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# Fate of Fertilizer Nitrogen Applied to Corn as Estimated by the Isotopic and Difference Methods

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## ABSTRACT

**The percentage of applied fertilizer N taken into plants is often estimated by measuring the difference in plant N uptake between treated and check plots. This method has often overestimated plant N uptake. The objectives of this study were to (i) compare the recovery of fertilizer N in corn (*Zea mays* L.) as calculated by the difference and isotopic methods and (ii) track fertilizer N in the plant–soil system using isotopic enrichment of N. Sixteen N plots (3 m × 3 m) were established on a Hecla fine-sandy loam (sandy, mixed, frigid Oxyaquic Hapludolls) and replicated four times in a completely random design. Corn received sidedressed band applications (15 cm from row and 5 cm deep) of $^{15}$N-enriched and nonlabeled urea N at 135 kg N ha$^{-1}$ in 1993 and 1994. Plant uptake of fertilizer N as estimated by the isotopic and difference methods was 45% and 39% in 1993 and 40% and 22% for 1994, respectively. Nearly 42% and 36% of the applied labeled N was accounted for in the soil at the end of 1993 and 1994, respectively. The difference method did not overestimate plant N uptake because of high soil N availability. Lower corn yield potential in 1993 was the consequence of a cooler, shorter growing season. This climatic difference had less effect on the results generated by the isotopic method. Reasons for the N deficit in this investigation are speculative since no attempts were made to measure gaseous emissions; however, denitrification and/or leaching are thought to be the primary mechanisms.**


The difference method, also known as the indirect, net effect, or nonisotopic method, has often been used in field experiments to estimate fertilizer nitrogen (N) recovery by crops. The total N uptake by plants from control plots is subtracted from the total N uptake by plants from the N-fertilized plots and divided by the amount of N added to the fertilized plots to obtain a measure of N recovery. There is, however, an assumption associated with this method that can lead to gross misinterpretations of recovery data. This assumption is that mineralization, immobilization, and other soil N transformations are the same for both control and N-fertilized plots, such as microbial activity and root growth being unaffected by fertilizer additions. To circumvent the possible errors inherent with the difference method, researchers have employed isotopic tracer techniques. Isotopic tracers afford distinction between fertilizer N and soil N and allow the researcher to directly determine fertilizer N recovery; hence its alternative name, the direct method.

Most N studies that employ isotope techniques use fertilizers enriched with $^{15}$N, the stable isotope of N, because it is nonradioactive, does not decay with time, does not pose a health threat to the investigator nor to the soil–plant system, and it can be used without a permit (Hauck and Bremner, 1976). The use of $^{15}$N in soil fertility research has two primary drawbacks: (i) the material is very expensive and is thus limited to small greenhouse or microplot investigations and (ii) fertilizer N recovery interpretations are complicated by the fact that $^{15}$N undergoes biological interchange when applied to the soil system.

Biological interchange can be defined as the process in which labeled ions or molecules are replaced with nonlabeled ions or molecules (or vice versa) by means of microbial synthesis or decomposition. In other words, a labeled molecule of the inorganic phase may be transpositioned into the organic phase as a nonlabeled molecule through immobilization; conversely, a nonlabeled molecule of the organic phase may be transpositioned into the inorganic phase as a labeled molecule through mineralization. For this reason, it has been advised that studies involving fertilizer N recovery should include control plots and calculate fertilizer N recovery by both isotopic and difference methods (Jansson, 1958). This reduces the chance of making erroneous interpretations due to the mineralization–immobilization turnover (MIT) and biological interchange processes (Jansson, 1958).

Many of the studies comparing the two methods of calculating fertilizer N recovery found the difference method consistently gave higher results. For instance, Westerman and Kurtz (1974) estimated recoveries of fertilizer N by sudangrass [*Sorghum bicolor* (L.). *Moench*] and found the difference method overestimated recovery of applied urea by 35% and 23% in 1966 and 1967, respectively. Moraghan et al. (1984a) found in their 1981 study on a Vertisol in the semiarid tropics that all treatments showed higher recoveries when calculated by the difference method. Other researchers who reported that the difference method produced greater fertilizer N recoveries than the isotopic method include Legg and Allison (1959) and Torbert et al. (1992).

Fertilizer N recovery calculated by the difference method is not always higher than isotopic recovery (Allison, 1966; Westerman and Kurtz, 1974; Rocous et al., 1988). Moraghan et al. (1984b) found that, when compared to the isotopic method, the difference method yielded lower fertilizer N recoveries in their 1980 sorghum study. They contend that low recoveries by the difference method are atypical and can be attributed to high soil N availability. For instance, when available soil N levels are relatively high (e.g., in first-year check

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**Abbreviations:** BMP, best management practice; MIT, mineralization–immobilization turnover.

treatments), a smaller percentage of that N being mineralized will be used by the soil microflora in the decomposition of organic materials; therefore more N will be available for plant uptake. As a result, both the aboveground plant parts and the roots will have a high N content relative to the treated plants. When the high N content of these plants is subtracted from that of the N-treated plants with only slightly higher N content, the calculated recovery values are generally lower (Allison, 1966). Also, if the treated area receives a low N rate, most of the added material will become immobilized and recovery will be lower (Allison, 1966).

The use of $^{15}$N in fertilizer research should be carefully planned. Because of its high cost, meticulous sample preparation requirements, and the interpretative complications of biological interchange, the difference method may prove more appropriate in estimating fertilizer N recovery. The objectives of this study were to (i) compare recovery of fertilizer N under irrigated, continuous corn production as calculated by the difference and isotopic methods and (ii) track fertilizer N in the plant–soil system using isotopic enrichment of N.

## MATERIALS AND METHODS

A study was initiated in June 1993 at the Best Management Practices (BMP) study site near Oakes, ND. Corn (*Zea mays* L.) had been grown on this site since the inception of the BMP project in 1989. The dominant soil series is a Hecla fine-sandy loam that is classified as a sandy, mixed, frigid Oxyaquic Hapludolls.

Four replicates of each treatment (labeled, nonlabeled, and check) were randomized within the treatment area. Sixteen N plots (3 × 3 m) were established parallel to the G and E transects in 1993 and 1994, respectively (Fig. 1). In 1993 all plots received a preplant, broadcast fertilizer application of mono ammonium phosphate in the percent element form (10-21.5-0) at the rate of 13.5 kg N ha$^{-1}$. On 30 June 1993 8 of the 16 plots received yield-goal-based band applications of urea N at 135 kg N ha$^{-1}$. Four of the eight N plots received an enrichment of 4.25 atom % $^{15}$N, while the other four N-treated plots received nonlabeled urea N at 0.3664 atom % $^{15}$N. The remaining eight plots were check plots and received only the 13.5 kg N ha$^{-1}$ of the preplant material. Thus, there was a total of four replications with each replication containing a labeled, a nonlabeled, and two check treatments. Urea N was sidedressed 15 cm from the corn row and 5 cm deep.

The 1994 N plots were established similarly to the 1993 N plots but with the following exceptions: (i) the N plots (including check plots) were established parallel to the E transect (Fig. 1) with preplant application of monoammonium phosphate in the percent element form (10–21.5–0) at rates of 35.8 kg N ha$^{-1}$ broadcast and 12.3 kg N ha$^{-1}$ applied with the seed; (ii) labeled and nonlabeled urea N were applied 13 June 1994 at 135 kg N ha$^{-1}$; and (iii) the urea N applied to the $^{15}$N treatments was enriched with $^{15}$N by 5.934%. The 1993 N plots were established after the preplant fertilizer application of 13.5 kg N ha$^{-1}$. Because of this, we wanted the 1994 check plots to receive the same preplant fertilizer rate. However, the preplant fertilizer applications were higher in 1994 because

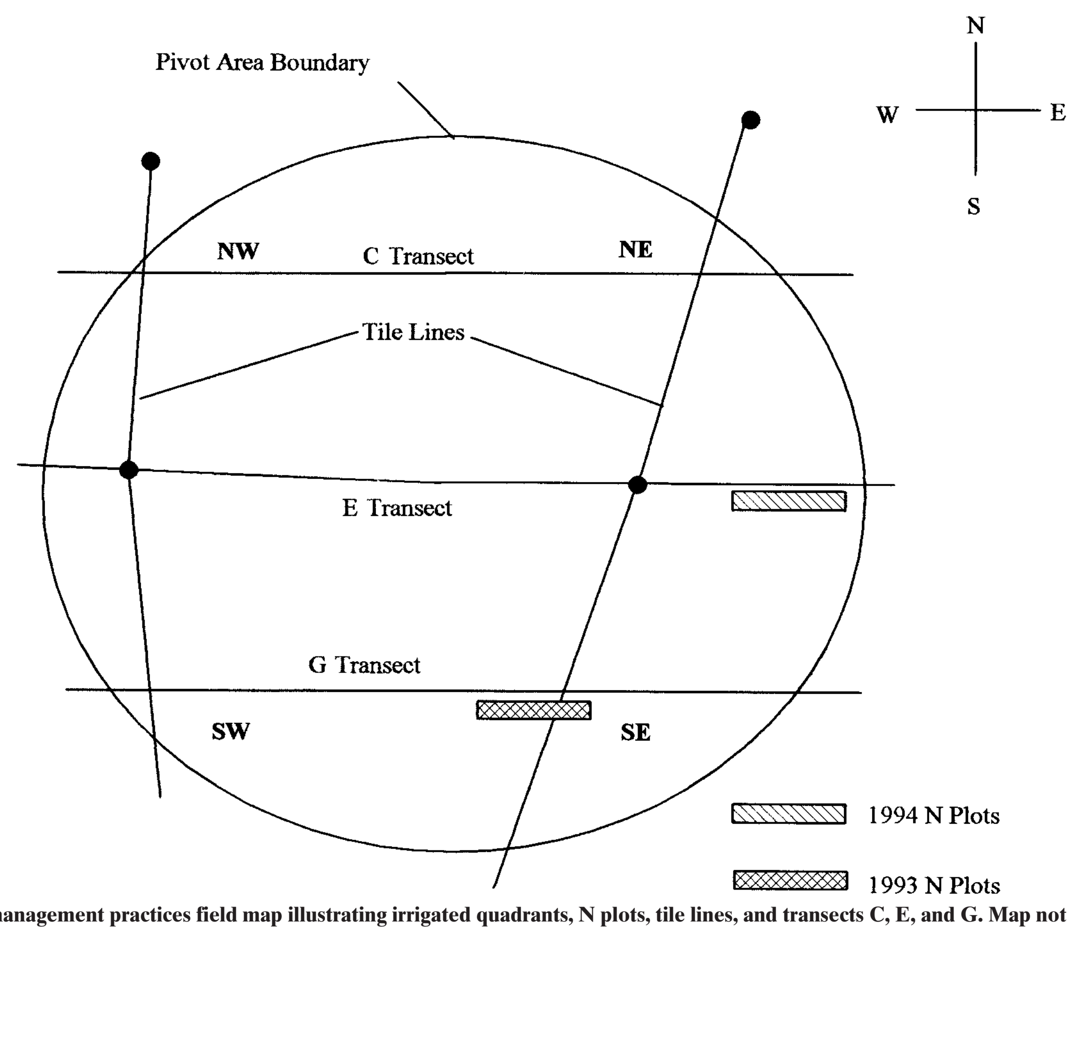


**Fig. 1. Best management practices field map illustrating irrigated quadrants, N plots, tile lines, and transects C, E, and G. Map not drawn to scale.**

the farmer–cooperator changed his practice to conform to other fields he was farming, without consulting us.

Final harvest of corn plants occurred at the R6 stage of development. Harvesting took place 25 Sep. 1993 and 24 Sep. 1994. Two 2.44-m rows in each plot were harvested and used for yield determinations. Ears were counted and weighed, stover was weighed and chopped, and all plant material was placed in cloth bags and dried at 60°C. The harvest rows consisted of 26 plants, 5 of which were randomly selected and harvested to include their adventitious roots. The roots were washed thoroughly of any adhering soil and ground with the stover. The five randomly selected plants and adventitious roots were taken from outside the 75 by 90 cm soil sampling area. This eliminated disruption of the soil sampling area, thus optimizing soil $^{15}N$ recovery. Plant material was separated into grain, stover and adventitious roots, and cob fractions. All plant material was ground twice, first in a Wiley mill with a 1-mm screen and then in a rotary grinder producing a particle size of 0.5 mm.

To reduce the likelihood of cross-contamination, all samples were ground in order from least $^{15}N$ concentration to greatest $^{15}N$ concentration. That is, the check samples were ground first followed by the nonlabeled samples and finally the labeled samples. In addition, samples from $^{15}N$-treated plots were placed in separate ovens during the drying process.

All samples were sent to Isotope Services, Inc., Los Alamos, NM, for total N and isotope-ratio analysis by a Dumas combustion analyzer (model 1500, Carlo Erba Instruments, Milan, Italy) and a VG Isomass mass spectrometer (prototype from VG Masslab., Altrincham, UK), respectively. The total N in the aboveground plant parts derived from fertilizer N was calculated by both the difference and isotope methods. Plant N uptake by the difference method was calculated as

$$\%\ \text{fertilizer N recovery} = \{[(Y_{fert})\ (N_{fert}) - (Y_{nonfert})\ (N_{nonfert})]/A\} \times 100 \quad [1]$$

where $Y_{fert}$ is the total dry matter yield in kg ha$^{-1}$ of fertilized plots, $N_{fert}$ is percent total N of fertilized plots, $Y_{nonfert}$ is the total dry matter yield in kg ha$^{-1}$ of nonfertilized plots, $N_{nonfert}$ is percent total N of nonfertilized plots, and A is kg ha$^{-1}$ of applied urea N. Plant N uptake by the isotopic method was calculated as

$$\%\ \text{fertilizer N recovery} = \{[(L_{fert})\ (N_L)\ (Q_P)]/Q_S\} \times 100 \quad [2]$$

where $L_{fert}$ is the total dry matter yield in kg ha$^{-1}$ of labeled treatments, $N_L$ is percent total N of labeled treatments, $Q_P$ is atom % excess $^{15}N$ in plant material, and $Q_S$ is kg ha$^{-1}$ excess $^{15}N$ applied to soil. The natural $^{15}N$ abundance of the plant material was determined by averaging the values of all check treatments.

Fall soil samples were taken on 2 Nov. 1993 and 28 Oct. 1994. All treatments were sampled to a depth of 1.8 m with increments of 0–15, 15–30, 30–60, 60–90, 90–120, 120–150, and 150–180 cm. Two 0.101-m$^3$ sections of soil were removed, mixed, and composited for all $^{15}N$ treatments at the 0–15 cm and 15–30 cm depths: for example, a 75 by 90 by 15 cm section was removed for the 0–15 cm subsample, followed by another section of equal area for the 15–30 cm subsample. For the remaining samples, two 3.75-cm diam. cores were taken from the excavated section of soil. The cores were composited and a subsample obtained. The nonlabeled and check plots were sampled similarly except the top 30 cm of soil was not removed. Instead, 10 1.88-cm diam. cores plus the two 3.75-cm diam. cores were composited for the 0–15 cm and 15–30 cm depths.

All soil samples were kept frozen until analysis. Soil samples were air-dried, ground, ball-milled (all root fragments were retained) to a particle size of 250 μm, and sent to Isotope Services, for total N and isotopic determinations. All soil samples were ground similarly to plant samples in that the check samples were ground first followed by the nonlabeled samples and finally the labeled samples. The percentage of labeled fertilizer N remaining in the soil at the end of the 1993 and 1994 growing seasons was calculated by the following equation:

$$\%\ ^{15}\text{N recovery} = [(\text{NR})\ (S_{excess})]/[(\text{NA})\ (U_{excess})] \times 100 \quad [3]$$

where NR is the amount of total N remaining in the soil after harvest in kg ha$^{-1}$, NA is the amount of urea N added to the soil in kg ha$^{-1}$, $S_{excess}$ is the atom % $^{15}N$ excess in soil, and $U_{excess}$ is the atom % $^{15}N$ excess in urea N. The natural $^{15}N$ abundance of the soil was determined by averaging the values of all check treatments.

Total N values for Eq. [3] were converted from mg kg$^{-1}$ to kg ha$^{-1}$ by using weighted bulk densities calculated from those listed in the 1990 BMP annual report (Stegman et al., 1990), which indicates bulk densities along each transect according to depth of horizon. Weighted averages were calculated from these horizonal bulk densities for each depth increment in this study. The BMP site possesses a very uniform, unstructured soil (minimal effects of macroporosity due to root or worm holes and shrink–swell phenomena); therefore, the authors felt it sufficed to use weighted bulk densities from previous measurements rather than taking individual bulk densities at each sample location and depth.

Paired *t* tests with unequal variances were used to compare mean differences. Statistical comparisons were made between treatments within year and plant fraction, and between treatments and years within plant fraction for average plant N content and dry matter yield. Statistical comparisons were made between plant N recovery method within and between years for each plant fraction, and between years at each depth increment for soil fertilizer N recovery.

## RESULTS AND DISCUSSION

The 1993 and 1994 growing seasons differed considerably. The growing degree unit accumulations in the Oakes area were 11% below the long-term average (1960–1990) for 1993 and 5.3% above the long-term average for 1994 (Steele et al., 1996). In addition, the 1993 growing season had an average irrigation plus total rainfall of 38 cm, whereas in 1994 the value was 51 cm (Steele et al., 1996). Corn plants were harvested on 25 Sep. 1993. The temperature on 18 Sep. 1993 dropped to −1.1°C, which forced physiological maturity of the corn plants. Conversely, freezing temperatures did not occur before plant harvest in 1994, thus allowing the plants to dry normally in the field and assimilate more soil N. The cooler, shorter season of 1993 hindered corn growth and production and resulted in lower plant N uptake and dry matter yields (Tables 1 and 2, respectively).

Approximately 31, 12, and 2% of the applied $^{15}N$-enriched urea N was in the grain, stover, and cob fractions of the corn plants in 1993. Likewise, 32, 7, and 0.7% of the applied $^{15}N$-enriched urea N was found in the grain, stover, and cob fractions of the corn plants in 1994 (Table 3). Percent fertilizer N recoveries in corn

**Table 1. Average plant N uptake in aboveground plant parts at the end of the 1993 and 1994 growing seasons.**

| Year | Plant fraction | Plant N† Treated plots | Plant N† Check plots |
|---|---|---|---|
| | | kg ha$^{-1}$ | |
| 1993 | Grain | 87.9 (a)‡ a§ (4.5)¶ | 52.1 (b) a (7.7) |
| | Stover | 34.5 (a) c (8.3) | 19.2 (b) c (29.5) |
| | Cob | 4.3 (a) e (10.5) | 2.6 (b) e (12.9) |
| 1984 | Grain | 161.5 (a) b (1.6) | 143.0 (b) b (3.6) |
| | Stover | 40.9 (a) d (8.6) | 30.1 (b) d (8.5) |
| | Cob | 3.8 (a) f (9.1) | 3.7 (a) f (8.6) |

† Average plant N of eight replicates.
‡ Means within a row followed by the same letter in parentheses were not significantly different at $\alpha = 0.05$. Statistical comparisons were made between treatments within and between years for each plant fraction.
§ Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$.
¶ Value in parentheses is coefficient of variation.

**Table 2. Average dry matter yield of aboveground plant parts at the end of the 1993 and 1994 growing seasons.**

| Year | Plant fraction | Dry matter† Treated plots | Dry matter† Check plots |
|---|---|---|---|
| | | kg ha$^{-1}$ | |
| 1993 | Grain | 5 790‡ (4.4)§ | 4 330 (7.5) |
| | Stover | 4 930 (3.7) | 4 220 (7.7) |
| | Cob | 1 240 (1.2) | 814 (5.2) |
| 1994 | Grain | 11 770 (6.9) | 11 430 (0.49) |
| | Stover | 6 620 (0.87) | 6 020 (1.3) |
| | Cob | 1 590 (1.9) | 1 500 (5.2) |

† Average yield of eight replicates.
‡ All mean values were significantly different at $\alpha = 0.05$. Statistical comparisons were made between treatments within and between years for each plant fraction.
§ Value in parentheses is coefficient of variation.

grain, stover, and cob fractions as estimated by the isotope and the difference methods are presented in Table 3. The isotopic method gave higher average fertilizer N recovery in all aboveground plant fractions for 1993 and 1994 and lower, but not significantly different, average fertilizer N recovery in the stover fraction for the 1994 growing season (Table 3). Average fertilizer N recoveries by the isotopic and difference methods were not significantly different among the grain, stover, and cob fractions for the 1993 growing season but were, however, significantly different between the cob and grain fractions for 1994 (Table 3).

The percentage fertilizer N recovery as estimated by the isotopic method was similar to those reported in other investigations (Moraghan et al., 1984a, b; Walters and Malzer, 1990; Torbert et al., 1992); however, the percentage fertilizer N recovery as estimated by the difference method was not. In studies comparing the percentage fertilizer N recovery as estimated by the isotopic and difference methods, most report higher recovery values using the difference method (Westerman and Kurtz, 1974; Moraghan et al., 1984a; Torbert et al., 1992), which are contrary to the findings of this investigation. In all instances except the 1994 stover, the isotopic method yielded higher recovery than the difference method (although not statistically different) indicating the difference method did not overestimate fertilizer N uptake.

The difference method in this study did not overestimate fertilizer N uptake, because the check plots were newly established in 1993 and 1994 and thus contained high levels of residual $NO_3^-$–N relative to the treated plots. According to the average BMP figures used for yield-goal-based N applications, 24.6 and 44.8 kg of $NO_3^-$–N ha$^{-1}$ were present in the top 60 cm of the soil profile and available for plant uptake at the start of the 1993 and 1994 growing seasons (Steele et al., 1996). These values do not appear very high, but when compared to the average residual $NO_3^-$–N of established, two-year check plots at the BMP site (e.g., 8.9 kg of $NO_3^-$–N ha$^{-1}$), they are quite high. The residual $NO_3^-$–N values for this study were obtained from areas adjacent to the microplot area. This was done to minimize microplot disturbance and the authors felt that these values would adequately represent residual soil N levels of the microplot area. Also, soil N availability can be verified by agronomic response to fertilizer additions (Moraghan et al., 1984b).

The relatively small difference in dry matter yield between treated and check plots is evidence of minimal fertilizer response (Table 2). Because of this lack of fertilizer response, the difference method did not overestimate fertilizer N recovery. Even though the plant N content in the check plot was significantly lower than in the treated plots (Table 1), this difference was apparently not large enough to result in overestimation of fertilizer N uptake by the difference method. In addition, the total N uptake in the check plots was greater than the difference between $^{15}N$ uptake and total N uptake in the treated plots, which indicates the priming effect was not a major factor in this investigation and that plants did not take up more soil N where fertilizer N was added (Westerman and Kurtz, 1974). According to Torbert et al. (1992), the *priming effect* often manifests itself when soil N availability is low.

Similar results were reported and discussed by Moraghan et al. (1984b) where the difference method yielded lower fertilizer N recoveries than the isotopic method in their 1980 sorghum study. They attributed the lower

**Table 3. Fertilizer N recovery in corn grain, stover (plus adventitious roots), and cob fractions as estimated by the isotopic (Eq. 2) and difference methods (Eq. 1) at the end of the 1993 and 1994 growing seasons.**

| Year | Plant fraction | Fertilizer N recovery† Isotopic | Fertilizer N recovery† Difference |
|---|---|---|---|
| | | % | |
| 1993 | Grain | 31.4 (a)‡ a§ (5.4)¶ | 26.2 (a) a (9.2) |
| | Stover | 11.8 (a) b (10.0) | 11.4 (a) c (27.6) |
| | Cob | 1.6 (a) d (14.8) | 1.3 (a) e (31.1) |
| | Total | 44.8 (a) f | 39.0 (b) g |
| 1994 | Grain | 32.2 (a) a (19.0) | 13.7 (b) b (13.9) |
| | Stover | 6.8 (a) c (32.0) | 8.0 (a) d (42.6) |
| | Cob | 0.7 (a) e (5.4) | 0.1 (b) f (59.1) |
| | Total | 39.7 (a) f | 21.8 (b) h |

† Recovery values are the average of four replicates.
‡ Means within a row followed by the same letter in parentheses are not significantly different at $\alpha = 0.05$. Statistical comparisons were made between recovery method within and between years for each plant fraction.
§ Means within a column followed by the same letter are not significantly different at $\alpha = 0.05$.
¶ Value in parentheses is coefficient of variation.

recoveries of the difference method to high soil N availability. Studies have shown that when there is no apparent priming effect, or when there is minimal MIT, due to low soil organic matter, coarse texture, or low N additions, recovery of fertilizer N as calculated by the isotopic and difference methods will be similar (Rocous et al., 1988; Torbert et al., 1992).

This study is evidence that climate can play an important role in soil N availability and in estimating fertilizer N recovery. Table 3 shows that there were no significant differences between years for the isotopic method but a large difference in the difference method. This indicates that climate played an important role in the efficiency in turnover of the organic N pool and in the efficiency of the plant to utilize fertilizer N. The difference method is affected more by the large swings that can occur from year to year in the availability of N from organic sources. Evidence to support this is the check plot/treated plot ratio. The treated plots had 11% more N in the grain fraction than the check plots for 1994 (Table 1), yet the treated plants accumulated only 3% more grain dry matter (Table 2). This indicates that considerable soil N was recovered by the plant, but the difference method showed a much lower fertilizer N recovery for 1994. The authors postulate that the cooler, shorter season of 1993 resulted in higher fertilizer N recoveries because of a less efficient organic N pool (reduced microflora activity and organic N mineralization); thus more N was recovered from the applied fertilizer fraction. Consequently there was no difference between the two methods for each plant fraction in 1993.

The lower recovery of fertilizer N by the difference method for 1994 may also be attributed to the erroneous preplant fertilizer application. Check plots received preplant N additions of 48 kg N ha$^{-1}$ instead of the desired rate of 13.5 kg N ha$^{-1}$ (preplant rate of 1993). This difference would undoubtedly increase the amount of soil N available to the check plants, and potentially decrease the difference in plant N uptake between the treated and check plants. A lower recovery of fertilizer N with the difference method would be expected. However, the treated plots received the same higher rate of preplant fertilizer as the check plots and thus, comparisons between treatments were on a relative basis. Moreover, because 1994 had a much higher yield potential (dry matter yield doubled from 1993), the increased preplant fertilizer rate of 1994 would not have had much effect on fertilizer N recovery as estimated by the difference method. Even at the 1994 preplant fertilizer N rate of 48 kg N ha$^{-1}$ plus the residual soil N of 44.8 kg N ha$^{-1}$ present at the start of the 1994 growing season, an additional 68 kg N ha$^{-1}$ is recommended to achieve a yield-goal of 7500 kg ha$^{-1}$ (120 bu/ac). At 68 kg N ha$^{-1}$ one would anticipate an agronomic response; we did not see a response in this study. Therefore climate, as opposed to the preplant fertilizer N rate, is believed to play a more significant role in the differences in fertilizer N recovery between years as estimated by the difference method.

**Table 4. Average recovery of labeled fertilizer N (Eq. 3) remaining in the soil at the end of the 1993 and 1994 growing seasons.**

| Depth | $^{15}$N recovery 1993 | $^{15}$N recovery 1994 |
|---|---|---|
| cm | % | |
| 0–15 | 20.4 a† (16.8)‡ | 10.5 b (21.0) |
| 15–30 | 5.0 a (12.4) | 2.6 b (25.0) |
| 30–60 | 9.6 a (66.8) | 2.7 a (68.9) |
| 60–90 | 4.0 a (95.4) | 11.2 a (95.1) |
| 90–120 | 1.0 a (101.3) | 8.2 b (35.0) |
| 120–150 | 0.8 a (99.2) | 0.5 a (76.6) |
| 150–180 | 0.6 a (31.8) | 0.1 b (68.9) |
| Total | 41.5 a | 35.7 a |

† Mean values within a row followed by the same letter are not significantly different at $\alpha = 0.05$. Statistical comparisons were made between years for each depth increment.
‡ Value in parentheses is coefficient of variation.

Approximately 42 and 36% of the applied labeled N (total N) remained in the soil at the end of the 1993 and 1994 growing season, respectively (Table 4). Approximately 39% and 27% of the applied fertilizer N was within the rooting zone (assumed depth of 90 cm) at the end of 1993 and 1994, respectively, and potentially available for subsequent cropping. These data provide further evidence of growing season variability between 1993 and 1994. That is, 1994 was a longer growing season and plants assimilated more soil N. For 1993 we had thought that 15 to 20% of the applied fertilizer N would have shown up in the subsurface drain effluent. Because of the high flow rate and isotopic dilution, leaching quantities were below detection levels.

Despite careful, uniform distribution of fertilizer N, there was considerable variability in $^{15}$N recovery among the replicates and between 1993 and 1994, resulting in high coefficients of variation (Table 4). Also, water levels varied considerably between 1993 and 1994 which accentuated replicate variability (data not presented).

The percentage of labeled fertilizer N found within the plant–soil system at the end of 1993 and 1994 was 86.3% and 75.4%, respectively (Table 5). The soil fertilizer N deficit for 1993 and 1994 can be attributed to several mechanisms. For instance, band applications of urea N have been shown to inhibit *Nitrobacter* sp. activity as a result of increased pH from the hydrolysis of $NH_3$–N. This inhibition results in the accumulation of $NO_2$–N that may diffuse from the alkaline environment surrounding the urea band into adjacent acid soil microzones. Here, nitrous acid ($HNO_2$) is formed (chemodenitrification) that may cause N losses to fixation or gaseous emission (Magalhaes et al., 1987).

**Table 5. Fate of labeled urea N applied under best management practices for the 1993 and 1994 growing seasons.**

| Plant–soil fraction | $^{15}$N recovery 1993 | $^{15}$N recovery 1994 |
|---|---|---|
| | % | |
| Soil | 41.5 | 35.7 |
| Grain | 31.4 | 32.2 |
| Stover | 11.8 | 6.8 |
| Cob | 1.6 | 0.7 |
| Total† | 86.3 (10.7)‡ | 75.4 (20.3) |

† Total mean values between 1993 and 1994 were not significantly different at $\alpha = 0.05$.
‡ Value in parentheses is coefficient of variation.

Ammonia volatilization loss from aboveground biomass can also be a significant contributor to fertilizer N deficits. According to Francis et al. (1993), a large amount of N (10 to 20% of the applied N) was volatilized from aboveground vegetation during the postanthesis stage of corn development. Another study found 21% of the applied fertilizer N was lost as $NH_3$–N from the wheat foliage during senescence (Harper et al., 1987). Gaseous N loss from plants can be significant, especially between anthesis and maturity and under conditions conducive to leaf and stem dehydration (Moraghan et al., 1984b).

Denitrification and/or leaching processes are, however, the most likely mechanisms responsible for the N deficits in this study, especially in 1994 when the N plots were established along the E transect (Fig. 1). The average depth to the water table along the E transect ranged from surface ponding to 234 cm deep, thus placing much of the soil profile in a saturated, denitrifying condition. The cooler growing season of 1993 (average growing degree unit accumulations 11% below long-term 50-yr average) and average irrigation plus total rainfall of 38 cm was also conducive to denitrification. It was beyond the scope of this investigation to collect and analyze gaseous N and verify denitrification. Research has definitively shown that N loss to denitrification is highly likely under wet conditions, and we therefore believe that the unaccounted-for N amounts of 13.8% and 24.6% in 1993 and 1994, respectively, were primarily the result of denitrification processes.

Leaching of N to groundwater is a potential fate of fertilizer N. Much data has been generated from the BMP project that shows an increase of N in the subsurface drainage and groundwater under corn production (Steele et al., 1996). This suggest that some leaching of fertilizer N likely occurred.

## CONCLUSION

Plant uptake of fertilizer N as estimated by the isotopic and difference methods was 45% and 39% in 1993, and 40% and 22% for 1994, respectively. Added N interaction or the "priming effect" was not a major factor in this study since soil N availability was high and total N uptake of the control plots was greater than the difference between $^{15}N$ uptake and total N uptake. The difference method did not overestimate fertilizer N recovery and consequently there was no advantage to using the isotopic method over the difference method. In fact, we recommend using the difference method to estimate fertilizer N use efficiency when (i) the fertilizer N experiment is newly established (i.e., high soil N availability) and (ii) the investigators are interested only in fertilizer N uptake of N nonresponsive sites and not in tracking the applied N through the various biological transformations.

Erroneous application of fertilizer N prior to planting in 1994 may have contributed to the lower fertilizer N recovery as estimated by the difference method. However, because of the high yield potential of 1994, preplant fertilizer N had minimal effect on fertilizer N recovered as estimated by the difference method. This study provides evidence that climatic conditions can affect fertilizer N use efficiency. We found that the isotopic method for estimating plant fertilizer N uptake is less affected by large climatic swings that can occur from year to year in the availability of N from organic sources. The authors feel that the isotopic method is more accurate and thus superior to the difference method in this regard.

The average quantity of applied labeled N remaining in the soil (180 cm profile depth) at the end of the 1993 and 1994 growing seasons was 42% and 36%, respectively. Approximately 39% and 27% of the applied fertilizer N was within the rooting zone (90 cm) at the end of 1993 and 1994, respectively, and potentially available for subsequent cropping. The average quantity of labeled fertilizer N accounted for within the plant–soil system at the end of 1993 and 1994 was 86% and 75%, respectively. Consequently, 14% and 25% of the labeled fertilizer N was not accounted for at the end of 1993 and 1994, respectively.

Reasons for the N deficit in this investigation are speculative since no attempts were made to measure the gaseous emissions. However, because of saturated conditions some denitrification and/or leaching likely occurred.

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# Phosphorous and Potassium Fertilizer Recommendation Variability for Two Mid-Atlantic Coastal Plain Fields

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## ABSTRACT

**Fertilizer recommendations for variable rate treatments developed from grid soil sampling protocols are unproven for mid-Atlantic Coastal Plain soils. The objectives of this study were to compare soil test results for P and K fertilizer recommendations for two fields utilizing two grid sampling sizes (0.33 ha and 0.83 ha), sampling by soil type, and standard composite sampling. The study location contained alluvial soils ranging from a loamy sand to a silt loam. The two fields totaled approximately 21 ha and were sampled on grids 18.5 by 30.4 m. Samples consisted of composites of eight cores to a 20-cm depth that were analyzed for Mehlich I extractable P and K. Two statistical models were developed for comparing the extractable P and K data and the resulting fertilizer recommendations. The first model, following a precision farming approach, implies sources of variation are systematic and attributable to narrow geographic locations. The second model, associated with composite sampling, utilizes less specific patterns of variability. Comparisons showed that the smaller grid (0.33 ha) produced more precise estimates of extractable K in only one field (with 67% of tested locations receiving appropriate fertilizer rates), with no improvement for extractable P in either field. Both grid-sampling systems improved estimate precision for extractable P and K (with a smaller average misapplication rate) compared with a whole-field composite. The composite-by-soil-type approach was superior to the whole-field composite for estimating extractable P and K with a lower average misapplication and higher percentage receiving appropriate fertilizer rates. The composite-by-soil approach produced the most precise fertilizer recommendations for small systematic variation and required fewer laboratory measurements. It approached the grids-sampling system precision of fertilizer recommendations for large in-field variation. Only when strong trends in extractable P and K exist would grid sampling be recommended over the composite-by-soil-type sampling approach.**

PRECISION AGRICULTURE USING the global positioning system (GPS), grid soil sampling, and variable rate fertilizer application is becoming more widely utilized, while the relative effectiveness of this strategy for determining fertilizer recommendations is unproven. In this paper we consider different methods for determining K and P fertilizer recommendations and use a model to explain some of the success and shortcomings of a variety of strategies. Fertilizer recommendations using a precision agriculture approach, with samples on 0.33- or 0.83-ha grids, is compared to more traditional approaches of a single recommendation based on a global composite, or a composite-by-soil-type represented in the field. Sawyer (1994) noted that "field research indicates . . . that positive economic return to variable rate application technology does not always occur."

We present individual results for the fields considered, as well as some general principles about identifying situations where precision agriculture approaches will likely outperform the traditional approaches of composites, or vice versa.

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## THEORY

To provide a more formal context to describe the nature of plant-available P and K variability in the field, we present general random effects models that incorporate the different sampling schemes to allow for more direct comparison between methods. Fertilizer recommendations are based on a two-phase process: In the first stage, plant-available K and P measurements (hereafter referred to as $y$) are taken according to either the precision farming approach on various sized grids or by using composites across sections of the field. The second stage takes the actual measurements of plant-available K and P and converts them to fertilizer recommendations (hereafter referred to as $z$) in 11.2–22.4-kg ha$^{-1}$ increments based on calibration curves from previous research (Donohue and Heckendorn, 1994). This conversion process involves transforming $y$ to $z$ using a step function with a small number of recommendation levels (11.2–22.4-kg ha$^{-1}$ measurements). This conversion masks much of the variation in the actual measurements and also provides a buffer to make small variations in the actual measurements of plant-available K and P less critical.

For the precision farming approach where sampling is done on a predesignated grid size, measurements of K or P take the following form

$$y_{ijkl} = \mu + R_i + C_j + RC_{ij} + \gamma_{k(ij)} + \varepsilon_{l(ijk)} \quad [1]$$

This model involves nested factors, where some observations are randomized within a particular combination of other factors. For more details on nested models, review an advanced experimental design text such as Box et al. (1978) or Winer et al. (1991). The terms $R_i$, $C_j$, and $RC_{ij}$ represent row and column main effects and the row-by-column interaction based on the location of the points. These terms are treated as random effects in the statistical model. This implies that the differences between row and column locations are not of particular interest individually but are considered primarily to obtain information about general patterns of differences within the