Impacts of Anthropogenic N Deposition on Weed Invasion, Biodiversity and the Fire Cycle at Joshua Tree National Park

Final Report

PMIS Number: 72123

9/2003-9/2006

Edith B. Allen[1,2*]
Andrzej Bytnerowicz[3], Mark E. Fenn[3]
Richard A. Minnich[4] and Michael F. Allen[2]

[1]Department of Botany and Plant Sciences and [2]Center for Conservation Biology,
[3]U.S. Forest Service Fire Laboratory, Riverside, CA 92507
[4]Department of Earth Sciences, University of California, Riverside, CA 92521

* email edith.allen@ucr.edu
tel. (951) 827-2123, fax (951) 827-4437

Abstract. The objectives of this research were to measure reactive N in the atmosphere and soils along a N deposition gradient at Joshua Tree National Park (JOTR), and to examine effects on invasive and native plant species cover, production and diversity. JOTR is downwind of nitrogen emissions from coastal and inland urban sources, especially automobiles. Measurements of atmospheric reactive N (nitric acid and ammonia) and ozone were elevated in western JOTR, although there were some high levels in the east that may be related to local sources. The central areas of the Park were lowest in reactive N. Nitric acid was higher in summer than winter, while ammonia concentrations were higher in winter. Extractable soil N was generally higher in sites that had higher atmospheric reactive N. The level of N deposition measured with bulk collectors under pinyon pine and in the open varied from 3 to 12 kg/ha/yr.

Invasive grasses and forbs, primarily *Schismus barbatus, Bromus madritensis*, and *Erodium cicutarium* become more productive and widespread in the last two decades. To test the hypothesis that elevated N may be related to invasive species, N fertilizer experiments were done at four sites in the Park at levels of 5, 15, and 30 kg N/ha from 2003-2005. In 2006 an additional treatment of 2 kg/ha was added, and the 30 kg/ha treatment was discontinued to determine whether soil N will begin to decline. Lower elevataion sites with creosote bush in higher N deposition (Wide Canyon) and lower N deposition (Pinto Wash) were selected, as well as high elevation sites with pinyon-juniper woodland under higher (Covington Flat) and lower N deposition (Pine City). The greatest number of significant responses occurred in 2005, the wettest year, when addition of 5 kg N/ha caused an increase in exotic grass cover at Covington Flat and Pinto Wash. In the drier 2004 season there were significant increases in exotic grasses with 30 kg N/ha at three of the four sites. There were no significant changes at all in 2006, the driest year, or 2003, the first year of N fertilization. The response of native forbs to fertilizer was related to the amount of exotic grass present initially. Pine City, the site with lowest initial exotic grass cover, had increased native forb cover with 30 kg/ha in 2004 and with 5 kg/ha in 2005. The richness of native forbs in 2004 declined with fertilization at a site with high initial exotic grass cover (Pinto Wash), but native richness and cover increased with fertilization at a site with low grass cover (Pine City).

In a survey of 22 sites across the Park, exotic grass cover was not related to soil N concentration, but rather is controlled by a combination of local soil conditions such as texture and soil N supply rate. The concentrations of soil N in sites in sites along a W to E gradient were as high as fertilized, low-deposition sites that had a significant response by exotic grasses, e.g., 23 μg N/g soil which caused a significant response. This indicates that long-term, low-level N inputs especially on the west end of the Park have already accumulated enough N in surface soils to increase exotic grass productivity. The significant response at the low level of 5 kg N/ha in the wet 2005 growing season indicates this may be an upper threshold level for promoting increased exotic grass during a wet year. This level of N deposition already occurs at Wide Canyon, and is exceeded when N from tree throughfall is considered at Covington Flat and Pine City.

Introduction

The western Mojave Desert is affected by air pollution generated in the Los Angeles air basin that moves inland with the predominant westerly winds (Edinger 1972, Fenn et al. 2003b). Both oxidized and reduced forms of nitrogen (N) are of concern because they are deposited on soil and plant surfaces, and fertilize plants with N. Nitrogen deposition may affect plant productivity differentially, with exotic grasses having higher rates of N uptake or production than many native species (Allen et al. 1998, Yoshida and Allen 2001, 2004, Brooks 2003) or similar rates in other studies (Padgett and Allen 1999, Salo et al. 2005). Exotic grasses such as *Schismus* spp. and *Bromus* spp. have become more abundant in the desert in the last two decades (Brooks 1999), and our objectives were to determine whether this is related to elevated N deposition. As exotic grasses increase in productivity, the native plants may become sparse (DeFalco et al 2001, Brooks 2000, 2003). This is especially a concern in protected areas with rare species such as Joshua Tree National Park (JOTR). The wind patterns create N deposition gradients that have been modeled with highest levels on the west side of the Park (Tonnesen et al. 2003). We selected sites along this modeled anthropogenic N gradient to make finer-scale measurements of reactive atmospheric as well as soil extractable N, and to determine N response of exotic grass cover and native species diversity.

N deposition in shrublands and forests of the Los Angeles air basin may be as high as 30-50 kg ha^{-1}yr^{-1} (Bytnerowicz et al. 1987, Fenn et al. 1998, 2003b). Most of this arrives as dry deposition in gaseous, ionic, and particulate form during the dry summer season, and is much more difficult to measure than wet deposition (Bytnerowicz et al. 2000). Relatively few estimates of N deposition have been done in the Mojave Desert, with a value of 8 kg ha^{-1}yr^{-1} calculated for the Black Rock site in northwestern JOTR (Fig. 1, Sullivan et al. 2001), and 12 kg/ ha/yr in the northwestern Coachella Valley (Tonnesen et al. 2003 and unpublished). Total N deposition reported for the CASTNET monitoring site near Black Rock in JOTR ranged from 3.2 to 5.9 kg ha^{-1} yr^{-1} from 1995 to 2003 (CASTNET 2005). However, CASTNET underestimates dry deposition of N (Baumgardner et al. 2002, Fenn et al. 2003a), particularly in California sites where dry deposition of ammonia is a significant fraction of inorganic N deposition (Fenn et al., submitted). Short term measurements at the western Salton Sea, when recalculated on a yearly basis, ranged from 0.4 to 6.6 kg ha^{-1}yr^{-1} for nitrate-N and 2.6 to 8.7 for ammonium-N (Alonso et al. 2005), but such a calculation is fraught with assumptions about variations in short-term rate and spatial distribution of deposition. The lack of actual measurements of N deposition in the desert means that observed vegetation changes cannot be explained with respect to air pollution, although field observations and N fertilizer experiments suggest there may be a relationship (DeFalco et al. 2001, Brooks 2003).

Soil N gradients caused by anthropogenic deposition have been measured in western Riverside County in coastal sage scrub vegetation (Padgett et al. 1999) and in coniferous forest in the San Bernardino Mountains (Fenn et al. 2003b), with values for extractable N increasing 5-fold across the gradients. This effect is especially pronounced in seasonally dry soils, where extractable N is highest during the dry season, both from dry deposition and mineralization. Thus soil surface N measurements during the dry season can be used as another indicator of the accumulation of N from air pollution (Padgett et al. 1999). The impacts of elevated N include changes in nutrient cycling as well as plant community composition. The rate of nutrient cycling and N leakage has increased in mesic forests of the eastern U.S. (Aber et al. 1998) as well as seasonally dry, mixed coniferous forests in California (Fenn et al. 2003b), but the rate of N loss is expected to be lower in arid or semi-arid ecosystems (Wood et al. 2005). Studies from Europe have shown a loss of diversity of native herbaceous species and an increase in native grass biomass with N deposition (Bobbink et al. 1998, Stevens et al. 2003). N fertilizer studies in the Mojave Desert (Brooks 2003) and coastal sage scrub (Allen 2004) have shown increased productivity of invasive grasses and decreased productivity and diversity of native species.

To control for the natural variability of soils, climate and vegetation inherent in any gradient, we also performed N fertilization experiments to determine the impacts of N to vegetation and soils using blocked, replicated designs. This was especially critical because of the low inputs of N in the Mojave Desert compared to other studies in mesic climates, that would make a N response difficult to detect in a heterogeneous environment. A rate of 30 kg N/ha increased biomass of *Schismus* spp. (Mediterranean split grass), *Bromus madritensis* ssp. *rubens* (red brome) and *Erodium cicutarium* (stork's bill) in one growing season in the western Mojave Desert (Brooks 2003). However, low productivity vegetation is more sensitive to N inputs, and may experience shifts in composition even with low levels of fertilization (Bowman and Steltzer 1998, Theodose and Bowman 1998). Therefore, our treatments also included a low level of N fertilizer of 5 kg/ha.

Air pollution measurements for the first phase of this study included ambient concentrations of ozone, nitric acid, and ammonium. Ozone co-varies with nitrogen oxides and has been reported at high levels at JOTR. Earlier work showed ozone damage to native plants in the desert (Thompson et al. 1984, Bytnerowicz et al. 1988). The specific objectives of this research were to

1) Measure gaseous N pollutant concentrations and N deposition rates to plant and soil surfaces along N deposition gradients in the Park using several techniques, including passive samplers, branch washing, deposition to filters, and deposition to ion exchange resins.
2) Measure exotic grass biomass in N-fertilized and control plots along N deposition gradients in creosote scrub and pinyon-juniper woodland.
3) Determine the relationships among soil N, exotic grass biomass, and plant biodiversity (including number of herbaceous plant species) along N deposition gradients.
4) Measure root and mycorrhizal response to elevated N in fertilized and unfertilized plots along a N deposition gradient in pinyon-juniper woodland. The fourth objective was included as a non-funded study, but was not completed due to lack of funds. A similar study has been completed in pinyon-juniper woodland in New Mexico (Treseder et al. 2004, 2005, Pregizter et al. 2002).

Methods

Air pollution measurements

Air samplers were deployed at 18 locations across the Park (Fig. 1). The locations were chosen to cover the Park, encompass the potential west to east gradient, and be accessible to roads (although not near any well-traveled highways that might contribute to air pollution). They covered a variety of vegetation types (creosote scrub, Joshua tree woodland, pinyon juniper woodland). Concentrations of ambient gaseous N pollutants (NO, NO_2, NH_3 and O_3) were determined with passive samplers in the selected sites (Koutrakis et al. 1993). The passive samplers consisted of teflon cartridges with pollutant-collecting filters placed in inverted PVC protective cups at 2 m above ground level. Nitric acid was collected on three nylon filters placed in double rings hung inside PVC caps protecting them from wind and rain (Bytnerowicz et al., 2001).Two-week long average concentrations of the pollutants were determined three times during the dry season and two times during the wet season. Results are shown for the 14 days preceding 2/10/04 and 7/21/04, which were precipitation-free periods. Additional air sampling was done during 2005; these data are currently being analyzed and will be provided in an updated version of the final report.

Tree throughfall

Ion exchange resin (IER) throughfall collectors (Fenn and Poth, 2004) were used to capture nitrate and ammonium ions in throughfall and precipitation at four sites. Throughfall was collected under pinyon pine (*Pinus monophylla*) trees at Covington Flats and Pine City. Ten throughfall collectors were employed at each of the two sites. Five of the same collectors were placed in open canopy-free areas at each of four sites to quantify bulk deposition fluxes of inorganic N. Bulk deposition was measured at Covington Flats, Pine City, Pinto Basin and Wide Canyon. The IER samplers collect throughfall or precipitation samples in rain gauge funnels (10 cm diameter) from which the solution is channeled through a PVC column filled with mixed bed (cation and anion exchange) resin which captures ions from the percolating solution. At the end of each exposure period the resin columns are extracted with 2N KCl and ions are quantified with colorimetric methods (Fenn and Poth, 2004). Data from two sampling periods were combined to determine annual deposition fluxes in throughfall and bulk precipitation. The first period was from November 23, 2004 to July 13, 2005. The second period was from July 13, 2005 to December 7, 2005. Landscape level atmospheric deposition fluxes were calculated considering percent canopy cover and the proportion of the area that consisted of interspaces or open areas.

Soil sampling

Soil samples for extractable N analysis were collected from the same 18 sites as the air sample sites during July 2004 and 2005, as well as one additional site outside the Park to the west (Snow Creek). Dry season samples are shown because prior analyses showed extractable N is greater than during the winter rainy season. Cores were taken 5 cm deep (n = 10) from interspaces between shrubs or trees. Soils were extracted in KCl, and ammonium and nitrate were measured colorimetrically using a Technicon Autoanalyzer.

Fertilization experiment

Fertilization was done at four sites, two on the west end of the Park and two further to the east (Fig. 1). Two vegetation types were chosen within each air pollution level, creosote (*Larrea tridentata*) scrub and pinyon-juniper (*Pinus monophylla-Juniperus californica*) woodland. The two vegetation types represent two of the most abundant vegetation types in JOTR as well as the extremes in elevation (550 to 1500 m). The fours sites are Wide Canyon (creosote scrub, high atmospheric reactive N, 550 m), Pinto Wash (creosote scrub, low N atmospheric reactive, 750 m), Covington Flat (pinyon-juniper woodland, high N, 1500 m) and Pine City (pinyon-juniper woodland, low N, 1400 m). Individual shrubs or trees were fertilized, encompassing an area beyond the tree canopy. Plot size was determined by the shrub or tree size, with 6 X 6m for creosote bush, 8 X 8m for juniper, and 10 X 10m for pine. For the intermediate fertilization level only 2 X 2m plots with grasses and forbs were fertilized. Three levels of fertilizer were used, 5, 15, and 30 $kg{\cdot}ha^{-1}\ yr^{-1}$, plus unfertilized controls. Ten replicates of each shrub or tree species were fertilized, and selected across the landscape as 10 replicate blocks, each block containing each of the three N fertilizer levels plus control. Fertilizer levels were chosen to compare with the high level of 30 $kg{\cdot}ha^{-1}\ yr^{-1}$ that has been tested previously in the Mojave Desert and showed a response by exotic grasses (Brooks 1998, 2003). The lower levels were chosen to determine if N would accumulate in a dry climate and eventually promote a response by exotic plants. The low level of 5 $kg{\cdot}ha^{-1}\ yr^{-1}$ was similar to the highest known level of 8 $kg{\cdot}ha^{-1}\ yr^{-1}$ calculated by the Environmental Protection Agency at the Black Rock Station (Sullivan et al. 2001). Plots were fertilized in December, 2002, 2003, and 2004 by broadcasting NH_4NO_3 granular fertilizer. In December 2005, an additional treatment of 2 kg/ha was added, and the high level of 30 kg/ha was discontinued to determine the rate at which N declines after N inputs cease. Soil cores were also collected from this experiment to 5 cm deep to determine N levels after fertilization. Growing season (March-May) and dry season (July) samples were taken. July values are shown, as these were higher in extractable soil N.

Vegetation sampling

Understory vegetation cover was monitored in 1.0 X 0.5 m sampling quadrats placed just outside the dripline of each shrub or tree. The percent cover of each species was estimated to the nearest 1% in a gridded frame. Very small plants with <1% cover in a quadrat frame were assigned cover values of 0.1 or 0.5%. North and south sides of shrubs or trees were measured separately. Vegetation cover on the north side was on average higher than the south side, but there were no statistical interactions of the N fertilizer effect on the two sides, so the mean values for the two sides are shown. Exotic grasses were clipped in 10 replicate, 25 X 50 cm plots in each fertilizer level to develop regressions of grass biomass with percent cover. Grass biomass was calculated from percent cover data in the 0.5 m^2 quadrats based on these regressions. Vegetation was monitored in March-May of 2003, 2004, and 2005, the date depending on peak plant production according to elevation. The vegetation of the 2 X 2 m fertilized plots was not comparable in ground vegetation cover composition to the larger tree or shrub plots because they were not aligned in any particular compass direction with regard to the nearest tree or shrub. Therefore vegetation cannot be compared with the north and south sample quadrats of the larger plots, and only soil N data are shown from the 2 X 2 m plots. Data for 2004, 2005, and 2006 are shown, as there were no significant differences for 2003.

Results

Air pollution and N deposition

Nitric acid had higher atmospheric concentrations across the Park in July than February (Fig. 2), but the reverse was true for ammonia with higher concentrations in winter (Fig. 3). Ozone followed the pattern of nitric acid (Fig. 4). The concentrations of nitric acid ranged from 1 to 5 $\mu g/m^3$ in February, but were 2 to 9 $\mu g/m^3$ in July (Fig. 2). The concentrations fell along a gradient of high to low nitric acid from west to east, higher in the west that is closer to the prevailing winds that likely bring air pollutants from the Los Angeles basin. The highest nitric acid value in winter was at Key's View (Fig. 1), a popular visitor overview on the ridge of the Little San Bernardino Mountains. This site had a higher value in the summer, although the highest summertime exposure was at Wide Canyon, one of the four experimental N fertilization sites.

Atmospheric concentrations of ammonia ranged from 4 to 8.5 $\mu g/m^3$ in February, with lower values of 2.5 to 7 $\mu g/m^3$ in July (Fig. 3). The summer concentrations of ammonia followed a west to east gradient as did nitric acid, but the winter pattern was different, with an area of high concentration at the east end of the Park at the Lily Preserve site (Figs. 1, 3). The sites in the Park interior were the lowest in ammonia.

Spatial and temporal patterns of ozone concentrations were similar to nitric acid with 35 to 45 ppb in February and 45 to 70 ppb in July (Fig. 4). Key's View was also the highest in ozone in February, and Wide Canyon in July. However, sites in the eastern side of the Park were also exposed to elevated levels of ozone air pollution, with intermediate values at the Lily Preserve and Cadiz Valley sites (Fig.1). Analyses of atmospheric measurements for 2005 are under way.

Covington Flat and Pine City had 36.2 and 23.1 kg $N \cdot ha^{-1}$ yr^{-1} as throughfall under pinyon pine, respectively, and 3.9 and 2.5 in the open (Table 1). When this was calculated as stand-level deposition, the values were 12.4 and 6.2 kg/ha assuming 27% and 20% tree cover, respectively. Although Wide Canyon received more bulk deposition than Covington Flat, the total amount of input to the landscape was higher at Covington Flat because of the higher leaf area provided by the tree canopy.

Soil nitrogen

Soil extractable N was analyzed in July 2004 from the top 0-1 cm and 1-2 cm of soil in the four sites selected for intensive study (Fig. 5). The surface soil was considerably higher in N than subsurface N, and furthermore sites to the west in areas with higher interspace bulk deposition had higher N. Overall the data suggest the input was from atmospheric N deposition. Concentrations of NH_4^+-N were higher than NO_3^--N, unlike the concentrations of atmospheric reactive N. Some of the NO_3^--N may be a production of mineralization.

Extractable Soil N was measured in 22 sites across the Park in 2004, 2005, and 2006, plus two sites west of the Park (Whitewater and Snow Creek). In 2004, soils from four sites on the western side of the Park (Wide Canyon, Key's View, Covington Flat, Pine City) and one site outside the Park (Snow Creek) had levels of extractable N greater than 15 μg/g (Fig. 6). These soil samples were collected from a limited area around the air samplers at each of these sites, so values were in some cases different from values reported in Figs. 5 and 7, that were collected across a broader area at those sites (Covington Flat and Pine City). Four sites on the eastern edge of the Park also had high soil N concentrations (Hayfield, Cadiz Valley, Lily Preserve, and Fish Farm; Fig. 6). In general, the sites that had higher reactive atmospheric N (Figs. 2 and 3) also had high extractable soil N concentrations (Black Rock, Key's View, Wide Canyon, Covington Flat, Lily Preserve, Cadiz Valley, Fish Farm, and Hayfield). In 2005 all sites had lower N than 2004 (except Fish Farm, which was not measured in 2004). This is likely due to much higher precipitation in 2005, up to three times above average. In 2006 the concentrations were higher again at most sites.

Additional edaphic factors were measured at the four N fertilizer sites. Bicarbonate extractable P ranged from 2.7-8.6 μg/g and total P was 780 to 1500 μg/g (Table 2). Total N was 0.040 to 0.078 % and total C was 0.22 to 0.84 %. Values for each of these were lowest at Pinto Wash. pH ranged from 6.8 to 7.9, with higher values for sites to the east. Soil texture was sandy loam at all the sites with varying amounts of gravel and pebble-sized particles. Pinto Wash has the lowest exposed rock on the surface as it lies in a basin that accumulates sandy loam soil on the surface, while the other three sites are a gravelly debris flow (Wide Canyon), rocky alluvial channel (Pine City) and an alluvial fan (Covington Flat).

In 2004, extractable N was higher with N fertilizer at the four fertilized sites, with values ranging from 6 to 18 μg/g with 5 kg/ha fertilizer, and 23-40 μg/g with 30 kg/ha fertilizer (Fig. 7a). Pine City had unexpectedly high soil N in the control plots, as high as the fertilized plots (small mammal activity occurred in several of those plots). Covington Flat control soils had low N concentrations (6 μg/g) that were more similar to other Park interior sites, even though this site lies on the western part of the Park (Fig. 1). Control plots in Wide Canyon had high soil N concentration with nearly 15 μg/g, congruent with the high level of N deposition. The concentration of soil N was lower in July 2005 than 2004, a result of higher precipitation that year (Fig. 7a).

Concentrations of soil N increased again in the drier 2006 year compared to 2005 (Fig. 7b). Fertilization of the 30 kg N/ha plots ceased at the December 2005 application date, and the soil N was no longer significantly higher in this treatment than plots receiving lower levels of N at any of the sites in July 2006. In fact, the only site that had significantly different concentrations of soil N with fertilization was Covington Flat. In the other sites the concentration of soil N was not significantly higher with N fertilization.

Response of vegetation to N fertilization

Vegetation changes were related to fertilizer level, initial soil N, and initial vegetation cover. There were no significant differences in response to N in 2003, and data are not shown. Biomass of exotic grasses increased significantly with N fertilization in three of the four sites in 2004 (Fig. 8). The exotic grass species at the two low elevation sites, Wide Canyon and Pinto Wash, were *Schismus barbatus* and *S. arabicus* (with little of the latter). *Bromus madritensis* ssp. *rubens* was the dominant exotic grass at the two high elevation sites, with 1-2% of *B. tectorum* and another 1-2% cover of *Schismus* *barbatus.* The dry mass of exotic grass in 2004 increased significantly ($p < 0.05$) with 30 kg/ha in three of the four sites, but not at Covington Flat ($p = 0.10$). There was not a significant increase in grass biomass with 5 kg N/ha fertilizer at any of the sites (Fig. 8). Overall Pine City had the lowest exotic grass biomass, and Pinto Wash had the highest in control plots, even though it had low extractable soil N and the lowest N deposition and lowest air pollution.

Percent cover of exotic species did not change significantly with N fertilization at any of the four sites in 2004, but there were significant increases in two sites (Covington and Pinto) in 2005 (Fig. 9a and b). Total exotic cover included grasses and *Erodium cicutarium*, but the latter contributed < 1.5 % cover at each site (Table 3). In 2006, there were also no significant effects of N fertilization on exotic species cover (Fig. 9c). Rainfall was very low at Pinto Wash, so that cover of herbaceous species was < 1%, and no data were taken. Precipitation was also lower at the other sites in 2006 than the previous years, so overall cover was low at all sites. However, exotic grass cover was higher at Covington Flat than the other sites, possibly from an October rain that triggered exotic germination with little subsequent rain.

Cover of native forbs increased significantly at Pine City in both 2004 and 2005 with 30kg/ha N, with an intermediate (but not significant) response with 5 kg/ha. This was also the site with the lowest exotic grass biomass. Conversely, cover of native species decreased significantly at Covington Flat in 2005 but not 2004 (Fig. 9a and 9b); this was the site with the highest exotic grass cover. In 2006 there were no significant changes in cover of native forbs with fertilization at any of the sites; overall, cover of forbs was very low in 2006, with 6 % or less at all the sites, (Fig. 9c).

The richness of native herbaceous species in 2004 at Pine City increased significantly following N fertilization at the highest rate, from 3.5 to 4.5 species per 0.5 m^2 plot (Fig. 10). Conversely, native species richness declined significantly at Pinto Wash from 1.3 to 0.2 species per plot, and there was not a significant change at the other two sites. Most of the diversity of this desert vegetation is due to annual forbs, which included 71 species at the four sites, plus 5 perennial grasses, 15 perennial forbs, and 21 shrubs (Table 3). Very few of these had greater than one percent cover, and most occurred sporadically with many zero values, so no statistical analyses could be done on individual species. Vegetation data are currently being collected for 2006, and will be analyzed for the final report.

The relationship between exotic ($R^2 = 0.01$, $p = 0.70$) and native forbs ($R^2 = 0.03$, $p = 0.51$) with soil N in 16 locations across the Park in 2005 was not significant (Fig. 11). The site with the highest exotic grass cover in 2005 was Pinto Wash with nearly 80%, even though this is a site with low extractable N. Thus factors other than soil N are also related to high grass cover, as discussed below.

Discussion

Reactive atmospheric and soil N

The relationship between reactive atmospheric N concentrations and soil N were consistent in most sites. The sites with highest extractable soil N (Black Rock, Key's View, Wide Canyon, Hay Field, and Lily Preserve) also had highest atmospheric nitric acid and/or ammonia concentrations. Cadiz Valley also had high soil N, and had higher than expected ozone for an eastern JOTR site. Ozone is an indicator of poor air quality, although we did not observe elevated atmospheric N at Cadiz Valley during the time periods under study. Additional monitoring is needed to determine if elevated levels of atmospheric N pollutants occur at Cadiz Valley, but it is also possible that the severity of ozone exposure is significantly greater than N pollution at this eastern site. The phenomenon of much greater eastern transport of ozone compared to N compounds and N deposition has been observed in the adjacent San Bernardino Mountains (Alonso et al. 2003, Fenn et al. 2003b). The sites to the west of JOTR also had high soil N. In all likelihood these sites also have relatively high atmospheric reactive N, as polluted air from the Los Angeles air basin funnels through the Banning Pass before spreading into the Coachella Valley (Edinger 1972). A modeling study estimated up to 12 kg/ha/yr of N deposition in the northwestern Coachella Valley (Tonnesen et al. 2003 and unpubl.). Additional studies currently underway will determine which sites are subject to the highest levels of air pollutants, and will include measurements of N deposition rates to validate air pollution models.

The high levels of ozone are also of concern at JOTR, and were the subject of earlier studies on physiological responses of Mojave Desert plants (Thompson et al. 1984, Bytnerowicz et al. 1988). Concentrations of 100 ppb, which occur at JOTR during the summer, affected performance of Mojave Desert plants (Bytnerowicz et al. 1988). A number of species were observed to have symptoms of ozone damage in the summer, primarily riparian or deep rooted species (Bytnerowicz et al. 1988). The visible damage was mainly in species that are physiologically active in summer, as winter-active species close their stomates or shed leaves in summer and are less impacted.

Unlike ozone, which no longer has environmental impacts after it is converted to O_2 upon reaction with other compounds, gaseous nitric acid and ammonia are deposited and accumulate in the soil during the dry season. Nitrogen deposition gradients have been detected by sampling soil N in the mixed coniferous forest of the San Bernardino Mountains (Fenn et al. 1998) and in the coastal sage scrub of the Riverside-Perris Plain (Padgett et al. 1999). In both cases soil N has been correlated with atmospheric N concentrations. Reactive nitrogen accumulates on leaf and soil surfaces during the dry season and moves to the rooting zone via canopy throughfall, stem flow, and leaching (Padgett et al. 1999, Fenn et al. 1998, 2003b). In dry environments soil N accumulates on the soil surface over time (Padgett et al. 1999, Wood et al. 2005). We measured higher concentrations of N in fertilized soils in July 2004, the second year of fertilization, than in 2003, and we also observed greater responses by the vegetation. Thus it is likely that soils exposed to N pollutants and fertilized soils are accumulating N over time in this dry climate where opportunities for leaching are limited to infrequent wet periods (Walvoord et al. 2003). Along the N gradient in 2004 we observed high values of 15-20 μg/g N, but at this time it is not clear whether this is an upper threshold to which N may accumulate under the current air pollution level, or whether higher soil concentrations will be observed over time. Fertilizing with 30 kg N/ha during the rainy season resulted in levels up to 45μg/g, so if air pollution increases, we expect to observe elevated soil N.

However, soil extractable N decreased considerably at all sites in 2005 when precipitation was three times normal. Soil N samples were collected again in July 2006 and are currently being analyzed to determine if soil N values will increase in a year of average to normal precipitation. In addition, we are collecting deep soil cores to 1 m this fall to determine whether the soil N from 2005 moved into the soil profile. This should be evident by comparing fertilized and unfertilized plots.

Soils may have elevated or variable N concentrations for reasons other than atmospheric inputs, a drawback of the gradient approach. Soil texture, pH, parent material, moisture, and other factors control the rate of N mineralization and alter the extractable N concentration (Pastor et al. 1984). Soil texture may control growth of exotic grasses with fine, shallow root systems. The two rocky/gravelly sites, Wide Canyon and Pine City, had lowest grass biomass, and Pinto Wash, which lies in a basin that accumulates sandy loam, had the highest grass cover and biomass even though it had lowest soil N. Mineralization studies are underway at all of the sites to determine the N supply rate of these soils.

Impacts of elevated N on native and exotic vegetation

Although observations along the N gradient did not reveal a clear relationship between exotic grass cover and soil N concentration, the fertilizer experiment at the four sites showed significant impacts of N on native and exotic plants. Pinto Wash had the highest grass cover and low soil N, but exotic grass biomass was even higher following 30kg N/ha fertilization. This level of N fertilization also caused increased *Schismus* and *Bromus* spp. productivity in the western Mojave Desert (Brooks 2003) in an area of low to moderate air pollution (Tonnesen et al. 2003 and unpublished). This suggests that, if N deposition increases further at any of the sites, the exotic grass biomass may increase with a potential for a loss in productivity and richness of native herbs. A surface soil N concentration of 23 and 30 µg/g in 2004 in the 30 kg/ha treatment in the two lower air pollution sites (Pinto Wash and Pine City), resulted in exotic grass growth response. Therefore, 23 µg/g can conservatively be considered the low threshold for significant plant N response in a dry year based on this fertilization study. Soil N values were much lower in the wet 2005 year, and they increased again during 2006.

We can conservatively estimate that sites along the gradient that had approximately 23 µg/g soil N during 2004 are already being affected by elevated N. It is yet not clear whether elevated N is caused by N deposition at all of these sites, especially the sites in the eastern edge of JOTR. Furthermore, the two high deposition N fertilizer sites (Covington Flat and Wide Canyon) had soil concentrations of 18-20 µg/g following fertilization with 5 kg N/ha. Exotic grass productivity is likely also elevated at these sites, but there is no longer an unpolluted control plot at these sites to test this statistically. This suggests that even small yearly N increments such as 5 kg/ha over two years in this study, will eventually raise the level of soil N to values high enough to cause a significant increase in exotic grass biomass.

The amount of initial grass biomass at each of the sites was critical to the changes that took place in native richness and cover following N fertilization. At Pinto Wash where grass biomass was the highest, the higher level of N fertilization caused a decrease in native species richness per plot, while at Pine City where exotic grass biomass was lowest, the native species richness and cover increased with N fertilization. This suggests that the native species are also N limited, but that the exotic grasses respond to N more rapidly, assuming the exotics have already colonized, and the site is suitable to their growth. In a grass removal experiment, the native forbs plus the exotic *Erodium* species responded to N fertilization in the absence of grass competition, but not when grasses were present (Brooks 2003). Another study showed that *Bromus madritensis* has a higher rate of ^{15}N uptake than native seedlings of *Artemisia californica* in coastal sage scrub vegetation (Yoshida and Allen 2004). However, in a growth chamber experiment native species responded to N fertilization with the same relative percentage of increase as *B. madritensis* (Salo et al. 2005). Both native and exotic species responded to N, so other factors may also be involved, such as seed production and phenology of germination. The exotic grasses may germinate and produce seed even in dry years when native plants do not germinate, maintaining the exotic seed bank (Brooks 1999). Thus it appears that the different responses of native species at Pinto Wash and Pine City may be interpreted as competitive interaction, but experimental research needs to be done.

The high grass biomass has been cited in part for an increase in fire frequency in the Mojave desert (Brooks 1999, Brooks et al. 2003), especially at the higher elevations with higher rainfall and grass productivity. A fire of 5500 ha burned in May 1999 at Covington Flat in blackbrush (*Coleogyne ramosissimum*), galleta grass (*Hilaria rigida*), and Joshua tree (*Yucca brevifolia*) and pinyon-juniper woodlands (JOTR staff, personal communication). This is the largest fire known at JOTR, and followed the wet spring of 1998 that had high production of *B. madritensis* at this high elevation (our N fertilization experiment at Covington Flat was in unburned vegetation). The fuel load for the fire was likely a combination of increased production of native plus exotic species, although the grass biomass at that time is not known. The fuel threshold for exotic grass biomass has been estimated at 0.5 to 1.0 T/ha dry matter (Fenn et al. 2003a). This level of biomass was produced in Pinto Wash in quadrats located just beyond the dripline of shrubs (50-70 g/m^2), but a fire would not be expected because the grass cover is discontinuous in the interspaces. More recent fires occurred at Snow Creek (450 ha, July 2004) and Morongo Valley (1250 ha, August 2005). Both sites lie just to the west of JOTR in areas of higher air pollution (Tonnesen et al. 2003), and we measured 20 μg/g soil N at Snow Creek, enough to trigger a growth response by exotic grasses. The exotic species that burned at Snow Creek were *Schismus* spp. and *Brassica tournefortii*, while the higher elevation Morongo Valley fire was primarily in areas colonized by *Bromus madritensis*. Typical for burned desert vegetation, recovery of native shrubs at Covington Flat and Snow Creek is slow (personal observations of the authors), and Snow Creek remains densely covered with exotic species.

Conclusions

This study has shown that a large pulse of 30 kg/ha N added over two years increased the biomass of exotic grass and either increased or decreased native forb richness depending on initial exotic grass production. However, the lower fertilizer level of 5 kg N/ha increased the cover of exotic grasses in two of the sites (Pinto Wash and Covington Flat) in 2005, a year with three times normal precipitation and following three years of fertilization. Furthermore, native forb cover increased with 5 kgN/ha in 2005 at Pine City, a site of low exotic grass cover. Thus even a low level of N input will affect grass production, and 5 kg/ha may be considered the threshold for response at this time. Wide Canyon already receives more than 5 kg N/ha deposition, so we can assume that the coverage of exotic grass measured there is higher than historic levels, and the 15 μg N/g extractable N in 2004 is sufficient to promote elevated exotic grass production.

Covington Flat with 12.4 kg N/ha deposition across the landscape had the highest grass cover in 2006 of the four sites, and well exceeds 5 kg N/ha deposition. The high grass cover in Pinto Wash may be related to the finer soil texture compared to the other sites, but 3.4 kg N/ha exceeds the amount of deposition we expected there. The new plots with 2 kg/ha fertilizer may help to determine whether there is an even lower detectable threshold.

Acknowledgments

We thank Leela Rao, Sheila Kee, Tracy Tennant, Abby Sirulnik, Cecilia Osorio, Greg Smith, Christopher True, Robin Marushia, William Swenson, Sarah Huels, Susan Determann, Tim Blubaugh, Tony Davila, Diane Alexander and Dave Jones for assistance in the field and lab. This research was funded by the National Park Service PMIS Number 72123.

Literature Cited

Aber, J., W. McDowell, K. 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.

Allen, E.B. 2004. Restoration of *Artemisia* shrublands invaded by exotic annual *Bromus*: A comparison between southern California and the Intermountain Region. Pp. 9-17 *in* A.L. Hild, N.L. Shaw, S.E. Meyer, E.W. Schupp, and T. Booth, compilers. Seed and Soil Dynamics in Shrubland Ecosystems: Proceedings; August 12-16, 2002, Laramie, Wyoming, Proceedings RMRS-P-31. U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Ogden, Utah. http://www.rfl.psw.fs.fed.us/pubs/psw-gtr-164/fulltext/allen/allen.html#anchor1473574

Allen, E. B., P. E. Padgett, A. Bytnerowicz, and R. A. Minnich. 1998. Nitrogen deposition effects on coastal sage vegetation of southern California. Pages 131-140 *in* Proceedings of the International Symposium on Air Pollution and Climate Change Effects on Forest Ecosystems. USDA Forest Service, Pacific Southwest Research Station, Riverside, CA.

Alonso, R., A. Bytnerowicz, J. L. Yee, and W. I. Boarman. 2005. Atmospheric dry deposition in the vicinity of the Salton Sea, California - II: Measurement and effects of an enhanced evaporation system. Atmospheric Environment **39**:4681-4689.

Alonso, R., M. J. Arbaugh, A. Bytnerowicz. 2003. Forest health research on a natural air pollution gradient in the San Bernardino Mountains, southern California, Ekologia (Bratislava), 22, 18-23.

Baumgardner, R. E., T. F. Lavery, C. M. Rogers, and S. S. Isil. 2002. Estimates of the atmospheric deposition of sulfur and nitrogen species: Clean air status and trends network, 1990-2000. Environmental Science & Technology **36**:2614-2629.

Bobbink, R., M. Hornung, and J. G. M. Roelofs. 1998. The effects of air-borne nitrogen pollutants on species diversity in natural and semi-natural European vegetation. Journal of Ecology **86**:717-738.

Bowman, W. D., and H. Steltzer. 1998. Positive feedbacks to anthropogenic nitrogen deposition in Rocky Mountain Alpine tundra. Ambio **27**:514-517.

Brooks, M. L. 1999. Alien annual grasses and fire in the Mojave Desert. Madrono **46**:13-19.

Brooks, M. L. 2000. Competition between alien annual grasses and native annual plants in the Mojave Desert. American Midland Naturalist 144: 92-108.

Brooks, M. L. 2003. Effects of increased soil nitrogen on the dominance of alien annual plants in the Mojave Desert. Journal of Applied Ecology **40**:344-353.

Brooks, M.L., C.M. D'Antonio, D.M. Richardson, J.B. Grace, J.E. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. Bioscience 54: 677-688

Bytnerowicz, A., J. J. Carroll, B. Takemoto, P. R. Miller, M. E. Fenn, and R. C. Musselman. 2000. Distribution and transport of air pollutants to vulnerable California ecosystems. Pages 93-118 *in* K. M. Scow, G. E. Fogg, D. E. Hinton, and M. J. Johnson, editors. Integrated Assessment of Ecosystem Health. Lewis Publishers, Boca Raton, FL.

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.

Bytnerowicz, A., D. M. Olszyk, C. A. Fox, P. J. Dawson, G. Kats, C. L. Morrison, and J. Wolf. 1988. Responses of desert annual plants to ozone and water stress in an insitu experiment. Japca-the International Journal of Air Pollution Control and Hazardous Waste Management **38**:1145-1151.

Bytnerowicz, A., P. E. Padgett, M. J. Arbaugh, D. R. Parker, and D. P. Jones. 2001. Passive sampler for measurement of atmospheric nitric acid vapor (HNO_3) concentrations. TheScientificWorld 1 (S2): 433-439.

CASTNET (Clean Air and Status Trends Network). 2005. http://www.epa.gov/castnet/sites/jot403.html

DeFalco, L. A., J. K. Detling, C. R. Tracy, and S. D. Warren. 2001. Physiological variation among native and exotic winter annual plants associated with microbiotic crusts in the Mojave Desert. Plant and Soil **234**:1-14.

Edinger, J. G., M. H. McCutchan, P. R. Miller, B. C. Ryan, M. Schroeder, and J. V. Behar. 1972. Penetration and duration of oxidant air pollution in the South Coast Air Basin of California. Journal of the Air Pollution Control Association **22**:881-886.

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. 2003a. Ecological effects of nitrogen deposition in the western United States. Bioscience **53**:404-420.

Fenn, M. E., G. S. Haeuber, J. S. Tonnesen, J. S. Baron, S. Grossman-Clarke, D. Hope, D. A. Jaffe, S. Copeland, L. Geiser, H. M. Rueth, and J. O. Sickman. 2003b. Nitrogen emissions, deposition and monitoring in the western United States. Bioscience **53**:391-403.

Fenn, M.E., and Poth, M.A. 2004. Monitoring nitrogen deposition in throughfall using ion exchange resin columns: A field test in the San Bernardino Mountains. J. Environ. Qual. 33:2007-2014.

Fenn, M. E., M. A. Poth, J. D. Aber, J. S. Baron, B. T. Bormann, D. W. Johnson, A. D. Lemly, S. G. McNulty, D. E. Ryan, and R. Stottlemyer. 1998. Nitrogen excess in North American ecosystems: Predisposing factors, ecosystem responses, and management strategies. Ecological Applications **8**:706-733.

Fenn, M. E., J. O. Sickman, A. Bytnerowicz, D. W. Clow, N. P. Molotch, J. E. Pleim, G. S. Tonnesen, K. C. Weathers, P. E. Padgett, and D. H. Campbell. submitted. Methods for measuring atmospheric nitrogen deposition inputs in arid and montane ecosystems of western North America. *in* A. H. Legge, editor. Developments in Environmental Science: Relating Atmospheric Source Apportionment to Vegetation Effects: Establishing Cause Effect Relationships. Elsevier, Amsterdam.

Hickman, J.C., editor. 1993. The Jepson Manual: Higher Plants of California. University of California Press, Berkeley.

Koutrakis, P., J. M. Wolfson, A. Bunyaviroch, S. E. Froehlich, K. Hirano, and J. D. Mulik. 1993. Measurement of ambient ozone using a nitrite-coated filter. Analytical Chemistry **65**:209-214.

Padgett, P. E., and E. B. Allen. 1999. Differential responses to nitrogen fertilization in native shrubs and exotic annuals common to Mediterranean coastal sage scrub of California. Plant Ecology **144**:93-101.

Padgett, P. E., E. B. Allen, A. Bytnerowicz, and R. A. Minich. 1999. Changes in soil inorganic nitrogen as related to atmospheric nitrogenous pollutants in southern California. Atmospheric Environment **33**:769-781.

Pastor, J., J. D. Aber, C. A. Mcclaugherty, and J. M. Melillo. 1984. Above-ground production and N and P cycling along a nitrogen mineralization gradient on Blackhawk Island, Wisconsin. Ecology **65**:256-268.

Pregitzer, K.S., J.L. DeForest, A.J. Burton, M.F. Allen, R.W. Ruess, and R.L. Hendrick. 2002. Fine root length, diameter, specific root length and nitrogen concentrations of nine tree species across four North American Biomes. Ecological Monographs 72: 293-309.

Salo, L. F., G. R. McPherson, and D. G. Williams. 2005. Sonoran desert winter annuals affected by density of red brome and soil nitrogen. American Midland Naturalist **153**:95-109.

Stevens, C. J., N. B. Dise, J. O. Mountford, and D. J. Gowing. 2004. Impact of nitrogen deposition on the species richness of grasslands. Science **303**:1876-1879.

Sullivan, T. J., C. L. Peterson, C. L. Blanchard, and S. J. Tanenbaum. 2001. Assessment of quality and air pollutant impacts in class I national parks of California. unpublished report National Park Service-Air Resources Division.

Theodose, T. A., and W. D. Bowman. 1997. Nutrient availability, plant abundance, and species diversity in two alpine tundra communities. Ecology **78**:1861-1872.

Thompson, C. R., D. M. Olszyk, G. Kats, A. Bytnerowicz, P. J. Dawson, and J. W. Wolf. 1984. Effects of ozone or sulfur-dioxide on annual plants of the Mojave Desert. Journal of the Air Pollution Control Association **34**:1017-1022.

Tonnesen, G. S., Z. Wang, M. Omary, and C.J. Chien. 2003. Formulation and application of regional air quality modeling for integrated assessments of urban and wildland pollution. Pages 285-298 *in* A. Bytnerowicz, M. J. Arbaugh, and R. Alonso, editors. Ozone Air Pollution in the Sierra Nevada: Distribution and Effects on Forests. Elsevier Press, Amsterdam.

Treseder, K.K., M.F. Allen, R.W. Ruess, K.S. Pregitzer, and R.L. Hendrick. 2005. Lifespans of fungal rhizomorphs under nitrogen fertilization in a pinyon-juniper woodland. Plant and Soil 270: 249-255.

Treseder, K.K., C.A. Masiello, J.L. Lansing, and M.F. Allen. 2004. Species-specific measurements of ectomycorrhizal turnover under N-fertilization: Combining isotopic and genetic approaches. Oecologia 138: 419-425.

Walvoord, M. A., F. M. Phillips, D. A. Stonestrom, R. D. Evans, P. C. Hartsough, B. D. Newman, and R. G. Striegl. 2003. A reservoir of nitrate beneath desert soils. Science **302**:1021-1024.

Wood, Y.A., T. Meixner, P.J. Shouse, and E.B. Allen. 2006. Altered ecohydrologic response drives native shrub loss under conditions of elevated N-deposition. Journal of Environmental Quality **35**: in press.

Yoshida, L. C., and E. B. Allen. 2001. Response to ammonium and nitrate by a mycorrhizal annual invasive grass and native shrub in southern California. American Journal of Botany **88**:1430-1436.

Yoshida, L. C., and E. B. Allen. 2004. N-15 uptake by mycorrhizal native and invasive plants from a N-eutrophied shrubland: a greenhouse experiment. Biology and Fertility of Soils **39**:243-248.

Table 1. Percent cover of the most abundant native species in 0.5 m^2 quadrats at four sites under two N fertilization levels and an unfertilized control. There were no significant differences for any of these species when analyzed individually, as there were many zero values for each species. Quadrats were placed just beyond the dripline of either *Larrea tridentata* (Pinto wash, Wide Canyon), or *Pinus monophylla* and *Juniperus californica* (Pine City, Covington Flat). Other species in sample quadrats that had less than 1% cover (total at four sites) are listed below.

	Pinto Wash			Wide Canyon			Pine City			Covington Flat		
N treatment (kg/ha):	**0**	**5**	**30**	**0**	**5**	**30**	**0**	**5**	**30**	**0**	**5**	**30**
Chaenactis fremontii		1.3		3.7	2.2	1.9						
C. stevioides							2.6	4.3	3.8		1.7	1.9
Coleogyne ramosissima								2.2				
Cryptantha angustifolia				6.6	4.9	8.2						
C. pterocarya							1.5	3.2	4.8			2.9
Descurainia pinnata							2.3	3.0	4.0			
Euphorbia polycarpa				1.2								
Gilia stellata							1.5	1.1	1.6			
Malacothrix glabrata				2.5	2.0	2.0						
Mentzelia affinis										1.2	3.3	
Mirabilis californica												1.6
Pectocarya recurvata				1.5	1.5	1.4						
Phacelia distans								2.4	2.9	4.5	4.8	5.8
Poa secunda												1.1
Salvia columbariae	8.3									1.4		

Other species with < 1% cover:
Shrubs (20 species):
Brickellia californica, Crysothamnus nauseosus, Echinocereus engelmannii, Ephedra nevadensis, Eriogonum fasciculatum, E. wrightii, Eriophyllum confertiflorum, E. wallacei, Gutierrezia microcephala, G. sarothrae, Hymenoclea salsola, Juniperus californica, Lycium andersonii, Nolina parryi, Opuntia erinacea, Purshia tridentata, Quercus dumosa, Salazaria mexicana, Viguirera parishii, Yucca schidigera
Perennial grasses (5):
Achnatherum lettermanii, A. speciosum, Aristida adscenscionis, Elymus elymoides, Erioneuron pulchellum
Annual forbs (57):
Adenophyllum porophylloides, Amsinkia tessellata, Anisocoma acaulis, Arabis pulchra, Arenaria macrademia, Calycoceris parryi, Calyptridium monandrum, Camissonia californica, C. campestrus, C. claviformis, C. pallida, Castelleja angustifolia, Caulanthus cooperi, Centrostegia thurberi, Chaenactis macrantha, Chorizanthe brevicornu, Crassula connata, Cryptantha barbigera, C. circumscissa, C. maritima, C. micrantha, C. nevadensis, C. utahensis, Draba cuneifolia, Eriogonum davidsonii, E. maculatum, E.

nidularium, E. pusillum, Eriastrum diffusum, Eschscholzia minutiflora, Eucrypta chrysanthemifolia, Euphorbia albomarginata, Filago arizonica, F. depressa, Layia glandulosa, Lepidium lasiocarpum, L. aureus, Linanthus biglovii, L. dichotomous, L. jonesii, Loeseliastrum matthewsii, Lotus strigosus, Lupinus concinnus, Mentzelia sp., Nama demissum, Nemophila menziesii, Pectocarya heterocarpa, P. penicillata, P. platycarpa, P. setosa, Phacelia ciliata, P. cryptantha, Plantago ovata, P. patagonica, Rafinesquia neomexicana, Syntrichopappus fremontii, Thysanocarpus curvipes, Uropappus lindleyi

Perennial forbs (15):

Allium parishii, Astragalus bernardanus, A. lentiginosus, A. nuttallianus, Calochortus kennedyi, Delphinium parishii, Dichelostemma capitatum, Dudleya saxosa, Eriogonum inflatum, Lomatium mohavense, Lotus argophyllus, L. rigidus, Mirablis bigelovii, Sphaeralcea ambigua, Stephanomeria exigua

Nomenclature from Hickman (1993).

Table 1. Soil nutrient and physical characteristics of four N fertilizer sites at JOTR.

Site	ppm Olsen P	% Total P	% Total N	% C	% Clay	% Sand	pH
Covington Flat	8.67	0.101	0.078	0.71	1.1	87.5	6.8
Pine City	8.57	0.078	0.072	0.84	3.1	74.8	7.7
Wide Canyon	6.68	0.150	0.052	0.31	1.5	88.3	7.1
Pinto Wash	2.68	nd	<0.04	0.22	1.0	81.1	7.9

Table 2. Nitrogen deposition collected as throughfall under pinyon pine and in the open. Stand level estimates calculated assuming a 20% cover of trees/tall shrubs at Pine City and 27% cover at Covington Flat.

	Throughfall and Open--N Values			Annual Stand Level Estimates		
	NO3-N	NH4-N	Total	NO3-N	NH4-N	Total
Site & Deposition type	kg/ha			kg/ha		
Covington Flat Throughfall	19.35	16.88	36.23	6.74	5.63	12.37
Pine City Throughfall	10.15	12.98	23.13	2.84	3.34	6.17
Covington Flat Open	2.26	1.60	3.86			
Pine City Open	1.28	1.17	2.45			
Wide Canyon Open	2.13	3.11	5.24	2.13	3.11	5.24
Pinto Wash Open	1.62	1.73	3.35	1.62	1.73	3.35

Figure captions

Figure 1. Map of air, soil, and vegetation sample sites at Joshua Tree National Park. The N fertilization experiments were carried out at the sites underlined, Wide Canyon (high atmospheric reactive N, creosote scrub) and Pinto Wash (low N, creosote scrub), and Covington Flat (high N, pinyon-juniper woodland) and Pine City (low N, pinyon-juniper woodland).

Figure 2. Nitric acid concentration ($\mu g/m^3$) in the atmosphere over Joshua Tree National Park in February (upper) and July (lower), 2004.

Figure 3. Ammonium concentration ($\mu g/m^3$) in the atmosphere over Joshua Tree National Park in February (upper) and July (lower), 2004.

Figure 4. Ozone concentration (ppb) in the atmosphere over Joshua Tree National Park in February (upper) and July (lower), 2004.

Figure 5. Extractable soil N as NH_4^+ and NO_3^- in the top 1 cm at four sites in Joshua Tree National Park used for intensive study of atmospheric N deposition on plants and soils.

Figure 6. Extractable soil N as NH_4^+ and NO_3^- in 22 sites in Joshua Tree National Park and one site west of the Park (Snow Creek) in July 2004 and July 2005 (map, Fig. 1).

Figure 7. Extractable soil N as NH_4^+ and NO_3^- in plots fertilized with NH_4NO_3 in a) 2004 and 2006 at three levels (5, 15, and 30 kg/ha) at four sites, Covington Flat, Wide Canyon, Pine City, and Pinto Wash, and b) in 2006 at four levels (2, 5, 15, and 30 kg/ha) at the same sites; but the 30 kg/ha level was discontinued after 2005.

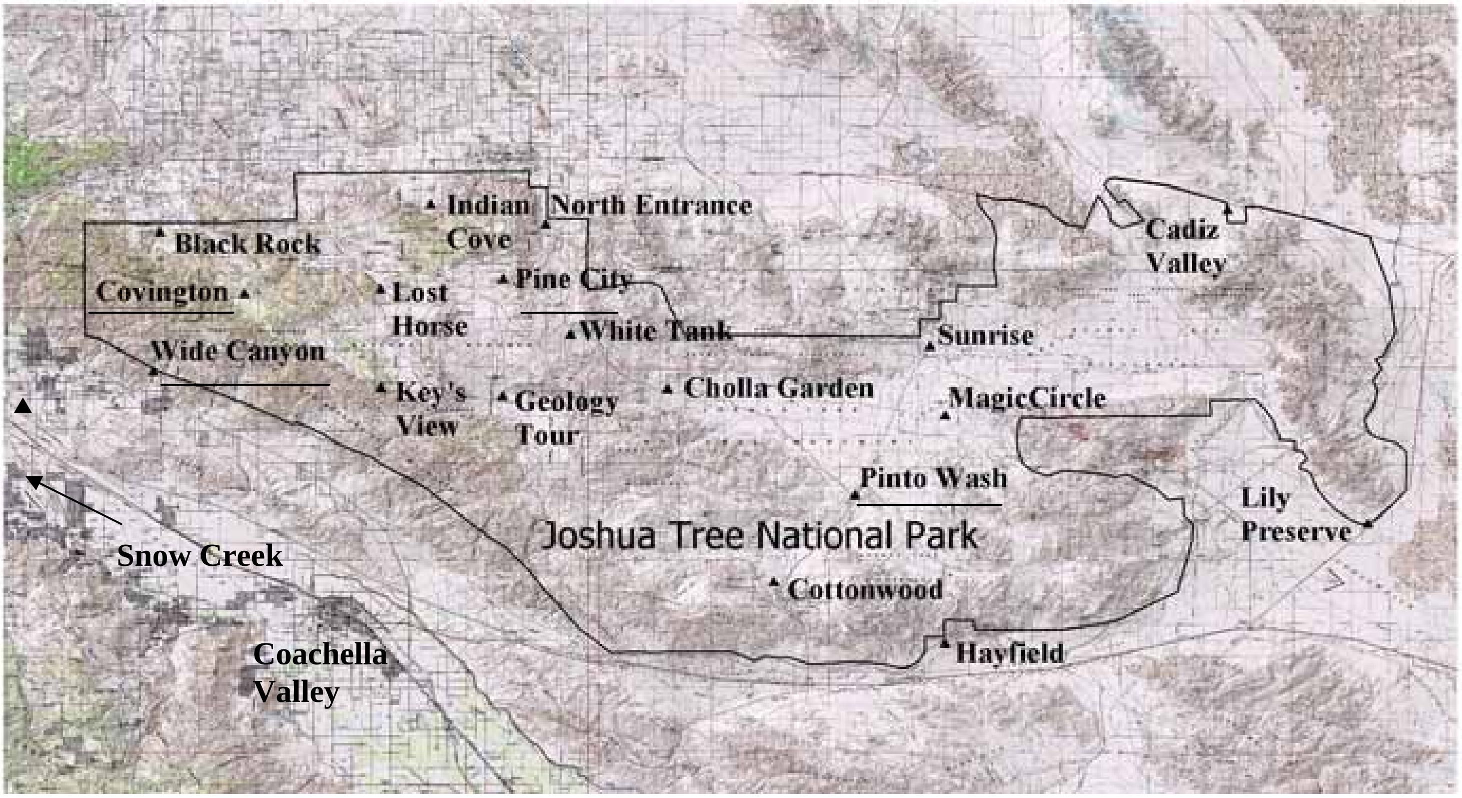
Figure 8. Dry weight of exotic grass in Mar-Apr 2004 following N fertilization at 5 and 30 kg/ha at four sites. Exotic grasses were primarily *Schismus barbatus* at Wide Canyon and Pinto Wash, and *Bromus madritensis* at Covington Flat and Pine City. Different letters above bars indicate significantly different at $p = 0.05$.

Figure 9. Percent cover of exotic species and native herbaceous species during Mar-Apr in a) 2004, b) 2005 and c) 2006 following N fertilization at 5 and 30 kg/ha at four sites. The 2 kg/ha treatment was added in December 2005, and fertilization ceased for the 30 kg/ha treatment at that time. There were no significant differences among treatments in 2006. See Table 1 for list of species. Different letters above bars indicate significantly different at $p = 0.05$.

Figure 10. Richness (number/$0.5m^2$) of native herbaceous species in Mar-Apr 2004 following N fertilization for two years at 5 and 30 kg/ha at four sites. See Table 1 for list of species. Different letters above bars indicate significantly different at $p = 0.05$.

Figure 11. Relationship of extractable N in July 2005 to percent cover of exotic grass (*Bromus madritensis* and *Schismus barbatus*) and native forbs. Neither regression is significant.

Fig. 1


Indian Cove
North Entrance
Black Rock
Cadiz Valley
Covington
Lost Horse
Pine City
White Tank
Sunrise
Wide Canyon
Key's View
Geology Tour
Cholla Garden
MagicCircle
Pinto Wash
Lily Preserve
Snow Creek
Joshua Tree National Park
Cottonwood
Coachella Valley
Hayfield

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Figure 2.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Figure 3

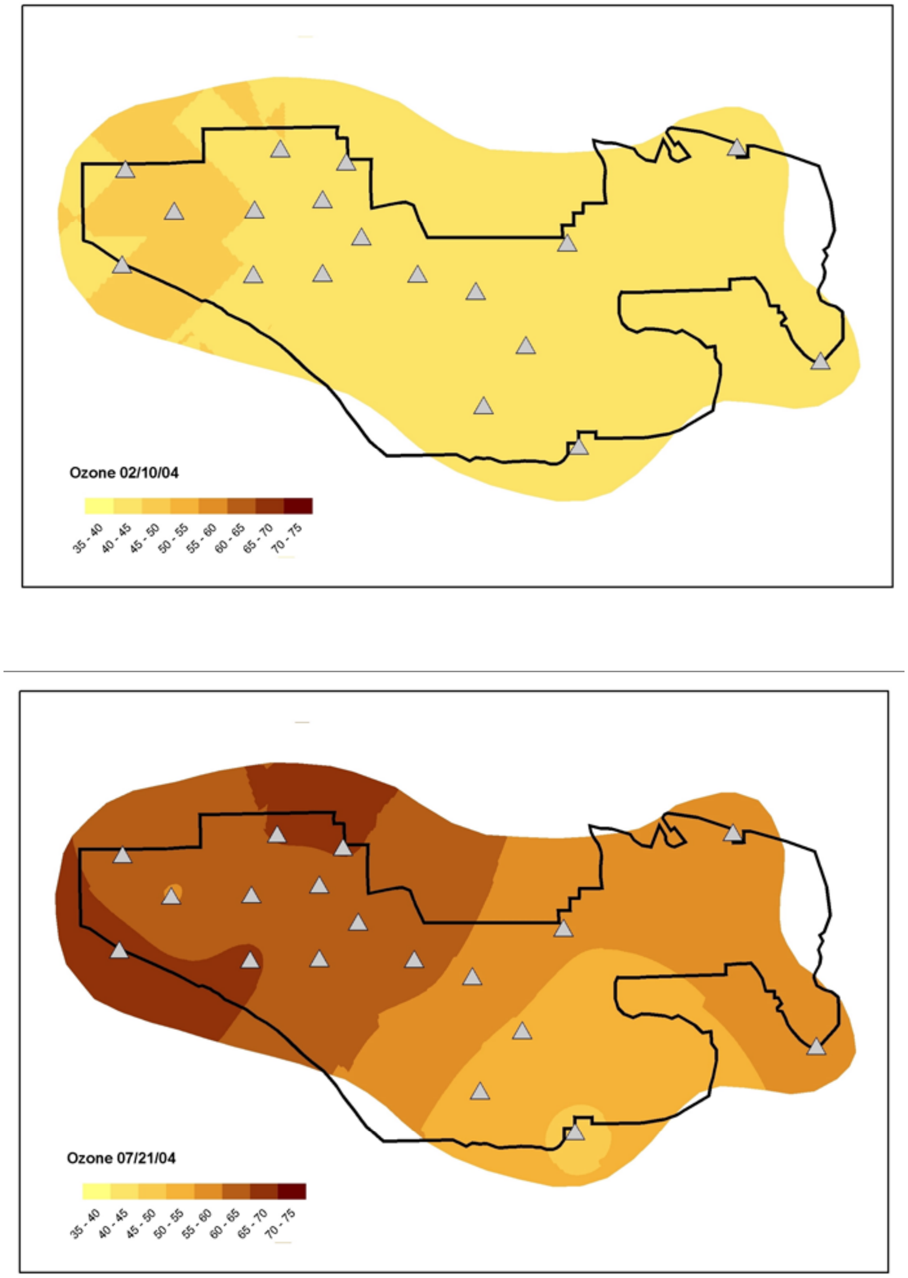
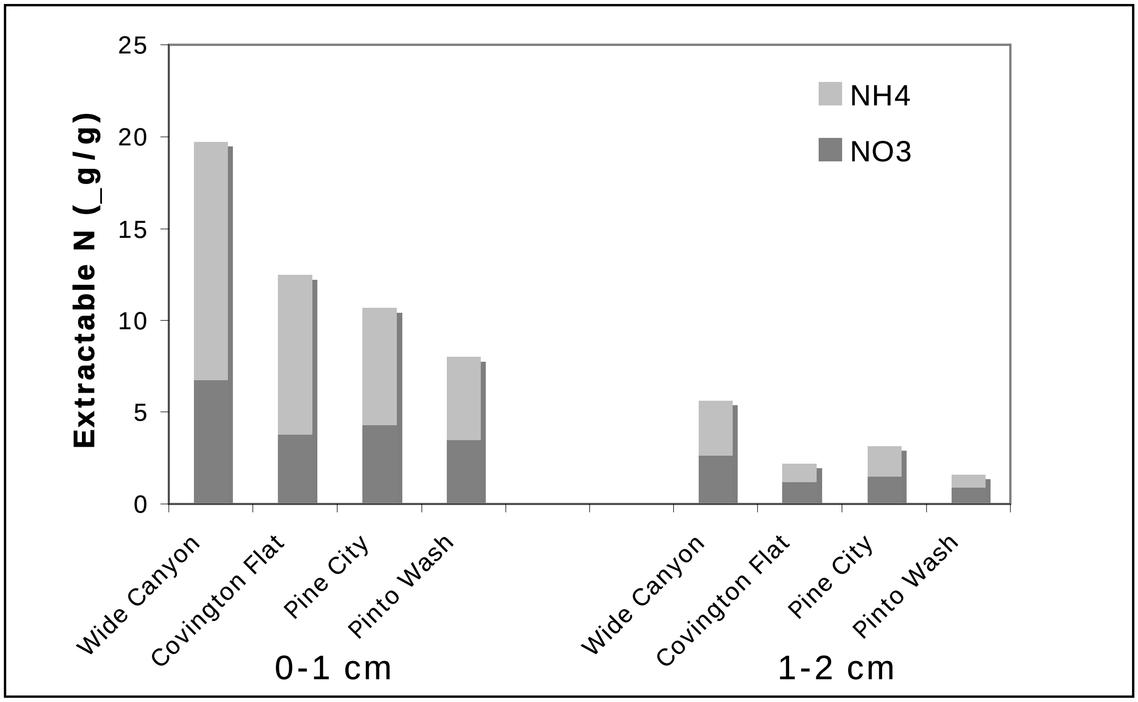

Ozone 02/10/04
35 - 40
40 - 45
45 - 50
50 - 55
55 - 60
60 - 65
65 - 70
70 - 75
Ozone 07/21/04
35 - 40
40 - 45
45 - 50
50 - 55
55 - 60
60 - 65
65 - 70
70 - 75

Figure 4

Fig. 5.


Extractable N (_g/g)
25
20
15
10
5
0
NH4
NO3
Wide Canyon
Covington Flat
Pine City
Pinto Wash
Wide Canyon
Covington Flat
Pine City
Pinto Wash
0-1 cm
1-2 cm

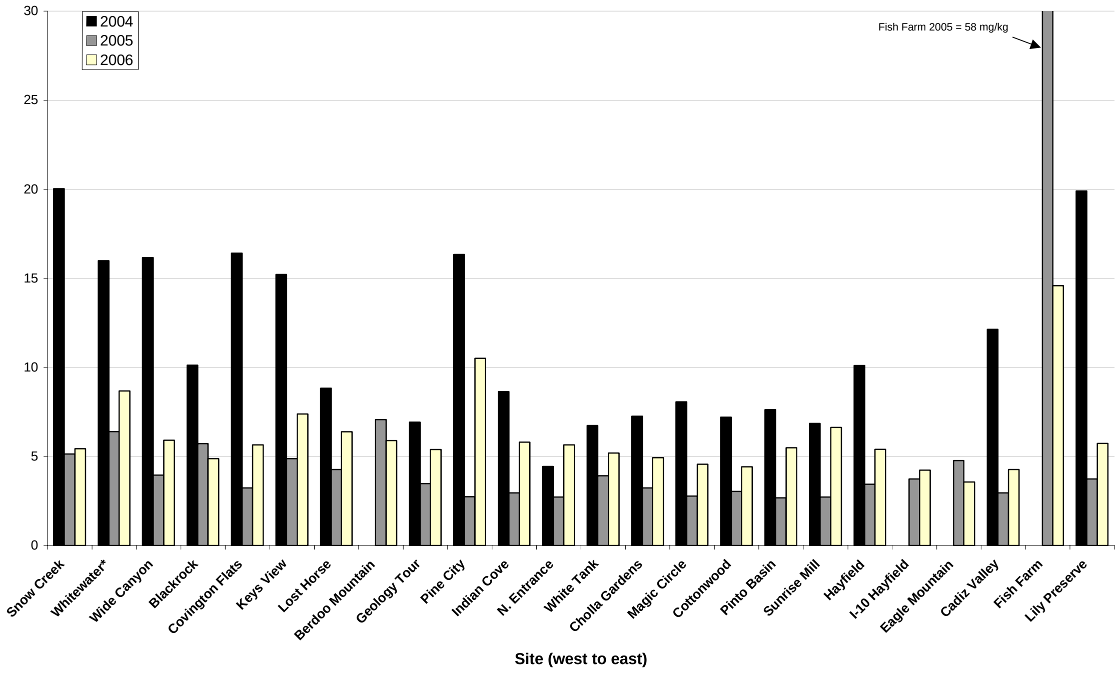

30
25
20
15
10
5
0
2004
2005
2006
Fish Farm 2005 = 58 mg/kg
Snow Creek
Whitewater*
Wide Canyon
Blackrock
Covington Flats
Keys View
Lost Horse
Berdoo Mountain
Geology Tour
Pine City
Indian Cove
N. Entrance
White Tank
Cholla Gardens
Magic Circle
Cottonwood
Pinto Basin
Sunrise Mill
Hayfield
I-10 Hayfield
Eagle Mountain
Cadiz Valley
Fish Farm
Lily Preserve
Site (west to east)

Figure 6

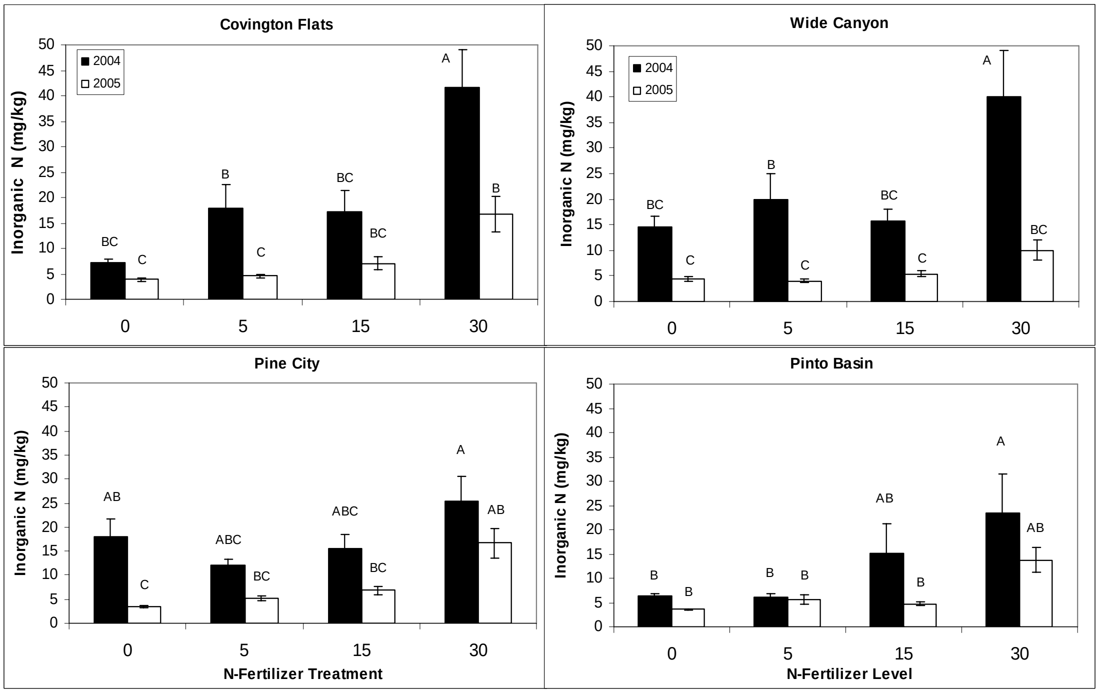

Covington Flats
Wide Canyon
Pine City
Pinto Basin
■ 2004
□ 2005
Inorganic N (mg/kg)
0
5
10
15
20
25
30
35
40
45
50
0
5
15
30
BC
C
B
C
BC
BC
A
B
BC
C
B
C
BC
C
A
BC
AB
C
ABC
BC
ABC
BC
A
AB
B
B
B
B
AB
B
A
AB
N-Fertilizer Treatment
N-Fertilizer Level

Fig. 7a

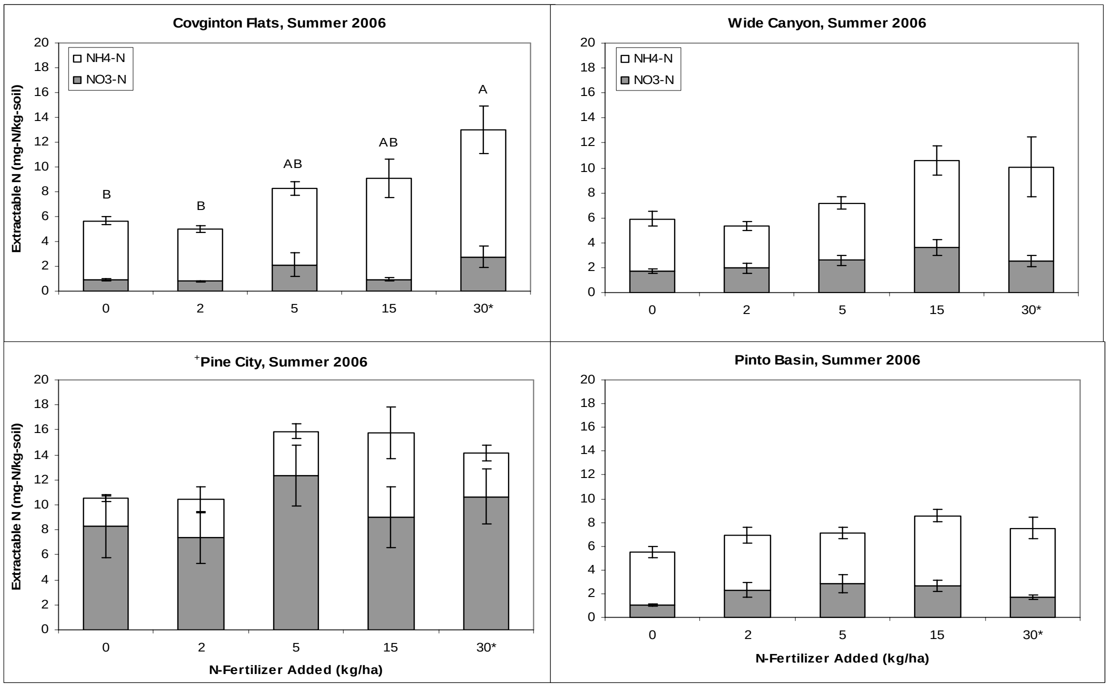

Covginton Flats, Summer 2006
Wide Canyon, Summer 2006
+Pine City, Summer 2006
Pinto Basin, Summer 2006
□ NH4-N
▨ NO3-N
Extractable N (mg-N/kg-soil)
0
2
4
6
8
10
12
14
16
18
20
0
2
5
15
30*
B
B
AB
AB
A
N-Fertilizer Added (kg/ha)

Fig. 7b

Figure 8

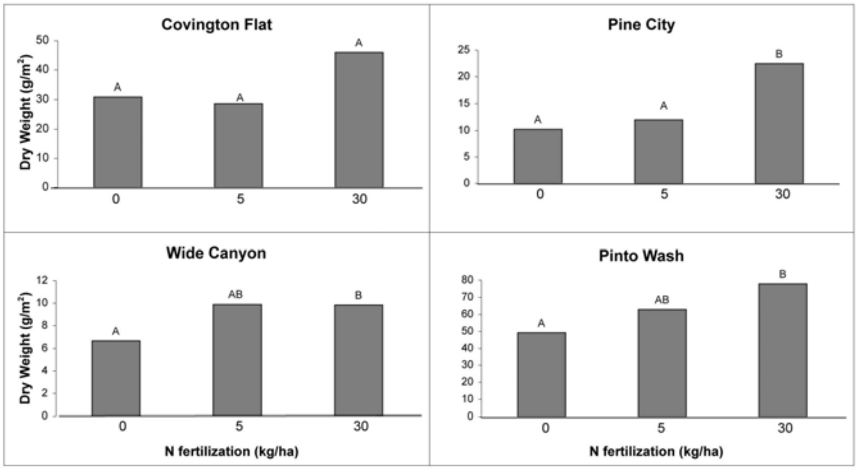

Covington Flat
Dry Weight (g/m^2)
50
40
30
20
10
0
A
A
A
0
5
30
Pine City
25
20
15
10
5
0
A
A
B
0
5
30
Wide Canyon
Dry Weight (g/m^2)
12
10
8
6
4
2
0
A
AB
B
0
5
30
N fertilization (kg/ha)
Pinto Wash
80
70
60
50
40
30
20
10
0
A
AB
B
0
5
30
N fertilization (kg/ha)

Figure 9a. 2004

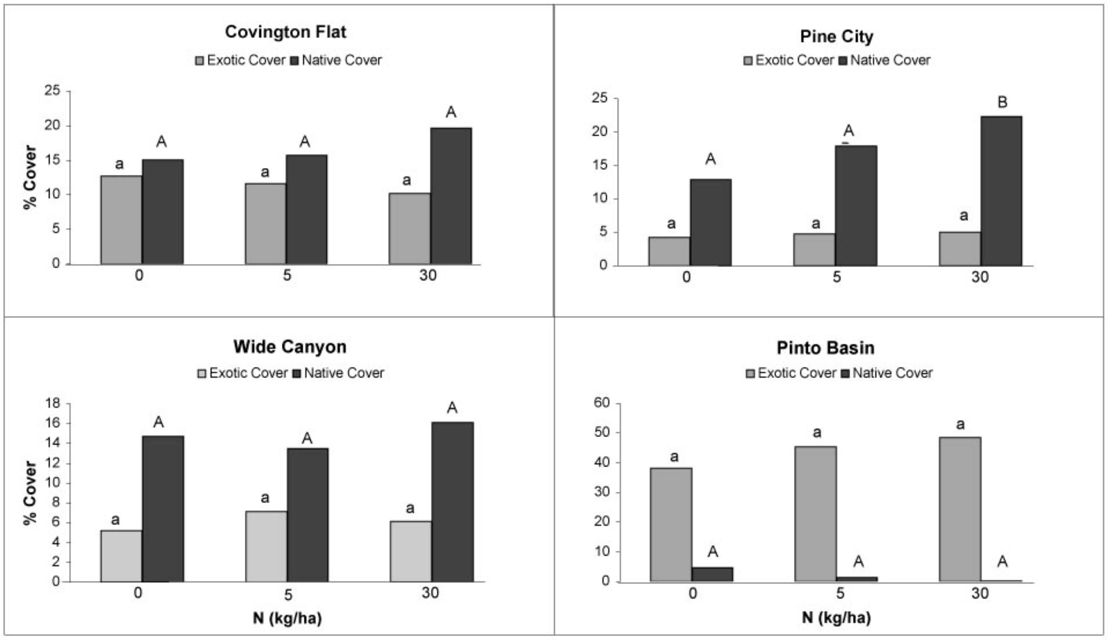


Figure 9b. 2005

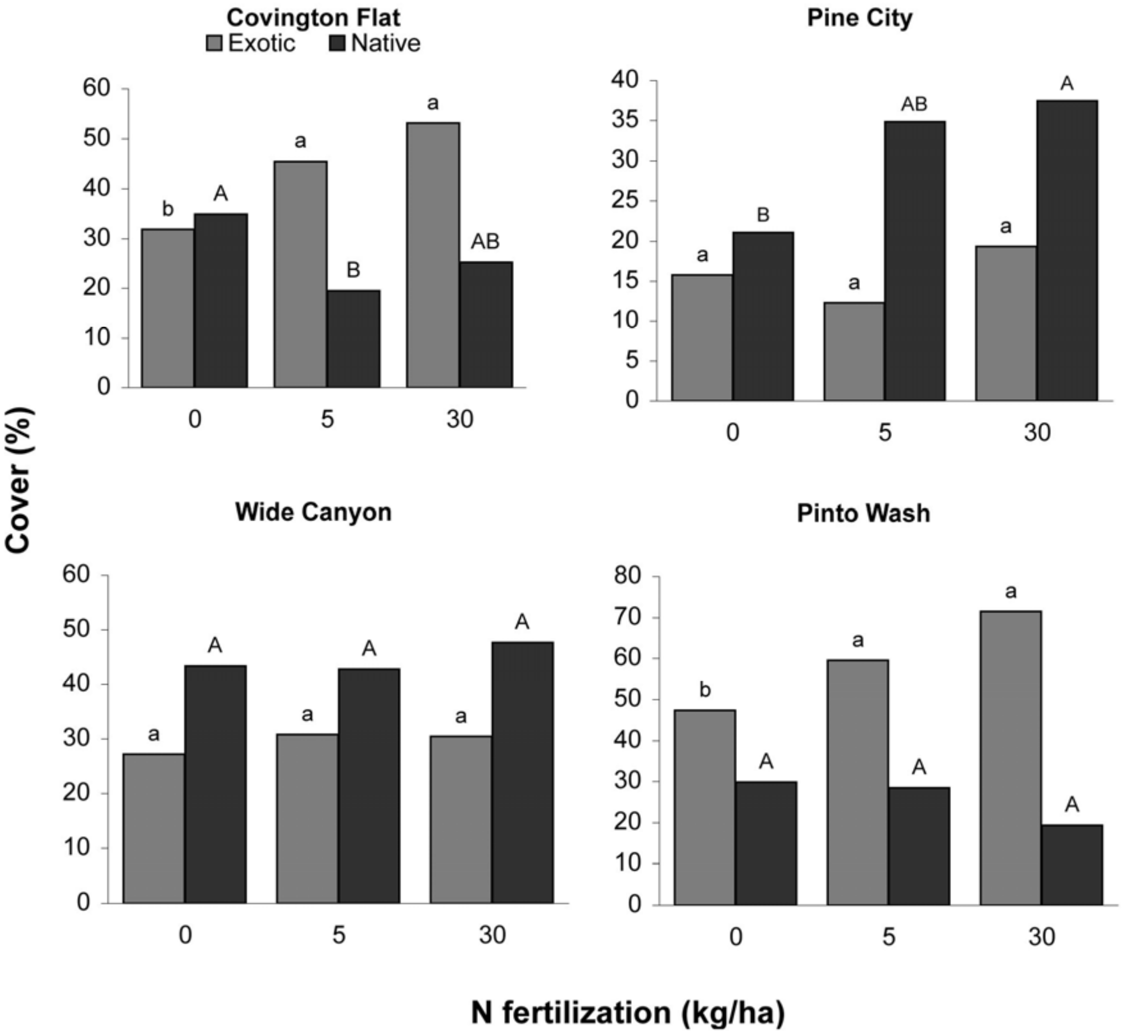


Fig. 9c. 2006

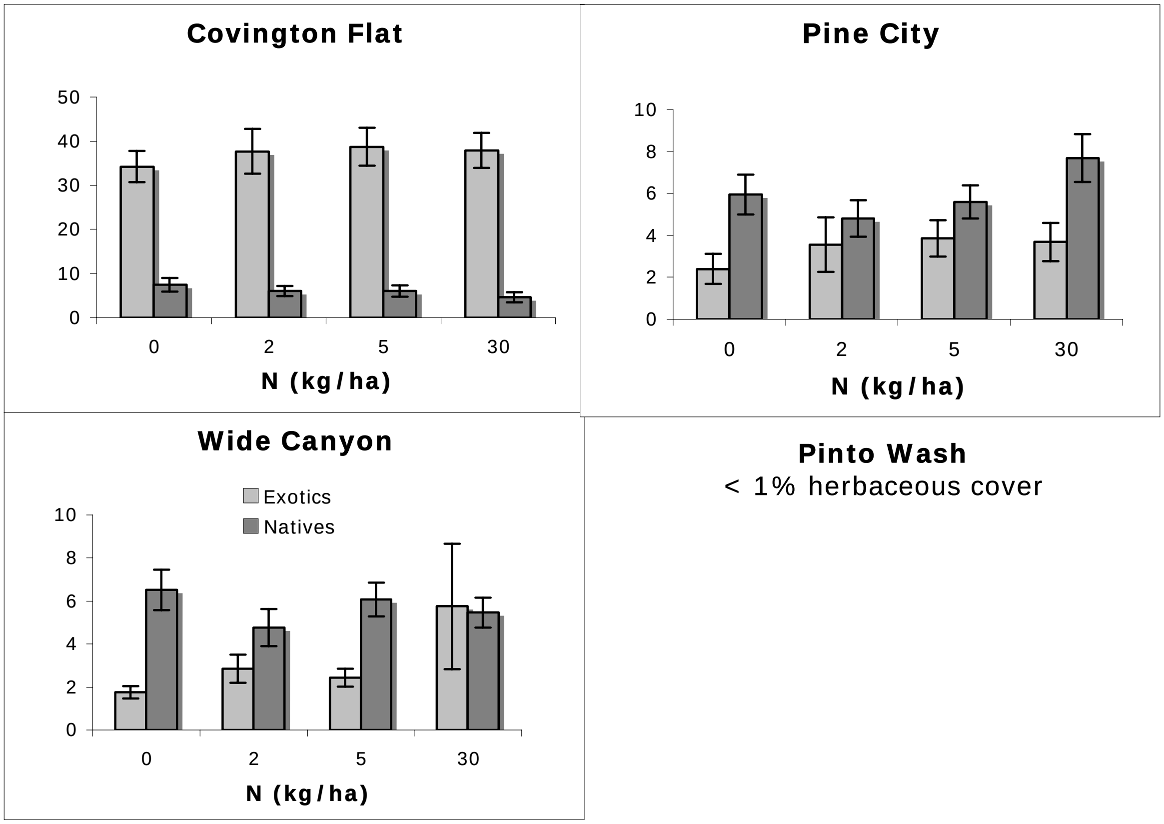

Covington Flat
50
40
30
20
10
0
0
2
5
30
N (kg/ha)
Pine City
10
8
6
4
2
0
0
2
5
30
N (kg/ha)
Wide Canyon
Exotics
Natives
10
8
6
4
2
0
0
2
5
30
N (kg/ha)
Pinto Wash
< 1% herbaceous cover

Figure 10

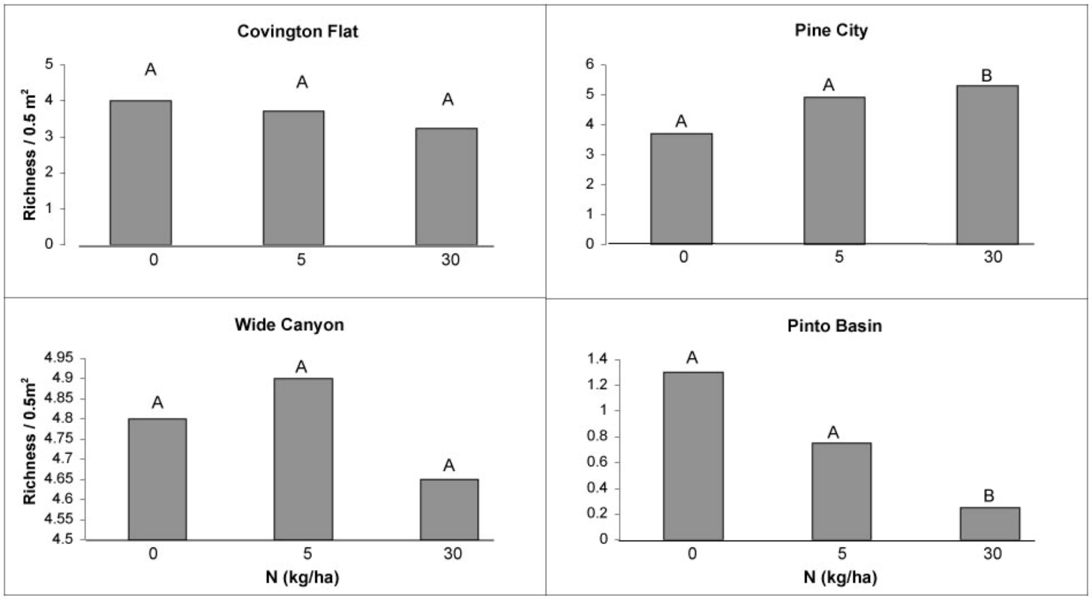
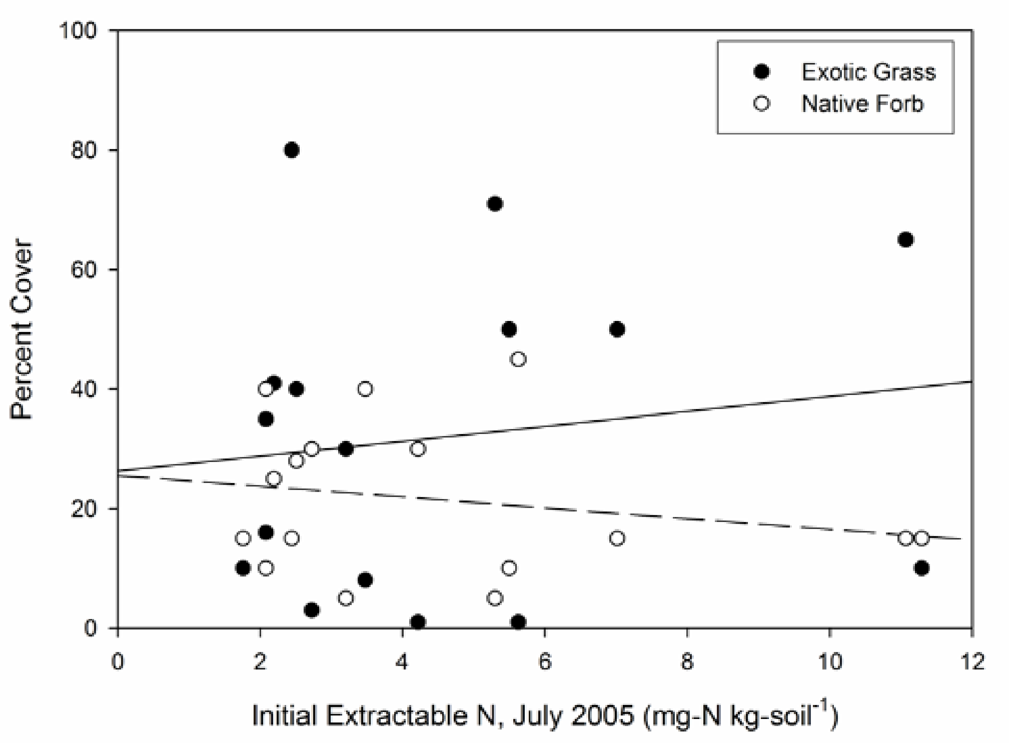

Covington Flat
Richness / 0.5 m²
5
4
3
2
1
0
A
A
A
0
5
30
Pine City
6
5
4
3
2
1
0
A
A
B
0
5
30
Wide Canyon
Richness / 0.5m²
4.95
4.9
4.85
4.8
4.75
4.7
4.65
4.6
4.55
4.5
A
A
A
0
5
30
N (kg/ha)
Pinto Basin
1.4
1.2
1
0.8
0.6
0.4
0.2
0
A
A
B
0
5
30
N (kg/ha)

Figure 11.


100
80
60
40
20
0
Percent Cover
0
2
4
6
8
10
12
Initial Extractable N, July 2005 (mg-N kg-soil^{-1})
● Exotic Grass
○ Native Forb