The Effect of Anhydrous Ammonia on Soil

by

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1. Introduction

Ammonia is a simple compound composed of one atom of nitrogen and three atoms of hydrogen and has a characteristically sharp, pungent odor (Andrews, 1956; Sharp, 1966). It has no cumulative toxic effect, however, it has a powerful corrosive action on tissue. Ammonia is a gas under normal conditions of temperature and pressure but is easily compressed and usually is handled as a liquid under pressure. The vapor pressure of ammonia varies with the temperature, increasing as the temperature increases (Table 1). Liquid ammonia boils at $-33^{o}C$ at atmospheric pressure.

Table 1. Relationship of vapor pressure, liquid density and specific volume of ammonia as related to temperature changes (Gillentine and Huey, 1966).

Temperature ^{o}C	Vapor Pressure kg/cm^2	Liquid Density kg/l	Specific Volume l/kg
-33	0	0.71	1.76
-7	2.3	0.68	1.85
4	4.1	0.66	1.89
16	6.5	0.64	1.94
27	9.7	0.63	2.00
38	13.8	0.61	2.06

Ammonia is made by compressing three volumes of hydrogen with one of nitrogen in contact with a catalyst:

$$N_2 + 3H_2 \underset{\longleftarrow}{\overset{catalyst}{\longrightarrow}} 2NH_3$$

The nitrogen is obtained from the atmosphere while the hydrogen is obtained by reacting petroleum products (methane) with steam:

$$CH_4 + 2H_2O \underset{steam}{\overset{\longrightarrow}{\longleftarrow}} CO_2 + 4H_2$$
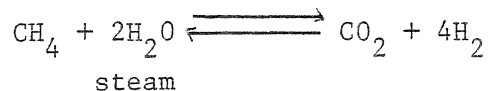
The direct synthesis of anhydrous ammonia was first accomplished in 1908 in Germany with commercial production beginning five years later. The first agricultural use of anhydrous ammonia was through application in irrigation water on citrus groves in Southern California in 1934. Previous to this "ammoniacal liquor" had been used in the fertilization of

crops in England in 1853 (Andrews, 1956).

Direct injection of anhydrous ammonia into the soil was considered for two reasons:

(1) losses of NH_3 were large when applied with irrigation water, and
(2) large dryland farming areas required nitrogen fertilizer.

Experimental work was started in 1944 in Mississippi and by 1947 some use of anhydrous ammonia on a commercial basis by farmers was permitted. In the period of time following 1947, a rapid expansion took place in the development of technology for the direct application of anhydrous ammonia to the soil.

In Western Canada, the use of anhydrous ammonia dates from about 1954 (Johnson, 1977). The volume of anhydrous ammonia has only increased substantially in the last ten years. The expansion in use of anhydrous ammonia in Western Canada has been accompanied by a number of rumors. One set of rumors states that anhydrous ammonia is almost a wonder product which will provide super yields in all cases and the other set of rumors states that anhydrous ammonia will ruin a soil in a matter of a few years.

Therefore, the object of this paper is to report on the effect of anhydrous ammonia on soil from a review of the published literature.

2. Temperature Effects Upon Application to Soil

Liquid anhydrous ammonia injected into soil has a pressure of approximately 10 atm. at the point of release. The resulting rapid varporization followed by expansion of gaseous ammonia causes an initial cooling effect at the release point as indicated by the following endothermic reaction (heat absorbed):

$$NH_3 \text{ (liquid, P = 10 atm.)} \longrightarrow NH_3 \text{ (gas, P = 1 atm.)}$$

$$\Delta \bar{H} = +5.264 \text{ kcal/mole}$$
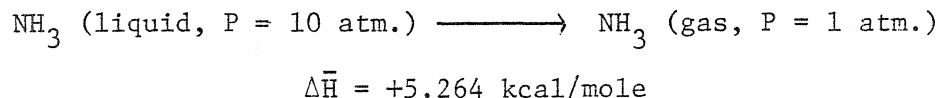
This effect is often observed under field conditions whereby frozen soil accumulates on the injector knives.

The ammonia gas formed can dissolve in water; the result is an exothermic reaction with the release of heat:

$$NH_3 \text{ (gas)} + H_2O \longrightarrow NH_3 \text{ (aqueous solution)}$$

$$\Delta \bar{H} = -8.280 \text{ kcal/mole}$$
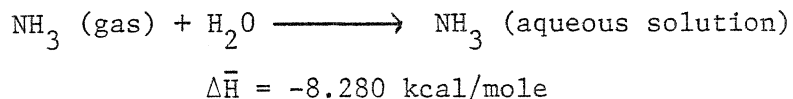
Protonation of the ammonia by surface acidity or protons donated from carboxylic $(-COOH)$ and phenolic $(-C_6H_5OH)$ groups in the soil organic matter results in another exothermic reaction and release of heat:

$$NH_3 \text{ (aqueous solution)} + H^+ \longrightarrow NH_4^+$$

$$\Delta \bar{H} = -13.70 \text{ kcal/mole}$$
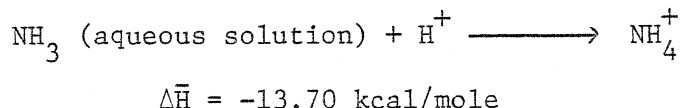
Therefore, the overall temperature effect upon application of liquid anhydrous ammonia to soil would be the heating up of the soil.

Khasawneh and Parr (1968) measured changes in temperature after injection of anhydrous ammonia into a soil. Temperature of the soil increased initially and declined within a few minutes (Figure 1). The greatest increase in temperature occurred at the ammonia release point and progressively smaller changes were recorded with increasing distance from the release point. The amount of heat evolved was of the same order of magnitude as that resulting from the dissolution of ammonia in soil water. From this these workers concluded that protonation of NH_3-N probably continues over a period of days or weeks as ammonia moves outward from the point of injection to react with available protons around the periphery of the retention zone.

3. Retention of Anhydrous Ammonia Applied to Soil

3.1 Reaction mechanisms

Anhydrous ammonia changes from a liquid to a gas immediately after application to soil, and in this highly mobile state would tend to escape to the external atmosphere. However, the NH_3 molecule is highly reactive and in the soil system reacts readily with the various organic and inorganic soil components with the ammonia being retained in a localized, horizontal, cylindrically shaped zone of high ammonia concentration and high pH along the line of injection (Blue and Eno, 1954; McDowell and Smith, 1958; McIntosh and Frederick, 1958; Parr and Papendick, 1966a; Papendick and Parr, 1966; Swart et al., 1971; Khengre and Savant, 1977).

The mechanisms involved in the retention of ammonia in soil may be chemical and/or physical in nature (Parr and Papendick, 1966b). Chemical mechanisms involve high energy level changes and the products are usually quite stable. Physical mechanisms on the other hand involve lower energy level changes with the products being less stable and ultimately subject to other retention mechanisms.

The possible ammonia retention mechanisms for different soil components are (Parr and Papendick, 1966b):

a) Chemical

(i)   reaction of ammonia with a proton to yield ammonium,
(ii)   solubilization of ammonia in water,
(iii)   reaction of ammonia with hydroxyl groups of clay minerals,
(iv)   reaction of ammonia with the tightly bound water of montmorillonitic clay minerals,
(v)   reaction with water of hydration around the exchangeable cations on the exchange complex,
(vi)   formation of coordination compounds (ammoniates) and complex ions (amines) of ammonia in clay systems with the exchangeable cations serving as the nuclei around which coordination and condensation occur.
(vii)   precipitation of Ca^{2+} and Mg^{2+} as carbonates in the presence of CO_2 and freeing the exchange sites for reaction with NH_4^+, and,
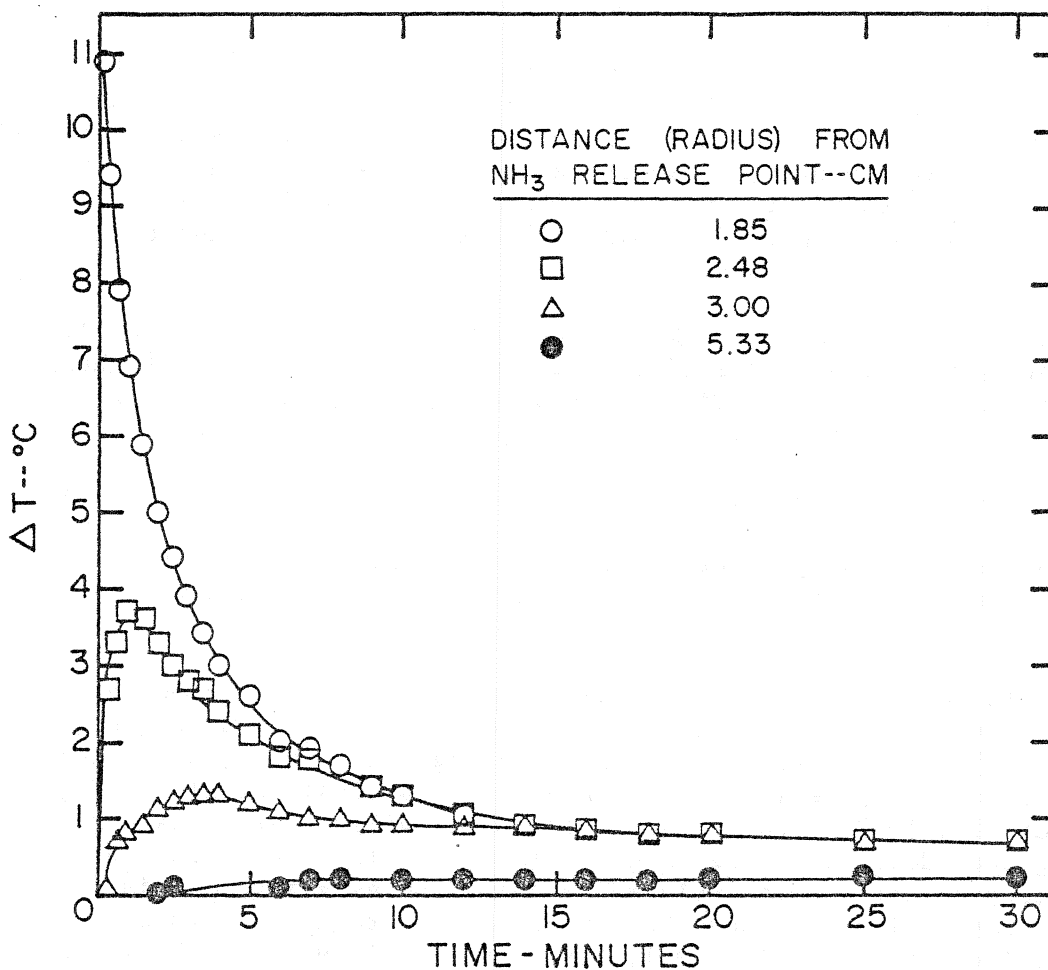
Figure 1. Change in temperature with time at each thermometer position after injection of anhydrous NH into Mountview silt loam. (Khasawneh and Parr, 1968)

(viii) reaction with organic matter.

b) Physical

(i)   entrapment of NH_3 between the lattices of montmorillonitic
        clays,
(ii)   the replacement of interlayer cations in an expanded clay
        lattice by NH_4^+, which in turn causes a contraction of the
        crystal lattice and an entrapment of the NH_4^+, and,
(iii)   adsorption by clay minerals and organic components through
        hydrogen-bonding.

Thus, it is apparent that a number of mechanisms may be involved in
the retention of ammonia in soils. The importance of any one of these
mechanisms to function effectively would depend on the specific properties
of a soil as well as the environmental conditions.

3.2 Techniques to study ammonia in soil

The special properties of anhydrous ammonia dictate that special
techniques be developed to enable the study of retention and reaction
zones.

Field techniques to isolate and sample the reaction zone include
indicator methods on a white background provided by $CaCO_3$ solution (Swart,
et al., 1971) or by filter paper (Parr and Engibous, 1967), and specially
constructed sampling devices (Blue and Eno, 1954; Chalk et al., 1975;
Denmead et al., 1977; McIntosh and Frederick, 1958). Data obtained by
utilizing such devices are presented in Table 2. Techniques to measure
field losses directly have included catching the escaping ammonia in an
inverted trap filled with absorbent materials impregnated with a standard
acid solution (Swart et al., 1971; Baker et al., 1959) and calculating the
aerial transport of ammonia across the downwind edge of a treated field
from measurements of wind speed and direction and atmospheric ammonia
concentrations (Denmead et al., 1977).

Many workers have devised and described methods for injection of
anhydrous ammonia into soils in the laboratory (Anderson, 1960; Jackson
and Chang, 1947; Nommik and Nilsson, 1963; Papendick and Parr, 1965;
Papendick and Parr, 1966; Smiley and Papendick, 1968; Stanley and Smith,
1956). The study of Nommik and Nilsson, (1963) involved an apparatus that
employed a small electric motor to draw a tube through a soil column
while anhydrous ammonia was being released. They then constructed a
sampler to allow precise sampling in relation to the injection point,
These methods resulted in very consistent and reliable data of the type
presented in Table 3.

4. Factors Affecting the Retention of Ammonia in Soil

4.1 Soil moisture

Soils have a greater capacity to retain ammonia as the moisture
content increases (Jackson and Chang, 1947; Blue and Eno, 1954; Stanley
and Smith 1956; McDowell and Smith 1958; Parr and Papendick, 1966a;

Table 2. Ammonia retention in the field at the time of application*
         (McIntosh and Frederick, 1958)

Depth cm	Analysis	cm from applicator row					
		7.5	5.0	2.5	0	2.5	5.0	7.5
0	pH	6.9	6.8	6.8	6.9	6.8	7.0
	NH_4-N ppm	0	0	0	0	0	0
	NO_3-N ppm	8	0	0	0	6	9
5.0	pH	7.2	7.1	7.3	7.2	7.2	6.8
	NH_4-N ppm	0	0	50	81	34	0
	NO_3-N ppm	5	6	10	6	5	8
7.5	pH	7.4	7.5	8.3	8.5	8.1	7.5
	NH_4-N ppm	0	298	592	234	287	58
	NO_3-N ppm	6	14	15	5	14	16
10.0	pH	7.4	8.3	9.5	8.4	9.2	8.1
	NH_4-N ppm	0	251	1215	958	853	251
	NO_3-N ppm	15	28	22	14	30	26
12.5	pH	7.2	7.6	9.2	9.5	9.2	7.9
	NH_4-N ppm	6	133	1021	1103	861	217
	NO_3-N ppm	22	37	41	38	45	41
15.0	pH	6.9	7.4	8.4	9.0	8.4	7.0
	NH_4-N ppm	0	0	218	457	280	0
	NO_3-N ppm	41	53	44	----	56	53
17.5	pH	6.0	6.9	7.0	7.2	7.0	6.9
	NH_4-N ppm	0	0	0	20	0	0
	NO_3-N ppm	46	47	58	54	57	78

* 134 kg N/ha applied.

Table 3. Changes in pH_{aq} and in content of ammonium, nitrite and nitrate nitrogen (ppm) in Gimo soil at different rates of ammonia application. (Nommik and Nilsson, 1963).

Soil moisture content 19%. Incubation temperature, $+18^{\circ}C$

Rate of application, g NH_3-N per m	Distance from line of injection, cm	Incubation period															
		1 day				1 week				2 weeks				4 weeks			
		pH	NH_4-N	NO_2-N	NO_3-N	pH	NH_4-N	NO_2-N	NO_3-N	pH	NH_4-N	NO_2-N	NO_3-N	pH	NH_4-N	NO_2-N	NO_3-N
1.9 (38)**	0-1.5	8.8	915	0.9	27	8.4	745	0.5	34	7.1	403	0.7	157	5.6	39	0.7	202
	1.5-3.0	7.1	173	0.2	26	8.2	326	0.1	60	5.5	119	2.6	139	4.8	18	0.6	164
	3.0-5.0	6.1	10	0.1a	25	5.7	23	---	45	5.3	15	---	92	5.1	8	0.1	114
	5.0-7.0	6.1	8	---	25	5.9	9	---	29	5.9	4	---	42	5.8	3	---	68
	7.0-9.0	6.1	9	---	26	6.0	7	---	26	6.0	5	---	31	5.9	3	---	48
2.9 (58)	0-1.5	9.0	1119	0.8	25	8.5	906·	0.5	24	8.2	700	7.6	95	6.3	156	1.9	229
	1.5-3.0	8.3	489	0.6	27	8.2	600	1.9	39	6.1	267	0.3	178	5.0	69	1.5	204
	3.0-5.0	6.1	20	---	25	6.1	92	---	51	5.2	45	0.1	121	4.9	17	0.3	145
	5.0-7.0	6.1	8	---	22	6.0	7	---	29	5.9	4	---	48	5.8	1	---	85
	7.0-9.0	6.2	8	---	22	6.1	7	---	30	6.0	4	---	31	6.0	3	---	55
6.1 (122)	0-1.5	9.0	1369	1.2	29	8.5	1088	0.9	23	8.5	924	1.9	42	7.9	648	0.6	189
	1.5-3.0	8.8	974	0.9	27	8.5	921	0.6	26	8.3	787	6.9	73	6.2	302	0.5	253
	3.0-5.0	6.6	91	---	28	7.5	380	0.7	45	6.1	246	0.1	137	4.9	104	---	209
	5.0-7.0	6.2	7	---	24	5.8	19	---	38	5.4	25	---	79	5.1	16	---	139
	7.0-9.0	6.2	9	---	26	5.9	4	---	26	5.9	4	---	39	5.7	3	---	86
8.5 (170)	0-1.5	9.9	1530	0.8	24	8.6	1186	2.7	22	8.4	1024	1.1	24	7.9	790	3.4	176
	1.5-3.0	8.7	1081	0.9	23	8.7	1055	2.1	26	8.5	907	4.4	41	6.6	427	1.9	250
	3.0-5.0	6.9	129	0.1	25	8.2	574	1.7	28	7.2	397	0.3	151	5.0	139	---	232
	5.0-7.0	6.3	7	---	23	6.0	6	0.2	30	5.5	56	---	88	4.8	35	---	153
	7.0-9.0	6.2	1	---	25	6.1	5	0.1	33	5.9	4	---	39	5.6	6	---	100
Control		6.1	8		23	6.0	5		28	6.1	3		35	6.0	2		54

* Gimo soil was loam fine sand texture.

** Numbers is brackets are equivalent rates in kg N/ha assuming applicaton at 50 cm spacing.

Khengre and Savant, 1977). This is probably due to the solvent action of water for ammonia. Maximum retention has been found to occur at or near field capacity of the soil with retention decreasing as the moisture content increases or decreases from this level (Figures 2 and 3). The lower retention of ammonia on wet soils possibly occurs because of upward movement and evaporation of water carrying along the dissolved ammonia which is then lost by volatilization. In dry soils there is probably a mass flow out because of pressure (Mortland, 1958).

The size of the initial zone of ammonia retention following both field (Blue and Eno, 1954) and laboratory (Papendick and Parr, 1966; Parr and Papendick, 1966a) applications of anhydrous ammonia has been shown to decrease with increasing soil moisture content. Increasing soil moisture content effectively impedes the initial movement of ammonia from the initial zone of retention (Khengre and Savant, 1977) and results in progressively higher ammonia concentrations within this zone. At very low moisture levels there appears to be a competitive interaction between NH_3 and H_2O molecules for specific adsorption and reaction sites in the soil system (Brown and Bartholomew, 1962; James and Harward, 1964; Young, 1964; Parr and Papendick, 1966a). However, this competitive interaction is effectively obscured in systems where there is sufficient water to act as a solvent for ammonia.

Another important consideration in regards to soil moisture is that it provides proper soil physical conditions to ensure rapid and complete sealing of the injection channel (Parr and Papendick, 1966b).

4.2 Texture

The capacity of a soil to retain ammonia has been found to be directly related to its texture, i.e., the retention capacity increases as the texture becomes heavier (Jenny et al., 1945; Stanley and Smith, 1956; McDowell and Smith, 1958; Swart et al., 1971) (Figure 4). Movement of applied ammonia is greater in sandy soils than in soils with higher clay content as indicated by the size of the retention zone and losses from the soil (Blue and Eno, 1954; McDowell and Smith, 1958). The greater movement in coarser than finer textured soils is due to:

(1) fewer adsorption and reaction sites in sand than in a corresponding volume of silt or clay, and,

(2) sands are more permeable to gases and thus offer less resistance to the rapid movement of the ammonia by mass flow and/or by diffusion during the period immediately following the injection of anhydrous ammonia.

The differences in ammonia retention as characterized by texture would be due primarily to the differences in the surface area per unit mass of soil. Such differences can be obscured by other soil properties such as type and amount of soil minerals, organic matter, moisture content and certain other chemical properties inherent in the soil (Parr and Papendick, 1966b). The interrelationship of these factors along with soil texture would determine to a considerable extent the ammonia retention capacity of a soil. This could possibly explain why little difference in ammonia retention has been observed among different textured soils in
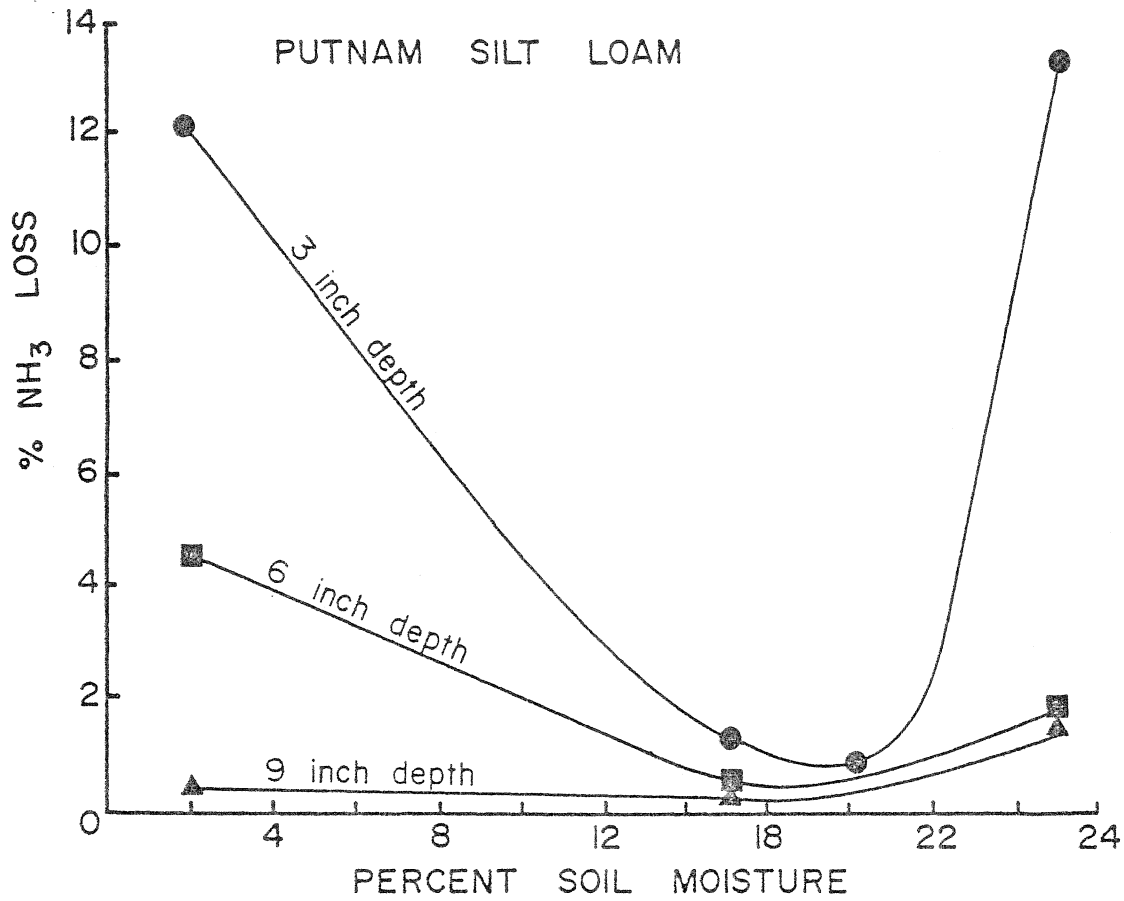
Figure 2. Losses of ammonia from a Putnam silt loam soil as in-
fluenced by depth of application and soil moisture. Anhydrous
ammonia applied at the rate of 100 pounds of nitrogen per
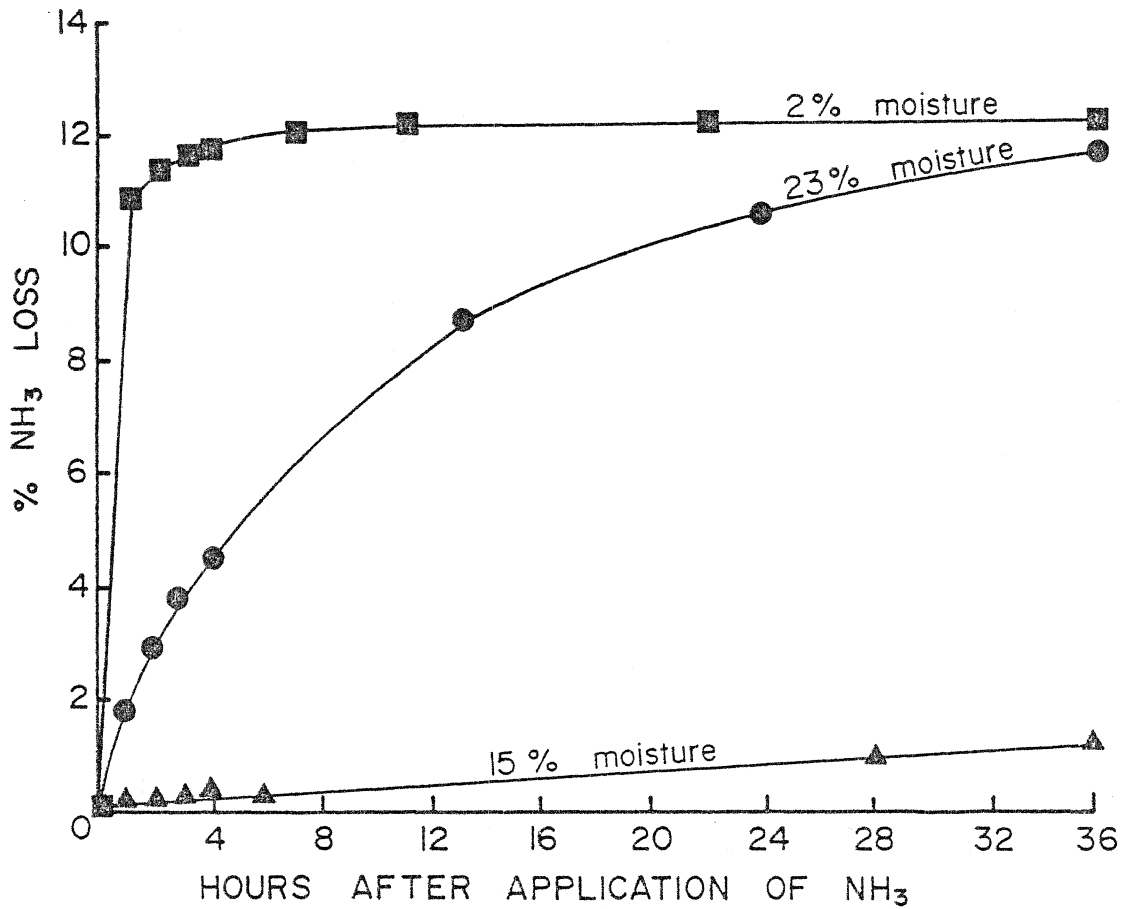acre in 40-inch spacings. (Stanley and Smith, 1956)

Figure 3. Rates of ammonia loss from Putnam silt loam at different soil moistures when applied 3 inches below the surface. Anhydrous ammonia applied at the rate of 100 pounds of nitrogen per acre in 40-inch spacings. (Stanley and Smith, 1956)
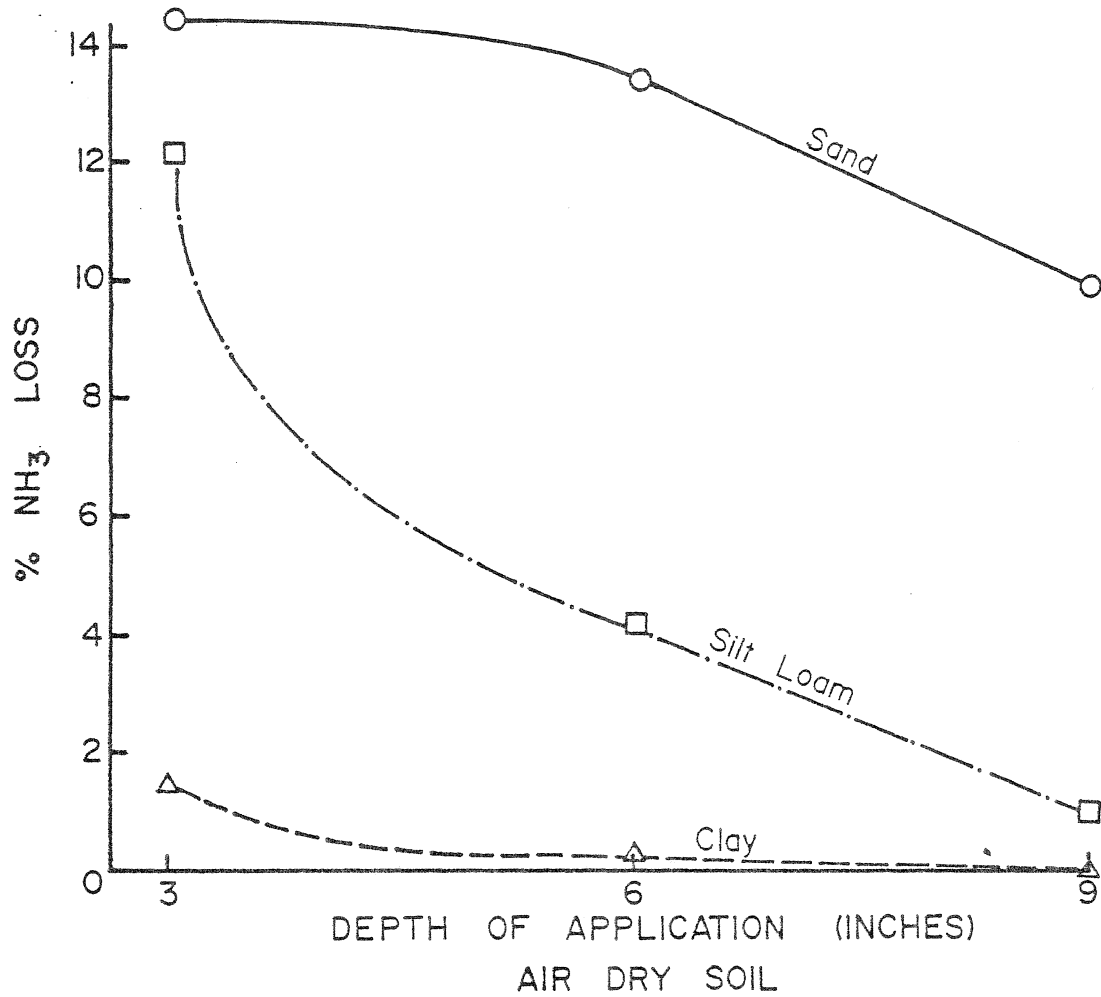
Figure 4. Losses of anhydrous ammonia according to soil texture, and depth of application. Anhydrous ammonia applied at the rate of 100 pounds of nitrogen per acre in 40-inch spacings. (Stanley and Smith, 1956)

some cases (Jackson and Chang, 1947).

4.3 Depth of application

The retention of applied ammonia is generally greater as the depth of application is increased (Jackson and Chang, 1947; Stanley and Smith, 1956; McDowell and Smith, 1958; Baker et al., 1959; Swart et al., 1971). However, the depth required to give maximum retention has been shown to be quite variable. Jackson and Chang (1947) in a lab experiment reported a depth of 2 to 4 inches adequate for maximum retention of ammonia regardless of soil texture. From field applications Baker et al. (1959) showed that retention was the same for ammonia applied at depths of 4 and 8 inches in a silt loam soil. Swart et al. (1971) found no loss of ammonia at a depth of 5 cm for a silt loam soil and 10 cm for a loamy sand soil. McDowell and Smith (1958) in a lab study found that retention was increased 50 to 60% when the depth of application was increased from 3 to 6 inches for sandy loam, silt loam and clay soils. They concluded a 6 inch depth was adequate for maximum retention except on dry sandy soils where losses can be considerable. In another lab study Stanley and Smith (1956) indicated ammonia losses from air-dry sandy, silt loam and clay soils was reduced with increasing depth of application (Figure 2). Thus, selecting the proper depth of application would appear to be important in preventing losses of applied ammonia, especially so in sandy soils.

4.4 Width of application

The smaller the applicator knife spacings the greater is the retention of ammonia in soil (McDowell and Smith, 1958; Swart et al., 1971). The movement of ammonia from the point of injection is relatively small. As a result, it is necessary for a small volume of soil to react with a large volume of gaseous ammonia. That portion of the gas which does not immediately react with the soil is forced toward the surface. There is less resistance to movement toward the surface than to lateral or downward movement. When the concentration of ammonia is reduced per unit volume of soil by narrower spacing of the injector knives, there is a greater efficiency of retention; consequently, less ammmonia is lost to the atmosphere.

The effect of applicator knife spacing is more pronounced for sandy soils than clay soils (McDowell and Smith, 1958). These soils lack the capacity for adsorption of large quantities of ammonia. As well, the closer spacing would provide a more uniform distribution of ammonia in the soil (Swart et al., 1971).

4.5 Tilth of the soil

Effects of soil structure on adsorption of ammonia have not been studied to any great extent. Coarse tilth was reported by Jackson and Chang (1947) to not greatly interfere with the efficiency of ammmonia adsorption after application of anhydrous ammonia. Stanley and Smith (1956) observed in a lab study that ammonia movement and retention were greater in a cloddy soil than where there was good granular structure. They attributed this to more rapid diffusion of the ammonia through the larger pores of the cloddy soil and more rapid contact with active soil

surfaces, resulting in more efficient adsorption.

.4.6 Soil organic matter

Organic matter is important in the retention of ammonia by soils with soils having a high organic matter content generally retaining the most ammonia (Sohn and Peech, 1958; Broadbent et al., 1960; Young, 1964; Nyborg, 1969). It's importance has been shown by a marked reduction in the ammonia retention capacity of soils upon the destruction of the organic matter by oxidation with hydrogen peroxide (Mortland, 1958; Sohn and Peech, 1958). At least 50% of the ammonia retention capacity of soils has been found to be associated with the organic matter.

5. Effect on the Soil Microbial Population

The application of anhydrous ammonia to soil can result in a drastic upset of the soil microbial population with the main effect along the line of injection (Eno and Blue, 1954; Eno et al., 1955; Zrazhevskig and Servy, 1969). The high concentration of ammonia as well as the high soil pH found in the retention zone immediately following the injection of anhydrous ammonia results in a partially sterilized condition. This partial sterilization effect is shown by reduced numbers of bacteria, actinomycetes, fungi (Eno and Blue, 1954; Zrazhevskig and Servy, 1969) and nematodes (Eno et al., 1955) and reduced microbial respiration levels as indicated by CO_2 evolution (Parr, 1969; Zrazhevskig and Servy, 1969) initially following the injection of anhydrous ammonia. The bacteria are probably selectively reduced in numbers by the free ammonia while the fungi are depressed by the high pH. These conditions rapidly change with bacteria and actinomycetes numbers (Table 4) and CO_2 respiration levels (Figure 5) increasing rapidly within a few days. Fungal numbers usually remain depressed until the pH of the soil is reduced. Although, the application of anhydrous ammonia has an effect on the microbial population of the soil it does not seem that it is likely to cause more than a temporarily unbalanced condition in the retention zone.

Table 4. Numbers of fungi, bacteria and actinomycetes in Arredondo loamy fine sand in the ammonia injector row compared with untreated areas (Eno and Blue, 1954).

Day After Treatment	Bacteria X 10^6/g		Actinomycetes X 10^6/g		Fungi X 10^3/g	
	Check	NH$_3$	Check	NH$_3$	Check	NH$_3$
0	2.3	0.3	1.5	0.4	20.1	5.1
3	1.3	6.3	0.9	1.0	20.2	10.4
10	3.1	9.2	0.9	2.0	15.0	9.3
24	1.3	4.2	0.5	1.3	22.7	9.2
31	4.5	3.4	0.4	1.0	20.0	13.3
38	0.9	0.9	0.3	0.7	24.0	4.0

The effect of anhydrous ammonia on soil organisms can also be shown, in part, by measuring its effect on the nitrifying organisms (Eno and
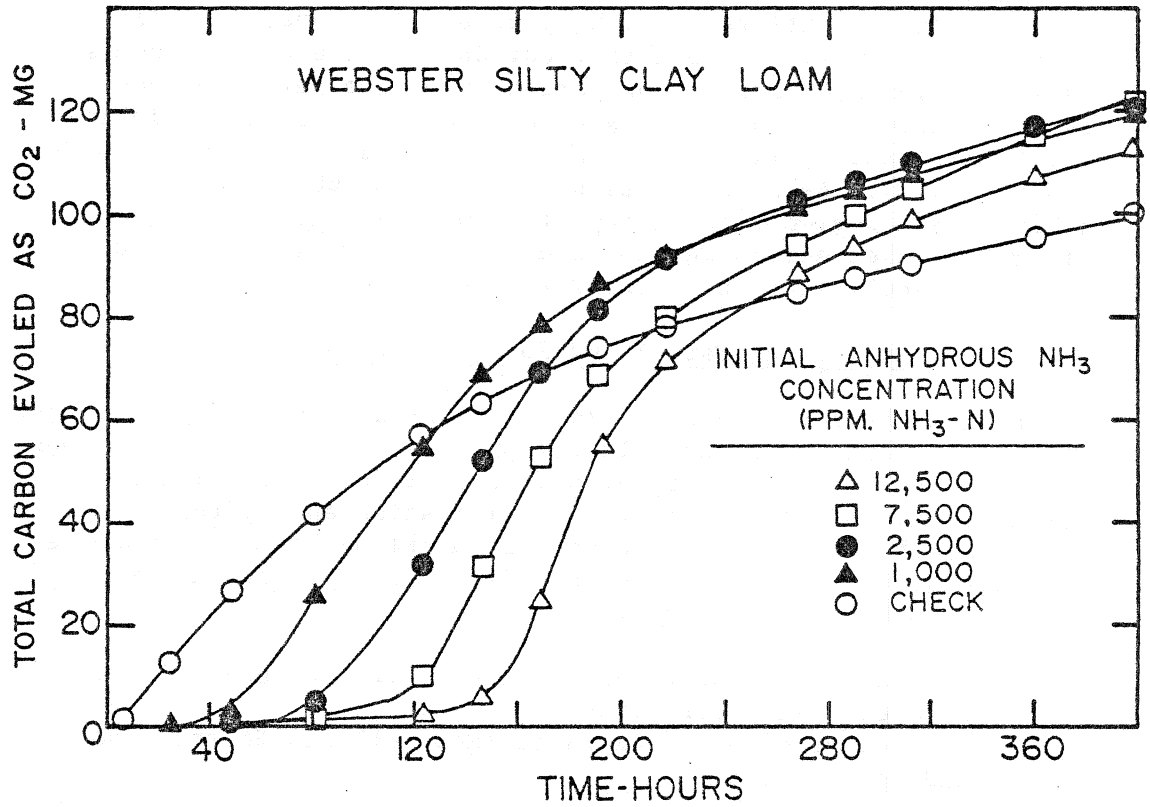
Figure 5. Effect of initial anhydrous ammonia concentration on the cumulative evolution of glucose carbon as CO_2 from Webster silty clay loam. (Parr, 1969)

Blue, 1954; Eno et al., 1955; Eno and Blue, 1957, Humbert and Ayres, 1957; McDowell and Smith, 1958). Like the nematodes, fungi and bacteria in general, the nitrifiers are inhibited by high levels of ammonia. This results in a delay in the nitrification of the applied ammonia. Usually, nitrification proceeds at the periphery of the retention zone where the ammonia concentration and pH are low enough so as not to inhibit the activity of the nitrifiers (McIntosh and Frederick, 1958; Khengre and Savant, 1977). As nitrification proceeds the pH of the soil is lowered (Figure 6) and along with a reduction of the ammonia concentration gradually makes environmental conditions favorable for microbial growth and thus recolonization of the retention zone.

6. Effect on Organic Matter and Soil Structure

Ammonium hydroxide has a strong solvent action, as well as hydrolytic action, on organic matter. Thus, applications of anhydrous ammonia which result in localized regions of high ammonia concentration in the soil might be expected to result in solubilization and hydrolysis of certain fractions of the soil organic matter (Mortland, 1958). Evidence of organic matter solubilization in soil after applications of anhydrous ammonia has been indicated by:

(1) dark areas in the retention zone (Gifford and Strickling, 1958; Papendick and Parr, 1966),
(2) dark color of water extracts (McDowell and Smith, 1958; Epshteyn and Agafonov, 1977),
(3) amount of water soluble organic matter (Mangum and Young, 1965; Zrazhevskig and Servy, 1969), and,
(4) slaking of soil at the centre of the retention zone (Parr and Papendick, 1966b).

Some of these effects are considered to be only temporary and disappear with time.

The increase in the solubilization of organic matter has also been suggested to result in part from the destruction of living organisms as well as from alkalization (Zrazhevskig and Servy, 1969).

Increased aggregate stability due to the solublization of soil organic matter has been suggested (Gifford and Strickling, 1958; Epshteyn and Agafonow, 1977). A possible explanation given for the increased aggregate stability following anhydrous ammonia application is a more uniform distribution of the organic matter upon dissolution and subsequent precipitation as well as the formation of new organic binding compounds after reaction between ammonia and organic matter (Gifford and Strickling, 1958). This increased aggregate stability is generally quite dynamic, changing as time progresses. The effect is limited to that fraction of the soil which is reached by a high concentration of ammonia.

Harmful effects to soil physical conditions have also been indicated upon ammonia application to soil. Jenny et al. (1945) observed reduced water penetration rates on some soils treated with ammonia compounds. As well, the surface application of ammonium nitrate to soils has been shown to cause a deflocculated condition resulting in a crusting of the
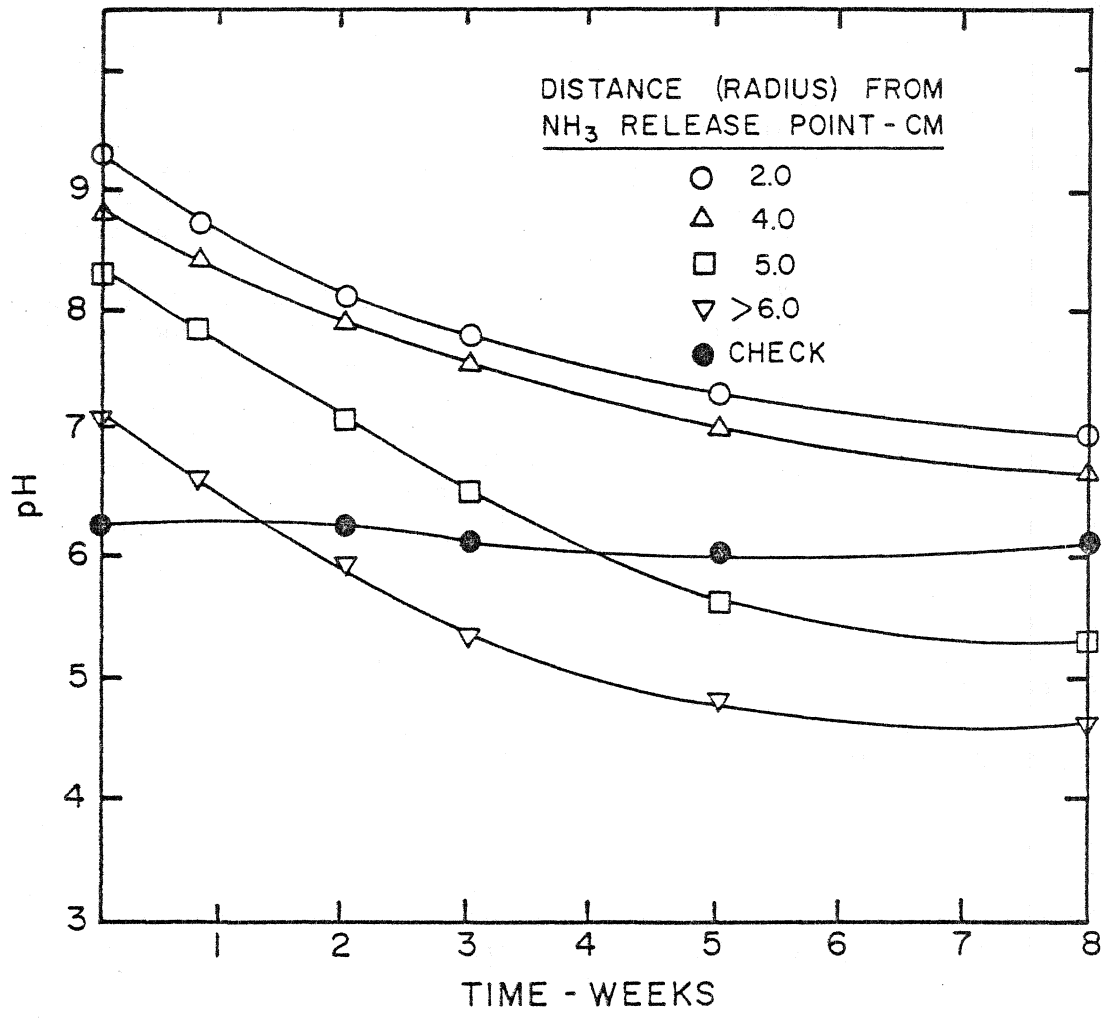
Figure 6. Change in pH with time in Hartsells fine sandy loam at increasing radial distance from the ammonia release point after injection of 680 mg N as liquid ammonia. (Parr and Khasawneh, 1968)

surface soil (Fox et al., 1952). A trend of reduced permeability with increasing rate of $\overline{NH_4^+}$ application results.

7. Effect on the Availability of Plant Nutrients

Since soil reaction affects the solubility and availability of various plant nutrients, applications of ammonia to soil should affect the status of these materials. These effects of ammonia on plant nutrients in soils could be expected to be quite variable and transitory since changes in pH occur (Mortland, 1958). The solubility of mineral forms of phosphorus in the soil would be affected by the change in pH upon ammonia application and in fact such changes have been observed in an increased availability of phosphorus (Stanley and Smith, 1956; Zrazhevskig and Servy, 1969). It is also possible that the ammonia would react with phosphorus compounds to form some of the more soluble ammonium phosphate compounds (Mortland, 1958). The amount of readily available potassium has also been shown to be increased but no effect on the total exchangeable calcium has been observed (Stanley and Smith, 1956). A considerable increase in available manganese has been observed after nitrification of the applied ammonia reduced the soil pH (McDowell and Smith, 1958).

The changes in availability of the plant nutrients occur within the ammonia retention zone. Since this zone occupies only a small volume of the soil in a field the increased availability of some of the plant nutrients would be of little practical importance.

8. Effect on Germination and Seedling Growth

Damage to germinating seedlings by high ammonia concentration has been well documented (Cooke, 1962; Allred and Ohlrogge, 1964; Cummins and Parks, 1961). Current recommendations in Saskatchewan suggest that spring applications of anhydrous ammonia should be made at least 5 days prior to seeding. This recommendation creates major problems in logistics and the need for such a separation time must be critically evaluated.

There has been at least one major study examining the effect of anhydrous ammonia on germination and early growth of corn in Illinois. The study included both field (Colliver and Welch, 1970b) and laboratory (Colliver and Welch, 1970a) components.

The field studies of Colliver and Welch involved application of 0, 112, 224, 448 and 672 kg N/ha at depths of 10, 17.5 and 25 cm based on 76 cm spacings. The applications were made 0, 1 and 2 weeks before planting corn. They found that increasing depth of application was more effective in reducing injury than was time (Figures 7 and 8). Their general conclusion was that delaying seeding just for the purpose of providing a separation time was not justified. A separate field experiment reported in the same paper established that ammonia concentrations in excess of 1000 ppm NH_3-N near the seed significantly reduced the stand of corn.

In a separate laboratory study (Colliver and Welch, 1970b) corn roots were grown into successive layers of soil containing increasing amounts of NH_3 and germination experiments were conducted in soil uniformly mixed with anhydrous ammonia. Germination and early growth was retarded when soil ($NH_3 + NH_4^+$) N concentration reached 944 ppm and essentially completely
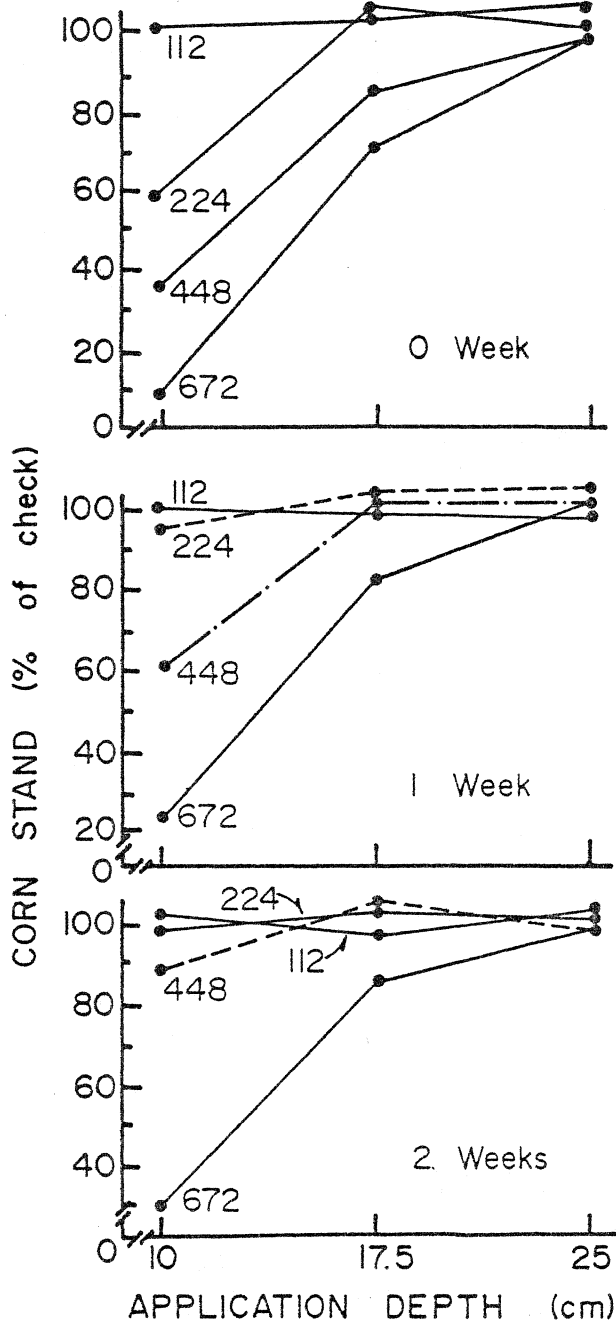
Figure 7. Effect of time, depth, and rate
of NH₃ application on stand 27 days after
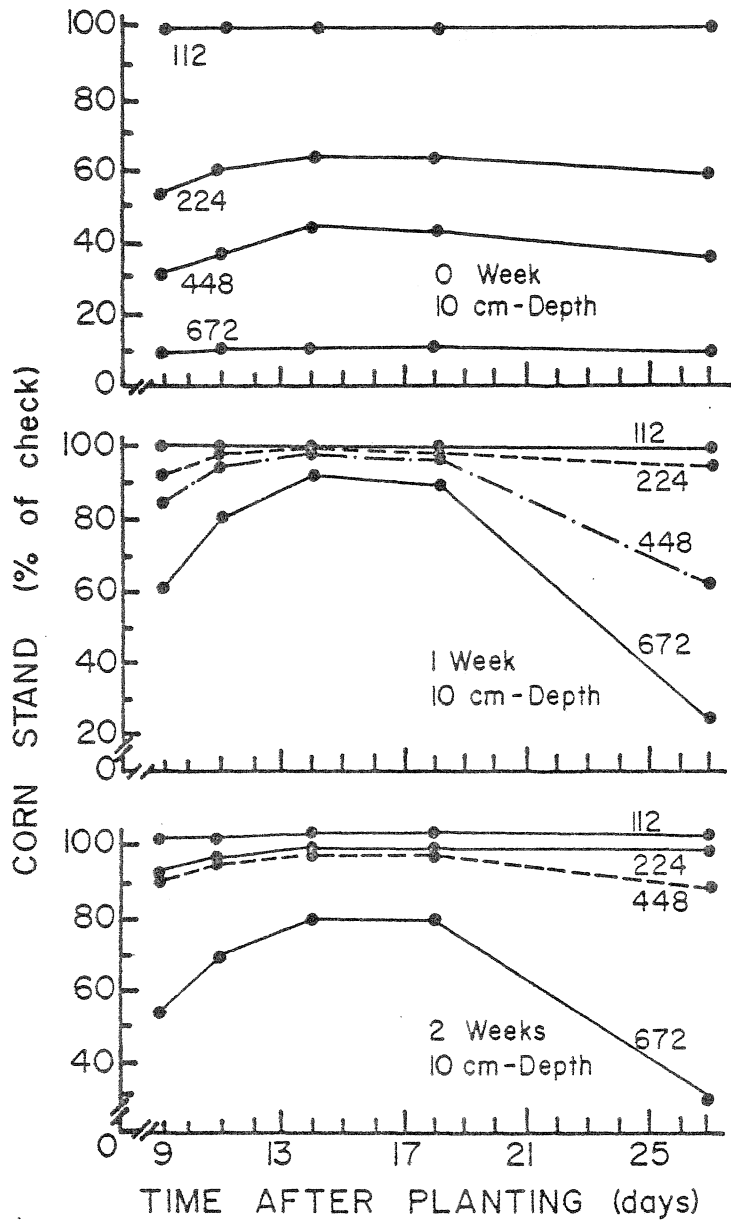planting (numbers by lines are kg/ha of N)
(Colliver and Welch, 1970 a)

Figure 8. Effect of NH₃ applied 10 cm deep at different rates and time intervals on stand at various times after planting (numbers by lines are kg/ha of N. (Colliver and Welch, 1970a)

inhibited when it reached 1628 ppm. Roots grew through 3 cm layers of soil containing 1172 ppm $(NH_3 + NH_4^+)$ N but did not grow into layers containing 1485 ppm $(NH_3 + NH_4^+)N$.

9. Current Status of Ammonia Use in the United States

Frequent inquiries from prospective users indicate that anhydrous ammonia use is declining in several states of the U.S. because of reported soil damage. The authors have had direct correspondence with agricultural scientists in Colorado, Kansas, Montana, Nebraska, North Dakota, South Dakota and Texas. In each case the scientists indicated that anhydrous ammonia use was either increasing or remaining constant, and that they knew of no harmful soil effects from its use. They further stated that in their opinion much of the unfavorable publicity resulted from competition within the nitrogen fertilizer industry.

Therefore there seems to be no credence to the reports of declining or discontinued use of anhydrous ammonia over large areas of the United States.

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