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STREAM NITROGEN RESPONSES TO FIRE IN THE SOUTHEASTERN U. S.

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Abstract: Fire can play a significant role in runoff, sediment yield, and nitrate transport in aquatic and terrestrial ecosystems in the southeast US. The typical impact of fire is an immediate change in the physical properties of the soil and forest floor surface, followed by mid- and long-term changes in biological pools and cycling processes. Depending upon the severity of the fire and pre-burn conditions, there is a potential for wildfire and prescribed burns to pose risks within the region to water quality. There has been little effort to specifically model the effects of prescribed burning and wildfire on water quality forest hydrology. Our approach was to combine field measurements and modeling to quantify the impacts of fire on water quality and hydrology in two sites characteristic of the mountain and piedmont regions of the southeastern US. We used the nutrient cycling model NuCM (Nutrient Cycling Model) as our platform for predicting ecosystem nitrogen response. Study sites were located in the Nantahala National Forest in the southern Appalachians and the Uwharrie National Forest in the piedmont region. Portable automated samplers were installed to sample stream water N; and soil solution lysimeters and overland flow collectors were installed to sample surface vs. subsurface N. We focused on inorganic nitrogen (NO_3-N, NH_4-N) in soil solution and streams draining the burned areas because they are key indicators of ecosystem response to disturbance and important water quality parameters. The Nantahala and Uwharrie sites were burned 7 and 5 months (respectively) after sampling began. NuCM was parameterized and calibrated with pre- and post-burn data from the Nantahala and Uwharrie sites. In addition, more severe and intense prescribed fires and wildfire scenarios were modeled by increasing fire effects on parameters that are directly or indirectly altered by fire. In general, both stream NO_3-N and stream NH_4-N concentrations were unaffected by prescribed fire at any level of intensity or severity. Slight increases in stream and soil solution NO_3-N concentration were observed under the wildfire scenario, but responses were well below levels of concern for aquatic resources and drinking water.

Key words: fire effects, water quality, nitrate, ammonium

Introduction

Fire has been a significant force shaping the structure and function of terrestrial ecosystems throughout much of the United States (U. S.). Throughout history, fires have originated from a mix of lightning and human caused ignitions. Pre-European settlement fire regimes varied considerably across the U. S. However, the onset of fire suppression early in the 20th century significantly reduced the role of fire in shaping the structure and function of forest ecosystems. A century of fire exclusion has resulted in a buildup of woody and fine fuels, increasing the risk of catastrophic wildfires, as well as altering ecosystems historically dependent on periodic wildfire for maintenance (Lorimer 1993, Clark *et al.* 1996, Brose *et al.* 2001). In many areas of the U. S., fuels management activities such as thinning and prescribed burning are being implemented to reduce wildfire risk and restore fire dependent ecosystems and species.

Although most ecosystems in the southern U. S. do not burn with a frequency or magnitude consistent with historic fire regimes, prescribed fire is used as a tool in many southern forest ecosystems to enhance overall stand health and productivity, and to reduce fuel loads (Sanders and Van Lear 1987, Van Lear and Waldrop 1989). The continued use of prescribed fire and potential for increased wildfire in the southern U. S. has raised considerable interest about the effects of fire on ecosystem integrity, and in particular, how it affects water quality. The typical impact of fire is an immediate change in the physical properties of the soil and forest floor surface, followed by mid- and long-term changes in biological pools and cycling processes. There is potential, depending upon the severity of the fire and pre-burn conditions, for wildfire and prescribed burns to pose risks to water quality (Neary and Currier 1982). However, there has been little effort to measure or model the effects of prescribed burning and wildfire on water quality across the southern U. S.

In this paper, we focus on the impacts of fire on N cycling pools and processes in two physiographic provinces in the southern U. S. The complexity of the interactions among fire intensity and severity, soils, vegetation, and environmental driving variables necessitated a modeling approach to evaluate potential responses. Our approach was to use prescribe burn field studies to parameterize and validate a detailed nutrient cycling model (NuCM; Liu *et al.* 1991), and then simulate varying fire intensities to determine the full range of potential N cycling responses. More specifically, we addressed the following questions: (1) what are the impacts of varying fire intensities on soil solution and stream nitrogen (NO_3-N and NH_4-N) concentrations, and (2) how does the magnitude of response vary between two southern U. S. physiographic provinces?

Materials and methods

Site Description

Three sites were chosen to represent the major physiographic regions (i. e., mountains, piedmont, and coastal plain) in the southern U. S. The coastal plain site was not burned as planned, so only the mountain and piedmont sites are reported in this paper. The mountain study site was located on the Robin Branch Watershed (drained by Robin Branch creek); a 120 ha mixed oak hardwood forest located in the Nantahala National Forest in the southern Appalachians of western North Carolina. Pre-burn data were collected 7 months prior to a prescribed burn. Approximately 30% (35 ha) of the watershed was burned in March, 2003 and post-burn data collection continued for 6 months. This site was burned using strip head fires ignited by drip torch. The burn was confined to the understory and consumed 18% of the forest floor mass. The fermentation and humus layers (Oe and Oa, respectively) were unaffected. The Piedmont site was located on the Rocky Creek Watershed (drained by Rocky Creek); a 240 ha mixed pine and hardwood forest on the Uwharrie National Forest in the Piedmont region of central North Carolina. Pre-burn data were collected for 5 months before the prescribed burn in March, 2003. Post-burn data collection continued for six months. The prescribed fire was set by helicopter and >90% of the watershed was burned. Fire intensity and severity were greater than the burn at the mountain site and removed 40% of the forest floor mass, including some fermentation and humus layer.

Field Measurements

Each site was instrumented with portable automated stream water samplers (American Sigma, Loveland, CO) programmed to take one stream sample per day, as well as record total daily streamflow. Daily streamflow samples were collected weekly and returned to the laboratory for chemical determinations. Porous cup lysimeters were installed at ten locations along the stream bank for soil water collection. A 30 cm and 60 cm slim tube lysimeter were installed at each location to measure soil solution chemistry at two depth layers. These were evacuated weekly at Robin Branch and biweekly at Rocky Creek. Ten overland flow collectors were installed at these same locations to determine the amount of runoff entering the stream system from upland areas.

Control sites were located near the treatment sites. Stream grab samples were taken from control sites on a weekly basis at Robin Branch, and a bi-weekly basis at Rocky Creek. All stream samples, soil solution samples and overland flow were analyzed for nitrate (NO_3-N) and ammonium (NH_4-N). Stream samples were composited on a weekly basis. Lysimeter samples were composited on a monthly basis. NO_3-N and NH_4-N concentrations were determined using Dionex ion chromatograph (Dionix, Sunnyvale, CO) and AutoAnalyzer alkaline phenol methods (Deal *et al.* 1996), respectively.

At each lysimeter location, a 30 cm and 60 cm deep soil sample was taken using a soil probe and placed in a plastic bag. These samples were stored in a cooler during transport back to the lab. Each sample was air-dried for 2–3 weeks, sieved and processed for cation concentrations. These sites and nearby locations were re-sampled immediately post-burn.

Forest floor components were sampled using a 0.3 x 0.3 m frame near each lysimeter location. The material within the frame was separated into 3 components: small wood (<7.5 cm), litter (Oi), and combined fermentation and humus (Oe + Oa) layer. Components were removed after cutting along the inside of the frame with a knife, placed in paper bags, dried for 72 hours at 60°C and weighed. Forest floor C and N were determined with a Perkin-Elmer 2400 CHN Analyzer (Deal *et al.* 1996). The same procedure was used for post-burn forest floor collection.

Nitrogen Cycling Model

The NuCM model was developed as part of the Electric Power Research Institute's Integrated Forest Study (Liu *et al.*, 1991). The model represents a forested ecosystem as a series of vegetation, litter and soil components. The soil includes multiple layers where each layer may have different physical characteristics. Tree growth potential is defined by the user and is subject to reduction in the event that nutrients or moisture become limiting. The model routes precipitation through the canopy and soil layers and simulates evapotranspiration, deep seepage and lateral flow. The processes governing interactions among nutrient pools include decay, nitrification, anion adsorption, cation exchange and mineral weathering (Johnson *et al.*, 1995).

The NuCM model was parameterized for Robin Branch and Rocky Creek using data from soil, stream and soil solution analysis, The National Climatic Data Center and The National Atmospheric Deposition Program according to procedures outlined in the user's manual (Liu *et al.*, 1991). This included site-specific physiographic, meteorological and atmospheric chemistry data, soil physical data, organic matter decay rates and nitrification rates. Other model parameters were set to default values typical for the specific forest type.

Once calibrated for each site with pre-burn or "initial state" data, we simulated a range of prescribed fire intensities and severities, as well as a severe wildfire. Our approach was to perform simulations under four scenarios: (1) actual (or inferred from the literature) post-burn conditions used to define model parameters, (2) actual post burn parameters changed by 25% (moderate intensity/severity prescribed burn), (3) actual post burn parameters changed by 75% (high intensity/severity prescribed burn), and (4) actual post burn parameters changed by 75%, plus complete overstory mortality, and high forest floor consumption (a severe wildfire). We parameterized post-burn conditions by decreasing standing and root biomass, monthly litterfall, the weight fraction of litter and humus and the C: N ratio, while increasing N mineralization, the amount of adsorbed and dissolved NH_4 in the top soil layer, the litter breakdown rate, and the soil nitrification rate. Initial post-burn conditions for soil, soil solution, litter, and stream chemistry were determined from actual measurements. Post-burn scenarios were run for 1 year.

Results and Discussion

Measured Responses: Effects of Fire on NO_3-N and NH_4-N Pools

Fire can result in changes in ecosystem N due to a combination of changes in chemical, physical, and biological processes that directly or indirectly influence N pools. For example, high severity fires can increase soil NH_4-N via a downward movement of volatilized organic N from surface soils and litter (Knoepp and Swank 1993, Klopatek *et al.* 1990). Changes in mineralization and nitrification (Knoepp and Swank 1993), organic matter pools (Vose and Swank 1993), and vegetation N uptake (Clinton *et al.* 2003) can further influence N pools. However, the magnitude and direction of response are highly variable. It is clear that the influence of fire on N pools is highly dependent on fire severity and the season of burn. For example, in southeastern ecosystems, low severity fires conducted in the late spring (just prior to leaf-out) often have very small or no impacts on overall ecosystem nutrient pools. For example, in pine/hardwood ecosystems of the southern Appalachians, Vose *et al.* (1999) found no changes in soil or stream NO_3-N or NH_4-N after a restoration burn of low severity. Similar results were observed after prescribed burning on Piedmont sites in South Carolina (Douglass and Van Lear 1983). Elevated levels of soil, soil solution, or stream N have occasionally been observed after high intensity or severity fires (e. g., site preparation or wildfire) (Clinton *et al.* 2003, Knoepp *et al.* 1993, Neary and Currier 1982). Conditions that promote elevated levels of stream N are (a) substantial consumption of the forest floor (Knoepp and Swank 1993, Neary and Currier 1982), (b) reduced vegetation N uptake via mortality or the timing of the burn (Clinton *et al.* 2003), and /or (c) post-burn rehabilitation procedures (e. g., fertilization) that add supplemental N to the ecosystem following a burn (Neary and Currier 1982). In our study, fires were prescribed burns conducted in the late spring, most of the forest floor remained intact, and no post-burn fertilizer was added. Post-burn measurements indicated that the combination of low intensity and severity fires, and the rapid flush of spring growth resulted in no measurable changes in soil, soil solution, or stream N (Table 1).

Table 1. Mean and standard error for pre- and post-burn prescribed fire nitrogen levels on Robin Branch and Uwharrie watersheds.

	Robin Branch						Uwharrie					
	Total N		NO_3^--N		NH_4^+-N		Total N		NO_3^--N		NH_4^+-N	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Forest Floor (%)												
Oi	0.877(0.02)	1.520(0.161)	NA	NA	NA	NA	0.811(0.03)	0.97(0.08)	NA	NA	NA	NA
Oe+Oa	1.37(0.04)	1.33(0.038)	NA	NA	NA	NA	0.994(0.04)	0.90(0.06)	NA	NA	NA	NA
Wood	0.519(0.04)	0.627(0.07)	NA	NA	NA	NA	0.30(0.05)	.042(0.05)	NA	NA	NA	NA
Soil ($mgkg^{-1}$)												
30 cm			0.044(0.02)	0.071(0.06)	4.04(0.6)	3.11(0.35)			0.017(0.004)	0.002(0.0005)	0.98(0.26)	0.73(0.08)
60 cm			0.016(0.007)	0.014(0.012)	2.89(0.46)	1.42(0.12)			0.007(0.002)	0.004(0.003)	0.90(0.24)	1.06(0.22)
Soil Solution (mgL^{-1})												
30 cm			0.007(0.003)	0.004(0.001)	0.015(0.005)	0.019(0.005)			0.013(0.003)	0.012(0.002)	0.12(0.03)	0.052(0.01)
60 cm			0.003(0.007)	0.004(0.001)	0.008(0.003)	0.004(0.001)			0.014(0.002)	0.01(0.003)	0.057(0.007)	0.05(0.02)
Overland Flow (mgL^{-1})			0.05(0.015)	0.623(0.25)	10.77(4.78)	20.44(6.98)			0.265(.124)	0.033(0.008)	1.54(0.76)	3.89(3.48)
Stream (mgL^{-1})			0.013(0.003)	0.015(0.002)	0.027(0.009)	0.012(0.004)			0.004(0.003)	0.005(0.001)	0.034(0.004)	0.038(0.009)

Simulated Responses: Effects of Varying Fire Intensity/Severity on NO_3-N and NH_4-N in Soil and Stream Water

Measured response parameters from the prescribed burns clearly indicated that the low intensity and severity burns did not have an appreciable impact on soil or stream NO_3-N or NH_4-N in the mountain and piedmont sites we evaluated. Evaluating a larger range of fire intensities at the watershed scale is a difficult task. However, information on ecosystem response to different prescribed fire intensities/severities as well as for wildfire is important to land managers evaluating burning prescriptions and fuel management treatments to reduce wildfire risk. Instead of implementing a wider range of field studies, we used a modeling approach to expand our evaluation of N responses to varying fire intensity and severity on the two sampled field sites

Soil Solution–For the pre-burn period (i. e., 7 months prior to burning at Robin Branch and 5 months at Uwharrie), the model over predicted soil solution NO_3-N. However, post NO_3-N burn predictions compared well with measured data at both sites (Figs. 1a & 1b). Post-burn NO_3-N concentrations were very low (i. e., < 0.1 $mg{\cdot}L^{-1}$) and not affected by the prescribed burns (Figs. 1a & 1b). The intra-annual variation in soil solution NO_3-N simulated by NuCM during the pre-burn period was not reflected in the actual pre-burn measurements at either site. The model predicted higher NO_3-N soil solution concentrations during the winter months when vegetation uptake is low. However, actual measurements showed very low NO_3-N concentrations in all months and no intra-annual pattern (Figs. 1a & 1b). Three factors could account for these discrepancies in NO_3-N levels and seasonal variability. First, the model could be under-representing the role of vegetation uptake (especially during winter months) in regulating soil solution NO_3-N availability. Second, the model could be under-representing the role of microbial and physio-chemical processes in NO_3-N immobilization, and third, the model could be over-representing microbial processing of NH_4-N to NO_3-N.

For soil solution NH_4-N, measured concentrations (pre and post-burn) at both sites were low (e. g., < 0.2 mg NH_4-$N{\cdot}L^{-1}$) and did not increase after burning (Figs. 2a & 2b). At both sites, the model predicted much lower values of NH_4-N in soil solution than what was measured (Fig. 2a & 2b). These results suggest that NuCM components regulating NH_4-N pools and cycling are not well characterized and further model refinements may be required to adequately model NH_4-N on these sites. It should be noted that measured and modeled NH_4-N concentrations were both very low and it would likely be difficult for any model (or a refined version of NuCM) to accurately simulate dynamics at such a low concentration level.

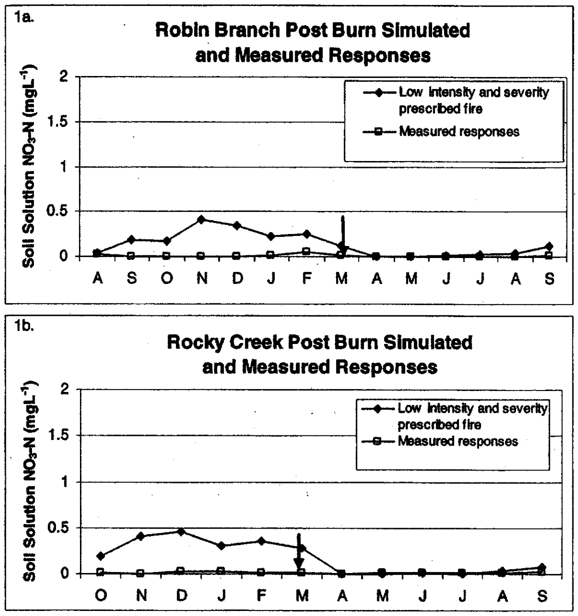

Fig. 1. Simulated soil solution NO_3-N responses and measured solution NO_3-N responses from the mountain (a) and piedmont (b) sites. Arrows denotes the months when the sites were burned.

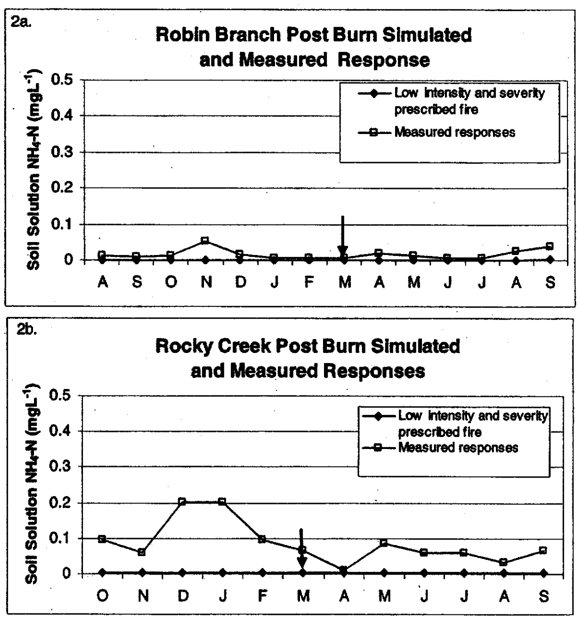

Fig. 2. Simulated soil solution NH_4-N responses and measured solution NH_4-N responses for the mountain (a) and piedmont (b) sites. Arrows denotes months when the sites were burned.

Simulated soil solution NO_3-N responses to increasingly severe and intense prescribed fire were comparable to the low intensity and severity responses at both sites (Fig. 3a & 3b). Although conclusions are dependent on the ability of the model to accurately simulate N cycling responses to fire, these results indicate that soil solution NO_3-N is not impacted by increasingly intense and severe prescribed fire at these sites, as characterized by our changes in model parameters. If the results of the simulation are generally correct, then altering burn prescriptions for specific management goals, such as increased fuel reduction, may have little impact on soil solution NO_3-N. By contrast, results from simulations of a severe wildfire (i. e., 100% overstory mortality and loss of organic matter in the forest floor) indicate the potential for relatively large increases in soil solution NO_3-N at both sites (Fig. 3a & 3b). The most obvious significance of increased soil solution NO_3-N is a threat to surface water quality and associated biota. However, the inherently low N availability in both ecosystems types limits the magnitude of potential N responses.

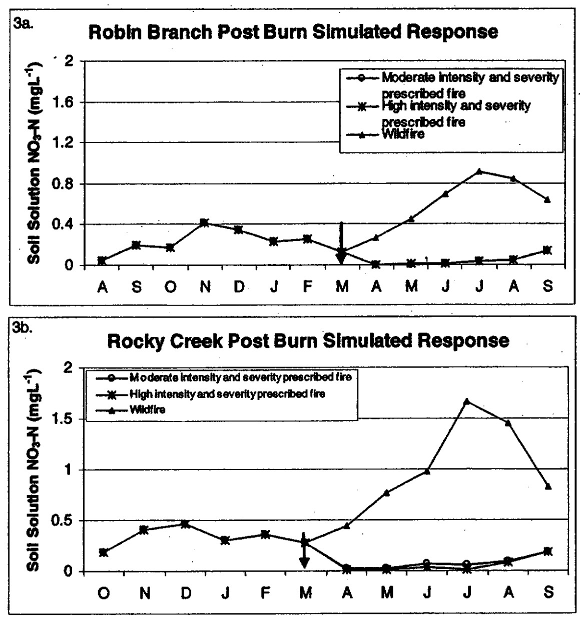

Fig. 3. Simulated soil solution NO_3-N responses for three fire intensity and severity scenarios for mountain (a) and piedmont (b) sites. Arrows denote month where fire effects were initiated in the model.

Soil solution NH_4-N was not impacted by any of the modeled fire scenarios (Figs. 4a & 4b). Similar to the conclusions evaluating responses to the actual fire, this may reflect a weakness in the NuCM model to adequately simulate NH_4-N responses to fire, or, poor representation of affected response parameters in our model formulation.

Stream Water - For stream water, both measured and modeled NO_3-N concentrations were extremely low (Figs. 5a & 5b) at both the mountain and Piedmont sites. Measured values were near the detection limits, and modeled values were only slightly higher (< 0.1 mg NO_3-$N{\cdot}L^{-1}$) (Fig. 5b). Several factors may explain the lack of either measured or simulated stream NO_3-N response. Both sites were burned in early spring and fires were confined primarily to the understory and forest floor. As a result, there was generally no overstory mortality to prevent the rapid vegetation N uptake and immobilization of soil nutrients typical of the spring growth flush. In addition, fires were of a low enough intensity to prevent significant overland flow and movement of nutrients off-site via physical changes in hydrologic processes. In terms of simulated responses, the model predicted slightly greater stream NO_3-N concentrations than were measured. This pattern is similar to the pattern observed in soil solution NO_3-N, and may reflect weaknesses in model components regulating stream water NO_3-N dynamics.

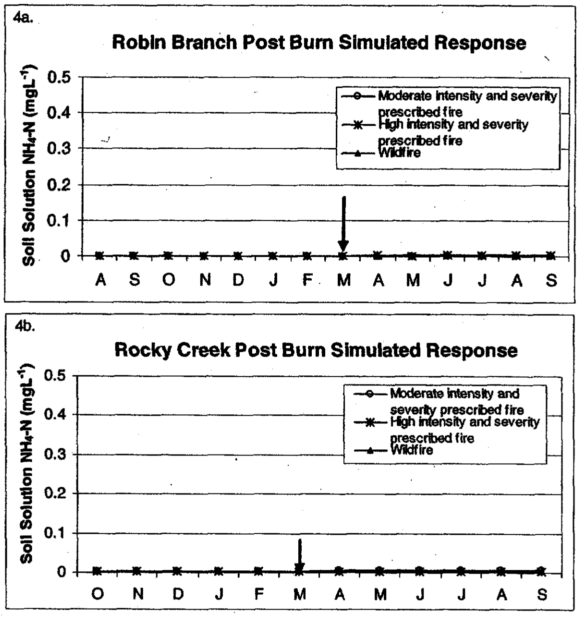

Fig. 4. Simulated soil solution NH_4-N responses for three fire intensity and severity scenarios for mountain (a) and piedmont (b) sites. Arrows denote month where fire effects were initiated in the model.

Both (pre-burn and post-burn) measured and modeled stream NH_4-N concentrations were low (< 0.1 mg NH_4-N·L^{-1}) (Figs. 6a & 6b). Like the patterns observed with soil solution NH_4-N, measured stream NH_4-N was always greater than predicted stream NH_4-N. Because the movement of soil solution to the stream is one of the primary factors driving stream chemistry, soil solution and stream NH_4-N should be related to each other (i. e., low soil solution nutrient concentration equals low stream nutrient concentration). The lack of measured stream water NH_4-N response (Figs. 8a and 8b) suggests that low intensity and severity fires characteristics of these two burns are unlikely to result in measurable increases in stream NH_4-N. Similar results have been observed in other southeastern regional assessments of stream NH_4-N response to fire (Neary and Currier 1982). Neary and Currier (1982) observed no increase in stream NH_4-N after a wildfire and concentrations on both control and burned watersheds were quite low (i. e., 0.002 to 0.005 mg NH_4-N·L^{-1})

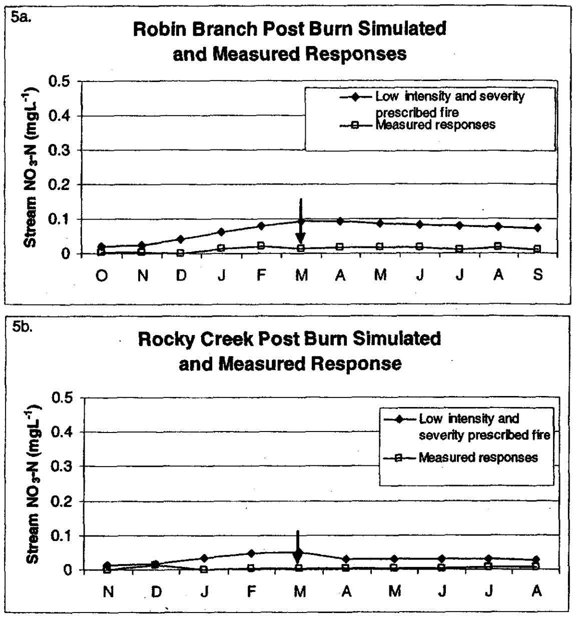

Fig. 5. Simulated stream NO_3-N responses and measured stream NO_3-N responses from the mountain (a) and piedmont (b) sites. Arrows denotes the months when the sites were burned.

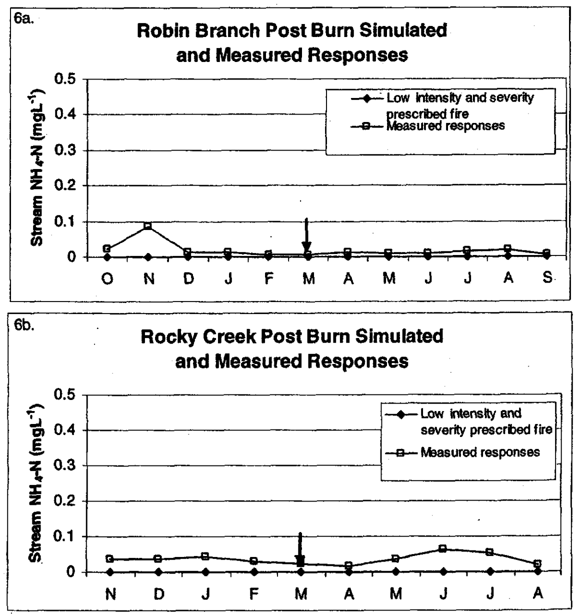

Fig. 6. Simulated stream NH_4-N responses and measured stream NH_4-N responses for the mountain (a) and piedmont (b) sites. Arrows denotes months when the sites were burned.

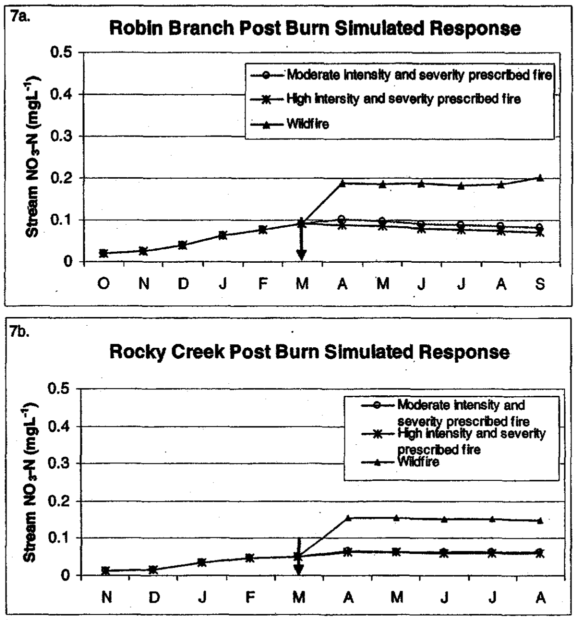

Fig. 7. Simulated stream NO_3-N responses for three fire intensity and severity scenarios for mountain (a) and piedmont (b) sites. Arrows denote month where fire effects were initiated in the model.

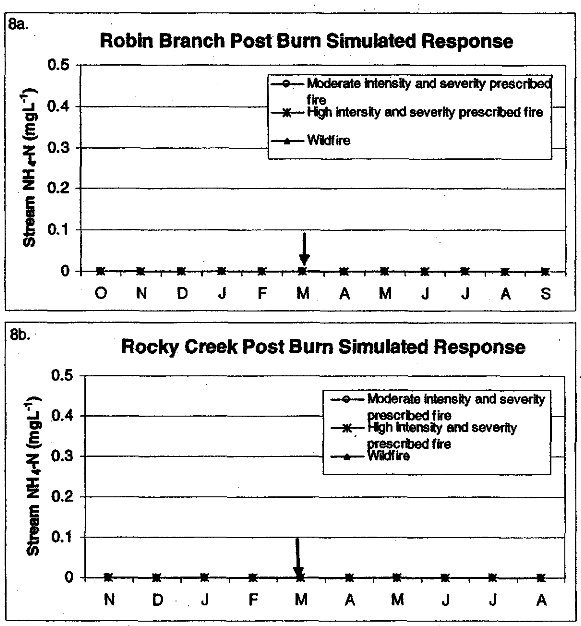

Fig. 8. Simulated stream NH_4-N responses for three fire intensity and severity scenarios for mountain (a) and piedmont (b) sites. Arrows denote month where fire effects were initiated n the model.

At both the mountain and piedmont sites, simulated stream NO_3-N concentrations did not change significantly with increased prescribed fire severity and intensity (Figs. 7a & 7b). However, at both sites, there was a significant increase in stream NO_3-N under the wildfire scenario. The most likely causal mechanism for the simulated increase in NO_3-N concentration is reduced uptake (wildfire = 100% overstory mortality). It is important to note that while the increase appears quite dramatic, these simulated stream NO_3-N concentrations have been generated by NuCM under conditions of extreme fire effects. Despite the extreme fire effects, NO_3-N concentrations are still quite low, and well below levels associated with degraded surface water quality (e. g., drinking water standard for North Carolina = 10 NO_3-N $mg{\cdot}L^{-1}$). The inherently low ambient N availability of both of these study areas is a likely contributing factor to the low stream NO_3-N concentrations observed and simulated by NuCM. Other studies measuring stream NO_3-N response to wildfire or high intensity/severity site preparation burns have shown small (e. g., concentrations < 0.20 mg NO_3-$N{\cdot}L^{-1}$), but detectable responses (Neary and Currier 1982, Knoepp and Swank 1993, Clinton *et al.* 2003), while lower intensity/severity prescribed fires have often shown no response (Douglass and Van Lear 1983, Vose *et al.* 1999, Clinton *et al.* 2003).

Conclusions

Post-burn measurements from this study and others, coupled with the NuCM simulations, suggest that the impacts of a varying range of fire intensities (from low to high; prescribed fire and wildfire) on inorganic stream and soil solution nitrogen levels (NO_3-N and NH_4-N) are of minor importance in both mountain and piedmont regions (Figs. 1–8; a-b). The general correspondence between field measurements and modeled data across a full range of fire effects adds confidence to the conclusions. However, more study areas, especially in areas that have greater ambient N availability, will be required to further validate these conclusions. In addition, it is possible that other water quality parameters not measured or modeled here, such as sediment or temperature, may respond to fire intensity or severity levels that pose risks to water quality.

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