Effects of harvesting on nitrogen and phosphorus availability in riparian management zone soils in Minnesota, USA

Douglas N. Kastendick, Eric K. Zenner, Brian J. Palik, Randall K. Kolka, and Charles R. Blinn

Abstract: Riparian management zones (RMZs) protect streams from excess nutrients, yet few studies have looked at soil nutrients in forested RMZs or the impacts of partial harvesting on nutrient availability. We investigated the impacts of upland clearcutting in conjunction with uncut and partially harvested RMZs (40% basal area reduction) on soil nutrients in forests in Minnesota, USA. Nitrate, ammonium, and phosphorus were measured using exchange resins. Upland clearcutting increased dormant and growing season nitrate, ammonium, and total inorganic nitrogen in the upland 2 to 5 times compared with uncut upland. Upland clearcutting increased dormant and growing season nitrate and total inorganic nitrogen just inside the RMZ boundary 2 to 5 times compared with this location adjacent to uncut upland. Dormant season nitrate and total inorganic nitrogen were 2 times higher in the entire RMZ adjacent to upland clearcut. Phosphorus was not affected by treatment. Partial harvesting of the RMZ did not increase nutrients compared with the uncut RMZ. Results suggest that nitrate is transported into the RMZ from adjacent clearcuts but partial harvesting of the RMZ does not increase nitrate availability.

Résumé : Les zones d'aménagement riverain (ZAR) protègent les cours d'eau contre les excès de nutriments mais peu d'études ont porté sur les nutriments du sol dans les ZAR qui supportent des forêts ou sur les impacts d'une coupe partielle sur la disponibilité des nutriments. Nous avons étudié les impacts de la coupe à blanc sur les terres hautes en lien avec des ZAR non coupées ou partiellement coupées (enlèvement de 40% de la surface terrière) sur les nutriments du sol dans des forêts du Minnesota, aux États-Unis. Le nitrate, l'ammonium et le phosphore ont été mesurés à l'aide de résines échangeuses. La coupe à blanc sur les hautes terres a entraîné une augmentation par un facteur de 2 à 5 du nitrate, de l'ammonium et de l'azote inorganique total pendant la saison de croissance et la saison dormante, comparativement à la forêt non coupée sur les hautes terres. La coupe à blanc sur les hautes terres a augmenté par un facteur de 2 à 5 le nitrate et l'azote inorganique total pendant la saison de croissance et la saison dormante seulement à l'intérieur des limites de la ZAR comparativement à un endroit similaire adjacent à la forêt non coupée sur les hautes terres. Durant la saison dormante, le nitrate et l'azote inorganique total étaient deux fois plus élevés dans toute la ZAR adjacente à la coupe à blanc sur les hautes terres. Le traitement n'a pas influencé le phosphore. La coupe partielle de la ZAR n'a pas entraîné d'augmentation des nutriments comparativement à la ZAR non coupée. Les résultats indiquent que le nitrate est transporté dans la ZAR depuis les coupes à blanc adjacentes mais que la coupe partielle de la ZAR ne cause pas d'augmentation de la disponibilité du nitrate.

[Traduit par la Rédaction]

Introduction

Stream riparian areas receive nutrient inputs from surrounding uplands that can result in soil nutrient concentrations exceeding those in adjacent upland areas (Giese et al. 2003; McClain et al. 2003). Forested riparian areas, through interception and storage, play a key role in protecting water resources from excess nutrients (Lowrance et al. 1997; Hazlett et al. 2008; McBroom et al. 2008). Water nitrate concentrations, for example, can be reduced by 60% to 100% before discharge to streams by passing through a forested riparian area (Peterjohn and Correll 1984; Spoelstra et al. 2010).

Assimilation by vegetation may play an important role in regulating nitrogen (Lowrance 1992; Yeakley et al. 2003). Phosphorus removal in riparian zones is often achieved by retention of sediment and adsorption of dissolved particles by mineral soil (Cooper and Gilliam 1987), but uptake by trees can also be important (Peterjohn and Correll 1984).

Timber harvests in riparian areas may affect their ability to regulate nutrient interception and uptake (Hazlett et al. 2007). Harvesting in riparian areas can increase percolation, throughflow, and export of nutrients to streams through mobilization and leaching (Hornbeck et al. 1990; Keim and Schoenholtz 1999; Boothroyd et al. 2004). For instance, following clearcutting in New Hampshire, USA, a fivefold in-

Received 12 April 2012. Accepted 19 August 2012. Published at www.nrcresearchpress.com/cjfr on 19 September 2012.

D.N. Kastendick, B.J. Palik, and R.K. Kolka. Northern Research Station, 1831 Highway 169 East, Grand Rapids, MN 55744, USA.
E.K. Zenner. School of Forest Resources, Penn State University, University Park, PA 16802, USA.
C.R. Blinn. Department of Forest Resources, University of Minnesota, St. Paul, MN 55108, USA.

Corresponding author: Douglas N. Kastendick (e-mail: dkastendick@fs.fed.us).

crease in stream nitrate concentration over pre-harvest levels was documented (Martin et al. 1986), while partial harvesting in upland and riparian forests in the southern Appalachians, USA, resulted in a twofold increase in stream nitrate compared with pre-harvest levels (Clinton 2011). Reductions in vegetative cover are also associated with increases in mineralization (Vitousek and Melillo 1979).

Nutrient leaching is usually at its maximum immediately after disturbance or in the early reestablishment phase of riparian forest development (Hornbeck and Kochenderfer 2000; Yeakley et al. 2003), with the pulse of increased nutrients following vegetation removal often diminishing within 5 years as plant uptake recovers (Mou et al. 1993; Clinton 2011). However, even mature riparian areas can be vulnerable to nutrient saturation if inputs from surrounding uplands are extreme (Hanson et al. 1994).

Many states have developed best management guidelines that include use of riparian management zones (RMZs) to protect water resources from the effects of upland forest management (Blinn and Kilgore 2001). The RMZ guidelines generally recommend a variety of strategies, including retaining specified amounts of basal area. Studies evaluating the effectiveness of riparian management strategies to maintain water quality have largely focused on the capacity of forested RMZs to remove nutrients that are discharged from upland agricultural settings (Hill 1996). There is much less information on nutrient movement and uptake potential of RMZs in forested settings or on the effects of partial timber harvesting on riparian nutrient dynamics (Edwards and Williard 2010). Although there is evidence that retaining residual trees after harvest in an RMZ can lessen harvesting-related increases in stream nutrient concentrations (Governo et al. 2004; Knoepp and Clinton 2009), understanding of the impacts of partial harvesting on nutrients in RMZs with adjacent clearcut uplands is incomplete.

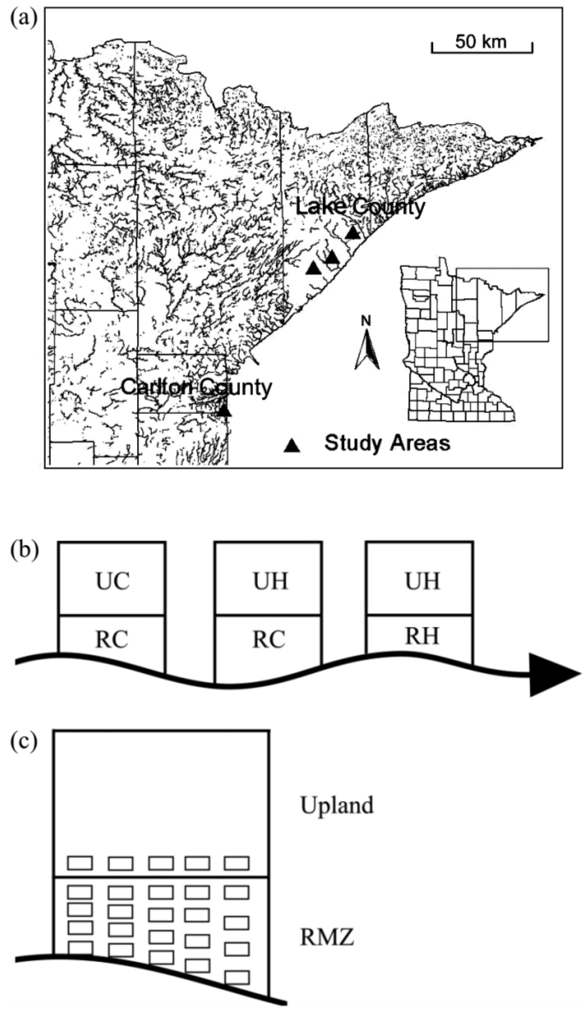
With this need in mind, we conducted a study to investigate the short-term effects of upland clearcutting and partial harvesting in riparian areas on the availability of nitrate, ammonium, and phosphorus within soils. We addressed the following questions: (1) does clearcutting the upland, adjacent to an RMZ, increase nutrient availability in the upland, (2) is there evidence that the upland nutrient pulse is transported into the RMZ, and (3) does partial cutting of the RMZ result in higher nutrient availability than if the RMZ is uncut? We addressed these questions using a planned, replicated harvesting experiment that manipulated upland and RMZ forest basal area and examined soil nutrient availability.

Methods

Study areas

We used four study sites in northern Minnesota, USA (Fig. 1*a*), that were part of a larger riparian management study to evaluate the long-term effectiveness of Minnesota's riparian management guidelines for sustaining water quality and stream habitat (Minnesota Forest Resources Council 2005; Blinn 2008). Sites were located within the Laurentian Mixed Forest Province, a broad ecotone between the eastern deciduous forest and boreal forest biomes (Minnesota Department of Natural Resources 2003). The area has a temperate climate with mean annual temperatures ranging from 1 to 4 °C and average annual precipitation ranging from 53 to 81 cm (Minnesota Department of Natural Resources 2003). Soils of the study sites originated from Pleistocene glacial tills (Keys et al. 1995) deposited in morainal complexes or till plains and included well-drained deep loamy sands in the uplands and sandy loams in lower landscape positions. Forest floor depths prior to harvesting ranged from 2.5 to 4 cm.

Fig. 1. (*a*) Map of study area locations in Minnesota, USA, (*b*) riparian–upland treatment combinations, and (*c*) transect and plot layout. UC-RC, upland control (uncut) – riparian control (uncut); UH-RC, upland harvest (clearcut) – riparian control; UH-RH, upland harvest (clearcut) – partial riparian harvest.



Forest stands of the study sites were second growth, developing after early 20th century logging, and were about 70 years old at the initiation of the study. Dominant tree species in the riparian forests included paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), balsam fir (*Abies balsamea* (L.) Mill.), black ash (*Fraxinus nigra* Marsh.), sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), and basswood (*Tilia americana* L.). Less common tree species included white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.), bigtooth aspen (*Populus grandidentata* Michx.), balsam poplar (*Populus balsamifera* L.), yellow birch (*Betula alleghaniensis* Britton), silver maple (*Acer saccharinum* L.), and eastern white pine (*Pinus strobus* L.). The upland forest was dominated by trembling aspen, with lesser amounts of paper birch, sugar maple, red maple, balsam fir, white spruce, basswood, and eastern white pine. Site index for trembling aspen (height at 50 years) ranged from 19 to 21 m among the four sites.

Treatments and experimental design

Each study site was treated as a block for statistical analysis because of their geographic distinctiveness. Each block consisted of three 3.3 ha (183 m by 183 m) treatment stands delineated on one side of the stream, with stands separated by at least 60 m of unharvested forest (Fig. 1*b*). Within each treatment stand, a 0.8 ha RMZ was delineated along the length of the stream (183 m) and extended 45 m towards the upland, a width that corresponded to recommended RMZ widths for even-age management in Minnesota (Minnesota Forest Resources Council 2005). The remainder of the treatment stand (2.5 ha) was outside the RMZ and considered as upland forest.

The following treatments were assigned to treatment stands: (1) a complete control: upland uncut – RMZ uncut (UC-RC), (2) a riparian control: upland clearcut – RMZ uncut (UH-RC), and (3) upland clearcut – RMZ partially harvested (UH-RH) to a target residual basal area of approximately 11.0 $m^2 \cdot ha^{-1}$. The tree retention levels tested in this study fell within the range of residual basal area values recommended for RMZs in Minnesota (Minnesota Forest Resources Council 2005). To lessen impacts of harvesting on streams (for other components of the larger study), treatment 1 (UC-RC) was always established upstream of harvest treatments, while the next treatment area downstream was assigned the UH-RC treatment followed by the UH-RH treatment (Fig. 1*b*). While this approach prevented random treatment assignment, it was necessary to satisfy the requirement of related aquatic research that was part of the broader project. We acknowledge that it may have biased results in some way. Timber harvesting operations were conducted by experienced operators on frozen ground when sufficient snow had accumulated during the winter of 2003–2004 using conventional harvesting equipment (feller-buncher and grapple skidder).

Vegetation plots

In each treatment stand, five transects were established running perpendicular to the average stream meander, originating at the stream bankfull edge and terminating in the upland (Fig. 1*c*). Five vegetation measurement plots were established on each transect; four plots (each 4.6 m wide by 7.6 m long = 35 m^2) were located within the RMZ beginning at the bankfull stream edge and one plot was located within the upland area (Fig. 1*c*). We felt that the upland forest at the stand scale was generally less variable in composition, topography, and soil condition compared with the RMZ such that one upland plot per transect was justified. The distance between RMZ plots varied because plots were constrained to be centered within one geomorphic position (i.e., floodplain, terrace, hillslope). The upland plot was always established 22.9–27.5 m from the RMZ–upland boundary. Each treatment stand contained a total of 25 plots (5 transects × 5 plots). Tree diameters were measured in each plot by recording diameter at breast height (at 1.4 m) on all stems ≥12.7 cm in diameter, which was the merchantable diameter used in the harvest. Measurements were taken once in the summer before harvesting and once in the summer after harvesting in all treatments.

Soil nutrient measurement

Soil nutrients were sampled using ion-exchange resins that capture nutrients by adsorption to charged particles and serve as indices of nutrient availability to plants (Montgomery et al. 2010). Approximately 10 g (wet mass) of Dowex Marathon MR-3 Mixed Bed (H-OH) resins were placed in nylon mesh bags and pre-treated with a 3 $mol \cdot L^{-1}$ HCl solution to remove any background nutrients. Washed bags were rinsed in an exchange bath of deionized water until a neutral pH was obtained. Resin bags were placed in situ just outside the right corner of the upstream edge of each plot. Nutrients were measured at two soil depths: one bag was placed 5 cm below the forest floor – mineral soil interface, which was consistently located within the A horizon, while the second bag was placed at varying depths but generally not exceeding a depth of 60 cm. The depth of the deeper bag depended upon the presence of a confining layer within the soil profile that would force water to typically flow laterally in the subsurface layers (i.e., fragipan, Bt horizon). To install resin bags below the rooting zone, a soil core was extracted using a perforated PVC casing designed to minimize soil disturbance. Resin bags were placed at the bottom of the core and both PVC and soil core were inserted back into the soil. Ion-exchange resins were placed at each plot in June 2004, extracted in October 2004 (153 day growing season deployment), immediately replaced with a new set of resin bags, and removed again in May 2005 (233 day dormant season deployment).

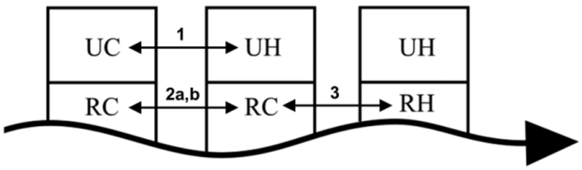
Nutrient analysis

Following removal, resin bags were rinsed in deionized water, dried to a constant mass, and cleared of any foreign objects. Dry resin mass was recorded. Absorbed nutrients were extracted from resins using 100 mL of a 2 $mol \cdot L^{-1}$ NaCl in 0.1 $mol \cdot L^{-1}$ HCl extractant that was passed through Whatman Ø glass microfibre filters. Extractants were stored at 3 °C until analyzed. Nutrient concentrations in the forms of ammonium, nitrate, and orthophosphate were determined for each sample by standard methods (Carter 1993) using a Lachat autoanalyzer (Lachat Instruments, Milwaukee, Wisconsin). Nitrate and ammonium concentrations were examined separately and also summed to give an index of total inorganic nitrogen availability (total inorganic nitrogen). Nutrient concentrations from all samples were less than the exchange capacity of the respective resin dry mass used. For comparative purposes, nutrients are reported as micrograms per gram of dry resin per 30 days for each deployment period. These values represent amount of nutrients that may be available to an equal mass of plant roots over a 30 day period.

Statistical analyses

We addressed our questions about soil nutrient availability using the following comparisons (Fig. 2). For Question 1 (Does clearcutting the upland, adjacent to an RMZ, increase

Fig. 2. Diagramatic representation of statistical comparisons and associated study questions. Question 1: harvested upland compared with unharvested upland, Question 2a, b: unharvested RMZ adjacent to unharvested upland compared with unhavested RMZ adjacdent to harvested upland, and Question 3: partially harvested RMZ compared with unharvested RMZ (both adjacent to harvested upland).



nutrient availability in the upland?), we compared nutrient responses for upland harvest plots with upland control plots. For Question 2 (Is there evidence that an upland nutrient pulse is transported into the RMZ?), we compared responses from riparian control plots that were to adjacent upland controls with responses from riparian control plots that were adjacent to upland harvests. In a second analysis for this question, we compared near-upland riparian plots (the plot immediately inside the RMZ–upland boundary) (Fig. 1*c*) of RMZs adjacent to uncut upland and RMZs adjacent to upland clearcuts. The rationale for this comparison was that a nutrient pulse from the upland may be detectable immediately inside the RMZ–upland boundary even if it is not detectable when examining the entire RMZ. For Question 3 (Does partial harvesting of the RMZ result in higher nutrient availability than if the RMZ is uncut?), we compared nutrient responses from uncut RMZs that were adjacent to upland harvests with responses from partially harvested RMZs that were adjacent to upland clearcuts. Treatment effects were analyzed separately for growing and dormant seasons. For both seasons, responses were analyzed separately by depth and also by pooling all samples between depths. A general linear models procedure was used to conduct analyses using SAS version 8.02 (SAS Institute Inc. 1999). A p value of 0.1 or less was considered significant. Some variables (Question 1: growing season total inorganic nitrogen, dormant season nitrate, and total inorganic nitrogen) were transformed with log (ln) transformations to meet the assumption of normality and to homogenize variances.

Results

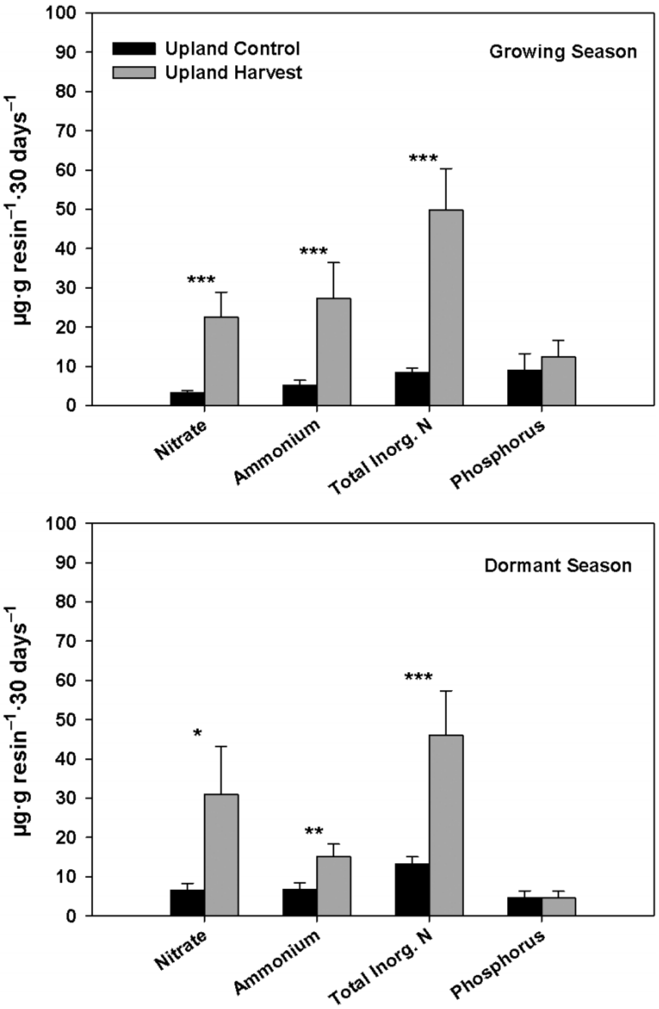
Change in forest structure

Generally, mean tree layer basal area (diameter ≥12.7 cm) was similar in the uplands, riparian controls, and partially harvested RMZs before treatment (21.4, 22.0, and 18.9 $m^2 \cdot ha^{-1}$, respectively). Harvesting in the upland clearcut was fairly complete, with only a small number of nonmerchantable trees left uncut (residual basal area = 1.5 $m^2 \cdot ha^{-1}$). Residual basal area in the partially harvested RMZs ranged from 5.4 to 15.5 $m^2 \cdot ha^{-1}$ among the four sites, averaging 11.2 $m^2 \cdot ha^{-1}$.

Question 1: Does clearcutting the upland, adjacent to an RMZ, increase nutrient availability in the upland?

Amounts of available ammonium, nitrate, and total inorganic nitrogen (pooled by soil depth) were all significantly greater ($p < 0.01$) in harvested uplands compared with upland controls during the growing season and dormant season (nitrate, $p < 0.1$; ammonium, $p < 0.05$; total inorganic nitrogen, $p < 0.01$) (Fig. 3). In contrast, phosphorus availability did not differ ($p > 0.1$) between harvested and unharvested uplands in either season (Fig. 3). The direction of differences between treatments, and significance levels, were the same when examined separately by depth for both seasons and values for nutrients between the two depths were similar (results not shown).

Fig. 3. Nutrient availability in unharvested and clearcut upland forest soils pooled by depth. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.



Question 2: Is there evidence that an upland nutrient pulse is transported into the RMZ?

Dormant season nitrate and total inorganic nitrogen were both significantly higher ($p < 0.05$) in RMZs that were adjacent to clearcut uplands compared with RMZs that were adjacent to unharvested uplands (Fig. 4). Nitrate and total inorganic nitrogen in the growing season, as well as ammonium and phosphorus availability in either season, did not differ ($p > 0.1$) between RMZs paired with unharvested uplands or clearcut uplands (Fig. 4). The direction of differences between treatments, and significance levels, were the same when examined separately by depth for both seasons (results not shown).

Fig. 4. Nutrient availability in unharvested RMZ soils, pooled by depth, that are adjacent to unharvested upland or clearcut upland forest. Significance level: $**p < 0.05$.

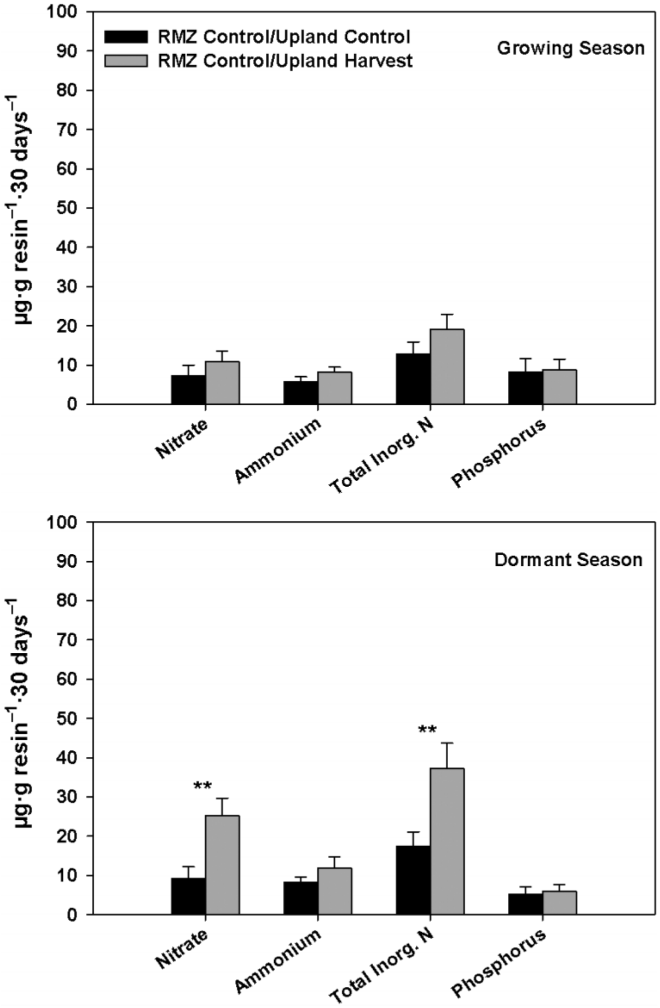
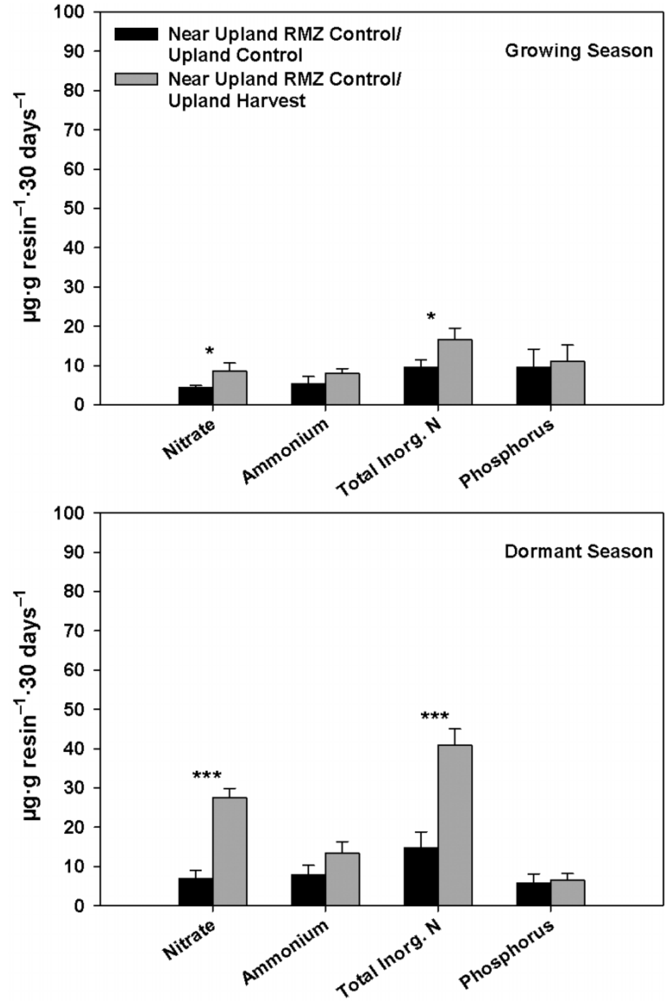


Fig. 5. Nutrient availability in soils, pooled by depth, of near-upland plots of unharvested RMZs that are adjacent to unharvested upland or clearcut upland forest. Significance levels: $***p < 0.01$, $*p < 0.1$.



Nitrate and total inorganic nitrogen availability (but not ammonium or phosporus) was also significantly greater in the growing season ($p < 0.1$) and dormant season ($p < 0.01$) in near-upland plots in unharvested RMZs that were paired with clearcut uplands than in RMZs paired with unharvested uplands (Fig. 5). Results were similar when examined separately by depth for both seasons (data not shown).

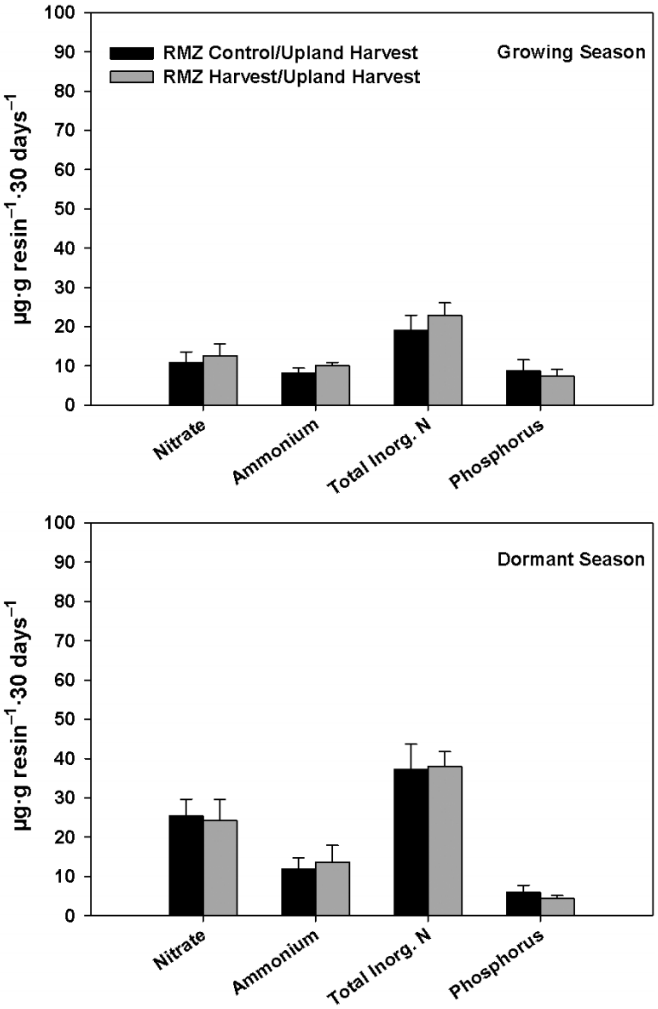
Question 3: Does partial harvesting of the RMZ result in higher nutrient availability than if the RMZ is uncut?

There were no significant differences ($p > 0.1$) in nitrogen or phosphorus availability in either season between partially harvested and unharvested RMZs (Fig. 6). The results were the same when examined separately by depth for both seasons (data not shown).

Discussion

Results from this study provide insight into the role of forested and partially harvested RMZs in regulating soil nutrient movement from the uplands. While much is known about this function in agricultural watersheds, considerably less is known from forested watersheds. We posed three questions to better clarify this function. First, we asked if clearcutting the upland, adjacent to an RMZ, increases nutrient availability in the upland forest? The impetus for this question was to determine whether there is a pulse of increased nutrient availability that potentially might be transported through the RMZ to the stream following upland harvesting, as has been found in other regions (Martin et al. 1986; Clinton 2011). Our results support this response for nitrogen. Availability of ammonium, nitrate, and total inorganic nitrogen was significantly greater in soils of clearcut uplands compared with uncut uplands. Phosphorus availability did not differ between treatments. Nitrogen availability in clearcuts were 4 to 5 times higher in the growing season and 3 to 6 times higher in the dormant season than in the control treatment. This suggests that a pulse of nitrogen may be available for translocation into the riparian area when uplands are clearcut, which is consistent with observations that clearcutting within forested ecosystems leads to higher rates of decomposition and increased net mineralization and nitrification (Hornbeck et al. 1990; Burns and Murdoch 2005). The magnitude of the increases that we detected are consistent with the expectation that upland harvesting can increase the potential for increased nutrient movement and leaching as well as increased stream

Fig. 6. Nutrient availability in unharvested RMZ soils, pooled by depth, and partially harvested RMZs adjacent to clearcut upland forest. No comparisons were significant at $p < 0.1$.



water nutrient concentrations (Holmes and Zak 1999; Briggs et al. 2000).

Second, we asked if there was evidence that an upland nutrient pulse is transported into the RMZ from the adjacent upland harvesting. Our results suggest that there was a moderate pulse that was restricted to the dormant season for nitrate (and total inorganic nitrogen) only. While there were small increases in the uncut riparian areas adjacent to clearcuts in the growing season, these differences were not significant. However, the results were more definitive with a restricted comparison of near-upland plots (just inside the RMZ boundary) adjacent to upland clearcuts. These results indicated a significant increase in both nitrate and total inorganic nitrogen in both the growing and dormant seasons (the dormant season increases were 2 to 3 times greater than growing season increases) in the RMZ edge, suggesting that a pulse of nitrate did move into the RMZ from the clearcut upland, but in the growing season, the plant community farther into the RMZ took up this nitrogen. This supports the observation that nitrate increases often occur within the first 5–20 m of the upland–riparian border but are reduced beyond this through uptake and (or) denitrification (Hill 1996).

Finally, we asked whether partial cutting of the RMZ resulted in higher nutrient availability than if the RMZ is uncut. Our results indicated that there was no difference with harvesting. Specifically, the amount of basal area reduction in our treatments was not extreme enough to reduce uptake compared with the uncut RMZ. Said another way, the range of residual basal areas used in this study was sufficient to maintain soil nutrient availability at levels similar to the uncut RMZ, a result that is perhaps surprising given results from studies that show significant increases in stream and soil nitrate concentrations with partial harvesting of magnitudes similar to our study (Wang et al. 2006; Siemion et al. 2011). We suspect that the disparate results might relate to different geologic conditions between study areas; watersheds in the cited studies were underlain by less permeable bedrock that likely reduced deep translocation of nutrients, whereas more of the latter may have occurred in our more permeable till-substrate watersheds. Differences may also be related to methodology. As such, we suggest that following up our study with more traditional approaches to examining nutrient fluxes through soil and into streams may be useful.

Management implications

The RMZ specifications (width and residual basal area) used in our study reflect recommendations included in voluntary forest management guidelines for Minnesota to protect water quality and riparian habitat (Minnesota Forest Resources Council 2005). Specifically, our RMZs were 45 m wide and when partially harvested retained an average of 11 $m^2 \cdot ha^{-1}$ of tree basal area. Our results indicate several important aspects about the effectiveness of these RMZ guidelines for regulating soil nutrient dynamics. First, upland clearcutting adjacent to an RMZ does release a pulse of nitrogen and some of it does move into the RMZ soil. Soil phosphorus availability is not increased by this harvesting. Second, this increase in soil nitrogen appears to be restricted to the upland boundary of the RMZ in the growing season but does appear to move farther into an uncut RMZ in the dormant season, when there is reduced plant uptake. Finally, the level of RMZ harvesting and retention that we used in this study did not result in an increase in nutrient availability, beyond what we found in uncut RMZs. Collectively, these results suggest that if the level of increased dormant season soil nitrate that we documented is acceptable from a stream water quality perspective, then RMZs managed similar to those in this study will be effective at sustaining riparian soil nutrient availability within an acceptable range of variation. In general, nitrogen is limiting to plants in temperate forests (LeBauer and Treseder 2008), so any increase, if it remains available for uptake in the growing season, may result in increased productivity in the riparian area (Brinson 1990; Naiman and Decamps 1997). However, we did not measure nitrogen concentration in the associated study streams, so we cannot speculate on the potential for increased dormant season nitrate to impact stream biota. Finally, the soil nutrient responses that we documented are likely short term. Reestablishment and rapid growth of woody vegetation cover will likely result in diminished nitrogen increases within about 5 years after harvesting, as shown by other studies (Mou et al. 1993; Clinton 2011).

Acknowledgements

The work was completed while D. Kastendick and E. Zenner were at the Department of Forest Resources, University of Minnesota. The authors would like to thank Dwight Streblow and Jeff Killmer for logistical and field support. Additionally, we appreciate the support of Rebecca Montgomery and the Forestry Sciences Laboratory, Grand Rapids, Minnesota, for laboratory support. Jeri Peck provided helpful comments on an earlier draft of this manuscript. This work was supported by the USDA Forest Service Northern Research Station, the University of Minnesota Department of Forest Resources, the Minnesota Agricultural Experiment Station (Projects MN 42-022 and 42-042), and the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources.

References

Blinn, C.R. 2008. Evaluating riparian timber harvesting guidelines: phase II. Final report to the Legislative Commission on Minnesota Resources. Available from http://www.lccmr.leg.mn/all_projects/2005_projects/2005_9d.pdf [accessed August 2012].

Blinn, C.R., and Kilgore, M.A. 2001. Riparian management practices: a summary of state guidelines. J. For. **99**: 11–17.

Boothroyd, I.K.G., Quinn, J.M., Langer, E.R., Costley, K.J., and Steward, G. 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams: 1. Riparian vegetation structure, stream geomorphology and periphyton. For. Ecol. Manage. **194**(1–3): 199–213. doi:10.1016/j.foreco.2004.02.018.

Briggs, R.D., Hornbeck, J.W., Smith, C.T., Lemin, R.C., Jr., and McCormack, M.L., Jr.. 2000. Long-term effects of forest management on nutrient cycling in spruce-fir forests. For. Ecol. Manage. **138**(1-3): 285–299. doi:10.1016/S0378-1127(00)00420-5.

Brinson, M.M. 1990. Riverine forests. *In* Forested wetlands. *Edited by* A.E. Lugo, M.M. Brinson, and S. Brown. Elsevier, Amsterdam and New York. pp. 87–141.

Burns, D., and Murdoch, P. 2005. Effects of a clearcut on the net rates of nitrification and N mineralization in a northern hardwood forest, Catskill Mountains, New York, USA. Biogeochemistry, **72**(1): 123–146. doi:10.1007/s10533-004-0355-z.

Carter, M.R. 1993. Soil sampling and methods of analysis. CRC Press, Boca Raton, Fl.

Clinton, B.D. 2011. Steam water responses to timber harvest: riparian buffer width effectiveness. For. Ecol. Manage. **261**(6): 979–988. doi:10.1016/j.foreco.2010.12.012.

Cooper, J.R., and Gilliam, J.W. 1987. Phosphorus redistribution from cultivated fields into riparian areas. Soil Sci. Soc. Am. J. **51**(6): 1600–1604. doi:10.2136/sssaj1987.03615995005100060035x.

Edwards, P.J., and Williard, K.W.J. 2010. Efficiencies of forestry best management practices for reducing sediment and nutrient losses in the eastern United States. J. For. **108**: 245–249.

Giese, L.A.B., Aust, W.M., Kolka, R.K., and Trettin, C.C. 2003. Biomass and carbon pools of disturbed riparian forests. For. Ecol. Manage. **180**(1–3): 493–508. doi:10.1016/S0378-1127(02)00644-8.

Governo, R., Lockaby, B.G., Rummer, B., and Colson, C. 2004. Silvicultural management within streamside management zones of intermittent streams: effects on decomposition, productivity, nutrient cycling, and channel vegetation. South. J. Appl. For. **28**: 211–224.

Hanson, G.C., Groffman, P.M., and Gold, A.J. 1994. Symptoms of nitrogen saturation in a riparian wetland. Ecol. Appl. **4**(4): 750–756. doi:10.2307/1942005.

Hazlett, P.W., Gordon, A.M., Voroney, R.P., and Sibley, P.K. 2007. Impact of harvesting and logging slash on nitrogen and carbon dynamics in soils from upland spruce forests in northeastern Ontario. Soil Biol. Biochem. **39**(1): 43–57. doi:10.1016/j.soilbio.2006.06.008.

Hazlett, P.W., Broad, K., Gordon, A.M., Sibley, P.K., Buttle, J.M., and Larmer, D. 2008. The importance of catchment slope to soil water N and C concentrations in riparian zones: implications for riparian buffer width. Can. J. For. Res. **38**(1): 16–30. doi:10.1139/X07-146.

Hill, A.R. 1996. Nitrate removal in stream riparian zones. J. Environ. Qual. **25**(4): 743–755. doi:10.2134/jeq1996.00472425002500040014x.

Holmes, W.E., and Zak, D.R. 1999. Soil microbial control of nitrogen loss following clearcut harvest in northern hardwood ecosystems. Ecol. Appl. **9**(1): 202–215. doi:10.1890/1051-0761(1999)009[0202:SMCONL]2.0.CO;2.

Hornbeck, J.W., and Kochenderfer, J.N. 2000. Linkages between forests and streams: a perspective in time. *In* Riparian management in forests of the continental eastern United States. *Edited by* E.S. Verry, J.W. Hornbeck, and C.A. Dolloff. Lewis Publishers and CRC Press LLC, Boca Raton, Fla. pp. 89–98.

Hornbeck, J.W., Smith, C.T., Martin, C.W., Tritton, L.M., and Pierce, R.S. 1990. Effects of intensive harvesting on nutrient capitals of three forest types in New England. For. Ecol. Manage. **30**(1–4): 55–64. doi:10.1016/0378-1127(90)90126-V.

Keim, R.F., and Schoenholtz, S.H. 1999. Functions and effectiveness of silvicultural streamside management zones in loessial bluff forests. For. Ecol. Manage. **118**(1–3): 197–209. doi:10.1016/S0378-1127(98)00499-X.

Keys, J.E., Jr., Carpenter, C.A., Hooks, S.L., Koeneg, F.G., McNab, W.H., Russell, W.E., and Smith, M.L. 1995. Ecological units of the eastern United States — first approximation. US For. Serv. Tech. Publ. R8-TP 21.

Knoepp, D., and Clinton, B.D. 2009. Riparian zones in southern Appalachian headwater catchments: carbon and nitrogen responses to forest cutting. For. Ecol. Manage. **258**(10): 2282–2293. doi:10.1016/j.foreco.2009.04.006.

LeBauer, D.S., and Treseder, K.K. 2008. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. Ecology, **89**(2): 371–379. doi:10.1890/06-2057.1. PMID:18409427.

Lowrance, R.R. 1992. Groundwater nitrate and denitrification in a coastal plain riparian forest. J. Environ. Qual. **21**(3): 401–405. doi:10.2134/jeq1992.00472425002100030017x.

Lowrance, R.R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correll, D.L., Gilliam, J.W., Robinson, J.L., Brinsfield, R.B., Staver, K.W., Lucas, W., and Todd, A.H. 1997. Water quality functions of riparian forest buffer systems in Chesapeake Bay watersheds. Environ. Manage. **21**(5): 687–712. doi:10.1007/s002679900060. PMID:9236284.

Martin, C.W., Pierce, R.S., Likens, G.E., and Bormann, F.H. 1986. Clearcutting affects stream chemistry in the White Mountains of New Hampshire. US For. Serv. Res. Pap. NE-579.

McBroom, M.W., Beasley, R.S., Chang, M., and Ice, G.G. 2008. Water quality effects of clearcut harvesting and forest fertilization with best management practices. J. Environ. Qual. **37**(1): 114–124. doi:10.2134/jeq2006.0552. PMID:18178884.

McClain, M.E., Boyer, E.W., Dent, C.L., Gergel, S.E., Grimm, N.B., Groffman, P.M., Hart, S.C., Harvey, J.W., Johnston, C.A., Mayorga, E., McDowell, W.H., and Pinay, G. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. Ecosystems (N.Y.), **6**(4): 301–312. doi:10.1007/s10021-003-0161-9.

Minnesota Department of Natural Resources. 2003. Field guide to the native plant communities of Minnesota: the Laurentian mixed forest province. Ecological Land Classification Program, Minnesota County Biological Survey, and Natural Heritage and Nongame Research Program. Minnesota Department of Natural Resources, St. Paul, Minn.

Minnesota Forest Resources Council. 2005. Sustaining Minnesota forest resources: voluntary site-level management guidelines for landowners, loggers and resource managers. Minnesota Forest Resources Council, St. Paul, Minn.

Montgomery, R.A., Reich, P.B., and Palik, B.J. 2010. Untangling positive and negative biotic interactions: views from above and below ground in a forest ecosystem. Ecology, **91**(12): 3641–3655. doi:10.1890/09-1663.1. PMID:21302835.

Mou, P.U., Fahey, T.J., and Hughes, J.W. 1993. Effects of soil disturbance on vegetation recovery and nutrient accumulation following whole-tree harvest of a northern hardwood ecosystem. J. Appl. Ecol. **30**(4): 661–675. doi:10.2307/2404245.

Naiman, R.J., and Decamps, H. 1997. The ecology of interfaces: riparian zones. Annu. Rev. Ecol. Syst. **28**(1): 621–658. doi:10.1146/annurev.ecolsys.28.1.621.

Peterjohn, W.T., and Correll, D.L. 1984. Nutrient dynamics in agricultural catchment: observation on the role of a riparian forest. Ecology, **65**(5): 1466–1475. doi:10.2307/1939127.

SAS Institute Inc.. 1999. SAS version 8.02. SAS Institute Inc., Cary, N.C.

Siemion, J., Burns, D.A., Murdoch, P.S., and Germain, R.H. 2011. The relation of harvesting intensity to changes in soil, soil water, and stream chemistry in a northern hardwood forest, Catskill Mountains, USA. For. Ecol. Manage. **261**(9): 1510–1519. doi:10.1016/j.foreco.2011.01.036.

Spoelstra, J., Schiff, S.L., Semkin, R.G., Jeffries, D.S., and Elgood, R.J. 2010. Nitrate attenuation in a small temperate wetland following forest harvest. For. Ecol. Manage. **259**(12): 2333–2341. doi:10.1016/j.foreco.2010.03.006.

Vitousek, P.M., and Melillo, J.M. 1979. Nitrate losses from disturbed forests: patterns and mechanisms. For. Sci. **25**: 605–619.

Wang, X., Burns, D.A., Yanai, R.D., Briggs, R.D., and Germain, R.H. 2006. Changes in stream chemistry and nutrient export following a partial harvest in the Catskill Mountains, New York, USA. For. Ecol. Manage. **223**(1–3): 103–112. doi:10.1016/j.foreco.2005.10.060.

Yeakley, J.A., Coleman, D.C., Haines, B.L., Kloeppel, B.D., Meyer, J.L., Swank, W.T., Argo, B.W., Deal, J.M., and Taylor, S.F. 2003. Hillslope nutrient dynamics following upland riparian vegetation disturbance. Ecosystems (N.Y.), **6**(2): 154–167. doi:10.1007/s10021-002-0116-6.