Nitrogen Mineralization in Riparian Soils along a River Continuum within a Multi-Land-Use Basin

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Nitrogen dynamics in riparian systems are often addressed within one land-use type and are rarely studied on watershed scales across multiple land uses. This study tested for temporal trends and watershed-wide spatial patterns in N mineralization and identified site factors related to N mineralization. We measured net N mineralization in situ at monthly intervals for 1 yr at 32 riparian sites along the 124-km length of the Calapooia River, Oregon. We observed seasonal trends of mean net N mineralization with relatively low rates in the fall (29.8 kg N ha^{-1} yr^{-1}) and winter (30.1 kg N ha^{-1} yr^{-1}) and relatively high rates in the spring (122.1 kg N ha^{-1} yr^{-1}) and summer (99.7 kg N ha^{-1} yr^{-1}) when conditions for microbial activity and decomposition were likely enhanced. Annual net N mineralization on an area basis ranged from −13.5 to 234.0 kg N ha^{-1} yr^{-1} with a mean for all sites of 50.1 kg N ha^{-1} yr^{-1}. Annual net N mineralization per kilogram of soil ranged from −16.2 to 207.1 mg N kg soil^{-1} yr^{-1}, with a mean for all sites of 64.4 mg N kg soil^{-1} yr^{-1}. Regression analysis revealed hardwood basal area and coverage of grass as significant positive predictors of kilograms of N mineralized per hectare. Location along the river explained 22% of the variability of N mineralization per hectare, indicating that riparian areas may function differently along the length of the river.

Abbreviations: DN, dissolved nitrogen;

S urface water quality is a growing concern in Oregon's Willamette River Basin because its expanding population creates increasing pressure on surface waters to provide market and non-market amenities. Nitrogen is one of the most widely studied nutrients because it often limits terrestrial and aquatic ecosystem productivity and it can negatively impact surface waters. An excess supply of N and misapplication or poor timing of N fertilizer in terrestrial systems can lead to conditions favoring transport of dissolved N (DN) into surface waters (Binkley et al., 1999; Dinnes et al., 2001; Fox, 2004).

Research from eastern North America has demonstrated the importance of riparian buffers in agricultural and forested settings in removing DN from soil water before it reaches surface waters (Hill, 1996; Mayer et al., 2007; Osborne and Kovacic, 1993). Similar work in western North America and, in particular, the Willamette River Basin soils is limited. Results from two studies in the Calapooia River Basin, a tributary to the Willamette River, indicate that riparian buffers may not enhance N retention. There is mounting evidence that the winter rains of western Oregon and poorly drained soils in the lower, agriculturally dominated section of the Willamette River Basin combine to shift hydrologic flowpaths overland and deliver DN directly to surface waters via temporary expansion of stream networks during rainstorms (Wigington et al., 2003; 2005). Additionally, DN concentrations in surface waters of the Calapooia Basin are reported to be highest in late fall through early spring (Evans, 2007; Floyd et al., 2009), at a time when most vegetation is dormant and microbial activity is minimized because of lower temperatures.

Environmental controls on N processes tend to be specific to individual ecosystems. In a multiple-continent review of studies of riparian buffer effectiveness, Hill (1996) concluded that hydrological structures of streamside environments provide the physical template that controls N processes. Groffman et al. (1996) reported that groundwater levels and soil organic matter were the best predictors of net N mineralization at four northeastern U.S. wetland sites. In upland ecosystems of humid tropical regions, disturbance, plant composition, and soil type were found to be controlling factors of nitrification and denitrification (Robertson, 1989). In a topo-sequence study in a savanna ecosystem, Bechtold and Naiman (2003) found that N mineralization was greatest in fine-textured soils with high levels of total N. Litter quality has also been identified as an important control on N mineralization with higher rates observed in soils dominated by hardwood litter compared with conifer litter (Scott and Binkley, 1997; Stump and Binkley, 1993; Van Cleve and Ericson, 1993).

There is also high variability in results of studies addressing landscape-scale patterns of N processing in relation to vegetation in riparian zones. In a study across a range of riparian ecosystems in Europe, Hefting et al. (2005) found that plant production, N uptake, and N retention were higher in forested buffer sites compared with herbaceous buffer sites. In the Adirondack Mountains, upland conifer systems exhibited lower N mineralization compared with lower-elevation hardwood systems (Ohrui et al., 1999). Bischoff et al. (2001) reported that in forested wetlands the supply of N from mineralization was less than uptake, suggesting that forested uplands are functioning as N sources and forested wetlands are functioning as N sinks. A landscape-level analysis in North Carolina showed that many sites were at a balance point between acting as a source or sink of N (Garten and Ashwood, 2003).

The relative role and temporal and spatial variance of nutrient-cycling processes within commonly occurring riparian systems are not well documented in the Willamette Basin or similar basins in the Pacific Northwest. In riparian zones of the Willamette River Basin, it is unclear how N processes change across the landscape and how N processes may be controlled by soil, litter, or vegetation management. Furthermore, it is unclear if riparian areas act as sources or sinks of N or if they act as both under different environmental conditions, seasons, or management scenarios.

The specific objectives of this study, which was conducted along the length of the mainstem of the Calapooia River, were to: (i) evaluate the seasonal fluxes and net annual accumulation of soil N mineralization in riparian soils; (ii) investigate spatial patterns and temporal trends in net N mineralization across multiple land-uses and soil types; and (iii) evaluate relationships between net annual accumulation of mineralized N and soil and vegetation characteristics of the local riparian zone.

MATERIALS AND METHODS
Study Area

The Calapooia River Basin is contained within the southern portion of the Willamette River Basin in western Oregon. The Calapooia River spans 124 km and drains 966 km^2 with elevations ranging from 54 m at the mouth to 1571 m at the headwaters in the western Cascade Mountains. The climate is Mediterranean with dry, warm summers and cool, wet winters. Average yearly precipitation is 914 mm in the lower area of the watershed and 1524 mm in the upper area with 80% falling from October through March (Woodward et al., 1998). Atmospheric N deposition is low with an estimated range of 1 to 3 kg N ha^{-1} yr^{-1} (NADP 2010).

The lower area of the basin is flat with average topographic slopes ranging from 0 to 5%, with low drainage densities for perennial streams but high drainage densities of intermittent and ephemeral streams during the winter (Wigington et al., 2005). The lower mainstem has an average river gradient of 0.11% with sections of constrained and unconstrained braided river channels. Grass seed grown with sheep grazing is the primary management regime. Poorly drained soils, referred to as the Willamette Silt (WS) layer, dominate the lower area of the basin and are generally classed as xeric and mesic mollisols and alfisols. Inclusions of less poorly drained alluvial soils are also common near present and past river corridors. Riparian management areas along the mainstem of the Calapooia River in the lower area of the basin range from hardwood forest to blackberry (*Rubus sp.*) thickets and managed grass buffers.

The upper area of the Calapooia Basin is comprised of steep, well-defined hillslopes with an average river gradient of 2.4% and a generally constrained river channel. The primary land use is timber production using short rotation (~40-yr) Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] management. The geology in the upper section of the watershed is comprised of weathered volcanic rock, such as basalts, andesites, and tuffs. The soils of the upper zone are well-drained and are dominated by udic, mesic, and cryic entisols with components of cobble and rock. Riparian management areas on the mainstem of the upper Calapooia River are dominated by mixed age classes of hardwood and coniferous tree species with isolated pockets of N-fixing red alder (*Alnus rubra* Bong.).

The role of riparian soils and plant communities along the mainstem of the Calapooia River in relation to in situ net N mineralization was analyzed and compared across the gradient of existing riparian conditions at 32 sites throughout the Calapooia Basin (Fig. 1). These sites were located among a mix of ownerships, management regimes, and soil types. Sampling plots were located 5 m perpendicular from the bankfull line of the river, with three subplots established at cardinal directions 1 m from plot center.

Net Nitrogen Mineralization

Net fluxes of inorganic-N were measured at a depth of 0 to 15 cm in the surface mineral soil at approximately monthly intervals (20–35 d) for 1 yr starting December 2005 using the buried-bag method (Eno, 1960). Initial and in situ incubated soil cores were passed through a 2-mm sieve before laboratory determination of inorganic N. Coarse fragments were oven dried at 105°C and weighed. Inorganic-N was analyzed following a 2 M potassium chloride (KCl) extraction of 5 g

of field-wet soil. All processing and KCl extractions were completed within 5 d of cores being removed from the field. Soils were stored at 4°C when not being processed.

Analysis of KCl extracts for nitrate N and ammonium N was conducted on a Lachat Quick Chem 4200 analyzer (Lachat Instruments, Loveland, CO). Net N mineralization was estimated by subtracting the initial values of nitrate N and ammonium N from final in situ incubated values.

Estimates of annual accumulated net N mineralization per kilogram of soil and per hectare were calculated by adding the 12 monthly incubations after weighting for the number of days of each incubation. In the case of missing incubations, we allowed one missing incubation value at any site to be interpolated from the two incubation values before and after the missing value. If more than one incubation failed at a site, annual accumulation values were not calculated for the site. This required the removal of five sites, resulting in 27 sites for annual analysis.

Seasonal net N mineralization values were calculated by averaging the three monthly incubations (weighted for incubation length) in each season. We used the beginning of the water year, October first, as the start of the fall season with 3-mo seasons continuing thereafter. Seasonal inorganic N pools at the 0- to 15-cm depth were estimated by averaging by season the initial nitrate N and ammonium N values for the in situ incubations.

Site Characterization

Soil characterization was performed at each sample site during the spring of 2006. Samples of the organic litter layer were collected from the three subplots measuring 0.25 × 0.25 m. These samples were dried at 65°C for 3 d and weighed. Bulk density volumetric cores were collected at the 0- to 15-cm depth within each of the three sub-plots at each sample site. These cores were dried at 105°C, weighed, and then sieved to 2 mm and weighed again to provide estimates of total- and soil-fraction bulk density. At sites with coarse fragments too large to fit in the soil cores, bulk density was estimated using the sand cone technique (Dane and Topp, 2002). Additionally, ten 0- to 15-cm deep cores were sampled of surface mineral soil at each site and composited. These samples were air dried and sieved to 2 mm for chemical characterization.

Soil subsamples were digested using pressure and microwave-assisted nitric acid (HNO_3) digestion and analyzed using a PerkinElmer ICP–OES Optima 4300 (PerkinElmer Life and Analytical Sciences Inc., Waltham, MA) for Ca, Mg, Mn, K, Fe, Cu, and P. We measured soil pH using a 2:1 deionized water/air-dried soil ratio with a Hanna HI98129 pH meter (Caprock Developments Inc., Morris Plains, NJ). Additionally, subsamples were ground and passed through a 0.85-mm sieve (20 mesh) and were analyzed for total N and total C on a LECO CNS 2000 analyzer (LECO Corporation, St. Joseph, MI). Particle-size analysis was performed using the pipette method (Day, 1965).

Basal area and composition of overstory trees were measured using variable-radius plots and understory vegetation cover was measured in 3.14 m² circular plots during the summer of 2006.

Statistical Analyses

Two-sample t tests were used to examine if differences in mean annual net N mineralization occurred between sample sites located within the Willamette Silt layer (lower sites 1–14) and for sites up-river from
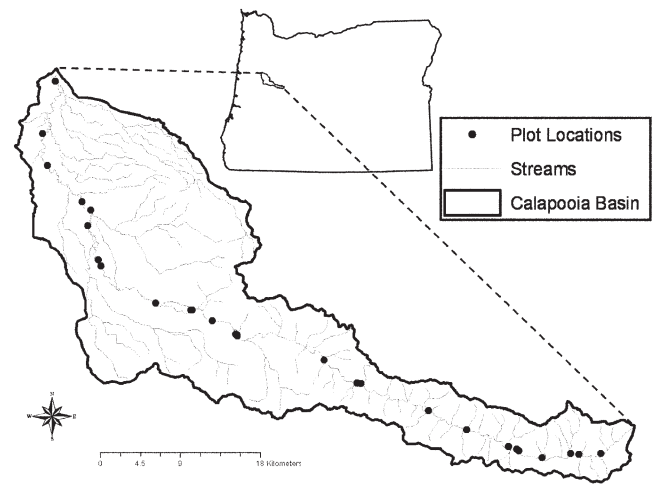

Fig. 1. Nitrogen mineralization study plot locations along the riparian zone of the Calapooia River, Oregon.

the Willamette Silt layer (upper sites 15–32). An a level of 0.05 was used for all significance tests. An additional t test was conducted to determine if there were differences between seasonal N mineralization rates per hectare. Relationships between annual N mineralization on a per hectare and per kilogram soil basis versus soil and vegetation characteristics at each of the sites were explored using stepwise regression analysis. Preliminary analysis indicated that 11 out of 14 of our candidate predictor variables were significantly correlated with location along the length of the river (Table 1). We therefore controlled for some of the systematic variation in site characteristics along the length of the river by forcing inclusion of river kilometer into a series of regression models. This allowed us to determine how much of the variability in N mineralization could be explained by location along the river and in turn assess how much of the residual variance could be explained by site variables. An a level of 0.05 was used for significance and entry into the stepwise procedure with no limits on the number of variables allowed in the models. All statistical analyses were conducted in SAS 9.1 (Cary, NC).

Table 1. Pearson correlations between river kilometer and site variables along the length of the Calapooia River, Oregon.

Variable	Pearson r	p-value
Total C	−0.642	0.001
Total N	−0.405	0.036
C/N	−0.764	< 0.0001
Total Ca	0.719	< .001
Bulk density	0.529	0.005
Soil fraction bulk density	0.824	< 0.0001
Percent clay	0.391	0.044
pH	0.757	< 0.001
Forest floor weight	−0.492	0.009
Conifer basal area	−0.594	0.001
Hardwood basal area	0.505	0.007
Grass percentage of cover	0.126	0.529
Total basal area	−0.192	0.337
Understory percentage of cover	0.218	0.275

Table 2. Soil properties at 32 N mineralization plot locations in riparian soils along the length of the Calapooia River, Oregon.

Site ID	River kilometer	C	N	C/N	Ca	pH	Forest floor	Total bulk density	Soil fraction bulk density	% Clay sized particles
		——g kg^{-1}——			µg g^{-1}		g m^{-2}	————Mg m^{-3}————		
1	129.61	11.5	0.7	16.4	4381	6.3	410	1.01	0.99	12
2	112.50	26.5	1.9	13.9	5665	5.7	1395	1.13	1.11	18
3	106.50	29.5	2.1	14.0	7432	6.0	279	0.76	0.76	22
4	96.70	35.1	2.1	16.7	9189	6.4	1224	0.76	0.75	17
5	95.03	25.4	1.7	14.9	7731	6.1	332	0.90	0.90	16
6	86.49	34.0	2.7	12.6	6906	5.8	108	0.58	0.57	31
7	84.59	35.7	3.1	11.5	7311	5.2	1422	0.86	0.84	22
8	83.40	37.7	2.6	14.5	8207	5.6	189	0.66	0.63	15
9	71.95	27.0	1.2	22.5	9101	6.6	553	0.61	0.59	10
10	66.74	28.3	1.4	20.2	8320	6.2	477	0.66	0.65	14
11	66.71	17.3	1.2	14.4	7787	6.6	223	0.69	0.68	27
12	66.65	31.2	2.2	14.2	7339	6.0	30	0.89	0.83	24
13	66.70	39.1	1.8	21.7	8983	6.1	206	0.71	0.69	13
14	59.70	7.5	0.3	25.0	8994	6.5	100	0.83	0.82	7
15	59.49	45.5	2.4	19.0	4105	6.1	1013	0.83	0.49	23
16	59.34	33.9	1.9	17.8	4815	6.1	1339	0.79	0.78	21
17	46.10	44.9	2.8	16.0	3461	5.7	419	0.90	0.63	30
18	40.79	31.8	1.6	19.9	4346	5.7	944	0.75	0.71	20
19	40.33	23.0	0.9	25.6	9306	5.8	434	0.71	0.71	7
20	29.99	43.2	1.8	24.0	1905	5.2	492	0.55	0.51	12
21	24.00	101.0	4.3	23.5	3157	5.1	873	0.33	0.24	7
22	17.10	167.9	5.9	28.5	4988	4.7	685	0.41	0.24	10
23	16.20	91.9	3.5	26.3	1875	5.2	1039	0.45	0.35	7
24	17.05	50.4	2.8	18.0	4987	5.6	743	0.70	0.55	9
25	15.80	35.4	1.9	18.6	2279	5.1	297	0.57	0.56	18
26	13.00	77.5	3.2	24.2	5785	5.4	3064	0.39	0.34	9
27	9.14	106.0	4.6	23.0	3413	4.6	2494	0.33	0.23	10
28	8.00	88.1	2.8	31.5	1252	4.5	2463	0.15	0.11	17
29	5.00	66.6	2.0	33.3	3101	5.4	1504	1.20	0.10	15
30	4.90	90.5	2.4	37.7	1794	4.2	1659	0.52	0.33	14
31	4.80	135.7	5.2	26.1	4440	4.6	1426	0.24	0.14	9
32	4.79	57.5	1.6	35.9	682	4.7	1727	0.55	0.39	23

RESULTS
Site Characterization

Riparian soils along the Calapooia River showed distinct trends in both chemical and physical characteristics (Table 2). Forest floor mass, total C, total N, and C/N were generally higher in upper, forested areas of the basin. Total soil Ca concentrations ranged from 682 to 9306 µg Ca g^{-1} soil^{-1} and pH ranged from 4.2 to 6.6 with both higher at the lower sites. Total bulk density ranged from 0.15 to 1.20 Mg m^{-3}, and soil-fraction bulk density ranged from 0.10 to 1.11 Mg m^{-3}, with both lower at the upper sites.

The lower riparian sites generally had more hardwood basal area and more diversity of hardwood species than the upper riparian areas (Table 3). Red alder (*Alnus rubra*) was found at only three upper sites (20, 28, 30), with 9.2 m^2 ha^{-1} of basal area at each. There were no conifers in the lower riparian areas, with an increasing trend of more conifer basal area from the middle of the basin to the upper areas. Total tree basal area was highest in the conifer-dominated upper forested sites, with less basal area in the lower sites. Five sites spread across the basin had ≤5 m^2 ha^{-1} of total tree basal area.

Net Nitrogen Mineralization

Mean seasonal in situ net N mineralization in riparian soils along the length of the Calapooia River ranged from −166.3 to 973.6 kg N ha^{-1} yr^{-1} (Fig. 2), with seasonal trends in net N mineralization occurring along the length of the river. The most rapid mean net N mineralization occurred in the spring (122.1 kg N ha^{-1} yr^{-1}; SE = 32.4) and summer (99.7 kg N ha^{-1} yr^{-1}; SE = 22.5) months, which were not significantly different from each other ($p = 0.67$). The lowest mean net N mineralization was in the fall (29.8 kg N ha^{-1} yr^{-1}; SE = 13.2) and winter months (30.1 kg N ha^{-1} yr^{-1}; SE = 10.3), which were also not significantly different from each other ($p = 0.99$). All other possible comparisons of seasonal mean N mineralization rates between seasons were significantly different ($p ≤ 0.01$).

Seventeen sites across the basin had negative values of net N mineralization during at least one season, indicating that net immobilization had occurred during that season. Nine sites had

Table 3. Vegetation description at N mineralization plots in riparian soils along the length of the Calapooia River, Oregon.

Site ID	River kilometer	Hardwood basal area	Conifer basal area	Total tree basal area	Understory vegetation cover	Grass cover
		$m^2\ ha^{-1}$	$m^2\ ha^{-1}$	$m^2\ ha^{-1}$	%	%
1	129.61	18.3	0.0	18.3	106	5
2	112.50	27.5	0.0	27.5	65	5
3	106.50	36.7	0.0	36.7	31	10
4	96.70	45.9	0.0	45.9	160	100
5	95.03	22.9	0.0	22.9	31	1
6	86.49	18.3	0.0	18.3	26	20
7	84.59	18.3	0.0	18.3	6	0
8	83.40	2.3	0.0	2.3	95	85
9	71.95	18.3	0.0	18.3	15	5
10	66.74	22.9	0.0	22.9	101	0
11	66.71	2.3	0.0	2.3	31	30
12	66.65	13.8	0.0	13.8	100	100
13	66.70	0.0	0.0	0.0	121	100
14	59.70	2.3	9.2	11.5	52	1
15	59.49	0.0	36.7	36.7	115	5
16	59.34	27.5	18.4	45.9	1	0
17	46.10	9.2	0.0	9.2	100	0
18	40.79	9.2	32.1	41.3	22	1
19	40.33	32.1	4.6	36.7	21	0
20	29.99	0.0	27.5	27.5	55	0
21	24.00	0.0	36.7	36.7	11	0
22	17.10	4.6	0.0	4.6	97	95
23	16.20	4.6	13.8	18.4	21	0
24	17.05	0.0	4.6	4.6	115	30
25	15.80	0.0	13.8	13.8	90	80
26	13.00	45.9	18.4	64.2	65	0
27	9.14	22.9	18.4	41.3	2	0
28	8.00	0.0	36.7	36.7	2	0
29	5.00	9.2	64.3	73.4	26	0
30	4.90	4.6	13.8	18.4	11	0
31	4.80	9.2	45.9	55.1	60	0
32	4.79	0.0	55.1	55.1	35	0

net N immobilization in the fall, eleven in the winter, five in the spring, and four in the summer. Spatial patterns were evident within seasons along the length of the river with greater net mineralization along the lower areas of the river and less net N mineralization (and more net immobilization) at upper areas in all seasons but summer.

Annual net N mineralization per kilogram of soil ranged from −16.2 to 207.1 mg N kg soil^{-1} yr^{-1}, with a mean value along the length of the Calapooia River of 64.4 (SE = 12.1) mg N kg soil^{-1} yr^1 (Fig. 3). Four sites in the upper section of the basin had annual net immobilization of N. However, there were sites in the upper and middle areas of the basin with annual net N mineralization that was greater than the mean for the basin, with three upper sites (No. 23, 24, and 28) in the upper quartile of observed values at 150 to 200 mg N kg soil^{-1} yr^{-1}. Mean net N mineralization for plots in the Willamette Silt layer was 66.5 (SE = 19.4) mg N kg soil^{-1} yr^{-1}, whereas it was 63.4 (SE = 15.8) mg N kg soil^{-1} yr^{-1} in plots up-river from the Willamette

Silt layer. This difference of 2.1 mg N kg soil^{-1} yr^{-1} was not statistically significant ($p = 0.45$).

Annual net N mineralization per hectare ranged from −13.5 to 234.0 kg N ha^{-1} yr^{-1} with a mean for all sites of 50.1 (SE = 10.0) kg N ha^{-1} yr^{-1} (Fig. 4). The highest values were at the lower and middle reaches of the basin, whereas lower values were observed at the uppermost reaches. Four sites (No. 25, 26, 31, and 33) in the upper basin had net immobilization of N per hectare. Mean annual net N mineralization per hectare for plots in the Willamette Silt layer was 74.8 (SE = 21.8) kg N ha^{-1} yr^{-1}, whereas it was 37.7 (SE = 9.4) kg N ha^{-1} yr^{-1} in plots located along reaches upstream from the Willamette Silt layer. This difference of 37.1 kg N ha^{-1} yr^{-1} was not statistically significant ($p = 0.08$).

Inorganic N pools per hectare were consistently higher in the lower sites compared with the upper sites in all seasons (Fig. 5). The upper sites were dominated by ammonium N and had relatively small variation across the four seasons. In contrast, the lower sites were dominated by nitrate N and there was more seasonal variability among these sites, with the winter period having the smallest inorganic N pools and fall having the largest.

Relationships between Net Nitrogen Mineralization and Characteristics of Riparian Zones

Stepwise regression selected total N, total Ca, and total tree basal area as significant positive predictors of N mineralization per soil mass, regardless of whether or not river kilometer was forced into the models (Table 4). River kilometer accounted for <1% of the variability in N mineralization per soil mass when it was forced into the model with total N, total Ca, and total tree basal area accounting for 32, 17, and 12%, respectively. Stepwise regression analysis selected the amount of hardwood basal area and the percentage of coverage of grass as significant positive predictors of N mineralization per hectare. When river kilometer was forced into the regression equation, it accounted for 22% of the variability in N mineralization per hectare, with an additional 25% accounted for by hardwood basal area and 10% accounted for by percentage of grass coverage (Table 4). When river kilometer was not forced into the model, hardwood basal area accounted for 45% of the variability in N mineralization per hectare, with an additional 11% accounted for by percent coverage of grass.

DISCUSSION
Net Nitrogen Mineralization

Seasonal changes in mean net N mineralization observed in riparian zones along the length of the Calapooia River support similar research addressing seasonal variation in this soil process (Gosz and White, 1986; Hefting et al., 2005) and agree with well-supported theories of soil microbial activity (Brady and Weil, 2002; Sylvia et al., 2005). It is likely that cooler tem-
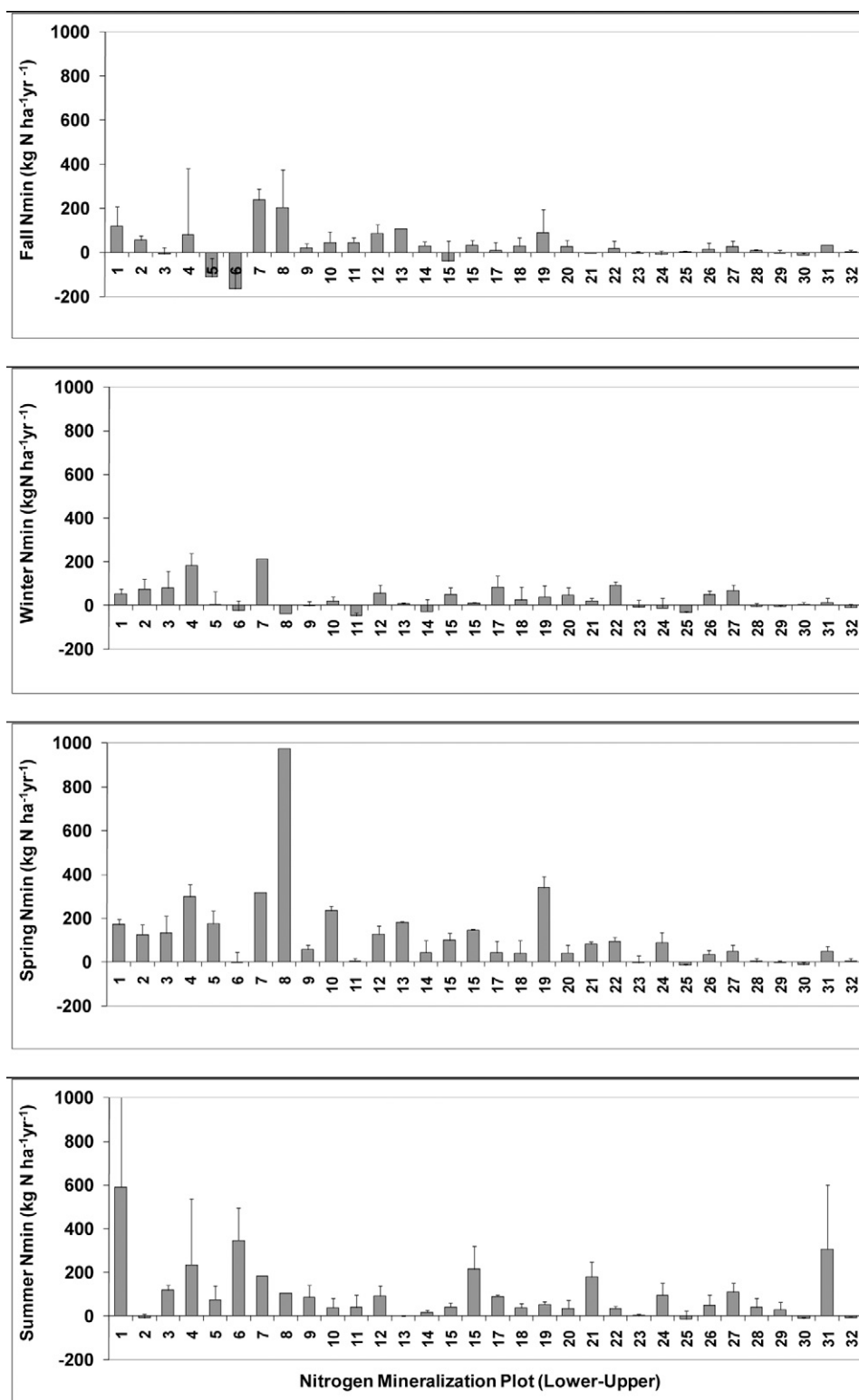
Fig. 2. Weighted mean N mineralization (Nmin) per hectare by season in riparian soils along the length of the Calapooia River, Oregon. Each bar represents a location along the mainstem of the river graphed in order from the bottom of the watershed on the left side of the graph with numbers indicating ordered site names. Error bars are one standard deviation. Lack of an error bar indicates only one successful incubation for that season.

promoting observed increases in net N mineralization. Changing soil moisture conditions and oxygen levels were also likely to play a role in the seasonal changes in net N mineralization we observed in riparian areas (Groffman et al., 1996). Spring and summer moisture conditions in riparian zones of the Calapooia River may be more conducive to microbial activity than in fall and winter because of unsaturated conditions and corresponding higher oxygen levels during the relatively dry spring and summer seasons. Increased net immobilization in the winter months may be caused by lower mineralization rates, with continued demand for nitrate N and ammonium N by microbes that require N to decompose C compounds.

The seasonal trends of net N mineralization and inorganic N pools in riparian soils support research in the Calapooia Basin indicating that DN concentrations in surface waters of the basin are highest during the onset of western Oregon's winter rains and during high precipitation periods in spring (Evans, 2007; Floyd et al., 2009). Late fall and early winter rains have been observed to hydrologically connect overland runoff to surface waters through expansion of the stream network, thereby delivering excess DN that was likely mineralized during the dry summer season to surface waters (Wigington et al., 2003; 2005). The peak of inorganic N pool sizes in surface mineral soils that we observed in the lower basin in the fall months corresponds to the period when DN concentrations are highest in the surface waters within the Calapooia Basin (Floyd et al., 2009), indicating that these riparian soils may be a potential source for N in surface waters. Our data suggest

perature regimes in the fall and winter suppressed microbial metabolism, which resulted in lower net N mineralization during these seasons. With the onset of warmer temperatures in the spring, microbial activity is likely to have increased, thereby

that the mineralized N from the spring and summer months may lead to greater inorganic N pool sizes that can be leached during the fall and winter rains. The spring flush of mineralized N could also be delivered to surface waters by strong spring storms,

if these storms occurred before the onset of significant vegetation uptake of N.

The seasonal fluxes in net N mineralization and inorganic N pools that we observed support the hypothesis that the riparian areas along the Calapooia River may be both net sources and sinks of N during different seasons. During warm seasons, net N mineralization in riparian soils may be high, resulting in net sources of N. Whereas, in the cooler fall and winter months, net N mineralization may be low or even negative, resulting in potential net sinks of N. It is likely that these processes act in concert with seasonal changes in denitrification, microbial assimilation, and plant uptake to reduce the potential export of N that our data suggest. Also, additions of surface litter in hardwood riparian areas are seasonal and may shift the soils from sinks to sources of N as the hardwood litter decomposes. This agrees with the work of Garten and Ashwood (2003), who emphasized the importance of timing of N inputs and outputs to determine if systems function as a source or sink of N.

Location along the River and Net Nitrogen Mineralization

Throughout the 124 km length of the Calapooia River, estimates of net N mineralization per hectare were strongly influenced by the amount of coarse fragments, which effectively dilute the estimated amount of N mineralization on a per hectare basis. Coarse fragment content increases steadily moving up the river basin, with many sites in the upper basin dominated by cobbles and rock. In the upper basin, where total- and soil-fraction bulk density were different, estimates of N mineralization per ha were substantially lowered when soil-fraction bulk density was utilized to estimate N mineralization on a per hectare basis (Fig. 3 and 4).

When combined with estimates of excess fertilizer loads that exceed plant uptake requirements, annual net N mineralization per hectare is appropriate for estimating the amount of N that could be potentially lost from the soil system because it is the biologically relevant amount of N that is mineralized at the site. However, it is confounded by any site characteristics that also vary systematically across the basin. Hence, regression analysis selects variables that simply correlate well with location or coarse fragments and may not select the mechanistic variables of interest. Regression analysis on a per kilogram of soil basis removes some of this effect of coarse fragments in our study, as can be evidenced by river kilometer, which is strongly correlated with coarse-fragment
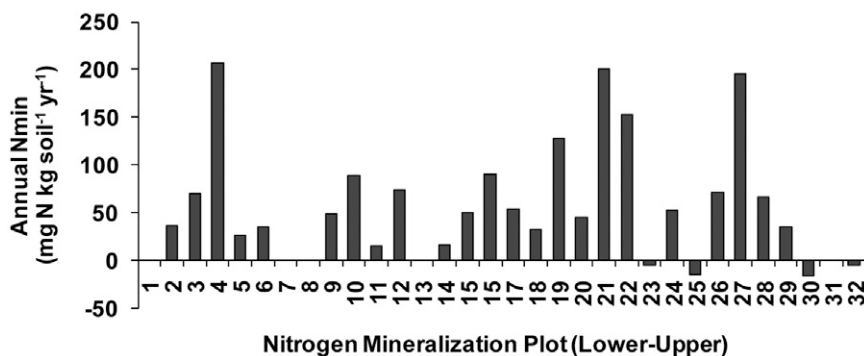

Fig. 3. Annual net N mineralization per kilogram of soil (Nmin) in riparian soils along the length of the Calapooia River, Oregon. Annual values computed from accumulation of nitrogen over 12 monthly incubations. Values < 0 represent annual net N immobilization. Each bar represents a location along the mainstem of the river graphed in order from the bottom of the watershed on the left side of the graph with numbers indicating ordered site names. Missing values indicate multiple failed incubations.

content, only explaining 1% of variability of this estimate of N mineralization.

Relationship between Site Variables and Net Nitrogen Mineralization

Stepwise regression analysis indicated that hardwood basal area and grass cover were significant positive predictors of annual N mineralization per hectare. The relationship with hardwood basal area is supported by a body of research addressing litter quality and N mineralization. The amount of decay-resistant lignin, C/N ratio, and lignin/N ratio are primary controllers of decomposition and N mineralization across various climates and forest ecosystems, with less N mineralization occurring as the C/N ratio, amount of lignin or lignin/N ratios increase (Fogel and Cromack, 1977; Melillo et al., 1982; Van Cleve and Ericson, 1993; Stump & Binkley, 1993; Scott and Binkley, 1997). Hardwood trees likely contribute litter of a higher quality than conifers at our sites, which is more easily decomposed and more rapidly mineralized. The relationship between net N mineralization and grass cover may also be related to litter quality in controlling decomposition and mineralization rates. Grass litter
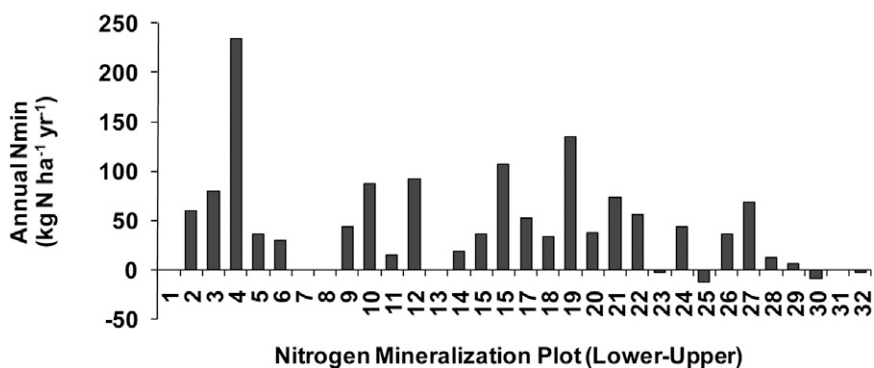

Fig. 4. Annual net N mineralization per hectare (Nmin) in riparian soils along the length of the Calapooia River, Oregon. Annual values computed from accumulation of nitrogen over 12 incubations. Each bar represents a location along the mainstem of the river graphed in order from the bottom of the watershed on the left side of the graph with numbers indicating ordered site names. Values < 0 represent annual net N immobilization. Missing values indicate multiple failed incubations.
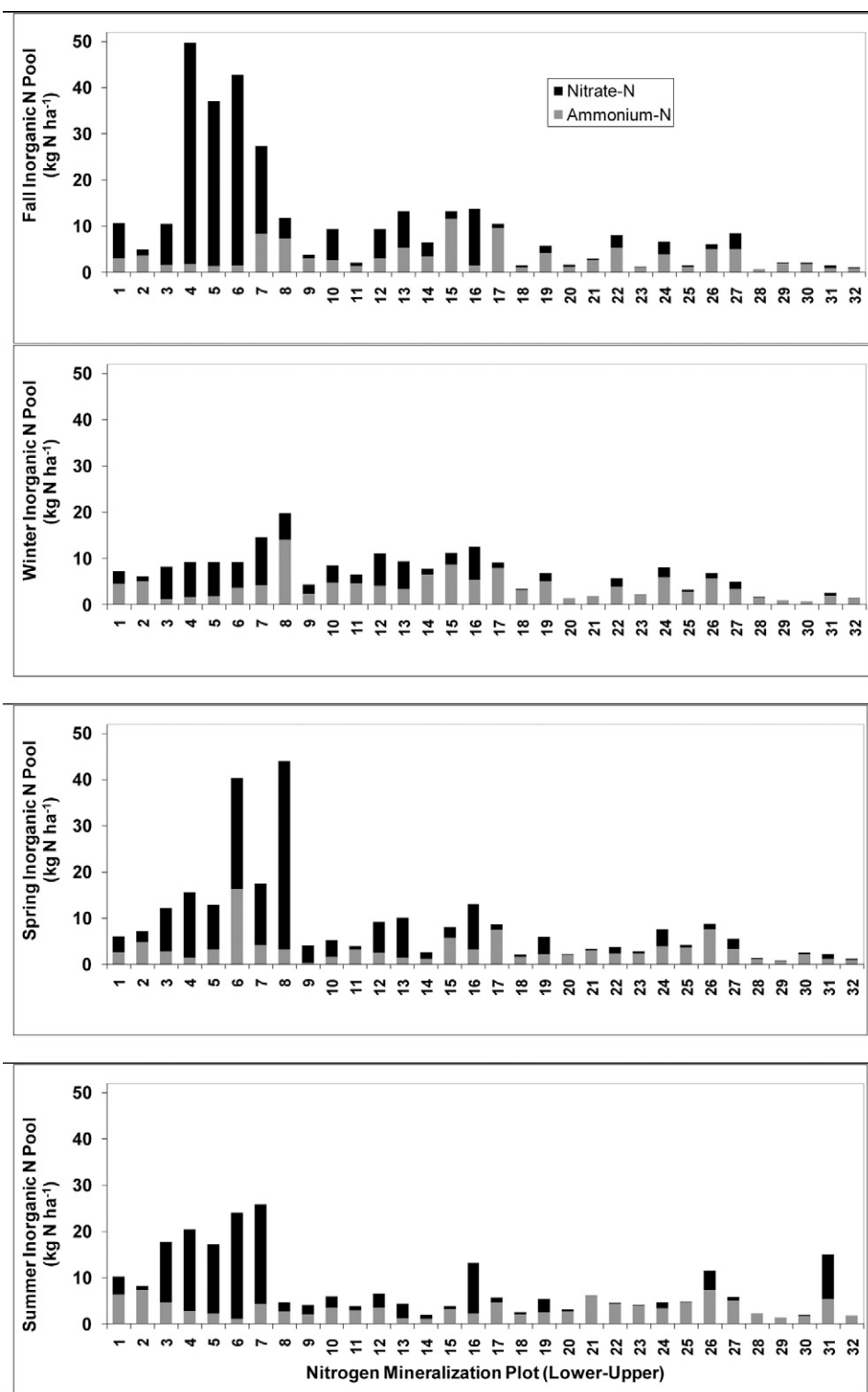
Fig. 5. Mean inorganic N pools per ha by season in riparian soils along the length of the Calapooia River, Oregon. Each bar represents a location along the mainstem of the river graphed in order from the bottom of the watershed on the left side of the graph with numbers indicating ordered site names.

14 candidate variables for regression analysis were significantly correlated with river kilometer (Table 1). In the stepwise analysis without river kilometer forced into the model, hardwood basal area explained 45% of the variability in N mineralization per ha but 20% of this predictive ability corresponded to site location along the river. This relationship between river kilometer and N mineralization per hectare confounds our ability to accurately estimate the relationships between N mineralization per hectare and our other site variables.

In an attempt to exclude the effects of river kilometer or coarse fragments along the basin, we conducted an identical regression analysis on N mineralization per kilogram of soil. In this model, river kilometer explained < 1% of the variability in N mineralization, likely because this measure of N mineralization excludes the spatially linked influence of coarse fragments in the Calapooia River Basin. Stepwise regression analysis indicated that soil total N and total Ca concentrations and total tree basal area were significant positive predictors of annual net N mineralization per kilogram of soil. As total soil N increases, there is more N available for mineralization and hence there is a greater potential for higher N mineralization. Base minerals, such as Ca, have also been reported to be positively associated with higher N mineralization rates (Persson et al., 1991; April and Newton, 1993; Moore, 1995). Hardwood basal area is a dominant subset of total tree basal area. These measures of basal area are significant positive correlates with each other, indicating it is likely that hardwood basal area accounts for much of the variability in N mineralization.

has a low C/N ratio compared with hardwood or conifer litter, which may increase N mineralization rates.

These relationships between N mineralization per hectare and hardwood basal area and grass cover may not be as strong in the Calapooia Basin as the initial regression analysis indicates. We found that location along the river explained 22% of the variability in N mineralization per hectare and that 11 of our

CONCLUSIONS

Patterns of net N mineralization that we measured along the length of the Calapooia River demonstrate the importance of coarse fragments in reducing estimates of the potentially available N in soils of the riparian zone in the upper Calapooia Basin

and indicate that there is more overall N mineralization and higher inorganic N pools in soils of the lower basin due partially to a lack of coarse fragments relative to the upper basin, as well as to increased hardwood basal area, total soil N, and total soil Ca in lower sites. This emphasizes that riparian zones along the river network and in different types of landscapes can have contrasting outcomes resulting from biogeochemical functions such as N mineralization and cannot be expected to provide the same degree of N pollution mitigation or ecosystem service in different systems. Future efforts to research riparian area functions should address the strong differences among landscapes and positions along river networks. Failure to understand the functional differences both among regions and within watershed-scale management areas may lead to nutrient management guidelines and policies that fail to achieve their goals.

ACKNOWLEDGMENTS

Table 4. Variable selection from stepwise regression for predicting annual net N mineralization in riparian soils along the length of the Calapooia River, Oregon.

	Coefficient	Standard error	p-value	R^2
Per kilogram of soil w/river kilometer forced				
Intercept	−140.42	37.43	0.001	
River kilometer	−0.09	0.36	0.812	0.003
Total N	39.77	7.91	< 0.0001	0.315
Total Ca	0.02	0.005	0.003	0.167
Tree basal area	1.26	0.48	0.015	0.124
Root mean square error				42.8
Per kilogram of soil				
Intercept	−141.89	36.16	0.0007	
Total N	40.12	7.61	< 0.0001	0.241
Total Ca	0.02	0.60	0.0003	0.240
Tree basal area	1.27	0.47	0.012	0.128
Root mean square error				41.9
Per hectare with river kilogram forced				
Intercept	2.61	12.26	0.833	
River kilometer	0.71	0.24	0.013	0.219
Hardwood basal area	2.10	0.56	0.001	0.254
Grass percentage of cover	0.49	0.21	0.030	0.100
Root mean square error				36.0
Per hectare				
Intercept	8.08	10.25	0.438	
Hardwood basal area	2.33	0.48	< 0.001	0.451
Grass percentage of cover	0.51	0.51	0.022	0.110
Root mean square error				35.7

REFERENCES

April, R.H., and R.M. Newton. 1993. Mineralogy and mineral weathering. *In* D.W. Johnson and S.E. Lindburg (ed.) Asmospheric deposition and forest nutrient cycling. Springer-Verlag, New York.

Bechtold, J.S., and R.J. Naiman. 2003. Toposequence in a semi-arid savanna. Soil Biol. Biochem. 38:1325–1333.

Binkley, D., H. Burnham, and H.L. Allen. 1999. Water quality impacts of forest fertilization with nitrogen and phosphorus. For. Ecol. Manage. 121:191–213.

Bischoff, J.M., P. Bukavecks, M.J. Mitchell, and T. Hurd. 2001. Nitrogen storage and cycling in vegetation of a forested wetland: Implications for watershed nitrogen processing. Water Air Soil Pollut. 128:97–114.

Brady, N.C., and R.R. Weil. 2002. The nature and properties of soils. Pearson Education, New Jersey.

Grossman, R.B., and T.G. Reinsch. 2002. The solid phase. p. 201–228. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA, Madison, WI.

Day, P.R. 1965. Particle fractionation and particle size analysis. p. 545–567. *In* C.A. Black et al. (ed.) Methods of soil analysis. Part 1. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Dinnes, D.L., D.L. Darlen, D.B. Jaynes, T.C. Kasper, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2001. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94:153–157.

Eno, C.F. 1960. Nitrate production in the field by incubating the soil in polyethylene bags. Soil Sci. Soc. Am. J. Proc. 24:277–279.

Evans, D.E. 2007. Dissolved nitrogen in surface waters and nitrogen mineralization in riparian soils within a multi-land use basin. M.S. Thesis. Oregon State University, Corvallis, OR.

Floyd, W.C., S.H. Schoenholtz, S.M. Griffith, P.J. Wigington, and J.J. Steiner. 2009. Nitrate-nitrogen, land use/land cover, and soil drainage associations at multiple spatial scales. J. Environ. Qual. 38:1473–1482.

Fogel, R., and K. Cromack, Jr. 1977. Effect of habitat and substrate quality on Douglas-fir litter decomposition in Western Oregon. Can. J. Bot. 55:1632–1640.

Fox, T.R. 2004. Nitrogen mineralization following fertilization of Douglas-fir forests with urea in Western Washington. Soil Sci. Soc. Am. J. 68:1720–1728.

Garten, C.T., and T.L. Ashwood. 2003. A landscape level analysis of potential excess nitrogen in East-Central North Carolina, USA. Water Air Soil Pollut. 146:3–21.

Gosz, J.R., and C.S. White. 1986. Seasonal and annual variation in nitrogen mineralization and nitrification along an elevational gradient in New Mexico. Biogeochemistry 2:281–297.

Groffman, P.M., G.C. Hanson, E. Kiviat, and G. Stevens. 1996. Variation in microbial biomass and activity in four different wetland types. Soil Sci. Soc. Am. J. 60:622–629.

Hefting, M.M., J.C. Clement, P. Bienkowski, D. Dowrick, C. Guenat, A. Butturini, S. Tota, G. Pinay, and J.T.A. Verhoeven. 2005. The role of vegetation and litter in the nitrogen dynamics of riparian buffer zones in Europe. Ecol. Eng. 24:465–482.

Hill, R.H. 1996. Nitrate removal in stream riparian zones. J. Environ. Qual. 25:743–755.

Melillo, J.M., J.D. Aber, and J.F. Muratore. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63:621–626.

Mayer, P.M., S.K. Reynolds, M.D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. J. Environ. Qual. 36:1172–1180.

Moore, A.K. 1995. Mineralogy and chemistry of an Adirondack spodosol at the Huntington Forest, Newcomb, New York. M.S. Thesis. State University of New York, Syracuse.

NADP. 2010. National Atmospheric Deposition Program (NRSP-3). Program Office. Illinois State Water Survey. Champaign, IL.

Ohrui, K., M.J. Mitchell, and J.M. Bischoff. 1999. Effect of landscape position on N mineralization and nitrification in a forested watershed in the Adirondack Mountains of New York. Can. J. For. Res. 29:497–508.

Osborne, L.L., and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biol. 29:243–258.

Persson, T., H. Lundkvist, A. Wiren, R. Hyvonen, and B. Wessen. 1991. Effects of acidification and liming on carbon and nitrogen mineralization and soil organisms in mor humus. Water Air Soil Pollut. 45:77–96.

Robertson, G.P. 1989. Nitrification and denitrification in humid tropical ecosystems: Potential controls on nitrogen retention. p. 55–69. *In* J. Proctor (ed.) Mineral nutrients in tropical forest and savannah ecosystems. Blackwell Science Publications. Oxford, UK.

Scott, N.A., and D. Binkley. 1997. Foliage litter quality and annual net N mineralization: Comparison across North American forest sites. Oecologia 111:151–159.

Stump, L.M., and D. Binkley. 1993. Relationships between litter quality and nitrogen availability in Rocky Mountain Forests. Can. J. For. Res. 23:492–502.

Sylvia, D.M., P.G. Hartel, J.J. Fuhrmann, and D.A. Zuberer. 2005. Principles and applications of soil microbiology. Pearson Education, New Jersey.

Van Cleve, K., J. Yarie, R. Erickson and C.T. Dyrness. 1993. Nitrogen mineralization and nitrification in successional ecosystems on the Tanana River floodplain, interior Alaska. Can. J. For. Res. 23:970-978.

Wigington, P.J., S.M. Griffith, J.A. Field, J.E. Baham, W.R. Horwath, J. Owen, J.H. Davis, S.C. Rain, and J.J. Steiner. 2003. Nitrate removal effectiveness of a riparian buffer along a small agricultural stream in western Oregon. J. Environ. Qual. 32:162–170.

Wigington, P.J., T.J. Moser, and D.R. Lindeman. 2005. Stream network expansion: A riparian water quality factor. Hydrol. Processes 19:1715–1721.

Woodward, D.G., M.W. Gannett, and J.J. Vaccaro. 1998. Hydrogeologic Framework of the Willamette Lowland Aquifer System, Oregon and Washington. U.S. Geological Survey Professional Paper 1424-B.