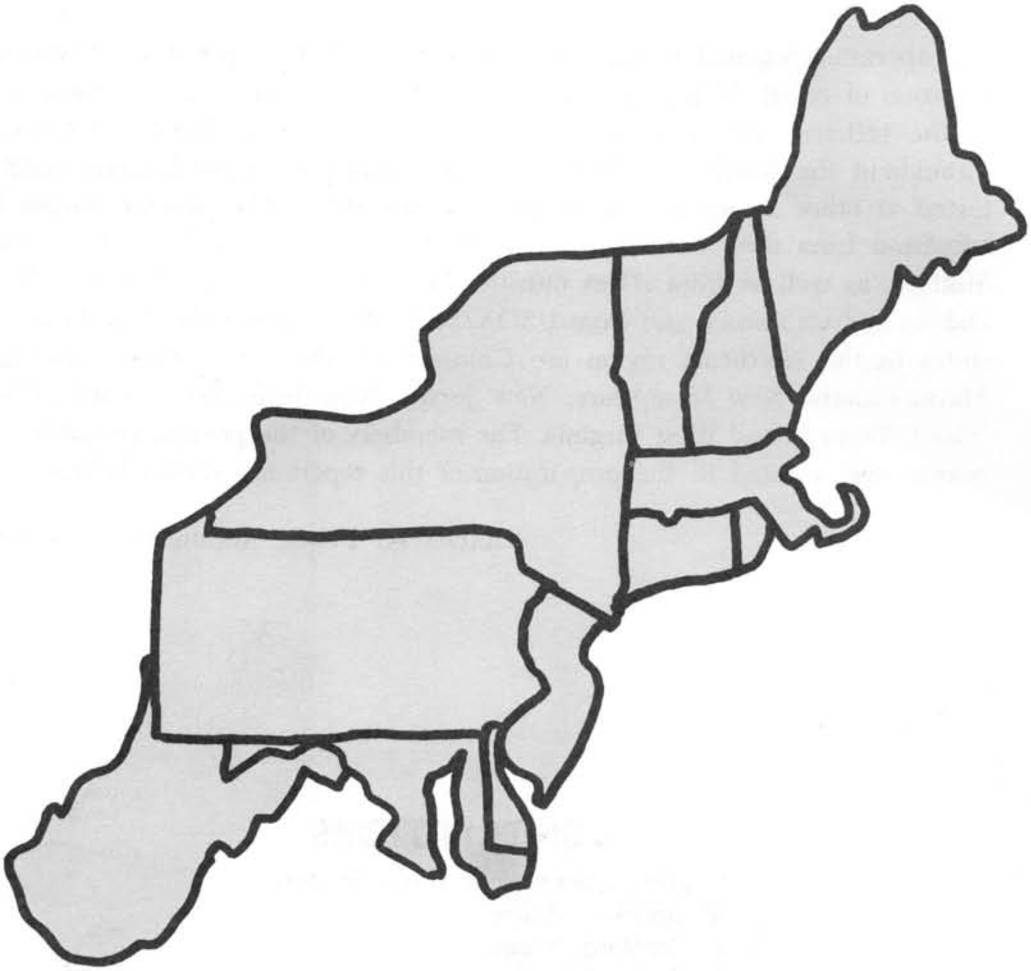
NORTHEAST REGIONAL RESEARCH PUBLICATION PROJECT NE-39

Efficient Use of Nitrogen on Crop Land in the Northeast

Allen V. Barker, Editor



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NORTHEAST REGIONAL RESEARCH PUBLICATION

Project NE-39: Origin, Transformation, and Management of Nitrogen in Soils, Waters, and Plants.

Cooperative regional research is designed to achieve replication without duplication of effort. It is particularly appropriate for examining problems such as the efficient use of fertilizer, since soils, crops and climate vary widely throughout the Northeast. Thus, principles developed at one location must be tested at other locations and modified as necessary. The present project has benefited from contributions from scientists at all the Northeast Experiment Stations, as well as from states outside the region including Michigan, North Dakota and California, and from USDA/SEA/AR at Beltsville, Maryland. The states in the Northeast region are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont and West Virginia. The members of the present research committee who assisted in the preparation of this report are shown below.

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Efficient Use of Nitrogen on Crop Land in the Northeast

Allen V. Barker, Editor

Principles of nitrogen (N) fertilization result from the cumulative knowledge of plant responses to soil fertility and to the environment. Research and experience in fertilizer management, however, continuously modify these principles by adding new ones and strengthening or eliminating old ones.

Nitrogen (N) management for production of crops involves two phases of plant nutrition:

1. The control of available N in the root zone during the growing season.
2. The uptake of N and response by plants to N during their growth, development and maturation.

Uptake curves show the amount of N absorbed by plants as a function of time during the growing season. The time of greatest uptake of N may not be the same as that of the greatest plant response in growth to the available N in the root zone. To obtain the desired final yield and quality of a crop, the levels of available N should be high during the time that plant response to N is maximum.

Nitrogen management systems are being developed to control the available N from soils and fertilizers during the growth, development and maturation stages to obtain reliable, economical and high quality produce and to minimize losses of N to the environment. Ideally, N management practices should control the soil-plant N system from planting to harvest. The management practices should insure that N is adequate for the development of uniform, vigorous seedlings and, during periods of rapid uptake, for the development of sturdy vegetative frames. As the plants approach harvest, available N in the soil should be essentially depleted. Analyses of plant samples at several stages of growth monitor uptake and assimilation of plant nutrients and are helpful in the development of systems of N management in crop production. Soil analyses provide an index of the availability of N during the growing season.

Plant and soil analyses, however, are not the only factors involved in developing a fertilization system for optimum production. The genetic yield potential of the crop variety, physical conditions of the soil, control of pests, and other cultural and environmental factors must be adequate to obtain a positive response to a fertilization system.

Crop Yield Goals in Nitrogen Management

When fertilizers are recommended for specific levels of production, the management program is directed toward a crop yield goal. For instance, if the production goal for corn is 100 bu/acre (6 tons/ha), the N management program should be developed to supply N to the crop in the quantities needed and at the proper time to meet this goal. Applications of recommended amounts of fertilizers do not guarantee reaching the production goals, for all other limiting factors must be corrected.

If all limiting factors are removed, exceptional yields may be obtained. Corn grain yields have approached 350 bu/acre (22 tons/ha) in areas with optimum climates for the crop, but in the Northeast, the maximum corn grain yields with optimum soil regimes for water and fertilizer have been between 200 and 240 bu/acre (12 to 15 tons/ha). These yields are only occasionally reached. For example, yields in research plots in Maryland, New York, and Pennsylvania have rarely exceeded the 200 bu/acre level. Among the nearly 2,000 entries in corn growing contests in Pennsylvania from 1968 to 1978, the 200 bu/acre level has been broken only twenty times, and the maximum yield reported was 239 bu/acre (15 tons/ha). A much more common maximum yield, and therefore yield goal, is about 180 bu/acre (11 to 12 tons/ha) in Pennsylvania and Maryland and 150 bu/acre (10 tons/ha) in New York and New England. It would be wasteful to attempt to fertilize corn for crop yields exceeding these yield goals, using present day production practices and genetic plant material.

Crop yield goals for other common field crops in the Northeast are listed below:

	Yield Goal	
Crop	**Common Units**	**Metric Units**
Corn silage	20 tons/acre	45 tons/ha
Soybeans	40 bu/acre	2.7 tons/ha
Millet	3 tons/acre	6.8 tons/ha
Sudangrass	3 tons/acre	6.8 tons/ha
Sorghum	5 tons/acre	11.3 tons/ha
Alfalfa	5.5 tons/acre	12.5 tons/ha
Clover	3 tons/acre	6.8 tons/ha
Wheat	60 bu/acre	4.1 tons/ha
Barley	75 bu/acre	5.1 tons/ha
Oats	80 bu/acre	2.9 tons/ha
Rye	30 bu/acre	2.0 tons/ha

Moisture and temperature are the principal limitations to yields on fertile, well-managed soils of the Northeast. A recent study for the feasibility of irrigation of corn in Pennsylvania (Kibler et al. 1977) concluded that supplemental irrigation would increase yields in one year out of two. In the sandy soils of the Maryland peninsula, water deficits limit maximum yields to 100 bu/acre (6.3 tons/ha). Cool temperatures, short growing season, and poorly drained soils limit maximum yields in many areas of the region to about 80 bu/acre (5 tons/ha).

In most areas of the region, the maximum yield goals are rarely met, and most farmers, due to limitations in soil, climate and management, attain yields lower than the maximum. Thus, when the average good farmer uses yield goals in N management, crops will be produced more efficiently and fertilization will cause less pollution if yield goals are realistic for the soil and climatic zone.

Fertilization to Meet Crop Production Goals

Nitrogen Fertilization of Corn in the Northeast

Amount

Ideally, the amount of fertilizer N applied to a corn crop is based on knowledge of plant needs, the amount of N that can be expected to be supplied by the soil, and a knowledge of fertilizer N efficiency under local conditions. Stanford (1973) expressed this in a formula $N_f = (N_p - N_s)/E$, where N_f = N fertilizer to apply, N_p = plant N uptake, N_s = N supplied by the soil, and E is efficiency of fertilizer N (i.e., the fraction of N fertilizer that becomes part of N_p).

Determination of N_p is easy. Stanford (1973) found from the literature that N was not limiting corn yields when about 1.2% N was in the above-ground plant at harvest. Experiments in Pennsylvania have shown that at optimum N fertilization rates, 18.5 kg N were in the above-ground dry matter for every ton of grain (15.5% H_2O) produced. Although the value for E can vary considerably, depending on growing conditions and fertilizer N management; it usually ranges between 0.5 and 0.7 (Stanford 1973). Fox & Piekielek in Pennsylvania recently found in experiments with corn over a 3-year period that, where a significant response to N was observed, the average value for E was 0.64. Progress is being made in developing soil tests to estimate N_s (see the section on Predicting Release of Soil Nitrogen), but there are not enough research data to assure that the test will work under all environmental and soil conditions in the Northeast.

Until a N availability test has been developed that is applicable to all conditions, N recommendations will have to be made on the basis of N fertilizer response experiments over a range of conditions. Eighteen field experiments were conducted in Pennsylvania by Fox & Piekielek from 1976 through 1978 to determine optimum N fertilizer rates for corn. The results indicate that recommendations should be: 18 kg N/ha per ton of expected grain yield (1 lb. of N/acre per bu/acre yield) for continuous corn; starter N only for the first year after alfalfa; with 9 kg N/ha per ton of production for the second year after alfalfa; and 15 kg N/ha per ton of production for the third year after alfalfa. In all but one experiment, an increase of one-third for silage corn and a reduction of 2.5 kg N/ha per metric ton/ha of cattle manure and 10 kg N/ha per metric ton/ha of chicken manure applied the previous year was sufficient for maximum yield (Table 1).

The yield in this experiment was higher than the 9.4 tons/ha predicted, and the slight underfertilization that would have resulted if the recommended rate had been used would have lowered yields by only a few percent. The average recommendation for the 18 experiments would have been 27 kg N/ha high. A

Table 1. N fertilizer response and recommendations for corn grain in Pennsylvania

Soil	Year	Grain Yield (15.5% H_2O) Starter N	Optimum N	Fert. N Needed for Optimum (F)	Empirical N Recommend (E)	Error in Recommend (E-F)
		ton/ha		kg/ha		
Murrill I	1976	6.3	9.6	162	169	7
Hagerstown I	1976	10.3	10.8	17	17	0
Berks	1976	8.7	8.7	17	17	0
Hagerstown II	1976	6.0	8.7	152	109	17
Pope I	1976	8.0	9.8	101	152	51
Pope II	1976	6.4	7.9	90	169	79
Murrill I	1977	5.5	11.1	140	169	29
Hagerstown I	1977	10.2	11.4	84	85	1
Hagerstown III	1977	9.7	9.7	17	17	0
Hagerstown IV	1977	7.8	9.3	67	169	102
Pope I	1977	9.8	11.1	96	169	73
Pope II	1977	3.7	11.0	202	226	24
Hagerstown I	1978	6.3	10.5	160	141	− 19
Murrill II	1978	6.8	9.7	129	169	40
Hagerstown III	1978	10.3	10.6	40	85	45
Hagerstown IV	1978	3.5	10.3	165	169	4
Penn	1978	6.0	9.0	112	141	29
Chester	1978	6.9	9.6	162	169	7
Average						24

Expected yield potential was 9.4 tons/ha (150 bu/acre) for all sites except for Penn, where it was 7.8 ton/ha. Data of R.H. Fox and W.P. Piekielek. The Pennsylvania State University.

94 kg N/ha excess would have occurred had the current recommendations of the Pennsylvania Soil Testing Program been followed. The N recommendations for corn in New York by Cornell University (1979) (also based on response experiments) are similar to those proposed above.

Further research is needed to determine the amount of residual N from legumes other than alfalfa and to ascertain if the proposed recommendations will be accurate under a wider range of soils, climate, and management conditions. Additional field experiments for this research can also be used to test the adequacy of proposed indices for soil N availability (N_s) so that fertilizer N recommendations in the future can incorporate the N-supplying capability of a given soil rather than depending on empirically-derived average N response curves.

Sources

Little difference in effectiveness among N fertilizer sources exists when they are incorporated in the soil either before planting or as a sidedress at least 15 cm from the corn plants. Therefore, the most economical and convenient source may be used. The higher residual acidity from $(NH_4)_2SO_4$ should be recognized and the increased cost of liming considered when comparing it to other sources. If the N fertilizer is not incorporated, however, as could be the case with no-till corn, a N source that does not contain urea will minimize volatilization losses. In an experiment on a Murrill silt loam comparing N sources on no-till corn in Pennsylvania, Fox and Piekielek found no differences among sources in two years where a rain fell within 2 days after the N application. In one year with three and one-half rain-free days after N application (1977), significantly lower yields (Table 2) were obtained and less plant N uptake was observed in the plots receiving urea or urea-containing N solution than in those that were fertilized with NH_4NO_3 or $(NH_4)_2SO_4$ at a rate of 118 kg N/ha. Urea also produced significantly lower yields and less plant N uptake was observed at the 218 kg N/ha rate. Bandel and co-workers at the University of Maryland (Bandel 1974, 1975; Bandel et al. 1976) have also shown that with no-till corn, urea-containing fertilizers produce lower yields than NH_4NO_3 (Table 3). Since urea and urea-containing N solutions are becoming the predominant N sources in the Northeast, more research is needed to learn how to reduce N volatilization losses from these sources.

Table 2. Effect of N rate and source on grain yield, Murrill sil, Pennsylvania, 1977.

N-source	N-rate (kg/ha) 17	60	118	218	Average
Starter	5.7 g				
NH_4NO_3		8.7 ef	10.7 bcd	11.1 abc	10.2
Urea		8.5 f	9.2 e	10.3 d	9.3
N-solution		8.1 f	9.2 e	11.3 ab	9.5
$(NH_4)_2SO_4$		8.5 ef	10.6 cd	11.5 a	10.2

Values not followed by the same letter are significantly different at the 5% level according to Duncan's LSD test. Data of R.H. Fox and W.P. Piekielek, The Pennsylvania State University.

Table 3. Average grain yield response of no-till and conventional till corn following application of 134 kg/ha N from three sources, Mattapex sil, Poplar Hill, Maryland. (Bandel et al. 1974, 1975, and 1976).

	Check	NH_4NO_3	Urea	30% N solution
	ton/ha			
No-tillage	3.5	8.3	7.1	8.0
Conventional	4.3	9.7	9.3	9.5

LSD .05 = 0.9.

Whenever N fertilizers are used on no-till corn, acidity produced from the nitrification of NH_4^+ is concentrated in the surface of the soil. Acidification is particularly severe with $(NH_4)_2SO_4$, which produces up to twice as many H^+ ions when nitrified as other common N sources, urea, NH_3, urea-NH_4NO_3 solution, or NH_4NO_3. In the three-year-experiment comparing N-sources on no-till corn, the soil pH values in the surface 2.5 cm of the plots receiving 212 kg N/ha as NH_4NO_3, N-solution, or $(NH_4)_2SO_4$ were significantly lower than in the check plots (Table 4). With $(NH_4)_2SO_4$, the most acidifying source, the soil pH in the surface 2.5 cm was 5.11, almost two units lower than the check plots. This low pH could reduce the effectiveness of herbicides such as triazine, and if continued, eventually could reduce germination and growth because of Al and Mn toxicity.

Table 4. Effect of N rate and source on the soil pH of 0 to 2.5 cm layer after three years of application to no-till corn, Murrill sil, Pennsylvania.

Nitrogen rate kg/ha	Urea	NH_4NO_3	Urea-NH_4NO_3 solution	$(NH_4)_2SO_4$
	pH			
50	6.96 a	6.66 ab	6.80 ab	6.68 ab
101	6.72 ab	6.84 ab	6.92 ab	6.23 c
202	6.65 ab	6.09 c	6.60 b	5.11 d

Values followed by the same letter are not significantly different at the 5% level, according to Duncan's LSD test. The pH of check plots with no N fertilization was 6.96 a. Data of R.H. Fox & W.P. Piekielek, The Pennsylvania State University.

The use of urea or diammonium phosphate (DAP) in starter fertilizers for corn can reduce germination and yield (Bouldin et al. 1968; Creamer 1978). Creamer (1978) found that urea was considerably more toxic than DAP and that to avoid potential germination problems, urea should not be used in starter fertilizer. It appeared that NH_3 was the phytotoxic agent with both urea and DAP. The higher pH in the zone of urea hydrolysis (pH 9.1 in Hagerstown silt loam, original pH 6.8) drove the equilibrium, $NH_4^+ + OH^- \rightarrow NH_3 + H_2O$, to the right, so that approximately 40% of the total ammoniacal N (TAN) was in the form of NH_3. The pH around a band of DAP was only 7.3. At this pH only 1.4% of the TAN would be NH_3, explaining the less severe toxicity of DAP. Peck (N.Y. State Agricultural Experiment Station, Geneva) also observed less severe toxicity to corn with banded DAP than with urea. These results indicate that DAP could be used safely in corn starter fertilizers if it is used at moderate rates (25 kg N/ha or less) and if the band is kept at least 5 cm to the side and 5 cm below the seed. Less care is needed when monoammonium phosphate or NH_4NO_3 is used as the N source in the starter fertilizer, for in soils with less than 7.0 pH, almost no NH_3 is formed with these fertilizers.

Timing

Lathwell and co-workers at Cornell (1970) demonstrated that side-dressed applications of N when the corn is 30 to 45 cm high are more efficient than either fall or spring preplant applications. They found that, on the average, fall-applied N was only 37% as effective as side-dressed N. Similar results have been reported for the Midwest (Olson et al. 1964) and Southeast (Pearson et al. 1961). Consequently, fall applications of N are not recommended for the Northeast. Although side-dress applications are the most efficient, many farmers still apply N as a preplant broadcast treatment because (1) there is a risk of wet soils during the time side-dressed N should be applied (2) the use of chemical herbicides has made it unnecessary for the farmer to cultivate for weed control, therefore a side-dressed application means an extra trip through the field.

Nitrogen Fertilization of Small Grains in the Northeast

Wheat, barley, oats and rye were bred for increased yields on relatively infertile soils before the present day use of commercial fertilizers. The result was that the use of small amounts of N (30 to 60 kg N/acre) would likely lodge these grains, especially oats, barley and wheat, in that order. In the past 50 years, improvement in these varieties has been made by decreasing stem length and increasing disease resistance. Now some varieties will yield two to three times more if fertilized with as much as 100 to 120 kg/ha of fertilizer N.

However, each variety of oats, barley or wheat has its own N requirement. New N availability tests now being developed in the Northeast will play a major role in small grain fertilization, because all varieties, old and new, can be lodged with excess fertilizer N. The rate of application is critical since maximum yields are obtained if N is just below the amount that causes lodging.

If lodging is expected, no N fertilizer or manure is used; however, in the absence of soil test recommendations, 70 kg of P_2O_5 and 70 kg of K_2O are often used per hectare.

If no lodging is expected, 15 kg N/ha are drilled with the seed, along with the P_2O_5 and the K_2O. The crop is then top-dressed, after growth has begun, with 20 to 60 kg of N/ha, depending on grain variety and soil. The county agent or state crops specialist can provide the proper fertilizer N recommendation.

In general, rye yields poorly in the Northeast and it is seldom grown other than for seed or for erosion control; its N requirement is often 20 to 30 kg/ha.

Nitrogen Fertilization of Vegetables Grown for Processing in the Northeast

Quality vs. Yield

The quality of vegetables used for processing is defined mainly by the stage of growth, development, or maturation of the edible portions at harvest. The optimum processing quality determines the harvest date, which in turn affects the yield. As most vegetables approach optimum harvest quality, yields rapidly increase.

Processing quality may also be defined by the concentrations of total N (including nitrate-N and other N compounds) accumulated by the vegetable and by other chemical and physical properties of the processed portions of the vegetable.

Uniformity

Vegetables grown for processing are harvested with once-over, plant-destructive mechanical harvesters. At harvest, the plants are at rapidly changing stages of growth, development and maturation. Only the plants or portions of the plants at an acceptable stage of growth and quality for processing are usable. Most vegetables are harvested when the most mature plants have reached processing maturity. The other plants are treated as weeds. Establishment of uniform, vigorous, potentially productive seedlings is the initial phase and the foundation leading to uniformity among plants harvested for processing. Any variation among seedlings may result in unevenness among plants at harvest time. To extend the harvest season, the first plantings of vegetables grown for processing are often seeded in cold, wet soils which retard seed germination and seedling growth. Late plantings are often made under stressful conditions of excessively high temperature or lack of adequate water in soil surrounding the seeds and in the root zone of the seedlings. Reliable yields of high quality produce are needed throughout the harvest season to ensure a continuous flow of raw product for processing.

Nitrogen fertilization affects the reliability of both quality and yield in vegetables grown for processing. Of the factors involved in crop production (genetic potential of plants, productivity of the soil, weather, and production management), control of available N in the rhizosphere is one of the most variable and difficult factors to manage. All other growth factors must be adequate to obtain a positive crop response to a N fertilization program.

A good N management system for crop production is based on preplant predictions of residual available soil N plus fertilizer N requirements, but continual adjustments in N fertilization must be made for unpredictable weather events which affect availability of soil and fertilizer N and plant responses during the growing season. Ideally, soil-fertilization management should control the soil-plant system from planting to harvest, insuring abundant N for development of uniform vigorous seedlings, supplementing soil N during periods of rapid uptake for development of sturdy vegetative structures, and allowing depletion of available N in the rooting zone as the plants approach harvest.

The practical application of N fertilization is considered in four steps:

1. Amount of N needed for profitable production of reliable yields of high quality produce.
2. Time the N is needed by the plants for optimum response.
3. The effect of N on the quality of the portion of the vegetables to be processed.
4. Management of soil N plus fertilizer N for optimum quality and yield.

Table Beets and Nitrogen

Since fertilization of table beets has been studied throughout the growing season, table beets will be used as a case history to illustrate a plant response to soil N plus fertilizer N. The responses of table beet plants to N fertilizers have been reported by Peck et al. (1974).

The practical application of these results to fertilization will be considered under the four steps: uptake, time, quality and availability.

1. **Uptake:** Amount of N needed for profitable production of reliable yields of high quality table beet roots for processing.

Table beet plants grown without fertilizer N removed 110 kg N/ha from the soil (Table 5). The soil was a Honeoye fine sandy loam (Glossoboric Hapludalf, fine-loamy, mixed, mesic), a productive

Table 5. Table beet responses to N

Fertilizer ammonium nitrate		Yield	Dry weight		Total N		
Preplant* May 4	Sidedressed July 1	roots (fresh wt.)	Tops	Roots	Tops	Roots	Total
kg N/ha		kg /ha	kg /ha		kg N/ha		
0	0	17000	3500	3400	70	40	110
0	110	21000	4600	3200	150	80	230
110	0	30000	3700	5500	90	100	190
110	110	28000	5000	4900	180	140	320

* Table beet seeds planted May 22. Roots harvested August 12.
Data of N.H. Peck, New York State Agricultural Experiment Station, Geneva.

soil derived from calcareous glacial drift, which had a cover crop of oats removed the previous year. Assuming that 110 kg N/ha came from the soil, an application of an additional 110 kg N/ha preplant was 70% taken up by the tops and enlarged portion of roots. Fertilizer N side-dressed early at 110 kg N/ha was nearly all taken up by the tops and roots.

Fertilizer N applied preplant increased yields more than side-dressed N. Fertilizer N applied preplant increased the total yield, especially the yield of the large diameter roots. These large roots are of less value for processing than small roots. A large amount of N was returned to the soil in the tops since only the roots are removed from the field by mechanical harvesters.

At the early harvest date, August 12, the table beet plants grown with only soil N plus preplant fertilizer N were approaching N deficiency. This made harvesting by "pulling the roots by the tops" difficult, for the petioles tended to break from the root. Thus, additional side-dressed N was needed to maintain healthy petioles and leaf blades for efficient mechanical harvesting.

2. **Timing:** Providing N at the time needed by the plants for optimum response.

Uptake of N preceded gain in dry weight by the table beet plants (Figure 1). Since the concentration of total N was high in the seedlings and the concentration decreased throughout the growing season, abundant available N was needed for the seedlings early in the season, followed by a large supply of available N during the rapid uptake and a depletion of available N in the soil as the plants approached harvest.

3. **Quality:** Effect of N on the quality of table roots to be processed.

Root size: Fertilizer N applied preplant increased the yield of large diameter roots, which are of less value for processing than are small roots.

Nitrate: An application of only 110 kg of fertilizer N/ha before planting caused rapid vegetative growth of the seedlings and a high concentration of plant nitrate (Figure 2). As the plants developed and as the portion of the roots used for processing enlarged, the concentration of nitrate gradually decreased resulting in high yields of roots low in nitrate at the early harvest date of August 12 (Figure 3).

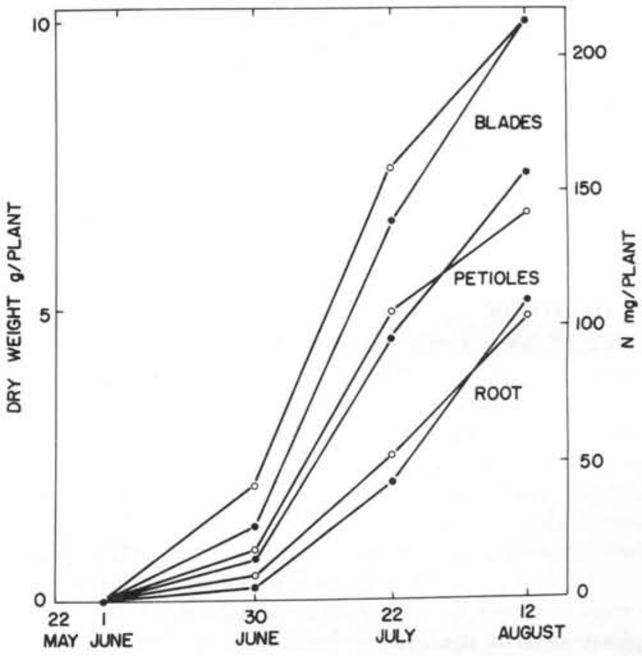

Figure 1. Growth and N uptake of table beet plants. Planted May 22 and harvested August 12. (N.H. Peck, New York)

Glutamine and sugar: Glutamine accumulation due to fertilizer N treatment occurred in the roots of the beet plants. In the petioles and blades, the glutamine concentration remained constant throughout the growing season at 0.5 to 1.0% on a dry basis.

In the roots, glutamine represented a third (20-40%) of the total N; and the buildup of this compound was directly related to the rate of fertilizer N application. If the plants eventually received some fertilizer N, the roots continuously increased in glutamine concentration to a steady-state concentration of 4 to 6%. Without glutamine, the maximum amount of accumulated glutamine was 2%.

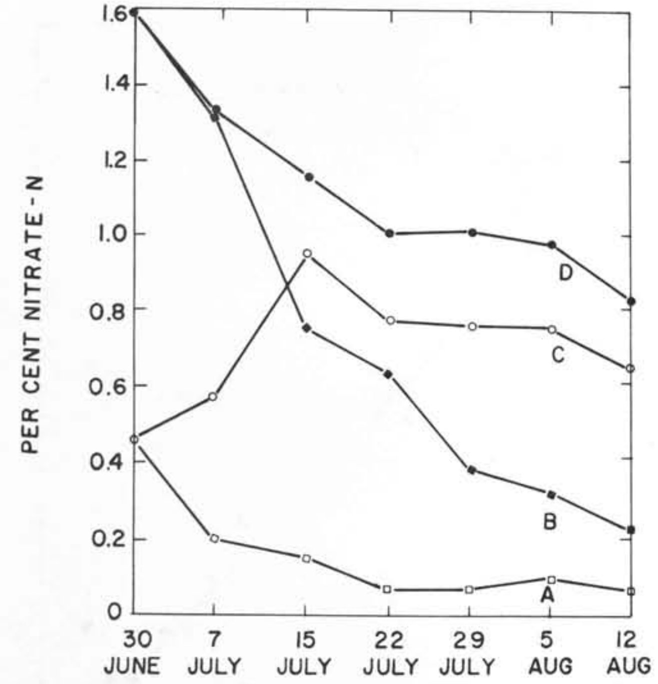

Figure 2. Concentration of nitrate-N in table beet petioles. A = No N fertilizer, B = N fertilizer May 4, C = N fertilizer July 1, D = N fertilizer May 4 and July 1. (N.H. Peck, New York)

When fertilizer N was applied before planting, the steady-state concentration of glutamine was reached early, and there was little response to additional side-dressing applications of fertilizer N. When fertilizer N was not applied before planting, there was marked response to side-dressing applications of fertilizer, leading again to a higher concentration of glutamine.

As the roots from plants grown on the various fertilizer treatments matured, the total sugar (sucrose) concentration increased, but at a rate inversely proportional to the total amount of fertilizer N applied. Plants that received no fertilizer N showed a linear increase in sugar from 25% dry basis in late June to 57% on August 12.

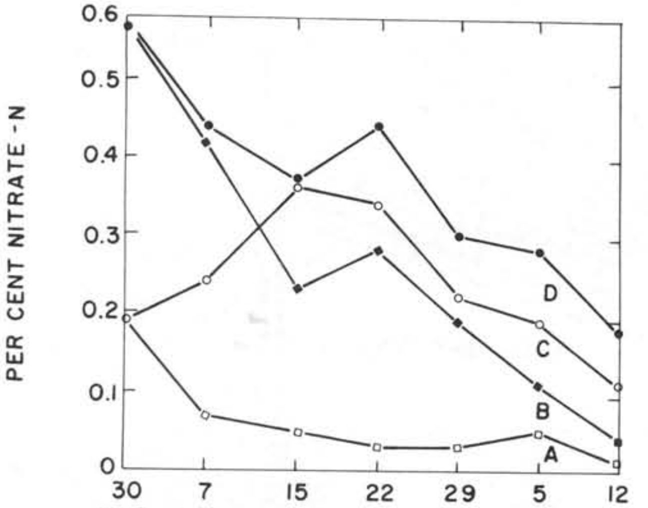

Figure 3. Concentration of nitrate-N in table beet roots. See Figure 2 for explanation of symbols. (N.H. Peck, New York)

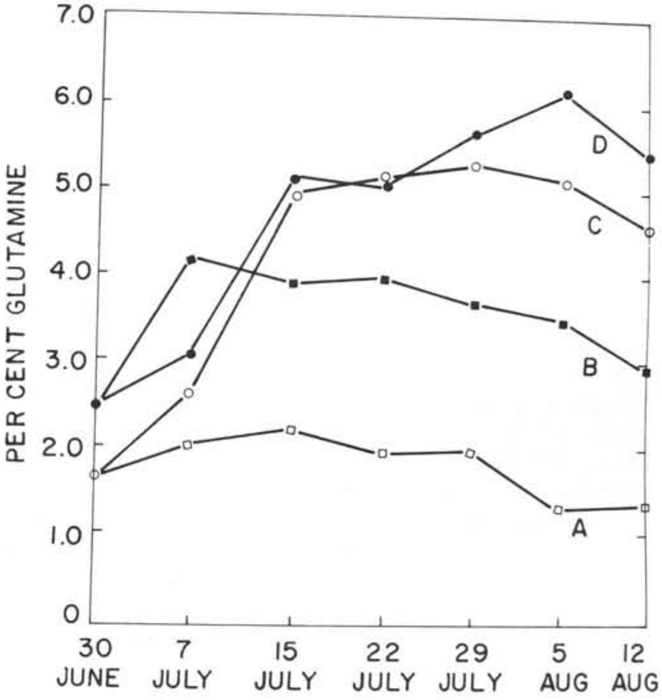

Figure 4. Concentration of glutamine in table beet roots. See Figure 2 for explanation of symbols. (N.H. Peck, New York)

At the other extreme, plants that received 330 kg or more fertilizer N had only 47 to 50% total sugar at harvest on August 12. An inverse relation was found between the amount of glutamine and sugar present in the roots at harvest on August 12. One example of this relation is shown in Figure 5, where the concen-

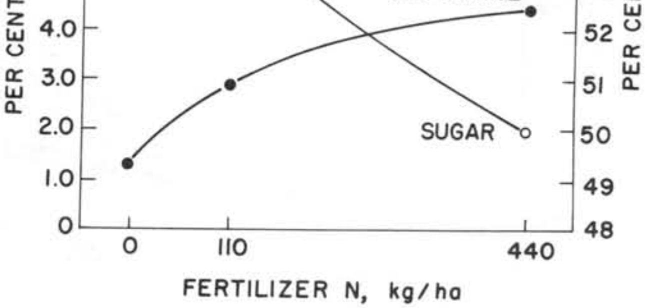

Figure 5. Concentration of glutamine and sugar in table beet roots as percent of dry weight. Fertilizer was added before planting. (N.H. Peck, New York)

trations of sugar and glutamine in the roots are shown only for those plants receiving fertilizer N before planting at the rate of 0, 110 and 440 kg N/ha. The regression of sugar on glutamine, taking results from all fertilizer N treatments, is shown in Figure 6. The fact that a 2% reduction in sugar leads to a 1% increase in glutamine suggests a stoichometric relation, with important organoleptic significance to processing quality.

4. **Availability:** Management of soil N and fertilizer for optimum quality and yield.

Research with New York soils which are in continuous vegetable crop production (with no legume in the rotation) indicates that such soils will supply about 110 kg N/ha to table beet plants during the growing season, depending on soil aeration, soil temperature, soil water available for soil organisms and plants, and losses of N due to leaching, runoff and volatilization (Figure 7). A warm, moist soil favors release of soil N to plants.

Fertilizer N needs may be estimated prior to planting. Some of the required N fertilizer may be applied preplant, but N fertilizer application rates and timing may be adjusted during the course of the growing season, depending on the weather, potential crop yield, and length of time to harvest.

Assuming that the soil supplies 110 kg N/ha and assuming that 20 to 40 kg N/ha are supplied in the starter band fertilizer, approximately 110 kg additional available N/ha from fertilizer are needed during the growing season, especially during the early "middle period" of the growing season, when uptake of N by the roots is rapid.

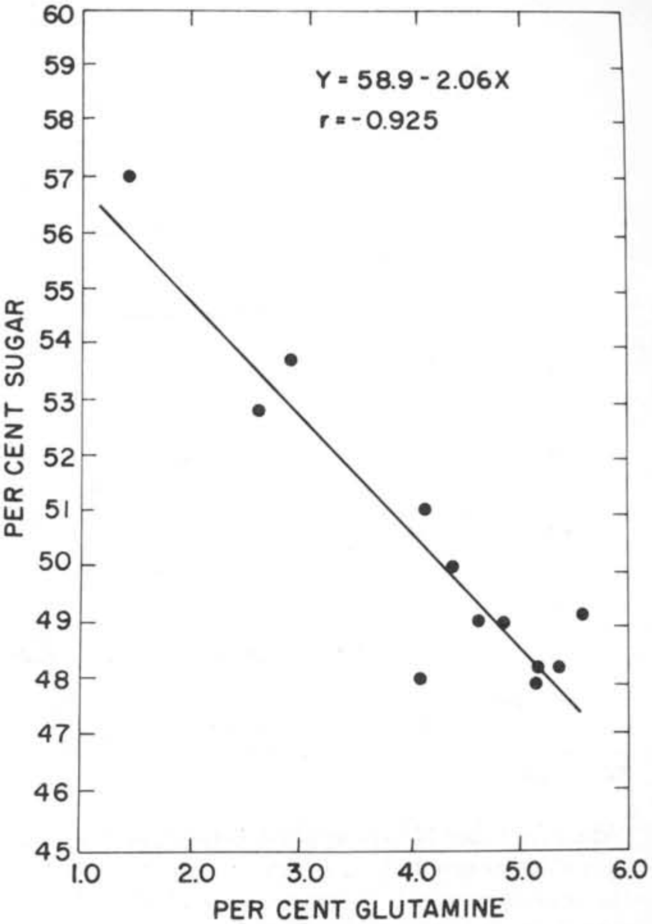

Figure 6. Sugar and glutamine correlation in table beet roots. (N.H. Peck, New York)

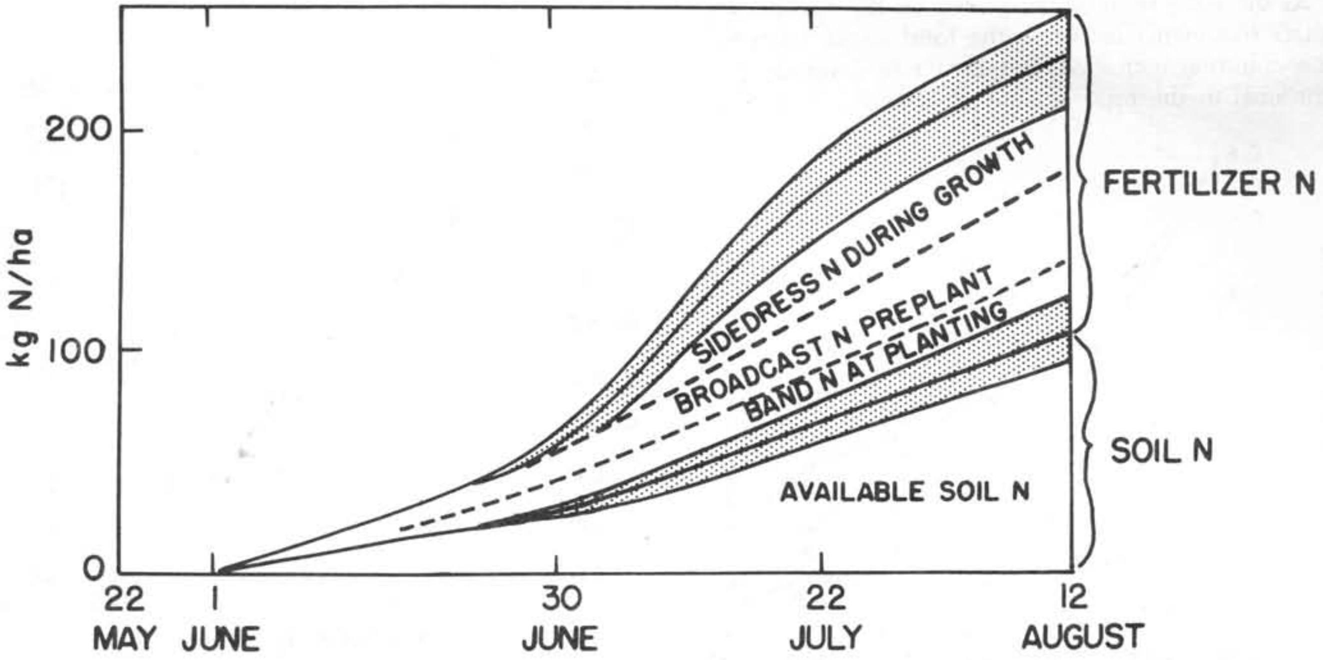

Figure 7. Available soil N plus fertilizer N for table beet plants planted May 22 and harvested August 12. The shaded areas indicate the variability in soil and fertilizer N caused by variable weather. (N.H. Peck, New York)

About two-thirds of the fertilizer N applied broadcast-preplant and worked into the soil is available to the plants during the growing season. Thus, 150 kg fertilizer N/ha are needed preplant to supply 100 kg available N/ha to the plants during the growing season.

Most efficient plant use of N fertilizer occurs when the N fertilizer is applied as side-dressed applications during the growing season just prior to the plant demand for rapid uptake and response. Early applications of side-dressed N are necessary within the limited rooting zone of seedlings to develop large plants and rooting systems which extend through the surface soil. Plants need a large, efficient root system to remove soil N during the growing season. As harvest approaches, the soil may be nearly depleted of available N. But side-dressed N applied below the surface and within the root zone is nearly all available to the plants. Sources of N fertilizer for side-dressing include solutions, urea and ammonium nitrate. Additional side-dressed N may be needed later in the growing season to maintain top growth for easy mechanical harvesting, if the beets are held for late harvest.

Overall fertilization system

Fertilizer N may be added to supplement soil N when the crop response is likely to be most intense. Seedlings fertilized with N at or near planting time had a high concentration of nitrate and developed large plants which used both the fertilizer and soil N during the growing season. As harvest approached, nitrate concentration in the roots declined to a low level. Further, the roots had a low glutamine concentration, and a high sugar concentration, and yields were abundant. Since excess nitrate and nitrite in food are potential health hazards and since excess glutamine may cause bitter flavor in canned beets, their levels should be low at harvest time. In this experiment, proper N management resulted in quality processing produce and the soil was nearly depleted of available N at harvest.

Predicting the Release of Soil Nitrogen

Review

Nationally, nitrogen fertilizer consumption has increased steadily over the past 15 years (Figure 8). In the Northeast, consumption has also been rising, although at a slower rate (Figure 9). Grain yields of corn have grown during this period (Figures 8, 10, 11), but yield increases have slowed in the past 5 years.

Fertilizer N is an important resource in crop production; however, crops also obtain significant quantities of N from other sources. The data in Figures 10 and 11 indicate that Maryland agriculture is more dependent on fertilizer N sources than is Pennsylvania agriculture, since the quantity of N applied per unit of yield is greater in Maryland. This situation reflects the greater livestock-based agriculture in

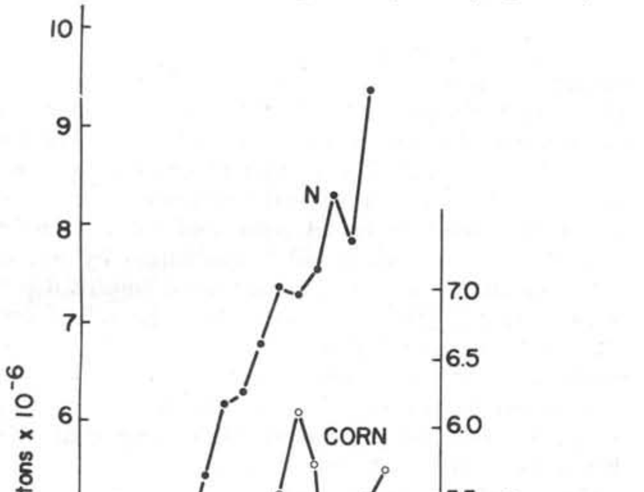

Figure 8. Nitrogen fertilizer use and maize and wheat yields for the United States since 1960. (J.J. Meisinger, USDA, Beltsville)

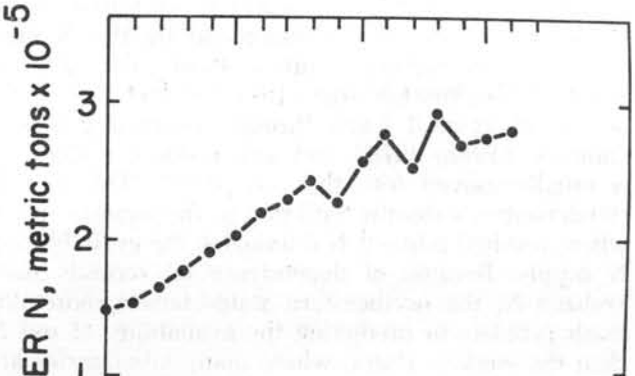

Figure 9. Nitrogen fertilizer use in the northeastern United States. (J.J. Meisinger, USDA, Beltsville)

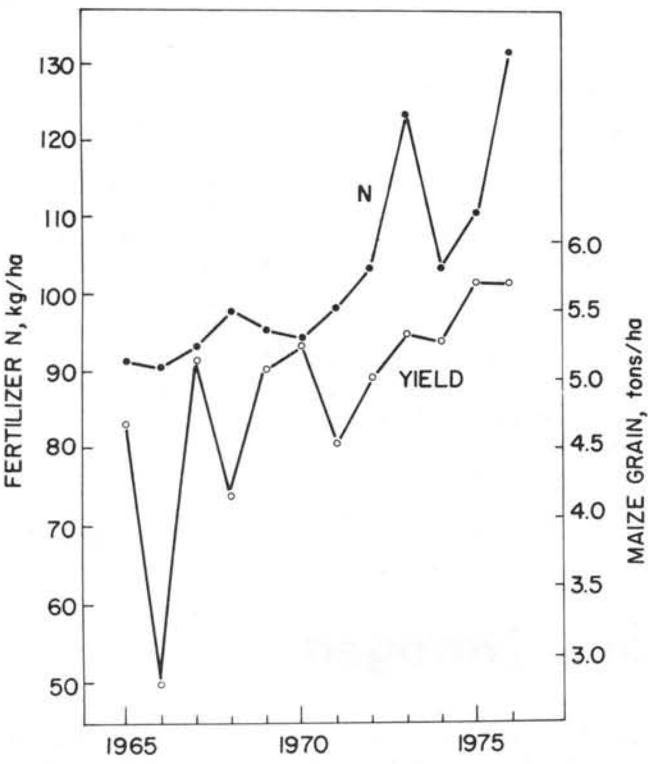

Figure 10. Maize grain yields and N fertilizer use for Maryland, 1960-1977. (J.J. Meisinger, USDA, Beltsville)

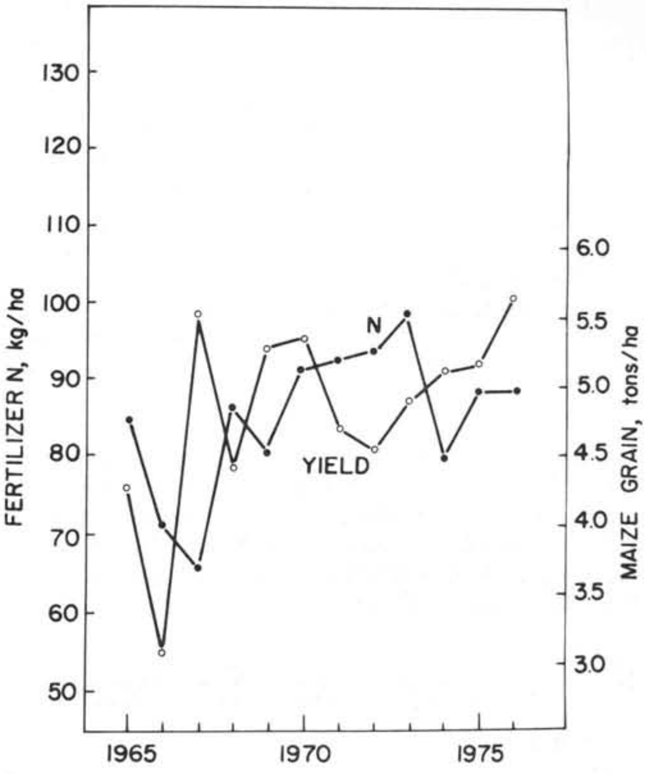

Figure 11. Maize grain yields and N fertilizer use for Pennsylvania, 1960-1977. (J.J. Meisinger, USDA, Beltsville)

Pennsylvania and the consequently greater use of legume and manure N in place of fertilizer N. Native soil N can supply significant quantities of N to a crop, but soils differ in their N-supplying capacity. The ultimate aim of any system used to assess soil N is to predict the N supply accurately so that the crop requirement can be met efficiently through some combination of native soil N and fertilizer N.

Predicting available soil N in the Northeast is difficult because the soil is dominated by the N mineralized from organic sources during the growing season. This situation arises from the fact that about 30 cm of rainfall leach through northeastern soils annually (Frere 1976) and any residual mineral N is usually moved into the soil profile. This soil N status contrasts sharply with that of the western states, where residual mineral N dominates the available soil N supply. Because of dependence on recently mineralized N, the northeastern states face a more difficult problem in predicting the availability of soil N than the western states, where many laboratories are using NO_3-N as a soil test (Carter et al. 1974; Dahnke & Vasey 1973).

Procedures to predict the release of soil organic N can be broadly grouped into crop vegetative tests, microbial tests, total analysis of soil components, and chemical extraction tests (Allison 1956; Dahnke & Vasey 1973). Vegetative tests include greenhouse and field studies. These procedures might involve measuring yield, dry matter, or total N uptake of a crop receiving no fertilizer N or a known quantity of N. These procedures have generally been accepted as the standard by which other methods are evaluated, since they integrate the factors of crop growth and soil N released under natural conditions. They represent the oldest group of tests, and form an indispensible part of modern soil N evaluation by serving as the means of calibrating other more empirical procedures. Grove (1979) suggested that the soil N supply can be estimated from corn grain yields on nonfertilized areas. The resultant grain yield is converted to a N uptake value, which is subtracted from the N uptake required for the grower's yield goal. The difference is the N fertilizer need.

Microbiological tests usually involve incubating a sample of soil under ideal temperature and water conditions and periodically measuring the N mineralized. Variations on this procedure involve differing lengths of incubation (1 week to several months), aeration conditions, and types and amounts of inert bulking materials added (Bremner 1965a; Dahnke & Vasey 1973). Sample pretreatment has a marked effect on microbial tests (Bremner 1965a; Harmsen & VanSchreven 1955; Stanford 1968), especially those involving short-term incubations. Microbial tests have been used for many years (Fraps 1921; Stanford & Hanway 1955; Waksman 1923) and are considered by most workers to be the most satisfactory method of assessing N status of the soil apart from field or vegetative tests. However, to obtain meaningful comparisons among soils, care must be taken to measure all of the inorganic N, to standardize the pretreatment of the sample prior to incubation, and to standardize the temperature and water during incubation. Several authors (Bremner 1965a; Dahnke & Vasey 1973; Harmsen & VanSchreven 1955) have reviewed these points, underscoring that soils are a complex biological entity. Nevertheless, microbial procedures have proven useful and have been shown to be a good indicator of soil N-supplying power (Bremner 1965a; Carter et al. 1974; Eagle and Matthew 1958; Gasser & Kalembasa 1976; Jenkinson 1968; Keeney & Bremner 1966b; Stanford & Legg 1968). Others have shown that laboratory mineralization data may be adjusted to field conditions by correcting for the field temperature and water regime (Smith et al. 1977; Stanford et al. 1977). This less empirical approach, however, is time consuming and is principally a research approach.

Procedures based on total soil analysis usually estimate soil organic matter, organic N, or organic carbon. These nonbiological procedures have proven most useful in separating soils with large differences in total N contents and in classifying soil within a series. This procedure has greatest acceptance in states with a large range of soils and crop management systems. Typically the soil organic N data are utilized with soil drainage class, soil texture, and previous management history to arrive at an estimate of soil N release. The major criticism of these procedures is that they measure the total N pool, which is composed mainly of slowly available material. The active fraction of the soil organic N makes up a small percentage of the total N but dominates the N release (Bremner 1965b; Jansson 1958). Thus, a procedure which measures the total soil N would be relatively insensitive to changes in the size of the small, active N pool. Predicting soil N release solely on the basis of a total analysis has, therefore, met with only limited success.

By far the most intensively investigated area for predicting N release has been the chemical extraction tests. These strictly empirical procedures provide simple, quick methods of selectively removing a portion of the active soil N. These tests are appealing for routine soil analysis because they require simple analytical procedures, are quick, and can be used on large numbers of samples. The range of chemical extractants includes water, weak to strong salt solutions, mild acids and bases, and strong acids and bases with or without an oxidant. The extracted material has likewise been analyzed in a number of ways including carbon content, distillable ammonia, absorption of ultraviolet radiation, and total N. The results of these empirical methods are usually influenced by factors such as extraction time, sample drying procedure, and soil to extractant ratio.

Livens (1959a, b) was one of the early investigators who showed the close relation between N extracted with boiling water and aerobic N mineralization. He also showed that the NaOH-distillable N fraction of the extract was more closely related to mineralization than the total N extracted. Large effects due to extraction time, extractant to soil ratio and quantity of soil were noted. The hot water procedure was later modified (Keeney & Bremner 1966a, b) to improve filtering and was again shown to be highly related to N released during aerobic and anaerobic incubation and to crop N uptake under greenhouse conditions. Keeney & Bremner (1966a, b) considered the hot water method to be as good as incubation methods; furthermore, they found that it was not subject to sample drying effects which influence the microbiological method. A boiling extract with a mild salt solution (0.01 M $CaCl_2$) has also been investigated (Fox & Piekielek 1978a; Stanford 1968; Stanford & Smith 1976) and has been shown to be highly related to biological mineralization and to crop N uptake.

Methods involving extraction with mild salt solutions at room temperature have centered on sodium bicarbonate (MacLean 1964) and have also been shown to be related to N mineralization and uptake (Fox & Piekielek 1978a; Jenkinson 1968; Smith 1966). Recent work (Fox & Piekielek 1978a, b) has shown that absorption of ultraviolet radiation by extracts with sodium bicarbonate bears a close relation to total N content. The quicker determination by ultraviolet absorption could be substituted for the more tedious total N analysis. Strong salt solutions, such as molar potassium salts at room temperature, have given mixed results when compared to crop N uptake (Fox & Piekielek 1978a; Lathwell et al. 1972).

Interest in basic and acidic extracting solutions developed as a natural extension of the procedures of fractionating soil organic matter with differential solubilities in acids or bases. The various reagents commonly involved are H_2SO_4 (Purvis & Leo 1961; Richard et al. 1960), $Ca(OH)_2$ (Prasad 1965), $Ba(OH)_2$ (Jenkinson 1968), and NaOH (Cornfield 1960). When strong acids or bases are used, much of the soil N is attacked and the N removal bears a close relation to the quantity of total soil N (Bremner 1965a). Strong acidic and basic extractants suffer the same disadvantages as those discussed above for the total N procedures. Milder acidic and basic extractants have been evaluated in several studies, performing well in some but poorly in others. The remaining group of chemical extractants has employed oxidizing agents (permanganate or chromate) in acidic or basic media to selectively oxidize a portion of the organic N (Nommik 1976; Stanford 1978a, b; Truog 1954). The alkaline permanganate procedure, including several modifications, has been widely tested (Keeney & Bremner 1966b; Prasad 1965; Richard et al. 1960; Stanford & Legg 1968) and the recent review of this procedure (Stanford 1978b) indicates that it has not given consistently good results. More recently, oxidation procedures have been investigated under acid conditions (Nommik 1976; Stanford 1978a) with encouraging results for their general applicability in a practical soil testing operation.

Research in the Northeast

In the Northeast, soils and farm management schemes are diverse, ranging from dairy farms using heavy, annual farm manure applications and alfalfa in the rotation every few years to farms that have grown corn every year on the same soil for at least 10 years with no manure applications. In view of this diversity, the N supplying capability of a soil must be known if accurate recommendations for fertilization are to be made. Though some allowance is made in N fertilizer recommendations for legumes in a rotation and for manure applications, enough research data are not available to reliably predict the effect of legumes and manures on the N availability in a soil.

A number of chemical tests have been developed in which an extracted fraction of soil organic N is moderately well correlated with the N supplying capacity of soils in greenhouse experiments (Keeney & Bremner 1966b; Lathwell et al. 1972; MacLean 1964; Purvis & Leo 1961) or with the N mineralization potential of a soil (Stanford & Demar 1969) but the reliability of these tests has not been checked under field conditions.

Experiments were conducted in Pennsylvania to determine if one or more of the chemical N availability indices were correlated with the capability of several soils to supply N to field grown corn (Fox & Piekielek 1978a). Rates of fertilizer N up to 179 kg/ha plus starter N were also applied to determine the N response by corn in these soils. Since the analyses for all the tested chemical N availability indices were time consuming, an attempt was made to develop a more rapid method of analysis without sacrificing the ability of the index to predict the N supplying capability of a soil (Fox & Piekielek 1978b).

The results of correlating eight chemical availability indices with soil N supplied to corn in 12 experiments on eight sites over a 2-year period demonstrated that four indices were significantly correlated with the N supplying capability of the soils (Table 6). The best correlated test was the amount of N extracted by refluxing with 0.01 M $CaCl_2$ for one hour ($r = 0.86$, modified Keeney & Bremner 1966b) followed by 0.01 M $NaHCO_3$ extractable N ($r = 0.77$, MacLean 1964), NH_4-N extracted by 0.01 M $CaCl_2$ in a 16-hour autoclave treatment ($r = 0.70$, Stanford & Demar 1969) and Kjeldahl total soil N ($r = 0.68$). The soils in these experiments were well drained Ultisols (Hagerstown silt loams) and Inceptisols (Pope silt loam and Berks shaley silt loam) in southeastern, central, and northeastern Pennsylvania. They had received a wide variety of previous management, including 10 years of corn with no manure, 8 years of alfalfa grass meadow, or continuous corn with annual applications of chicken manure. This diversity of management was reflected in the wide range of N, 27 to 170 kg/ha/season, supplied by these soils to a growing corn crop. In the two corn crops planted the first year after alfalfa, there was enough residual N from the alfalfa to obtain maximum grain yields (10.3 and 9.7 metric tons/ha) with only starter N.

The analysis for the N availability indices which correlated significantly with the N supplying capability of the soil required either a Kjeldahl total N analysis or an overnight autoclaving. These analyses were thought to be too time consuming and expensive to include in a routine soil testing program where hundreds of samples per week are analyzed. In seeking ways to simplify and shorten the analysis of the soil extracts used for these indices, the ultraviolet (UV) absorption of the 0.01 M $NaHCO_3$ extract at 260 nm was found to be as well correlated with the field measured soil N supplying capability as the best of the previously tested indices (Figure 12) (Fox & Piekielek 1978b).

Table 6. Linear correlation coefficients between several N availability indices and soil N supplying capability.

			Index for Assessing N Availability[1]					
Year	O.M.	Total N	Average NO_3-N 0-60 cm	Keeney Bremner N	MacLean N	Stanford NH_4-N	Purvis Leo NH_4-N	Lathwell N
				r†				
1976	0.77	0.65	0.49	0.88°	0.76	0.72	0.51	0.56
1977	0.03	0.81°	0.10	0.90°	0.94°°	0.92°°		
combined	0.38	0.68°	0.16	0.86°°	0.77°°	0.70°		

[1] See bibliography for references to named procedures.

° Significant at the 5% probability level.

°° Significant at the 1% probability level.

† Linear correlation coefficient for index with total plant N in check treatments minus 0.75 × starter N added.

Adapted from Fox & Piekielek (1978a).

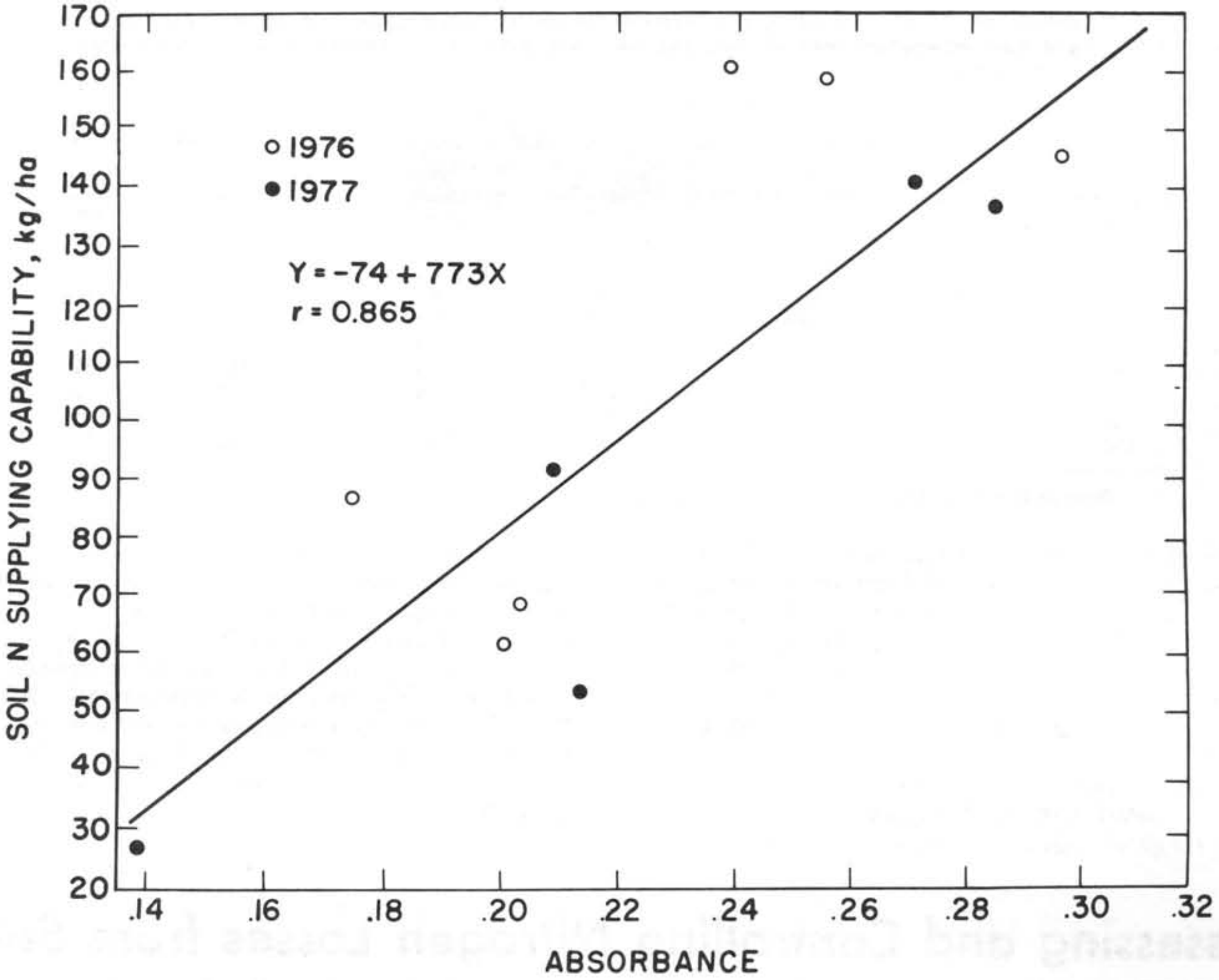

Figure 12. Nitrogen supplying capacity of soil vs. ultraviolet absorption of soil extract. (R.H. Fox, Pennsylvania)

The double bonds in organic matter absorb UV light near 260 nm; the absorption by the extract is a measure of the organic matter content of the extract (Rao 1967). Further, the concentration of N in the organic matter is assumed to be quite constant from soil to soil (Bremner 1949). In support of this assumption the coefficient between the UV absorption at 260 nm and the N concentration of the 0.01 M $NaHCO_3$ extracts was 0.91. Therefore, it follows that if the N content of the extract was correlated with the N supplying capability of soil, the UV absorption by the extract would also be correlated with this capability.

The equation, $N_f = \frac{N_p - N_s}{E}$, proposed by Stanford (1973) illustrates how this test could be used to predict N fertilizer requirements of a crop of corn. Assumptions to be made for a corn crop follow:

N_p (kg/ha) = 18.5 × (maximum grain yield expected, metric ton/ha, 15.5% H_2O)
N_s (kg/ha) = 773 × (UV abs at 260 nm of 0.01 m $NaHCO_3$ extract) − 74
E = 0.6
N_f (kg/ha), maximum = 20 × (maximum grain yield expected, metric ton/ha, 15.5% H_2O)
minimum = 15 in starter fertilizer

The N_p factor was calculated from the ratio of the grain yield to total crop N at the lowest N rate that produced maximum yields in the N response experiments (Fox & Piekielek 1978a). The equation for N_s was derived from the regression between the UV absorbance of the 0.01 M $NaHCO_3$ soil extract and the N supplying capability of the soil shown in Figure 12. An E of 0.6 was fairly representative of the fertilizer N efficiency that can be expected at N fertilizer rates adequate for maximum yields with good crop and fertilizer management.

Using the above equation and the data from the 1977 corn yield response to N fertilization experiments, the N fertilizer recommendations would have averaged 24 kg/ha high for the six sites with a range of 0 to 56 kg/ha high for the individual sites (Table 7). The validity of the test for the equation may be questionable, since 1977 data were used in formulating the equation for N_s; however, it does serve as an ex-

Table 7. Comparisons of N fertilizer recommendations for maximum corn grain yields by N availability index and crop requirement methods with experimentally determined requirement, 1977 experiments in Pennsylvania.

	Field Experiment		N-recommendation method		Error in recommendation	
Experiment site	Maximum yield	N-applied max. yield (NF)	Crop require. (CR)	N-avail. index (NAI)	CR minus NF	NAI minus NF
	ton/ha	kg/ha	kg/ha		kg/ha	
1	11.0	140	269	187	129	47
2	11.3	84	269	103	185	19
3	9.7	17	140	17	118	0
4	9.1	67	224	123	157	56
5	11.0	112	269	114	157	2
6	11.0	202	269	220	67	18
avg.	10.5	104	240	127	136	24

Data of R.H. Fox, The Pennsylvania State University.

ample of the improvement that can be made on the current practice of basing N fertilizer recommendations solely on crop requirements. If the currently used N fertilizer recommendations, based on the N requirement of the crop, had been used for the 1977 experiments, they would have been on the average 136 kg/ha too high with a range of 67 to 185 kg/ha in excess.

If further field studies show that this test is as well correlated with the N supplying capability of a wide range of soils as it was for the soils tested, it could greatly increase the accuracy of N fertilizer recommendations made with routine soil testing. The test is as simple, quick, and inexpensive as any nutrient availability test currently used and would certainly be more accurate than making N recommendations based solely on crop N requirements (Schulte 1977). This increased accuracy will not only increase the efficiency of N fertilizer use by farmers, but will also minimize possible water and air pollution from excess N fertilization.

Assessing and Controlling Nitrogen Losses from Soils

Management of N in the environment to conserve N against losses is of increasing priority in the Northeast. One of the first requirements of management is to determine the relative quantities of N moving into subsurface waters and lost through denitrification or ammonia volatilization. Within the Northeast Region, assessments of N losses have been made in laboratory and field studies under different cropping and fertilization regimes.

Leaching Losses of Nitrogen

Studies in Connecticut

Tobacco plots: Nitrogen movement through a Merrimac sandy loam (Entic Haplorthod) and losses to ground water under shade tobacco were studied by Starr and DeRoo (cf. Starr 1975) for 3 years at the Valley Laboratory, Windsor, Connecticut. Nitrogen losses from conventional organic fertilizers for cigar tobacco (DeRoo 1958) were compared with losses observed when nitrogen was supplied from ammonium sulfate. In the first 2 years with conventional fertilization of 224 kg N/ha, results showed that most of the movement of N to the ground water occurred during the fall season, resulting in a NO_3-N content of about 25 ppm in the groundwater, with little difference between organic and inorganic N sources (Figures 13, 14). In the third year, 40% less N fertilizer was applied at five intervals as ammonium sulfate during the growing season, and was compared with the standard fertilizer practice of broadcasting 224 kg/ha at the time of planting (Figure 15). Under these conditions, the concentration of NO_3-N in the water table from October to December under the low N plots was 50% less than that under the plots with the standard fertilizer treatment.

These studies were expanded to a commercial field of shade-ground cigar tobacco. This study on a Melrose sandy loam (Entic Haplorthod) showed that the NO_3-N concentrations in the ground water at a depth of 1.8 to 2.4 meters were 14 to 27 ppm, and tended to remain at these concentrations through the year. This result is indicative of the cumulative effect of long term, intensive fertilizations with predominantly organic materials. Decreasing the total amount of applied fertilizer, which was detrimental to tobacco quality, or increasing the number and amount of postplanting application, which was slightly beneficial, did not significantly affect NO_3-N leaching (DeRoo 1980).

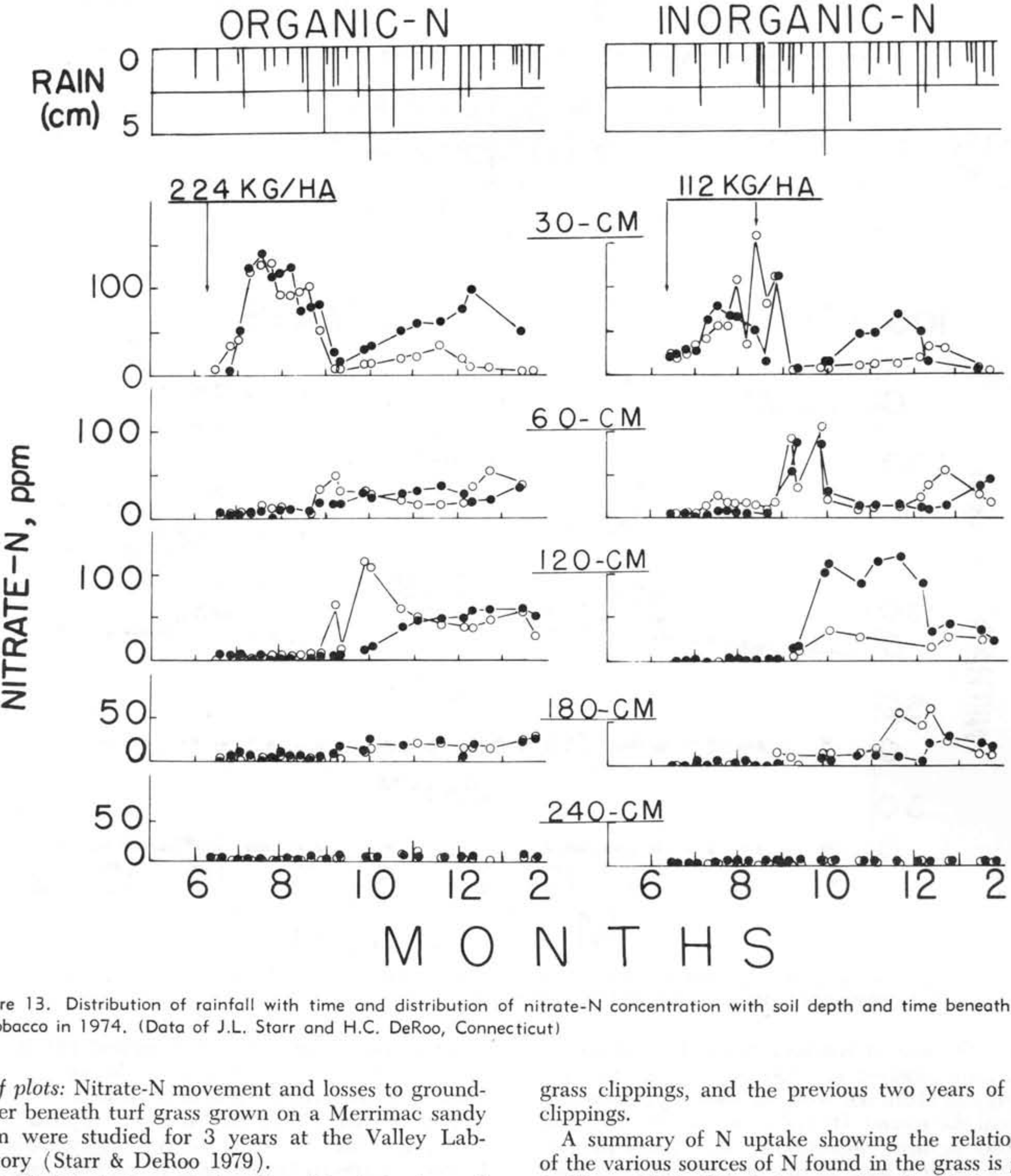

Figure 13. Distribution of rainfall with time and distribution of nitrate-N concentration with soil depth and time beneath shade tobacco in 1974. (Data of J.L. Starr and H.C. DeRoo, Connecticut)

Turf plots: Nitrate-N movement and losses to groundwater beneath turf grass grown on a Merrimac sandy loam were studied for 3 years at the Valley Laboratory (Starr & DeRoo 1979).

Field plots, instrumented with suction lysimeter and neutron probe access pipes, were utilized to study the fate of N fertilizer applied to turf grass. Fertilizer N was applied at an annual rate of 180 kg/ha to each plot in a split application of 90 kg/ha each in May and September for three consecutive years. Grass clippings were returned, after subsampling, on two of the four plots. In the third year, the use of ^{15}N as a tracer in conjunction with management of grass clippings provided the means to quantify the N in the grass derived from fertilizer, soil, current year's grass clippings, and the previous two years of grass clippings.

A summary of N uptake showing the relationship of the various sources of N found in the grass is given in Figure 16. In this study, on a low-N soil (i.e., 0.06-0.08% total N) when clippings were not returned, approximately half of the plant-N was derived from the fertilizer and half from the soil. When clippings were returned, yield of grass increased by about one-third, with approximately one-third of the total N in the grass being derived from the cumulative return of the clippings.

The rate of fertilizer N uptake was initially high, with 20% of the fertilizer N applied being taken up within 2-3 weeks following both applications. Subse-

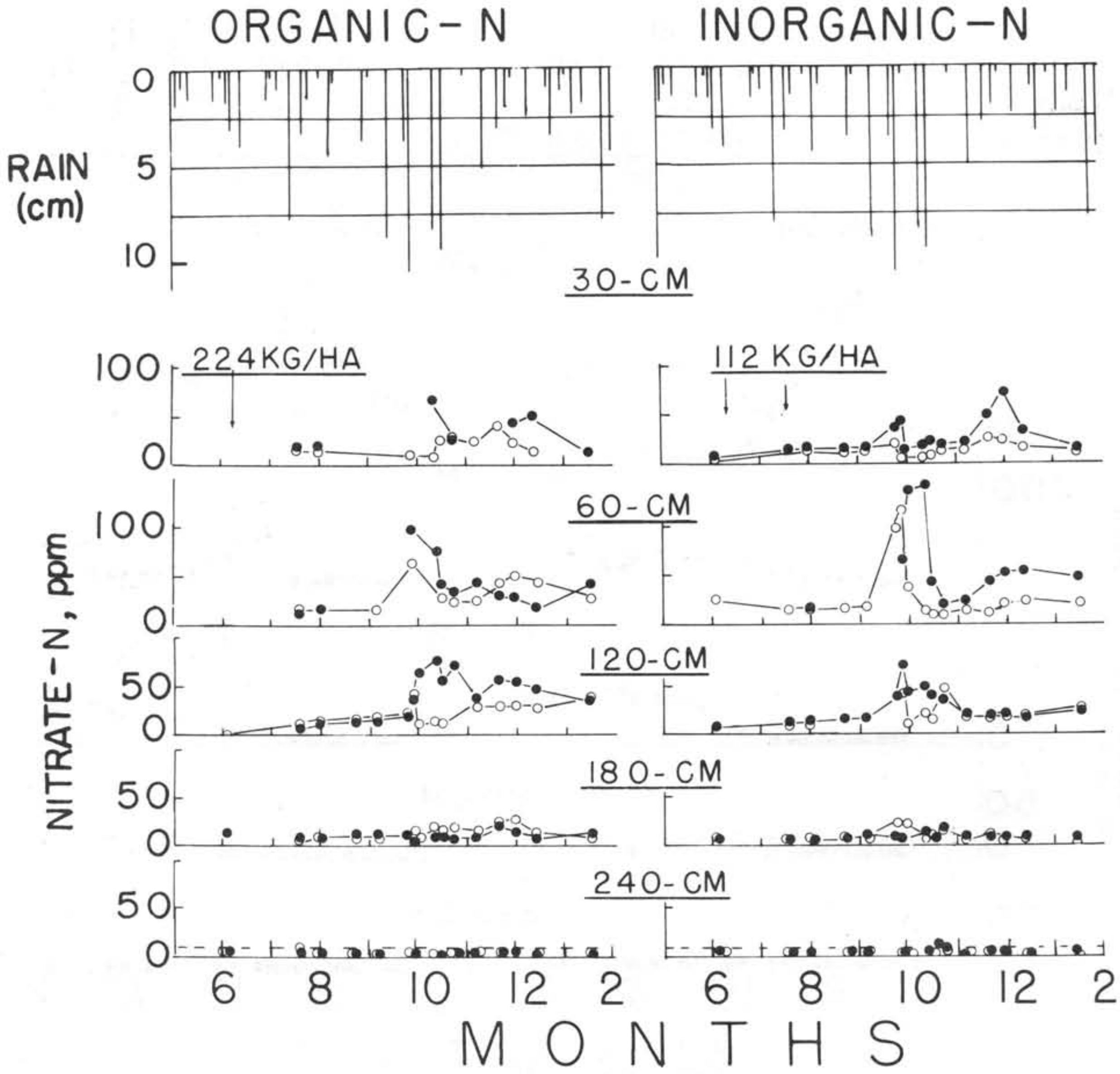

Figure 14. Distribution of rainfall with time and distribution of nitrate-N concentration with soil depth and time beneath shade tobacco in 1975. (Data of J.L. Starr and H.C. DeRoo, Connecticut)

quently, the rate of fertilizer N uptake dropped to nearly zero, resulting in a low overall total fertilizer efficiency of about 35% from the first application and 20% from the second. Owing to the low leaching loss observed in these experiments, the low efficiency must be due to a large degree of immobilization and/or denitrification.

Studies in Maine

The impact of rates of N fertilizer applied to potatoes on the soil solution levels and on the leaching losses of NO_3-N to groundwater was investigated at Presque Isle, Maine, from 1973 to 1978. The soil at the site was classified as a Caribou loam (coarse-loamy, mixed, frigid Typic Haplorthod). Samples of soil solution were removed from the B and C horizons at respective depths of about 45 cm and 120 cm. Katahdin potatoes were grown in an alternate year rotation with buckwheat. Rates of N applied to potatoes were 0, 168 and 224 kg/ha. No N was applied to the buckwheat. Samples of soil solution were removed at bi-weekly intervals beginning at spring thaw and continuing until freeze-up. Potato yields were measured annually. Potato tubers were the only material removed from the plots during the rotation; all other organic residues were incorporated into the soil.

Tuber yields obtained over a 6-year period are shown in Table 8. The addition of 168 kg N/ha resulted in tuber yields that were not significantly different from those at 224 kg/ha. The lack of response by Katahdin potatoes to the 224 kg/ha rates of N as compared to 168 kg/ha indicated that the additional

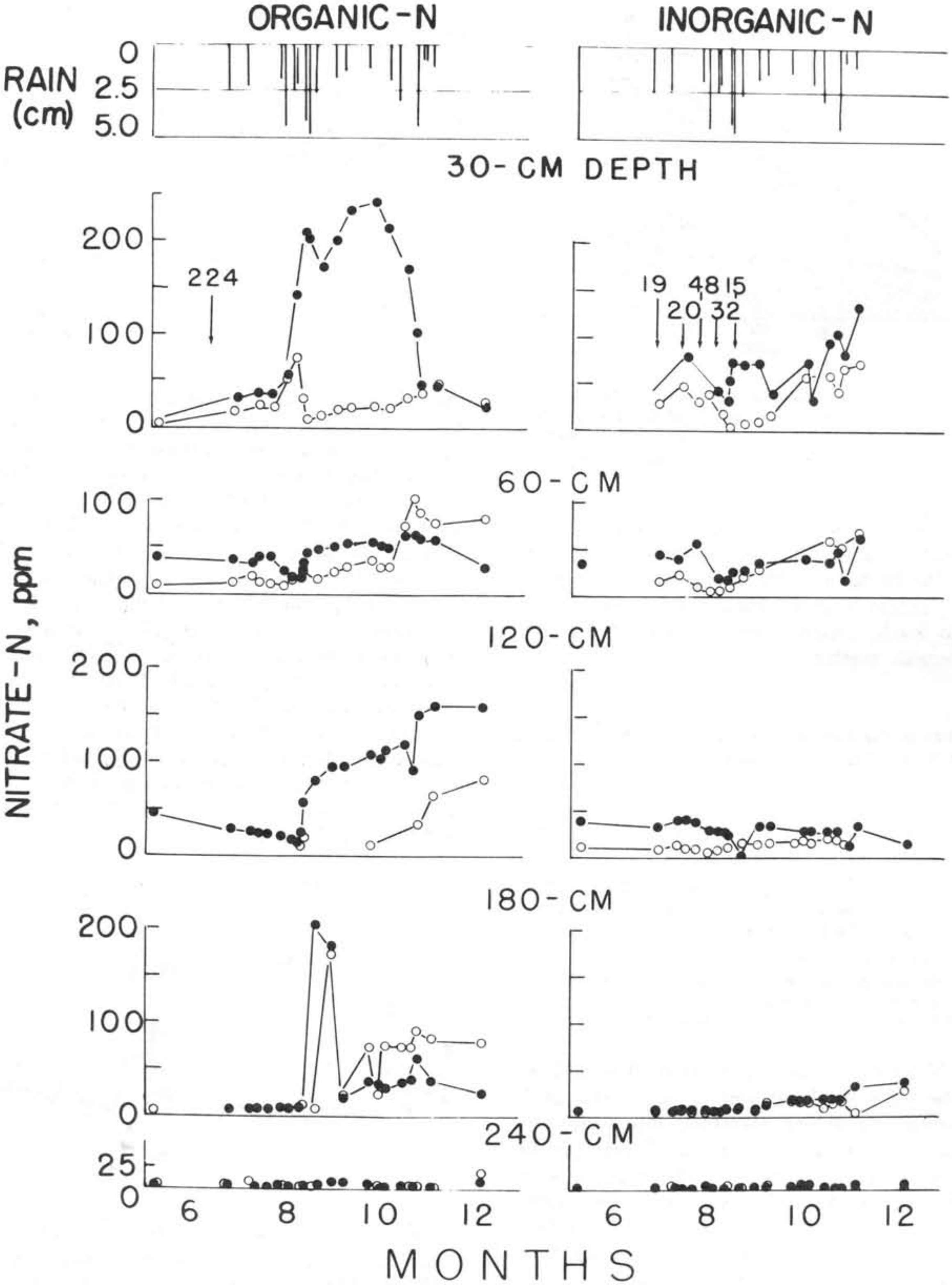

Figure 15. Distribution of rainfall with time and distribution of nitrate-N concentration with soil depth and time beneath shade tobacco in 1976. (Data of J.L. Starr and H.C. DeRoo, Connecticut)

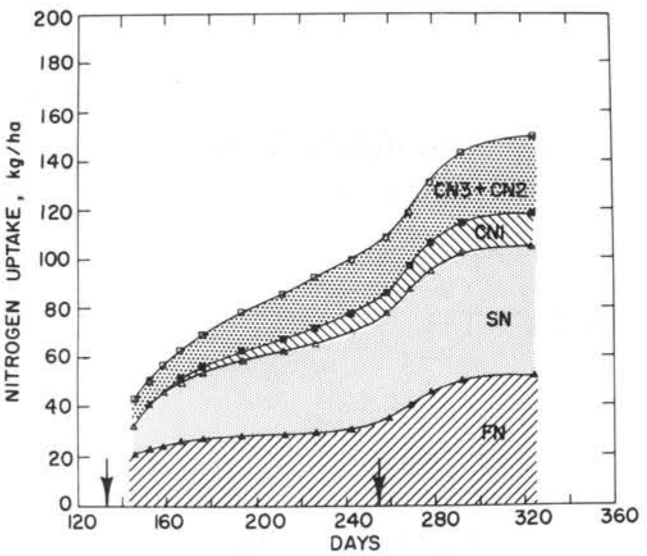

Figure 16. Cumulative N uptake derived from fertilizer N (FN), soil N (SN) and grass clippings of the current year (CN1) and of the previous two years (CN2-CN3). Arrows indicate dates of fertilizer application. (Data of J.L. Starr and H.C. DeRoo, Connecticut)

56 kg/ha was not needed. As can be seen in Table 9, N removal in tubers was not significantly different when the 168 kg/ha and 224 kg/ha rates were compared. The excess N at the highest rate remained in the soil to leach, denitrify, or be incorporated into the soil organic matter.

Table 8. Yield of Katahdin potatoes obtained with three levels of N at Presque Isle, Maine.

Rate of N	1973	1974	1975	1976	1977	1978
kg/ha	q/ha					
0	116 a*	205 a	150 a	184 a	125 a	174 a
168	179 b	394 b	239 b	341 b	277 b	318 b
224	185 b	396 b	289 b	314 b	279 b	299 b

* Numbers followed by the same letter within columns are not significantly different at Bayes .05 level.
Data of R.V. Rourke, University of Maine, Orono.

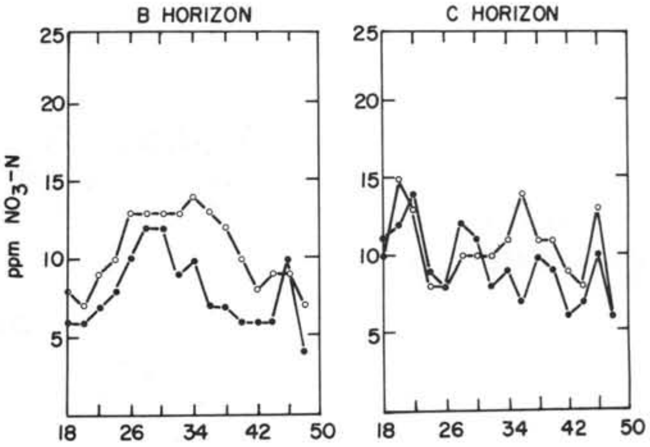

Figure 17. Six-year average of nitrate-N contents in soil solutions from plots that received no N. Open circles are potatoes, closed circles are buckwheat. (R.V. Rourke, Maine)

Nitrate-N levels in soil solution from B or C horizons of the plots fertilized with various rates of N over a 6-year period are presented graphically for buckwheat and potatoes in Figures 17 through 19. The data in Figure 17 show that NO_3-N levels were higher in the B horizon when the area was planted to potatoes that received no N than when buckwheat was rotated on the same plots. In both of the rotations, peak values of NO_3-N in the B horizon were reached by late August. Less than 10 ppm NO_3-N existed in the soil solution from the B horizon of plots seeded to buckwheat by late August. Nitrate-N concentrations in soil solutions from the B horizon did not drop to less than 10 ppm on the potato plots until late October. Peak levels of NO_3-N in the soil solution from the C horizon occurred in mid-May for both crops where no N was added. Less than 10 ppm of NO_3-N were in the soil solution from the C horizons of the buckwheat plots from mid-August until freeze-up, whereas NO_3-N level in soil solution from the C horizon of the potato plots exceeded 10 ppm from late August to late September and for a brief period in early November.

A comparison of NO_3-N levels in the B and C horizons, where 168 kg N/ha were applied to potatoes, is presented in Figure 18. Levels of NO_3-N in the solution from the B horizon were above 10 ppm from mid-May until freeze-up in late November for the

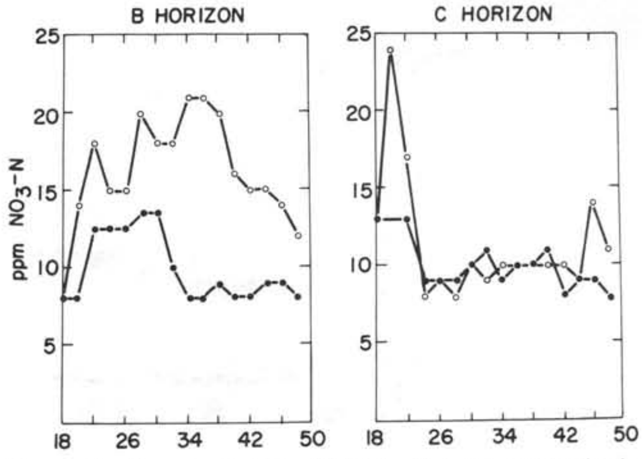

Figure 18. Six-year average of nitrate-N contents in soil solutions from plots that received 168 kg N/ha. Open circles are potatoes, closed circles are buckwheat. (R.V. Rourke, Maine)

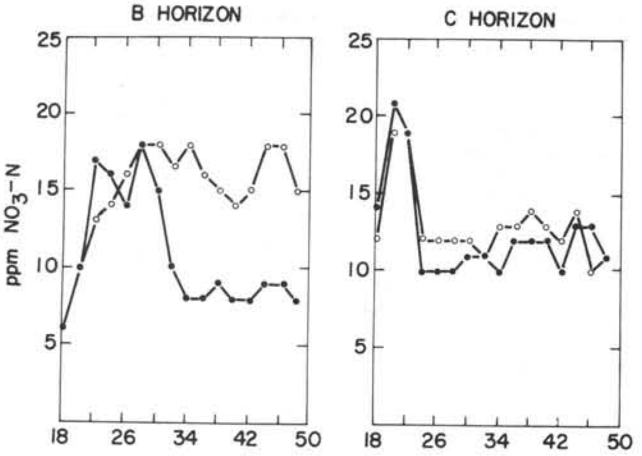

Figure 19. Six-year average of nitrate-N contents in soil solutions from plots that received 224 kg N/ha. Open circles are potatoes, closed circles are buckwheat. (R.V. Rourke, Maine)

year in which potatoes were grown. When buckwheat was grown, soil solution levels of NO_3-N in the B horizon were similar to those with no N treatment. An early peak of NO_3-N in the soil solution in the C horizon was found in mid-May with potatoes. The early level of NO_3-N in the C horizon of the buckwheat plots was half as high. Following the early peak concentration, the NO_3-N in soil solution remained at or below 10 ppm in the C horizon until mid-November for potatoes and varied from 8 to 11 ppm from mid-June to freeze-up for buckwheat. Little change in the NO_3-N content of the C horizon occurred relative to that of the control after the initial early season high.

Table 9. Nitrogen removal in tubers of Katahdin variety, Presque Isle, Maine.

Rate of N	1973	1974	1975	1976	1977	1978
	kg/ha					
0	26.0 a*	......†	24.5 a	35.1 a	24.7 a	33.8 a
168	59.5 b	......	63.0 b	93.8 b	74.6 b	94.5 b
224	60.5 b	......	79.5 b	90.4 b	80.9 b	94.8 b

* Numbers followed by the same letter within columns are not significantly different at Bayes .05 level.

† Data not available.

Data of R.V. Rourke, University of Maine, Orono.

The level of NO_3-N in the soil solution from the B horizon of soils receiving 224 kg N/ha when the plots were planted to potatoes is presented in Figure 19. Soil solution levels for the potato plots increased slowly from late April, when NO_3-N in the soil solution averaged 6 ppm, until mid-July, when the concentration in the B horizon was 18 ppm. The soil solution level of NO_3-N for potatoes remained between 14 and 18 ppm from late June through freeze-up. In late July and early August, the soil solution level of NO_3-N decreased in the buckwheat plots and in late August was below 10 ppm, where it remained with only slight fluctuations until freeze-up. After an early peak of 19 ppm NO_3-N with potatoes or of 21 ppm with buckwheat, levels of NO_3-N in the soil solution of the C horizon dropped rapidly and reached a low point by early June. The soil solution level of NO_3-N for the remainder of the year changed only slightly with both crops and remained between 10 and 14 ppm until freeze-up. Soil solution levels in the C horizon of the high N treatment (224 kg/ha), although slightly higher, demonstrated a pattern similar to that of the 168 kg/ha rate.

The application of N to potatoes increased the soil solution levels of NO_3-N in the B horizon the first year of application, and the highest levels were associated with the highest N treatment. A carry-over of N in the soil solution levels was evident with the highest N rate the following year, but these values decreased to levels similar to lower N application rates by early August. Leaching losses were possible, as judged from soil solution levels of the C horizon, from late April to mid-June. There was little evidence of any further leaching loss during the remainder of the freeze-free period.

A field study with poultry manure initiated in 1970 measured long-term effects of annual applications of different rates of manure on NO_3-N concentration and movement in two soils. The soils were a Colton gravelly loamy sand (Typic Haplorthod sandy-skeletal, mixed, frigid) and a Peru fine sandy loam (Typic Fraglorthod, coarse-loamy, mixed, frigid) having a firm layer at approximately 75 cm. The manure was applied annually in the fall for 5 years, 1970-74. All treatments were replicated four times.

The results of spring and fall samplings from in-place, suction lysimeters in the Peru soil are presented in Table 10. The data obtained from well heads three meters deep in a Colton soil are presented in Table 11. Total soil N levels in both soils at different times and depths are shown in Tables 12 and 13 respectively. Data shown in tables for years 1971-72 were taken from a Project Completion Report by Hutchinson (Hutchinson, F.E., University of Maine, Orono, 1972 "Effect of Animal Wastes Applied to Soils on Surface and Ground Water Systems," Project #A-020-ME).

Within plots, the 5-year mean values of NO_3-N concentration in the spring soil solution samples ranged from 1.73 ppm for the control up to 57.1 ppm for the high manure rate (Table 10). These mean values show a definite relationship to manure rate. However, the values obtained at 6.1 m and 12.2 m downslope were not related to manure rate. As the NO_3-N moved over the firm layer down a 10% slope from the plots, it

Table 10. The NO_3-N concentration (ppm) of soil solution samples collected on top of the firm layer in a Peru fine sandy loam treated with five rates of poultry manure.

Nitrogen kg/ha	Sampling	1971	1972	1973	1974	1975	1976	Mean 70-75
				Within plots				
0	spring	3.00	0.12	1.14	3.29	1.09	0.44	1.73
	fall	0.03	......	0.06	1.09	0.08	......	
330*	spring	4.00	0.69	2.47	5.00	2.31	1.52	2.89
	fall	0.02	......	0.03	0.88	2.83	......	
660*	spring	11.00	11.67	7.42	5.70	51.15	1.25	17.39
	fall	3.87	......	0.09	0.01	1.10	......	
1240*	spring	7.00	41.25	17.38	5.10	51.39	0.37	24.42
	fall	1.94	......	1.98	0.48	2.01	......	
2040*	spring	23.00	100.00	14.25	44.20	104.04	2.63	57.10
	fall	......	......	6.40	0.13	4.67	......	
				6.1 meters downslope				
	spring	10.20†	20.2	20.59	6.20	7.86	0.56	
	fall	0.65	......	0.14	0.45	0.25	......	
				12.2 meters downslope				
	spring	0.92	4.1	10.85	3.49	0.50	0.41	
	fall	0.07	......	0.12	0.13	0.25	......	

* Five-year average rate of N applied annually through poultry manure in fall, 1970-1974.

† Values for 6.1 and 12.2 m downslope are means for five nitrogen treatments applied through poultry manure.
Data of R.F. Stafford, University of Maine, Orono.

diffused throughout the area; therefore, values shown for downslope (Table 10) are means for all manure rates. There was no indication of any NO_3-N movement downslope beyond the 6.1 m distance until spring 1973, where values greater than 10 ppm were obtained 12.2 m downslope (Table 10). The NO_3-N concentration of the soil solution for all treatments decreased greatly from spring to fall throughout the period of study. Assuming that little NO_3-N would be leached downward through the firm layer, much of the NO_3-N present in the spring must have been denitrified. This speculation is further supported by the low soil N values obtained at the 75 to 90 cm depth, a zone below the firm layer (Table 13). The low NO_3-N values obtained in the spring of the residual year 1976, show little carryover of NO_3-N from the previous years of manure application (Table 10).

The NO_3-N concentration in ground water samples taken at the 3-meter depth in a Colton soil reached a high of 10 ppm in the spring of 1972 at the 710 kg/ha rate of N (Table 11). At the same time, a low value of 0.21 ppm occurred at the highest rate, showing that all values obtained were not related to manuring rate and that lateral movement of the soil water occurred. It is also possible that higher concentrations of NO_3-N in the ground water could have occurred at times other than the three sampling times used. However, it is important to note that the concentrations of nitrates decreased to less than 1 ppm in the fall samples for all manure rates throughout the period of the study.

Total soil N, before and after five applications of manure, ranged from a low of 0.150 to 0.316 for the Colton soils, and from 0.213 to 0.303 for the Woodbridge soils (Tables 12, 13).

Table 11. The NO_3-N concentration (ppm) in ground water samples taken at a 3-meter depth in a Colton gravelly loamy sand.

Nitrogen* kg/ha	Sampling	1971	1972	1973	1974	1975	1976
0	spring	1.77	1.81	7.83	0.27	2.36	1.62
	fall	0.27	......	0.64	0.06	0.59	......
390	spring	1.94	0.27	2.35	0.14	2.43	1.28
	fall	0.07	......	0.12	0.05	0.59	......
710	spring	0.42	10.03	2.83	0.08	4.48	1.96
	fall	0.07	......	0.16	0.04	0.31	......
1160	spring	3.06	6.77	9.30	3.78	3.29	3.85
	fall	0.07	......	0.44	0.07	0.42	......
1730	spring	2.69	0.21	1.72	0.17	0.17	0.84
	fall	0.06	......	0.29	0.40	0.90	......
Mean	spring	1.98	3.82	4.81	0.89	2.55	2.90
Mean	fall	0.11	......	0.35	0.12	0.56	......

* Five-year average rate of N applied annually through poultry manure in the fall, 1970-1974.
Data of R.F. Stafford, University of Maine, Orono.

Table 12. Total soil nitrogen of samples collected at a depth of 0-15 cm prior to initial application and after the third and fifth applications of poultry manure.

Manure rates Mt/ha	Nitrogen* kg/ha	Prior to initial	After third	After fifth
			% Total N	
Colton gravelly loamy sand				
0	0	0.188	0.166	0.160
28	390	0.175	0.179	0.224
56	710	0.178	0.188	0.235
84	1160	0.150	0.207	0.265
112	1730	0.155	0.232	0.316
Woodbridge fine sandy loam				
0	0	0.230	0.232	0.245
24	330	0.213	0.211	0.206
47	660	0.220	0.209	0.234
94	1240	0.217	0.227	0.249
188	2040	0.233	0.268	0.303

* Five-year average rate of N applied annually through poultry manure in the fall, 1970-1974.
Data of R.F. Stafford, University of Maine, Orono.

Table 13. Total soil nitrogen of samples collected at three depths, (October 1975)

Manure rates Mt/ha	Nitrogen kg/ha	Soil depth (cm) 0-15	30-45	75-90
			% Total N	
Colton gravelly loamy sand				
0	0	0.160*	0.010	0.021
56	710	0.235	0.074	0.042
112	1730	0.316	0.049	0.042
Woodbridge fine sandy loam				
0	0	0.245	0.062	0.033
47	660	0.234	0.062	0.008
188	2040	0.303	0.088	0.017

* Five-year average rate of N applied annually through poultry manure in the fall, 1970-1974.
Data of R.F. Stafford, University of Maine, Orono.

Losses of Nitrogen to the Atmosphere by Denitrification and Volatilization

Denitrification

Denitrification is the process by which nitrate is reduced to gases, principally nitrous oxide (N_2O) and nitrogen (N_2), not directly available to plant life. This process is carried out by a diverse group of bacteria which are widely distributed in soils and sediments. Denitrifying bacteria are numerous in most soils; a population density of about 1 million per gram of soil is expected for most agricultural soils (Gamble et al. 1977). Thus, the potential for significant nitrate removal by denitrification exists in most soils. The process is inhibited by oxygen, however, causing denitrification to be relatively insignificant when soils are well-drained and well-aerated.

The amount of N lost to denitrification is fundamental to goals of efficient fertilizer use and to predicting and minimizing nitrate pollution of ground waters. Quantitative answers to this central question have long been sought, but the methodology has not allowed more than qualitative answers. The best estimates come from lysimeter studies in which ^{15}N is added as fertilizer, and unaccounted losses are assumed to be due to denitrification. From a recent evaluation of all lysimeter studies, Hauck has indicated that about 25% of fertilizer is lost to denitrification under normal agricultural conditions (Hauck 1977). This evaluation provides a useful estimate but is not helpful for specific cases caused by different soils, seasonal changes and other influential management factors.

Studies at Michigan State University (J.M. Tiedje, Dept. of Crop and Soil Sciences) have focused on using new methods which measure short-term denitrification rates to determine the environmental factors affecting denitrification. These studies have evaluated how these factors affect the proportion of N_2O produced. This gas has received much attention recently, since atmospheric chemists found that it stimulates destruction of the protective ozone layer of the earth. Because a principal source of N_2O is denitrification, some have suggested that expanding fertilizer use could cause further destruction of ozone, thereby enhancing the flux of damaging ultraviolet radiation at the surface of the earth.

Table 14. Denitrification rate of Miami sandy loam as influenced by oxygen.

Soil treatment	Denitrification rate nmol N_2O/g dry soil · min
Anaerobic aggregates	0.15
Aerobic aggregates	0.00027

Adapted from Smith & Tiedje (1979a).

Effect of aeration status: Denitrifying activity has been found in all soils examined, even in well-drained sandy soils (Smith & Tiedje 1979a). This indicates that the denitrifying enzymes are generally present and that denitrification can occur immediately once the O_2 is removed. The pronounced effect of the O_2 inhibition is shown in Table 14. The rate under air is about 1/1000 of that under an anaerobic atmosphere. Increased moisture content causes reduction in available O_2 by restricting diffusion of this gas, thereby allowing zones of anoxia to grow in aggregates. The effect of various moisture contents on denitrification rate is shown in Table 15. This increased rate does not occur immediately after wetting, probably because time is needed for O_2 consumption by respiration, but it usually occurs within 6 to 10 hours. Thus, the increased rate could be observed naturally after rain or irrigation.

The rates of denitrification observed in dry, aerobic soils are low, in the range of 0.1 g N/ha · day. The rates following wetting typical of a heavy rain can be a hundred times greater, reaching a maximum rate of a few kg N/ha · day.

Table 15. Denitrification rate of Spinks loamy sand (Psammentic Hapludalf) preincubated aerobically at varying water contents.

Gravimetric water content (%)	Denitrification rate
	nmol N_2O/g soil · min
6	0.06 ± .02*
16	0.05 ± .01
27	0.10 ± .02
37	0.16 ± .06
58	0.38 ± .09

* ± $s_b t$ .05.

Adapted from Smith & Tiedje (1979a).

This estimate lies in the range expected for a 25% loss of fertilizer N. Using the above estimates for "wet" days, one could envision a reasonable case of 20 days when the soil was rather wet and a denitrification rate of 2 kg N/ha · day for those days, which would equal 40 kg N/ha lost, about 25% of the N from typical fertilization rates (160 kg N/ha). These calculations are only estimates extrapolated from limited laboratory data. No one has yet measured rates of denitrification in the field, and laboratory measurements under realistic conditions are limited; thus, these projections should neither be accepted as precise nor as transferable to other soils and conditions.

Phases of denitrification: As stated previously, denitrifying enzymes exist in the indigenous denitrifying bacteria despite the dry, aerobic state of most soils. Once soils become wet (anoxic or partially so), additional denitrifying enzymes are made by the existing organisms, thereby increasing the capacity of soils for denitrification. The increased synthesis occurs within 1 to 3 hours after anaerobiosis and is usually complete after 4 to 8 hours (Smith & Tiedje 1979a). Apparently only the enzymes responsible for the conversion of NO_3^- to N_2O are synthesized early, causing an increase in the proportion of N_2O produced (Firestone & Tiedje 1979). Eventually the enzyme reducing N_2O to N_2 is synthesized in greater quantity, and N_2O is removed. At this stage the soil becomes a sink for N_2O.

The early period before *de novo* synthesis is called Phase I, and the period after synthesis is called Phase II (Smith & Tiedje 1979a). When these rates are measured under anaerobic conditions with adequate nitrate, the rate reflects the quantity of enzyme present. Since *in situ* synthesis supposedly occurs only under conditions conducive to denitrification, the quantity of enzyme, as determined by a Phase I anaerobic assay, can be used to indicate previous soil conditions suitable for denitrification. Because these measurements are given as rates, readers may consider these activities as reflecting field rates. This is incorrect, for these rates are determined under total anaerobiosis and are therefore much higher than expected for field rates. They reflect, however, a denitrification potential of soils. This potential is different from that which is usually cited in the literature and which is based on long-term measurements from the Phase II period, or after growth of denitrifiers. This rate is farther removed from the true *in situ* state and gives high and unrealistic values.

Using the Phase I assay, synthesis of denitrifying enzymes has been shown in response to irrigation of corn plots (Smith & Tiedje 1979a). The denitrification activity prior to a 4-hour irrigation period was 0.11 (±0.3) nanomoles N_2O/g soil · min, compared to 0.25 (±0.3) after irrigation. The Phase II rate was 0.68 (±0.6). This increase in activity suggests an *in situ* synthesis of denitrifying enzymes in response to O_2 stress caused by irrigation.

Effects of roots: Increased carbon (excreted by roots), lower O_2 due to respiration, and more nitrate being brought to the rhizosphere by mass flow should make the rhizosphere a zone of more active denitrification. Using a Phase I assay, it was shown that denitrification enzymes increase near the rows in corn fields. Denitrification activities measured as picomoles N_2O/g soil · min are given as follows in order of increasing distance from the corn row: 83 (±7) at 0 cm, 66 (±7) at 15 cm and 64 (±12) at 30 cm. This and other studies always showed more denitrifying enzymes near roots; these measurements, however, do not reveal whether actual denitrification was greater in the rhizosphere (Smith & Tiedje 1979b).

A new method was developed which gave denitrification estimates under more realistic conditions. Corn and orchard grass were grown in pots, and then acetylene, which inhibits N_2O reduction (Smith et al. 1978), was added to the soil atmosphere and to a Saran bag placed over the plant top and pot. The increase in N_2O, reflective of total denitrification, was measured by gas chromatography for an 8 to 10-hour period. The main point of this assay is that the soil atmosphere remains aerobic; the rates should approximate true denitrification rates.

The findings are summarized in Table 16. The nitrate content of the soil influenced denitrification dramatically. When nitrate content was high, the results verified the prevailing opinion that the denitrification was higher in the rhizosphere. However, when nitrate

Table 16. Denitrification rate of soil as affected by plant roots and nitrate concentration.

Plant and soil	Nitrate*	Denitrification rate	
		Planted	Unplanted
		(pmol N_2O/g	soil · min)
Corn, Brookston	High	18.6	2.6
	Low	1.5	9.1
Grass, Miami	High	87.1	19.4
	Low	1.8	9.4

* High NO_3^- is greater than 25μg N/ml, and low NO_3 is less than 5μg N/ml soil solution.

Adapted from Smith et al. 1978.

content was low, denitrification was reduced, by a factor of at least five, over that in unplanted soils. This result suggests that competition for nitrate between denitrifiers and plant roots results in reduced denitrification when nitrate is low, as in most nonfertilized habitats. Thus, the percentage of N lost to denitrification is probably influenced by the fertilizer regime.

Factors affecting proportion of N_2O produced: Early estimates of N_2O production assumed that a constant percentage of N_2O is produced from denitrification in all terrestrial habitats (CAST Report 1976). At the time, this was probably the only reasonable approach for large-scale approximations, and it is probably not surprising that many factors have now been shown to affect this percentage. Perhaps what is surprising is the magnitude of the effect and the number of environmental factors; some of these responses are summarized in Table 17.

Table 17. Influence of various factors on the quantity of N_2O produced from soil denitrification.

Factor	Concentration	Percent of gas product as N_2O
None	....	1
NO_3	2 ppm	10
NO_3	20 ppm	18
NO_2	2 ppm	30
NO_2	20 ppm	80
O_2	0.016 atom	50
pH	6.5	4
pH	4.9	6
pH + NO_3	6.5 + 10 ppm	15
pH + NO_3	4.9 + 10 ppm	70
Time anaerobic	1 hour	14
Time anaerobic	12 hours	60
Time anaerobic	24 hours	1

Adapted from Firestone et al. 1979.

Thus far, increasing concentrations of nitrate, nitrite, oxygen and sulfide have been shown to increase the proportion of N_2O. Furthermore, lower temperature, increasing time of anaerobiosis and lower pH also raise the proportion of N_2O (Firestone et al. 1979; Firestone & Tiedje 1979). A number of denitrifier strains have been shown to be incapable of N_2O reduction or to lose the capacity for N_2O reduction on cultivation (Gamble et al. 1977; Okereke 1978). The impact of this phenomenon on N_2O production in nature is not known. The effect of pH is not as dramatic as previously reported, since interaction of high nitrate plus low pH cause the large increase in N_2O (Table 17).

The mechanisms causing the increase in N_2O production have been determined in soil slurries where rates of diffusion were not limiting; therefore, interpretation was not confounded by physical factors. These factors may affect the magnitude of response in N_2O emissions from the soil surface, since N_2O diffusion through soil is slow and the path is heterogeneous. Thus, the net emission is probably modified from that at the sites of production. These studies do point out which habitats and activities of man might alter the normal state of N_2O emission.

Denitrification kinetics in a flowing system were studied in the laboratory by Starr and Parlange (1975, 1976) in Connecticut. They developed a model in which the rate of denitrification could be described regardless of the kinetics observed.

To determine the dynamics of denitrification in a field soil, Volz and Starr (1977) continuously passed a solution of nitrate and glucose through a laboratory column of Cheshire fine sandy loam. Oxygen was excluded by passing N_2 gas through the soil. The time for solution to pass through the column was about 10 hours. Concentrations of nitrate, nitrite and soluble carbon were monitored in the effluent. The quantity of NO_3 in the effluent was reduced steadily, converting largely to nitrite during the first 60 hours. During this time the total of nitrate plus nitrite was reduced slightly. Presumably, if the soil were to become aerobic again, much of the nitrite present would be oxidized back to nitrate. Such a cycling has been observed to occur in the field. After 70 hours of anaerobiosis, however, the inflowing nitrate was denitrified rapidly, and the concentration of both nitrate and nitrite in the effluent was reduced essentially to zero after 96 hours. Nitrate reducers and denitrifiers were enumerated, and specific denitrification rates per microbe were calculated. These rates decreased with time from about 1×10^{-4} to 2×10^{-6} μg N/ml/hr/microbe.

Ammonia Volatilization

Urea offers more N per unit of weight than other solid commercial fertilizers. It is now manufactured in granules similar in size to other fertilizer particles used in bulk blending. Urea formerly would cake in storage, and so manufacturers were reluctant to use it.

Coating these granules with urea formaldehyde has practically prevented caking, and safe storage is almost assured. This new product is so acceptable that fertilizer companies promote it as the N of the future.

Urea, in addition to its obvious advantages, has disadvantages as follows: (1) when broadcast-urea is not incorporated into the soil, substantial losses of urea N in the form of ammonia may occur, (2) when it is incorporated into the soil, ammonia toxicity to germinating seedlings may occur where it is applied too close to the seedlings, and (3) if placed too close to the seedling, it may increase the soil pH sufficiently to seriously reduce the availability of some nutrients.

Ammonia losses to the atmosphere from surface-applied urea may be large and are governed to a degree by the acidity of the soil, by the type of soil (cation exchange), and by protective materials which can be added with the urea.

The TVA Fertilizer Summary Data (Hargett 1976) states that 63% of all the N directly applied to soils in the Mid-Atlantic states (which include Pennsylvania, New York and Maryland) was applied in N solutions (41%) or urea (22%). The use of N solution in this region has increased from 82,900 tons in 1970 to 165,900 tons in 1976, a 100% increase in 6 years. The greater use of N solutions (which contain urea) and urea, combined with the high percentage of no-till corn with surface-applied fertilizers, has undoubtedly resulted in greater volatilization losses of N.

Ammonia is lost into the atmosphere from unincorporated surface-applied urea prills regardless of the initial soil pH (Ernst & Massey 1960; Martin & Chapman 1951; Volk 1961), for the enzymatic hydrolysis product of urea, $(NH_4)_2CO_3$, is basic and raises the pH of the soil around the prill to approximately 9.0, resulting in the conversion of NH_4^+ into NH_3. Other conditions that lead to increased volatilization losses from prilled urea are low CEC (Gasser 1964; Lippold et al. 1975; Overrein & Moe 1967; Volk 1961), higher temperature (Fernando & Roberts 1975; Martin & Chapman 1951; Matocha 1976), higher initial soil pH (Ernst & Massey 1960; Lippold et al. 1975; Matocha 1976; Olson et al. 1964; Volk 1961), high N applications (Overrein & Moe 1967). larger prills (Volk 1961), and rain-free weather after application (Forster & Lippold 1975). The effect of soil moisture on NH_3 volatilization is not clear. Ernst & Massey (1960), Nommick (1966), and Kresge and Satchell (1960) found that higher initial soil water contents increased volatilization losses from urea; Lippold et al. (1975) reported that increasing the water content lowered NH_3 losses, and Martin & Chapman (1951) and Gasser (1964) found no effect of soil water on NH_3 losses. The presence of litter does not seem to affect losses from solid urea, but it substantially increased losses from N solutions (Olson et al. 1964). Crop cover has been reported either not to affect losses from urea (Nommick 1966) or to decrease them (Kresge & Satchell 1960).

In spite of the heavy use of N solutions, especially in the Mid-Atlantic states, surprisingly little research has been conducted on NH_3 volatilization from surface-applied, unincorporated solutions. Olson et al. (1964) found that with a soil pH of 6.8, three times as much N was lost from surface-applied urea as from the same rate of N solution; but with a soil pH of 7.8, the losses from N solution and urea were approximately equal. Kresge & Satchell (1960) also observed that losses from N solutions were only one-fourth to one-third as much as from the same rate of urea applied to soils with a pH of 6.3. As mentioned earlier, Olson et al. (1964) also found that applying N solutions on crop litter increased losses by about 50% over applications on bare soil.

In N fertilization of no-till corn, nitrification of NH_4 fertilizer will create an acidic soil surface (Blevins et al. 1978), which may inhibit seed germination and decrease the effectiveness of triazine herbicides (Hiltbold & Buchanan 1977).

A field experiment was initiated at Pennsylvania State University in 1975 to compare the effect of four N fertilizer sources [urea, urea-NH_4NO_3 solution, NH_4NO_3 and $(NH_4)_2SO_4$] on the yield and N content of continuous corn and on the soil pH. The fertilizers were applied at three rates to five replications on a Murrill silt loam (Typic Hapludult; fine-loamy mixed mesic) in the last week of April, about a week before planting.

Rain fell within 2 days of fertilizer application in the first 2 years of the experiment, and no differences occurred among N sources in the effect on corn yield or N content. In the third year, 1977, there were three and a half rain-free days after fertilizer application, and the grain yields in the urea and N solution plots were significantly lower than in the $(NH_4)_2SO_4$ and NH_4NO_3 plots at the 118 kg/ha rate (Table 2). The grain yield in the urea treatment was also significantly lower than with NH_4NO_3 or $(NH_4)_2SO_4$ at the 218 kg/ha rate. The amount of N taken up by the above-ground portion of the corn was also significantly less in the urea and N solution treatments at the 118 kg N/ha rate and for urea at the 218 kg/ha rate.

Research from Maryland shows that acid (pH 5.5) soils lose less ammonia than limed (pH 7.5) soils, that sandy soils with low cation exchange capacities will lose more NH_3 from surface applied urea than will loamy soils with their higher cation exchange, and that urea may be protected in part from ammonia loss by having a coat of $Fe_2(SO_4)_3$ which affords a hydroxyl ion sink (Table 18 and 19).

Urea placed in the soil too close to the germinating plant may result in loss of stand, late germination, lower overall thriftiness and limited yield (Table 20).

Table 18. NH_3 lost to the atmosphere from urea applied to the surface of a Lakeland sand treatment.

Treatment	Amount	NH_3-N Lost pH 5.5	 pH 7.5
	kg N/ha	%	
No urea	0	0	0
Urea only	184	59.2	76.3
Urea + $Fe_2(SO_4)_3$	184	0	66.8

Data of F.A. Abbruscato and J.H. Axley, University of Maryland.

Table 19. NH_3 lost to the atmosphere from urea applied to the surface of a Penn loam.

Treatment	Amount	Ammonia N Lost	
		pH 5.5	pH 7.5
	kg N/ha	%	
No urea	0	0	0
Urea only	184	4.6	15.9
Urea + $Fe(SO_4)_3$ coating	184	0.8	4.9

Data of Abbruscato and Axley, University of Maryland.

Winter wheat increased in yield as the rate of NH_4NO_3 fertilizer increased (Table 20). This was not so for urea. As NH_4NO_3 has a salt index of 49.3 for its major nutrients and urea has only 26.7, NH_4NO_3 should create the greater toxicity, but it does not. Ammonia toxicity, not increased osmotic pressure of the soil solution, is the reason for the poorer yields from the soil treated with urea.

Finally, soils with excessive free ammonia from urea treatments have a higher pH and less available Ca, Mg, Mn and K than similar soils treated with NH_4NO_3. Plants growing on such soil may temporarily suffer from the lack of one or more of these nutrients.

Table 20. Yield of winter wheat as influenced by urea and ammonium nitrate drilled with the seed.

Applied nitrogen	Granular Urea Wheat	Ammonium Nitrate Wheat
kg/ha	kg/ha	kg/ha
0	1060 cd*	1060 cd
16.8	823 bc	1394 def
33.6	1381 de	1394 def
67.2	1185 de	1687 fg
134.4	377 a	1952 g

* Mean separation by Duncan's multiple range test at 0.05 level.

Data of Abbruscato and Axley, University of Maryland.

Nitrate Accumulation in Vegetables

For the most part, vegetables are fast-growing, succulent crops which respond quickly to N fertilization. The response is generally favorable and results, in many cases, in improved yields and quality of the commodity. An important part of the vegetable nutrition research in the Northeast has been directed toward efficient N use for high yields and quality together with minimal nitrate concentrations in the harvested commodity.

Nitrate accumulation in plants is a natural occurrence caused by nitrate uptake beyond that which is reduced and assimilated into organic N compounds. The degree of accumulation is controlled by the genetic potential of the plant and is influenced by the nitrate content of the soil and the plant environment. Nitrate concentrations differ among plant parts and with stages of growth and development.

Distribution of Nitrate in the Plant

Nitrate concentrations vary among plant parts; highest concentrations are generally found in stems and petioles with decreasing concentrations in roots, lamina, grain or fruit, and flower parts (in that order). This order may not apply to all species, but is correct in most cases. Variation among species has also been noted, e.g., carrot and sweet potato roots are generally low in nitrates while radish and beet roots are high in nitrates (Table 21).

Nitrates accumulate with time when soil nitrate is not limiting. Workers at Cornell University (Aworh et al. 1980) found that nitrate concentrations increased from seeding in spinach fertilized with 340 kg N/ha, but declined in unfertilized spinach. Minotti (Maynard et al. 1976) found that nitrate concentrations in older celery petioles were about 2.8 times higher than in younger petioles and that older lettuce leaves had 2.6 times higher nitrate concentrations than younger lettuce leaves. On the other hand, nitrate is readily translocated to younger plant parts when soil nitrate is limiting or moves to nitrate sinks such as developing vegetative storage organs.

Genetic Control of Nitrate Accumulation

Nitrate accumulation differs among species and among cultivars within a species. Whole plant variation may result from differences in nitrate uptake or reduction, whereas differential translocation may affect nitrate concentrations in a specific plant organ.

The best known example of cultivar variation in nitrate concentrations is in spinach, where savoyed-leaved types consistently have higher nitrate concentrations than smooth-leaved types (Barker et al. 1974).

Table 21. Nitrate-N Concentrations in the edible portion of fresh vegetables.

Plant part	Vegetable	NO_3-N (ppm fresh wt.)
Leaves	cabbage	165
	lettuce	170
	spinach	524
Petiole	celery	535
	rhubarb	91
Roots	beet	600
	carrot	32
	sweet potato	0
	radish	402
Fruit	peas	26
	snap bean	35
	tomato	20
Stem	asparagus	25
Bulb	onion	14
Tuber	potato	42

Adapted from Maynard et al. 1976.

Semi-savoyed types are generally intermediate between these extremes, but individual cultivars may overlap into one or the other group (Table 22).

Table 22. Nitrate concentration in spinach.

Leaf type	Blades 7.5	Blades 15	Petioles 7.5	Petioles 15
	(meq/liter)			
	NO_3-N (% Dry wt.)			
savoyed	0.30	0.56	1.15	2.95
semi-savoyed	0.18	0.50	0.84	2.48
smooth	0.08	0.45	0.42	2.56

Means of six cultivars of each leaf type.
Adapted from Barker et al. 1974.

The savoyed-leaf character is not universally associated with higher nitrate concentrations. Kowal (J.J. Kowal, unpublished data, University of Massachusetts) studied smooth and savoyed-leaved cultivars of cabbage, endive and spinach fertilized with 56, 112, 225 or 456 kg N/ha in field experiments. Smooth-leaved cabbage and endive cultivars generally had higher nitrate concentrations than did savoyed-leaved cultivars, and the savoyed-leaved spinach cultivar had a higher nitrate concentration than the smooth-leaved type (Table 23).

Table 23. Nitrate-N accumulation in smooth and savoyed-leaf cabbage, endive and spinach cultivars.

Species plant part leaf form	N Application (kg/ha) 56	112	225	450
Cabbage Head Smooth	NO_3-N (% dry wt.)			
Harris' Resistant Danish	0.19	0.24	0.28	0.31
Market Prize	0.28	0.31	0.37	0.42
Market Victor	0.27	0.33	0.38	0.44
Cabbage Head Savoy				
Chieftain Savoy	0.24	0.27	0.35	0.37
Savoy Ace	0.24	0.26	0.27	0.32
Savoy King	0.19	0.27	0.30	0.34
Cabbage Leaves Smooth				
Harris' Resistant Danish	0.22	0.27	0.41	0.49
Market Prize	0.51	0.61	0.75	0.91
Market Victor	0.65	0.80	1.01	1.12
Cabbage Leaves Savoy				
Chieftain Savoy	0.26	0.31	0.52	0.66
Savoy Ace	0.35	0.42	0.52	0.54
Savoy King	0.24	0.33	0.60	0.63
Endive Leaves Smooth				
Florida Deep Heart	0.60	0.81	0.82	0.97
Endive Leaves Savoy				
Green Curled	0.35	0.38	0.53	0.74
Spinach Leaves Smooth				
Hybrid 424	0.24	0.27	0.28	0.33
Spinach Leaves Savoy				
Long Standing Bloomsdale	0.38	0.39	0.42	0.43

Unpublished data of John Kowal, University of Massachusetts.

Differential nitrate assimilation in savoyed and smooth-leaved spinach types seems to account for the difference in nitrate accumulation in specific cultivars. Nitrate reductase activity of smooth-leaved 'Hybrid 424' was 2.1 to 3.3 times greater than in savoyed-leaved 'America' spinach (Olday et al. 1976). Minotti noted marked differences among lettuce cultivars in nitrate accumulation (Maynard et al. 1976). Regardless of the nutritional or environmental regime, 'Minetto' plants consistently have higher nitrate concentrations than 'Val Rio' lettuce plants.

Environmental Control of Nitrate Accumulation

Nitrate accumulation: The root and aerial environment of the plant affect the uptake, reduction and transport of nitrate in the plant. In addition, environmental variables, particularly temperature and precipitation, affect the nitrate content of the soil. In most cases, however, the predominant influence determining plant nitrate concentrations is the rate, source, and timing of N fertilizer applications.

Nitrogen fertilizer rate: Nitrogen concentrations in vegetables generally increase with rate of N fertilization. In greenhouse experiments, Maynard and Barker (1971) showed that nitrate did not accumulate in lettuce, radish and spinach until nitrate concentrations in solution exceeded 3, 1.5 and 6 mM, respectively. Significant increases in plant nitrate concentrations occurred at each successive increment to 48 mM. Similar results are usually obtained from field experiments, *e.g.*, Peck and associates (1971) found that the nitrate content of whole beet plants doubled with the addition of 56 kg N/ha. The nitrate-N contents of beet plants at harvest was 4 mg/plant without N fertilizer, 8 mg with 56 kg/ha, and increased to 67 mg with 450 kg/ha.

Nitrogen forms and sources: Nitrate is the usual form of soil N available to plants, assuming that sufficient time is allowed and that suitable temperatures are present for mineralization of organic N and nitrification of ammonium to occur. With low soil temperatures or shortly after ammonium fertilizer application, nitrate uptake may be low because of the failure to convert ammonium to nitrate. The influence of low soil temperature on nitrification is illustrated in results obtained by Minotti with head lettuce grown on organic soil. A spring crop fertilized with 224 kg N/ha from ammonium sulfate had 0.49% NO_3-N, whereas a summer crop fertilized in the same way contained 1.16% NO_3-N (Maynard et al. 1976). With a short time interval between side-dressed fertilizer application and harvest, Barker et al. (1971) showed that nitrate accumulation was greatest from potassium nitrate, intermediate from ammonium nitrate and least from urea. Controlled-release nitrogen sources may limit nitrate accumulation in certain instances.

Time of N Application: When the effects of preplant and side-dress applications of equivalent amounts of N are compared on plant nitrate accumulation, results may vary depending on the species. Spinach accumulated more nitrate from a preplant, broadcast application than from side-dressings 9 days before harvest (Barker et al. 1971). On the other hand, side-dressed N applications resulted in higher nitrate concentrations in beet roots (Peck et al. 1974). In both cases, the highest nitrate concentrations resulted from a combination of preplant and broadcast applications.

Light: Nitrate concentrations are greater when plants are exposed to low light intensities or to short photoperiods. The effect of low light is primarily due to restricted nitrate reductase activity without a concomitant restriction in nitrate uptake. Thus, Minotti and Stankey (1973) found more than a tripling of nitrate-N concentrations from late afternoon to sunrise in young beet plants. In like manner, the nitrate-N concentrations in beet leaves fertilized with 225 kg N/ha doubled when the plants received 8 hours of light as compared to 20 hours. Differences were less pronounced at lower rates of fertilization (Cantliffe 1972a).

Temperature: Plant science literature concerning temperature effects on nitrate accumulation is ambiguous. This may be due to the inability to separate temperature effects on nitrate uptake and on reduction or to confounded effects of temperature on soil N dynamics and plant N metabolism. A study of temperature effects on nitrate accumulation by Cantliffe (1972b) showed that under light conditions conducive to nitrate accumulation, nitrate accumulated at 5° C from 112 and at 10° from 56 kg N/ha. Nitrate accumulation did not occur where N was not applied until the temperature reached 15°, presumably because mineralization and nitrification were impeded at lower temperatures.

Carbon dioxide: The available evidence suggests that elevated nitrate concentrations may occur in plants growing in CO_2-limiting atmospheres. The effect appears to be indirect, i.e., caused by a lowered amount of photosynthetically produced substrate for the generation of reducing equivalents. In addition, active nitrate reductase systems in some species may be dependent on the presence of CO_2 (Maynard et al. 1976).

Water: The accumulation of nitrates is enhanced during water stress. Assimilation of nitrate may be restricted by lowered nitrate reductase activity or by reduced availability of photosynthetic reducing equivalents.

Minotti showed that nitrate accumulation occurred under high atmospheric moisture as well as with low soil moisture. He postulates that higher humidity restricts transpirational flow of the nitrate ions to the leaves, where most of the substrate-inducible nitrate reductase is found. Consequently, he found that nitrate accumulated away from the primary sites of reduction in the plant (Maynard et al. 1976).

Postharvest Nitrate Conversions

The measurement of nitrate concentrations in harvested vegetables is useful because it provides an indication of potential adverse effects on health. Nitrate, however, is relatively low in toxicity in comparison with its possible conversion products—nitrite and nitrosamines. These toxicants are undetected or are negligible in freshly harvested vegetables. The conversion to nitrosamines has not been widely studied, but postharvest nitrite production has been conclusively demonstrated in vegetables (Minotti 1978).

Aworh and associates (1978) showed that nitrite accumulated in spinach when it was exposed to simulated transit at 5° C for 14 days followed by post-transit storage at 10° for 3 days. Pretransit storage at 21° for 15 hours caused additional nitrite accumulation. Nitrite did not accumulate at lower temperatures or shorter time periods. Nitrite-N concentrations greater than 10 ppm were found only in visibly decayed samples.

Nitrite concentrations increased with time of storage at 10° C in spinach grown at 0 or 340 kg N/ha. Nitrite concentrations at harvest were the same for both treatments, but were twice as great in the fertilized spinach after 15 days at 10°. Nitrite concentrations were higher following 15 days at 10° in spinach harvested at market maturity than spinach harvested 10 days earlier (Aworh et al. 1978).

Storage of spinach in modified atmospheres (1.8% O_2, 19.4% CO_2) resulted in improved appearance but increased conversion of nitrate to nitrite over rates in normal atmospheric storage (Aworh 1976).

Potentially toxic nitrite concentrations may occur in vegetables stored for excessive periods or at high temperatures. Microorganisms probably contributed substantially to nitrite accumulation under abusive storage (Minotti 1978).

Regulation of Nitrates in Vegetables

Since the magnitude of nitrate accumulation in vegetables depends upon an array of internal, environmental and fertilization variables, opportunities for controlling the nitrate accumulation through these variables are substantial. Maynard (1978) has summarized for spinach the potential restriction in nitrate concentration by choice of cultivar, choice of nitrogen fertilizer form, use of a nitrification inhibitor, time of harvest in respect to light conditions, and preparation for the table (Table 24). The previous discussion of genetic and environmental effects on nitrate accumulation has suggested numerous possibilities for control of nitrate accumulation. The use of controlled-release N sources or inhibitors of nitrification offer alternatives for limiting nitrate accumulation (Maynard and Lorenz 1979).

Table 24. Procedures for reducing nitrate concentrations in vegetables.

Condition	Specific adjustment	Original	Adjustment	Reduction (%)	Reference
		NO_3-N (ppm)			
Cultivar	Use of smooth-leaved (Tuftegard) instead of savoyed-leaved (Bloomsdale)	1673	444DW*	74	Cantliffe (1972a)
Fertilizer	50% NH_4-N and 50% NO_3-N instead of 100% NO_3-N	20300	13000DW	36	Mills et al. (1976b)
	Nitrapyrin used with 1 : 1 NH_4-N : NO_3-N fertilizer	13000	9000DW	31	Mills et al. (1976b)
Light	Harvest after 12 hr light instead of 0 hr	1164	839DW	28	Minotti & Stankey (1973)
Preparation	Petiole removal				
	cv. America	545	394FW	28	Olday et al. (1976)
	cv. Hybrid 424	220	121FW	45	Olday et al. (1976)

* DW = Dry weight basis
FW = Fresh weight basis

Detailed studies have been conducted of the use of nitrapyrin, a nitrification inhibitor, for restricting nitrate concentrations in vegetables, particularly in the nitrate accumulators, radish and spinach.

Mills and associates (1976a) studied the effects of N form and presence or absence of nitrapyrin on radish growth and nitrate accumulation. Nitrate accumulation was restricted with ammonium sulfate as compared to potassium nitrate at low N application rates. No differences between N forms in respect to nitrate accumulation occurred at high N rates. Nitrapyrin was effective, however, in suppressing nitrate accumulation with high rates of ammonium-N application. Reductions of at least 70% in nitrate concentrations were attributable to nitrapyrin application with ammonium sulfate. The optimum nutritional regime for growth and low nitrate concentrations in radish was 25% nitrate, 75% ammonium and at least 5 ppm nitrapyrin. Results similar to those with radish were obtained with spinach. Nitrate accumulation was lower with the ammonium form than with the nitrate form of N, and further reductions in nitrate accumulation occurred with the addition of nitrapyrin to the ammonium treatments; but unacceptable growth restrictions accompanied the lower nitrate concentrations. Maximum growth coupled with low nitrate accumulations occurred when 50% of the N was supplied from nitrate and 50% from ammonium sources with 5 ppm nitrapyrin added (Mills et al. 1976b).

Conclusions

Most cultivated crops remove from the soil more N than any other plant nutrient, and N is the plant nutrient to which crops most often produce increased growth and economic yield in response to field applications of fertilizers. Crops are often fertilized on the basis of their estimated N removal with considerations being given to the nitrogen-supplying power of the soil and to any losses or conversions of N which may occur. Notwithstanding the difficulty of estimating N contained in roots and other underground plant portions, tissue analysis and dry matter production factored together give fairly accurate estimates of N removal by a crop. The nitrogen-supplying power of the soil and the losses of N from the soil are much more difficult to assess. Some of this difficulty arises from the many reactions in which N participates in nature as shown by the Nitrogen Cycle (Figure 20).

In most agricultural soils, nitrate is the primary source of the inorganic N upon which plants feed. The nitrate in soils may be derived directly from additions to the soil or indirectly from ammoniacal sources or soil organic matter. Ideally, therefore, nitrate levels in the soil should predict the status of a soil with respect to its ability to supply N to a crop. However, in the humid Northeast, amounts of nitrate in the soil can be highly variable, their levels being controlled by biological and environmental factors. Plant growth, fallowing, rainfall, soil moisture, and soil temperature are among factors governing nitrate concentrations in the soil. Consequently, their concentrations at any given time may have no bearing on the fertility of a soil with respect to its N supply.

Soil tests for N availability have been researched considerably. Many of the tests are highly empirical and involve extraction procedures or incubation periods which have been developed for conditions of importance to a particular investigator. Direct comparisons of the various soil tests are difficult because comparable procedures for evaluation of the tests have not been used. Soil scientists in the Northeast have been evaluating and developing laboratory procedures to predict mineralization rates for soil organic matter

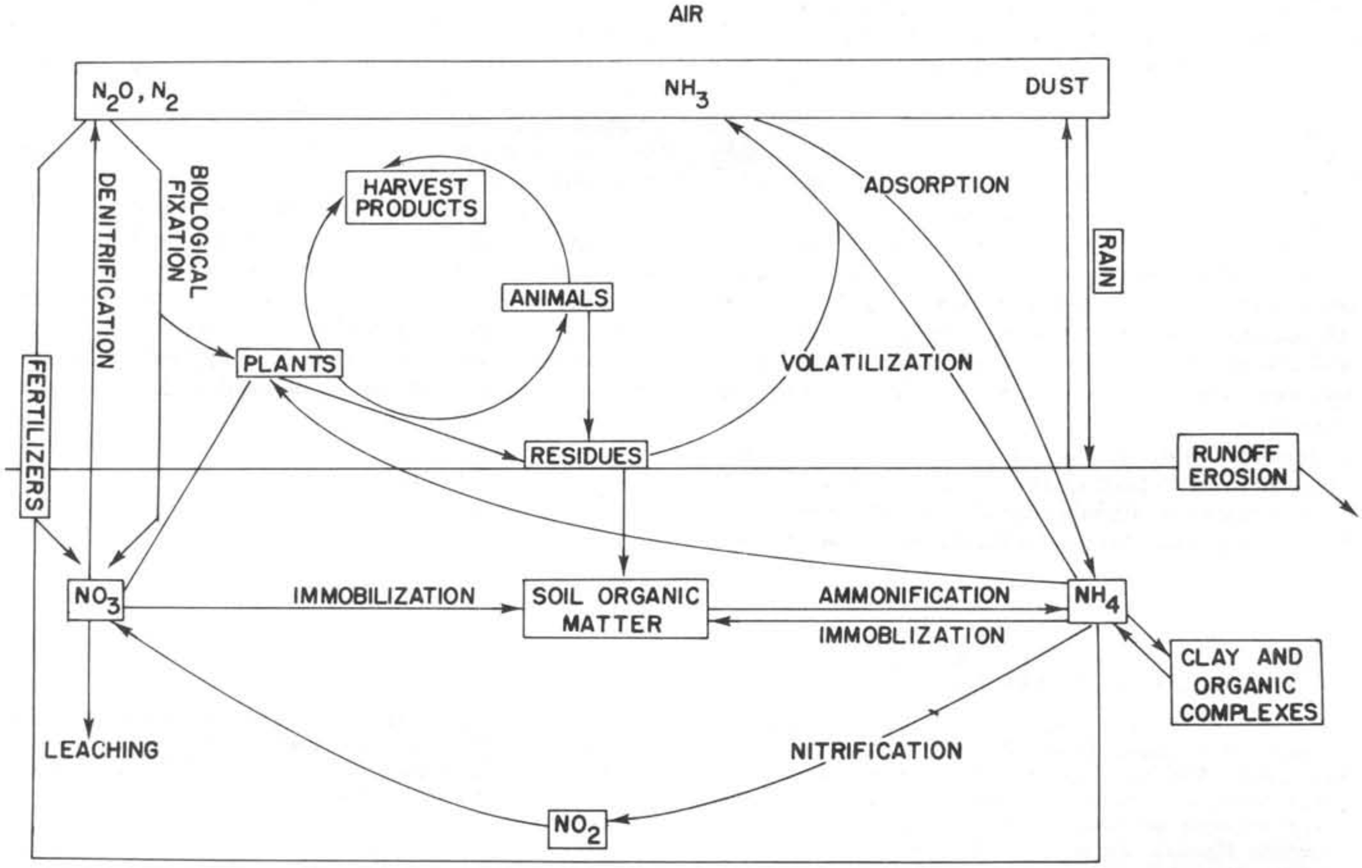

Figure 20. The Nitrogen Cycle.

or to predict the contribution of soils to the N demands of a crop.

Some laboratory procedures appear promising, but calibration of these procedures in the field with crop demands is lacking. More data must be obtained from research under farm conditions and at numerous sites before laboratory evaluations of the N status of soil can be correlated to field conditions. Heretofore, time and expense has limited these investigations; however, increased support of this research may now be justified by the rising costs of N fertilizers and by the necessity to improve the efficiency of N use.

The concern for the effects of N on our environment is another factor pressing for efficient use of N in agriculture. The recovery by a crop of only half of the applied N is a frequently cited statistic. Therefore, some of the fertilizer N is said to be a source of environmental pollution. Research is underway in the Northeast that indicates that the fraction of fertilizer N recovered by a crop under good management practices may approach 90%.

Ammonia volatilization from urea and other ammoniacal fertilizers is likely to result from poor management. Research is needed to develop procedures to diminish these losses.

The leaching of nitrates into ground water and the movement of nitrate into drinking and recreational waters has been a long-term environmental concern. Agriculture has frequently been accused of being a source of nitrates found in these waters, although leaching losses from applied fertilizers have been difficult to verify. On the other hand, agriculturists have had difficulty in inventorying and accounting for all of the N applied to the soil. Investigations on the movement of N in the soil and on the conversion of N into soil organic matter and into gaseous denitrification products are needed to provide definite answers to the fate of fertilizer N applied to cropland.

Denitrification losses of N from the soil have been considered harmless and nonpolluting since such losses do not enter the ground water. Today, attention must be given to the effect which N_2O produced in the soil and escaping into the atmosphere has on the ozone layer of the stratosphere. The contribution of fertilizer to N for denitrification must be evaluated. Research is needed on methods of assessing denitrification in the soil and for measuring on-site, field losses of N through denitrification and the products and significance of these losses under various management practices, including the presence or absence of crops or of crop residues.

Management practices are a key factor in the efficient use of N. The validity of a field-calibrated soil test may be lost if the correct procedures for applying N to a crop are not understood and followed. Hence, efficient procedures for the use and conservation of N must be integrated into management systems involving no-till or preplanted sidedress applications of N in cultivated soils. The uptake, transport, and utilization of N by crops must be known so that fertilization may be correlated with crop demands in time and quantity.

Excessive uptake and accumulation of nitrate in plants used for food or feed crops has been a long-term concern for the health of humans and livestock. All management systems must consider the potential and consequences of luxury consumption of nitrates by crops. Nitrate accumulation in a crop may be considered as wasteful, but on the other hand, efforts to restrict nitrate accumulation may lead to diminished yield or to poor quality of the produce. Efforts to limit nitrate availability by the use of chemical inhibitors and ammonium fertilizers may lead to ammonium toxicity or may otherwise adversely affect crop growth and composition.

Postharvest conversions of nitrate in plant products are not thoroughly investigated. Researchers in the Northeast must continue to study nitrate accumulation in vegetables and livestock feed and postharvest conversions of nitrate to nitrite.

Nitrate fertilization is a factor contributing to the annual increase in crop productivity which has been observed consistently over the past 30 years. Therefore, the use of N fertilizers in agriculture will continue. Presently, crop yields are increased in at least 70% of the cases where some N is applied to the soil. Research must continue to determine the amount of N fertilizer which must be applied to reach yield goals and to minimize losses through leaching, denitrification, and luxury consumption. This research will lead to efficient use of N in Northeast agriculture.

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