

1 **Deep soil cores reveal large end-of-season residual mineral nitrogen pool**

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6 Core Ideas:

- 7 • Residual mineral N in 0-210 cm deep soil following summer crops was evaluated
- 8 • Soils contained a mean of 253 kg ha⁻¹ mineral N, 115 kg ha⁻¹ as NO₃-N
- 9 • 55% of mineral N was 90-210 cm deep, where it is most at risk for leaching loss
- 10 • More residual NO₃-N remained after soybean than after corn
- 11 • Awareness of residual deep N levels is essential to develop N conservation practices

12 Abstract

13 The amount of mineral N remaining after cash crops informs agronomic and conservation
14 practices. Few studies investigate mineral N below 30 cm, yet deeper N is more at risk for
15 leaching to groundwater. We found, on average, 253 kg ha⁻¹ of mineral N, 115 kg ha⁻¹ in the
16 NO₃-N form, remaining after summer cash crop growth in the mid-Atlantic region. Of this
17 residual mineral N, 55% was 90-210 cm deep. More residual NO₃-N remained after soybean than
18 after corn. These substantial pools of mineral N remaining deep in the soil profile after
19 productive cash crops, even unfertilized soybean, suggest that practices should be designed to
20 scavenge residual N from deep soil layers in the fall, before it is lost over winter.

21 Nitrogen (N) loading to water bodies in humid temperate regions occurs primarily by
22 leaching during the non-growing season when evapotranspiration is minimal (Meisinger and
23 Delgado, 2002). In the Mid-Atlantic USA, where corn (*Zea mays* L.) and soybean (*Glycine max*
24 (L.) Merr.) are the main annual crops (USDA NASS, 2012), NO₃-N commonly leaches >1 m
25 between fall and spring (Angle, 1990; Forrester, et al., 2014; Meisinger and Delgado, 2002).
26 Here, corn typically ceases N uptake by early-September when maturity is approached
27 (Ciampitti, et al., 2013; Hanway, 1963). Excessive N contributes to eutrophication and hypoxia
28 in the Chesapeake Bay (Ator and Denver, 2015; Phillips and Caughron, 2014), motivating the
29 Maryland legislature to mandate nutrient management plans (Parker, 2000) which regulate N
30 application to crops (Maryland Department of Agriculture, 2014). However, even with mandated
31 efforts, N leaching continues to be a concern in Maryland (USEPA, 2017).

32 Spatiotemporal patterns of soil N influence the accessibility of N to growing crops and its
33 susceptibility to leaching. End of growing season residual N, especially in deeper soil layers, is at
34 risk of leaching below the root zone of subsequent crops and eventually into groundwater
35 (Thorup-Kristensen, 1994). Even when crops are fertilized at recommended rates, substantial
36 mineral N (N_{min}) remains in the soil at the end of the growing season. In Pennsylvania, following
37 corn fertilized at economic optimum rates, 74 and 94 kg NO₃-N ha⁻¹ remained in the upper 120
38 cm of non-manured and manured soils, respectively (Roth and Fox, 1990). Furthermore, fall
39 uptake of 80 to 220 kg N ha⁻¹ by early-planted cover crops (Dean and Weil, 2009; Wang and
40 Weil, 2018) suggests that substantial soil N remains following even high yields of cash crops.

41 Data on the amounts and depth distribution of residual N_{min} in fall could assist in
42 optimizing N conservation practices, such as cover cropping.

43 **Materials and Methods**

44 Twenty-nine row-crop fields were sampled across the Piedmont, Ridge and Valley, and
45 Coastal Plain regions of Maryland and southeast Pennsylvania between 2014 and 2016. Fields
46 were selected from farm operations that responded to our request via Extension educators and
47 agronomy news outlets. The area has a temperate humid climate with 11°C mean annual
48 temperature and 1044 mm mean annual precipitation uniformly distributed among all months
49 (Maryland Department of State Planning, 1973; Polsky, et al., 2000). Soil infiltration rates are
50 typically 6-15 cm h⁻¹ in the Piedmont and 13-28 cm h⁻¹ in the Coastal Plain (Markewich, et al.,
51 1990). The crop grown prior to sampling was corn on 20 fields, soybean on four, perennial
52 grasses on two, fertilized winter wheat on two, and tobacco on one. Most fields were managed
53 with no-tillage or other conservation tillage and practiced winter cover cropping. Fields included
54 a range of dairy or poultry manure histories: 11 with no manure, 11 with regular manure
55 applications, and seven with occasional manure (one to two applications in past 10 years, or
56 history of regular manure applications but none applied in the past three years). The 23 fields in
57 Maryland applied N according to N-based nutrient management plans. The fields were grouped
58 by their soil parent materials: Coastal Plain sediments, acidic rocks, and calcareous rocks.

59 To evaluate effects of previous crop on residual N, four pairs of adjacent corn and
60 soybean fields were sampled in 2016. Three pairs had Coastal Plain sediments (Coastal Plain
61 region) and one pair had acidic rock (Piedmont region) parent materials. The cropping histories
62 included corn, soybean, small grain, and hay (see Figure 1). Paired-fields were sampled on the
63 same day and had the same soil series, manure and tillage history.

64 Soil sampling and analysis

65 Soil cores 210 cm deep were collected using hand-driven probes (Dean and Weil, 2009;
66 Veihmeyer, 1929) from 14 fields between 20-Aug and 20-Sep in 2014, from seven fields

67 between 17-Aug and 25-Sep in 2015, and from eight fields between 24-Sep and 29-Oct in 2016.
68 In 2014 and 2016 two soil cores were collected at five points along a straight transect; in 2015
69 three soil cores were collected at four points within the field. Points were 20 to 50 m apart,
70 depending on the size and shape of the field; cores at a point were less than 1 m apart. In 2014
71 and 2016, soil was divided into 15 cm increments and two soil cores taken from each point along
72 the transect were composited for each depth increment. In 2015, soil was divided into 30 cm
73 increments, and the values of the three cores per point were averaged after soil analysis.

74 The soil was dried, sieved to 2 mm, and $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ was extracted (2 g soil in 20
75 mL solution) with 0.5 M potassium sulfate (K_2SO_4) and filtered. A Lachat QuikChem 8500
76 Automated Ion Analyzer (Hach Company, Loveland, CO) was used to analyze the filtrate for
77 $\text{NH}_4\text{-N}$ (salicylate method) and for $\text{NO}_2\text{-N} + \text{NO}_3\text{-N}$ (cadmium reduction method). Stocks of
78 $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ (kg ha^{-1}) were calculated from concentrations of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ using
79 soil bulk density values (core method). Soil particle size analysis was performed by the modified
80 pipette method (Gavlak, et al., 2005).

81 Statistical analysis

82 All analyses were performed using SAS version 9.4 (SAS Institute, 2012). The level of
83 probability considered significant was $p < 0.05$, unless otherwise stated. All ANOVA tests were
84 performed using Proc Mixed. An ANOVA was performed to compare the $\text{NO}_3\text{-N}$ or $\text{NH}_4\text{-N}$
85 amounts among parent material groups for 0-210 cm, 0-30 cm, 30-90 cm, 90-150 cm, and 150-
86 210 cm depth increments, with parent material group as the fixed effect and field as a random
87 effect. A Pearson product-moment correlation was performed using Proc Corr to relate the soil
88 $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ to soil percentages of sand and clay by depth. Proc Means was used to
89 calculate the coefficient of variation (CV) among the four to five points in the field (each point

90 averaging two to three cores) of the total 0-210 cm $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ for 19 of the fields. To
91 compare pools of inorganic N following corn versus soybean, for the paired fields, an ANOVA
92 was performed for each 30 cm increment soil depth on the stocks of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$, with
93 crop type (corn or soybean) as the fixed effect and field as a random effect.

94 **Results**

95 Following summer crop senescence, on average 253 kg ha^{-1} of N_{min} remained in the upper
96 210 cm of soil, with 22% located at 0-30 cm, 23% at 30-90 cm, 27% at 90-150 cm, and 28% at
97 150-210 cm depth. Across the 29 fields, 115 kg ha^{-1} of the total N_{min} was $\text{NO}_3\text{-N}$ and 138 kg ha^{-1}
98 was $\text{NH}_4\text{-N}$. Nitrate-N levels for Coastal Plain sediments fields were lower than acidic rock
99 fields in the 90-150 cm depth and than calcareous rock fields in the 150-210 cm depth ($p < 0.10$;
100 Table 1).

101 Across the 29 fields, sand percentage was negatively correlated with $\text{NO}_3\text{-N}$
102 concentration ($p < 0.10$) at 0-30 cm, 90-150 cm, and 150-210 cm depths, but neither sand nor
103 clay percentage was correlated with $\text{NH}_4\text{-N}$ concentration. Within-field CV of 0-210 cm total
104 stock of $\text{NO}_3\text{-N}$ was on average 35% (standard error (SE) = 5.1, N = 19) and of $\text{NH}_4\text{-N}$ was on
105 average 44% (SE = 5.0, N = 19). The CVs for the two N species were uncorrelated.

106 Based on the four pairs of adjacent corn and soybean fields sampled in 2016, there was
107 significantly more soil $\text{NO}_3\text{-N}$ following soybean than corn at 30-60 cm, 120-150 cm, 150-180
108 cm, and 180-210 cm. Levels of soil $\text{NH}_4\text{-N}$ differed between corn or soybean only at 180-210 cm
109 (Fig. 1).

110 **Discussion**

111 Why so much residual N?

112 The large pools of residual N represent both fertilizer N unused by summer crops (Wang
113 and Weil, 2018) and N mineralized from soil and plant organic matter (Dahnke and Johnson,
114 1990; Weil and Brady, 2017). Residual soil N is often assumed to be a result of N fertilizer
115 over-application, or low N uptake during drought years (Forrestal, et al., 2012); hence, N
116 management and policies to reduce N loading primarily focus on N fertilized fields (Maryland
117 Department of Agriculture, 2014). However, we believe that large pools of residual N_{\min} are
118 more universal. Our data, in agreement with previous studies (Gentry, et al., 2001; Jaynes, et al.,
119 2001; Kessavalou and Walters, 1999; Pantoja, et al., 2016; Rembon and MacKenzie, 1997)
120 indicates soybeans without N fertilizer can leave even more residual nitrate in the soil profile
121 than corn receiving fertilizer. Compared to corn, soybean creates a high N environment with less
122 (and lower C/N ratio) residues, and therefore less N is immobilized (Angle, 1990; Gentry, et al.,
123 2001; Green and Blackmer, 1995).

124 While stocks of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in the soil profiles were similar, our results suggest
125 that $\text{NO}_3\text{-N}$ is more transient, leaching through the soil, whereas $\text{NH}_4\text{-N}$ is accumulating through
126 cation exchange sorption. For example, crop (corn versus soybean) affected $\text{NO}_3\text{-N}$ levels much
127 more than $\text{NH}_4\text{-N}$ levels. Similar results were found in Wisconsin (Bundy, et al., 1993) for the
128 upper 90 cm of soil in spring. Kristensen and Thorup-Kristensen (2004) and Bergström (1986)
129 also found that crop species affected residual $\text{NO}_3\text{-N}$ more than residual $\text{NH}_4\text{-N}$. The negative
130 correlation between sand and soil $\text{NO}_3\text{-N}$ concentration (but not $\text{NH}_4\text{-N}$ concentration) supports
131 the expected faster $\text{NO}_3\text{-N}$ leaching in sandier soils. The lack of correlation between clay and
132 $\text{NH}_4\text{-N}$ concentration is not surprising as the $\text{NH}_4\text{-N}$ ions measured would occupy only a small
133 fraction of the cation exchange sites on any of the soils.
134 Importance of vertical location of N

135 Many studies report how soil N is affected by cover crops (Chu, et al., 2017; Ebelhar, et
136 al., 1984; Kuo and Jellum, 2002; Ladoni, et al., 2015; Ruffo, et al., 2004; Sainju, et al., 2006) or
137 other cropping practices (Anderson and Peterson, 1973; Poudel, et al., 2002; Rice, et al., 1986;
138 Scalise, et al., 2015) after sampling only 15 to 30 cm of soil. However, it is the deeper N (1-2
139 meters deep) that is most at-risk for leaching to groundwater before plants can take it up. Across
140 all our fields, 57% (65 kg N ha^{-1}) of $\text{NO}_3\text{-N}$ and 55% (138 kg N ha^{-1}) of total N_{min} to 210 cm was
141 at 90-210 cm.

142 Land management implications

143 In regions, such as the mid-Atlantic, with year-long rainfall, favorable mineralization
144 conditions during much of the “off-season” and permeable soil types, scavenging residual N as
145 soon as possible after crop harvest will be important to prevent N from leaching beyond rooting
146 depth. We suggest that early-planted, deep-rooted cover crops could be a tool to accomplish such
147 N conservation.

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254 Table 1. Soil NO₃-N, NH₄-N, and mineral N (N_{min}) (kg N ha⁻¹) for 0-30 cm, 30-90 cm, 90-150
 255 cm, 150-210 cm, and 0-210 cm. Values are means with standard error (SE) in parenthesis for all
 256 fields (N=29), Coastal Plain sediments fields (N=14), calcareous rock fields (N=6), and acidic
 257 rock fields (N=9). Within a mineral N type and depth increment, values followed by the same
 258 letter do not differ significantly among Coastal Plain sediments, acidic rock, and calcareous rock
 259 fields. The symbols * and † indicate $p < 0.05$ and 0.1, respectively.

Soil parent material	Depth increment	NO ₃ -N	NH ₄ -N	N _{min}
	----- cm -----	----- kg N ha ⁻¹ (SE) -----		
All fields	0-210	115 (12.5)	138 (15.6)	253 (23.5)
	0-30	24.9 (3.83)	31.3 (2.74)	56.3 (5.43)
	30-90	25.2 (3.27)	33.6 (3.90)	58.7 (5.89)
	90-150	30.8 (3.66)	37.0 (4.70)	67.7 (7.16)
	150-210	33.9 (5.61)	36.0 (4.94)	69.9 (8.27)
Coastal Plain sediments	0-210	88.4 (17.8) a	137 (24.6) a	226 (37.8) a
	0-30	23.9 (5.08) a	30.0 (3.86) a	53.9 (8.22) a
	30-90	23.8 (6.11) a	33.5 (5.98) a	57.3 (10.4) a
	90-150	20.0 (3.55) a*	35.7 (6.63) a	55.7 (9.43) a
	150-210	20.7 (4.27) a†	38.1 (8.61) a	58.8 (11.5) a
Acidic rocks	0-210	136 (45.4) a	153 (51.0) a	289 (96.5) a
	0-30	24.1 (8.03) a	35.9 (12.0) a	60.0 (20.0) a
	30-90	25.2 (8.41) a	36.2 (12.1) a	61.4 (20.5) a
	90-150	44.5 (14.8) b*	43.0 (14.3) a	87.5 (29.2) a
	150-210	42.4 (14.1) ab†	38.1 (12.7) a	80.5 (26.8) a
Calcareous rocks	0-210	144 (58.8) a	117 (47.6) a	261 (106) a
	0-30	28.5 (11.6) a	27.8 (11.4) a	56.3 (23.0) a
	30-90	28.1 (11.5) a	29.9 (12.2) a	58.0 (23.7) a
	90-150	35.3 (14.4) ab*	30.9 (12.6) a	66.3 (27.1) a
	150-210	52.2 (21.3) b†	28.0 (11.4) a	80.2 (32.7) a

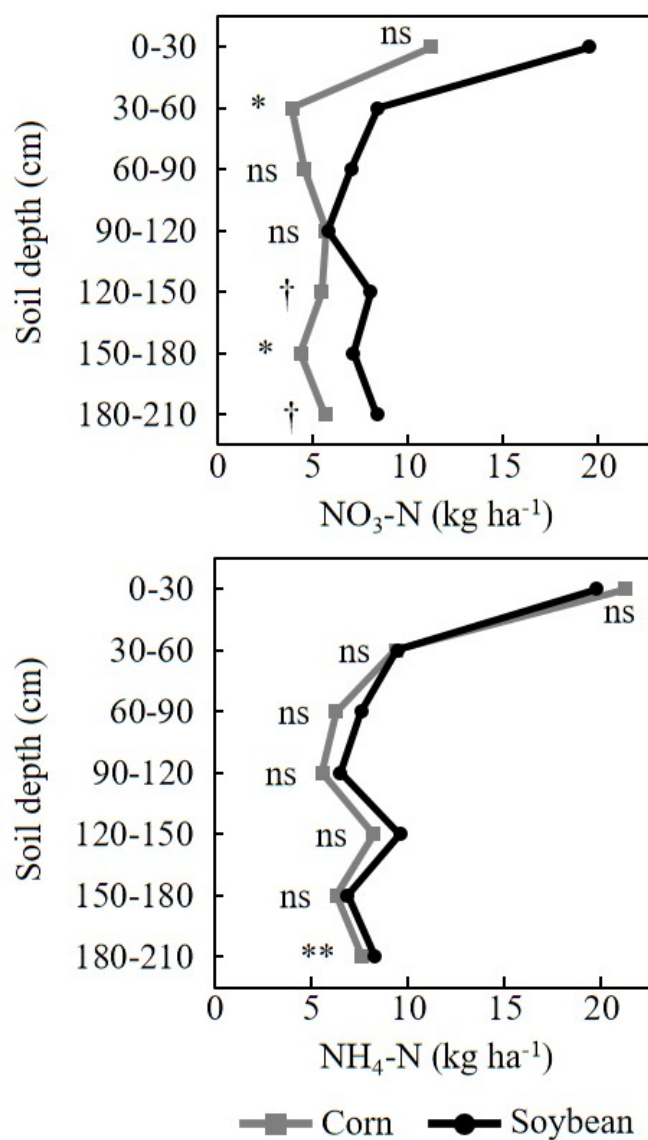


Figure 1. NO₃-N and NH₄-N (kg N soil layer⁻¹ ha⁻¹) in four pairs of adjacent corn and soybean fields. Crop history of fields included: Field 1A 2016 corn, 2013-2015 Timothy hay; Field 1B 2016 soybean, 2015 corn silage, 2014 corn, 2013 sorghum; Field 2A 2016 corn, 2015 wheat/soybean, 2014 corn, 2013 wheat/soybean; Field 2B 2016 soybean, 2015 wheat/soybean, 2014 soybean, 2013 wheat/soybean; Field 3A 2016 corn, 2015 wheat/soybean, 2014 soybean, 2013 soybean; Field 3B 2016 soybean, 2015 wheat/soybean, 2014 soybean, 2013 corn; Field 4A 2016 corn, 2015 soybean, 2014 corn, 2013 soybean; Field 4B 2016 soybean, 2015 soybean, 2014 soybean, 2013 corn. Corn and wheat received 123-168, and hay received 73 kg N ha⁻¹. All fields had winter cover crops or small grains for the previous five years. No-till was practiced for five years on three pairs, and two years on one pair. Three pairs had no manure applied; one pair had one to two applications of dairy manure in the past 10 years. The symbols **, *, †, ns indicate $p < 0.01$, 0.05, 0.1, and not significant, respectively.

82x141mm (150 x 150 DPI)

