



## Tree species, root decomposition and subsurface denitrification potential in riparian wetlands

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### Abstract

Patches of organic matter have been found to be important 'hotspots' of denitrification in both surface and subsurface soils, but the factors controlling the formation and maintenance of these patches are not well established. We compared the concentration of patches of organic matter and root biomass in the subsurface (saturated zone) beneath poorly drained riparian wetland soils at four sites in Rhode Island, U.S.A. - two dominated by red maple (*Acer rubrum*) and two dominated by white pine (*Pinus strobus*). Denitrification enzyme activity (DEA) and carbon (C) content of patch material were compared between sites and between patches with different visual characteristics. Root decomposition was measured in an 8-week ex-situ incubation experiment that compared the effects of water content, root species, and soil matrix origin on CO<sub>2</sub> evolution. We observed significantly greater concentrations of patches at 55 cm at one red maple site than all other sites. DEA and percent C in patches was generally higher in patches than matrix soil and did not vary between sites or by patch type. White pine roots decomposed at a faster rate than red maple roots under unsaturated conditions. Our results suggest that faster root decomposition could result in lower concentrations of patches of organic material in subsurface soils at sites dominated by white pine. Tree species composition and root decomposition may play a significant role in the formation of patches and the creation and maintenance of groundwater denitrification hotspots in the subsurface of riparian wetlands.

**Abbreviations:** DEA – denitrification enzyme activity; DOC – dissolved organic carbon; PD – poorly drained; RM-1 – red maple-1 site; RM-2 – red maple-2 site; WP-1 – white pine-1 site; WP-2 – white pine-2 site.

### Introduction

Concern over eutrophication of coastal waters resulting from high nitrate concentrations in streams and groundwater has spurred interest in the management of riparian zones, i.e., transition areas between uplands and surface waters (Gregory et al. 1991), as a means to protect water quality. While numerous studies have found riparian zones prevent the movement of nitrate from upland land uses to streams (Lowrance et al. 1984; Peterjohn and Correll 1984; Hill 1996; Gilliam et al. 1997; Jordan et al. 1997; Lowrance 1997), there remains considerable uncertainty regarding the role of

vegetation in these processes (Corell 1997; Lowrance 1998; Korom 1992; Hill 1996; Verchot et al. 1997). Studies reporting high rates of groundwater nitrate retention during the dormant season (Nelson et al. 1995; Lowrance et al. 1984; Simmons et al. 1992; Haycock and Pinay 1993; Haycock and Burt 1993; Jordan et al. 1993) highlight the importance of microbial denitrification processes over plant uptake. The role of vegetation in mediating these soil processes remains poorly understood.

The efficacy of different types of riparian vegetation in promoting groundwater nitrate removal is uncertain (Correll 1997; Lowrance 1998). Comparisons of groundwater nitrate removal between forested and

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non-forested riparian zones have produced conflicting results. While some studies (Osborne and Kovacic 1993; Hubbard and Lowrance 1997; Haycock and Pinay 1993) found higher groundwater nitrate removal in forested riparian zones, other studies (Lowrance et al. 1995; Schnabel et al. 1996) found higher removal at herbaceous dominated riparian sites. Addy et al. (1999) found no significant difference in groundwater nitrate removal between forested and herbaceous dominated riparian sites. These studies suggest that variations in vegetative supplies of carbon (C) to the subsurface account for a portion of the observed differences in groundwater nitrate removal between studies. Carbon can serve as an essential electron donor for the denitrification process.

Differences in the density, quality, and location of roots and C in the subsurface have been attributed to different plant and tree species (Johansson 1992; Finzi et al. 1998; Binkley and Giardina 1998; Tufekcioglu et al. 1999). The density, composition, and distribution of root-derived material (Johansson 1992; Jobbagy and Jackson 2000), the proportion of fine to thick roots (Hendrick and Pregitzer 1992), and the rate of root turnover and decomposition (Fahey and Hughes 1994) influence the concentration and distribution of organic C in soils.

Characterizing the subsurface concentrations of organic material may be a key to understanding spatial variability in groundwater nitrate removal in riparian zones. Several studies have found that subsurface N transformations are dependent on the distribution of 'hotspots' of microbial activity resulting from microsites or 'patches' of organic material in the subsurface (Parkin 1987; Gold et al. 1998; Jacinthe et al. 1998). In a previous study, we found that riparian groundwater nitrate removal was correlated with the amount of C found in patches of organic matter (Addy et al. 1999). We suggested that the total mass of patch C per unit of subsoil could serve as an indicator of riparian groundwater nitrate removal potential (Jacinthe et al. 1998; Gold et al. 1998; Addy et al. 1999).

The origin of subsurface organic patches remains uncertain. Patches often appear as small areas of dark-stained media located intermittently in the subsurface (Gold et al. 1998). Patches often are composed of root-derived material or surround roots in various stages of decay (Gold et al. 1998; Addy et al. 1999). In saturated riparian zone soils, red maple (*Acer rubrum*) and speckled alder (*Alnus rugosa*) roots have been observed up to 90 cm below the surface (Addy et al. 1999), and hybrid poplar (*Populus × euroamericana*'

*Eugenei*) roots have been noted down to 180 cm depth (Tufekcioglu et al. 1999). In unsaturated temperate soils, roots of white pine (*Pinus strobes*) and red maple trees have been observed up to 3 m below the surface (Stone and Kalisz 1991). Canadell et al. (1996), in a comprehensive literature synthesis, determined the average maximum rooting depth globally was 3.9 m and 2.9 m for unsaturated temperate coniferous and deciduous forests, respectively. Jackson et al. (1996) reported only 52% and 65% of global roots appear in the upper 30 cm of a soil profile in temperate coniferous and deciduous forests, respectively. Clearly, the presence of roots and any associated C at deep depths may influence the nature, extent and importance of hotspots of nitrogen cycling in groundwater.

Surface organic material that leaches into the subsurface or dissolved organic carbon (DOC) in groundwater can also lead to patch formation (Gold et al. 1998). However, when Jacinthe et al. (1998) amended patch material with DOC from surface soils, no significant increase in denitrification potential was evident indicating the potential primacy of root-derived C over surface-derived C as a driver of subsurface denitrification. The observation that groundwater nitrate removal and root mortality in northern deciduous forests are both highest in November (Nelson et al. 1995; Fahey and Hughes 1994; Hendrick and Pregitzer 1992) suggests a strong relationship between root turnover and the generation of pools of labile organic material in the subsurface to drive microbial activity. This effect is augmented in riparian zones when the seasonal rising of the water table leads to additional root mortality (Gold et al. 1998). However, factors that regulate the contribution of root-derived labile C to patches and microbial denitrification within the patches remain largely unknown.

In this study we investigated the relationship between root biomass, distribution of patches, denitrification potential of subsurface riparian zone soils, and root decomposition at sites dominated by different tree species. Our objectives were to assess 1) variation in the concentration, denitrification potential and visual characteristics of patch material within the shallow groundwater at riparian wetland sites with different dominant tree species (red maple or white pine) and 2) differences in the rate of decomposition of red maple and white pine roots under saturated and unsaturated soil conditions.

Table 1. Vegetation characteristics and sample replicates. Species composition for the shrub layer ( $\geq 97$  cm height and  $\geq 7.6$  cm diameter) and herb layer. Average percent cover by basal area of red maple and white pine per plot

Site	Shrub layer	Herb layer	Tree Layer (% Basal Area)			Number of Sample Replicates <sup>†</sup>		Root Biomass (g m <sup>-2</sup> ) <sup>¶</sup>	
			Red Maple	White Pine	Other Deciduous	55 cm depth	85 cm depth	55 cm depth	85 cm depth
RM-1	<i>Vaccinium corymbosum</i> , <i>Clethra alnifolia</i> , <i>Viburnum regnitum</i>	<i>Osmunda cinnamomea</i> , <i>Rubus hispidus</i>	100	0	0	3	3	26.1 (13.2)	19.5 (10.9)
RM-2	<i>C. alnifolia</i> , <i>V. regnitum</i>	<i>Lilium canadense</i> , <i>O. cinnamomea</i> , <i>V. regnitum</i> , <i>C. alnifolia</i>	82	0	18	2	0 <sup>‡</sup>	4.2 (4.0)	n.d.
WP-1	<i>Lindera benzoin</i> , <i>C. alnifolia</i> , <i>V. corymbosum</i>	<i>Aralia nudicaulis</i> , <i>Lilium canadense</i> , <i>O. cinnamomea</i> , <i>Pinus strobus</i>	12	77	11	3	3	10.9 (4.8)	3.9 (1.4)
WP-2	<i>V. corymbosum</i>	<i>A. nudicaulis</i> , <i>L. canadense</i> , <i>O. cinnamomea</i> , <i>Lichopodium</i> , <i>Sphanum</i>	8	71	21	3	2 <sup>¶</sup>	2.8 (0.9)	2.4 (2.4)

<sup>†</sup>One sample is an aggregation of seven to nine cores taken from a single face of a soil pit.

<sup>‡</sup>A high water table at RM-2 and pump failure limited the deep analysis to visual inspection.

<sup>¶</sup>SE values presented in parenthesis. n.d. = not determined.

## Methods

### Site descriptions

Study sites were located within four riparian wetlands along first order streams within the 63,000 ha Pawcatuck watershed in southern Rhode Island, U.S.A. Sampling focused on hydric, sandy soils adjacent to the stream as our previous research has found these soils to be critical areas for groundwater nitrate removal (Simmons et al. 1992; Nelson et al. 1995; Gold et al. 1998). All four sites were mapped as glacial outwash (Rector 1981) and had comparable soil textures and hydrology to permit our focus on the role of vegetation. The annual high water table was at the surface at all sites. Two sites were dominated by red maple and two sites were dominated by white pine (Table 1).

### Red Maple sites

The Red Maple-1 (RM-1) site (41°30' N, 71°30' W) was along White Horn Brook, a tributary of the Pawcatuck River. The Red Maple-2 (RM-2) site (41°27' N,

71°42' W) was along a tributary of the Usquepaug River, approximately 1.0 km from RM-1. Soils at both red maple sites were mapped as Walpole sandy loam (sandy, mixed, mesic Aeric Haplaquepts).

### White Pine Sites

The White Pine-1 (WP-1) site (41°22' N, 71°42' W) was along Tanyard Brook, a tributary of Watchaug Pond. The soil was mapped as Windsor loamy sand (Mixed, mesic Typic Udipsamments). The White Pine-2 (WP-2) site (41°30' N, 71°37' W) was along Acid Factory Brook, a tributary of the Flat River, approximately 4.4 km from WP-1. The soil was mapped as Scarboro sandy loam (sandy, mixed, mesic Histic Humaquepts). Both sites were dominated by White Pine (*Pinus strobus*), but deciduous species were present.

### Site characterization

Detailed soil morphology was obtained from soil pits at each site. Percent cover of tree species by basal

area and general shrub and herb layer species composition at each site was determined using nested plots of different sizes where the pit was approximately the center point (Table 1). The largest plot size (7 m × 14 m) was used to characterize the tree layer by species and the diameter at breast height. The shrub and herb layers were characterized using 2.5 m × 4.5 m plots and 0.7 m × 1.4 m plots, respectively, to characterize the approximate percent cover of the herb layer by species.

#### *Soil sampling and handling*

One sample was an aggregate of seven to nine cores obtained from a single face of a soil pit. Samples were separated spatially from each other by a minimum of 1 m and from trees by a minimum of 3 m. Within a given site and given depth, the number of sample replicates ranged from two to three (Table 1). During the summer of 1999, horizontal cores (15 cm length by 10 cm diameter) were extracted using a golf course hole cutter (Par Aide Products Co., St. Paul, MN) that maintained the structural integrity of the cores. We sampled at 55 cm and 85 cm below the ground's surface to be at least 35 cm below the seasonal high water table and to correlate with depths chosen in a similar study (Addy et al. 1999). Groundwater was pumped out of pits to facilitate sampling.

The undisturbed soil cores were stored at 4 °C until analysis. When dissecting each core, particulate organic matter in the form of identifiable patches, roots, and buried horizons (when present in sufficient extent to recognize as a layer rather than a patch) was separated from the soil matrix material. The patches were defined using parameters outlined in Addy et al. (1999) as darker stained material within the lighter soil matrix material. The patches were sorted into types based on visual characteristics including color, texture, and the degree to which edges were discernable. *Type 1* patches consisted of dark stained black greasy organic material with defined edges. *Type 2* patches were defined as the dark brown to reddish material surrounding a root. *Type 3* patches lacked a defined edge and consisted of sand grains coated with organic material (illuvial). These different patch types were chosen based on previous observations of variations in patch appearance and lability (Jacinthe et al. 1998). The mass and % moisture (subsample dried at 105 °C for 24 hours) of each type of patch and the matrix soil was obtained. Patch concentration was calculated as the total dry mass of patches divided by the total dry

mass of the sample. Root biomass was obtained after root material detectable to the eye was removed from each core, separated from soil by dipping in sodium metaphosphate, and dried at 60 °C for 24 hours.

#### *Soil analyses*

Denitrification enzyme activity (DEA, Smith and Tiedje, 1979) was measured in both matrix and patch material. As described by Groffman et al. (1999) field moist samples were amended with nitrate (100 mg N kg<sup>-1</sup>), dextrose (40 mg kg<sup>-1</sup>), chloramphenicol (10 mg kg<sup>-1</sup>), and acetylene (10 kPa), and were incubated under anaerobic conditions for 90 minutes. Gas samples were taken at 30 and 90 minutes, and analyzed for N<sub>2</sub>O by electron capture gas chromatography (Tracor 540, Houston, TX).

Subsamples of matrix and patch material were dried at 100 °C for 24 hrs and analyzed for total C using the modified Dumas Combustion method (Nelson and Sommers, 1982).

#### *Collection and incubation of root material*

Incubations of red maple and white pine fine roots were carried out with soil matrix material at two moisture contents (saturated and unsaturated). Roots and matrix material were taken from WP-1 and RM-1. Roots, predominantly live, were taken from 1–2 m tall saplings at 10 cm depth. The soil was carefully excavated around the trunk starting at the base and working out following the roots. Roots were cut at the point closest to the trunk. Matrix material was sampled from 55–65 cm below the surface at each site (Cg horizon at RM-1 and Bwb horizon at WP-1) using an auger. Soil and roots were stored at 4 °C until incubation setup.

Approximately 30 cm length of fine roots (diameter less than 2 mm), with a weight of 0.3–0.8 g, were placed with 55–75 g wet weight of soil in 250 mL headspace sampling jars fitted with septa. Roots of white pine and red maple were placed with matrix from both sites (e.g. white pine roots in WP-1 matrix, and white pine roots with RM-1 matrix). Half were placed in saturated matrix (moisture of 25% by weight) and half in unsaturated matrix (moisture of 15% by weight). The saturated matrix represented the water content of the soils at time of sampling, while the unsaturated matrix was produced by adding ambient groundwater to air dried matrix material. Control incubations of only matrix soil without roots were included. Each treatment was replicated three times. Jars were stored in the dark and open for eight weeks

at 11 °C, the mean groundwater temperature in late autumn and early spring for southern Rhode Island (Nelson et al. 1995).

During the course of the incubation, samples were maintained at constant moisture by periodically (one to two times a week) weighing and adding the mass of ambient groundwater required to restore the moisture content of the sample to the level at the initiation of the experiment. The groundwater was sampled from a piezometer (55 cm depth) installed at the same site as the matrix and stored at 11 °C.

The rate of carbon dioxide (CO<sub>2</sub>) flux was measured weekly by capping the jar and taking 9 mL head-space samples by syringe at time zero and 24 hours. After the 24 hour sampling, the jars were uncapped. These gas samples were analyzed for CO<sub>2</sub> by thermal conductivity gas chromatography (Tracor 540, Houston, TX). The rate of CO<sub>2</sub> evolution from the control incubations was subtracted from the root and soil incubations to represent CO<sub>2</sub> evolution attributable to the presence of roots. The resulting CO<sub>2</sub> evolution values ( $\mu\text{g CO}_2 \text{ g}^{-1} \text{ root h}^{-1}$ ) were a measure of root decomposition rates (Robinson et al. 1999). At the end of the incubation, DEA was measured on the soil material as described above.

#### *Data analysis*

Total concentrations of patch material, C content of patch and matrix, and DEA of patch and matrix were compared by one-way analysis of variance (ANOVA), comparing all sites, depths and patch types simultaneously. Specific differences were tested with a Fisher's least significant difference test. Total production of CO<sub>2</sub> over the 8 week ex-situ incubations with different root materials, matrix and moisture conditions were also compared using one-way ANOVA. Fisher's least significant difference test was used a posteriori to determine differences between specific treatments. A linear regression was run to determine correlations between patch concentration and root biomass. All analysis were considered significant at the  $p < 0.05$  level.

## **Results**

### *Soil cores: characteristics*

Patches were found in all samples taken at each site. *Type 1* patches were the dominant type found at all sites, ranging from 60–99% of total patch material.

The other two types of patches were present in such small quantities [*Type 2* (< 1–14%), *Type 3* (0–33%)] that comparison between the three types was only feasible at RM-1. To compare properties in patch material between depths and sites, the three different types of patch material were combined and are referred to as 'total patch'. Generally, *Type 1* and *Type 3* patches were amorphous features in the soil ranging from 1 to 5 cm wide while *Type 2* patches were generally elongated features ranging from 2 to 10 cm long and 0.2 to 1.5 cm wide.

The concentration of total patch varied with depth and vegetation type (Figure 1). At 55 cm, the concentration of total patch was significantly greater at RM-1 than all other sites. In three out of four sites minimal patches were found at 85 cm. WP-1 had significantly greater concentrations of total patch at 85 cm than the other three sites at 85 cm. These WP-1 patches coincided with a distinct buried A horizon at the same depth (85 cm).

The C content of patches was significantly higher than matrix material (Table 2). There was no significant difference in percent C between different types of patch material at RM-1, the only site with sufficient amounts of the three patch classes to permit comparisons. There was also no significant difference in percent C in patches between sites with different vegetation. The buried horizon at WP-1 had C content similar to patches and significantly greater than matrix soil.

DEA at the depth where patches prevail (Figure 1) was significantly higher in the patches (range: 0–2.55 ng N<sub>2</sub>O-N g<sup>-1</sup> soil h<sup>-1</sup>) than in matrix material (range: 0–0.66 ng N<sub>2</sub>O-N g<sup>-1</sup> soil h<sup>-1</sup>) at three of the four sites (Table 2). RM-2 was the only site where patches had negligible DEA. At RM-1, patch *Types 1*, *2* and *3* had similar DEA. The buried horizon sampled at WP-1 had comparable DEA as the *Type 1* patch.

Root biomass was computed at 55 and 85 cm depths (Table 1). Mean root biomass did not vary significantly between depths within each site or between sites. Root biomass was significantly correlated with patch concentration at 55 cm ( $r^2 = 0.7$ ) but not at 85 cm.

### *Incubations: CO<sub>2</sub> evolution*

All treatments exhibited a general decrease in the rate of CO<sub>2</sub> evolution over the course of the 8 week incubation. Differences in the rate of the CO<sub>2</sub> evolution between week 1 and week 8 were fairly consistent within treatments.

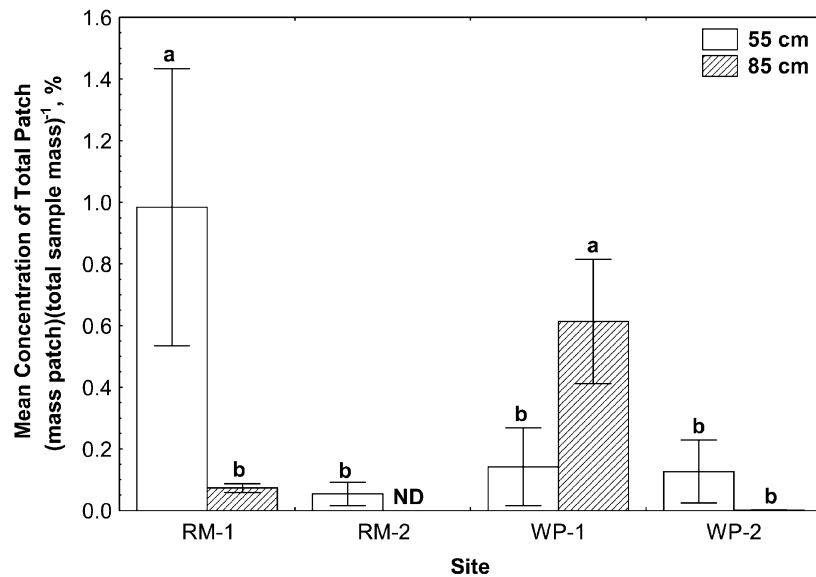


Figure 1. Concentration of total patch material (dry mass patch/total dry mass of soil sample, %) from cores extracted at 55 and 85 cm from two red maple sites and two white pine sites. Values are the mean (SE) of replicates (number of replicates listed in Table 1), except at RM-2 where no cores were extracted (visual inspection indicated no patch material). Different letters indicate significant differences ( $p < 0.05$ ). ND = no data.

Comparisons among treatments were more striking when averaged over the entire eight weeks of the incubation (Figure 2). There was no significant difference in mean  $\text{CO}_2$  evolution among the saturated root incubations. Under unsaturated conditions, white pine incubations produced significantly more  $\text{CO}_2$  than red maple incubations which were comparable to the saturated incubations. There was no effect of matrix type on  $\text{CO}_2$  evolution. Control incubations generated significantly less  $\text{CO}_2$  (mean:  $0.02 \mu\text{g CO}_2 \text{ g}^{-1} \text{ soil h}^{-1}$ , SE: 0.0) than all root incubations, except the red maple root saturated incubation in red maple soil, and were not significantly different than each other.

#### *Incubations: denitrification enzyme activity*

Denitrification enzyme activity of the red maple root in white pine saturated incubation material (mean:  $4.2 \text{ ng N}_2\text{O-N g}^{-1} \text{ soil h}^{-1}$ , SE: 2.2) was significantly greater than DEA of all other incubation material (mean:  $0.4 \text{ ng N}_2\text{O-N g}^{-1} \text{ soil h}^{-1}$ , SE: 0.1) at the completion of the experiment.

## Discussion

The origin of *Type 1* patches is somewhat obscure since there were no obvious roots, pieces of leaf litter, earthworm channels, or buried horizons present.

Since this was the most dominant patch type at all four riparian sites, the dynamics of this subsurface carbon source is important. RM-1 with the greatest concentration of patches at 55 cm also contained the greatest root biomass of all sites, although the difference was not significant. The relationship between roots and patch formation at 55 cm was strengthened by the significant correlation between patch concentration and root biomass. The observation of significant concentrations of total patch at the deeper depth at WP-1 is in contrast to both the other sites and to Addy et al. (1999), who reported an absence of patch material at 90 cm. We suggest that the fluvial processes that formed the buried horizon also impacted patch formation at this location. The patches observed at this depth may represent portions of partially decomposed buried horizons which no longer stand apart as a continuous layer. Additionally, the buried horizon may have encouraged root growth and subsequent patch formation to deeper depths as root growth has previously been reported to increase in response to fertilization in experiments intending to mimic the spatial heterogeneity of nutrients in subsurface soils (Fahey and Hughes 1994).

Our measurements of patch concentration and root biomass on the scale of soil cores were supported by similar patterns observed in the independent visual assessment done as part of the pit descriptions.

Table 2. Mean percent carbon and DEA values (standard error) for matrix and patch material at the four sites at depth with the highest amount of patch material (Figure 1). Different scripts within an entire column correspond to significant differences ( $p < 0.05$ )

Site	Material	n	Mean % C	Mean DEA (ng N <sub>2</sub> O-N g <sup>-1</sup> soil h <sup>-1</sup> )
Red Maple-1	Matrix	3	0.28a (0.03)	0.35a (0.24)
	Type 1 patch	3	3.78b (2.10)	2.12b (1.08)
	Type 2 patch	3	0.57b (0.02)	1.27b (0.92)
	Type 3 patch	3	0.50b (0.09)	0.81b (0.09)
Red Maple-2	Matrix	2	0.13a (0.02)	0.0a
	Total patch	1	1.39b	0.0a
White Pine-1	Matrix-1	3	0.39a (0.06)	0.41a (0.20)
	Buried Horizon <sup>†</sup>	3	3.71b (0.76)	1.45b (0.45)
	Total patch	3	1.32b (0.50)	2.55b (1.32)
White Pine-2	Matrix	2	0.37a (0.03)	0.0a
	Total patch	2	1.52b (0.82)	2.43b (2.32)

<sup>†</sup>Buried Horizon only was found at one site, WP-1, at 85 cm.

The concentration of patches was the only variable that yielded significant differences between the sites and depths. Different concentrations of patch material between sites with different dominant tree species have also been reported between red maple and speckled alder sites (Addy et al. 1999). The concentration of subsurface patches may be a useful indicator of site differences in subsurface groundwater denitrification, but these results need to be verified with field denitrification measurements.

Since the C content of the patches and the buried horizon was significantly higher than the matrix soil at all sites, we feel confident that our visual observation and sampling of patch material distinguished between two distinct categories of soil with different functions and microbial activity in the subsurface. At three out of four sites, the DEA of the patch material was significantly greater than the matrix soil. These patches were functioning as ‘hotspots’ of microbial activity which is in agreement with many studies (Parkin 1987; Christensen et al. 1990; Jacinthe et al. 1998; Addy et al. 1999). However, the fact that the DEA of RM-2 patch material was negligible suggests that the lability of patches is variable and simple visual observation is not enough to assess the C in terms of denitrification potential. The elevated and comparable levels in DEA within the buried horizon at WP-1 and patches, suggests that both sources of enriched C promote similar microbial functions. Factors that influence the presence of buried horizons (e.g., windthrow, alluvial processes) could be important controllers of riparian

nitrate dynamics at the landscape scale and warrant further attention (Haycock and Pinay 1993).

The rapid accumulation of CO<sub>2</sub> initially observed in the incubations is consistent with other studies (McClagherty et al. 1982; Schipper et al. 1994). Some of the early respiration may have been respiration of residual carbohydrates, as the roots likely remained alive for some time after being separated from the trees. However, the vast majority of respiration over the 8-week incubation arose from decomposition of dead root material. The lack of differences in CO<sub>2</sub> evolution of root incubations in different matrix materials suggests that decomposition rates were dependent on the root species rather than the substrate. In fact, the control incubations produced minimal CO<sub>2</sub> indicating that soil respiration was a minor contributor to CO<sub>2</sub> evolution in the incubations. Schipper et al. (1994) attributed decreases in the rate of CO<sub>2</sub> evolution observed in an ex-situ incubation study to a decline in readily degradable plant matter. A similar decline in labile organic matter is likely driving the decline seen in the CO<sub>2</sub> emitted in our incubations. This temporal pattern was also observed in a study of nitrate removal rates within mesocosms in which the rapid initial decomposition of root material was suggested as the mechanism driving the high initial rates of nitrate removal (Addy et al. 1999). The generally low DEA of incubation material adds further support to labile C depletion due to root decomposition at the completion of the incubation experiment.

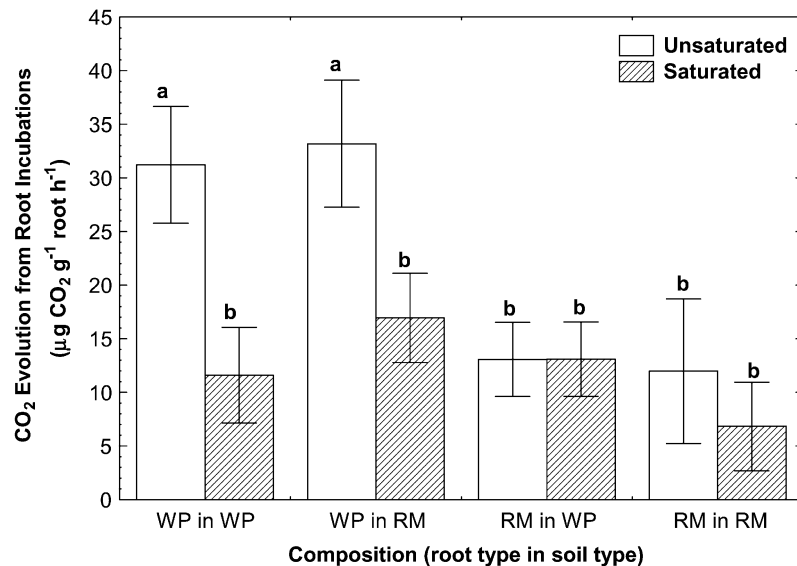


Figure 2. Mean CO<sub>2</sub> evolution ( $\mu\text{g CO}_2 \text{ g}^{-1} \text{ root h}^{-1}$ ) over 8 week root incubation study. Values are the mean (SE) of three replicate incubations. Different letters indicate significant differences ( $p < 0.05$ ).

Mean CO<sub>2</sub> evolution was relatively low in all saturated root incubations since decomposition tends to occur more slowly under these conditions (Bowden 1987). Alternatively, these incubations may have been producing methane which we did not measure. Evolution of CO<sub>2</sub> was the same in saturated and unsaturated incubations of red maple roots indicating that red maple root decomposition was proceeding slowly. On the other hand, white pine roots decomposed at a significantly higher rate under unsaturated conditions, suggested that white pine roots are more decomposable than red maple roots. We suggest that this high rate of root decomposition explains the lack of patches at WP-1 and WP-2 (except near the buried horizon as explained above). Rapid decomposition of root material would convert the labile C to CO<sub>2</sub> leaving less in the form of observable patches of organic matter. Lower concentrations of patches of organic material may reduce the presence of microsites of anaerobic conditions in subsurface soils that function as 'hotspots' of denitrification (Christensen et al. 1990; Jacinthe et al. 1998). Thus a more labile resource (white pine roots) would lead to lower levels of subsurface groundwater denitrification than a less labile resource (red maple roots) due to the necessity of having specialized microsites for denitrification to occur. (17) Further support for this idea comes from the fact that only red maple roots supported substantial DEA at the end of the incubation. However, this pattern

needs to be verified with actual field measurements of subsurface denitrification and in situ root turnover.

Our results are similar to those of McClaugherty et al. (1982) who reported higher rates of decomposition in roots sampled from a coniferous plantation of red pine versus roots sampled from a deciduous site. However, a review by Silver and Miya (2001) of global trends in root decomposition, typically assessed by litterbag techniques, found lower rates of root decomposition in conifers than in deciduous species. Root decomposition and turnover has been related to root chemistry (Silver and Miya 2001), nitrogen availability (Hendricks et al. 2000), hydrologic fluctuations (Baker III et al. 2001), temperature (Gill and Jackson 2000), and precipitation (Gill and Jackson 2000). Since the later three factors were constant between sites, difference in species-level root chemistry or groundwater nutrient availability between sites likely explain the differences in root decomposition rates noted in this study.

It is possible that root decomposition in the unsaturated incubations was stimulated by rewetting of air dried matrix material (Groffman and Tiedje 1988). However, the low level of organic matter and microbial biomass in the matrix material makes this scenario unlikely as the flush of decomposition from rewetting arises from killed microbial biomass (Groffman and Tiedje 1988). Processes occurring under rewetting conditions are particularly interesting to riparian zone

research because these areas exhibit highly fluctuating water tables that result in varying amounts of saturated and unsaturated conditions during the year. This fluctuation is believed to be one of the main forces driving nitrate removal from groundwater in these areas (Gold et al. 1998). During unsaturated periods decomposition and accumulation of available C occurs, while low rates of decomposition occur during periods of saturation. Field studies of nitrate removal also follow this pattern with the highest groundwater nitrate removal rates reported in the dormant season when the water table is high (Simmons et al. 1992; Nelson et al. 1995). Hydrologic fluctuations influence root dynamics (Hendrick and Pregitzer 1996; Jones et al. 2000; Baker III et al. 2001) and may consequently impact patch formation. The role of water table fluctuation as a regulator of subsurface biogeochemistry in riparian zones is clearly worthy of further study.

Site characteristics such as the presence of buried horizons, particle size, land use history, geomorphic setting and water table dynamics may influence root dynamics and patch formation in the subsurface. There is a need for research to better define landscape-scale controls on these dynamics, as they may be critical controllers of riparian nitrate removal functions at this scale.

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