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

James M. Vose
USDA Forest Service, Southern Research Station, Coweeta Hydrologic Lab, Otto NC 28763.

Stephanie H. Laseter
USDA Forest Service, Southern Research Station, Coweeta Hydrologic Lab, Otto NC 28763.

Ge Sun
USDA Forest Service, Southern Research Station, Global Change Program, Raleigh NC 27602.

Steve G. McNulty
USDA Forest Service, Southern Research Station, Global Change Program, Raleigh NC 27602.

I. ABSTRACT

Fire can play a significant role in runoff, sediment yield and nutrient transport from aquatic and terrestrial ecosystems in the southeast US. Hydrologic and nutrient cycling interactions with fire are likely to vary considerably across the physiographic regions of the southern U.S.; however, there have been few large comparative studies. Our approach was to combine field measurements and modeling to quantify the impacts of fire on water quality and hydrology at three sites characteristic of the mountain, piedmont and coastal plain regions of the southeastern U.S. We used the nutrient cycling model NuCM (Nutrient Cycling Model) as our platform for predicting nutrient response. Study sites were located in the Nantahala National Forest in the southern Appalachians, the Uwharrie National Forest in the piedmont region and the Croatan National Forest in the coastal plain region.

We focused on inorganic nitrogen (NO_3, NH_4) because it acts as a key indicator of ecosystem response to disturbance and are important water quality parameters. NuCM was parameterized and calibrated with pre-burn data from the three 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 NO_3-N and NH_4-N concentrations were unaffected by prescribed fire at any level of intensity or severity.

II. INTRODUCTION

Fire has been a significant force shaping the structure and function of terrestrial ecosystems throughout much of the United States. These fires have originated from a mix of lightning and human caused ignitions. A century of fire exclusion has resulted in a buildup of woody and fire 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. 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.

We determined the impacts of fire on N cycling pools and processes in three 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. We used prescribe burn field studies to parameterize and validate a detailed nutrient cycling model (NuCM,; Liu et al. 1991), and then simulated varying fire intensities (from low to high severity and intensity) to determine the full range of potential N cycling responses. 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 three southern U.S. physiographic provinces?

III. MATERIALS AND METHODS

Site Description

Three sites were chosen to represent the major physiographic regions (mountains, piedmont, and coastal plain) in the southern U.S. 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 prior to a prescribed burn in March, 2003. Post-burn data collection continued for 6 months. The fire was set by helicopter and >90% of the watershed was burned. Fire intensity and severity were greater than the mountain burn and removed 40% of the forest floor mass, including some fermentation and humus layer. The Coastal Plain site was located on the Holston Creek Watershed (drained by Holston Creek); a 160 ha mixed longleaf pine and hardwood forest on the Croatan National Forest in the coastal plain region of North Carolina. Pre-burn data were collected for 6 months prior to a prescribed burn in January, 2005. Post-burn data are currently being collected and only the first month of post-burn response is presented in the paper. Approximately 75% of the watershed was burned using strip head fires, back fires and flank fires ignited by drip torch and removed 30% of the forest floor mass, including some fermentation and humus layer.

Field Measurements
Each site was instrumented with portable automated samplers (American Sigma, Loveland, CO) programmed to take one sample per day, as well as record total daily streamflow. A 30 cm and 60cm slim tube lysimeter were installed at ten locations along the stream bank for soil water collection at two depth layers. Ten overland flow collectors were installed at these same locations to determine the amount of surface runoff entering the stream system from upland areas. All stream samples, soil solution samples, and overland flow were analyzed for nitrate (NO_3-N) and ammonium (NH_4-N).

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 sieved and processed for nitrogen (NO_3-N, and NH_4-N) and 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, Rocky Creek and Holston 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 NH4 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.

IV. 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. The influence of fire on N pools is highly dependent on fire severity and the season of the burn. In our study, 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 N pools or processes, and hence little response in soil solution or stream N (Table 1). In other studies conducted in southeastern ecosystems, low severity fires conducted in the late spring (just prior to leaf-out) also documented 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 a Piedmont site in South Carolina (Douglass and Van Lear 1983).

Simulated Responses: *Soil Solution Nitrogen*
For the pre-burn period, the model over predicted soil solution NO_3-N. However, post NO_3-N burn predictions compared well with measured data at both sites. Post-

burn NO_3-N concentrations were very low (<0.1 mg L^{-1}) and not affected by the prescribed burns. 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. 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 all sites were low (<0.2 mg L^{-1}) and did not increase after burning. At both sites, the model predicted much lower values of NH_4-N in soil solution than what was measured. 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_3-N concentrations were both very low and it would likely be difficult for any model (or a refined versions of NuCM) to accurately simulate dynamics at such a low concentration level.

Simulated soil NO_3-N responses to increasingly severe and intense prescribed fire were comparable to the low intensity and severity responses at both sites. Although conclusions are dependent on the ability of the model to accurately simulate N cycling responses to fire, these results indicated 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 (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. 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 the different ecosystem types limits the magnitude of potential N responses.

Soil solution NH_4-N was not impacted by any of the model fire scenarios. 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 Nitrogen

For stream water, both measured and modeled NO_3-N concentrations were extremely low at all sites. Measured values were near the detection limits, and modeled values were only slightly higher (<0.1 mg L^{-1}). Several factors may explain the lack of either measured or simulated stream NO_3-N response. Two 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.

Both (pre and post-burn) measured and modeled stream NH_4-N concentrations were low (<0.1 mg L^{-1}). 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 (low soil solution nutrient concentration equals low stream nutrient concentration). The lack of measured stream water NH_4-N response suggests that low intensity and severity fire characteristics of these 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 (0.002 to 0.005 mg NH_4-N L^{-1}).

At all sites, simulated stream NO_3-N concentrations did not change significantly with increased prescribed fire severity and intensity. However, 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 (drinking water standard for North Carolina= 10 NO_3-N L^{-1}). The inherently low ambient N availability of these study sites is a likely contributing factor to the low stream NO_3-N concentrations observed and simulated by NuCM. Other studies measuring NO_3-N response to wildfire or high intensity/severity site preparation burns have shown small (concentrations <0.2 mg NO_3-N 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).

V. 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. 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.

	STREAM ($mg^{-1}L$)				SOIL SOLUTION ($mg^{-1}L$)			
	NO_3^--N		NH_4^+-N		NO_3^--N		NH_4^+-N	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Mountains	0.01(0.003)	0.016(0.001)	0.018(0.009)	0.012(0)	0.005(0.003)	0.004(0.001)	0.01(0.005)	0.013(0.006)
Piedmont	0.004(0.003)	0.005(0.001)	0.034(0.004)	0.038(0.009)	0.013(0.003)	0.012(0.002)	0.12(0.03)	0.052(0.01)
Coastal Plain	0.008(0.003)	0.001(0)	0.166(0.05)	0.587(0)	0.02(0.007)	0.02(0.004)	0.096(0.02)	0.07(0.03)

Table 1. Mean and standard error for pre- and post-burn prescribed fire nitrogen levels.

REFERENCES

Brose, P., Schuler, D. Van Lear, D. and Berst, J. 2001. Bringing back fire: the changing regimes of the Appalachian mixed-oak forests. Journal of Forestry, 99, 30-35.

Clark, J.S., Royall, P.D. and Chambley, C. 1996. The role of fire during climate changes in an eatern deciduous forest at Devil's Bathtub, New York. Ecology, 77, 2148-2166.

Clinton, B.D., Vose, J.M., Knoepp, J.D., and Elliott, K.J. 2003. Stream nitrate response to different burning treatments in southern Appalachian forests. Pages 174-181 in K.E.M. Galley, R.C. Klinger, and N.G. Sugihara (eds.). Proceedings of Fire Conference 2000: The First National Congress on Fire Ecology, Prevention and Management. Miscellaneous Publication No. 13, Tall Timbers Research Station, Tallahassee, FL.

Douglass, J.E. and Van Lear, D.H. 1983. Prescribed burning and water quality of ephemeral streams in the piedmont of South Carolina. Journal of Forest Science, 29(1), 181-189.

Johnson, D.W., Swank, W.T. and Vose, J.M. 1995. Effects of liming on soils and streamwaters in a deciduous forest: Comparison of field results and simulations. Journal of Environmental Quality, 24, 1105-1117.

Klopatek, J.M., Klopatek, C.C. and DeBano, L.F. 1990. Potential variation in nitrogen transformations in pinyon-juniper ecosystems resulting from burning. Biology and Fertility of Soils, 10, 35-44.

Knoepp, J.D. and Swank, W.T. 1993. Site preparation burning to improve southern Appalachian opine-hardwood stands: Nitrogen responses in soil, soil water and streams. Canadian Journal of Forest Research, 23, 2263-2270.

Liu, S., Munson, R., Johnson, D.W., Gherini, S., Summer, K., Hudson, R., Wilkinson, K., and Pitelka, L. 1991. Applications of a nutrient cycling model (NuCM) to northern mixed hardwood and southern coniferous forest. Tree Physiology, 9, 173-182.

Lorimer, C.G. 1993. Causes of the oak regeneration problem. In: D. Loftis and C.E. McGee (eds.), Oak Regeneration: Serious problems, practical recommendations. USDA Forest Service Technical Report SE-84, Asheville, NC. 20 pp.

Neary, D.J., and Currier, J.B. 1982. Impact of wildfire and watershed restoration on water quality in South Carolina's Blue Ridge Mountains. Southern Journal of Applied Forestry, 6(2), 81-90.

Vose, J.M., Swank, W.T., Clinton, B.D., Knoepp, J.D., and Swift, L.W. 1999. Using stand replacement fires to restore southern Appalachian pine-hardwood ecosystems: effects on mass, carbon and nitrogen pools. Forest Ecology and Management, 114, 215-226.

Vose, J.M., and Swank, W.T. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: aboveground biomass, forest floor mass, and nitrogen and carbon pools. Canadian Journal of Forest Research. 23, 2252-2262.

BIOGRAPHY

Stephanie H. Laseter

Hydrologist with the US Forest Service at Coweeta Hydrologic Lab in Otto, North Carolina

B.S. from Auburn University in Wildlife Biology, M.S. from University of Georgia in Forest Resources