Atmospheric nitrogen deposition in the northern Chihuahuan desert: Temporal trends and potential consequences

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Abstract

Rates and impacts of atmospheric nitrogen (N) deposition are poorly understood in arid land ecosystems where soils are typically low in plant available N. To address this issue, we quantified long-term trends in N deposition and estimated its impact on plant community structure in the northern Chihuahuan desert of Central New Mexico, USA. Annual and seasonal rates of N deposition were strongly positively correlated with precipitation. When precipitation effects were removed statistically, N deposition increased at an annual rate of $0.049 \, \text{kg} \, \text{ha}^{-1} \, \text{yr}^{-1}$ between 1989 and 2004. Based on two independent fertilization studies at our desert grassland field site, continued atmospheric inputs are likely to increase grass cover, decrease legume abundance, and may favor blue grama (*Bouteloua gracilis*) at the expense of the current dominant species, black grama (*Bouteloua eriopoda*). We conclude that, although arid lands have low rates of N deposition and are primarily water limited, observed trends in N deposition rates may lead to significant changes in plant community structure.

1. Introduction

Nitrogen (N) is often considered to be the key limiting nutrient in terrestrial ecosystems (Vitousek and Howarth, 1991). Although water is considered to be the main driver of

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ecosystem processes in most arid areas, N may limit net primary production when moisture is available following rainfall events (Austin et al., 2004). N deposition in the northern temperate zone, including arid shrublands and grasslands, has increased more than five-fold during the last few decades (see Holland et al., 1999 for pre- and post-industrial estimates by biome; see also Vitousek et al., 1997; Nilles and Conley, 2001) which may have significant consequences for community structure and dynamics in these ecosystems. Agricultural and industrial activities release NO_x ($NO + NO_2$) and ammonia (NH_3) to the atmosphere where they undergo chemical changes and are eventually deposited as NO_y (mostly HNO_3) and NH_x ($NH_3^+ + NH_4^+$). These compounds are then transformed by bacterial activity into plant available forms including nitrate (NO_3^-) and ammonium (NH_4^+) depending on rainfall event size, interval and intensity (Welter et al., 2005). Hence, N deposition increases the availability of N, which may release the constraints of N limitation on arid land plant communities when soil moisture is available (Hooper and Johnson, 1999).

Anthropogenic N addition can reduce biodiversity, change the structure of plant communities, and alter ecosystem functioning (Krupa, 2002; Sala et al., 2002; Zavaleta et al., 2003; Schwinning and Sala, 2004; Stevens et al., 2004; Schwinning et al., 2005). Most research on N deposition and its effects on natural vegetation has concentrated on temperate humid regions of the northern hemisphere where industrial development has increased N deposition by at least an order of magnitude (Holland et al., 1999). However, even small amounts of N fertilization in arid and ecosystems, where N availability is chronically low to begin with (Kieft et al., 1998), may have important repercussions for biodiversity and ecosystem functioning.

In south-western North America, N deposition has increased steeply in the last two decades due to the rapid growth of urban areas, and to an increase in agriculture and animal production (Fenn et al., 2003). Recent evaluations of the rates and patterns of N deposition show that areas located near large urban centers are more prone to receive high amounts of atmospheric N (Baker et al., 2001; Burns, 2003; Fenn et al., 2003). However, for most major cities in the south-west, the actual magnitude and temporal trends in these effects are unknown.

This study examines long-term N deposition data from desert mixed grassland vegetation in the northern Chihuahuan desert, and its potential effects on the structure of native ungrazed grassland plant communities. Our objectives are to (1) quantify the temporal and seasonal rates of N deposition at the Sevilleta National Wildlife Refuge, and (2) explore the potential effects of N on plant community composition and productivity by looking at the outcomes of N addition experiments carried out at our study site.

2. Methods

2.1. Study area

This study was conducted at the Sevilleta National Wildlife Refuge (SNWR), a 100,000 ha area located along the Rio Grande Valley in Central New Mexico, USA. The Refuge is located in the transition zone between Great Plains grassland and Chihuahuan desert grassland and shrubland biomes. The area was grazed by domestic cattle until 1973. Vegetation is dominated primarily by two C_4 perennial grasses, blue grama (*Bouteloua gracilis*) and black grama (*Bouteloua eriopoda*), and a long-lived C_3 shrub, *Larrea*

tridentata (Kroel-Dulay et al., 2004). Mean annual temperature is 13.2 °C, with a low of 1.6 °C in January and a high of 25.1 °C in July. Average annual precipitation is 255 mm, approximately 60% of which occurs during the monsoon season from June through September (Gosz et al., 1995). The remainder of the precipitation during the rest of the year comes primarily from Pacific frontal systems. The relative contribution of summer monsoon and non-monsoon rains varies considerably from 1 yr to the next (e.g. over the course of this study the percentage of summer monsoon precipitation ranged from 37% in 2000 to 74% in 1999), with a greater proportion of annual precipitation falling during the monsoon season in high precipitation years.

2.2. Field methods

N deposition was measured between 1989 and 2004 in a network of six funnel precipitation collectors located throughout the Sevilleta, covering an elevation gradient between 1472–1970 m. These funnels collect all N deposited (bulk deposition) in precipitation (wet deposition) along with any dry deposition that lands in the funnel between rain events that is washed into the sample. Compared to independent dry and wet deposition measurements taken at one of the sites for the last 16 yr, the rates of N deposition measured via our method are about 17% higher (D. Moore, unpublished data, see also Welter et al., 2005). This difference presumably occurs because, when it rains, dry deposition is washed into the funnel samples. However, in wet and dry collectors, dust in the dry collector is kept dry and can blow out after rainstorms, reducing the amount of dry deposition sampled by this method. Funnel samples were collected after significant rainfall events or once per month, whichever was shorter. On average, 14 N samples were collected per site per year. One ml of 1000 ppm phenol mercuric acetate was added to each sample bottle to prevent microbial transformation of N in the interval between collection and analysis. Prior to 1992, both NO_3 and NH_4 were measured using a Technicon Auto-analyser II. Starting in May 1992, NO_3 analyses were conducted on a Dionex D-100 Ion Chromatograph. Precipitation volume data were obtained from the funnels used to measure N deposition.

Several experiments have been carried out at the Sevilleta to explore the potential effects of N deposition, including their effects on the productivity and structure of plant communities. An ongoing long-term N addition experiment has evaluated the effects of the addition of 100 kg of N ha^{-1} yr^{-1} on plant–mycorrhizae interactions in desert grassland (Johnson et al., 2003), but no data on plant responses have previously been reported from this experiment. The experiment consisted of twenty 5×10 m plots. N has been added as granular NH_4NO_3 in two equal aliquots twice a year (fall and spring) to ten treatment plots since December 1995. In 2004, percent cover by species of above-ground vegetation in four $1 \times 1 m^2$ quadrats in each of the treatment and control plots was estimated in March, May and September. We analysed the response of total cover in September (when total cover is highest), which was predicted to increase with fertilization, and the response of legume cover in March (when legume cover is highest), which was predicted to decrease with fertilization (Suding et al., 2005).

In addition, in 1998 a one-season N addition experiment was conducted in two distinct plant communities dominated either by black grama or blue grama. At each site, forty 1×1 m unfertilized controls plots and forty 1×1 m plots fertilized with 20 kg N ha^{-1} were established. At the end of the growing season, the area and height were recorded for each

individual plant of the dominant species. We used these areas and heights to calculate volume, and then used allometric relationships between volume and mass to estimate biomass (Huenneke et al., 2001). We generated allometric relationships for blue and black grama in both fertilized and unfertilized areas adjacent to the experimental plots. For 21 individuals in each species by fertilizer combination (84 individuals total), we estimated cover and height, and harvested, dried, and weighed all above-ground green biomass. This generated the following allometric relationships, using linear regressions fit through the origin (i.e. Biomass = $m*$volume): black grama fertilized, $m = 0.12$, $R^2 = 0.98$; black grama unfertilized, $m = 0.13$, $R^2 = 0.99$; blue grama fertilized, $m = 0.11$, $R^2 = 0.90$; blue grama unfertilized, $m = 0.09$, $R^2 = 0.87$).

For comparison with responses to fertilization, we analysed temporal trends in blue and black grama in unfertilized vegetation. The relative cover of blue and black grama was calculated using cover data from 1989 to 2004 in an area of mixed blue and black grama near the Sevilleta's Deep Well meteorological station. Along a 400-m linear transect, the length of transect covered by each species was recorded at 1 cm resolution. Cover was estimated in this manner two or three times during the growing season (May–November) each year and the total cover for each species was summed across all sampling dates within a year. Relative cover for each year was calculated as the cover of each species of grass divided by the total plant cover for that year. Relative cover was used in order to detect changes in relative species abundance separate from inter-annual variation in cover.

2.3. Data analyses

Precipitation has strong effects on N deposition, requiring us to statistically control for this effect when testing for temporal trends. Linear regressions were used to evaluate NO_3, NH_4, and total N ($NO_3 + NH_4$) deposition rates (kg N ha^{-1} yr^{-1}) as a function of precipitation (mm yr^{-1}). The residuals of the regressions of NO_3, NH_4, and total N versus precipitation, were regressed against the years of the study to test for temporal changes in N deposition independently of precipitation volume. To evaluate whether the seasonal patterns of N deposition changed over the course of the study, we conducted a multiple regression with the annual proportion of N deposited during the monsoon season (June–September) as a response variable and the annual proportion of monsoon precipitation and year as predictors. The effects of N addition on plant cover and biomass were evaluated using t-tests. Temporal trends in the cover of blue and black grama were assessed through linear regressions.

3. Results

The amounts of total N deposited were positively related to precipitation volume (Fig. 1, Table 1, Appendix A). This is consistent with data from 16 yr of wet/dry deposition collection at one site on the Sevilleta showing that 69% of the deposition occurs as wet deposition (D. Moore, unpublished data). After controlling for the effect of precipitation, total N, NO_3, and NH_4 deposition significantly increased from 1989 to 2004 (Fig. 1, Appendix A). Total N deposition increased at a rate of 0.049 ± 0.008 kg N ha^{-1} yr^{-1} (linear regression, $F_{1,94} = 41.48$, $R^2 = 0.31$, $p < 0.001$, estimates $y = -97.09 + 0.049x$). The identical yearly increase (0.049 ± 0.008) was estimated in a multiple regression analysis with both precipitation and time as predictors ($F_{1,94} = 87.14$, $R^2 = 0.65$, $p < 0.001$,
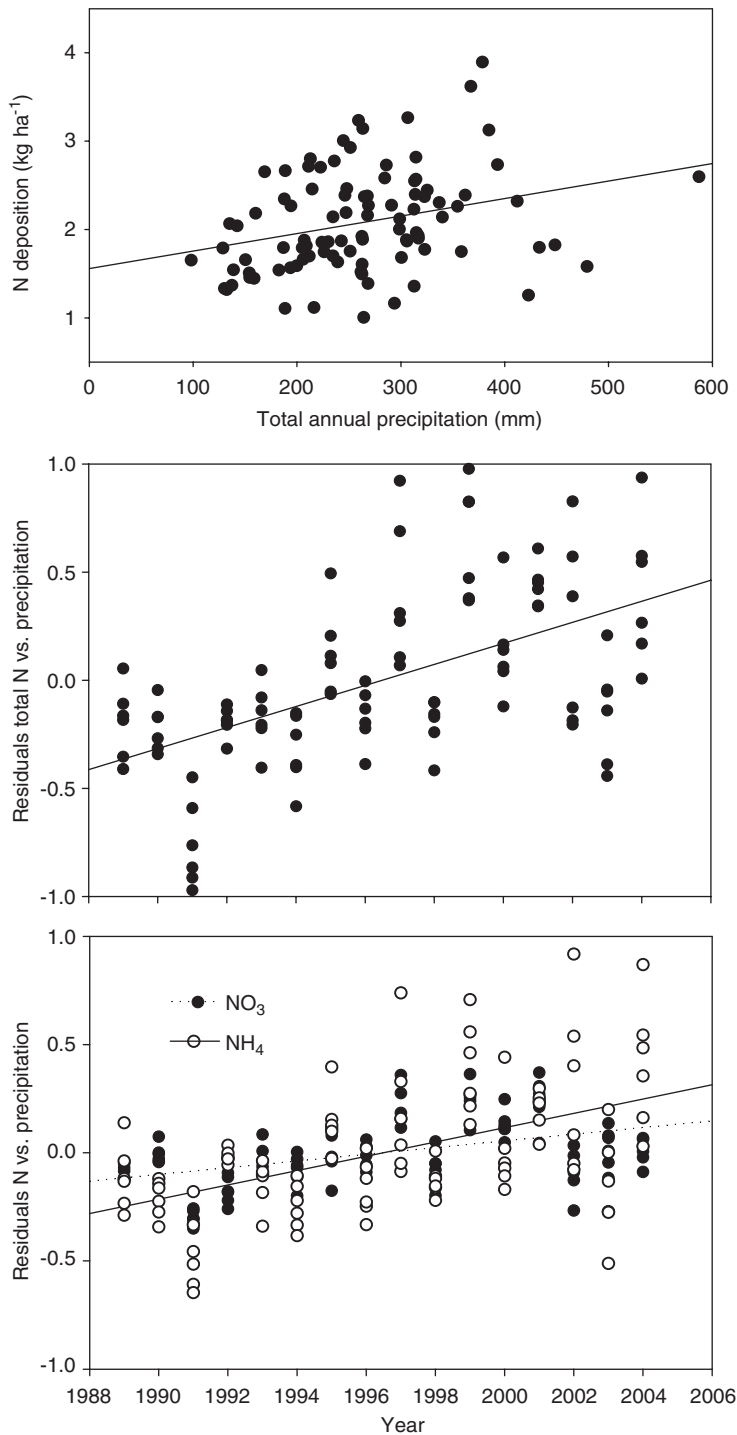
Fig. 1. Linear regression of annual N deposition against precipitation. N deposition $= 0.0046 + 0.85$ precip, $R^2 = 0.50$, $p < 0.001$. Linear regression of the residuals of total N, NO_3, and NH_4 versus precipitation, against time. Results: residuals total $N = -66.04 + 0.049$ yr, $R^2 = 0.25$, $p < 0.001$; residuals $NO_3 = -31.04 + 0.016$ yr, $R^2 = 0.20$, $p < 0.001$; residuals $NH_4 = -7.09 + 0.033$ yr, $R^2 = 0.30$, $p < 0.001$. In all analyses $N = 96$.

Table 1

Annual means of precipitation and N deposition during monsoon and non-monsoon seasons at the Sevilleta LTER, from 1989 through 2004

	Non-monsoon	Monsoon	Total
Precipitation (mm yr^{-1})	113	149	262
NO$_3$ (kg ha^{-1} yr^{-1})	0.38	0.51	0.89
NH$_4$ (kg ha^{-1} yr^{-1})	0.45	0.74	1.19
N total (kg ha^{-1} yr^{-1})	0.82	1.26	2.08

precipitation slope estimate $= 0.005$, $p < 0.001$, time slope estimate $= 0.049$, $p < 0.001$). This pattern of increased N deposition through time persisted when a potential outlier data value, the highest value of precipitation and N deposition, was deleted from the regression analyses ($F_{1,93} = 46.48$, $R^2 = 0.30$, $p < 0.001$, estimates $y = -96.66 + 0.048x$).

Thus, given our observed average rate of deposition of 2.08 ± 0.05 kg N ha^{-1} and our estimated rate of increase 0.049 ± 0.008, the rate of N deposition has increased from 1.71 kg N ha^{-1} yr^{-1} in 1989 to 2.45 kg N ha^{-1} yr^{-1} in 2004, a 43% increase. Therefore, over the 15 yr from 1990 to 2004, this annual increase in the rate of N deposition has resulted in an additional 5.88 kg ha^{-1} of N ($5.88 = 0.049 \sum_{i=1}^{15} i$) that would not have been deposited if rates had stayed at the 1989 level of 1.71 kg N ha^{-1} yr^{-1}.

During the 16 yr of our study, more N was deposited as NH$_4$ (19.03 kg ha^{-1}, 57.2%) than as NO$_3$ (14.25 kg ha^{-1}, 42.8%), and the rate of increase in deposition was significantly higher for NH$_4$ (0.033 ± 0.006 kg ha^{-1} yr^{-1}) than NO$_3$ (0.016 ± 0.003 kg ha^{-1} yr^{-1}, $p = 0.01$ for t-test of the slopes; Table 1). In addition, our data suggest that N deposition was not uniform across the Sevilleta, but instead was higher at upper elevations (Appendix B).

The seasonal pattern of N deposition did not change over time (multiple regression, $R^2 = 0.38$, $F_{2,13} = 4.13$, overall $p = 0.04$). During the years of the study, the proportion of N deposited during the monsoon season (60 ± 8.7%) depended significantly on the annual proportion of rain (57 ± 1.3%) that fell during these months (Estimate $= 0.36 \pm 0.127$, $t = 2.84$, $p = 0.01$; Table 1). The proportion of N that was deposited during the monsoon did not change over years, as indicated by a non-significant effect of year (Estimate $= 0.10 \pm 0.31$, $t = 0.33$, $p = 0.747$).

The long-term fertilization experiment showed significant responses of plant abundance and community composition. Specifically, in the summer, when warm-season grass abundance is highest, there was a 30% increase in cover in the N fertilized plots compared to control plots ($F_{1,18} = 6.7$, $p = 0.019$). In the spring growing season, when legume abundance is highest, there was a 52% decrease in the cover of legumes in the fertilized plots compared to control plots ($F_{1,18} = 11.5$, $p = 0.003$).

In the one-season fertilization experiment conducted in two grassland patch types (blue grama and black grama), we found that blue grama in the blue grama-dominated community significantly increased its above-ground volume and biomass in response to the addition of 20 kg N ha^{-1} yr^{-1}, whereas black grama in the black grama-dominated community did not (Fig. 2). The differences between species among communities in responses to N addition could be influenced by differences in the responsiveness to N of each species and to edaphic differences among sites. If blue grama is more responsive to N fertilization than black grama, we would expect a relative increase in blue grama over time
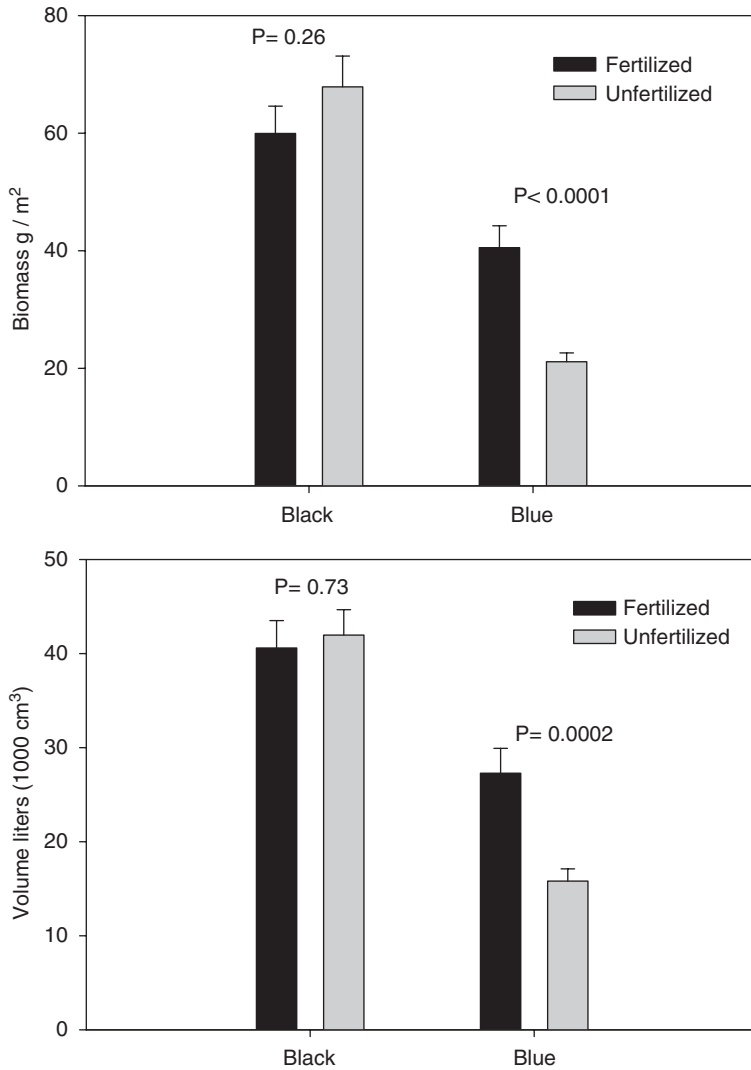
Fig. 2. Responses of black and blue grama to $20 \, \text{kg ha}^{-1}$ of N addition. In each analysis $N = 79$.

with increasing N deposition. In contrast, temporal trends of blue and black grama in unfertilized vegetation showed that the relative cover of black grama increased while there is no trend in the relative cover of blue grama since 1989 (Fig. 3). Hence, rates of N deposition thus far, are not sufficient to alter competitive interactions between the dominant grasses at our study site.

4. Discussion

N deposition is increasing in and around the Sevilleta National Wildlife Refuge. This finding is consistent with previous studies showing that during the last two decades N
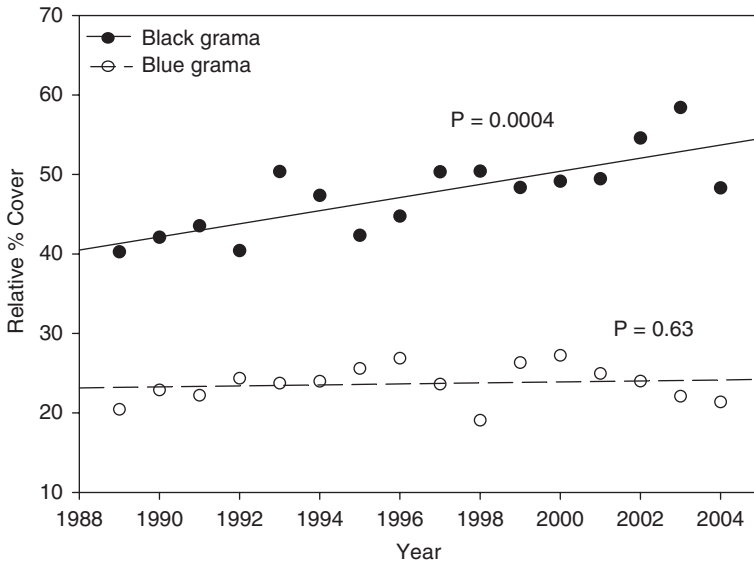
Fig. 3. Linear regressions of cover of black and blue grama versus time. In each analysis $N = 16$.

deposition has increased in areas near large urban centers (Fenn et al., 2003); the Sevilleta is 100 km south of the city of Albuquerque, New Mexico, and likely receives pollutants from Albuquerque via wind drainage down the Rio Grande Valley. The average rate of N deposition at the Sevilleta (2.08 kg ha^{-1} yr^{-1}) over 16 yr is on the lower end of the regional deposition patterns in the south-western United States. Deposition rates in this region vary from a low of 1–4 kg N ha^{-1} yr^{-1} to as high as 30–90 kg N ha^{-1} yr^{-1} downwind of major urban and agricultural areas (Fenn et al., 2003). For example, parts of the Sonoran desert in and around Phoenix, Arizona, receive between 7.5 and 30 kg N ha^{-1} yr^{-1} (Baker et al., 2001; Nilles and Conley, 2001).

In our study, most (57.2%) of the N was deposited as NH_4, which is likely produced in local agricultural/animal facilities emitting NH_3 (Krupa, 2002). Albuquerque might be the second major contributor to N in the form of NO_3 (42.8%). These findings differ from the emissions rates of N-compounds recorded for the state of New Mexico, where three times more NO_x than NH_x was emitted between 1989 and 1999 (Fenn et al., 2003). This comparison of local N deposition versus large-scale N emissions highlights the spatial heterogeneity of local N deposition patterns.

The temporal increase of N deposition at the Sevilleta was not associated with changes in the season of deposition. Rather, the seasonal pattern of N deposition varied from year to year in synchrony with inter-annual variation in seasonal patterns of rainfall. Thus, $57 \pm 1.3\%$ of the annual precipitation fell during the monsoon months, and $60 \pm 8.7\%$ of annual N deposition occurred during this season. These precipitation patterns are consistent with long-term trends reported for this area (Gosz et al., 1995; Milne et al., 2003). In addition, there is evidence that at our study site N accumulates during periods of drought, and that more N is immobilized during periods of high precipitation (Stursova et al., 2006). Thus, in this arid ecosystem, where water and N appear to be co-limiting factors, the observed pattern of higher rates of N deposition during months with higher

precipitation may result in a stronger fertilization effect than if N deposition were independent of precipitation (Hooper and Johnson, 1999; Asner et al., 2001; Knapp and Smith, 2001; McLain and Martens, 2006).

N fertilization experiments that use a high rate of N deposition may be useful for predicting the long-term effects of chronic low rates of N deposition. Although we do not expect chronic low rates of N addition to have effects identical to the short-term effects of higher rates of N addition, we expect that any effects of chronic low level N addition are likely to be similar in direction, if not magnitude, to the short-term effects of high rates of N addition. There is evidence that N accumulates in these arid systems, suggesting that effects of increased N addition may be at least partially cumulative (White et al., 2004). For example, it has been shown that more N is accumulated than is lost to runoff in the arid lands of the Jornada basin in the Chihuahuan desert south of the Sevilleta (Schlesinger et al., 2000; see also Welter et al., 2005). Also, in the long-term fertilization experiment conducted at our study site, after 10 yr of N fertilization at $100 \, \text{kg} \, \text{ha}^{-1}$, percent soil N was 15–61% higher, extractable NO_3 was 25–175% higher, and extractable NH_4 was 247–1721% higher compared to control plots (Stursova et al., 2006).

Our N fertilization experiments suggest that higher deposition rates and/or accumulation of N in the system are likely to affect patterns of species diversity, community structure, and primary productivity. Our results show that addition of 100 and $20 \, \text{kg}$ of $N \, \text{ha}^{-1}$ increased total cover, and decreased the cover of leguminous forbs. These results are consistent with patterns in a broad range of herbaceous communities (Suding et al., 2005).

With regard to the two dominant species of grass at the Sevilleta, we found that black grama cover is increasing over time, while blue grama cover is not changing directionally (Fig. 3). This pattern is the opposite of that found in our N addition experiments, where blue grama increased in response to fertilization but black grama did not. Therefore, the temporal trends of dominant species in our system do not appear to be caused by changes in N deposition, but are likely caused by other factors. The increase of black grama at the Sevilleta during the last 30 yr may result from vegetation change after the removal of cattle from the area in 1973, along with changes in climatic conditions (Ryerson and Parmenter, 2001).

Consistent with our finding that black grama does not respond to lower levels of N addition, experiments carried out in the Jornada basin show that two of the dominant species in our study site (black grama [*B. eriopoda*] and creosote bush [*L. tridentata*]) significantly increase their biomass after additions of $100 \, \text{kg} \, \text{N} \, \text{ha}^{-1} \, \text{yr}^{-1}$, but not after experimental additions of $25 \, \text{kg} \, \text{N} \, \text{ha}^{-1} \, \text{yr}^{-1}$ (Ettershank et al., 1978; Fisher et al., 1988). Other studies in arid systems have found differences in species responses. Scwinning et al. (2005) found that Indian ricegrass [*Oryzopsis hymenoides*] increased tiller density at $\geqslant 20 \, \text{kg} \, \text{N} \, \text{ha}^{-1} \, \text{yr}^{-1}$, but not $10 \, \text{kg} \, \text{N} \, \text{ha}^{-1} \, \text{yr}^{-1}$, whereas galleta grass [*Hilaria jamesii*] showed no increase in tiller density with any level of N addition, and Russian thistle [*Salsola iberica*] dramatically increased biomass m^{-2} during a wet year when $40 \, \text{kg} \, \text{N} \, \text{ha}^{-1} \, \text{yr}^{-1}$ was added.

These results suggest that N deposition, at a high enough rate, could cause increases in cover of blue grama relative to black grama, reversing the recent temporal pattern in the relative abundances of these two species (Ryerson and Parmenter, 2001). It is unclear what rate of N deposition would be necessary to cause such a reversal, but if the effects of N deposition are cumulative, blue grama could be favored within decades. If N deposition

continues to increase at the rate of 0.049 kg ha^{-1} yr^{-1} at our study site, it will increase from 2.45 kg N ha^{-1} yr^{-1} in 2004 to 3.87 kg N ha^{-1} yr^{-1} in 2033. Therefore, over the 29 yr from 2005 to 2033, the Sevilleta will receive an additional 21.3 kg ha^{-1} (21.3 = 0.049 $\sum_{i=1}^{29} i$) of N that would not have been deposited if rates had stayed at the 2004 level of 2.45 kg N ha^{-1} yr^{-1}, an amount exceeding the 20 kg N ha^{-1} added in the 1yr fertilization experiment. If the effects of N deposition are not at all cumulative, then such a change might not be apparent until annual rates of deposition reached 20 kg N ha^{-1} yr^{-1}, which would take hundreds of years under observed rates of increase.

It is likely that the effects of N deposition on productivity will not be substantial in the short term (e.g. by 2020). Current estimates suggest that productivity increases in arid systems (with 0-300 mm of precipitation) by 5.5 kg of biomass ha^{-1} yr^{-1} for every kg ha^{-1} yr^{-1} of N added, although responses vary widely among systems (Hooper and Johnson, 1999). Therefore, the increase in N deposition rates recorded in this study could presently be increasing productivity at a rate of 0.27 kg ha^{-1} yr^{-1}, which would result in a productivity increase of only 4.0 kg ha^{-1} between 2005 and 2020 (4.0 = 0.27 × 15), a 0.2% increase of the 1 845 kg ha^{-1} yr^{-1} produced in this system (Knapp and Smith, 2001).

5. Conclusions

N deposition has increased in the Chihuahuan desert in central New Mexico over our measurement interval from 1989 to 2004. The observed annual rate of N deposition, although low in comparison with regional estimates, is increasing. In this ecosystem N deposition was strongly associated with seasonal patterns of precipitation. An N fertilization experiment at our site suggests that chronic N deposition is likely to eventually change the patterns of species dominance favoring blue grama over black grama, which could reverse recent temporal trends in relative cover of these two species. A long-term N fertilization experiment at our site further suggests that chronic N deposition is likely to decrease legume abundance in arid lands, as has been found across other North American sites (Suding et al., 2005). We conclude that, although arid lands have low rates of N deposition and are primarily water limited, observed trends in N deposition rates may lead to significant changes in community composition and structure. Continuation of long term monitoring of both N deposition and plant community composition in desert grassland with historically low levels of available N will provide a sensitive method to test for the effects of increasing N deposition on arid land plant communities.

Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jaridenv.2006.06.011

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