Denitrification potential in sediments of headwater streams in the southern Appalachian Mountains, USA

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Abstract. We investigated variations in resource availability (NO$_3$-N and labile organic C [LOC]) as determinants of potential denitrification in stream sediments in the southern Appalachian Mountains, USA. Stream water and sediments were sampled seasonally in 2 streams of contrasting NO$_3$-N availability, Noland Creek (high NO$_3$-N) and Walker Branch (low NO$_3$-N). Eight additional streams with varying NO$_3$-N levels were sampled once during summer. Stream sediments were incubated at ambient stream temperatures, and nitrous oxide accumulation was quantified following acetylene inhibition of nitrous oxide reduction. Denitrification potential was greater in Noland Creek than Walker Branch. In autumn and spring, NO$_3$-N and LOC amendments indicated that denitrification potential in Walker Branch sediments was NO$_3$-N limited, whereas temperature had no effect on rates. Denitrification potential in Noland Creek sediments was not limited by NO$_3$-N or LOC, but was significantly affected by season and temperature. However, no differences in denitrification potential were detected when Noland Creek seasonal data were adjusted to a common temperature. NO$_3$-N in the 10 surveyed streams ranged from 10 to 549 μg/L, with the highest NO$_3$-N levels and denitrification rates generally occurring in the higher-elevation streams of Great Smoky Mountains National Park. Our results suggest that NO$_3$-N availability is the primary factor limiting potential denitrification in Southern Appalachian streams. Despite the ideal conditions of slurry studies, extrapolation of potential rates to estimate denitrification loss in the catchment channels indicates that the process is an insignificant N sink (1.7% of stream N export in Walker Branch and 1.5% of N export in the Noland Divide Watershed).

Key words: denitrification, sediments, nutrient limitations, temporal variability, nitrate, dissolved organic carbon, nitrogen deposition, stream ecology.

Several mass-balance studies have investigated N dynamics at the catchment scale (Vitousek and Reiners 1975, Bormann and Likens 1979, Hedin and Brown 1994, Swank and Vose 1997), yet few studies of this type have been conducted in streams (Triska et al. 1984, Webster and Swank 1985, Duff and Triska 1990, Burns 1998). Stream studies have led to the conclusion that stream export of N is often less than catchment inputs, suggesting significant N-retention in catchments. Sinks for N in catchments are considered to be primarily terrestrial (e.g., vegetation uptake, incorporation into soil organic matter, etc.), whereas instream sinks have been largely ignored. Several recent studies have suggested that instream processes may be important N sinks, exerting significant controls on N outputs from catchments (Holmes et al. 1996, Mulholland and Hill 1997).

Denitrification may be a significant mechanism for N loss in streams (Swank and Caskey 1982, Cooke and White 1987, Triska et al. 1993, Bradley et al. 1995). Denitrification is a microbially mediated process in which facultative bacteria oxidize organic C while using NO$_3$-N as an alternative electron acceptor (Rosswall 1981), often producing N gases such as nitrous oxide (N$_2$O) and dinitrogen gas (N$_2$). In contrast to the assimilatory pathway of NO$_3$-N reduction, which produces NH$_4$-N for biosynthesis under aerobic conditions, denitrification ultimately removes available N from an ecosystem. Denitrification may improve surface-water quality and thereby help offset the negative ef-
Effects of N enrichment in streams characterized by high concentrations of NO$_3^-$-N (Ventullo and Rowe 1982, Holmes et al. 1996, Jordan and Weller 1996). Additional loss of NO$_3^-$-N through denitrification can negatively affect ecosystem production in streams with low concentrations of NO$_3^-$-N and/or where N is limiting to algae and microbes (Neilsen et al. 1990, Rysgaard et al. 1994). Yet, our understanding of N loss from streams via denitrification is limited (Sinsabaugh 1994) because denitrification is potentially regulated by complex hydrological, chemical, geological, and biological factors.

We investigated the patterns of seasonal variation and role of resource availability on denitrification potential in the sediments of headwater streams in the southern Appalachian Mountains. Two streams of contrasting NO$_3^-$-N availability (West Fork of Walker Branch and Noland Creek) were selected as primary sites for the investigation. Denitrification potential was also surveyed in 8 additional streams with different NO$_3^-$-N concentrations located near the 2 primary study streams. Specific objectives of our study were: 1) to characterize the denitrification potential in the sediments of 2 headwater streams of contrasting NO$_3^-$-N concentration, 2) to identify temporal variation in denitrification potential, and 3) to determine whether NO$_3^-$-N or labile organic C (LOC) limit denitrification potential.

**Study Sites**

The West Fork of Walker Branch is located within the Ridge and Valley Province in eastern Tennessee (lat 35°58'N, long 84°17'W) and drains a 38.4-ha catchment at an elevation of 265 m located on the US Department of Energy's Oak Ridge National Laboratory Reserve (Fig. 1). It arises from 4 perennial springs, resulting in base flows of generally 5 to 10 L/s (Mulholland 1992). The width and depth of the West Fork of Walker Branch during base flow are ~1.5 to 3.0 m and ~5.0 to 10.0 cm, respectively. The streambed consists of heterogeneous cobble, gravel, and fine-grained organic-rich sediments, with sections of exposed dolomitic bedrock. Baseflow alkalinity and pH are moderately high, with values of 2 to 3 meq/L and 7.8 to 8.2, respectively. Riparian vegetation is primarily oaks, red maple, yellow poplar, and other mesophytic hardwoods.

Noland Creek drains a 17.4-ha catchment located in the Great Smoky Mountains National Park (GSMNP) (lat 35°34'N, long 83°28'W) (Fig. 1), situated at 1692 m elevation along the Tennessee-North Carolina border (Shubzda et al. 1995). Noland Creek is a poorly buffered high-elevation stream with high NO$_3^-$-N concentrations as a result of high rates of atmospheric deposition and low rates of uptake by vegetation in the catchment (Nodvin et al. 1995). The soils of the Noland Creek catchment are poorly buffered inceptisols formed from the underlying Thunderhead Sandstone (King et al. 1968, Johnson et al. 1991). The overstory vegetation of the catchment is dominated by mature stands of red spruce, yellow birch, beech, and hemlock. The riparian understory consists of dense rhododendron, contributing to stream shading (Johnson et al. 1991). The streambed of Noland Creek consists of large boulders and woody debris dams along riffle/run reaches.

Four additional streams on the Oak Ridge reservation (East Fork Walker Branch, Upper White Oak Creek, Pinhook Branch, and Gum Hollow Branch) and 4 additional streams in the GSMNP (Tatterbox Creek, Mossy Rock Creek, Hickory King Branch, and Beech Flats Prong) were studied. Stream elevations ranged from 244 to 1646 m. The streams on the Oak Ridge reservation were expected to have relatively low NO$_3^-$-N concentrations, whereas concentrations in the GSMNP streams were expected to vary greatly depending on elevation.

**Methods**

**Sampling and analyses**

Seasonal sampling in Walker Branch and Noland Creek included measurements of stream temperature, conductivity, NO$_3^-$-N, and dissolved organic C (DOC) concentrations, and collection of sediments. Sampling was conducted seasonally in 1998 through 1999 (Table 1). The survey of the additional 8 streams was conducted in summer 1999, at which time stream water pH was also measured.

Following measurement of stream temperature and conductivity, water for chemical analyses was filtered (0.45-μm membrane filters), placed on ice, and then frozen upon return to the laboratory. NO$_3^-$-N plus NO$_2^-$-N concentrations were determined by the Cd-reduction
Fig. 1. Oak Ridge and Great Smoky Mountains National Park (GSMNP) sites sampled in this study. Oak Ridge: 1 = West Fork Walker Branch, 2 = East Fork Walker Branch, 3 = Upper White Oak Creek, 4 = Finhook Branch, 5 = Gum Hollow Branch. GSMNP: 6 = Rattlebox Creek, 7 = Mossy Rock Creek, 8 = Hickory King Branch, 9 = Noland Creek, and 10 = Beech Flats Prong.

Denitrification assays

Sediment denitrification rates were estimated based on the accumulation of N$_2$O after addition of acetylene (C$_2$H$_2$) to inhibit N$_2$O reduction (Tiedje et al. 1989, Holmes et al. 1996). Approximately 150 g (wet mass) of each sediment sample collected on each sampling date using a 385-cm$^3$ aluminum corer, then transferred to 1.6-L Whirlpak$^*$ bags. Sediment samples were stored at ~4°C until each denitrification assay was initiated (4–24 h following sample collection).
TABLE 1. Temporal variation in stream water biogeochemical data measured quarterly (1998-1999) in Walker Branch and Noland Creek. Annual means and SEs were calculated for each site's parameters using seasonal data. m.d. = missing data. DOC = dissolved organic C, OM = organic matter.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Date</th>
<th>Season</th>
<th>NO₃-N (µg/L)</th>
<th>DOC (mg/L)</th>
<th>Stream temperature (°C)</th>
<th>% OM in sediments*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walker Branch</td>
<td>18 Nov 98</td>
<td>Autumn</td>
<td>7.4</td>
<td>0.54</td>
<td>11.3</td>
<td>2.11</td>
</tr>
<tr>
<td></td>
<td>18 Feb 99</td>
<td>Winter</td>
<td>20.0</td>
<td>m.d.</td>
<td>11.8</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>21 Apr 99</td>
<td>Spring</td>
<td>19.4</td>
<td>0.32</td>
<td>13.0</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>21 Jun 99</td>
<td>Summer</td>
<td>50.0</td>
<td>0.11</td>
<td>15.3</td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>24.2</td>
<td>0.32</td>
<td>12.9</td>
<td>2.11</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td></td>
<td>9.1</td>
<td>0.11</td>
<td>0.9</td>
<td>0.0013</td>
</tr>
<tr>
<td>Noland Creek</td>
<td>21 Oct 98</td>
<td>Autumn</td>
<td>620</td>
<td>1.25</td>
<td>12.3</td>
<td>2.30</td>
</tr>
<tr>
<td></td>
<td>2 Mar 99</td>
<td>Winter</td>
<td>682</td>
<td>0.55</td>
<td>4.7</td>
<td>3.34</td>
</tr>
<tr>
<td></td>
<td>9 May 99</td>
<td>Spring</td>
<td>634</td>
<td>0.63</td>
<td>8.4</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>8 Jul 99</td>
<td>Summer</td>
<td>549</td>
<td>0.71</td>
<td>11.8</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>621</td>
<td>0.78</td>
<td>9.3</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>SE</td>
<td></td>
<td>27.5</td>
<td>0.16</td>
<td>1.8</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

*Significant differences exist between the means of each site in paired t-test, p < 0.05

...
oxic, and natural diffusion of NO$_3$-N across the sediment–water interface would be enhanced in the slurried conditions in these assays.

Differences in denitrification rates between streams were compared using a t-test for each sampling date. Seasonal variation in denitrification rates for each stream was investigated using nonparametric ANOVAs on ranked rates (Kruskal–Wallis) because of the skewed distribution and lack of normality among rates for each season. These analyses were conducted on rates normalized to gAFDM as well as gDM when appropriate. Percent OM data were arcsin-square root transformed for ANOVA between sites. All statistical analyses were conducted using SAS (Windows version 4.10.2222, release 7.00, SAS Institute, Inc., Cary, North Carolina) with a significance level of $p < 0.05$.

**Nutrient limitations**

To identify how NO$_3$-N or LOC availability may limit rates of denitrification, microcosms similar to those described above were set up with nutrient-amended stream water during autumn 1998 and spring 1999. Unfiltered stream water was amended with 200 mg NO$_3$-N/L (as KNO$_3$), 1 g C$_{12}$H$_{24}$O$_{12}$-C/L (as dextrose), or both. Six microcosms were set up for each of the 3 amendments and all were run concurrently with the 12 unamended microcosms described above. Gas headspace samples for N$_2$O were collected, stored, and analyzed as above. Treatment effects were investigated using a 1-way ANOVA for each stream and each sampling date, the Dunnett's post hoc multiple comparisons test (MCT) was used to identify significant differences between samples of a respective treatment as compared to the unamended samples. Scheffe's post hoc MCT was also conducted to identify significant differences among samples of the 3 treatments.

**Temperature effects**

Relationships between denitrification potential and temperature were determined for sediments collected in winter and summer 1999 in Walker Branch and Noland Creek. For this experiment, 12 sediment samples collected from each stream were pooled and homogenized. For each stream, 5 microcosms were set up with unamended stream water and incubated at each of 4 temperatures (4, 9, 12, and 18°C ± 1°C). Gas headspace samples were collected, stored, and analyzed as described above. $Q_{10}$ coefficients were calculated for each stream for winter and summer samplings as $e^{10k}$, where $k$ is the slope of the regression between the In-transformed denitrification rates and temperature (Tank 1992).

**Stream survey**

The stream survey was conducted over a 3-wk period during the summer 1999 sampling season. The Oak Ridge streams were sampled on 17 June 1999 and the GSMNP streams were sampled on 28 June 1999. Eight 1-kg sediment samples were collected from areas of fine-sediment accumulation in each stream. Unfiltered stream water was collected and used in the C$_2$H$_2$ inhibition experiments for each stream, as described above. Samples were incubated at the average ambient stream temperatures of each site group (16°C for all Oak Ridge streams and 14°C for all GSMNP streams). The Walker Branch and Noland Creek samples obtained in this survey were also used as summer samples in the seasonal investigation of denitrification potential. Stream water NO$_3$-N and DOC concentrations, pH, conductivity, temperature, sediment % OM, and elevation values obtained during the stream survey were entered into a stepwise multiple regression analysis to identify predictors of denitrification potential (default significance level for variable entry = 0.15).

**Results**

**Stream characteristics**

Characteristics of the study streams and their sediments are summarized in Table 1. The average NO$_3$-N concentration observed in the surface water of Noland Creek was significantly different (~25 times greater) from Walker Branch (paired t-test, $p = 0.0004$). Minimum and maximum NO$_3$-N concentrations in Walker Branch were observed during autumn (7.4 μg/L) and summer (50.0 μg/L) sampling, respectively. In contrast, seasonal variation in NO$_3$-N concentrations in Noland Creek was small (620–682 μg/L). DOC concentrations in the surface water of Noland Creek (mean of 0.78 mg/L) were significantly greater than in Walker Branch.
Temperature significantly affected denitrification potential in Noland Creek sediments during both winter and summer when rates were expressed as both gAFDM and gDM (Fig. 2). $Q_{10}$ coefficients of 1.29 and 2.49 for gAFDM were determined for winter and summer, respectively. No significant effect of temperature on denitrification was detected for Walker Branch sediments because no denitrification activity was observed in any samples during the temperature experiments.

**Denitrification in streams of contrasting NO$_3$-N availability**

Denitrification potential in Noland Creek was high, averaging ~891 ng N$_2$O gAFDM$^{-1}$ h$^{-1}$, whereas denitrification rates in Walker Branch were much lower and more variable, averaging ~61 ng N$_2$O gAFDM$^{-1}$ h$^{-1}$ (Table 2). Eighty per-
Table 2. Denitrification rates (ng N₂O gAFDM⁻¹ h⁻¹) in sediments from streams of contrasting NO₃-N availability. SEs are indicated in parentheses. Rates were significantly different between sites each season (t-test, p < 0.05).

<table>
<thead>
<tr>
<th>Season</th>
<th>Walker Branch</th>
<th>Noland Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autumn</td>
<td>12.1 (4)</td>
<td>1004 (290)</td>
</tr>
<tr>
<td>Winter</td>
<td>50.1 (14)</td>
<td>300 (86)</td>
</tr>
<tr>
<td>Spring</td>
<td>152 (44)</td>
<td>1231 (355)</td>
</tr>
<tr>
<td>Summer</td>
<td>30.9 (9)</td>
<td>1041 (301)</td>
</tr>
<tr>
<td>Annual mean</td>
<td>61.3 (23)</td>
<td>891 (133)</td>
</tr>
</tbody>
</table>

Denitrification rates were significantly greater in Noland Creek sediments than in sediments from Walker Branch in all sampling seasons (t-tests, p < 0.05, Table 2). No significant seasonal variation in Walker Branch denitrification rates was observed, regardless of data normalization (p > 0.05, Fig. 3). Nonparametric ANOVA of denitrification rates normalized to gDM and gAFDM in Noland Creek sediments among seasons detected significant seasonal variation (p = 0.01 and 0.02, respectively, Fig. 3A, B). However, seasonal variation was no longer significant upon adjustment of these denitrification rates to a

![Graph A](image1)

![Graph B](image2)

**Fig. 3.** Seasonal variation in denitrification rates (+1 SE) in sediments from Walker Branch and Noland Creek normalized to gDM (A) and gAFDM (B). Bars with the same letters and unlettered bars are not significantly different (p > 0.05).
Fig. 4. Effect of nutrient amendments on denitrification rates (+1 SE) in Walker Branch and Noland Creek sediments. Amendments yielding denitrification rates significantly different from those of the unamended controls are indicated by a letter different from that of the unamended sample set (ANOVA followed by Dunnett’s multiple comparison test, p < 0.0001) (letters for the autumn 1998 experiment are lower case and those for spring 1999 are upper case).

common temperature (8.5°C) using each season’s corresponding Q₁₀ value (a mean Q₁₀ value of 1.94/gDM and 1.89/gAFDM was used for autumn and spring denitrification rates). Seasonal denitrification rates in each stream normalized to either gDM or gAFDM were not significantly correlated with any of the individual stream characteristics presented in Table 1.

Nutrient limitations

Nutrient additions to the sediment microcosms yielded consistent results for both the autumn 1998 and spring 1999 experiments for each site (Fig. 4). In Walker Branch sediments, addition of NO₃-N or NO₂-N + LOC significantly increased denitrification rates 5- to 50-fold for spring and autumn, respectively (p < 0.0001). The addition of LOC alone did not significantly change denitrification potential relative to unamended controls. Denitrification in Walker Branch was not statistically different between microcosms amended with NO₃-N or NO₂-N + LOC during either season (Scheffe’s MCT).

Survey of denitrification potential in streams along a NO₃-N gradient

Surface water NO₃-N in the 10 streams sampled in the NO₃-N gradient study ranged from
TABLE 3. Mean physical and biogeochemical characteristics for stream sites sampled during summer 1999. Elevations were estimated across the sampling reach. DOC = dissolved organic C, OM = organic matter.

<table>
<thead>
<tr>
<th>Site</th>
<th>Elev. (m)</th>
<th>[NO₃-N] (µg/L)</th>
<th>[DOC] (mg/L)</th>
<th>% OM</th>
<th>Conductivity (µS/cm)</th>
<th>Stream temp. (°C)</th>
<th>Denitrification (ng N₂O gAFDM⁻¹ h⁻¹)</th>
<th>Mean</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oak Ridge (17 Jun 99)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Fork Walker Branch</td>
<td>270</td>
<td>43.0</td>
<td>0.27</td>
<td>2.47</td>
<td>242.0</td>
<td>8.37</td>
<td>14.4</td>
<td>78.2</td>
<td>27.6</td>
</tr>
<tr>
<td>West Fork Walker Branch</td>
<td>265</td>
<td>50.0</td>
<td>0.11</td>
<td>3.79</td>
<td>282.0</td>
<td>7.76</td>
<td>15.3</td>
<td>30.9</td>
<td>8.9</td>
</tr>
<tr>
<td>Upper White Oak Creek</td>
<td>271</td>
<td>77.4</td>
<td>0.28</td>
<td>1.83</td>
<td>246.0</td>
<td>7.67</td>
<td>15.0</td>
<td>197.4</td>
<td>69.8</td>
</tr>
<tr>
<td>Gum Hollow Branch</td>
<td>250</td>
<td>85.7</td>
<td>0.63</td>
<td>3.05</td>
<td>276.0</td>
<td>7.93</td>
<td>17.0</td>
<td>118.2</td>
<td>41.8</td>
</tr>
<tr>
<td>Pinhook Branch</td>
<td>244</td>
<td>97.6</td>
<td>0.75</td>
<td>4.11</td>
<td>253.0</td>
<td>7.89</td>
<td>18.6</td>
<td>87.0</td>
<td>50.8</td>
</tr>
<tr>
<td>Great Smoky Mountain National Park (8 Jul 99)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rattlebox Creek</td>
<td>610</td>
<td>10.2</td>
<td>1.38</td>
<td>2.14</td>
<td>12.6</td>
<td>6.30</td>
<td>18.2</td>
<td>422.3</td>
<td>149.3</td>
</tr>
<tr>
<td>Mossy Rock Creek</td>
<td>678</td>
<td>63.0</td>
<td>1.08</td>
<td>3.06</td>
<td>25.6</td>
<td>6.84</td>
<td>18.8</td>
<td>125.8</td>
<td>44.5</td>
</tr>
<tr>
<td>Hickory King Branch</td>
<td>521</td>
<td>37.6</td>
<td>0.46</td>
<td>3.42</td>
<td>20.9</td>
<td>6.24</td>
<td>13.9</td>
<td>1348.6</td>
<td>476.8</td>
</tr>
<tr>
<td>Beech Flats Prong</td>
<td>1250</td>
<td>532</td>
<td>0.31</td>
<td>2.84</td>
<td>41.0</td>
<td>5.99</td>
<td>11.6</td>
<td>894.1</td>
<td>316.1</td>
</tr>
<tr>
<td>Noland Creek</td>
<td>1646</td>
<td>549</td>
<td>0.71</td>
<td>1.52</td>
<td>14.0</td>
<td>5.76</td>
<td>11.8</td>
<td>1041.5</td>
<td>300.7</td>
</tr>
</tbody>
</table>

10 to 549 µg/L, with the highest NO₃-N levels generally occurring in the higher-elevation streams in the GSMNP (Table 3). Surface water DOC concentrations in these streams ranged from 0.11 to 1.38 mg/L and sediment OM content varied from 1.52 to 4.11%. Conductivity and pH ranged from 12.6 to 282 µS/cm and 5.76 to 8.37, respectively, and were consistently lower in the streams of the GSMNP compared to streams on the Oak Ridge reservation.

Sediment denitrification potentials were most strongly related to stream water NO₃-N concentrations ($r^2 = 0.74, p = 0.001$) (Fig. 5). Denitrification was generally higher in sediments from the higher elevation streams ($r^2 = 0.45$), and this relationship was stronger when data were normalized to grams dry sediment ($r^2 = 0.77$). Denitrification rates were negatively related to stream water pH ($r^2 = 0.68, p = 0.003$), conductivity ($r^2 = 0.53, p = 0.02$), and temperature ($r^2 = 0.43, p = 0.04$), but were not significantly related to % OM and DOC concentration.

A stepwise multiple regression analysis (Table 4) identified NO₃-N concentration as the primary predictor of denitrification potential normalized by gAFDM (model $R^2 = 0.74, p = 0.001$). The stepwise incorporation of conductivity (model $R^2 = 0.83$) into the model, followed by elevation ($R^2 = 0.93$) explained an additional 19% of variation in denitrification potential ($p = 0.0008$). Elevation was identified as the sole significant predictor ($R^2 = 0.77, p = 0.0009$) of denitrification potential normalized to gDM.

Discussion

Factors influencing denitrification potential

In our 2-stream comparison, Noland Creek denitrification potential in unamended slurries were an order of magnitude greater than those of Walker Branch. Denitrification potentials in sediments from Walker Branch were lower than those observed in most studies, but they were similar to denitrification rates observed in sediments from the upwelling hyporheic zones of Sycamore Creek (Holmes et al. 1996) using similar techniques. They were also similar to rates observed 1 to 5 m into the parafuvial flowpaths of this N-limited Sonoran Desert stream. In contrast, the average annual denitrification potential in sediments from Noland Creek was >2 times the maximum denitrification potential observed by Holmes et al. (1996), and only approached rates observed in other aquatic sediments (Seitzinger et al. 1993).

Noland Creek had considerably higher levels of NO₃-N and organic C availability (both as DOC and as % OM in sediments) than the West Fork of Walker Branch. Until now, the degree to which these factors potentially affect denitrification in stream sediments in the southern Ap-
Fig. 5. Linear regressions between denitrification rates and stream characteristics measured during summer 1999 survey of Oak Ridge streams and Great Smoky Mountains National Park (GSMNP) streams. DOC = dissolved organic C, OM = organic matter.
palachian mountains had not been investigated, although N loading via atmospheric deposition has received considerable attention (Johnson and Lindberg 1992, Flum and Nodvin 1995, Shubzda et al. 1995). Our results clearly showed neither NO$_3$-N nor LOC enrichment significantly enhanced denitrification potential in sediments collected from Noland Creek.

Unlike some studies that have demonstrated C-limited denitrification (Knowles 1982, Limmer and Steele 1982, Tiedje et al. 1982), we found that NO$_3$-N availability, rather than LOC availability, directly influenced the potential for denitrification in Walker Branch. Enrichment of the Walker Branch sediments with NO$_3$-N, or with NO$_3$-N + LOC, but not LOC alone, resulted in significant increases in denitrification rates. Similar results were reported for Sycamore Creek where NO$_3$-N addition alone generated a 2- to 10-fold increase in denitrification rates in hyporheic and parafluvial sediments and an ~30-fold increase in denitrification in the bank sediments (Holmes et al. 1996).

Denitrification potential in sediments from Noland Creek and Walker Branch was generally lower in autumn than other seasons, when DOC availability was maximum. The relatively low autumn denitrification rates and the lack of response when the LOC concentration was increased during the nutrient amendment experiments strongly suggests that C availability was not the primary limiting factor of denitrification potential in sediments from these streams. It is possible that the lack of response in denitrification following LOC additions was caused by a metabolic shift toward dissimilatory reduction of NO$_3$-N to NH$_4$-N as observed by Knowles (1982), although the relatively low ambient LOC availability year-round likely precludes this pathway.

The results of our stream survey further emphasized that NO$_3$-N rather than C availability likely determines the potential for denitrification in sediments from these streams in the southern Appalachian Mountains. However, this conclusion may be biased by high particulate organic C (POC) accumulations in our study streams. C might more likely limit denitrification in streams with less POC. Where NO$_3$-N availability was limited, as in the lower-elevation Oak Ridge streams, denitrification potential was low regardless of C availability or ambient stream temperatures. Where NO$_3$-N concentration was high and neither NO$_3$-N nor LOC limitations were evident, as in Noland Creek, denitrification potential was high and primarily influenced by temperature.

Denitrification potential in sediments from Rattlebox Creek was similar to other GSMNP stream sediments at similar elevation, although it had the lowest NO$_3$-N concentration of all streams in the survey. There are several possible explanations for why the denitrification potential in Rattlebox Creek was higher than would be predicted based on background NO$_3$-N concentration. First, NO$_3$-N concentrations during the survey may have been higher than much of the year, and the observed activity of the denitrifier community may reflect higher NO$_3$-N concentrations. Second, the highest DOC concentration observed in this survey was measured in Rattlebox Creek. Although DOC did not significantly affect denitrification potential in Noland Creek and Walker Branch, it could have contributed to the higher denitrification activity of Rattlebox Creek sediments.

### Table 4. Summary of stepwise selection of predictor variables in multiple regression with denitrification rates normalized by either grams ash-free dry mass (gAFDM) or grams dry mass (gDM). Default significance level for variable entry = 0.15.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Predictor variable</th>
<th>Model coefficient</th>
<th>Partial $R^2$</th>
<th>Model $R^2$</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denitrification rate* (ng N$_2$O gAFDM$^{-1}$ h$^{-1}$)</td>
<td>NO$_3$-N</td>
<td>-25.76</td>
<td>0.74</td>
<td>0.74</td>
<td>22.96</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Conductivity</td>
<td>17.37</td>
<td>0.08</td>
<td>0.83</td>
<td>3.4</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Elevation</td>
<td>6.76</td>
<td>0.1</td>
<td>0.93</td>
<td>8.63</td>
<td>0.03</td>
</tr>
<tr>
<td>Denitrification rate (ng N$_2$O gDM$^{-1}$ h$^{-1}$)</td>
<td>Elevation</td>
<td>-1.89</td>
<td>0.77</td>
<td>0.77</td>
<td>26.6</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

* Overall model was significant at $p = 0.0008$
Our stream survey also suggested that additional stream characteristics may have influenced denitrification potential. Not surprisingly, elevation was a secondary predictor of denitrification potential normalized to gAFDM and the primary predictor for rates normalized to gDM, as identified in the stepwise regression. The higher elevation streams in the southern Appalachian Mountains receive among the highest atmospheric inputs of NO$_3$-N in North America (Nodvin et al. 1995). Shubzda et al. (1995) demonstrated that N-deposition rates increased with increasing elevation in this region, and NO$_3$-N concentrations were higher in the higher-elevation streams in the GSMNP (Flum and Nodvin 1995).

The significant correlation between denitrification and conductivity and the appearance of conductivity as a significant predictor in the model were likely the result of the contrast in bedrock type between the Oak Ridge and Smoky Mountains stream catchments. The high conductivity of the Oak Ridge streams is likely a result of relatively high rates of weathering of the underlying dolomite formations, whereas the highly resistant sandstone formations of the GSMNP typically produce streams with lower pH and total ionic strength. Thus, the effect of conductivity on denitrification rate was probably not causal.

Stream pH can indirectly influence denitrification in stream sediments. Several studies have shown that acidic conditions may reduce or even completely inhibit the process in stream sediments (Klemetsson et al. 1977, Knowles 1982, Davidson and Swank 1987), although bacterial numbers and activity in sediment are not necessarily correlated with the pH of overlying water (Palumbo et al. 1987). Our study suggested a significant negative relationship between pH and denitrification, a pattern opposite to most studies. NO$_3$-N concentrations and pH were also inversely related in our study, with the high-elevation, high-NO$_3$-N GSMNP streams (e.g., Noland Creek, Beech Flats Prong, and Hickory King Branch) exhibiting significantly greater denitrification potential than the lower-elevation, higher-pH streams in the Oak Ridge area. We suspect that the high NO$_3$-N inputs from atmospheric deposition in high-elevation streams in the southern Appalachian Mountains sustain endogenous assemblages of denitrifying organisms in otherwise suboptimal, mildly acidic conditions.

**Within-site variability among denitrification rates**

The variability observed in denitrification potential among sediment samples in each stream was relatively high, especially in Walker Branch. Such variability is consistent with observations of substantial patchiness of denitrification hotspots in studies in other streams (Parkin 1987, Steinhart et al. 2000). We originally hypothesized that normalization of N$_2$O production data to gAFDM would reduce much of the anticipated variability associated with heterogeneous organic content of sediments and differential nutrient retention among samples. However, the OM content in the depositional zones sampled was not highly variable (SE = 0.0013 and 0.0031 for Walker Branch and Noland Creek, respectively). Hence, statistical analyses of denitrification potential in these streams were consistent regardless of data normalization to sediment OM content.

Our study did not address variability introduced by sediment-particle-size distribution. Several studies have shown that denitrification activity is higher in fine-textured sediments (<100 μm) where the probability of anaerobic conditions is greater (Groffman and Tiedje 1989, Garcia-Ruiz et al. 1998, Steinhart et al. 2000). In contrast, depositional areas characterized by more coarsely textured substrates are likely to be more oxic and support less active denitrification. Therefore, one might expect a reduced potential for denitrification in these areas (Rysgaard et al. 1994). The degree of sediment homogeneity in the denitrification assays might further explain the variability in denitrification potentials observed.

The preparation time allotted for experimental setup through the He-flushing step was presumed to be sufficient for sample warming and reacclimatization, yet a lag in denitrification activity was observed early in the incubations. Sudden shifts to anoxia in laboratory experiments through such treatments as He flushing do not permit denitrifiers to acclimatize to optimum denitrifying conditions as they would if oxygen were depleted gradually (i.e., through a natural cascade of metabolic processes, Knowles 1982). In addition, the time required for sample reacclimatization to ambient stream tempera-
Denitrification in stream sediments may contribute to loss of NO$_3$-N from catchments in the southern Appalachian Mountains. Our study suggests that ~100 and 600 ng N gAFDM$^{-1}$ h$^{-1}$ could be lost via denitrification in the stream sediments of Walker Branch (East and West Forks) and Noland Creek, respectively. These potential denitrification rates assume the optimum conditions of complete anoxia in the sediments and intersitial NO$_3$-N concentrations equal to those of overlying stream water. The effect of C$_2$H$_4$ inhibiting nitrification and thus limiting NO$_3$-N availability has not been considered. Tiedje et al. (1982) proposed that in situ denitrification rates are probably only a few % of the potential rates observed in vitro (Tiedje et al. 1982), but the C$_2$H$_4$ inhibition technique for measuring denitrification in vitro bears many limitations and can underestimate in situ denitrification potential in some aquatic sediments (Seitzinger et al. 1993, Bollmann and Conrad 1997, Paerl 1998). The magnitude to which in situ denitrification serves as a mechanism of NO$_3$-N removal from these southern Appalachian Mountain streams appears low. Regardless, even modest rates of denitrification can significantly impact stream-water NO$_3$-N (Holmes et al. 1996), particularly in N-limited streams.

**Catchment significance of denitrification in southern Appalachian Mountain streams**

We attempted to estimate the catchment significance of stream denitrification using our measured rates of potential denitrification, catchment inputs and outputs of N, and streambed characteristics. The Walker Branch catchment receives ~10 kg N ha$^{-1}$ y$^{-1}$ (or 975 kg N/y) from atmospheric deposition, whereas ~0.2 kg N ha$^{-1}$ y$^{-1}$ (19.5 kg N/y) are lost as stream export, mostly as NO$_3$-N (PJM, unpublished data). Nodvin et al. (1995) reported that the catchment of Noland Creek receives ~20 kg N ha$^{-1}$ y$^{-1}$ (348 kg N/y), ~17 kg N ha$^{-1}$ y$^{-1}$ (296 kg N/y) of which is lost from the catchment via stream export. Our study indicates a denitrification rate of 100 and 600 ng N$_2$O-N gAFDM$^{-1}$ h$^{-1}$ in the stream sediments of Walker Branch (East and West Forks) and Noland Creek, respectively. Assuming that 505 gAFDM/m$^2$ of benthic particulate OM, as reported for Walker Branch (Muholland 1997), is typical of streams in the southern Appalachian Mountains (Webster and Meyer 1997), denitrification in the stream sediments in Walker Branch and in Noland Creek produces 0.39 and 2.52 g N$_2$O-N m$^{-2}$ y$^{-1}$, respectively. The East and West Forks of Walker Branch constitute ~1800 m$^2$ of the entire 975,000-m$^2$ catchment (PJM, unpublished data). The streambed area of Noland Creek is unknown, but based on estimates of streambed area throughout the region (Webster and Meyer 1997), we estimate that Noland Creek constitutes 1%, or 1740 m$^2$, of the entire 174,000-m$^2$ catchment. Using these values, we calculate that 0.34 kg N/y and 4.38 kg N/y may be lost via denitrification from the stream sediments of Walker Branch (East and West Forks combined) and Noland Divide, respectively. Thus, denitrification in stream sediments is ~0.03% of total N inputs and ~1.7% of stream N export in the Walker Branch catchment, and ~1.3% of total N inputs and 1.5% of stream N export in the Noland Divide catchment.

Considering the ideal conditions for denitrification in the slurry studies, the proportion of N loss from the catchment via denitrification in these stream sediments appears insignificant. However, Holmes et al. (1996) proposed that even modest rates of denitrification have significant impacts on the fate of stream-water NO$_3$-N, particularly in N-limited streams. Future investigations in the southern Appalachian mountains should focus on the magnitude to which in situ denitrification serves as a mechanism of NO$_3$-N removal in streams draining areas of high atmospheric deposition, perhaps with a concentration of effort on porewaters of bankside riparian habitats where conditions to support high denitrification rates may be present.

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