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**Alien Invasion: Effects of Atmospheric Nitrogen Deposition on
Sagebrush Steppe Vegetation Dynamics at Upper Columbia Basin
Network Parks**

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Summary

Agricultural operations within the Snake River Plains cause emissions of nitrogen (N) -to the atmosphere. This nitrogen is deposited through a combination of wet and dry deposition both locally and downwind from emission sources. Nitrogen additions to the ecosystem can cause changes to nutrient cycling and vegetation community dynamics. In this project, we measured atmospheric concentrations of nitrogen species NO_x , NO_2 , NH_3 , and HNO_3 at 10 sites within the Upper Columbia Basin Network Monuments and compared them to 2006 CMAQ modeled deposition values. We also measured perennial and annual vegetation to determine if the spread of the invasive grass *Bromus tectorum* (cheatgrass) was correlated with the nitrogen deposition gradient.

The passive atmospheric samplers were consistent with modeled values in that NH_3 was the dominant N species in the area and that the highest concentrations were near the concentrated animal feeding operations near the Snake River. Bulk deposition samplers were contaminated by birds where NH_3 concentrations were high, but a high correlation between the noncontaminated sites allowed us to calculate expected deposition values. The N deposition at all sites was higher than was previously modeled. This was especially true at the low deposition sites where measured values were 200% higher than modeled values.

There was an increase in cheatgrass cover as nitrogen deposition increased across the region. As cheatgrass increased, there was concomitant decrease in native forb and native grass species. There was also a decrease in shrub cover as nitrogen deposition decreased. The combinations of these vegetation changes have the potential to increase fire risk in high deposition areas due to an increase in standing biomass of cheatgrass in the summer. The degradation of native vegetation may also lead to changes in higher trophic levels in the ecosystem.

Our results raise these park specific concerns and management recommendations: **Craters of the Moon National Monument (3.0-8.1 kg/ha/yr)** has the largest gradient of N deposition within its boundaries due to its size and north/south orientation. The southern and western regions of the park are at highest risk as they are closest to emission sources. These areas also seasonally grazed; which disturbs the soil and can increase the potential for cheatgrass invasion. The northern region of the park near the Visitor's Center currently has low levels of deposition, but the levels are considerably higher than previously modeled. As this area is protected by the National Park Service, there is no grazing. If N levels increase there may soon be shifts in vegetation communities toward more cheatgrass.

Hagermann Fossil Beds National Monument (10.4 kg/ha/yr) and **Minidoka National Historic Site (11.2 kg/ha/yr)** are most at risk due to vegetation changes due to N deposition. They are both located in high deposition areas and are adjacent to large agricultural operations. Restoration would require control of invasive species, a difficult task when their productivity is increased under high N deposition. If the number of CAFOs increases the impacts of nitrogen on the ecosystem will become more severe. **City of Rocks National Reserve (4.0 kg/ha/yr)** consistently had the lowest concentrations measured during the project. The northwest region of the park may have higher nitrogen concentration than have been modeled due to emission sources to the west. This area of the park should be watched closely as it is the most likely path of a future invasion front.

Introduction

The Upper Columbia Basin Network (UCBN) Monuments have been experiencing an increase in alien species invasion, especially *Bromus tectorum* (cheatgrass) which is expanding in areas that are protected and not subject to anthropogenic disturbance—except for air pollution. Experimental studies have shown that cheatgrass invades most readily in areas that have been burned or grazed (Chambers et al. 2007). However, these monuments have been protected from grazing for decades, and even areas that have not burned are invaded. Anthropogenic nitrogen (N) deposition is another perturbation that increases soil resources, and cheatgrass is known to be responsive to elevated soil N (Chambers et al. 2007, Lowe et al. 2003, Monaco et al. 2003). N emissions in the form of nitrogen oxides (NO_x) and ammonia, from such sources as vehicle traffic, fertilizer plants, and confined animal feeding operations, have been increasing in southern Idaho and northern Utah. Model simulations show that the region is a hot spot of high N deposition with up to $12 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (Fenn et al. 2003b, Tonnesen et al. 2003). Data from the National Atmospheric Deposition Program indicate that ammonia deposition is increasing at Craters of the Moon National Monument and Preserve (CRMO), a monument and preserve designated as Class 1 under the Clean Air Act. Other UCBN units particularly at risk include Hagerman Fossil Beds National Monument and City of Rocks National Reserve.

The Snake River Plains have been affected by N deposition for decades with increases in agriculture, including croplands, confined animal feeding operations (CAFO), and expansion of the fertilizer industry. The levels of N deposition in southeastern Idaho and northern Utah are $6\text{--}12 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, most coming as dry deposition in the form of ammonium (Fenn et al. 2003b). At the same time, there has been an alarming invasion of the alien cheatgrass in the region. Research started in this area in the 1940's to document the conversion of sagebrush steppe to non-native annual grassland (Piemeisel 1951, Hironaka and Tisdale 1963). However, until recent modeling efforts (Tonnesen et al. 2003, 2007), the high amounts of N deposition in this rural area were not recognized. The ecological effects of N deposition have been studied to some extent in other areas of the western U.S., including forests, shrublands and deserts of southern California, Colorado alpine and grasslands, and lichens of the Pacific Northwest (Fenn et al. 2003).

The major form of deposited plant-available N in urban areas is HNO_3 or NO_3^- , while in agricultural areas NH_3 and NH_4^+ are most important sources of N for plants (Fenn et al. 2003, Krupa 2003). These compounds may be deposited to vegetation via dry deposition of gases and particles or wet deposition of ions. The NADP collector located at the north end of CRMO was erected in 1980 and has shown a trend of increasing NH_4^+ concentration in precipitation since about 2000 (NTN 2013), but no trend in NO_3^- , suggesting that agricultural inputs are the most important in this rural region. The increase in NH_4^+ has been small, about $1.5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ over two decades, but this represents a doubling. The NADP collector is located at the clean air end of CRMO, so it is unclear how this increase is related to trends in the polluted southern end that is closer to CAFOs and urban areas. Most importantly, the NADP collector measures only wet deposition, which may be only 10–20% of total N deposition in semi-arid regions (Padgett et al. 1999), but nonetheless these data clearly indicate increasing atmospheric inputs of reduced forms of N at CRMO.

The invasion of cheatgrass into the Great Basin and adjacent plateaus and basins has been documented since the early 1930's (Mack, 1981), and began well before large-scale anthropogenic N

deposition occurred. This invasion may be related to a combination of disturbances such as grazing and fire, and natural fertility levels of these soils that are sufficient for cheatgrass growth (Chambers et al. 2007). However, cheatgrass is spreading into areas with no recent history of disturbance and is becoming locally more productive (Bashkin et al. 2003, Chambers et al. 2007). N deposition is increasing as agriculture and urbanization increase across the western states (Fenn et al. 2003b), and especially as CAFOs increase in Idaho (Greenaway, 2011). Increased NH_4^+ may be another perturbation that promotes greater invasion and productivity of cheatgrass.

A number of N fertilization studies have been done using cheatgrass and other brome species. These studies show relatively large responses of cheatgrass to elevated N, and in the same plots the native species had smaller growth responses to N (Lowe et al. 2002, Monaco et al. 2003). Chambers et al. 2007 showed that the high N resulting after fire also stimulates cheatgrass growth. A study on ^{15}N uptake showed that red brome took up more ^{15}N tracer than co-occurring California sagebrush (Yoshida and Allen 2004). These studies indicate that as soil N increases, cheatgrass and other brome grasses benefit more than native species. Thus invasion of cheatgrass can be expected in soils with high N, whether the soils are naturally fertile as was shown by examining soil fertility patterns of invasion (Bashkin et al. 2003) or subject to N deposition.

The overall objective of our research was to determine whether there are also high levels of dry N deposition, which has not been measured in this area, and whether elevated N deposition is related to increased cheatgrass invasion. We examined a gradient of N deposition from south to north across CRMO and across the Snake River Plains, and compared N deposition rates at CRMO with rates at Hagerman Fossil Beds and City of Rocks. The stable isotope ^{15}N and N content of plants and soils were measured along the hypothesized gradient. Deposited N accumulates on the soil surface and in plant tissues, so soil and plant nitrogen may serve as a proxy for the N deposition gradient and to determine the levels of N experienced by plants (Padgett et al. 1999). Stable isotope measurement may provide additional information on potential sources of N deposition, since many of the potential sources of NO_x and NH_3 in the region have distinctive isotopic signatures. We selected sites along the gradients for vegetation surveys to measure cover of native and invasive species.

Information gained from the research will assist regulatory agencies and land managers by: a) expanding the number of sites where atmospheric deposition is measured in the UCBN region, b) expanding deposition monitoring beyond wet deposition by including passive measurements of atmospheric concentration to infer dry deposition c) determining if bioindicators (i.e., soil and plant N content and isotopic composition) can be used to estimate N deposition rates, d) identifying likely sources of atmospheric N deposition in the region, and e) linking N deposition to cheatgrass invasions which will assist with the determination of critical loads of N deposition in sagebrush-steppe ecosystems.

Methods

Site Description

A nitrogen deposition gradient was identified within the Snake River Plains using CMAQ modeled N deposition values (Figure 1). Ten field sites were established within the gradient. The

westernmost sampling site was located at Hagermann Fossil Beds National Monument (HAFO), the southernmost point at City of Rocks National Reserve (CIRO), the easternmost site on an Idaho State University research site in Pocatello, and the northernmost site within Craters of the Moon National Monument (CRMO) (Figure 1). Additional sites were established at Minidoka National Historic Site (MINI) and on BLM land between park units. Each site was located within sagebrush steppe habitat with the dominant shrub species being *Artemisia tridentata* Nutt. ssp. *tridentata* with associated species including *Artemisia tripartita* Rydb., *Purshia tridentata* (Pursh) DC., *Hesperostipa comata* (Trin. & Rupr.) Barkworth (Species List in Appendix I).

The Snake River Plains have extensive agriculture and animal feed operations that are the primary sources of NH_3 . The cities of Twin Falls and Pocatello contribute additional sources N through vehicle exhaust that are the primary sources of NO_x . Based on the CMAQ model N deposition is highest in the areas near the CAFOs with concentrations diluted as N is transported north towards CRMO. The north end of the study area is surrounded by grazed native sagebrush-steppe vegetation and low intensity agriculture (especially hayfields). Nitrogen values from a NADP sampler at the CRMO Visitor's Center show low values of N at the north end of the park (NADP 2012). The extent of the downwind source of deposited N from fertilizer production in the Pocatello area to the east of CRMO is unknown and was also examined as part of this research.

Atmospheric Nitrogen Measurements

Community Multiscale Air Quality (CMAQ) Model

The CMAQ model estimates annual adjusted deposition with an interim bi-directional NH_3 formulation on a 12km grid spanning the contiguous United States based on emissions from 2006. The model combines NO_x and NH_3 emissions with measured deposition at NADP sites to predict annual wet + dry (total) deposition of reduced and oxidized N.

Atmospheric Concentration

Time-averaged concentrations of HNO_3 , NO_x , NO_2 , and NH_3 were measured with passive samplers deployed for 2 weeks at a time. HNO_3 passive samplers of Bytnerowicz's (2005) design were used in the study. The samplers contained a 47mm Pall-Gelman Nylasorb™ nylon filter (HNO_3 collecting medium) that was covered by a 47mm Zefluor™ PTFE Membrane filter of 2 μm pore-size to prevent particulate contamination and provide steady diffusive flow of air into the sampler. NO_x , NO_2 , and NH_3 were collected on 14.5 mm Ogawa samplers (Ogawa & Co. USA, Inc.) and analyzed according to Ogawa, Inc. (2006) and Roadman et al. (2003). All samplers were installed on a crossbar 2.4 meters above the ground under PVC caps protecting the filters from contamination by rain and dust blowing at ground level. The sampling deployments occurred every 2 months for a total of 6 deployments over a 1 year period starting in June 2010 and ending in June 2011 (Table 2). Two of the sites (PRBR, WOOD) only had 4 exposures because they were inaccessible during winter.

Bulk Deposition

Bulk deposition samplers were installed at each site in June 2010. Collectors consisted of a 21.1 cm inner diameter funnel connected to a 12" long by ½" diameter tube containing mixed bed (cation

and anion) exchange resin beads (Fenn and Poth 2004). The funnel was covered with a one meter long tube to allow snow to collect during the winter. A metal ring crisscrossed with 15 lb. test fishing line was placed on top of the tube to prevent birds from perching on the edge of the collector. The resin tubes were swapped out every 6 months to capture seasonal variability between summer and winter (Table 2). Due to contamination from birds during the first year of deployment, Tanglefoot Bird Repellent (Contech Inc, Victoria, BC) was applied to the rings prior to the June 2011 deployment.

In June 2011, bulk throughfall deposition samplers were installed at each site alongside the open bulk deposition samplers. Five bulk throughfall samplers were placed under 5 individual *A. tridentata* shrubs. Each sampler consisted of a 10.16 cm inner diameter funnel attached to a 3" x ½" pvc riser filled with mixed bed (cation and anion) exchange resin beads. Resin columns were changed on the same schedule as open collectors (Table 2).

Soil Nutrients

Five soil samples were collected at each site in August 2010 during peak N deposition times. For each sample, three 5 cm deep by 2.54 cm diameter soil cores were composited into a single sample. Extractable NO_3^- -N and NH_4^+ -N were extracted from the soil using a 1 M KCl solution. NO_3^- -N and NH_4^+ -N concentrations in the soil extracts were determined colorimetrically using a Seal AQ2 discrete analyzer (SEAL Analytical Inc., Mequon, Wisconsin). Extractable soil phosphorus was measured at the UC Davis Analytical Laboratory using the Olsen method (Olsen and Sommers 1982).

Vegetation Assessment

Perennial Vegetation

Perennial vegetation was differentiated among sites by measuring the length of each individual shrub that intersected five 100m transects. Shrub cover was estimated by calculating the total length of the transect that intercepted a shrub. Transects were compared among sites to classify vegetation.

Annual Vegetation

Five 100m transects were established at the 5 sites that had *A. tridentata* stands that were not disturbed by grazing, fire, or lava outcroppings (Table 1). Along each transect percent cover of all vegetation rooted within the plot was taken within a 1m x 1m quadrat at 5 standardized locations. All other annual vegetation within the 1 x 100m transect was recorded for beta diversity. At the 5 other sites, percent cover of vegetation was recorded within five 5m x 5m plots.

Biomass

Biomass of *B. tectorum* was collected from each site based on its coverage in a 250cm x 250cm plot. Biomass was collected at a site when *B. tectorum* was present in patches that covered greater than 50% of the plot. Ten collections were made per site; increasing from 1% coverage of the plot to the highest cover present. Biomass was dried at 40° C for 48 hours and weighed. A linear regression was performed between percent cover and grams of *B. tectorum* with the intercept of the relationship forced through the origin. The slope of the relationship represented the biomass per unit area and was compared among sites.

Tissue Analysis

Biomonitoring and bioindicators are powerful tools used to study the impacts of N deposition on terrestrial ecosystems (Sutton et al. 2004). These techniques are based upon the observation that increasing N deposition commonly leads to increasing N storage in terrestrial ecosystems, particularly those where denitrification and hydrologic losses of N may be low (e.g., semiarid grassland ecosystems like those found in the UCBN). Numerous large-scale experimental fertilization experiments (Magill et al. 2000) and field studies (Pitcairn et al. 2003) have demonstrated strong relationships between N deposition rates and bioaccumulation of N in plant or lichen tissues and soils; in some cases these relationships are strong enough that models can be developed to predict N deposition rates solely from tissue and soil N levels (Root et al. 2013, Sutton et al. 2004).

Plant tissue samples were collected from *A. tridentata* ssp. *tridentata* and *B. tectorum* at each of the air quality sample sites when they were available. Five individuals of each species were collected in June 2010 from each site. Leaf tissue was dried at 40° C for 48 hours and ground to pass through a 2mm sieve using a mortar and pestle. Seed heads were removed from *B. tectorum* samples before processing. Samples were combusted in a Costech ECS 4010 elemental analyzer (Costech Analytical Technologies, Inc., Valencia, CA) connected to a Thermo Fisher Delta V (Thermo Fisher Scientific Inc., Waltham, MA) isotope ratio mass spectrometer. Isotopic values are reported in units of per mil (‰) and were computed using Eqn. 1, where X = N or C. Isotopic values for carbon are reported relative to PeeDee Belemnite (PDB) and for nitrogen are reported relative to atmospheric N₂

$$\delta X = \left[\left(\frac{R_{\text{Sample}}}{R_{\text{Standard}}} \right) - 1 \right] * 1000 \quad (\text{Eq. 1})$$

Data Analysis

All statistical analyses were performed with SAS 9.2 (SAS Institute, Inc. Cary, NC)

Results and Discussion

Atmospheric Nitrogen

Passive Samplers

There was a higher concentration of reduced N than oxidized nitrogen compounds across the study area. As expected, the highest levels of NH₃ were found near the high density agricultural zones. The Pocatello site consistently had the highest levels of HNO₃ collected among all of the sites, which is also consistent with modeled values. Annual HNO₃ trends followed the same bimonthly pattern with the highest atmospheric HNO₃ concentrations being measured during the summer sampling period. Pocatello had an additional HNO₃ peak during the January deployment period which may have been caused by an inversion that trapped pollutants locally or increased transport from the Salt Lake City area.

All sites had higher concentrations of atmospheric NH₃ during the summer months than during the winter (Figure 2, A). Values began to increase again around May as temperatures increased and NH₄⁺

volatilized. During the summer and fall months, the atmospheric NH_3 concentrations were significantly higher at the sites closest to the high concentration of dairies and agriculture (HAFO and MINI). During the winter and early spring there was a smaller difference in values between the high concentration sites and the intermediate ones. Pocatello was the one site where NH_3 concentrations increased strongly during the winter relative to the summer. This is likely due to the same inversion system that led to the increase in HNO_3 concentrations in winter. The peak may also have been associated with the production of ammonium phosphate from the fertilizer plant in the area. A sampler would need to be placed closer to the plant in the future to measure its emissions.

The NO_x (Figure 2, C) and NO_2 (Figure 2, D) atmospheric concentration values were more variable among sites than the HNO_3 and NH_3 concentrations. The highest values were consistently recorded at the SHOS site, which may be explained by the fact that the sampler was placed near the Shoshone BLM office where there was increased vehicle activity relative to the surrounding area. The POCA samplers recorded high values during the winter.

Bulk Samplers

During the first year of exposure, the majority of bulk deposition collectors were contaminated by various animals (birds, insects) either defecating in the collector or falling in and not being able to escape. Contamination was confirmed by high levels of PO_4 in these collectors. This led to unreliable deposition data the first year. Before the start of the second year of collection, the funnels and snow tubes were cleaned and additional deterrents were put into place to reduce contamination. Even with additional deterrents the collectors at the 4 higher modeled deposition sites had too much contamination to measure accurate deposition values.

Of the remaining 6 sites that had uncontaminated samplers, all of the measured NH_4^+ (Figure 3) and NO_3^- (Figure 4) bulk deposition were higher than modeled values, indicating that the CMAQ model is underestimating deposition at CRMO. The bulk deposition samples consist primarily of wet deposition while the CMAQ estimates include wet and dry deposition of N, including organic N. Thus, the CMAQ values should be greater than bulk deposition measurements. The sites at Craters of the Moon National Monument had over twice as much bulk deposition of NH_4^+ compared to the CMAQ modeled estimates. The range of the atmospheric plume seems to extend farther out from the emissions center near the dairies than the model predicted. The measured bulk NO_3^- deposition values were slightly higher than modeled values, but followed a similar distribution to expected values (Figure 4).

There was a positive, linear relationship between the measured atmospheric NH_3 concentration and the amount of NH_4^+ collected in the bulk deposition collectors. We used the passive sampler data from the contaminated sites to extrapolate the regression equation and calculate the amount of deposition at the high contamination sites (Figure 5, red circles). These calculated deposition values are higher than modeled values, but relatively closer to the model than the modeled low deposition areas (Figure 6, red circles). The extrapolated data need to be interpreted with caution, due to the extent of extrapolation required. It will be imperative to take additional steps to prevent contamination of future measurements. These measurements suggest that current model parameters are reliable near the N emission sources, but may be underestimating the distance that NH_3 is transported away from the source. There was also a positive linear relationship between atmospheric HNO_3 concentration and NO_3^- -N deposition at each site (Figure 7). The regression equation was used to calculate bulk NO_3^- -N

deposition values for the samplers that had been contaminated by wildlife (Figure 7, red circles). The sites with the contaminated samplers had mid-range deposition values so there was no change in the relationship between measured and modeled values (Figure 8). Interpolating the calculated bulk deposition values (Inverse Distance Weighting, ArcGIS 10.2 (ESRI, Redlands, CA)) shows that the areas of highest deposition have a wider spatial extent than those from the original CMAQ model (Figure 9). This suggests that as emissions increase through the addition of more CAFOs to the area, a broader area will be impacted by N.

The bulk throughfall samplers did not collect consistent measurements within or among sites. This may have been due to the fact that *A. tridentata* has a vertical branching pattern that leads to increased stem flow toward the base of the plant and may decrease throughfall deposition. There was also a difference in snow accumulation under each shrub and among sites during the winter. Alternative methods are being considered to increase the accuracy of bulk throughfall measurements under *A. tridentata*.

Soil

There was no relationship between extractable soil NO_3^- -N or NH_4^+ -N collected once during August 2010 and the amount of N deposition occurring at each site (Figures 10 and 11). Given that the samples were collected during the dry season, it was expected that the N deposited during this period would remain on the soil surface until subsequent rain events (Padgett et al. 1999, Padgett and Bytnerowicz 2001). The lack of relationship between atmospheric deposition and soil N levels suggests N deposited during the summer may be quickly cycled off the soil surface. It may either be immobilized by soil organic matter or absorbed by perennial vegetation.

Vegetation

Perennial Vegetation

The number of perennial vegetation transects were limited by continuous stands of sagebrush at the study sites. While a small sample size, the density of the perennial vegetation decreased as N deposition increased from 17% at sites with 3 kg/ha/yr to 12% at sites with 8 kg/ha/yr (Figure 12). Based on Idaho fire history data, none of the sites have burned within the last 50 years and none of them are currently being grazed. The presence of cheatgrass at higher deposition sites (Figure 13A) could alter ecosystem processes such as seedling recruitment and resource availability which can negatively affect shrub growth (D'Antonio and Vitousek 1992).

Annual Vegetation

The amount of *B. tectorum* present at each site increased from 2% cover to 50% cover with increasing nitrogen deposition (Figure 13A) while the native forbs decreased from 15% cover to 2% cover as N deposition increased (Figure 13C). The overall cover of species increased at sites with higher deposition, based on the smaller portion of bare ground remaining at the sites dropping from 24% at low deposition sites to only 2% at high deposition sites (Figure 13D). This suggests that *B. tectorum* is using the increased nitrogen levels to expand quicker than native populations and are outcompeting them for space and resources (Figure 14A). The cover of native grasses did not correlate with the

amount of N deposition at each site (Figure 13B), but as *B. tectorum* increased towards 100% cover, the cover of native grasses dropped from 20% to 2% (Figure 14B).

The vegetation communities at the HAFO and MINI sites (high deposition) were disturbed by historic grazing and are within more urbanized areas relative to the low deposition sites. While neither site has recently burned or is currently grazed, there may be past land use history that has led to a very low abundance of native forbs. While visiting the sites, the majority of the undeveloped ground was covered by exotic grasses and native diversity was low.

The biomass of *B. tectorum* per unit area trended downward as the cover of *B. tectorum* increased across sites (Figure 15). When *B. tectorum* populations are small, they are able to exploit disturbed microsites and have an abundance of resources to grow. As the number of individuals increase, each plant is left with fewer resources and therefore there is less biomass per unit area. By combining the cover of *B. tectorum* at a site with its biomass / m² we calculated aboveground net primary production across the gradient (Figure 16). The total biomass of *B. tectorum* per site did not change at varying levels of N deposition, although the phenology of the plants was at a later stage at the high deposition sites. A larger sample size is needed to determine definitive relationships.

Tissue Analysis

Tissue analysis of *B. tectorum* and *A. tridentata* showed different responses to local nitrogen levels. *B. tectorum* leaf tissue N increased with soil NH₄⁺ content (Figure 17) suggesting that *B. tectorum* has a preferential uptake of NH₄⁺. While this study did not show a direct correlation between atmospheric deposition of NH₄⁺ and soil NH₄⁺, this finding strengthens the idea that NH₄⁺ deposition may be playing a role in the increased spread of *B. tectorum* in undisturbed areas. In contrast, *B. tectorum* leaf tissue N decreased with increasing NH₄⁺ deposition (Figure 18). We hypothesize that this occurred because the grass samples were all collected during the same week, but some sites were more phenologically advanced than others. The high deposition sites were the driest in June 2010 and the plants had all almost dried up and gone to seed, while some of the low deposition sites were still in flower. This also may have been due to the higher density of plants at the high deposition sites which led to increased competition for soil N.

There was no relationship between soil N concentration and *B. tectorum* δ¹⁵N (Figure 20), but as soil PO₄⁺ concentration increased the δ¹⁵N of *B. tectorum* leaf tissue increased (Figure 21). We hypothesize that when PO₄⁺ levels are low, *B. tectorum* may establish a more expansive mycorrhizal hyphal network which would assist in the uptake of N. When plants have a larger pool of N available, there is biological fractionation toward less enriched isotopologues of N which would result in a more negative δ¹⁵N value (Hogberg 1997).

A. tridentata leaf tissue N increased with NH₄⁺ deposition (Figure 21A) but was not responsive to soil N levels collected in August 2010. As a perennial plant, *A. tridentata* is able to take advantage of N available on top of the soil after precipitation pulses and may also adsorb NH₃ through its stomata. Although, since the δ¹⁵N of *A. tridentata* leaf tissue also increased with increasing NH₄⁺ deposition (Figure 21B), it is assumed that the main source of N comes from the soil, as the δ¹⁵N of atmospheric NH₃ is expected to range from -40 to -20 ‰ (Felix et al. 2012). The increasing values are consistent with previous research which measured an increase in soil δ¹⁵N as a site becomes invaded by *B. tectorum*

(Sperry et al. 2006). Additional isotopic studies should be completed at both high and low deposition sites to measure how N deposition and *B. tectorum* are altering the cycling of N through the ecosystem.

Conclusion

This study marks the first empirical values of atmospheric nitrogen concentration and nitrogen deposition measured within the Snake River Plain. Based on the 2006 CMAQ model compared to measured and calculated bulk deposition values from 2102, there has been a significant increase in anthropogenic nitrogen deposition between 2006 and 2012, especially in areas far from the Snake River Plain. This was expected as there has recently been an increase in the number of dairies that operate within the Snake River Plain. The large increase in N deposition at the sites farthest from the central agricultural zone suggest that there is an increasing amount of previously undisturbed land that is more at risk from invasion by exotic species due to an altered nitrogen regime.

Critical loads of N deposition have been established for many ecosystems across the United States (Fenn et al. 2010, Pardo et al. 2011). Within arid and semi-arid habitats in California low levels (3-8 kg N ha⁻¹ yr⁻¹) are enough to change ecosystem structure and function including loss of lichen species (Jovan et al. 2005), increase exotic annual vegetation cover leading to increased fire risk (Rao et al. 2010), and increase the spread of exotic grass species (Brooks 2003). The vegetation surveys that accompanied our N measurements show *B. tectorum* increasing in cover at high deposition zones. Increased cover of *B. tectorum* in grazing lands on the outskirts of the high agricultural zone will not only reduce rangeland quality, but will also increase the rate of spread of the grass through propagule pressure.

It will be important to continue evaluating both the amount of N deposition occurring within the Snake River Plain as well as the vegetation response at both high and low deposition sites in order to establish critical loads for the sagebrush-steppe ecotype. The current placement of the NADP sampler at CRMO is insufficient to capture the changes in source emissions that are impacting an extensive area. It would be beneficial if additional NADP collectors were established in high deposition areas such as HAFO to provide seasonal measurements to correlate with the collector at CRMO. The CMAQ model uses NADP wet deposition data as an input to determine regional deposition. Having a collector near the emission source will provide increased accuracy of local N dynamics and allow for changes in local deposition to be recognized immediately. To capture total N deposition, it would also be beneficial to install a CASTNET monitoring system which calculates dry deposition based on active collection of air samples. These measurements, along with continued analysis of the native and invasive plant communities will allow managers to understand what areas are most at risk of fire and type conversion.

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Tables

Table 1. Site names with abbreviations used in maps and text. The columns indicate at which sites vegetation was collected and sampled.

<u>Location</u>	<u>Site Name</u>	<u>Abbreviation</u>	<u>BRTE Biomass Collected</u>	<u>Vegetation Transects</u>	<u>5 x 5 m survey</u>
CRMO	Arco	ARCO		X	
CIRO	City of Rocks	CIRO			
HAFO	Hagermann Fossil Beds	HAFO	X		X
MINI	Minidoka National Historic Site	MINI	X		X
ISU	Pocatello	POCA	X		
CRMO	Preacher's Bridge	PRBR	X		X
BLM	Shoshone	SHOS	X		X
BLM	Near Star Lake	STAR	X	X	
CRMO	Visitor's Center	VC	X	X	
CRMO	Wood Road Kipuka	WOOD	X	X	

Table 2. Dates of passive and bulk deposition deployment. Passive samplers were deployed for 2 weeks. Asterisks represent sampling period when WOOD and PRBR were inaccessible due to snow cover. Bulk deposition columns were collected on the day the next set of collectors were deployed.

<u>Passive Sampler Deployment Dates</u>	<u>Bulk Deposition Deployment Dates</u>
6/15/10	6/15/10
8/17/10	10/26/10
10/26/10	6/22/2011
1/4/11*	10/28/2011
3/15/11*	Collected- 6/22/2012
5/24/11	

Figures

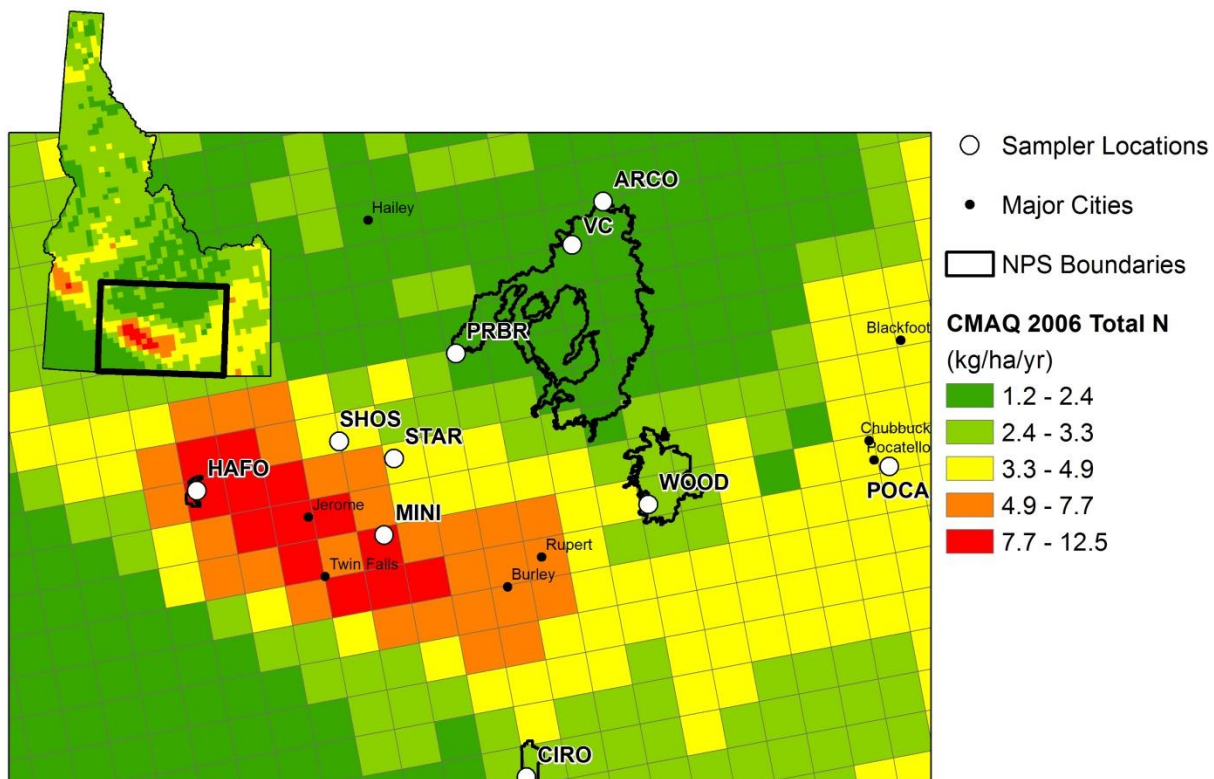


Figure 1. Geographic locations of sites in southern Idaho. Total N deposition ($\text{NH}_4^+ + \text{NO}_3^-$) values are modeled by CMAQ on a 12 km grid using 2006 emissions. Site legends in Table 1.

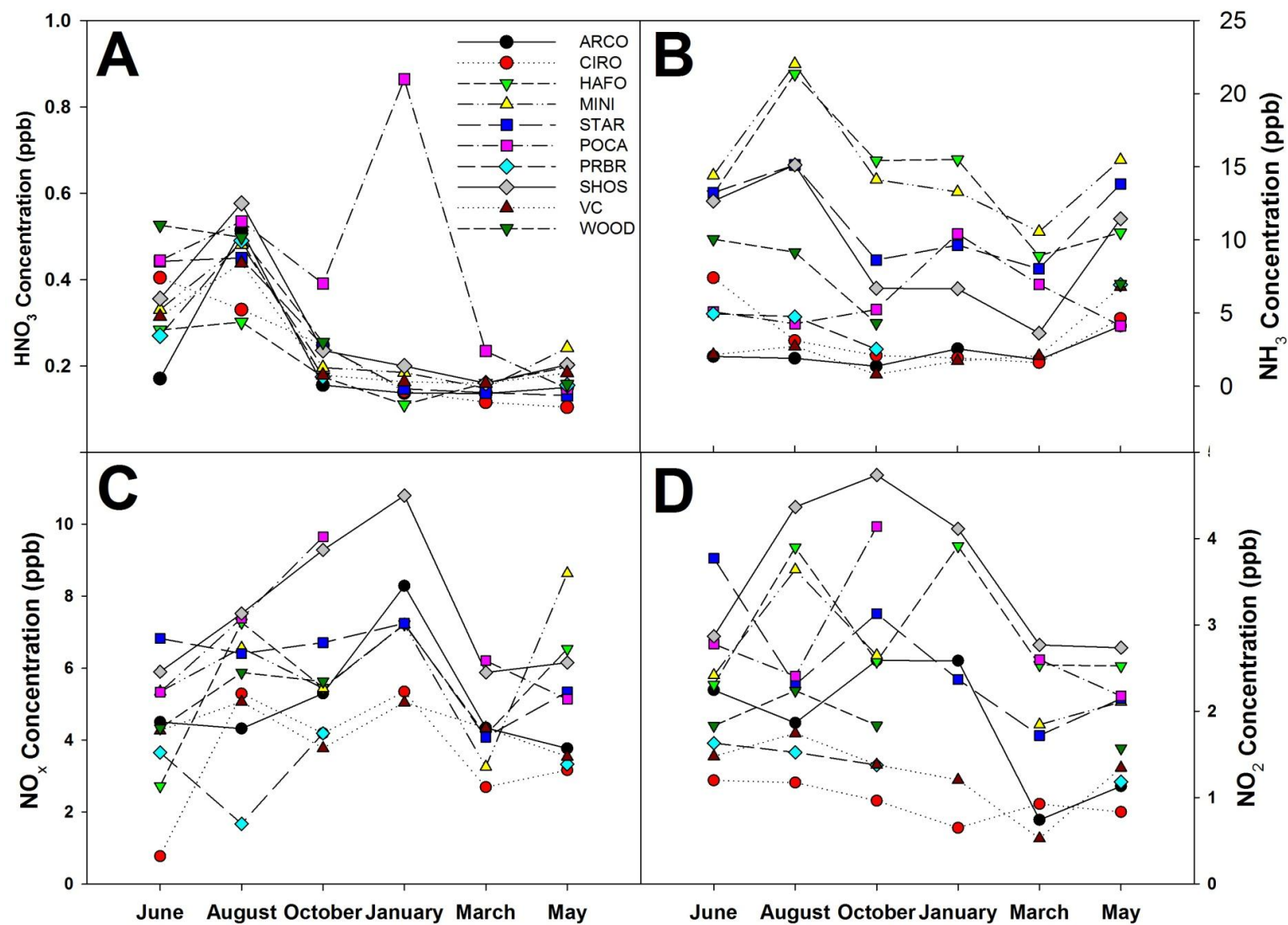


Figure 2. Concentrations of passively collected gaseous N from each of the 10 sites over a 1 year sampling period. Note the varying scales on the y axis.

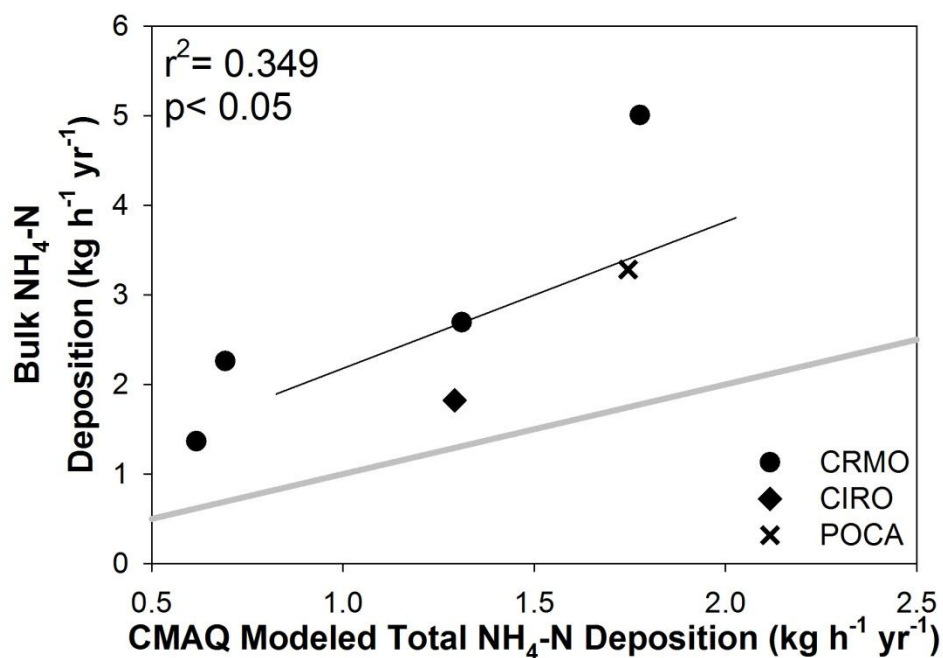


Figure 3. Measured $\text{NH}_4^+\text{-N}$ deposition from bulk deposition collectors relative to predicted $\text{NH}_4^+\text{-N}$ deposition from the CMAQ model. Grey line is the 1:1 line of bulk deposition of $\text{NH}_4\text{-N}$ vs. CMAQ modeled total $\text{NH}_4\text{-N}$ deposition. Site legends in Table 1.

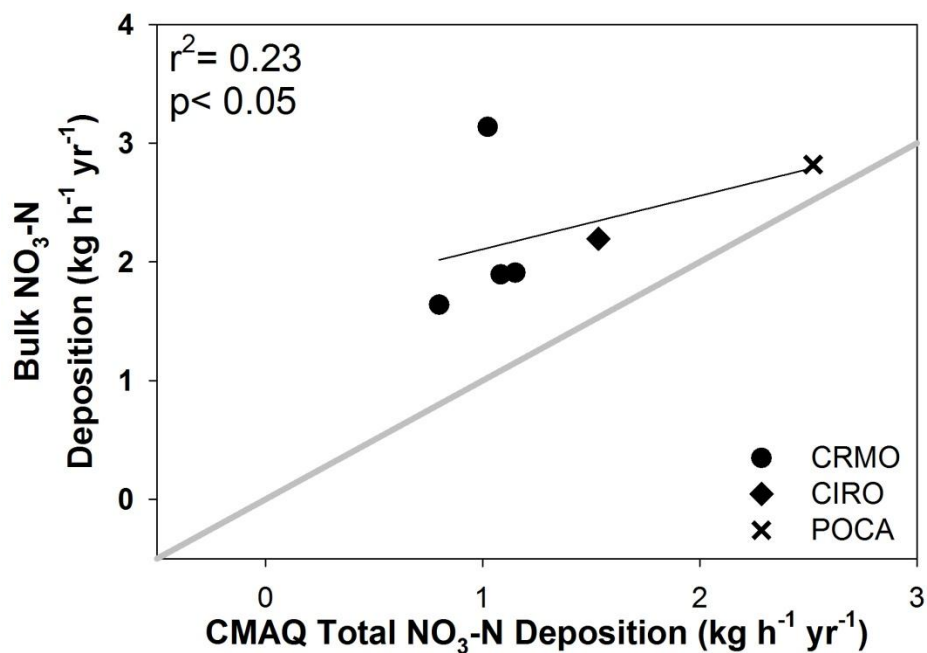


Figure 4. Measured $\text{NO}_3^-\text{-N}$ deposition from bulk deposition collectors relative to predicted $\text{NO}_3^-\text{-N}$ deposition from the CMAQ model. Grey line is the 1:1 line of bulk deposition of $\text{NO}_3\text{-N}$ vs. CMAQ modeled total $\text{NO}_3\text{-N}$ deposition.

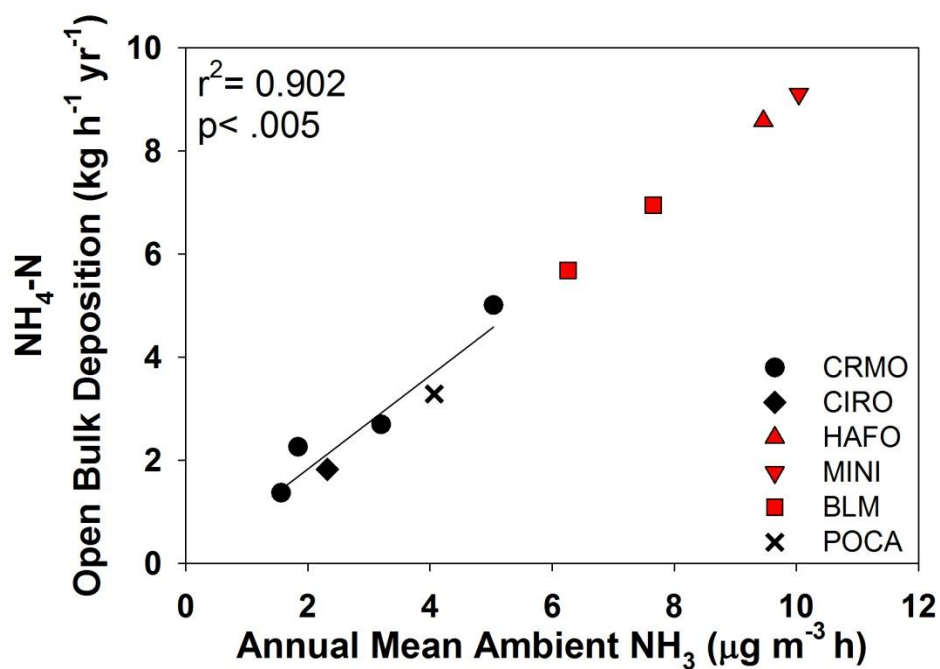


Figure 5. NH_4^+ -N bulk deposition relative to mean annual ambient NH_3 collect on passive samplers. Values for are bulk deposition sites contaminated by birds (red dots) were calculated using the regression equation through the remaining sites.

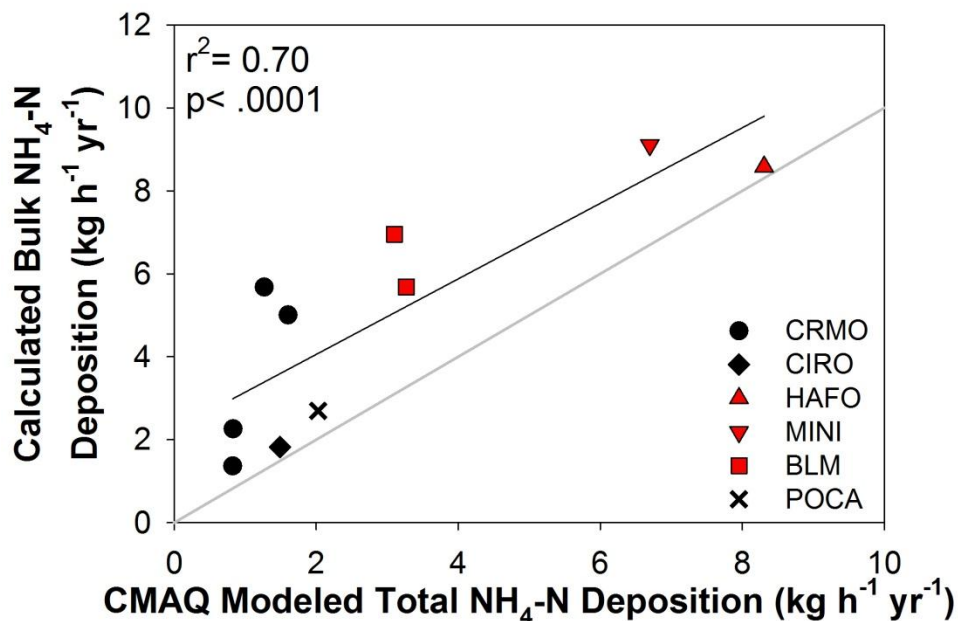


Figure 6. Measured and calculated NH_4^+ -N deposition compared to CMAQ modeled NH_4^+ deposition. Red dots represent sites where deposition values had to be calculated due to contamination. The grey line is the 1:1 line of modeled vs calculated NH_4^+ -N deposition.

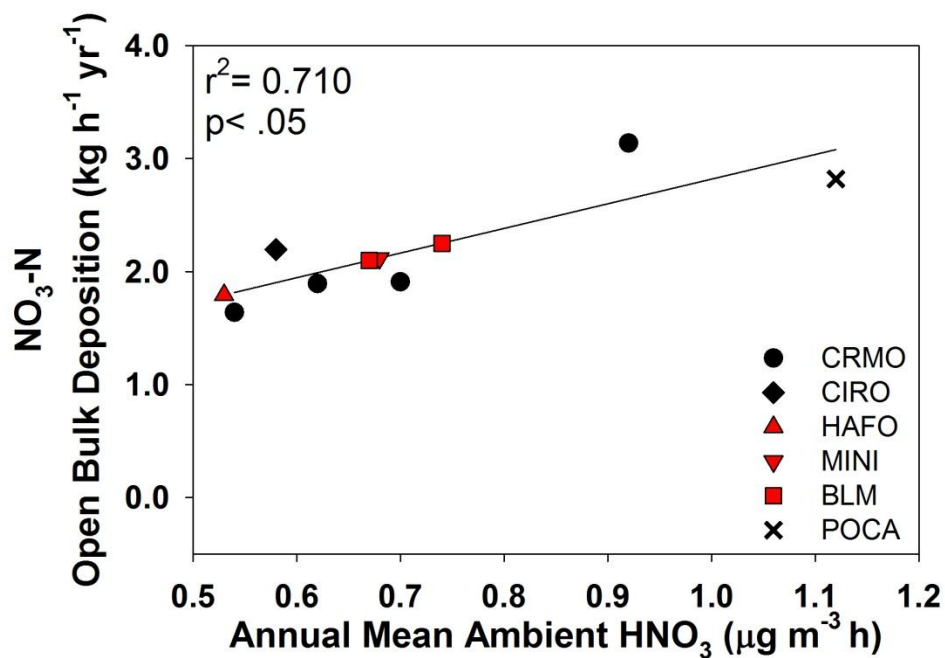


Figure 7. $\text{NO}_3\text{-N}$ bulk deposition relative to mean annual ambient HNO_3 collect on passive samplers. Values for are bulk deposition sites contaminated by birds (red dots) were calculated using the regression equation through the remaining sites.

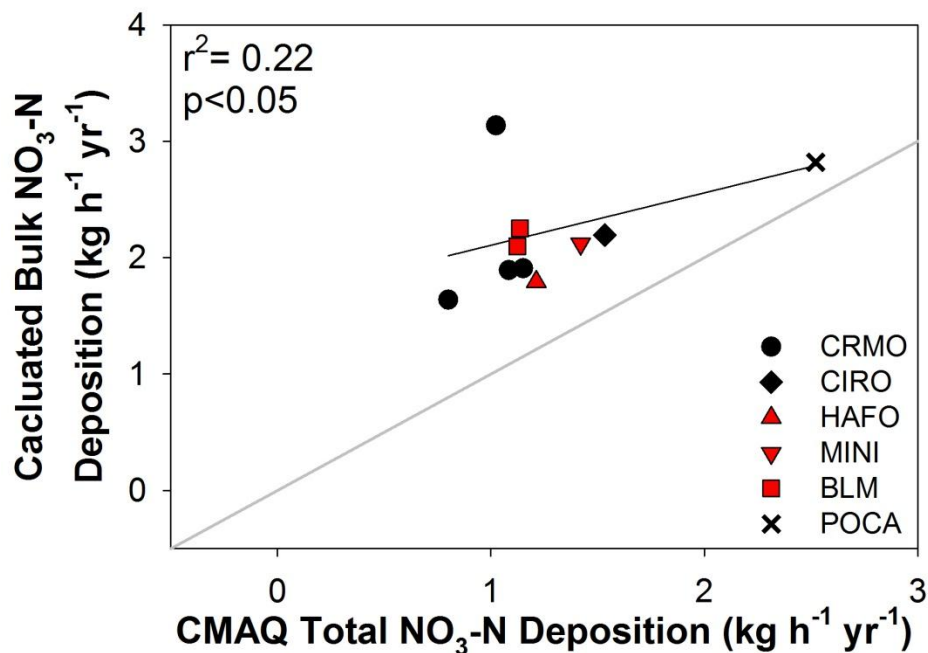


Figure 8. Measured and calculated $\text{NO}_3\text{-N}$ deposition compared to CMAQ modeled $\text{NO}_3\text{-N}$ deposition. Red dots represent sites where deposition values had to be calculated due to contamination. The grey line is the 1:1 line of modeled vs calculated $\text{NO}_3\text{-N}$ deposition.

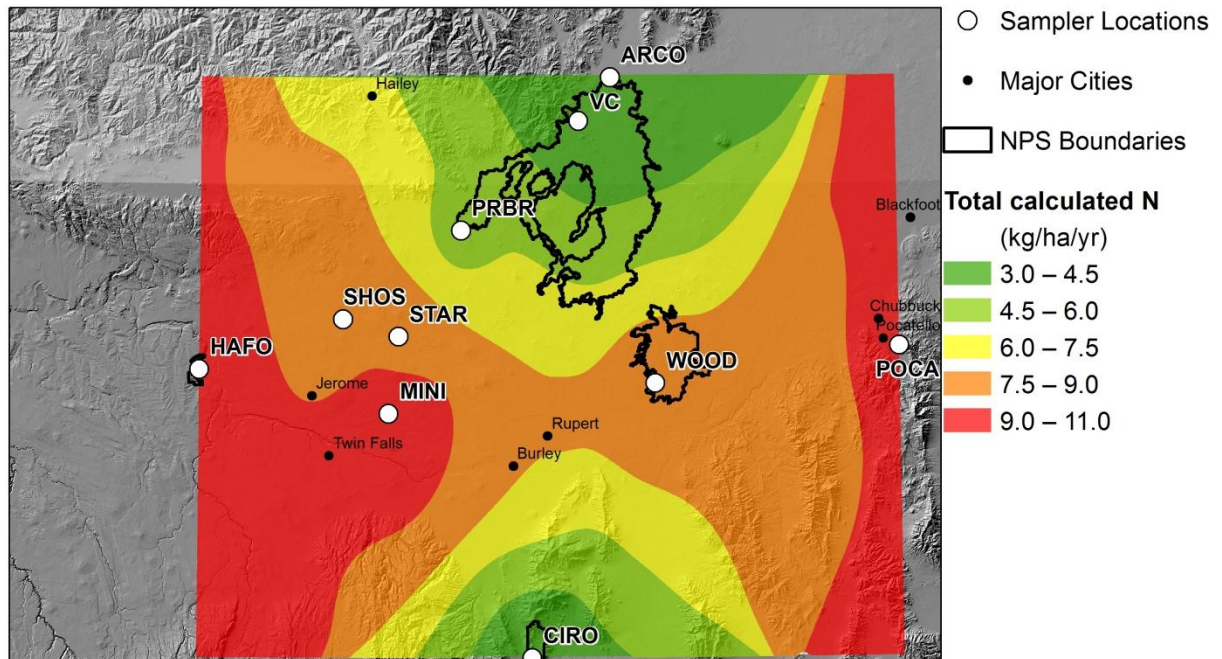


Figure 9. Calculated 2011-2012 bulk N deposition values for the entire study area. Values were interpolated using Inverse Distance Weighting in ArcGIS 10.2

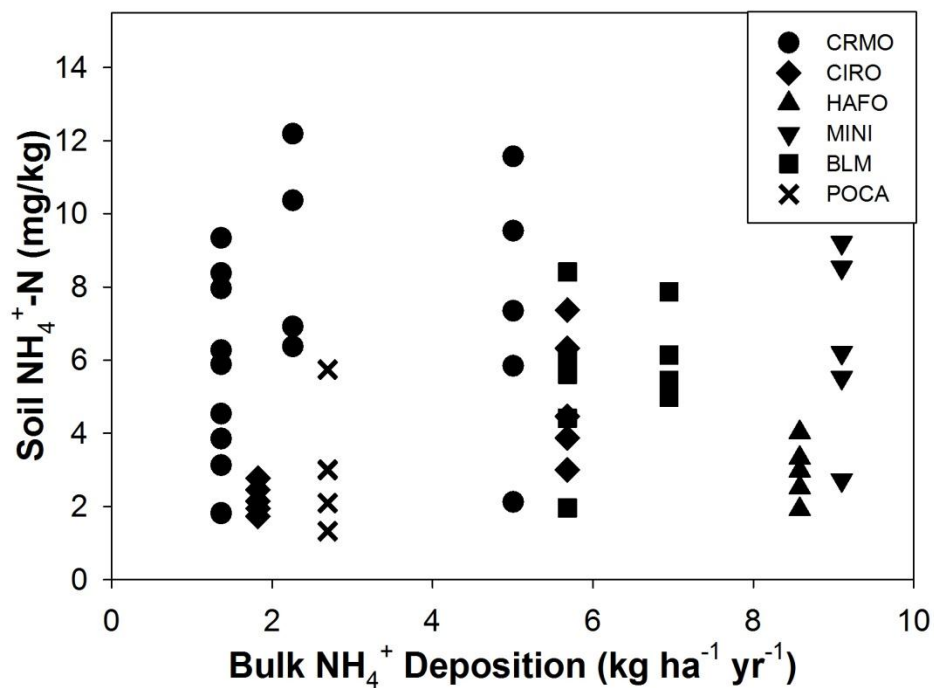


Figure 10. Soil NH_4^+ from August 2010 extracted in 1M KCl compared to calculated 2011-2012 bulk NH_4^+ -N deposition.

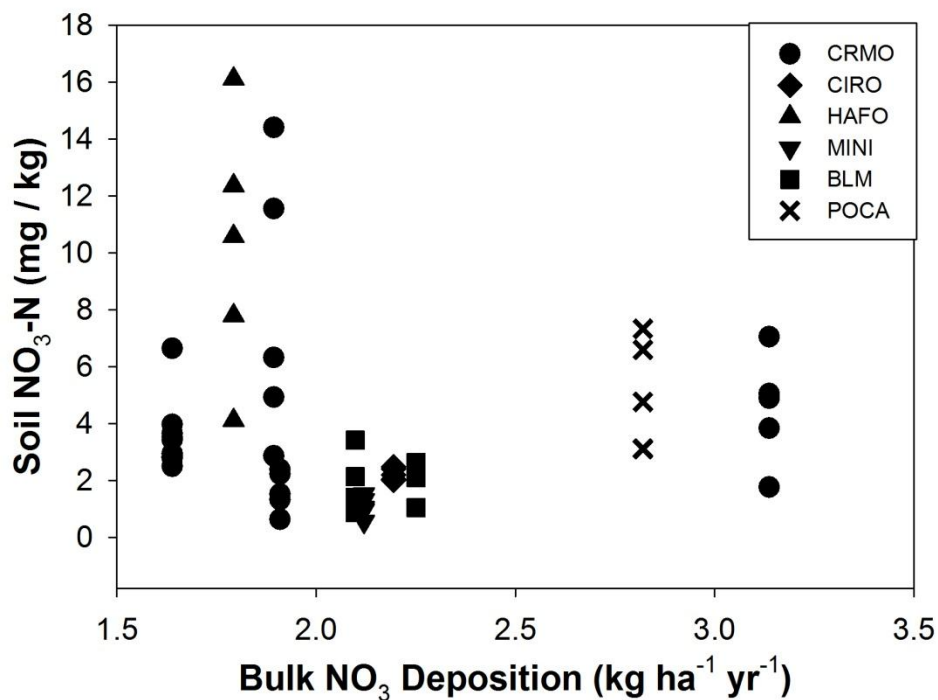


Figure 11. Soil NO_3^- extracted in 1M KCl relative to calculated 2011-2012 bulk NO_3^- deposition.

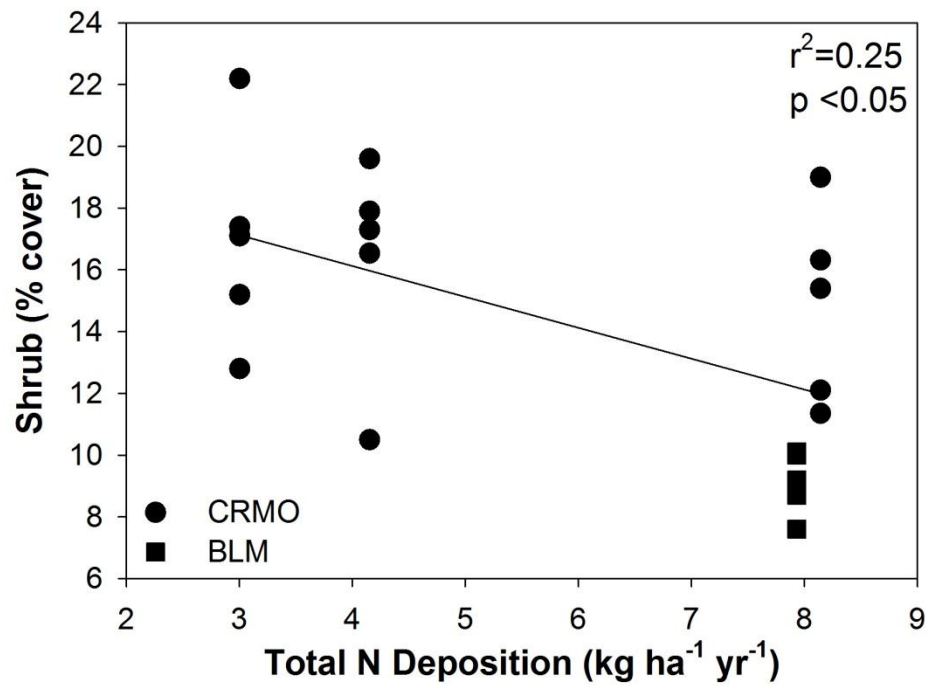


Figure 12. Shrub percent cover based on 100m line-intercept transects at sites with increasing levels of calculated 2011-2012 total nitrogen deposition.

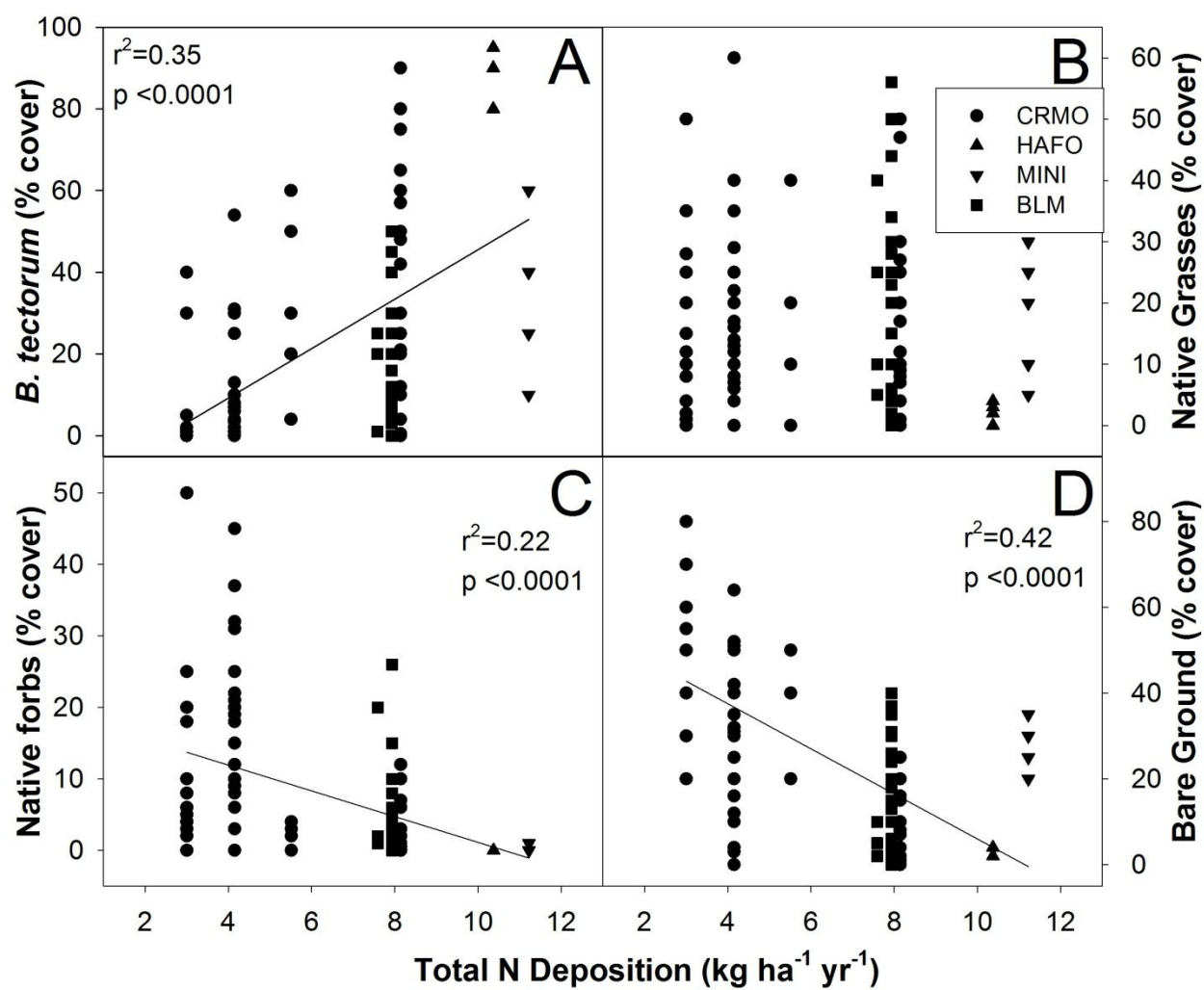


Figure 13. Change in percent cover of vegetation classes (A-C) and unvegetated space (D) with changing levels of calculated 2011-2012 total nitrogen deposition based on 2010 vegetation surveys.

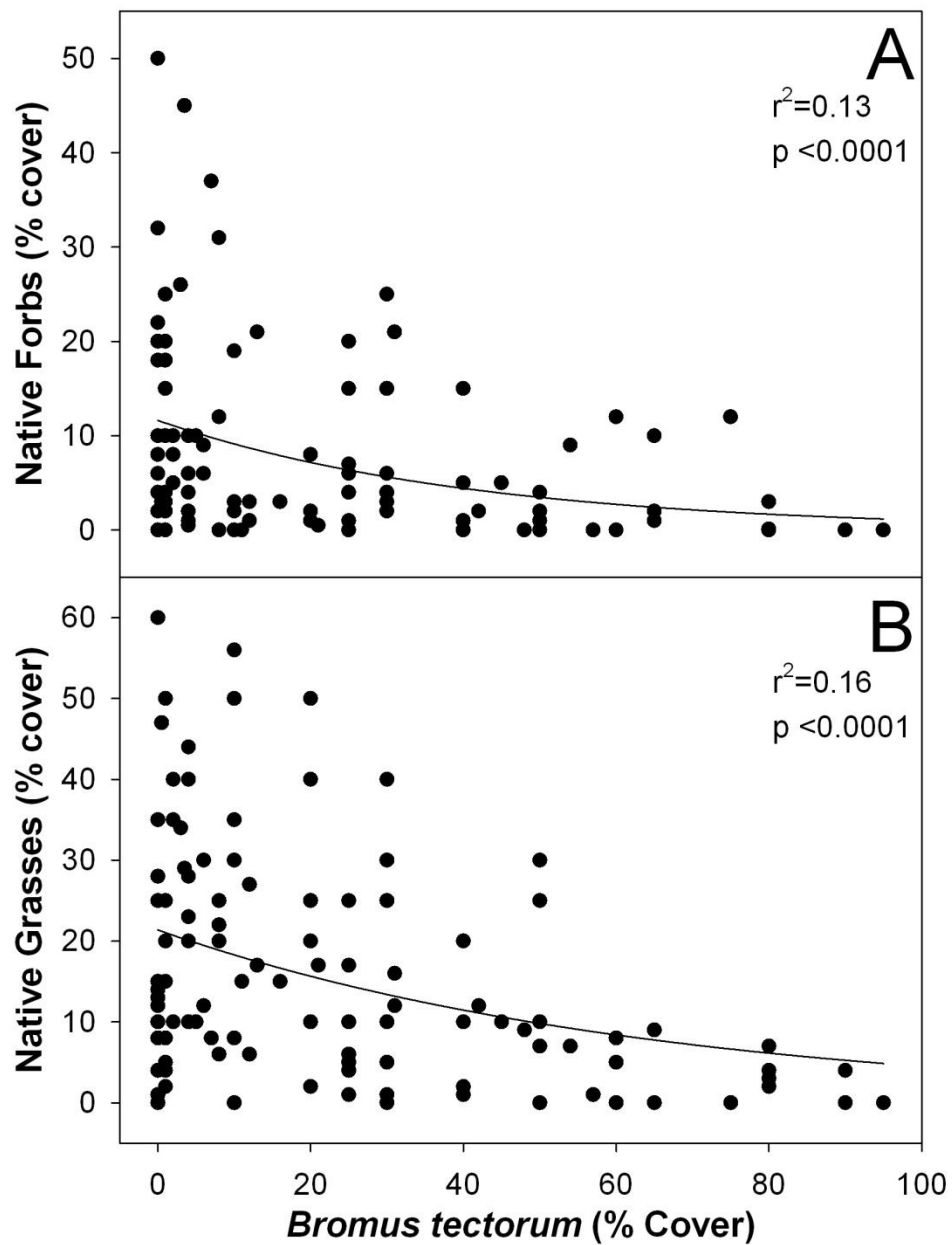


Figure 14. The relationship between *B. tectorum* cover and the cover of native forbs (A) and native grasses (B) within individual plots from 2010 vegetation surveys. An exponential decay model was used to evaluate the relationship.

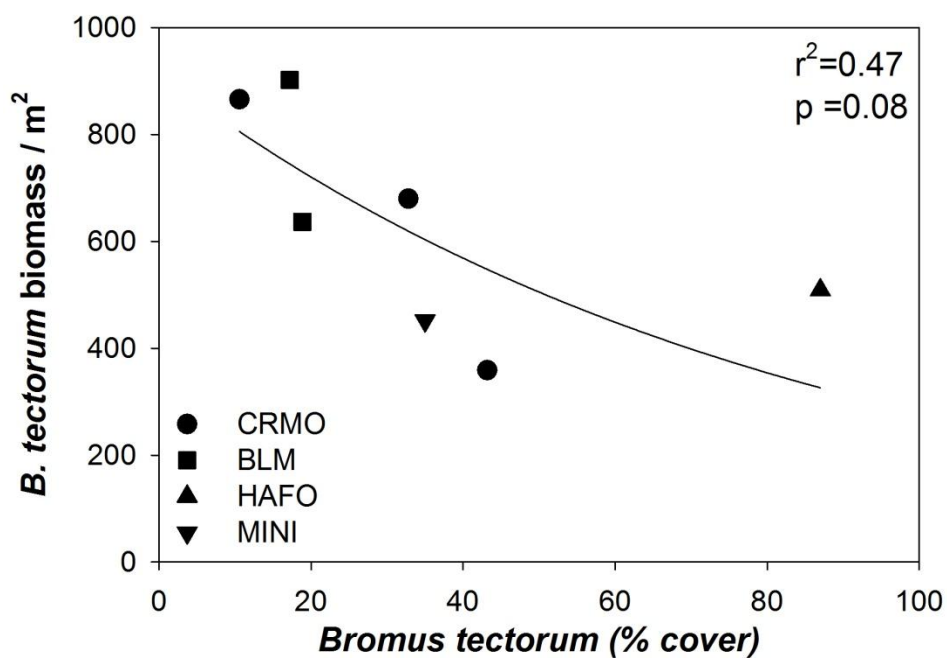


Figure 15. Biomass of *B. tectorum* per unit area based on the average percent cover of *B. tectorum* present at a site. Modeled relationship based on exponential decay.

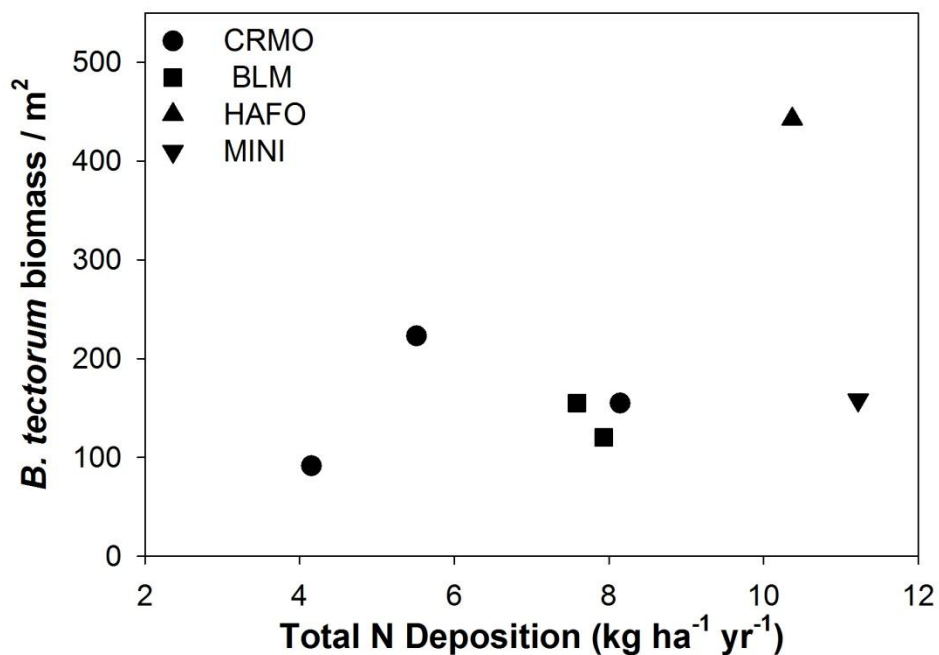


Figure 16. Calculated biomass of *B. tectorum* / m² (potential biomass x percent cover) as a function of increasing calculated 2011-2012 total nitrogen deposition.

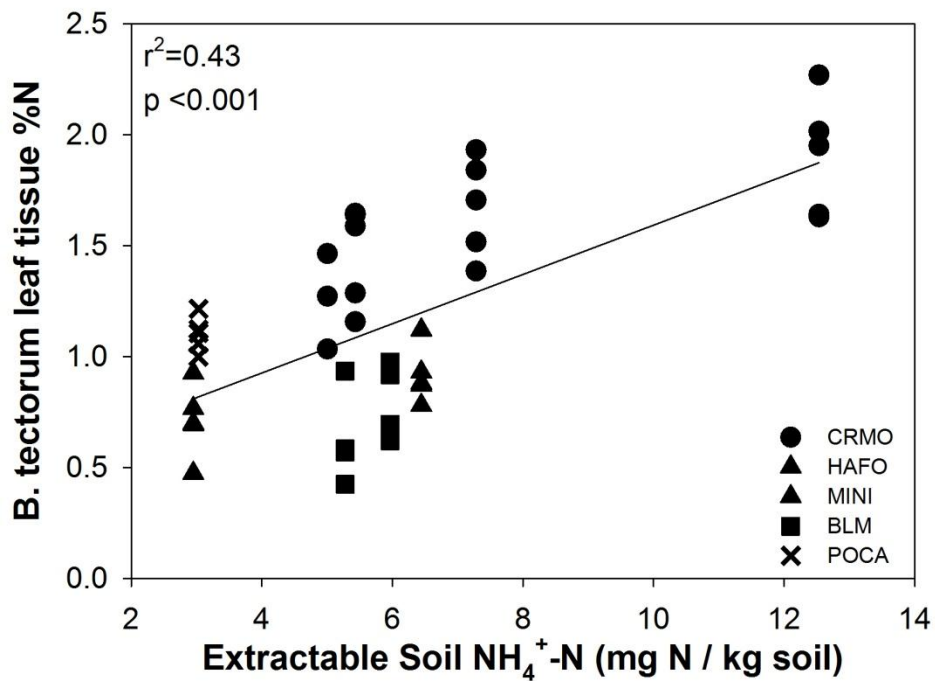


Figure 17. *Bromus tectorum* leaf tissue percent N compared to extractable soil NH_4^+ -N at each site.

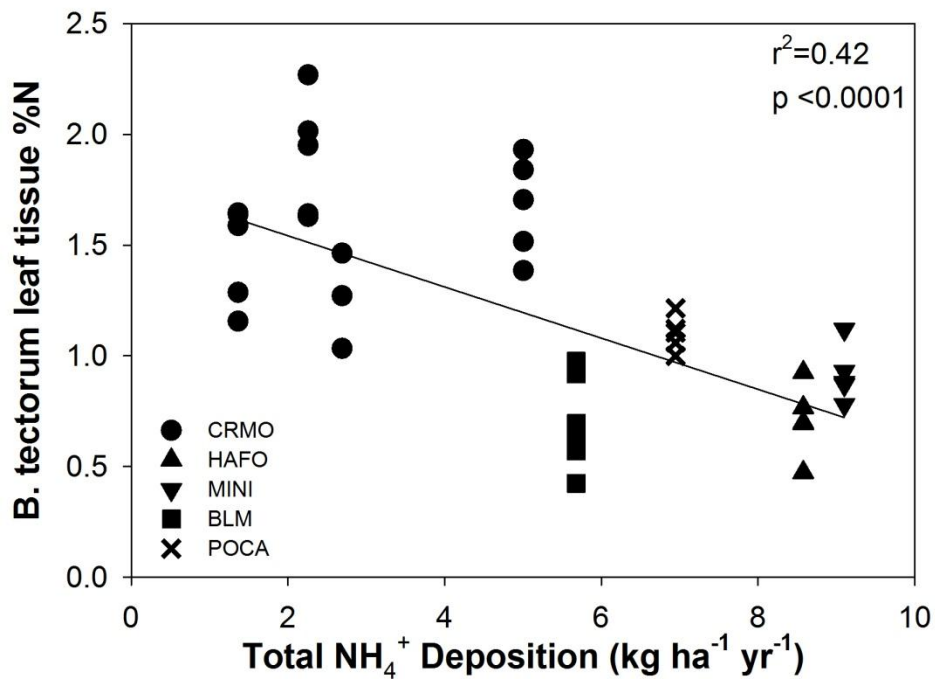


Figure 18. *Bromus tectorum* leaf tissue percent N compared to calculated 2011-2012 atmospheric NH_4^+ deposition at the site.

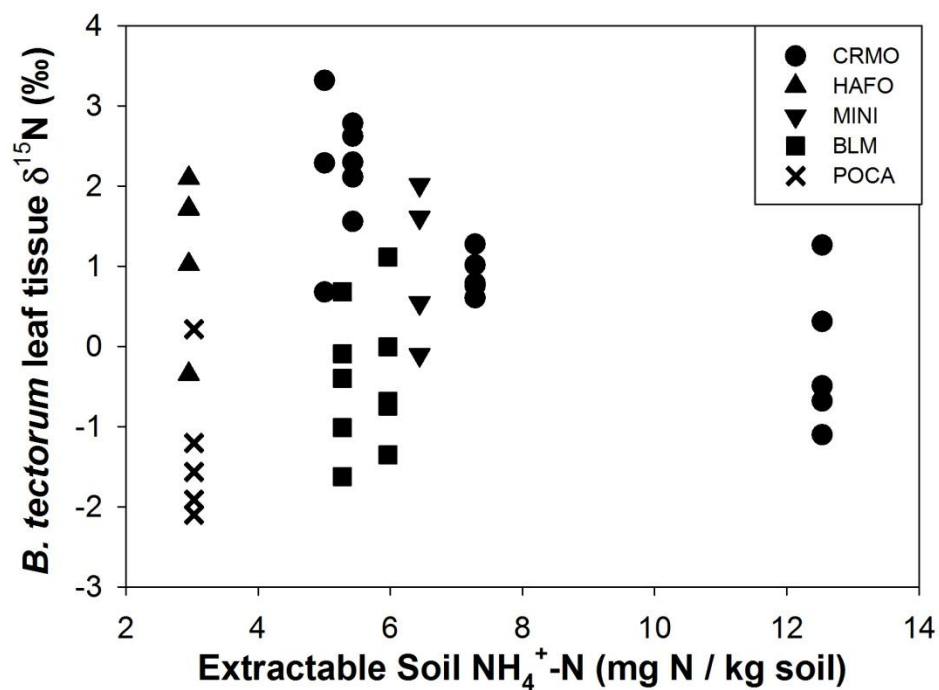


Figure 19. *Bromus tectorum* leaf tissue $\delta^{15}\text{N}$ compared to soil extractable $\text{NH}_4^+\text{-N}$ at each site.

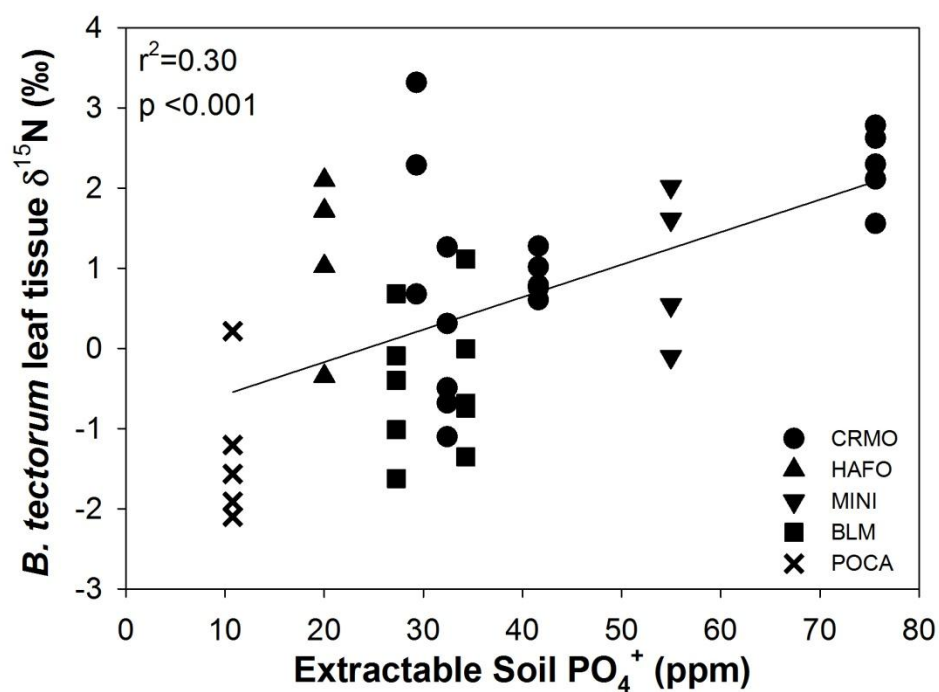


Figure 20. *Bromus tectorum* leaf tissue $\delta^{15}\text{N}$ compared to soil extractable PO_4^+ at each site.

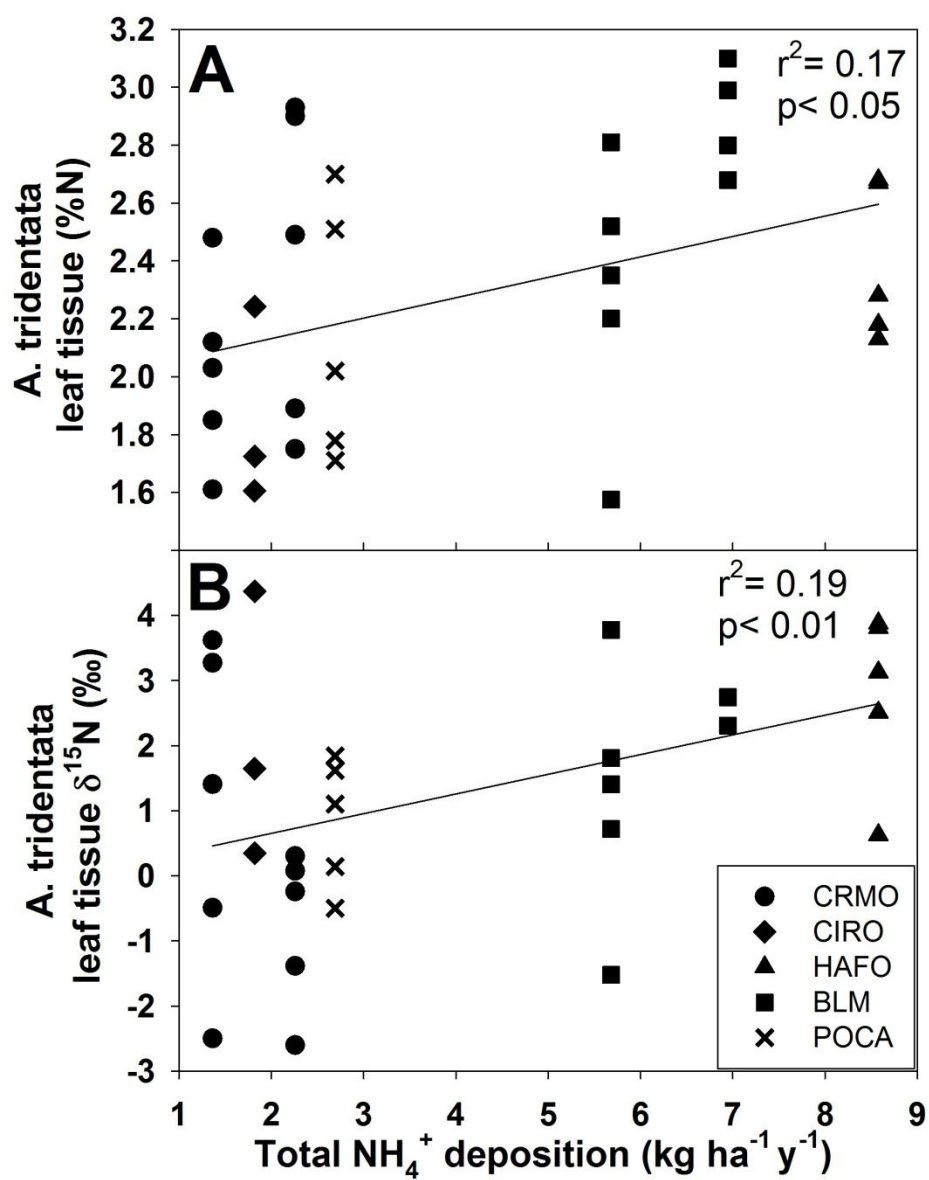


Figure 21. *Artemisia tridentata* leaf tissue percent N (A) and leaf tissue $\delta^{15}\text{N}$ (B) compared to calculated 2011-2012 NH_4^+ deposition across all sites.

Appendix I

Species list for vegetation surveys

<u>Species</u>	<u>WOOD</u>	<u>VC</u>	<u>PRBR</u>	<u>HAFO</u>	<u>MINI</u>	<u>STAR</u>	<u>ARCO</u>
<i>Agoseris</i> spp.	X	X	X				X
<i>Agropyron elongatum</i>			X		X		
<i>Agropyron smithii</i>			X		X		
<i>Agropyron spicatum</i>	X	X	X			X	X
<i>Agropyron</i> spp.				X	X		
<i>Allium</i> spp.	X						
<i>Apiaceae</i> spp.					X		
<i>Arabis</i> spp.	X						
<i>Artemisia tridentata</i>	X		X	X	X	X	X
<i>Artemisia triparta</i>	X		X				X
<i>Asteraceae</i> spp.			X				
<i>Asteraceae</i> spp. (aromatic)					X	X	X
<i>Asteraceae</i> spp. (fuzzy basal leaves)						X	
<i>Astragalus filipes</i>							X
<i>Astragalus</i> spp.							X
<i>Astragalus</i> spp. (white flower)	X		X				
<i>Atriplex polycarpa</i>				X			
<i>Brassicaceae</i> spp. (elongate pods)					X		
<i>Brassicaceae</i> spp. (oblong pods)						X	
<i>Bromus japonicus</i>							X
<i>Bromus secalinus</i>					X	X	
<i>Bromus tectorum</i>	X	X	X	X	X	X	X
<i>Carex</i> spp.	X						
<i>Chaenactis douglasii</i>		X	X				X
<i>Chenopodium pratericola</i>		X					
<i>Chrysothamnus nauseosus</i>		X	X	X	X		X
<i>Chrysothamnus viscidiflorus</i>	X	X	X	X		X	X
<i>Clarkia</i> spp.	X	X	X		X	X	X
<i>Collinsia parviflora</i>		X					X
<i>Crepis acuminata</i>		X			X		X
<i>Crypantha</i> spp.						X	X
<i>Crypantha</i> spp. (fuzzy)						X	
<i>Cryptantha</i> spp.		X				X	
<i>Delphinium hydraphylla</i>		X					
<i>Delphinium</i> spp.	X	X					
<i>Descurainia</i> spp.	X			X			
<i>Draba</i> spp.	X						
<i>Elymus canadensis</i>		X					

<i>Elymus cinereus</i>							X
<i>Elymus elymoides</i>	X	X			X		X
<i>Elymus spp.</i>	X						
<i>Erigeron purple</i>					X		
<i>Erigeron spp.</i>							X
<i>Eriogonum spp.</i>		X					
<i>Eriogonum umbellatum</i>		X					
<i>Erodium cicutarium</i>					X		
<i>Festuca octoflora</i>					X		
<i>Festuca spp.</i>	X						
<i>Gayophytum ramosissimum</i>		X				X	X
<i>Gayophytum spp.</i>	X	X					
<i>Gilia spp.</i>	X						
<i>Gnaphalium spp.</i>		X					
<i>Gnaphalium spp.</i> (fuzzy leaf)		X	X				
<i>Gutierrezia spp.</i>			X				
<i>Hesperostipa comata</i>		X				X	X
<i>Lactuca serriola</i>	X		X		X	X	X
<i>Lepidium densiflorum</i>			X			X	
<i>Leptodactylon pungens</i>							X
<i>Lithospermum spp.</i>		X					
<i>Lomatium spp.</i>						X	
<i>Lupinus spp.</i> (purple, tall)						X	X
<i>Lupinus spp.</i> (silvery leaves)							X
<i>Mentzelia dispersa</i>		X				X	X
<i>Mimulus nanus</i>		X					X
<i>Mimulus pilosus</i>		X	X				
<i>Mysotis spp.</i>	X						
<i>Nemacladus spp.</i>	X						
<i>Oryzopsis hymenoides</i>				X			X
<i>Penstemon spp.</i>	X	X	X				X
<i>Phacelia hastata</i>		X					
<i>Phlox hoodii</i>	X	X			X	X	
<i>Phlox longifolia</i>							X
<i>Plantago spp.</i>			X				
<i>Poa bulbosa</i>	X				X		
<i>Poa secunda</i>	X	X	X	X	X	X	X
<i>Poa spp.</i>				X			
<i>Polygonum douglassi</i>							X
<i>Purshia tridentata</i>		X					
<i>Sisymbrium altissimum</i>	X			X	X	X	
<i>Sphaeralcea coccinea</i>					X		
<i>Stipa spp.</i> (fine leaves)							X

<i>Taraxacum officinale</i>				X	
<i>Tragopagon dubious</i>	X		X	X	X
<i>Trifolium spp.</i>					X
Unknown 1		X			
Unknown 2		X			
Unknown 3				X	
Unknown 4 (Red-green tiny)	X				
Unknown 5	X				
<i>Viola spp.</i>		X			X
<i>Vulpia octoflora</i>	X		X		X