Nitrogen (N) loading to water bodies in humid temperate regions occurs primarily by leaching during the nongrowing season when evapotranspiration is minimal (Meisinger and Delgado, 2002). In the mid-Atlantic United States, where corn (Zea mays L.) and soybean (Glycine max (L.) Merr.) are the main annual crops (USDA NASS, 2012), NO₃⁻-N commonly leaches >1 m between fall and spring (Angle, 1990; Forrestal et al., 2014; Meisinger and Delgado, 2002). Here, corn typically ceases N uptake by early September when maturity is approached (Ciampitti et al., 2013; Hanway, 1963). Excessive N contributes to eutrophication and hypoxia in the Chesapeake Bay (Ator and Denver, 2015; Phillips and Caughron, 2014), motivating the Maryland legislature to mandate nutrient management plans (Parker, 2000) that regulate N application to crops (Maryland Department of Agriculture, 2014). Even with mandated efforts, however, N leaching continues to be a concern in Maryland (USEPA, 2017).

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

Materials and Methods

Twenty-nine row-crop fields were sampled across the Piedmont, Ridge and Valley, and Coastal Plain regions of Maryland and southeastern Pennsylvania between 2014 and 2016. Fields were selected from farm operations that responded...
to our request via county extension educators and agronomy news outlets. The area has a temperate humid climate, with 11°C mean annual temperature and 1044 mm mean annual precipitation uniformly distributed among all months (Maryland Department of State Planning, 1973; Polsky et al., 2000). Soil infiltration rates are typically 6 to 15 cm h
−1 within the Piedmont and 13 to 28 cm h
−1 in the Coastal Plain (Markewich et al., 1990). The crop grown prior to sampling was corn on 20 fields, soybean on 4, perennial grasses on 2, fertilized winter wheat (Triticum aestivum L.) on 2, and tobacco (Nicotiana tabacum L.) on 1 field. Most fields were managed with no-tillage or other conservation tillage and practiced winter cover cropping. Fields included a range of dairy or poultry manure histories: 11 with no manure, 11 with regular manure applications, and 7 with occasional manure (one to two applications in past 10 yr, or a history of regular manure applications but none applied in the past 3 yr). The 23 fields in Maryland applied N according to N-based nutrient management plans. The fields were grouped by their soil parent materials: Coastal Plain sediments, acidic rocks, and calcareous rocks.

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

**Soil Sampling and Analysis**

Soil cores 210 cm deep were collected using hand-driven probes (Dean and Weil, 2009; Veihmeyer, 1929) from 14 fields between 20 August and 20 September in 2014, from 7 fields between 17 August and 25 September in 2015, and from 8 fields between 24 September and 29 October in 2016. In 2014 and 2016, two soil cores were collected at five points along a straight transect; in 2015, three soil cores were collected at four points within the field. Points were 20 to 50 m apart, depending on the size and shape of the field; cores at a point were less than 1 m apart. In 2014 and 2016, soil was divided into 15-cm increments, and two soil cores taken from each point along the transect were composited for each depth increment. In 2015, soil was divided into 30-cm increments, and the values of the three cores per point were averaged after soil analysis.

The soil was dried and sieved to 2 mm, and NO
3–N and NH
4–N were extracted (2 g soil in 20 mL solution) with 0.5 M potassium sulfate (K_2SO_4) and filtered. A Lachat QuikChem 8500 Automated Ion Analyzer (Hach Company) was used to analyze the filtrate for NH
4–N (salicylate method) and for NO
3–N + NO
2–N (cadmium reduction method). Stocks of NO
3–N and NH
4–N (kg ha
−1) were calculated from concentrations of NO
3–N and NH
4–N using soil bulk density values (core method). Soil particle size analysis was performed by the modified pipette method (Gavlak et al., 2005).

**Statistical Analysis**

All analyses were performed using SAS version 9.4 (SAS Institute, 2012). The level of probability considered significant was p < 0.05, unless otherwise stated. All ANOVA tests were performed using Proc Mixed. An ANOVA was performed to compare the NO
3–N or NH
4–N amounts among parent material groups for 0- to 210-cm, 0- to 30-cm, 30- to 90-cm, 90- to 150-cm, and 150- to 210-cm depth increments, with parent material group as the fixed effect and field as a random effect. A Pearson product-moment correlation was performed using Proc Corr to relate the soil NO
3–N and NH
4–N to soil percentages of sand and clay by depth. Proc Means was used to calculate the coefficient of variation (CV) among the four to five points in the field (each point averaging two to three cores) of the total 0 to 210 cm NO
3–N and NH
4–N for 19 of the fields. To compare pools of inorganic N following corn versus soybean, for the paired fields, an ANOVA was performed for each 30-cm-increment soil depth on the stocks of...
NO₃⁻N and NH₄⁺-N, with crop type (corn or soybean) as the fixed effect and field as a random effect.

Results

Following summer crop senescence, 253 kg ha⁻¹ of N₉min on average remained in the upper 210 cm of soil, with 22% located at 0 to 30 cm, 23% at 30 to 90 cm, 27% at 90 to 150 cm, and 28% at 150 to 210 cm depth. Across the 29 fields, 115 kg ha⁻¹ of the total N₉min was NO₃⁻-N and 138 kg ha⁻¹ was NH₄⁺-N. Nitrate-N levels for Coastal Plain sediments fields were lower than calcareous rock fields in the 90 to 150 cm depth and lower than calcareous rock fields in the 150 to 210 cm depth (p < 0.10; Table 1).

Across the 29 fields, sand percentage was negatively correlated with NO₃⁻-N concentration (p < 0.10) at depths 0 to 30 cm, 90 to 150 cm, and 150 to 210 cm, but neither sand nor clay percentage was correlated with NH₄⁺-N concentration. Within-field CV of 0- to 210-cm total stock of NO₃⁻-N was on average 35% (SE = 5.1, N = 19) and of NH₄⁺-N was on average 44% (SE = 5.0, N = 19). The CVs for the two N species were uncorrelated.

Based on the four pairs of adjacent corn and soybean fields sampled in 2016, there was significantly more soil NO₃⁻-N following soybean than corn at 30–60 cm, 120–150 cm, 150–180 cm, and 180–210 cm. Levels of soil NH₄⁺-N differed between corn or soybean only at 180–210 cm (Fig. 1).

Discussion

Why So Much Residual Nitrogen?

The large pools of residual N represent both fertilizer N unused by summer crops (Wang and Weil, 2018) and N mineralized from soil and plant organic matter (Dahne and Johnke, 1990; Weil and Brady, 2017). Residual soil N is often assumed to be a result of N fertilizer overapplication or low N uptake during drought years (Forrestal et al., 2012); hence, N management and policies to reduce N loading primarily focus on N-fertilized fields (Maryland Department of Agriculture, 2014). However, we believe that large pools of residual N are more universal. Our data, in agreement with previous studies (Gentry et al., 2001; Jaynes et al., 2001; Kessavalou and Walters, 1999; Pant jo et al., 2016; Rem bon and MacKenzie, 1997), indicate soybeans without N fertilizer can leave even more residual nitrate in the soil profile than corn receiving fertilizer. Compared with corn, soybean creates a high N environment with fewer (and lower C/N ratio) residues, and therefore less N is immobilized (Angle, 1990; Gentry et al., 2001; Green and Blackmer, 1995).

While stocks of NO₃⁻-N and NH₄⁺-N in the soil profiles were similar, our results suggest that NO₃⁻-N is more transient, leaching through the soil, whereas NH₄⁺-N is accumulating through cation exchange sorption. For example, crop (corn versus soybean) affected NO₃⁻-N levels much more than NH₄⁺-N levels. Similar results were found in Wisconsin (Bundy et al., 1993) for the upper 90 cm of soil in spring. Kristensen and Thorup-Kristensen (2004) and Bergström (1986) also found that crop species affected residual NO₃⁻-N more than residual NH₄⁺-N. The negative correlation between sand and soil NO₃⁻-N concentration (but not NH₄⁺-N concentration) supports the expected faster NO₃⁻-N leaching in sandier soils. The lack of correlation between clay and NH₄⁺-N concentration is not surprising as the NH₄⁺-N ions measured would occupy only a small fraction of the cation exchange sites on any of the soils.

Importance of Vertical Location of Nitrogen

Many studies show how soil N is affected by cover crops (Chu et al., 2017; Ebelhar et al., 1984; Kuo and Jellum, 2002; Ladoni et al., 2015; Ruffo et al., 2004; Sainju et al., 2006) or other cropping practices (Anderson and Peterson, 1973; Poudel et al., 2002; Rice et al., 1986; Scalise et al., 2015) after sampling only 15 to 30 cm of soil. However, it is the deeper N (1–2 m deep) that is most at risk for leaching to groundwater before plants can take it up. Across all our fields, 57% (65 kg N ha⁻¹) of NO₃⁻-N and 55% (138 kg N ha⁻¹) of total N₉min to 210 cm was at 90 to 210 cm.

Land Management Implications

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

Table 1. Soil NO₃⁻-N, NH₄⁺-N, and mineral N (N₉min) (kg N ha⁻¹) for depths 0–30 cm, 30–90 cm, 90–150 cm, 150–210 cm, and 0–210 cm. Values are means with standard error (SE) in parenthesis for all fields (N = 29), Coastal Plain sediments fields (N = 14), calcareous rock fields (N = 6), and acidic rock fields (N = 9).

<table>
<thead>
<tr>
<th>Soil parent material</th>
<th>Depth increment</th>
<th>NO₃⁻-N</th>
<th>NH₄⁺-N</th>
<th>N₉min</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td>kg N ha⁻¹ (SE)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All fields</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–210</td>
<td>115 (12.5)</td>
<td>138 (15.6)</td>
<td>253 (23.5)</td>
<td></td>
</tr>
<tr>
<td>0–30</td>
<td>24.9 (3.83)</td>
<td>31.3 (2.74)</td>
<td>56.3 (5.43)</td>
<td></td>
</tr>
<tr>
<td>30–90</td>
<td>25.2 (3.27)</td>
<td>33.6 (3.90)</td>
<td>58.7 (5.89)</td>
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</tr>
<tr>
<td>90–150</td>
<td>30.8 (3.66)</td>
<td>37.0 (4.70)</td>
<td>67.7 (7.16)</td>
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</tr>
<tr>
<td>150–210</td>
<td>33.9 (5.61)</td>
<td>36.0 (4.94)</td>
<td>69.9 (8.27)</td>
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<tr>
<td>Coastal Plain sediments</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0–210</td>
<td>88.4 (17.8)‡</td>
<td>137 (24.6)</td>
<td>226 (37.8)</td>
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<tr>
<td>0–30</td>
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<td>30.0 (3.86)</td>
<td>53.9 (8.22)</td>
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<tr>
<td>30–90</td>
<td>23.8 (6.11)‡</td>
<td>33.5 (5.98)</td>
<td>57.3 (10.4)</td>
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</tr>
<tr>
<td>90–150</td>
<td>20.0 (3.55)‡</td>
<td>35.7 (6.63)</td>
<td>55.7 (9.43)</td>
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</tr>
<tr>
<td>150–210</td>
<td>20.7 (4.27)‡</td>
<td>38.1 (8.61)</td>
<td>58.8 (11.5)</td>
<td></td>
</tr>
<tr>
<td>Acidic rocks</td>
<td></td>
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</tr>
<tr>
<td>0–210</td>
<td>136 (45.4)†</td>
<td>153 (51.0)</td>
<td>289 (96.5)</td>
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</tr>
<tr>
<td>0–30</td>
<td>24.1 (8.03)†</td>
<td>35.9 (12.0)</td>
<td>60.0 (20.0)</td>
<td></td>
</tr>
<tr>
<td>30–90</td>
<td>25.2 (8.41)†</td>
<td>36.2 (12.1)</td>
<td>61.4 (20.5)</td>
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</tr>
<tr>
<td>90–150</td>
<td>44.5 (14.8)‡</td>
<td>43.0 (14.3)</td>
<td>87.5 (29.2)</td>
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</tr>
<tr>
<td>150–210</td>
<td>42.4 (14.1)‡</td>
<td>38.1 (12.7)</td>
<td>80.5 (26.8)</td>
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<tr>
<td>Calcareous rocks</td>
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<td></td>
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</tr>
<tr>
<td>0–210</td>
<td>144 (58.8)†</td>
<td>117 (47.6)</td>
<td>261 (106)</td>
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<tr>
<td>0–30</td>
<td>28.5 (11.6)†</td>
<td>27.8 (11.4)</td>
<td>56.3 (23.0)</td>
<td></td>
</tr>
<tr>
<td>30–90</td>
<td>28.1 (11.5)†</td>
<td>29.9 (12.2)</td>
<td>58.0 (23.7)</td>
<td></td>
</tr>
<tr>
<td>90–150</td>
<td>35.3 (14.4)†</td>
<td>30.9 (12.6)</td>
<td>66.3 (27.1)</td>
<td></td>
</tr>
<tr>
<td>150–210</td>
<td>52.2 (21.3)†</td>
<td>28.0 (11.4)</td>
<td>80.2 (32.7)</td>
<td></td>
</tr>
</tbody>
</table>

* p < 0.05.
† Within a mineral N type and depth increment, values followed by the same letter do not differ significantly among Coastal Plain sediments, acidic rock, and calcareous rock fields.
‡ p < 0.1.
Acknowledgments

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