

Fire Disturbance and Nitrogen Deposition Impacts at the Watershed Scale in Southern California

Thomas Meixner, Mark E. Fenn, Peter M. Wohlgemuth

Abstract

The mountains of southern California have some of the highest rates of atmospheric deposition in the world. Over the last two decades a consistent picture of unusually high levels of nitrate in streams has been painted using field sites at the San Dimas Experimental Forest (SDEF) and across southern California. Within the context of southern California, three major processes appear to drive the observed variability in nitrate concentrations in streams. First, chronic atmospheric nitrogen deposition leads to high nitrate concentrations. Second, the profound inter-annual variability in rainfall drives nitrate concentrations in streams. Wet years produce a more thorough flushing of nitrate from the watershed resulting in higher nitrate concentrations compared to dry years. Third, fire is a critical process for most ecosystems in southern California; its impacts vary from vegetation and hydrologic consequences to more subtle impacts on biogeochemical fluxes. The results of a prescribed fire experiment in 1984 at the San Dimas Experimental Forest indicate that fire initially causes elevated stream nitrate concentrations but that over the longer term watersheds with more frequent fire have lower nitrate export. This longer term decrease after fire is likely due to losses of nitrogen to the atmosphere during burning and to surface water export in sediment and dissolved load in the immediate post-fire environment. These losses are then followed by rapidly aggrading vegetation during the ensuing years of post-fire recovery that provides a sink for nitrate originating from either atmospheric deposition or N mineralization/nitrification.

Meixner is an Assistant Professor, University of California, Riverside, CA 92521. E-mail: tmeixner@mail.ucr.edu. Fenn is a Research Scientist and Wohlgemuth is a Hydrologist and Manager of the San Dimas Experimental Forest, both at the U.S. Forest Service, PSW-Riverside Fire Lab, Riverside, CA 92507.

Keywords: nitrogen deposition, nitrogen saturation, chaparral, Mediterranean climate, fire response and recovery

Introduction

Atmospheric nitrogen deposition can adversely impact terrestrial and aquatic ecosystems through fertilization and acidification of ecosystems (Stoddard 1994, Aber et al. 1998, Fenn et al. 1998). The mountains of southern California receive some of the highest rates of atmospheric deposition in the world ($\sim 35 \text{ kg ha}^{-1} \text{ year}^{-1}$) (Bytnerowicz et al. 1987). While the ecosystems downwind of the southern California metropolis are impacted by these high rates of deposition, the consequence of soil and aquatic ecosystem acidification is not generally one of the most critical problems (Fenn et al. 2003). Instead terrestrial and aquatic ecosystems in southern California are most affected by the fertilization effects of atmospheric nitrogen deposition and by the concurrent increase in stream NO_3^- concentrations (Meixner and Fenn 2003).

The response of ecosystems to increased atmospheric nitrogen deposition is not linear and can be affected by any number of factors including: history of disturbance, rate of atmospheric nitrogen deposition, climate, and ecosystem structure (Fenn et al. 1998). Among the types of disturbance that can effect long term ecosystem response to atmospheric nitrogen deposition are logging activities, wind blowdowns and fire (Vitousek et al. 1979, Lovett et al. 2000). Of these disturbances fire in particular is not well studied especially in terms of its long-term impact on ecosystem dynamics and biogeochemical fluxes (Wan et al. 2001). Given the current interest in re-introducing fire on the landscape as a land management practice, it will be important to understand the impact of fire on long-term

biogeochemical fluxes from many types of ecosystems.

The San Dimas Experimental Forest offers an opportunity to investigate the long-term impact of fire on biogeochemical fluxes. Several natural burns have occurred in the last century as well as several prescribed burns conducted for research projects. The forest is impacted by high rates of deposition and the chaparral ecosystem of the forest has a quick recovery from fire, reaching climax structure in as little as 40 years. This pattern of rapid recovery to climax offers an opportunity to investigate the short and long-term impacts of fire on an ecosystem during a reasonable period of time as opposed to the much longer-term recovery from disturbance that occurs in more humid ecosystems. Additionally the highly variable annual precipitation of southern California offers an opportunity to investigate the impacts of climatic forcing on biogeochemical fluxes.

This paper answers three questions:

- 1) How do biogeochemical fluxes from a chaparral ecosystem respond after a fire and as the ecosystem recovers over the following 15 years?
- 2) What is the effect of inter-annual variability in precipitation on biogeochemical fluxes?
- 3) What part might fire management have in controlling the impacts of atmospheric deposition on chaparral ecosystems?

Methods

Site description

The San Dimas Experimental Forest (34° 12' N, 117° 40' W) was established in 1934 to study the interaction between chaparral ecosystems and water availability (Figure 1). The forest is subject to dramatic variation in annual precipitation and frequent wildfires (Meixner and Wohlgemuth this volume). Chaparral watersheds supply much of the groundwater recharge in southern California and it is one of the most extensive ecosystems in the American Southwest. In 1984 several prescribed burns were conducted that were intended to study the effect of fire on watershed hydrology, water quality and sediment transport (Riggan et al. 1994). These experiments took place against a backdrop of very high rates of atmospheric deposition (Riggan et al. 1985) and an existing disturbance history, as fire is a dominant ecosystem process in chaparral catchments

(Minnich and Bahre 1995). This paper focuses on comparing nitrogen export from two catchments, Bell 3 (25.1 ha) which last burned in a wildfire in 1960 and represents a control and Bell 4 (15.9 ha) which was burned in the same wildfire and then burned under prescribed conditions in October of 1984 (Riggan et al. 1994). The data reported in this paper covers the time period from the fall of 1987 until the fall of 2001.

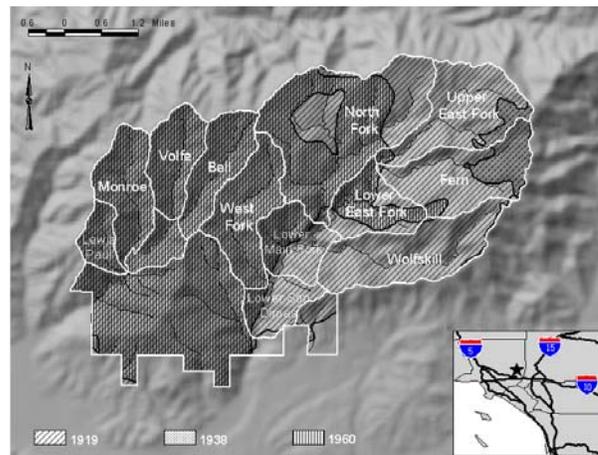


Figure 1. Location, catchment delineation and fire perimeters for the San Dimas Experimental Forest.

Water quality and streamflow measurement

Stream water samples were collected as often as four times daily using ISCO water samplers. Each sample was analyzed for NO_3^- using a Technicon AutoAnalyzer II. Based on past studies at San Dimas, stream concentrations of NO_3^- are equivalent to inorganic nitrogen flux since NH_4^+ concentrations are typically not detectable. Annual export and volume weighted mean (VWM) concentrations were calculated by integrating concentration values with streamflow. Streamflow in each catchment was monitored continuously using electronic data loggers with paper charts as backups. Streamflow records have only been quality checked for some of the years. For these years VWM concentration and export per unit area are reported. Additionally for all years the ratio of nitrate (NO_3^-) in streamflow of the burned catchment (Bell 4) to NO_3^- in streamflow of the control catchment (Bell 3) was calculated. When this ratio is greater than 1 the burned watershed had higher NO_3^- concentrations than the control.

Results and Discussion

In both watersheds stream NO_3^- concentrations vary wildly and have a high degree of correlation with streamflow, with higher concentrations during periods of high streamflow and lower concentrations during stream baseflow periods (Figure 2). Also noticeable in a temporal comparison is that the year closest to the 1984 fire (i.e. 1988) has the largest difference in NO_3^- concentrations between the two watersheds. In subsequent years NO_3^- concentrations were more closely matched between the two watersheds with more and more of the samples having lower concentrations on the burned catchment than on the control.

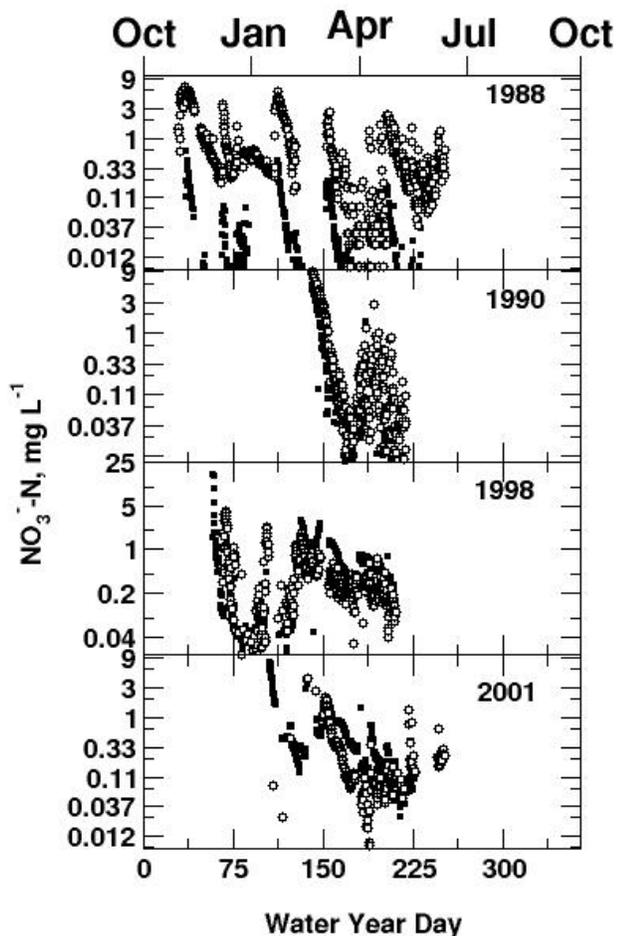
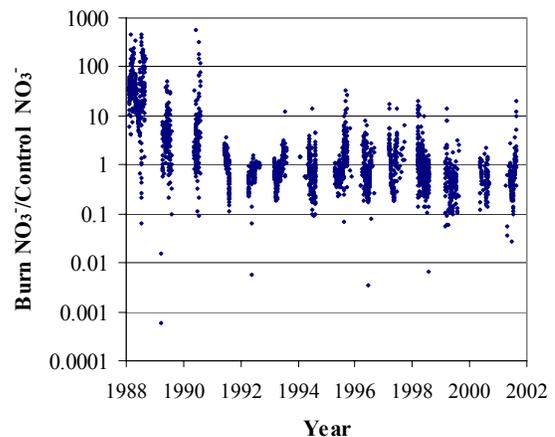


Figure 2. Stream NO_3^- concentrations for the watershed burned in 1984 (Bell 4, gray circles) and for the control watershed (Bell 3, black squares). Note that all y-axes are logarithmic.

The dramatic change in the difference in NO_3^- concentrations can be seen more clearly by looking at the ratio of concentrations between the burned (Bell 4) and unburned (Bell 3) catchments (Figure 3). Initially the ratios indicate that concentrations on the burned catchment are as much as 600 times those on the unburned, but as the experiment moves forward

in time the ratio declines to being less than one for most of the last several years of the available data. This result is supported by looking at the number of simultaneous stream samples from the burned watershed that had lower concentrations than the control (Table 1). At the beginning of the period only 3 percent of the observations were lower on the burned catchment, but by the end of the period 85% of the stream samples on the burned catchment had



lower concentrations. Figure 3. Ratio of NO_3^- in the burned catchment to that in the control catchment. Values greater than one indicate higher concentrations in the burned catchment and less than one indicate lower concentrations in the burned catchment as compared to the control catchment. Note logarithmic y-axis.

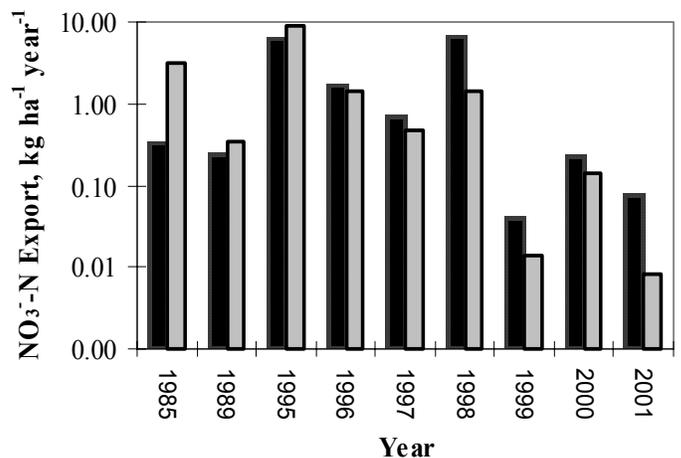


Figure 4. Nitrate export in each year with available streamflow data. Burned catchment in gray, unburned catchment in black. Note y-axis is logarithmic.

The change in concentrations for the individual samples is reflected in changes in annual export of NO_3^- (Figure 4) and in VWM results (Figure 5). At the beginning of the period NO_3^- export and VWM NO_3^- concentrations are higher on the burned catchment but by the end of the study period concentrations and export of NO_3^- are higher on the control catchment. Export per unit area is highly variable from one year to the next, mostly due to changes in streamflow related to the amount of rainfall and resulting streamflow in any one year (Figure 4). However the increases in export are further supported by increases in VWM NO_3^- concentration during the wetter years (Figure 5).

Table 1. Observed NO_3^- Burned < Unburned

Year	number of observations		
	Burn < Unburn	Total	Percent <
1988	10	303	3
1989	28	205	14
1990	18	169	11
1991	58	192	30
1992	281	405	69
1993	246	354	69
1994	119	172	69
1995	180	273	66
1996	188	247	76
1997	88	175	50
1998	299	415	72
1999	147	168	88
2000	79	95	83
2001	142	167	85

This increase in export in wet years and decrease in dry years indicates that there is a catchment hydrologic control on stream export of NO_3^- . This hydrologic control might be through shorter sub-surface residence times in the wet years and concurrent decreases in denitrification. Alternatively the inter-annual variability may be caused by year to year storage of inorganic nitrogen in the catchment in the dry years due to lack of water to move the NO_3^- out of the watershed (Vitousek et al. 1979). This second hypothesis is somewhat supported by the VWM data which shows heightened VWM NO_3^- concentrations in years like 2000 which followed dry years like 1999 (precipitation was similar in 2000 and 2001 but VWM concentrations were higher in 2000).

Fire recovery and biogeochemistry

Most studies of fire effects on ecosystem processes, hydrology or biogeochemical processes have focused on the immediate post-fire period and the large increases in streamflow, sediment export, nutrient export, and dissolved load that typically follow fires (e.g. Riggan et al. 1994, Townsend and Douglas 2000). However, as several hydrologists have shown, fire and ecosystem recovery can have long term impacts on water yield and thus might be expected to have an impact on other ecosystem processes (Kuczera 1987, Watson et al. 1999).

Our results illuminate several points about the effect of fire and the following recovery on biogeochemical fluxes from chaparral ecosystems. First, as noted above the immediate post-fire period has a noticeable increase in concentrations and export of dissolved nitrogen. Second, this increase persists for a period of up to 5 years in the post-fire environment. Third, the short period of increased export is followed by a longer period of decreased export in the burned system (Bell 4) compared to the unburned control (Bell 3).

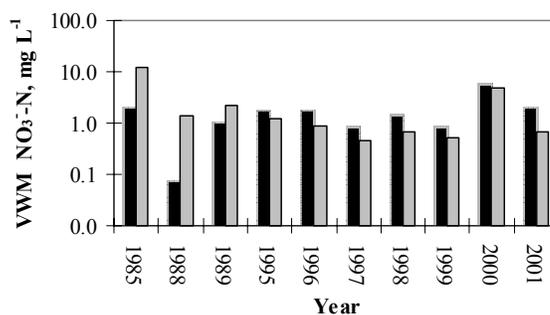


Figure 5. VWM NO_3^- for each year with available streamflow data. Burned catchment in gray, unburned catchment in black. Note y-axis is logarithmic.

In general it has been observed that canopy closure after a stand replacing chaparral fire takes five to seven years. Often times climax growth of chaparral vegetation can occur in as little as 20 years but may also take much longer. In both cases ecosystem response depends on precipitation and local site geology and soils (Horton and Kraebel 1955, Minnich and Bahre 1995). This pattern of vegetation recovery parallels the nitrogen export results presented here. Initially, after the fire has removed vegetation, NO_3^- export is dramatically increased (Figures 2-5 and Table 1). This increase may be due to several factors including: increases in streamflow

in the post-fire environment (Loaiciga et al. 2001), decreased plant uptake and increased mineralization and nitrification rates, and loss of organic matter (Vitousek and Matson 1985). However, as the ecosystem recovered from disturbance and the vegetation grew back, nutrient export declined (later time periods in Figure 2-5) as the ecosystem sequestered more nitrogen and possibly other nutrients in response to the large losses that occurred during and after the fire. While studies of the long term effects of fire as an ecosystem disturbance are poorly known, other forms of ecosystem disturbance such as clear cut logging and other forms of vegetation removal have been studied in more depth (e.g. Likens et al. 1978, Vitousek et al. 1979). These studies have also shown an increase in nutrient export immediately following disturbance but a longer term decrease in nutrient export as the ecosystem recovers from the disturbance.

The data available in this study indicate another potential explanation for the pattern of higher concentrations of nitrate in the control catchment in the later years of our study. The control catchment in this study was the Bell 3 catchment that had last burned in 1960. Chaparral ecosystems burn on average every 40 to 60 years and therefore the Bell 3 watershed was at climax and ready to burn towards the end of this experiment. Other studies have indicated that as ecosystems approach their climax state that they will begin to leak nitrogen (Vitousek and Farrington 1997). With the high rates of atmospheric deposition in southern California, even rapidly aggrading catchments such as Bell 4 (burned in the late 1990's still leak some inorganic nitrogen, possibly due to processes operating at seasonal transitions (Vitousek and Field 2001) and thus explaining the high concentrations of NO_3^- during periods of high streamflow. As the Bell 3 catchment approached 40 years since the last burn NO_3^- export and VWM NO_3^- concentrations may have increased as the vegetative N demand decreased with maturation of the chaparral ecosystem.

The interplay between the high rates of atmospheric deposition and fire history in the mountains of southern California indicates some possible challenges and opportunities for land managers. The effect of time since the last fire in chaparral ecosystems indicates that land managers need to take into account the immediate and long-term impacts of fire suppression, prescription, and management on catchment nutrient export. Chaparral catchments provide a water resource to southern California, and

the short and long term effects of fire may have an adverse impact on the water quality of this resource. On the one hand fires in chaparral ecosystems cause dramatic short-term increases in nutrient export and NO_3^- concentrations, often above the federal drinking water standard of 10 mg L^{-1} . On the other hand fire suppression may lead to similarly high NO_3^- concentrations (Figure 2, 1998 unburned data).

Conclusions

This study provides preliminary evidence that long-term ecosystem recovery from fire in chaparral ecosystems leads to decreases in nutrient flux. This decrease in the long term follows an initial large flux of inorganic nitrogen in the immediate post-fire period. Export as well as VWM concentrations increase dramatically in wet years and are orders of magnitude lower in dry years. This inter-annual variability in export that is dependant on precipitation as well as antecedent conditions indicates that there is a hydrologic control on nutrient export from chaparral catchments. Finally, the influence of the post-fire recovery process and the hydrologic controls on nutrient export indicate some interesting trade-offs for land managers as they try to manage fire in chaparral ecosystems under high N deposition conditions. This study hopefully will help them balance the countervailing impacts of atmospheric deposition and fire recovery on the water quality consequences of these two activities.

Acknowledgments

The United States Forest Service supported this research. We wish to especially thank Phil Riggan whose visionary 1984 experiment made this current work possible.

References

- Aber, J.D., W. McDowell, K.J. Nadelhoffer, A. Magill, G. Berntson, M. Kamakea, S. McNulty, W. Currie, L. Rustad, and I. Fernandez. 1998. Nitrogen saturation in temperate forest ecosystems - Hypotheses revisited. *BioScience* 48:921-934.
- Bytnerowicz, A., P.R. Miller, and D.M. Olszyk. 1987. Dry deposition of nitrate, ammonium and sulfate to a *Ceanothus crassifolius* canopy and surrogate surfaces. *Atmospheric Environment* 21:1749-1757.

- Fenn, M.E., J.S. Baron, E.B. Allen, H.M. Rueth, K.R. Nydick, L. Geiser, W.D. Bowman, J.O. Sickman, T. Meixner, D.W. Johnson, and P. Neitlich. 2003. Ecological effects of nitrogen deposition in the western United States. *BioScience* 53:404-420.
- Fenn, M.E., M.A. Poth, J.D. Aber, J.S. Baron, B.T. Bowman, D.W. Johnson, A.D. Lemly, S.G. McNulty, D.F. Ryan, and R. Stottlemyer. 1998. Nitrogen excess in North American ecosystems: A review of geographic extent, predisposing factors, ecosystem responses, and management strategies. *Ecological Applications* 8:706-733.
- Horton, J.S., and C.J. Kraebel. 1955. Development of vegetation after fire in the chamise chaparral of southern California. *Ecology* 36:244-262.
- Kuczera, G. 1987. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *Journal of Hydrology* 94:215-236.
- Likens, G.E., F.H. Bormann, R.S. Pierce, and W.A. Reiners. 1978. Recovery of a deforested ecosystem. *Science* 199:492-496.
- Loaiciga, H.A., D. Pedreros, and D. Roberts. 2001. Wildfire-streamflow interaction in a chaparral watershed. *Advances in Environmental Research* 5:295-305.
- Lovett, G.M., K.C. Weathers, and W.V. Sobczak. 2000. Nitrogen saturation and retention in forested watersheds of the Catskill Mountains, New York. *Ecological Applications* 10:73-84.
- Meixner, T., and M.E. Fenn. 2003. Biogeochemical budgets in a Mediterranean catchment with high rates of atmospheric N deposition - Importance of scale and asynchrony. *Biogeochemistry*: (in review).
- Minnich, R.A., and C.J. Bahre. 1995. Wildland fire and chaparral succession along the California Baja-California Boundary. *International Journal of Wildland Fire* 5:13-24.
- Riggan, P.J., R.N. Lockwood, P.J. Jacks, C.G. Colver, F. Weirich, L.F. DeBano, and J.A. Brass. 1994. Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. *Environmental Science and Technology* 28:369-375.
- Riggan, P.J., R.N. Lockwood, and E.N. Lopez. 1985. Deposition and processing of airborne nitrogen pollutants in Mediterranean-type ecosystems of southern California. *Environmental Science and Technology* 19:781-789.
- Stoddard, J.L. 1994. Long-Term Changes in Watershed Retention of Nitrogen: Its Causes and Aquatic Consequences. In L.A. Baker, ed., *Environmental Chemistry of Lakes and Reservoirs*, pp. 223-284. American Chemical Society, Washington, DC.
- Townsend, S.A., and M.M. Douglas. 2000. The effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (northern Australia). *Journal of Hydrology* 229:118-137.
- Vitousek, P.M., and H. Farrington. 1997. Nutrient limitation and soil development: Experimental test of a biogeochemical theory. *Biogeochemistry* 37:63-75.
- Vitousek, P.M., and C.B. Field. 2001. Input/Output Balances and Nitrogen Limitation in Terrestrial Ecosystems. In E.D. Schulze, M. Heimann, S. Harrison, E. Holland, J. Lloyd, I.C. Prentice, and D. Schimel, eds., *Global Biogeochemical Cycles in the Climate System*, pp. 217-225. Academic Press, New York.
- Vitousek, P.M., J.R. Gosz, C.C. Grier, J.M. Melillo, W.A. Reiners, and R.L. Todd. 1979. Nitrate losses from disturbed ecosystems. *Science* 204:469-474.
- Vitousek, P.M., and P.A. Matson. 1985. Disturbance, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. *Ecology* 66:1360-1376.
- Wan, S., D. Hui, and Y. Luo. 2001. Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis. *Ecological Applications* 11:1349-1365.
- Watson, F.G.R., R.A. Vertessy, and R.B. Grayson. 1999. Large-scale modeling of forest hydrological processes and their long-term effect on water yield. *Hydrological Processes* 13:689-700.