N or out? Examining the effects of drought on nitrate retention.

By

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0.1 Abstract

Models predict that future precipitation in the Midwestern United States will display increased year-to-year variablity in total rainfall, as well as more droughts interspersed with heavy rainfall events. These factors, along with anthropogenic changes in land use, are known to increase nitrate losses in many soil systems. This nitrate usually goes on to pollute surface waters and promote harmful algal blooms. Much of the past work on this topic has been done only at a watershed scale, in pursuit of understanding surface water pollution. Thus, there remains a gap in the understanding of these dynamics at the pedon scale. To investigate this gap, we collected 135 intact large soil mesocosms from across Kansas. We collected cores from similar soil series but from differing management strategies and from different levels of historical precipitation. We brought them together in a common garden style experiment design, and applied a two-level rainfall treatment, an extended drought period, and several heavy rainfall events. The concentration of exported leachate was very consistent across land uses, historical precipitation regimes, and across rainfall levels, but did show a large increase directly after a long drought. The soil itself did contain more nitrate in certain western soils, but was unresponsive to the rainfall treatment. We expect that droughts will predict nutrient loss patterns of the future, particularly when followed by a large rainfall event.

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0.2 Introduction

Precipitation patterns in the Midwestern United States are changing. Many models of future climate predict increased year-to-year rainfall variablility, as well as increased seasonal variability ((Armal, Devineni, and Khanbilvardi 2018, @Hatfield2013)). These models predict lengthening periods of drought broken by extreme rainfall events (Hatfield, Cruse, and Tomer 2013).

The ability of soils to retain their function is strongly dependent on available moisture and changes in precipitation. Periods of drying have long been known to increase soil respiration rates and mineralized N content (Birch 1958), which damages water holding capacity (Doran and Zeiss 2000), lowers soil quality (Doran and Zeiss 2000), and enables greater N loss (Ramundo, Tate, and Seastedt 1992).

Historical precipitation also plays a role in mediating the soil's response to droughts and heavy rainfall. Research has shown that although microbes are ubiquitous and easily-spread, the history of a microbial community affects its present-day function and its responses to changing weather (Evans and Wallenstein 2012, @Fierer2002). These effects can partially govern the soil's ability to retain N, ability to retain water, and whether it retains or respires soil carbon. Examining the influence of historical precipitation now will help predict how soil function will change in the face of a changing climate.

Further, changes that come with anthropogenic land uses, such as tillage and altered plant communities, change the soil's ability to retain nutrients, and reduce its resilience to altered weather (Keesstra et al. 2012, @DeVries2012). Studies have demonstrated that these effects can interact with drought and changes in precipitation to reduce the soil's capability to retain nutrients further than any of these factors would alone (Osburn et al. 2021), but there has not yet been a pedon-scale study of these interactions with soils from the Midwestern United States.

While research into these dynamics has been conducted within prairie systems worldwide, much of this past research has been set at a watershed scale or greater (Hatfield, Cruse, and Tomer 2013, @SheikhyNarany2017). It remains unknown if these changes and interactions produce an effect at the pedon scale, or if some larger phenomenon is causing this nutrient loss.

Therefore, we ask: How will worsening droughts and sharpening rainfall curves affect nutrient retention on pedon scale? To help answer this question, we investigate six questions: 1) Do leachate N concentrations from native soils increase when rainfall is halved? 2) Is that response stronger in tilled, agricultural systems? 3) Do soil N concentrations respond as well? 4) Does an extended drought further strengthen these three effects? 5) Does ANPP respond negatively to lower rainfall? 6) Do microbial communities produce higher amounts of greenhouse gasses in response to lowered precipitation and drought?

We wanted to address these questions in an intact soil environment, with field-quality soil aggregation and high root establishment. Aggregates provide extremely important microsites for denitrification and other nitrogen interactions. Dense aggregates provide anaerobic sites in otherwise oxygenated soils, and small changes in aggregate structure can enhance or remove this effect (Sexstone et al. 1985). Plants grown in an undisturbed environment have higher mycorrhizal association than freshly disturbed roots, especially under conditions of water stress (Mickan et al. 2019). These associated fungi provide plants with a greater surface area with which to interact with the soil environment and influence nutrient concentrations. We also wished to control variation due to differences in daily weather, so we used a common garden-style approach in our experimental design.

1 Methods

1.0.1 Site Selection and Collection

We selected our sites to assess several of the distinct soil histories in Kansas, so as to ensure our results would be broadly applicable. We wanted to incorporate both agricultural and native land uses, as well as different levels of historic precipitation. Therefore, we collected samples from four locations: 1) Kansas State University's Western Kansas Agricultural Research center outside of Hays, KS (38.843°N, -99.318°W), 2) the Konza Prairie LTER field station near Manhattan, KS (39.101°N, -96.608°W), 3) Kansas State University's East Central Experiment Field (38.539°N, -95.244°W), and 4) The Nature Conservancy's Anderson County Prairie Preserve (38.183°N, -95.272°W). Each of these sites, like most of the Kansas landscape, are composed of loess-derived Mollisols. Specifically, the Western Kansas Agricultural Research center is on a Harney soil series (Fine, smectitic, mesic Typic Argiustoll), Konza holds a Reeding series (Fine, mixed, active, thermic Abruptic Durixeralf), the East Central Experiment Field is Kenoma (Fine, smectitic, thermic Vertic Argiudoll), and the Anderson County Prairie Preserve is Woodson (Fine, smectitic, thermic Abruptic Argiaquoll, (USDA-NRCS 2021)). The thirty-year mean annual precipitation ranges from 592mm at the Hays site to 1010mm at the Ottawa site (PRISM Climate Group 2018).

We collected 135 intact soil cores from across the state of Kansas in 2018, with the help of a large piece of custom hydraulic machinery (Figure 1). This machine anchored itself into the soil before extending a large press plate downwards (Swallow, E., and Owensby 1987). A beveled section of 12-inch diameter PVC well pipe was mounted under the press plate, and was driven c.a. 60 cm into the soil. The casing retained an intact plug of soil after retraction. At each site, except Konza, we collected cores from untilled native tallgrass prairie, active agricultural fields, and retired agricultural fields that had been restored via seeding with native species . Since the Anderson County Prairie preserve had no closely paired agricultural site, we used the East Central Experiment Field. Wet soil conditions prevented us from collecting samples representative of Konza's agricultural and post-agricultural fields, leaving only native prairie samples from Konza. We extracted a minimum of 18 cores from each other combination of site and land use.

Figure 1: Machine used to extract cores. This was pulled behind another vehicle.

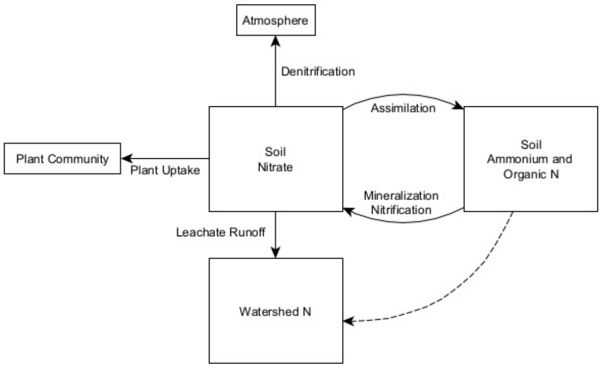

Figure 2: Conceptual figure detailing the different locations N moves through in prairie ecosystems.

1.0.2 Rainfall Manipulation

We randomly assigned each core to receive either a dry rainfall treatment or a wet rainfall treatment. We chose the dry treatment's rainfall total (820mm) by averaging the past thirty years of PRISM yearly rainfall data for Hays, Kansas, then raised that number by roughly forty percent to account for increased transpirative demand due to the high temperature of our greenhouse. The wet treatment received twice this amount

(1640mm). 450mm of each treatment was held in reserve in order to administer three 150mm intense rainfall events per year, to ensure production of leachate and mimic the storm events common across the study systems. During the second growing season, we randomly selected half of the remaining cores from each group, and applied a 45-day drought. We selected a length of 45 days by choosing the 99th percentile among intervals without more than 5mm of rainfall, from the past 30 years of PRISM rainfall data, combined between stations at Hays, KS, at Konza Prairie Biological Station, and at Garnett, KS.

1.0.3 Construction and Sampling

After returning these cores to our greenhouse, we added 8-10cm of pea gravel to form a reservoir on the bottom of each soil plug, and added a PVC cap to the underside, affixed with latex caulk. We then inserted a tap into the side of the well pipe, 1 cm from the bottom, in the middle of the gravel layer. The purpose of this tap was to allow any internal water to flow out for collection.

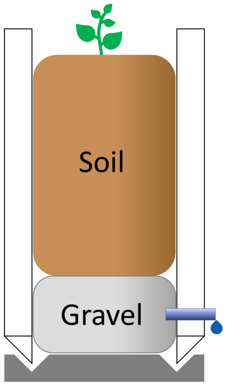

Figure 3: Cross section of the monolith design.

We set up a drip irrigation system to feed water to the top of each core, according to its assigned rainfall treatment. Three times per year, we used the irrigation system to apply 150mm of the reserved 450mm all at once to the cores, again to simulate a large storm event and to help ensure production of leachate.

At the end of the first growing season, we randomly selected half of each site/use/treatment group for destructive sampling. We split the cores vertically and took samples at four depth increments (0-5cm, 5-15cm, 15-30cm, 30cm to end-of-core, referred to as 45cm hereafter) to be later used in Denitrification Enzyme Assays (DEAs), respiration incubations, and nitrate extractions. We kept samples stored at 4° C until tests could be performed.

1.0.4 Chemical analysis

We spectroscopically analyzed leachate samples for ammonium and soluble reactive phosphorous (SRP) concentrations, and chromatographically for nitrite and nitrate concentrations. After one growing season, we randomly selected half of each 9 core group to be removed from their casing. We collected soil from each core destroyed in this way at 5cm, 15cm, 30cm, and 45cm depths. We performed 2M potassium chloride extractions, carbon dioxide production incubations, DEAs, and soil C analyses on each sample. At the end of the first and second growing seasons, we harvested, dried, and weighed the total aboveground biomass from every core.

1.0.5 Statistical analysis

Soil, leachate, and biomass data were analyzed using mixed effects linear models implemented in R and the lme4 package (R Core Team and RStudio Team 2020; RStudio Team 2020; Bates et al. 2015). Land use, site of origin, and rainfall treatment were treated as fixed effects, and soil depth (when applicable) was integrated as a random effect. Higher-order non-significant interactions were culled from each model to produce final models. The predicted means and standard errors of these models were used to produce the figures below (Lenth 2021).

As the experiment progressed, we were not able to consistently get every sample to produce leachate at every leaching event. Many cores simply ponded (Figure 4). Cores which ponded were not correlated with site of origin or land use. As a result, we had to choose how to handle quite a bit of missing data. Rather than leave missing samples in our datasets as false zeroes, we chose instead to cull those particular missing samples from our analyses.

2 Results

Western native sites contained 3750% more soil nitrate than eastern native soils ($P<0.0001$), varying from an average 5.897 μg/g soil to 0.157 μg/g soil (Figure 5). Restored soils were also affected. Western restored soils contained 1644% more nitrate than eastern restored soils($P<0.0001$), and varied from a mean concentration of 2.245 μg/g soil to 0.137 μg/g soil (Figure 5). Agricultural soils had similar nitrate levels at both sites, and held more nitrate than eastern native or restored soils, containing roughly 1 μg/g soil.

Leachate concentrations produced from western soils ranged from 200% to 600% greater than those produced by eastern soils. Leachate concentrations increased slowly as the experiment progressed, and we observed a large increase in leachate concentration after the imposed drought. After compensating for initial concentration,

Figure 4: Picture of a flooded, non-draining, core.

the 45-day drought in year two universally increased leachate nitrate concentrations by roughly 55% (Figure 8 and Table 2,P=0.0039).

We also tested for an interaction between land use and site in our yearly biomass data, as well as testing for the effects of the drought. The drought reduced AGB in the western site's native plant community 71% more than it did in the eastern site, but there was too much variation to support a valid difference (Table 3). The effect of the drought was similar within the restored agriculture and active agriculture cores.

In agricultural and restored soils, denitrification potential rates were marginally higher in the wet rainfall treatment compared to the dry rainfall treatment, but were not different enough to be statistically significant. Denitrification potential rates within each land use showed unexpected patterns. Native soils and restored soils showed 37 times and 16 times greater denitrification potential, respectively ($P<0.0001$,$P<0.0001$), in the historically drier western soil systems than in soils from the eastern sites. Agricultural soils showed a smaller form of the same change, but were too similar to be statistically distinguished (Figure 11,12).

Soil respiration rates varied only by land use, and not by precipitation treatment or site of origin. Restored soils produced the most carbon dioxide during a four-week incubation, followed by native soils, then agricultural soils. (Figure 13)

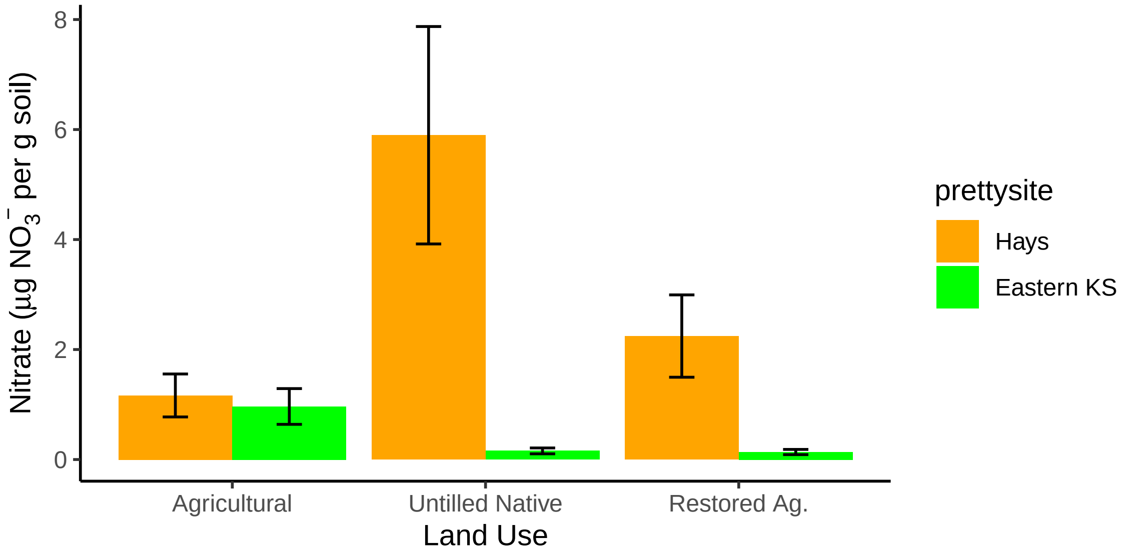

Figure 5: Modeled average soil nitrate concentrations per site and land use. Plotted points represent the modeled mean per group, and error bars represent the model's standard error.

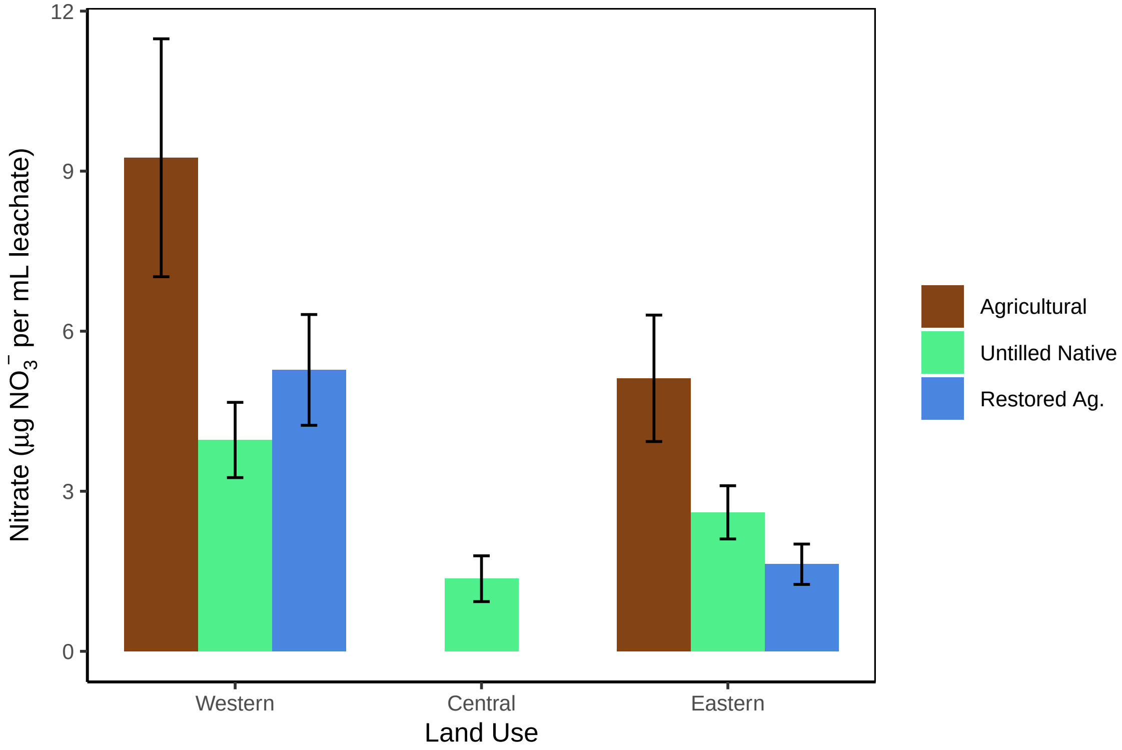

Figure 6: Plot of pretreatment nitrate concentrations. Plotted points represent the modeled mean per group, and error bars represent the model's standard error.

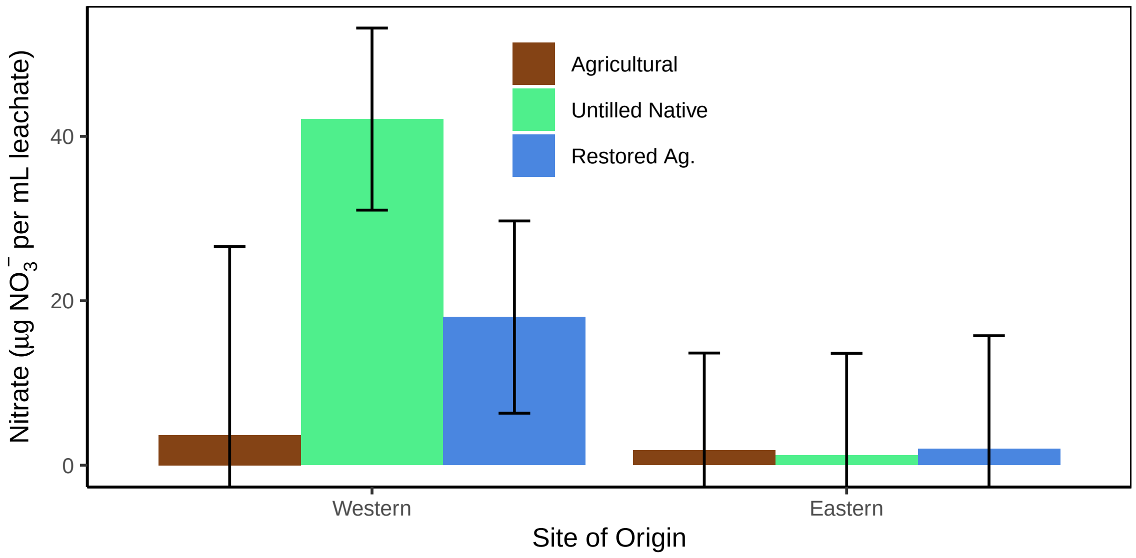

Figure 7: End year 1 leachate nitrate concentration by site. Plotted points represent the modeled mean per group, and error bars represent the model's standard error.

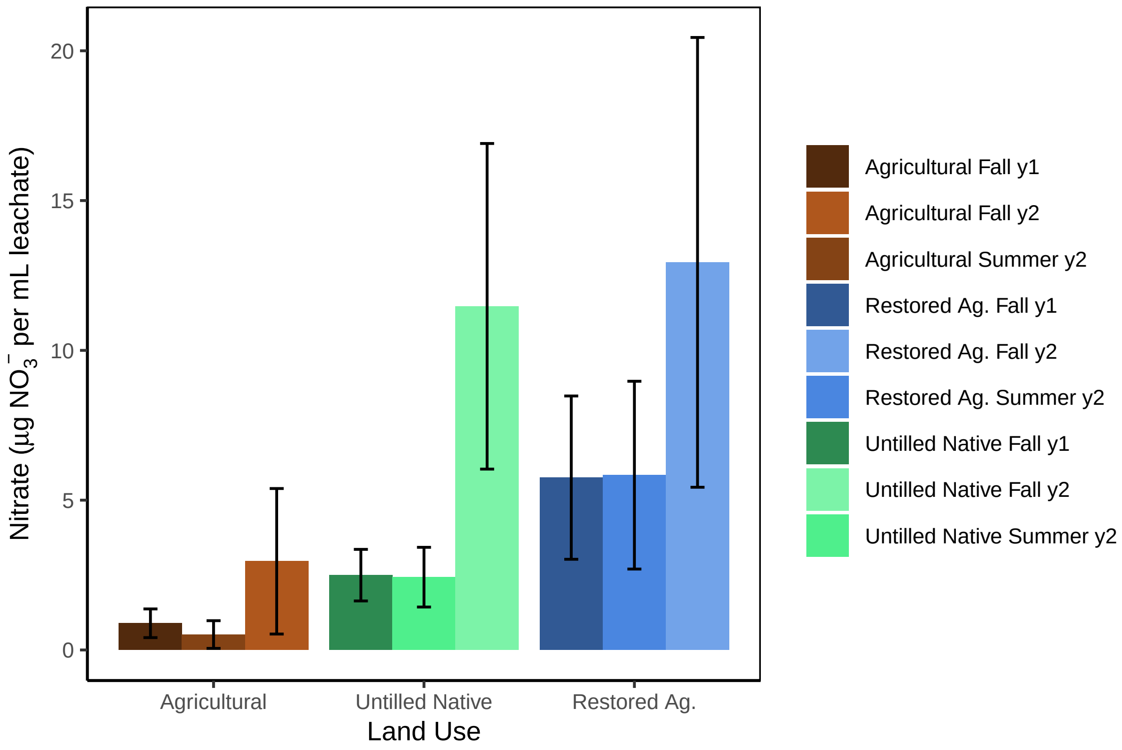

Figure 8: Mean and 95 percent C.I. of leachate nitrate concentration, collected at four timepoints through the experiment.

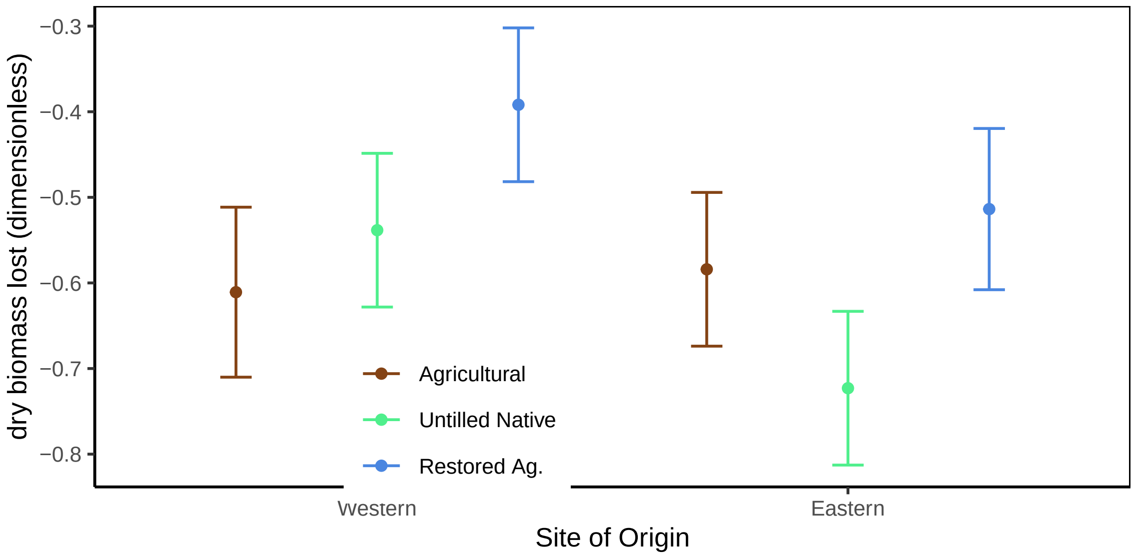

Figure 9: Standardized change in ANPP. The difference in dried aboveground biomass relative to first-year biomass. (y1-y2)/y1. Plotted points represent the modeled mean per group, and error bars represent the model's standard error.

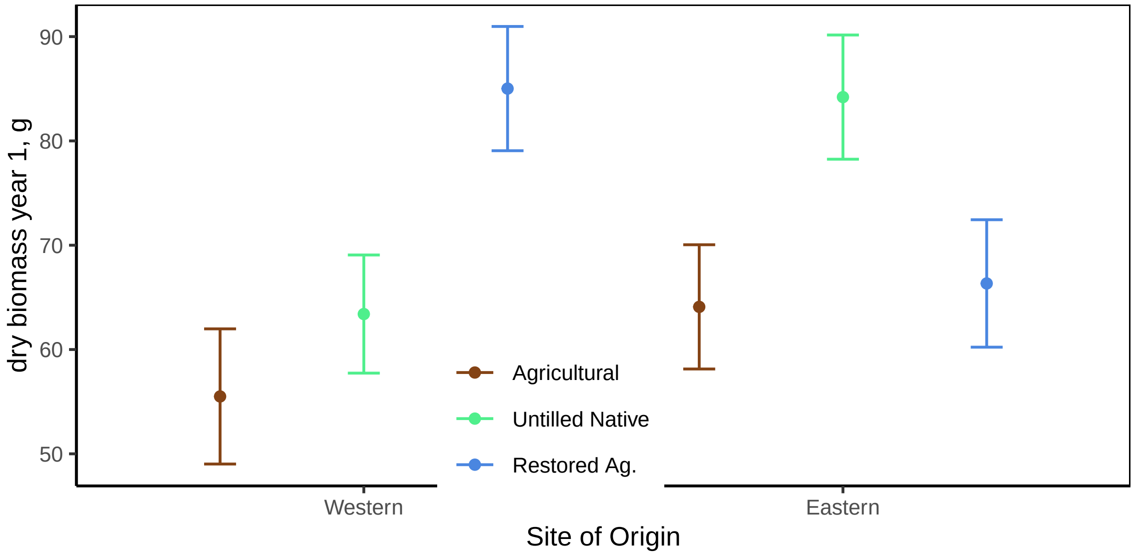

Figure 10: Dried biomass recorded from year one of the experiment. These plants were harvested after one growing season of the two-level rainfall treatment, and serve as the y1 reference mass. Plotted points represent the real mean per group, and error bars represent the 95 percent C.I.

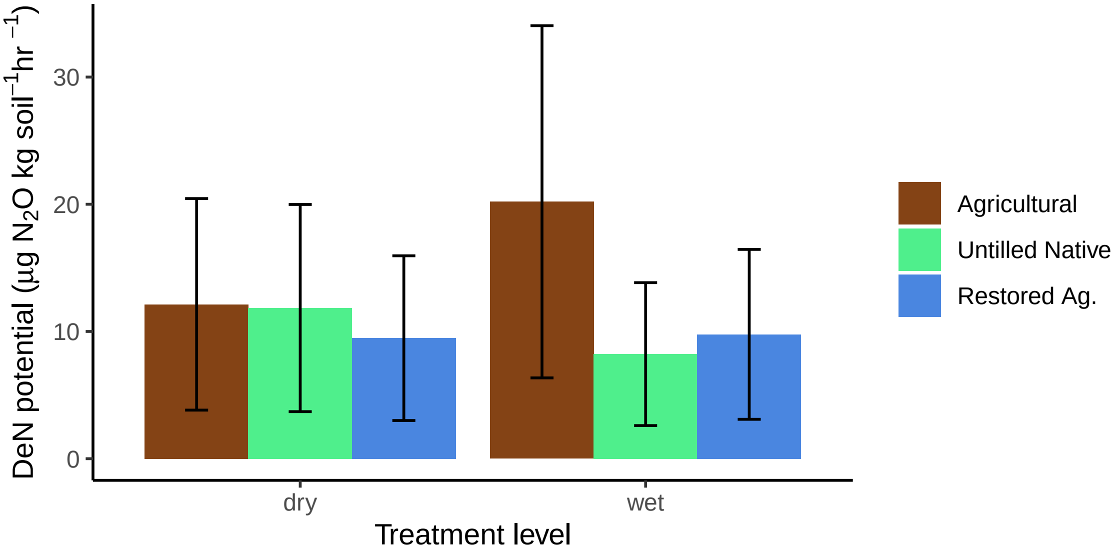

Figure 11: Hays denitrification rates. Points represent the modeled mean and 95 percent C.I. of denitrification enzyme potential observed during a DEA. Data are from soils from the 0 to 5cm depth increment.

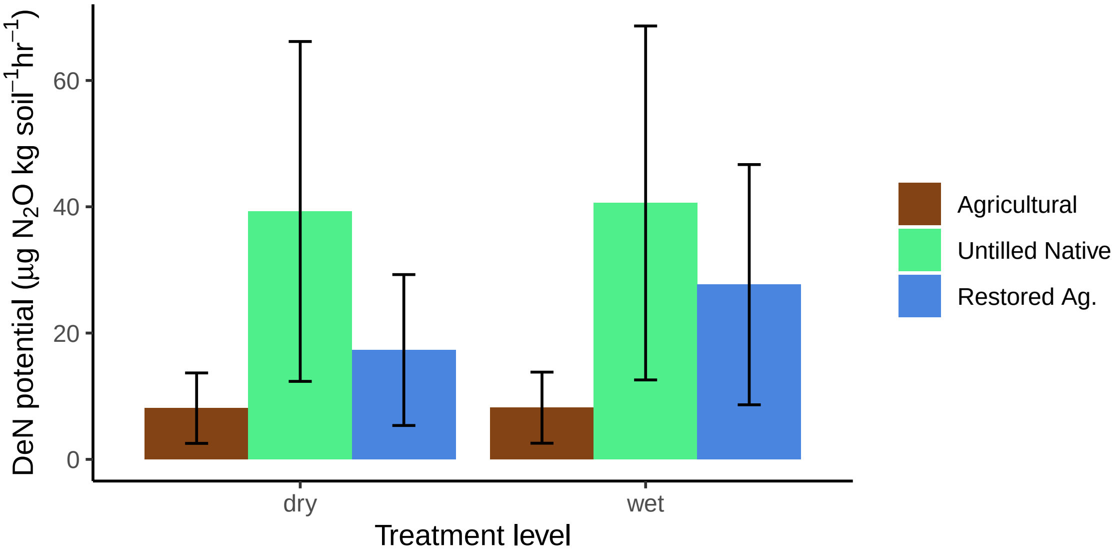

Figure 12: Eastern Kansas denitrification rates. Again, points represent the modeled mean and 95 percent C.I. of denitrification enzyme potential observed during a DEA. Data are from soils from the 0 to 5cm depth increment.

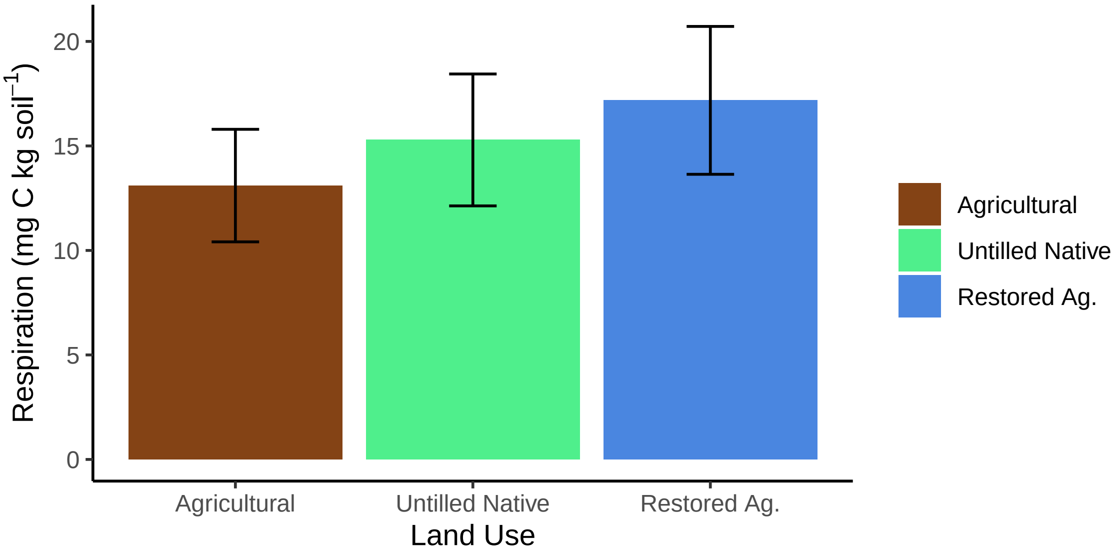

Figure 13: Soil respiration rates. Both rainfall treatments and sites of origin had little effect, so they have been pooled together here. Points represent the modeled mean per group, and error bars represent the model's standard error.

Table 1: Anova table regarding soil nitrate concentrations.

	Sum.Sq	Mean.Sq	NumDF	DenDF	F.value	Pr..F.
Site	215.738364	215.738364	1	166.0683	189.444831	0.0000000
Land Use	14.345948	7.172974	2	166.0256	6.298754	0.0023083
Treatment	3.085927	3.085927	1	166.0192	2.709824	0.1016238
Site:Land Use	97.047619	48.523810	2	166.0394	42.609876	0.0000000
Site:Treatment	30.570736	15.285368	2	166.0076	13.422434	0.0000040
Land Use:Sample Date	10.172669	10.172669	1	166.0193	8.932856	0.0032265

3 Discussion

Soil nitrate concentrations were higher in the historically drier western soils than they were in the historically wetter eastern soils 5. This could be the result of lower denitrification rates in the west, since the drier soil allows fewer secluded anaerobic microsites. Data from figures 11 and 12 support this idea. A more productive and diverse plant community could more effectively use the N present, which is in agreement with previous studies (Kleinebecker et al. 2014).

Leachate nitrate concentrations in Year 1 were much higher in western soils than in eastern soils (Figure 7. We expected this to be the case, due to lower historical denitrification rates and plant uptake rates in the drier, more aerated western soils. Leachate nitrate concentrations also continually increased throughout the experiment (Figure 8). We applied a higher amount of precipitation to the monoliths than the yearly averages, in order to help the plants meet the increased transpirative demand caused by the hot greenhouse environment. We may have still not provided enough extra water, however. If so, then we would see increased

Table 2: Anova table regarding leachate nitrate concentrations over time.

	Df	Sum.Sq	Mean.Sq	F.value	Pr..F.
Site	2	91.565687	45.7828438	11.9496064	0.0000178
Land Use	2	24.193774	12.0968868	3.1573626	0.0459501
Sample Date	2	43.999517	21.9997585	5.7420735	0.0041137
Site:Land Use	2	2.823502	1.4117509	0.3684758	0.6925369
Site:Sample Date	4	11.070263	2.7675656	0.7223518	0.5782340
Land Use:Sample Date	4	1.242916	0.3107291	0.0811022	0.9880351
Site:Land Use:Sample Date	3	1.233270	0.4110901	0.1072971	0.9556928
Residuals	125	478.915813	3.8313265		

Table 3: Anova table regarding standardized loss in ANPP between year 1 and year 2.

	Df	Sum.Sq	Mean.Sq	F.value	Pr..F.
Land Use	2	0.3904513	0.1952257	2.2004431	0.1200760
Site	1	0.1475101	0.1475101	1.6626270	0.2024568
Land Use:Site	2	0.1212364	0.0606182	0.6832447	0.5090630
Residuals	57	5.0571011	0.0887211		

leachate nitrate concentrations, because nitrate pools increase under water stress.

Total annual rainfall did not produce an effect in any leachate patterns (Figure 7). This is not in agreement with other studies, which have shown that watershed nutrient concentrations respond very strongly to variations in precipitation (Dodds and Oakes 2006).

Historical rainfall, as represented by site of origin, had a much stronger and much more significant effect on these samples than either land use or precipitation did (Figure 7). In past studies, historical precipitation has been shown to be a driving factor for differences in nitrate release rates (Evans and Wallenstein 2012).

The increase in leachate nitrate concentrations after the year two drought is remarkable. This effect was rather consistent between land uses and sites, and matches observations reaching as far back as 1958 (Birch 1958). In native and restored land uses, the post-drought leachate nitrate exceeds pretreatment concentrations by more than twofold.

Denitrification patterns differed wildly from east to west. Western agricultural soils displayed a higher rate of denitrification when exposed to the high-rainfall treatment, but the other two types of western soil had no response to the treatment (Figure 11). Eastern soils displayed a different pattern entirely. Eastern agricultural soil denitrification rates were lower than the other two land uses and did not change between rainfall treatments. Similarly, eastern native soil denitrification rates also remain the same between treatments, but were the highest out of the three land uses. Restored soils did vary with rainfall treatment, and displayed intermediate levels of denitrification in both cases (Figure 12).

Table 4: Data split by land use and site.

Group	Bulk Density (g/cm^3)	Pretreatment Infiltration Rate (cm/s)	Soil NO$_3$ Content μ g/g	Pretreatment Leachate [NO$_3$]	Midtreatment Leachate [NO$_3$]	Post-drought Leachate [NO$_3$]
Hays Agriculture	1.43 ± 0.1	0.4 ± 0.56	2.9 ± 2.01	20.39 ± 36.75	$NaN \pm NA$	$11.31 \pm NA$
Hays Native	1.41 ± 0.19	0.33 ± 0.69	43.49 ± 39.7	7.34 ± 12.18	14.49 ± 19.24	18.37 ± 19.25
Hays Post-Ag	1.37 ± 0.14	0.45 ± 0.52	7.39 ± 6.32	6.1 ± 3.65	14.26 ± 9.79	20.9 ± 10.19
Konza Agriculture	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$
Konza Native	1.17 ± 0.18	0.53 ± 0.4	4.67 ± 11.1	3.15 ± 5.67	5.17 ± 3.38	13.38 ± 8.26
Konza Post-Ag	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$	$NaN \pm NA$
Eastern Kansas Ag.	1.56 ± 0.08	0.63 ± 0.93	2.64 ± 1.99	7.14 ± 6.34	9.06 ± 18.99	9 ± 7.23
Eastern Kansas Native	1.42 ± 0.13	0.38 ± 0.6	0.72 ± 1.01	2.95 ± 1.89	5.1 ± 6.48	11.16 ± 7.65
Eastern Kansas Post-Ag	1.45 ± 0.12	0.18 ± 0.39	0.7 ± 0.96	1.83 ± 0.58	6.96 ± 5.28	8.22 ± 2.84
Dry Treatment	1.35 ± 0.17	0.32 ± 0.52	13.1 ± 25.49	6.45 ± 9.42	15.77 ± 14.64	19.51 ± 13.43
Wet Treatment	1.44 ± 0.16	0.5 ± 0.69	5.49 ± 15.38	7.25 ± 18.71	2.97 ± 3.2	8.52 ± 5.35

4 Conclusions

Extended droughts like our 45-day drought clearly increase leachate nitrate concentrations, and increase leachate losses if such a drought is followed by a rain event in excess of the soil's water holding capacity. This confirms that drought-rewetting cycles will increase both nitrate losses from soil systems and increase levels of nutrient pollution in surface waters. The post-drought increase relative to pre-drought nitrate concentrations was also consistent across site of origin and land use. Going forward, as droughts lengthen and rainfall events intensify, we expect to see that the worst offenders of nitrate release will release proportionally equal, but greater total, amounts of nitrate into surface- and ground-waters.

Leachate concentrations showed no substantial effect from land use or rainfall treatment, but were higher in the western Kansas sites. As an extension of the above prediction, we expect to see a similar pattern across historical rainfall levels - the worst offenders of nitrate release (drier areas) will release proportionally equal, but greater total, amounts of nitrate into surface- and ground-waters.

We were only able to sample soil to assess in-soil nitrate only once, after only one growing season of the two-level rainfall treatment. This may have been too short of a time for the rainfall treatment to produce any effects. Western soils held more nitrate than those in the east, showing increased potential for nutrient pollution in the watersheds of Western Kansas. In the east, converting soils from native prairie to agriculture raises the amount of nitrate they hold and increases pollution potential. However, it seems that implementing restorative management does restore the soil to its former concentrations. Where do these nutrients go after restoration, though? They can be incorporated into biomass, lost downstream, or lost as denitrification. The truth is likely an uneven mixture of these. The best reality would be incorporation into biomass, but our ANPP assessment showed that agricultural soils and restored soils support a similar amount of biomass(Figure 10). Additionally, our denitrification assays showed that these restored soils have a lower denitrification rate than the original native soils (Figure 12). This leads us to conclude that the missing nitrate is lost through leaching.

The differing patterns of denitrification we observed suggest that denitrification rates are governed by factors more complex than just soil moisture and soil nitrogen content. The western Harney soils drain only slightly more quickly than the eastern Woodson soils (USDA-NRCS 2021), but maybe their response to disturbance is different. If Harney soils lose much of their drainage rate when tilled, that could help explain why western agricultural soils responded so vigorously to the increased rainfall. To build on this, if Woodson soils are more resilient to the clogging effects of tilling, then that could help explain the lack of response in eastern agricultural soils.

4.1 Appendices

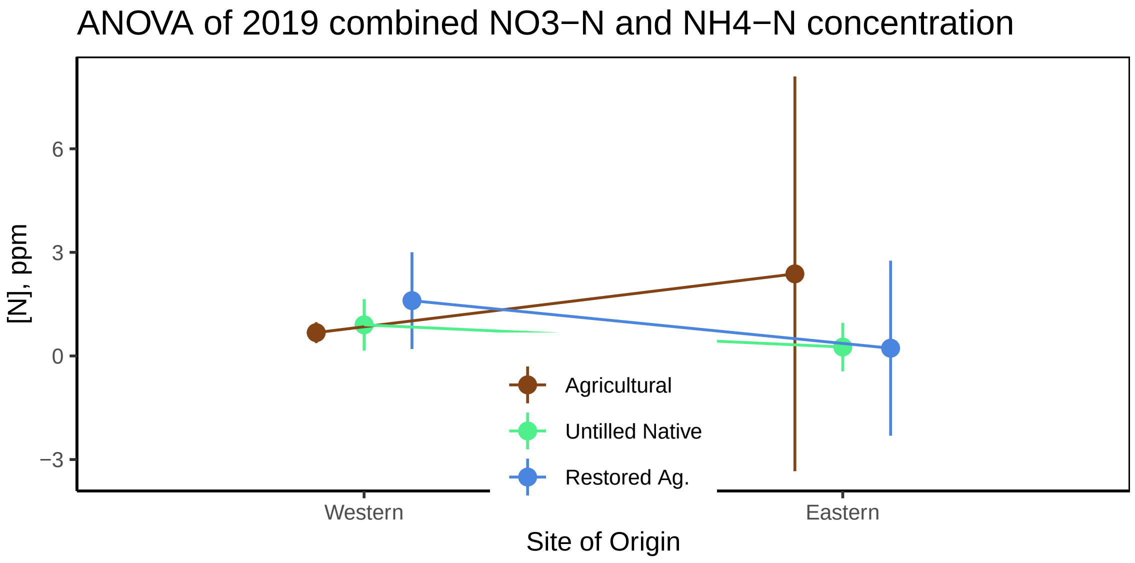

Figure 14: Pooling NO3-N and NH4-N as just N does not reveal any relationships.

Table 5: Means of different parameters for each factor group.

Group	Bulk Density (g/cm^3)	Infiltration Rate (cm/s)	Soil NO_3 Content μ g/g	Pretreatment Leachate [NO_3]	Midtreatment Leachate [NO_3]	Post-drought Leachate [NO_3]
Hays (West)	1.4 ± 0.14	0.39 ± 0.59	18.58 ± 29.41	9.92 ± 19.76	14.38 ± 14.81	19.04 ± 14.84
Konza (Central)	1.17 ± 0.18	0.53 ± 0.4	4.67 ± 11.1	3.15 ± 5.67	5.17 ± 3.38	13.38 ± 8.26
Eastern Kansas	1.47 ± 0.12	0.4 ± 0.7	1.41 ± 1.67	3.84 ± 4.16	6.94 ± 11.42	9.34 ± 5.8
Agricultural	1.49 ± 0.11	0.51 ± 0.76	2.76 ± 1.93	13.5 ± 26.17	9.06 ± 18.99	9.38 ± 6.53
Post-Agricultural	1.41 ± 0.13	0.32 ± 0.47	4.04 ± 5.57	4.31 ± 3.5	11.65 ± 8.99	15.62 ± 10.11
Native	1.33 ± 0.2	0.41 ± 0.58	18.33 ± 31.63	4.99 ± 8.75	8.65 ± 12.83	15.11 ± 13.88
Dry Treatment	1.35 ± 0.17	0.32 ± 0.52	13.1 ± 25.49	6.45 ± 9.42	15.77 ± 14.64	19.51 ± 13.43
Wet Treatment	1.44 ± 0.16	0.5 ± 0.69	5.49 ± 15.38	7.25 ± 18.71	2.97 ± 3.2	8.52 ± 5.35

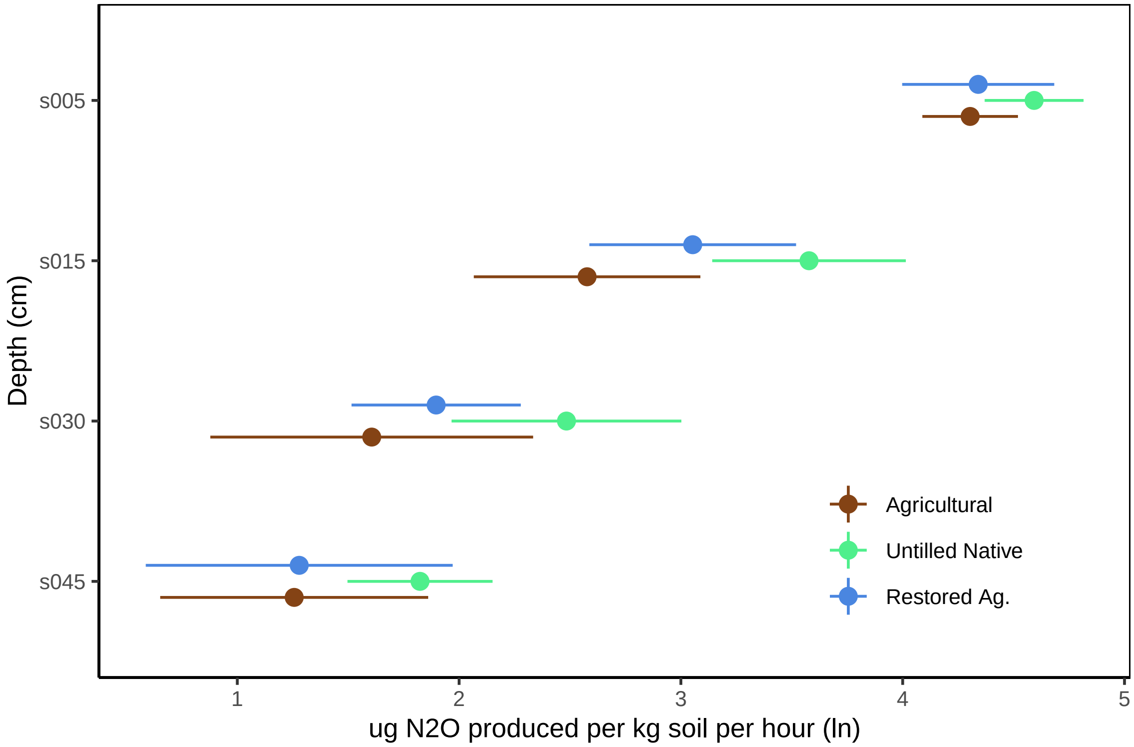

Figure 15: Points represent the mean and 95 percent C.I. of denitrification rates observed for each depth grouping during a DEA. Native soils displayed a higher dentrification rate across all depth increments.

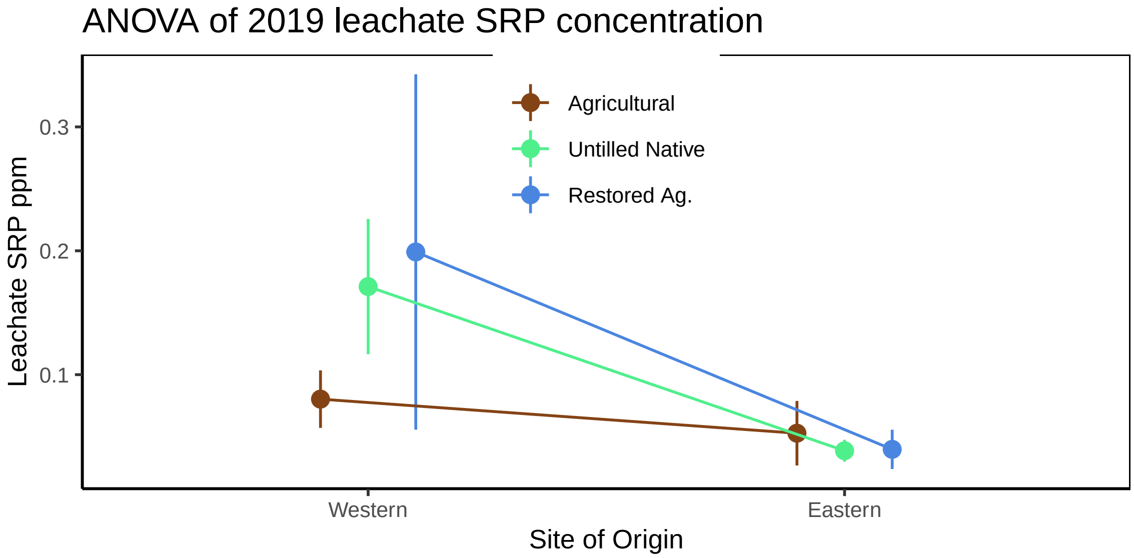

Figure 16: Leachate SRP concentrations also show a significant interaction between land use and site of origin. Native and restored communities produced leachate with significantly different concentrations of SRP between west and east, but agricultural communities produced a roughly consistent concentration.

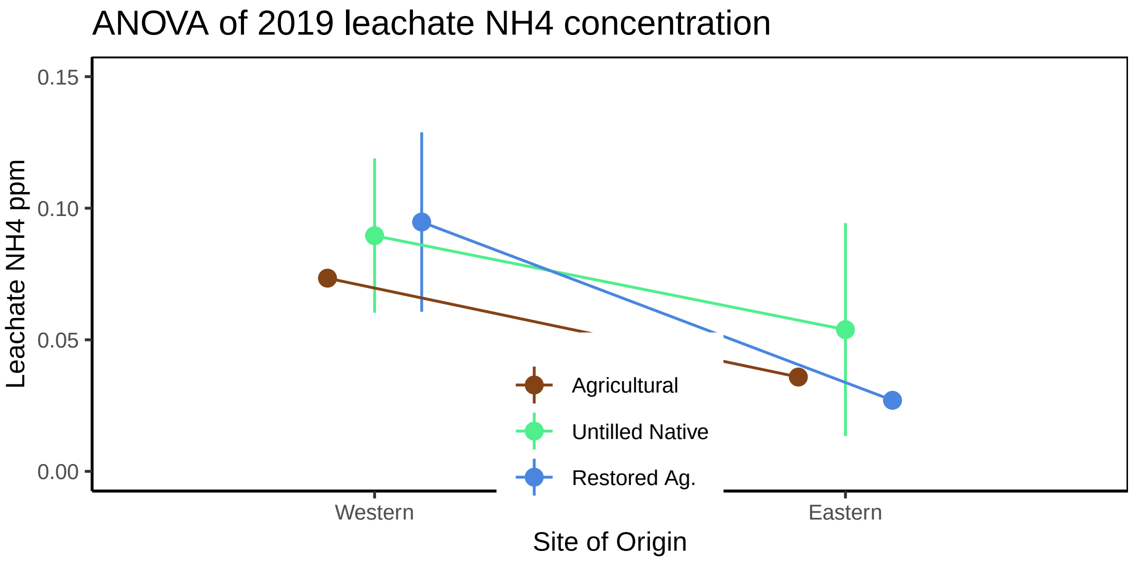

Figure 17: We found a significant, consistent difference in leachate ammonium concentration depending on site of origin. The concentrations here are small, but represent a 140 percent difference. Points without error bars indicate that only a single observation was successful for that category.

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