	
300	CaNO ₃	1	27.6	47.9	20.3	.58	.45
		2	17.6	47.0	29.4	.37	
		3	19.4	47.5	28.1	.41	
300	Urea (NH ₄)	1	31.2	47.0	15.8	.66	.67
		2	36.6	48.4	11.8	.75	
		3	29.4	48.4	19.0	.61	

Analysis of variance of aggregated silt plus clay (grams)

Source	df	SS	MS	F
Replication	2	35.9	17.95	1.52
Treatment	2	187.2	93.6	7.93*
Error	4	47.2	11.8	
Total	8	270.3		

Treatment means—grams of silt plus clay aggregated

Check	CaNO ₃	Urea (NH ₄)
<u>17.2</u>	<u>25.9</u>	<u>15.5</u>

L.S.D. .05 = 6.47

Table XVII. Measurement of ammonium fixation in Bowdoin clay under air-dry conditions.

	Sample		Average
	1	2	
Milliequivalents of ammonium fixed per 100 gm. of soil	7.20	10.40	8.80

Table XVIII. Milliequivalents of ammonia volatilized from Bowdoin clay.

Treatment	Mgm. of nitrogen applied as ammonia	Meq. volatilized	Mgm. of nitrogen volatilized	% Volatilized of added material
Urea (NH ₄)	88.2	.49	6.77	7.7
NH ₄ NO ₃	88.1	.20	2.82	3.2

DISCUSSION

The results presented from the greenhouse studies suggest that nitrogen loss could be through any of three means. The presence of a large internal surface area of the clay minerals in the soil would indicate the possibility of ammonium fixation. Since the soil is slightly alkaline, the volatilization of ammonia could be expected to occur during the drying of the moist clay. Also, surface application of the fertilizer material could result in increased volatilization by the addition of a material with an alkaline reaction since the soil could become highly alkaline in the zone of application. The high clay content of the soil and the high moisture-holding capacity give an indication that elemental nitrogen could be lost through denitrification. In the clay soil, the pore space is largely filled with water at the lower tensions, giving rise to local anaerobic conditions.

Some significance can be attached to the difference in response from the two greenhouse experiments where the nitrogen materials were applied on the surface in one experiment while the materials were mixed with the soil in the other experiment.

The results of the first greenhouse experiment indicated a low nitrogen recovery from the ammonium source. Table XII shows that 15 to 20% of the applied nitrogen was recovered from the urea treatment at the different rates. When only half the nitrogen applied was in the ammonium form, 30 to 35% of the applied nitrogen was recovered under different rates of application. The percent nitrogen recovered was still greater when the nitrogen source was in the nitrate form. These differences

could be due either to the loss of ammonia by volatilization or through the fixation of the ammonium ion.

It was believed that denitrification played only a small part in the nitrogen loss measured. Table XII shows that 30 to 50% of the nitrate nitrogen applied was not recovered in the plant material; however, it was speculated that some of the nitrogen was utilized in root growth and some still remained in the soil. The amount of the added nitrogen remaining in the soil was not determined since it was felt that the error in the measurement of total nitrogen would be greater than the amount of applied nitrogen actually remaining.

Further conclusions of the type of nitrogen losses occurring and the conditions under which they occur were made from the nitrogen uptake of the greenhouse experiment where the nitrogen applications were mixed with the soil. Wahhab (1957) and other workers have shown that placement is a factor in ammonia volatilization.

The results of the second experiment (table XV) showed good nitrogen recovery with all sources from all levels of application. The possibility of any appreciable loss occurring through denitrification in Bowdoin clay was ruled out. The nitrogen recovered in the plant material from the calcium nitrate source in this greenhouse experiment was also high, although nitrogen placement was in a zone of poorer aeration. Deeper placement or mixing the material with the soil did reduce the losses from the ammonium source. The sources of nitrogen applied at two rates showed that 80 to 90% of the nitrogen applied was recovered (table XV). This was an improvement over the percent

recovered from the ammonium source (table XII).

The differences in nitrogen recovery noted in the two greenhouse experiments were due mainly to nitrogen placement. While the ammonium source placed near the surface could have been lost by means of volatilization, as explained by Wahhab (1957), there is a possibility of positional unavailability. In a clay high in cation exchange capacity, such as Bowdoin clay, much of the ammonium source applied on the soil surface would be absorbed by the clay. The ammoniacal nitrogen held at the surface is not subject to leaching, and plant roots could not reach it, particularly after the soil surface became dry previous to watering. While this is not a nitrogen loss, it may have been responsible for the apparent loss; however, urea would not be absorbed as readily as other ammonium materials.

Since the greenhouse experiment where nitrogen was applied on the soil surface showed poor recovery from the application of the ammonium source, a measurement of ammonia volatilization and ammonium fixation was made on this soil in the laboratory.

The ammonium fixation measured on Bowdoin clay of 8.8 meq. per 100 gm. of soil was substantial (table XVII). Fixation was measured on a sample which was treated with the ammonium ion, then air dried. Moody⁷ found the wet ammonium-fixing capacity of the Bowdoin clay to be 0.43 meq. per 100 gm. of soil. These data indicate that major amounts of the ammonium ion are fixed on drying. Conditions for fixation on drying

⁷Moody, C. Dawson. Personal communication.

would exist on the soil surface either in the field or in greenhouse pots. On the basis of an acre furrow slice, this soil showed the capacity to fix 1,700 pounds of nitrogen per acre. While this maximum fixation of ammonium does not take place in one fertilizer application since all the ammonium applied would not be situated between the crystal lattice, a substantial loss due to fixation could occur. The soil moisture content under the soil surface would not dry completely, preventing maximum fixation.

The amount of ammonia volatilized was very slight. Only 3 to 7% of the nitrogen applied on the surface was lost and collected as a gas. (table XVIII). While appreciable losses would be expected to occur from a soil with an alkaline pH, the high cation exchange capacity of the soil apparently maintained the concentration of ammonium ions in the soil solution at a low level, resulting in only a small amount of ammonia being volatilized. Volatilization was measured as the soil dried; this condition is typical in the field and greenhouse.

The loss of twice as much ammonia from the urea-treated soil as from the ammonium-nitrate-treated soil was perhaps due to an increase in alkalinity when the ammonium carbonate was formed from urea. If this soil is low in carbonates, volatilization losses would be less from ammonium nitrate than from urea because urea is the only material that would form ammonium carbonate in any appreciable amount. Appreciable amounts of ammonium carbonate would have to be formed to get substantial losses at the pH (7.7) of the soil.

While significant amounts of ammonia were not released from the soil

as a gas during the incubation period in the laboratory, the occurrence of volatilization should not be ruled out. It is possible that ideal conditions for extensive ammonia loss were not present during incubation in the laboratory.

While incubation was for a period of 7 days, it is doubtful whether continued incubation would have shown any greater loss, since the soil surface was dry at the end of the incubation period. As reported by Wagner and Smith (1958), the largest amount of ammonia was found to be present during the first week of incubation with urea applications. Following this period, the amount of ammonium nitrified increased. It is doubtful whether rewetting of the soil would have shown any greater volatilization of ammonia.

While Caster (1942) and Morrill and Dawson⁸ report a lag in the formation of nitrate in some alkaline soils with an accumulation of nitrite and Wahhab and Uddin (1954) give evidence of the spontaneous decomposition of nitrite, it is doubtful if this loss occurs in the alkaline Bowdoin clay. Since no appreciable loss occurred from the application of ammoniacal nitrogen when the materials were mixed with the soil, it is unlikely that this loss occurs in the clay soil.

While the fertilizer materials were selected in order to avoid any side effects, an improvement in soil structure was noted where calcium nitrate was applied on the soil surface. It was also shown that the calcium nitrate at the 300 pounds N per acre application improved

⁸Morrill and Dawson, loc. cit.

aggregation (table XVI). This would be associated with the addition of the calcium ion. The improved structure may have resulted in improved soil aeration and increased root development, resulting in more efficient use of the nitrogen. Mean separation of milligrams of nitrogen recovered in this experiment shows that the recovery of calcium nitrate at 300 pounds N per acre was significantly greater than the recovery from any of the other sources and rates. This increased recovery could have been influenced by the improvement of soil structure. The improvement of soil structure also may have resulted in more nitrogen being released from the soil organic matter, increasing nitrogen uptake.

While this effect is not directly concerned with nitrogen loss, it is mentioned since it could have been a factor in this study.

SUMMARY AND CONCLUSIONS

The treatment of greenhouse pots with ammonium and nitrate sources of nitrogen and the measurement of the resulting nitrogen uptake by barley plants was selected as a means of exploring the type of nitrogen loss or losses which occur from Bowdoin clay. Nitrogen loss from the nitrogen sources applied would be reflected in the amount of nitrogen uptake of the plant grown under various nitrogen source treatments, since nitrogen loss would mean a reduction in the nitrogen available to the plant.

Pots treated with the ammonium source did not show as large a nitrogen uptake as pots treated with the nitrate source when the nitrogen materials were applied on the surface. Similar treatments showed no differences in nitrogen uptake between the sources when the nitrogen was mixed with the soil. Furthermore, 80 to 90% of the applied nitrogen was recovered.

From the results of these experiments, it can be concluded that nitrogen loss could be due to either ammonium fixation or ammonia volatilization. There was no evidence in support of appreciable loss by denitrification.

Direct measurement of ammonia volatilization and ammonium fixation was made on Bowdoin clay. The results of these determinations showed that nitrogen loss was due largely to ammonium fixation upon drying of the clay soil. Losses due to volatilization were very small.

Nitrogen placement was a deciding factor affecting nitrogen uptake. Also, there were indications that positional unavailability may have resulted in the decrease in nitrogen uptake from the ammonium source where the materials were applied on the soil surface.

The results of the greenhouse and laboratory experiments indicate that nitrogen loss from Bowdoin clay can be reduced. Placement of nitrogen materials below the soil surface resulted in good nitrogen uptake from all sources. Surface application of a nitrate source would also result in good nitrogen recovery.

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APPENDIX

Table XIX. Tillering data of barley fertilized on the soil surface (pots thinned to 10 plants).

Treatments		Replication					
		1		2		3	
Rate (lbs. N/A)	Nitrogen source	No. tillers over 10	No. grain heads	No. tillers over 10	No. grain heads	No. tillers over 10	No. grain heads
<u>Minimum moisture, 50%</u>							
0	CaNO ₃		10		9*		9*
0	NH ₄ NO ₃		10		10		10
0	Urea (NH ₄)		10		10		8**
100	CaNO ₃		10	1	9*		9*
100	NH ₄ NO ₃		9*		9*		10
100	Urea (NH ₄)		10		8**		10
200	CaNO ₃	1	11	3	13	1 (not headed)	8**
200	NH ₄ NO ₃		10		10		10
200	Urea (NH ₄)		8**		9*		10
300	CaNO ₃	5	15	11	19**	9	19
300	NH ₄ NO ₃		10		8**		9*
300	Urea (NH ₄)		10		10		10
<u>Minimum moisture, 75%</u>							
0	CaNO ₃		10		10		9*
0	NH ₄ NO ₃		10		10		10
0	Urea (NH ₄)		10		9*		10
100	CaNO ₃		10		9*	1	10*
100	NH ₄ NO ₃		10		9		10
100	Urea (NH ₄)		10		10		10
200	CaNO ₃		8**	3	13	3	11**
200	NH ₄ NO ₃		9*		10	1 (not headed)	9*
200	Urea (NH ₄)		10		10		10
300	CaNO ₃	1 (not headed)	11*	11	20*	8	18
300	NH ₄ NO ₃		10		8**		10
300	Urea (NH ₄)		10		10		8**

* 1 smut
**2 smut

Table XX. Tillering data of barley when fertilizer was mixed with the soil (pots thinned to 10 plants).

Treatment		No.	Heads	Comments
Rate (lbs. N/A)	Nitrogen source	tillers over 10	harvested	
<u>Replication 1:</u>				
0	CaNO ₃	0	10	
0	KNO ₃	0	10	
0	NH ₄ NO ₃	0	10	
0	Urea (NH ₄)	0	10	
100	CaNO ₃	3	10	
100	KNO ₃	4	14	
100	NH ₄ NO ₃	5	15	
100	Urea (NH ₄)	7	17	
200	CaNO ₃	12	22	2 plants with 3 tillers
200	KNO ₃	10	20	1 plant with 2 tillers
200	NH ₄ NO ₃	12	21	
200	Urea (NH ₄)	9	19	2 plants with 2 tillers
<u>Replication 2:</u>				
0	CaNO ₃	0	10	
0	KNO ₃	0	10	
0	NH ₄ NO ₃	0	10	
0	Urea (NH ₄)	0	10	
100	CaNO ₃	6	14	1 plant with 2 tillers---not headed
100	KNO ₃	5	15	
100	NH ₄ NO ₃	8	18	
100	Urea (NH ₄)	2	12	
200	CaNO ₃	12	20	1 plant with 2 tillers---headed
200	KNO ₃	12	21	1 plant with 2 tillers---headed
				1 plant with 3 tillers---2 headed
200	NH ₄ NO ₃	15	23	1 plant with 2 tillers---headed
				1 plant with 3 tillers---headed
200	Urea (NH ₄)	12	21	
<u>Replication 3:</u>				
0	CaNO ₃	0	10	
0	KNO ₃	0	10	
0	NH ₄ NO ₃	0	10	
0	Urea (NH ₄)	0	10	
100	CaNO ₃	2	10	
100	KNO ₃	6	15	
100	NH ₄ NO ₃	6	15	
100	Urea (NH ₄)	6	13	
200	CaNO ₃	8	18	3 plants with 2 tillers
200	KNO ₃	9	18	1 plant with 2 tillers
				1 plant with 1 tiller---not headed
200	NH ₄ NO ₃	10	20	2 plants with 2 tillers
200	Urea (NH ₄)	10	19	

Table XXI. Analysis of variance of total barley plant material weight (nitrogen applications at soil surface).

Variance	df	SS	MS	F
Replication	2	8.41	4.21	---
Nitrogen source	2	1,904.10	952.05	41.09**
Nitrogen rate	3	5,678.87	1,892.96	81.70**
Linear	1	5,587.7	5,587.7	234.8 **
Quadratic	1	74.2	74.2	3.12
Cubic	1	16.9	16.9	---
Moisture level	1	19.95	19.95	---
N source x N rate	6	940.62	156.77	6.77**
N source x moisture level	2	113.80	56.90	2.46
N rate x moisture level	3	121.35	40.45	1.75
N source x N rate x moisture level	6	180.79	3.01	---
Error	46	1,066.01	23.17	
Total	71	10,033.90		

Table XXII. Average weight of barley grain harvested with surface applications of nitrogen.

Nitrogen rate (lbs. N/A)	Nitrogen source			Mean nitrogen rate
	CaNO ₃	NH ₄ NO ₃	Urea (NH ₄)	
0	3.86	3.56	3.99	3.80
100	10.67	8.39	6.54	8.53
200	13.85	11.94	8.61	11.47
300	13.77	12.57	11.16	12.50
Nitrogen source mean	10.54	9.12	7.58	9.08
Mean				
	Minimum moisture, 50%		9.03	
	Minimum moisture, 75%		9.13	

Table XXIII. Analysis of variance of barley grain weight with surface applications of nitrogen.

Variance	df	SS	MS	F
Replication	2	0.46	0.23	---
Nitrogen source	2	105.14	52.57	23.26**
Nitrogen rate	3	820.00	273.33	120.94**
Linear	1	758.44	758.44	335.59**
Quadratic	1	61.55	61.55	27.23**
Cubic	1	0.27	0.27	---
Moisture level	1	0.19	0.19	---
N source x N rate	6	51.51	8.59	3.80**
N source x moisture level	2	0.88	0.44	---
N rate x moisture level	3	0.19	0.06	---
N source x N rate x moisture level	6	9.18	1.53	---
Error	46	103.84	2.26	
Total	71	1,091.39		

Table XXIV. Multiple comparison tests for mean separation of barley grain treatment weights.

Nitrogen source x rate interaction--SSR mean separation, 5% level			
Rank	Rate (lbs. N/A)	Nitrogen source	Mean weight plant material* gm.
A	0	NH ₄ NO ₃	3.56
B	0	NO ₃	3.86
C	0	Urea (NH ₄)	3.99
D	100	Urea (NH ₄)	6.54
E	100	NH ₄ NO ₃	8.39
F	200	Urea (NH ₄)	8.61
G	100	NO ₃	10.67
H	300	Urea (NH ₄)	11.16
I	200	NH ₄ NO ₃	11.94
J	300	NH ₄ NO ₃	12.57
K	300	NO ₃	13.77
L	200	NO ₃	13.85

*Treatment comparisons above each bracket versus those below the bracket are significant at the 5% level.

Nitrogen source means:

	Nitrogen source		
	CaNO ₃	NH ₄ NO ₃	Urea (NH ₄)
Mean weight--grams	10.54	9.12	7.58

L.S.D. .01 = 1.17
.05 = .87

Table XXV. Percent nitrogen in barley grain and straw with nitrogen treatments on the soil surface.

Treatment		Replication					
Rate (lbs. N/A)	Nitrogen source	1		2		3	
		Grain %	Straw %	Grain %	Straw %	Grain %	Straw %
<u>Minimum moisture, 50%</u>							
0	CaNO ₃	1.31	.61	1.41	.72	1.34	.53
0	NH ₄ NO ₃	1.31	.66	1.44	.75	1.44	.70
0	Urea (NH ₄)	1.31	.66	1.38	.50	1.44	.58
100	CaNO ₃	1.34	.43	1.44	.62	1.42	.53
100	NH ₄ NO ₃	1.22	.53	1.38	.58	1.38	.53
100	Urea (NH ₄)	1.26	.50	1.31	.54	1.30	.50
200	CaNO ₃	1.65	.58	1.68	.75	1.68	.75
200	NH ₄ NO ₃	1.41	.53	1.42	.53	1.44	.66
200	Urea (NH ₄)	1.30	.53	1.42	.58	1.38	.56
300	CaNO ₃	2.14	1.17	2.11	1.09	1.97	1.04
300	NH ₄ NO ₃	1.73	.61	1.65	.67	1.58	.61
300	Urea (NH ₄)	1.41	.48	1.44	.56	1.44	.54
<u>Minimum moisture, 75%</u>							
0	CaNO ₃	1.33	.67	1.33	.61	1.44	.59
0	NH ₄ NO ₃	1.30	.69	1.30	.62	1.38	.54
0	Urea (NH ₄)	1.33	.67	1.41	.61	1.38	.54
100	CaNO ₃	1.31	.53	1.31	.67	1.42	.48
100	NH ₄ NO ₃	1.41	.56	1.26	.48	1.31	.50
100	Urea (NH ₄)	1.38	.56	1.26	.53	1.44	.62
200	CaNO ₃	1.58	.62	1.26	.67	1.66	.67
200	NH ₄ NO ₃	1.44	.96	1.41	.53	1.38	.43
200	Urea (NH ₄)	1.44	.53	1.38	.50	1.39	.53
300	CaNO ₃	1.97	1.09	2.03	.88	2.13	.94
300	NH ₄ NO ₃	1.60	.54	1.58	.93	1.60	.59
300	Urea (NH ₄)	1.31	.54	1.41	.51	1.28	.56

Table XXVI. Grams of grain and straw produced when nitrogen treatments were applied on the soil surface.

Treatment		Replication								
Rate	Nitrogen	1			2			3		
(lbs. N/A)	source	Straw	Grain	Total	Straw	Grain	Total	Straw	Grain	Total
<u>Minimum moisture, 50%</u>										
0	CaNO ₃	7.89	4.81	12.7	7.77	3.93	11.7	6.77	3.83	10.6
0	NH ₄ NO ₃	7.67	4.23	11.9	8.03	2.77	10.8	7.68	3.02	10.7
0	Urea (NH ₄)	8.23	3.87	12.1	6.27	4.73	11.0	11.18	3.02	14.2
100	CaNO ₃	17.03	12.87	29.9	14.42	9.98	24.4	23.31	9.49	32.8
100	NH ₄ NO ₃	11.96	8.54	20.5	15.93	7.57	23.5	17.68	8.02	25.7
100	Urea (NH ₄)	8.02	7.48	15.5	12.99	5.71	18.7	8.37	7.13	15.5
200	CaNO ₃	10.10	16.40	26.5	28.21	14.59	42.8	25.26	12.24	37.5
200	NH ₄ NO ₃	12.09	12.21	24.3	19.99	12.61	32.6	22.23	11.07	33.3
200	Urea (NH ₄)	14.55	7.45	22.0	16.14	7.96	24.1	14.46	8.04	22.5
300	CaNO ₃	22.19	11.61	33.8	33.46	13.14	46.6	28.59	14.71	43.3
300	NH ₄ NO ₃	25.79	13.31	39.1	8.80	11.05	20.3	20.63	14.07	34.7
300	Urea (NH ₄)	17.30	12.60	29.9	18.23	10.37	28.6	11.27	10.53	21.8
<u>Minimum moisture, 75%</u>										
0	CaNO ₃	10.47	3.73	14.2	9.64	3.36	13.0	7.62	3.48	11.1
0	NH ₄ NO ₃	9.13	3.57	12.7	5.66	3.94	9.6	6.06	3.84	9.9
0	Urea (NH ₄)	7.44	4.26	11.7	11.23	3.67	14.9	5.30	4.40	9.7
100	CaNO ₃	18.48	11.62	30.1	19.25	8.85	28.1	15.40	11.20	26.6
100	NH ₄ NO ₃	14.32	7.68	22.0	10.81	9.19	20.0	10.85	9.35	20.2
100	Urea (NH ₄)	13.33	5.97	19.3	8.60	7.20	15.8	12.15	5.75	17.9
200	CaNO ₃	30.77	9.33	40.1	24.22	15.38	39.6	17.82	15.18	33.0
200	NH ₄ NO ₃	22.13	10.07	32.2	18.33	13.17	31.5	14.08	12.52	26.6
200	Urea (NH ₄)	10.87	8.65	19.5	7.86	10.34	18.2	9.36	9.24	18.6
300	CaNO ₃	28.77	12.83	41.6	49.11	15.09	64.2	51.08	15.22	66.3
300	NH ₄ NO ₃	19.94	14.66	34.6	18.74	8.56	27.3	18.71	13.79	32.5
300	Urea (NH ₄)	16.79	12.11	28.9	14.38	12.12	26.5	16.55	9.25	25.8

