

Effect of Nitrogen on *Linaria vulgaris* and Native Species

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Abstract

We studied the effect of varying amounts of soil nitrogen on *Linaria vulgaris* and native species. *Linaria vulgaris* is an invasive weed in the Rocky Mountains that forms monocultures, hindering the growth of native plants. The Rocky Mountain soils are nitrogen-poor, and we expected nitrogen-reduced soils to favor native species. Thus, we expected increased values in the percent cover of native species, species richness, species diversity, plant growth of native species, and net photosynthesis of native species when there was less nitrogen in the soil. Our results showed that species richness decreased over in all plots from 2017 to 2024, with no significant effect of treatment. We also found that species diversity decreased significantly in plots over time, and there was significantly lower species diversity in nitrogen addition plots. Through analyses of historical data from 2017 to 2024, we found that there is no effect of treatment on the percent cover of species for all native plants. However, we found that *Linaria vulgaris* had a significantly higher percentage of cover in nitrogen addition plots. We also found that treatment had no significant effect on both plant growth and photosynthetic rate in 2024. All data collection was done in Gothic, Colorado. We found that nitrogen treatments do not have a positive effect on the plant community in the nitrogen-poor soils of the Rocky Mountains. This research aids in effective conservation efforts to help preserve biodiversity in the Rocky Mountains by managing *Linaria vulgaris*.

Introduction

Both natural and anthropogenic disturbances can disrupt the structure of ecosystems on a significant scale, leading to negative changes in the composition of species and the dynamics of a population (Baumeister 2024 et al.; Newbold et al., 2015). Over time, these disturbances diminish biodiversity, making ecosystems less functional and less resilient as a whole (Vantarová et al., 2023). Natural disturbances, such as wildfires, avalanches, hurricanes, and more can disrupt ecosystems and lead to issues such as habitat loss, species displacement, and more (Viljur et al., 2022). Anthropogenic disturbances such as pollution and climate change have contributed to the decline of biodiversity and the increase in extinction rates (Leddin, 2024). This contributes to the constant pressure to keep biological communities intact and prevent

the extinction of certain species (Borgelt, 2022). Conservation efforts and restoration efforts are becoming more common, and knowledge of prediction models through long-term studies will allow for the most efficient ways to respond to different changes in the environment (Zwiener et al., 2023).

Invasive plants can invade disturbed areas, forming monocultures and overtaking areas that native plants have once inhabited (Marbuah, 2014). It is important to focus on the conservation of native plants because diverse native plant communities support wildlife populations, promote soil health, and encourage resilient ecosystems. (Weidlich et al., 2020). The presence of nitrogen in the soil is known to help plants grow quickly, which can benefit both native and invasive species (Olfs et al., 2005). Nitrogen is also lower in the soils of the Rocky Mountains, hence the fact that native plants do well in these nitrogen-poor soils (Wolf et al., 2004). Yet, these areas are still vulnerable to invasive plant species that proliferate well in these dry and high-elevation disturbed areas. Possible conservation efforts can take the approach of managing nitrogen levels in the soil to prevent the invasive species from spreading (Uddin et al., 2020).

Linaria vulgaris is a significant threat to native plant species in the Rocky Mountains because it grows better than native plants, possibly leading to their extinction (Sutton et al., 2007). These weeds must be managed efficiently in order to promote the growth of native species. *Linaria vulgaris* may grow aggressively in these areas, but the growing conditions of this weed are still unknown. By addressing this gap in knowledge, we can understand the mechanisms by which *Linaria vulgaris* successfully competes with native plants. This study focuses on identifying the soil conditions that may facilitate or hinder the growth of *Linaria vulgaris*. Finding different management techniques to control *Linaria vulgaris* will allow for a more balanced environment that is required for native species to flourish and contribute to a healthy ecosystem.

In our research, we investigated the effect of varying amounts of nitrogen on *Linaria vulgaris* and native species in the Rocky Mountains. We measured a variety of factors including plant species richness, plant species diversity, plant size measured by the height of stems, net photosynthesis, and percentage cover by species. By understanding if there is a relation between the amount of nitrogen in the soil and the growth of plants, we could better manage *Linaria vulgaris*. We hypothesized that the presence of less nitrogen in the soil would allow native plant species to grow more efficiently. We expected there to be increased values in the percent cover of native species, species richness, species diversity, plant growth of native species, and net photosynthesis of native species when there is less nitrogen in the soil.

Methods

Site description

The location of this experiment was the town of Gothic, Colorado, USA. The field site is by the Billy Barr Community Center, at 106° 59' 25.31" W 38° 57' 34.50" N. We have 24 plots, each at the size of two meters by two meters. Six plots are located in front of the center on flat ground, eight plots are located behind the center on a slope, and the remaining ten plots are located on the hillside at the back corner of the center.

Experimental treatments

This experiment was originally set up in 2017 and consisted of three treatments: 8 plots with additional nitrogen, 8 plots with reduced nitrogen, and 8 control plots. In the plots with additional nitrogen, we added ammonium nitrate at the rate of $29.4 \text{ g m}^{-2} \text{ yr}^{-1}$ (Classen et al., 2011; J. Reithel, personal communication, June 2024). In the plots with reduced nitrogen, we added carbon in the form of sucrose at a rate of $167 \text{ g m}^{-2} \text{ yr}^{-1}$ (Blue et al. 2011). Control plots were left alone. After adding nutrients, we watered each of the 24 plots with 7 liters of water for each plot. This was done each month of the field season, including June, July, August, and September annually. This was done consistently throughout every year except in 2020, when nutrients were only added twice: once in July and once in September.

Data Collection & Analysis: Richness, Diversity, & Cover

We used a one-meter by one-meter quadrat with a ten by ten grid that was placed at the center of each plot to collect data. We measured variables only within the quadrat such as percent cover by species, species richness, species diversity, plant size, and photosynthetic rate. Percent cover, richness, diversity, and photosynthetic rate were measured once in mid-July when the majority of plants were at their peak growth. This data collection was done within one week. To measure the percent cover, we counted the number of squares of the quadrat that were filled up by each species and estimated it to the best of our ability. Species richness was measured as the number of species within a plot. This excluded the count of species for grasses, sedges, and rushes. We used the Shannon-Weiner index to calculate diversity for each plot. We used the percent cover of species to calculate the proportion of plants because it is a better representation of the data when compared to the number of individuals, although both methods are commonly used. We have records of this data from 2017 to 2024. Throughout the years, we have data collected on the following species for percent cover: *Achillea millefolium*, *Androsace septentrionalis*, *Boechera stricta*, *Brome* spp., *Bromopsis inermis*, *Caryx* spp., *Chenopodium album*, *Cirsium arvense*, *Collomia linearis*, *Elymus* spp., *Erigeron eliator*, *Erigeron speciosus*, *Erigeron* spp., *Festuca* spp., *Fragaria* spp., *Heckelia foribunda*, *Helianthella* spp., *Heraclium* spp., *Heterotheca* spp., *Hymenoxys hoopesii*, *Ipomopsis aggregata*, *Lathyrus leucanthus*, *Linaria vulgaris*, *Linum lewissii*, *Oenothera flava*, *Oligosporus* spp., *Poa* spp., *Polemonium*

foliosissimum, *Polygonum douglasii*, *Potentilla pulcherrima*, *Ranunculus* spp., *Rumex triangulivalvis*, *Salsify* spp., *Taraxacum* spp., *Taraxacum officinale*, *Thlaspi arvense*, *Timothy* spp., *Trifolium* spp., *Vicia* spp., *Viguera* spp., and *Viola* spp. There was an unidentified species described as a “needle-seed grass”. All statistical analyses were done using JMP software. In addition to the data collected in the year 2024, I also utilized Dr. Jennifer Reithel’s data from 2017 to 2023, as this project is a contribution to her long-term study. I performed historical analyses on the following variables: percent cover of each species, species richness of each plot, and species diversity of each plot. This was done by performing multiple linear regression models and analyzing the effect of year and treatment on each of these variables. Percent cover, species richness, species diversity, and year are all considered continuous variables. Analyses were only done for percent cover if there was at least one data point per treatment over the years. We also used the JMP software to analyze the effect of the percent cover of *Linaria vulgaris* on richness and diversity in all plots over the years from 2017 to 2024. We performed a linear regression analysis for richness and diversity separately. Percent cover, richness, and diversity are all considered continuous variables. To take a closer look at the plant community, we examined species presence in plots by the number of plots containing each species for 2017 and 2024, but we did not conduct statistical analyses.

Data Collection & Analysis: Plant Growth

For plant size, we measured the height of each species' tallest plant at its natural height without stretching out the plant. This was measured in the last week of June and the last week of July to calculate plant growth by subtracting the June height from the July height. In order to have a better representation of each treatment, we only measured the following common species: *Erigeron speciosus*, *Linaria vulgaris*, *Brome* spp., *Poa* spp., *Polemonium foliosissimum*, *Potentilla pulcherrima*, and *Taraxacum officinale*. I would like to note that *Taraxacum officinale* is a species that is alien to this location but does not exhibit invasive traits. We considered a species as common if there were at least three plots with that species per treatment. Statistical analyses on plant growth were also done using JMP software. We performed ANOVA tests Tukey-Kramer tests and to analyze the effect of treatment on plant growth in each species. Plant growth and year are both considered continuous variables.

Data Collection & Analysis: Photosynthetic Rate

We also determined the photosynthetic rate once in mid-July when the majority of plants were at their peak growth using the LI-COR 6400 photosynthesis system. This data was collected within one day when the sun was out and the plants were photosynthesizing well. The LI-COR 6400 photosynthesis system measures gas exchange variables. Due to the time constraint, we measure the photosynthetic rate for

only *Brome* spp. and *Linaria vulgaris*. This was done by placing the leaf of the plant within the leaf chamber of the LI-COR 6400 photosynthesis system and recording the photosynthetic rate given (Campbell, et al., 2010). However, the leaves of *Linaria vulgaris* were too small to work with, so we inserted the leaf and the stem of the individual plant into the leaf chamber. We also marked each plant with Sharpie to indicate the area that was within the leaf chamber. Afterward, we calculated the leaf area by hand. We traced the outline of the leaf on millimeter graph paper and counted and estimated the number of squares within the outline. Afterward, we converted this area to a percentage to find the true leaf area that was photosynthesizing within the leaf chamber. These measurements were taken on the same day as the data collection. Statistical analyses on photosynthetic rates were also done using JMP software. We performed ANOVA tests to analyze the effect of treatment on photosynthetic rate in each species. Photosynthetic rate and year are both considered continuous variables.

Results

Native Species

By looking at the plant community as a whole, we found that there was no significant effect of nitrogen treatment on the species richness in each plot (Fig. 2). However, it is important to note that the species richness decreased in plots over time (Fig. 2, $P < 0.0001$). We also found that treatment had a significant effect on species diversity in each plot from 2017 to 2024, with nitrogen addition plots having lower species diversity when compared to control plots (Fig. 3, $P = 0.0024$). There was also a significant decrease in the diversity of plots over time (Fig. 3, $P=0.0002$). There was no significant effect of nitrogen treatment on the percent cover of all native plant species from 2017 to 2024 (Figs. 8-46). However, we did find that the following species significantly increased in percent cover over time: *Achillea millefolium*, *Erigeron speciosus*, *Fragaria* spp., *Lathyrus leucanthus*, *Oligosporus* spp., *Poa* spp., *Polemonium foliosissimum*, *Polygonum douglasii*, *Potentilla pulcherrima*, *Salsify* spp., *Thlaspi arvense*, *Timothy* spp, and *Viola* spp. (Fig. 8, 19, 21, 27, 31, 32, 33, 34, 35, 38, 41, 42, & 46). The following species decreased in percent cover of time: *Androsace septentrionalis*, *Boechera stricta*, *Brome* spp., *Elymus* spp., *Heckelia floribunda*, *Oenothera flava*, *Rumex triangulivalvis*, and *Taraxacum* spp. (Fig. 9, 10, 11, 18, 22, 30, 37, & 39). The remaining species had no significant change in percent cover over time: *Bromopsis inermis*, *Caryx* spp., *Chenopodium album*, *Cirsium arvense*, *Collomia linearis*, *Elymus* spp., *Festusca* spp, *Heckelia floribunda*, *Helianthella* spp., *Heterotheca* spp., *Hymenoxys hoopesii*, *Ipomopsos aggregata*, *Linum lewisii*, “needle seed grass,” *Ranunculus* spp., *Taraxacum officinale*, *Trifolium* spp., *Vicia* spp., and *Viguera* spp (Fig. 12, 13, 14, 15, 16, 17, 20, 22, 23, 24, 25, 26, 28, 29, 36, 40, 43, 44, & 45). We also found no significant effect of treatment for plant growth of common native species in 2024, when taking the treatment factor out of consideration. There was also no

significant effect of treatment on the photosynthetic rate of *Brome* spp. in 2024. When taking a closer look at the effect of *Linaria vulgaris* on the plant community, we found that the increase in percent cover of *Linaria vulgaris* leads to a significant decrease in species richness for all plots over time (Fig. 4, $P = 0.0007$). We also found that the increase in percent cover of *Linaria vulgaris* leads to a significant decrease in species diversity over time (Fig. 4, $P < 0.0001$). When looking species presence in plots for 2017 and 2024, we observed that the following species were present in 2017 but are no longer present in our plots: *Androsace septentrionalis*, *Boechera stricta*, *Bromopsis inermis*, *Caryx* spp., *Cirsium arvense*, *Mertensia* spp., “Native thistle,” and *Oenethara flava* (Fig. 6). We also observed that the following species were not present in 2017 plots, but present in 2024 plots: *Chenopodium album*, *Elymus* spp., *Festuca* spp., *Gayophytum diffusum*, *Heterotheca* spp., *Ipomopsis aggregata*, *Lathyrus leucanthus*, “Needle-seed grass,” *Pyrocoma* spp., *Ribes* spp., *Thlaspi arvense*, and *Valeriana edulis* (Fig. 6).

Linaria vulgaris

There was a significant difference in treatment on the percent cover of *Linaria vulgaris*, shown by the significantly greater measures in percent cover for nitrogen addition plots from 2017 to 2024 (Fig. 27, $P < 0.0001$). The data also shows that the percent cover of *Linaria vulgaris* has increased significantly over time (Fig. 7, $P < 0.0001$). There was no significant effect of nitrogen treatment on plant growth of *Linaria vulgaris* in 2024 (Fig. 47). We also found no significant effect of nitrogen treatment on the photosynthetic rate of *Linaria vulgaris* in 2024 (Fig. 55). Another important observation to note is that *Linaria vulgaris* was absent from most of our plots located in front of the billy barr community center in 2024, while *Linaria vulgaris* has been present in all plots for years 2017 to 2023.

Discussion

Native Species

We hypothesized that there would be increased values in the percent cover of native species, species richness, plant growth of native species, and net photosynthesis of native species when there is less nitrogen in the soil. However, we found that the nitrogen manipulation of the soil did not have a significant effect on the percent cover of native species, species richness, photosynthetic rate, and plant growth of native species. When looking at the plant community as a whole, we did see that species richness and species diversity decreased over the years from 2017 to 2024. There was a slight trend that treatment had an effect on species richness. With further analyses, we found that a nitrogen addition treatment had a significant effect on species diversity. We also observed the presence of different species found in plots when comparing the

years of 2017 and 2024. This change in plant composition may be due to ecological succession, in which other plants may outcompete these native plants over time due to how common they are. We believe that this change in the plant community is also significantly affected by the competition of *Linaria vulgaris*. Future studies can look into the mechanism of competition in which *Linaria vulgaris* outcompetes native plant species and causes detriments to the plant community by decreasing species richness and species diversity. This can include looking into other variables such as water, sunlight, and other nutrients to pinpoint the strengths and weaknesses of *Linaria vulgaris*.

Rocky Mountain soils are already known to be very low in nitrogen soil content, so it may have been difficult for the nitrogen reduction treatment to work effectively. Since the nitrogen content is already very low, the percent change in nitrogen may have been very small. We can further investigate this by taking samples of the soil to test for the amount of nutrients within the soil. Additionally, the native plant species present at the Gothic townsite have already adapted to these low-nitrogen soils, and may not need additional nitrogen to grow. As per the nitrogen addition treatments, there may be effects on the characteristics of the plants that have not been measured, such as biomass and specific leaf weight, which is known to increase with the increase of soil nitrogen (Fichtner & Schulze, 1992). We plan to end the experiment next year, in the summer of 2025, and measure the biomass of these plants. This can be another useful variable to effectively measure and compare the growth of the plants.

Linaria vulgaris

We also hypothesized that there would be decreased values in the percent cover, plant growth, and net photosynthesis of *Linaria vulgaris*, when there is less nitrogen in the soil. However, we found there to be no significant effect of nitrogen reduction in soils for percent cover, plant growth, and net photosynthesis. In our nitrogen addition plots, however, we found that there was a significantly greater percent cover of *Linaria vulgaris* when compared to control and nitrogen reduction plots. The invasive weed is slowly overtaking the plots, and this is shown by the effect of treatment on the species diversity of the plots. We had an important observation that there was little to no presence of *Linaria vulgaris* in the plots in front of the billy barr community center. After the extreme drought in 2023, *Linaria vulgaris* was absent from many of the front plots in 2024. This suggests a possible effect of rainfall on *Linaria vulgaris*, which can be further studied by testing the effects of water treatment on *Linaria vulgaris* compared to native species.

Site Variation

Our plots were scattered across three locations surrounding the billy barr community center, with slightly different environments for each site. Although we had replications to make up for the variability between these sites, there are still environmental variables that affect the plant species differently across the sites and differences in environmental variables over the years as well. We observed that the site in front of the billy barr community center was extremely dry with very little vegetation, even for *Linaria vulgaris*. The site behind the billy barr community center had moderate plant growth. The site on the hillside behind the billy barr community center had rampant overgrowth. We can further investigate these observations by taking soil moisture levels in each of these plots to confirm or deny our speculations.

Nutrients in the plots may also leach into other areas when there are strong environmental factors such as heavy rainfall, leading to the poor retention of soil nutrients. The nitrogen addition plots are also vulnerable to losing nitrogen, due to competition with the increase of soil microbial biomass which is common in soils with low water content (Li, et.al., 2023). Since our sites vary in vegetation, we may access the water content levels as a future area of research, and group the sites accordingly. This will allow us to take a different approach to our data analysis. We could also measure additional variables such as soil pH and the chemical composition of the soil, which may reveal other factors that affect the nitrogen available to plants for uptake.

Sources of Error

Some sources of error may include biotic interactions that we cannot control. Some of the plants in our plots were eaten by deer or other herbivores. When measuring plant growth, we only took the height of the tallest plant within the one-by-one meter plot. If we were to continue collecting data for plant growth, it would be important to add plant tags to give plant IDs and ensure that we are measuring the same plant before and after plant growth.

Additionally, we may have some sources of error in our individual methodologies. The LI-6400 is used to measure the photosynthetic rate of plant species by placing their leaf in a chamber, but the leaves of *Linaria vulgaris* were much too small, making it difficult for us to do this. By clamping the stem and the leaves of the plant, we may have caused some errors in the measurement of photosynthetic rate. Additionally, I measured the leaf area by hand, and this can introduce more errors than compared to using updated technologies such as an electronic scanner and computer programs to calculate leaf area digitally. We also only measured the photosynthetic rate of two species of plants due to time constraints. In the future, we could measure additional plant species, and investigate the effects of nitrogen on their photosynthetic rates.

Conclusion

In conclusion, nitrogen treatments were unable to shift mechanisms of competition to favor native species due to the nitrogen-poor soils in the Rocky Mountains. We found that soil nitrogen does not have a significant effect on native plants when looking at nitrogen reduction plots, possibly due to the difficulty of reducing nitrogen in soils that are already very nitrogen-poor. The nitrogen addition treatment is causing *Linaria vulgaris* to have increased percent cover, thus leading to a decrease in species richness over time. We also found that nitrogen addition treatments, in comparison to no treatment, negatively affect native plants by causing a decrease in species diversity over time. Our results may show that native plants have already developed adaptations to these low-nitrogen soils, thus explaining their stagnant state over the years when looking at the percent cover of species. *Linaria vulgaris* is an invasive weed that must be controlled to preserve biodiversity, and this may be done through future experiments testing with different nutrients that plants may uptake, or taking other variables into account.

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Figure 1. Map of field site location with 24 plots in Gothic, Colorado, USA.

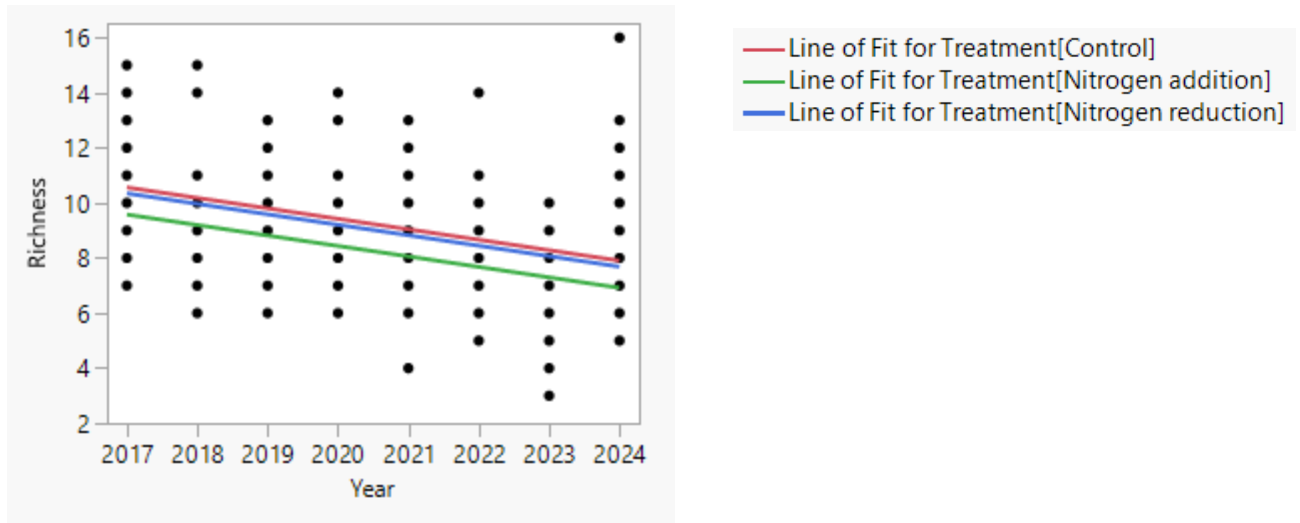


Figure 2. Effect of treatment and time on species richness from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 22.53$, $P < 0.0001$).

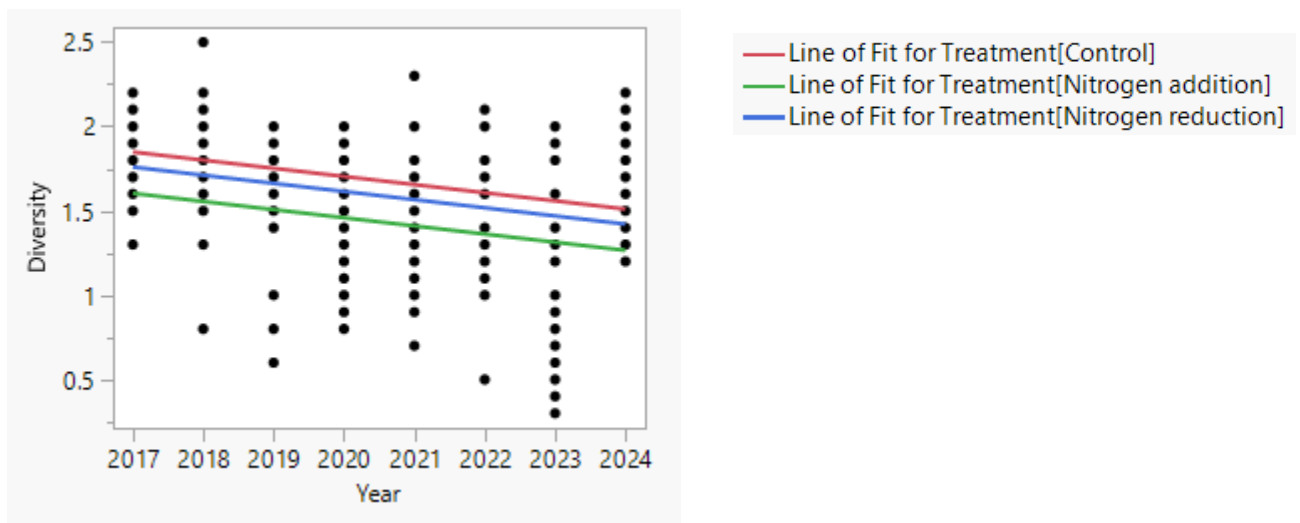


Figure 3. Effect of treatment and time on species diversity from 2017 to 2024 (Multiple linear regression; Treatment effect: $F = 6.24$, $P = 0.0024$; Year effect: $F = 14.74$, $P = 0.0002$).

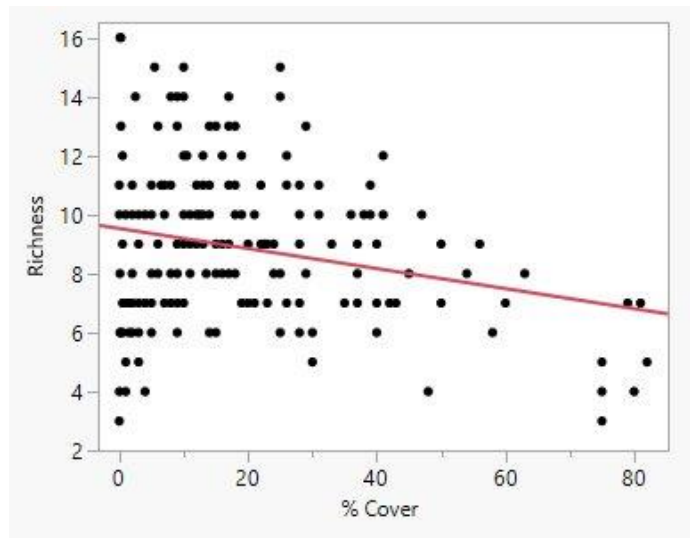


Figure 4. Relationship between percent cover of *Linaria vulgaris* and species richness in plots from 2017 to 2024. (Linear regression: $F = 11.85$, $P = 0.0007$).

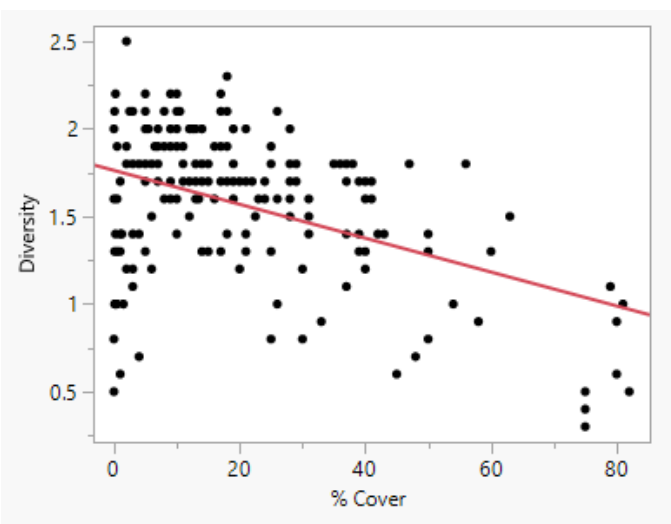


Figure 5. Relationship between percent cover of *Linaria vulgaris* and species diversity in plots from 2017 to 2024. (Linear regression: $F = 45.58$, $P < 0.0001$).

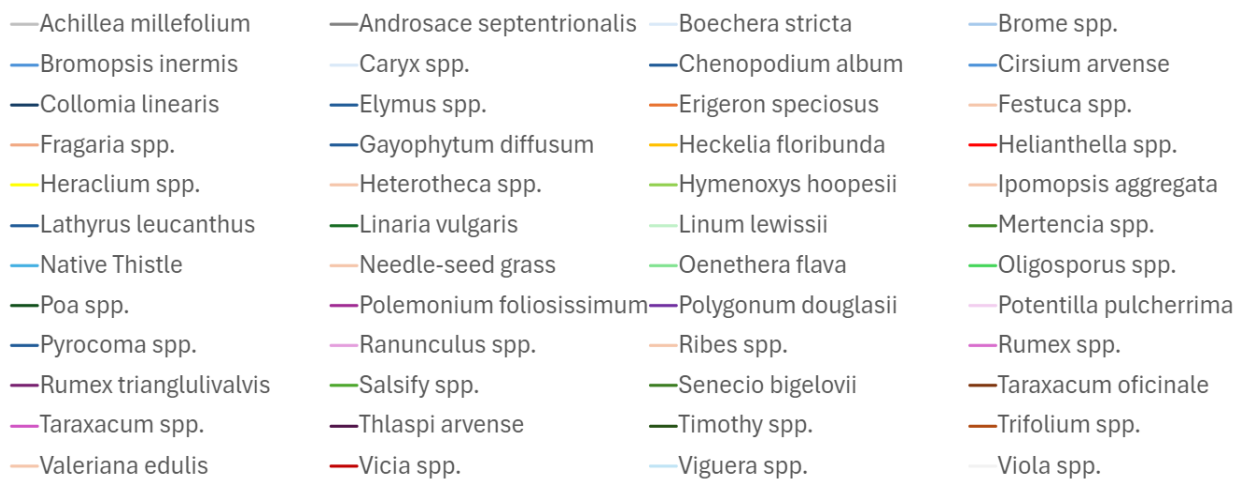
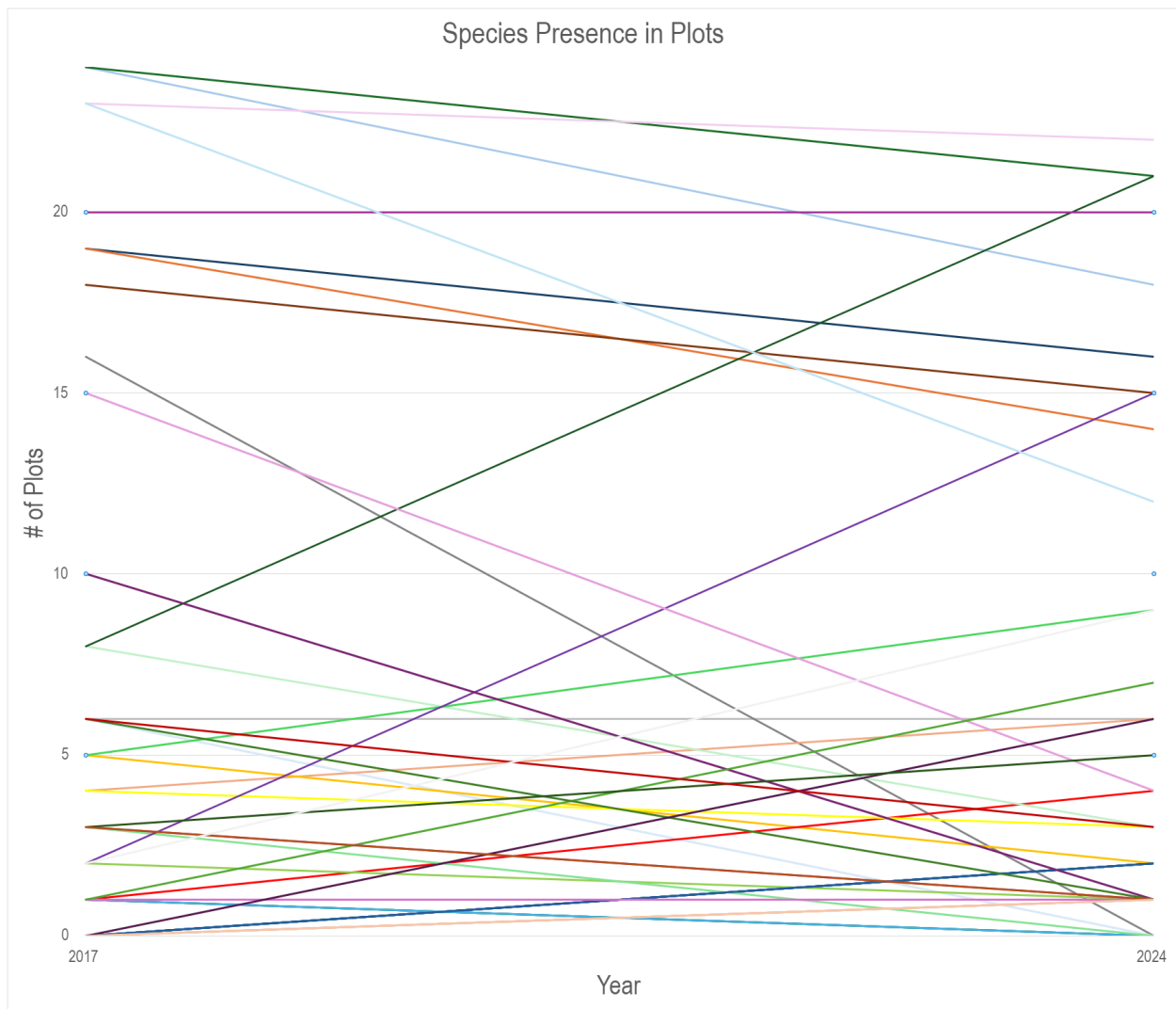


Figure 6. Changes in species presence in plots: a 2017 vs. 2024 comparison.

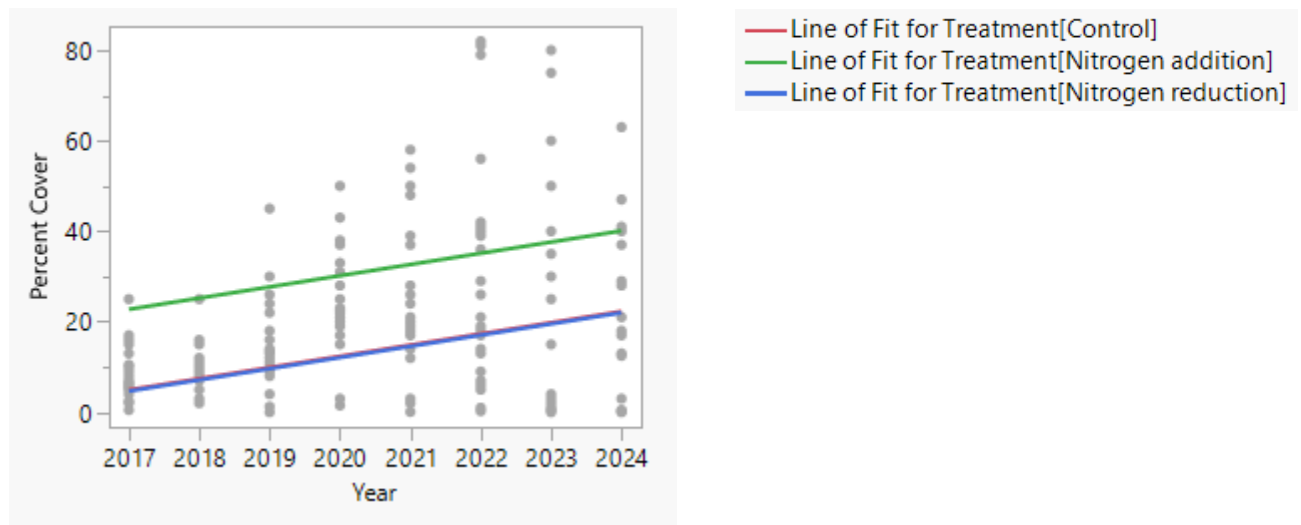


Figure 7. Effect of treatment and time on percent cover of *Linaria vulgaris* from 2017 to 2024 (Multiple linear regression; Treatment effect: $F = 26.15$, $P < 0.0001$; Year effect: $F = 23.53$, $P < 0.0001$).

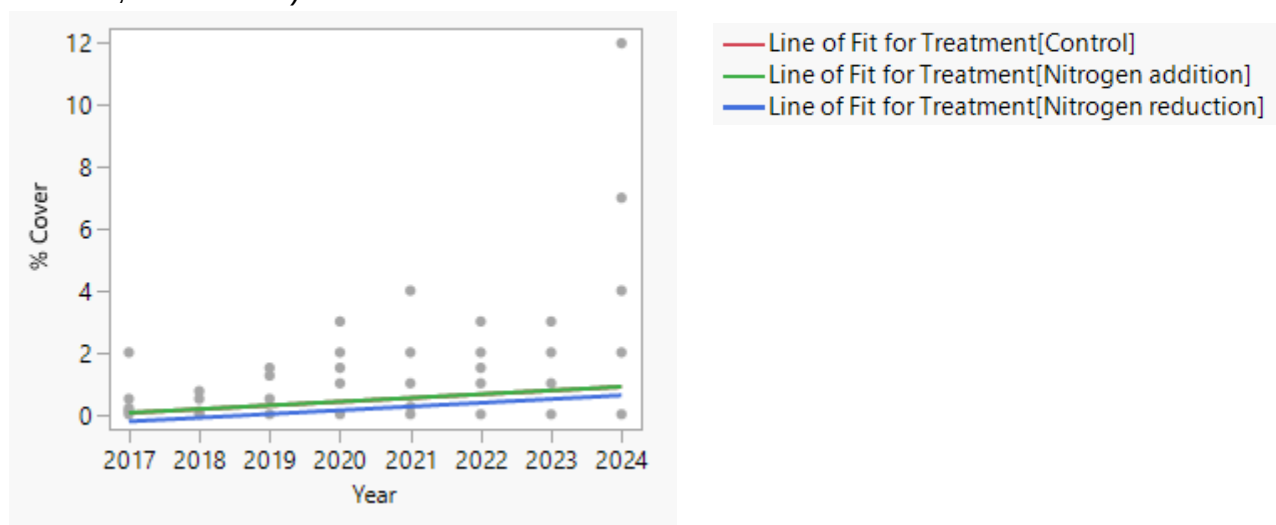


Figure 8. Effect of treatment and time on percent cover of *Achillea millefolium* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 10.06$, $P = 0.0018$).

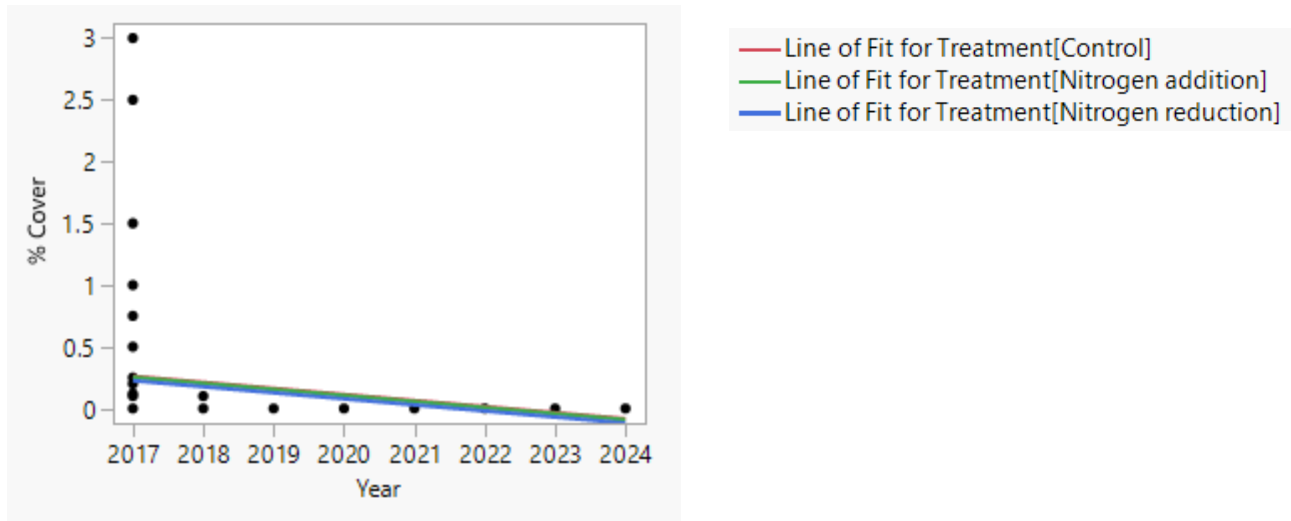


Figure 9. Effect of treatment and time on percent cover of *Androsace septentrionalis* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 24.36$, $P < 0.0001$).

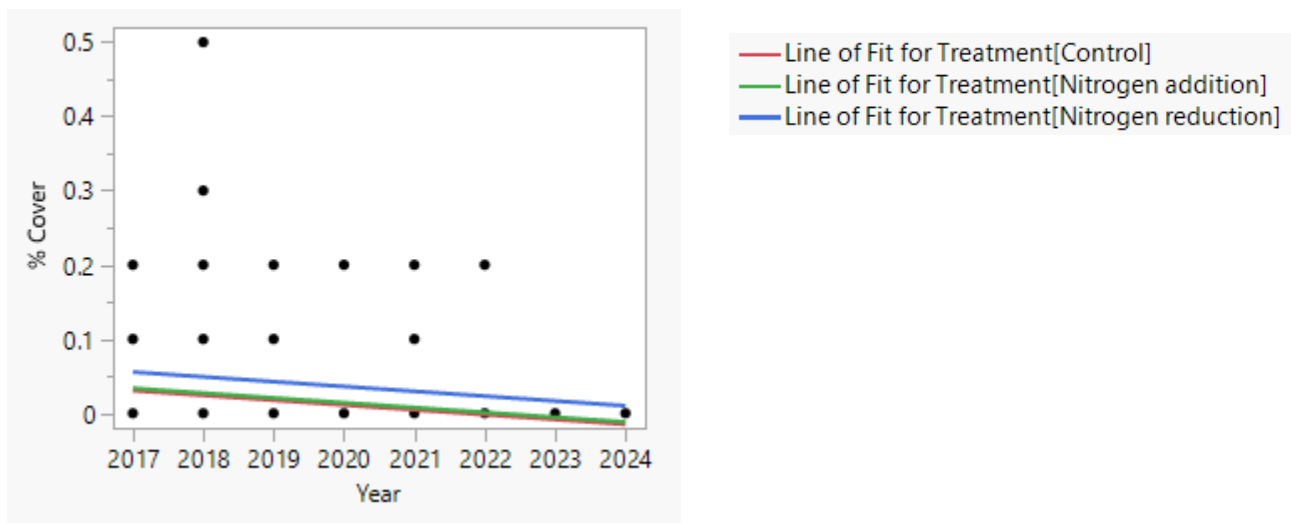
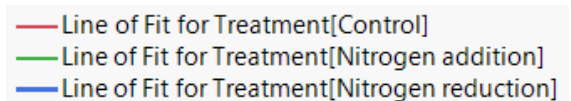


Figure 10. Effect of treatment and time on percent cover of *Boechnera stricta* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 10.17$, $P = 0.0017$).



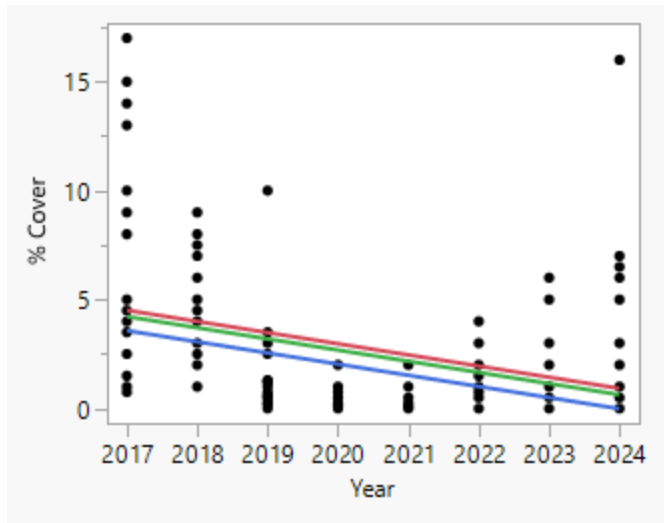


Figure 11. Effect of treatment and time on percent cover of *Bromo* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 29.53$, $P < 0.0001$).

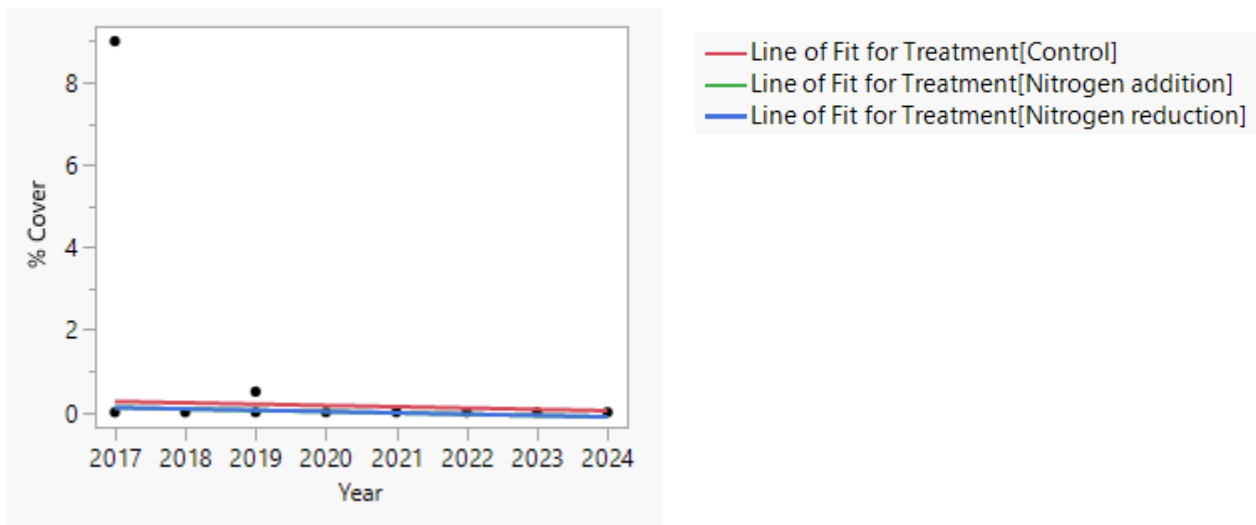


Figure 12. Effect of treatment and time on percent cover of *Bromopsis inermis* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

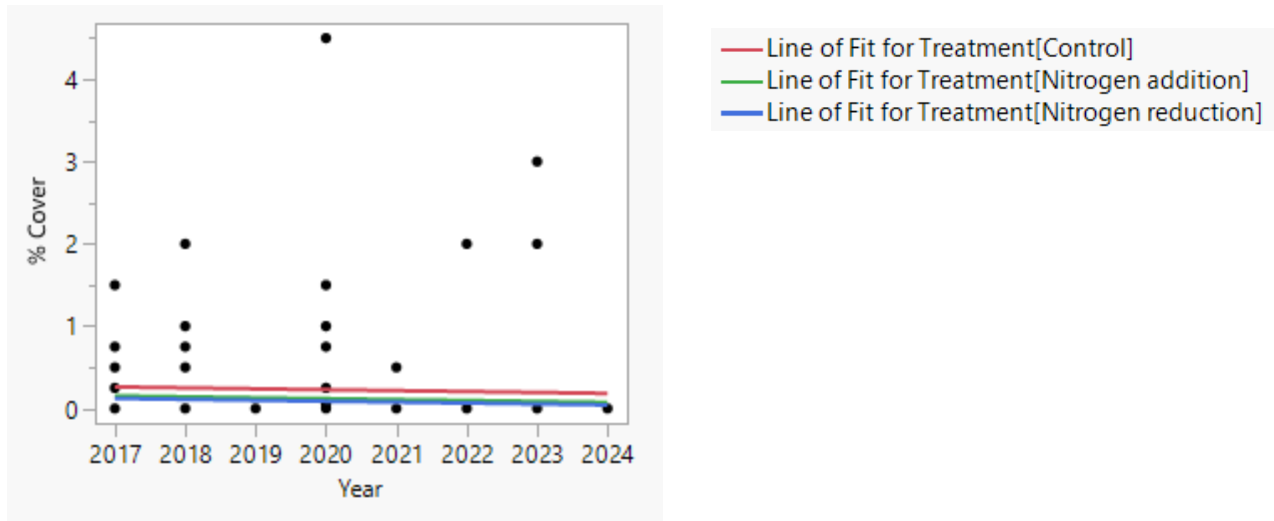


Figure 13. Effect of treatment and time on percent cover of *Caryx* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

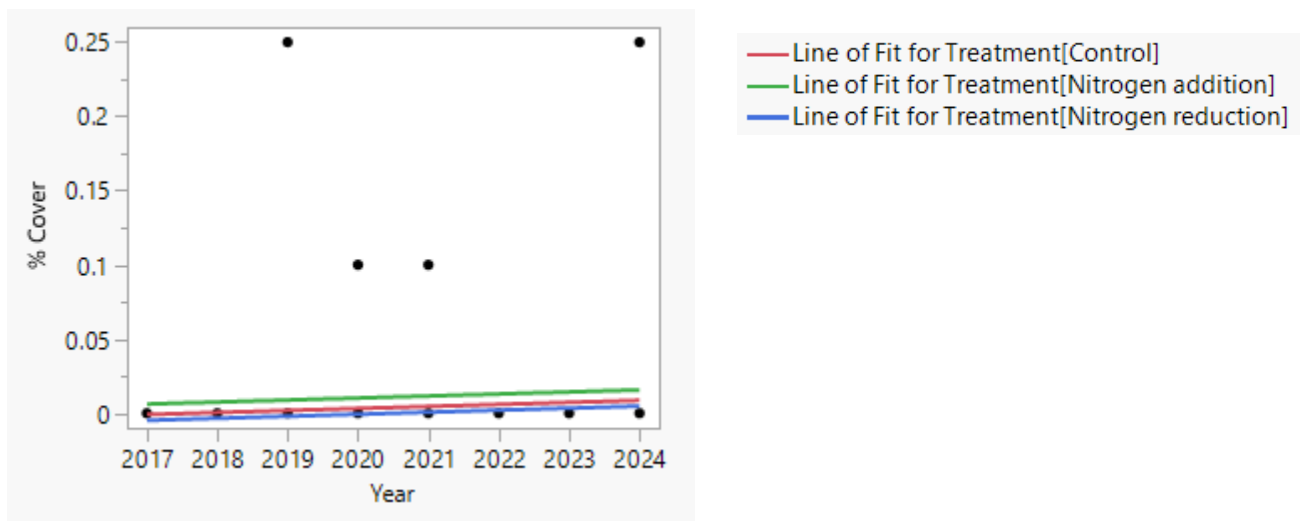
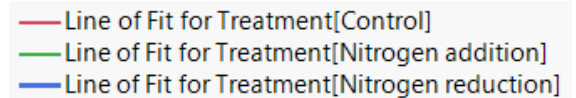


Figure 14. Effect of treatment and time on percent cover of *Chenopodium album* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).



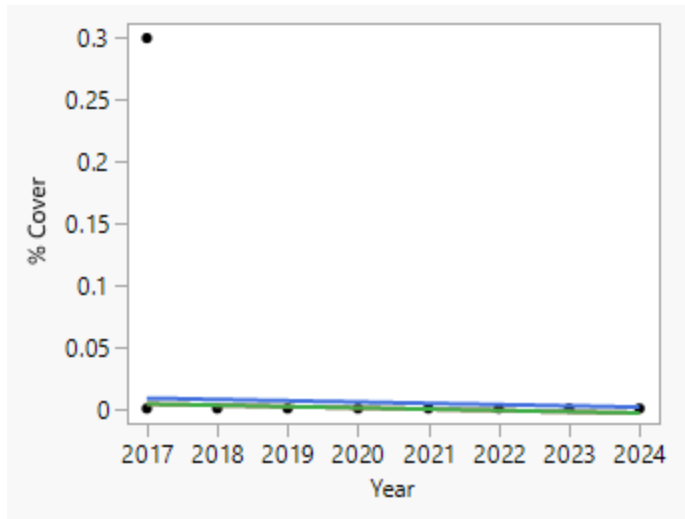


Figure 15. Effect of treatment and time on percent cover of *Cirsium arvense* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

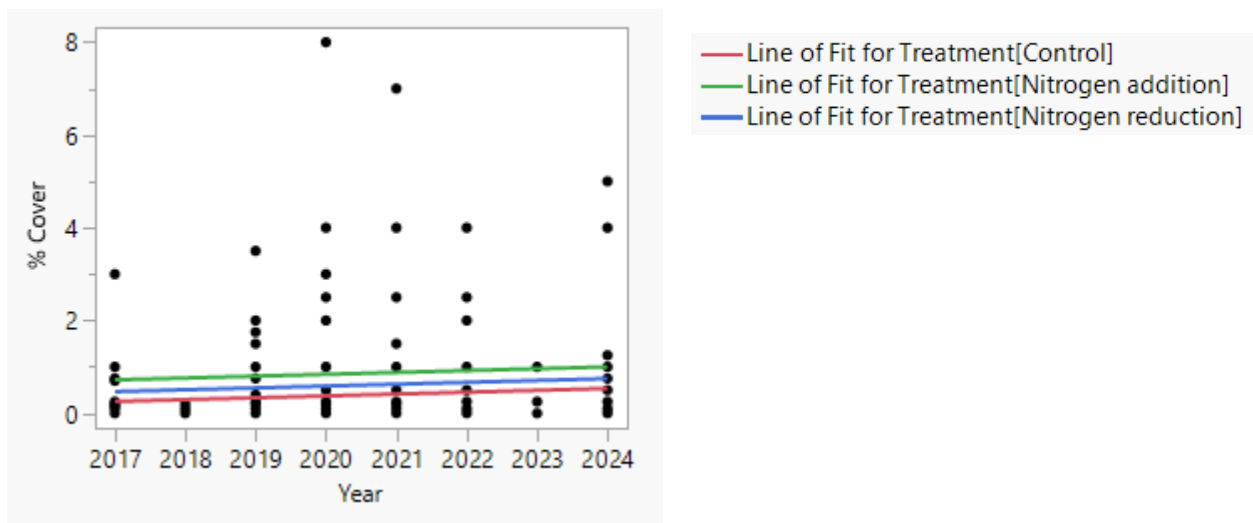
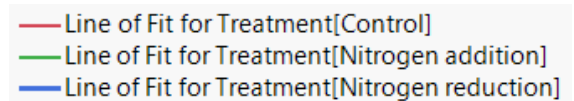


Figure 16. Effect of treatment and time on percent cover of *Collomia linearis* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).



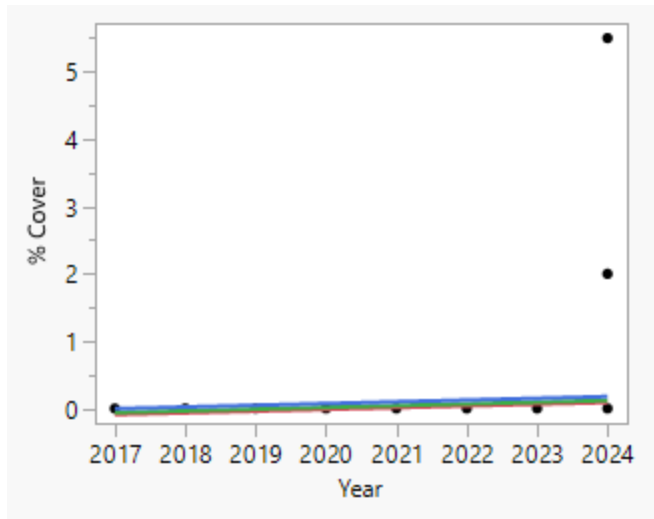


Figure 17. Effect of treatment and time on percent cover of *Elymus* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

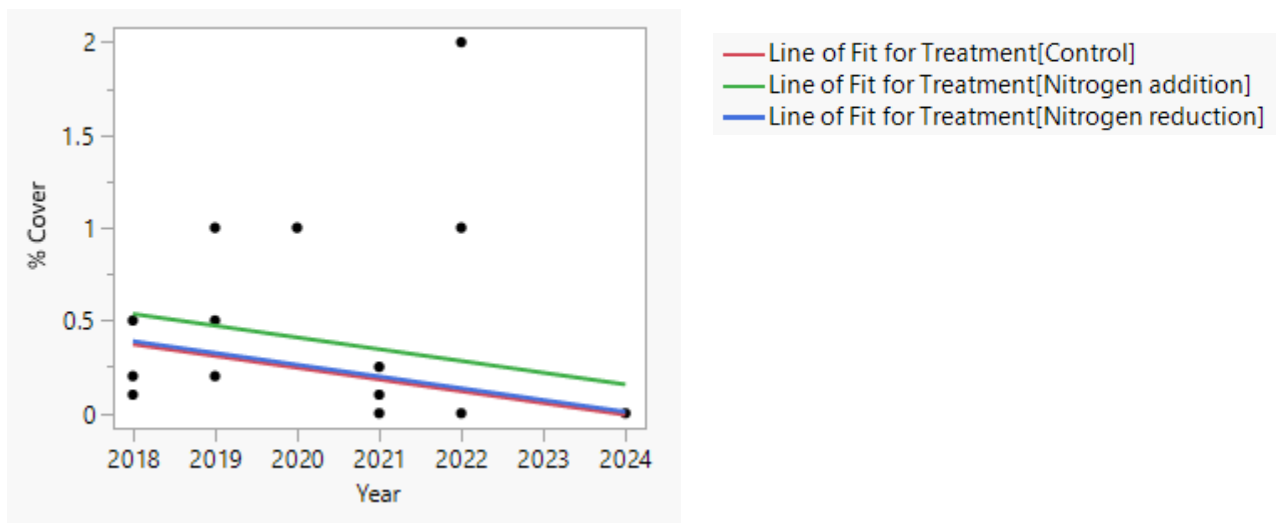


Figure 18. Effect of treatment and time on percent cover of *Erigeron* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 6.12$, $P = 0.0177$).

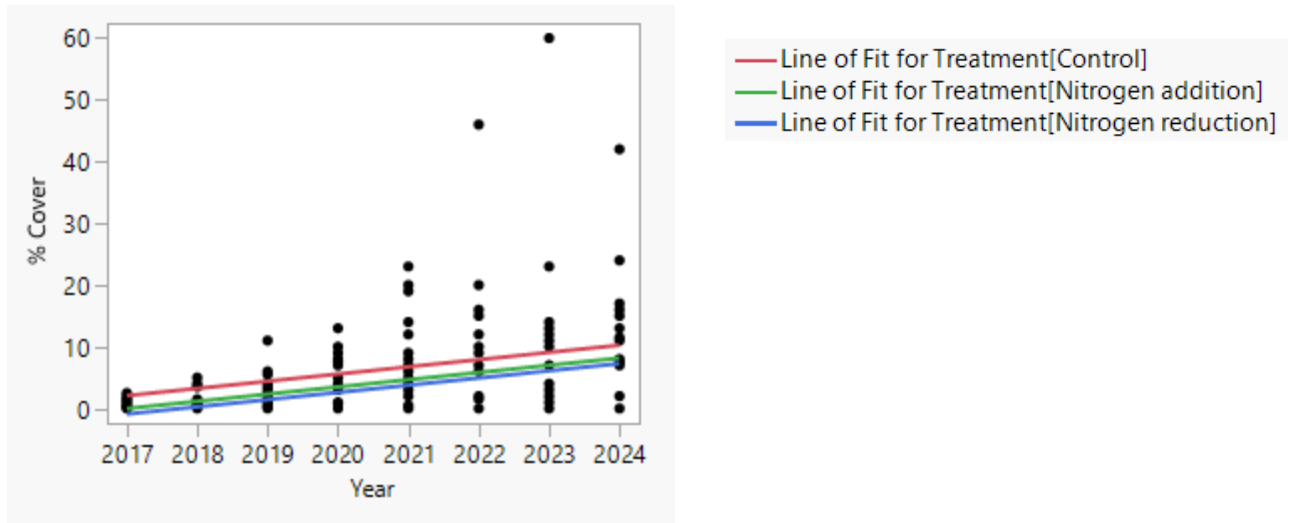


Figure 19. Effect of treatment and time on percent cover of *Erigeron speciosus* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 25.41$, $P < 0.0001$).

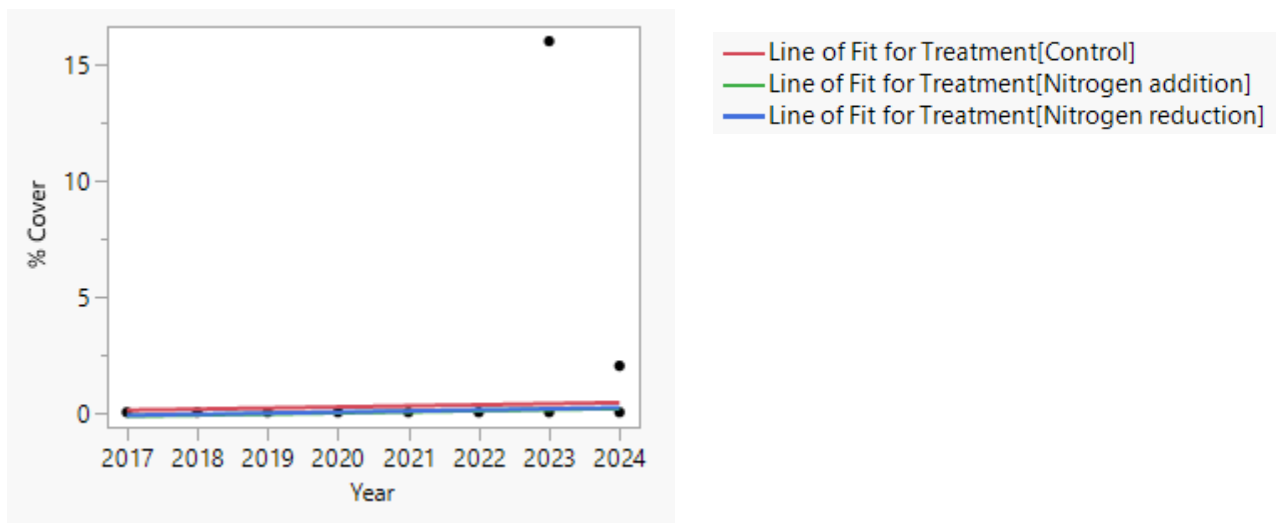


Figure 20. Effect of treatment and time on percent cover of *Festusca* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

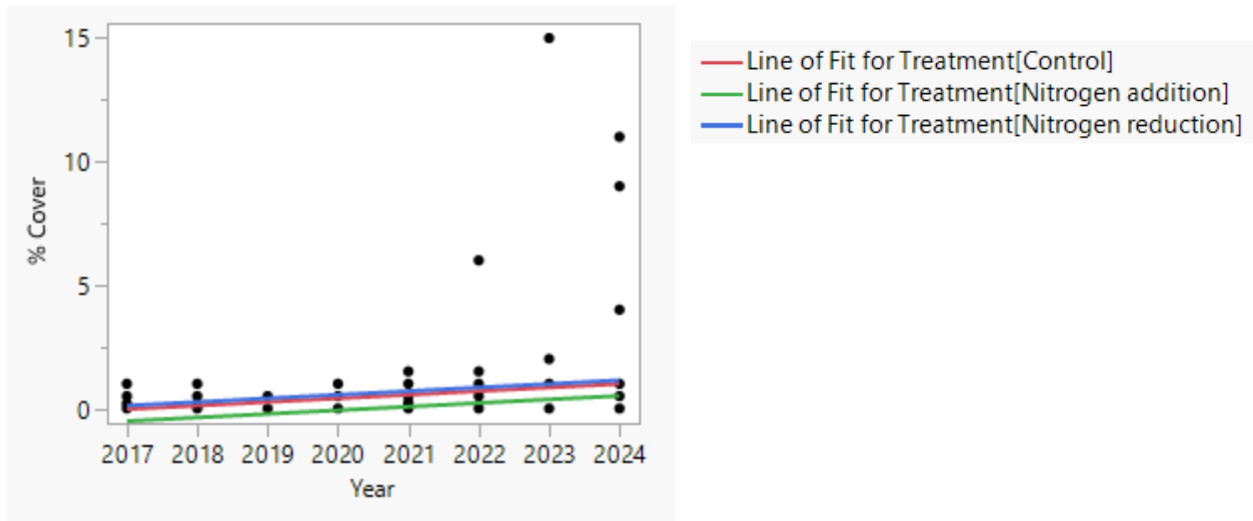


Figure 21. Effect of treatment and time on percent cover of *Fragaria* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 9.12$, $P = 0.0029$).

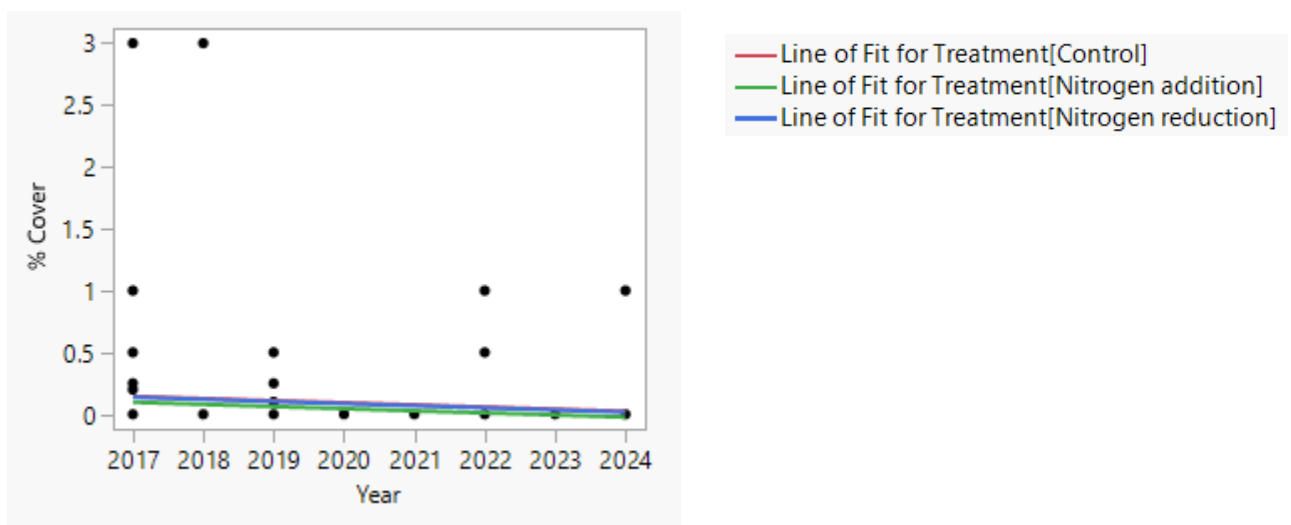


Figure 22. Effect of treatment and time on percent cover of *Heckelia floribunda* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

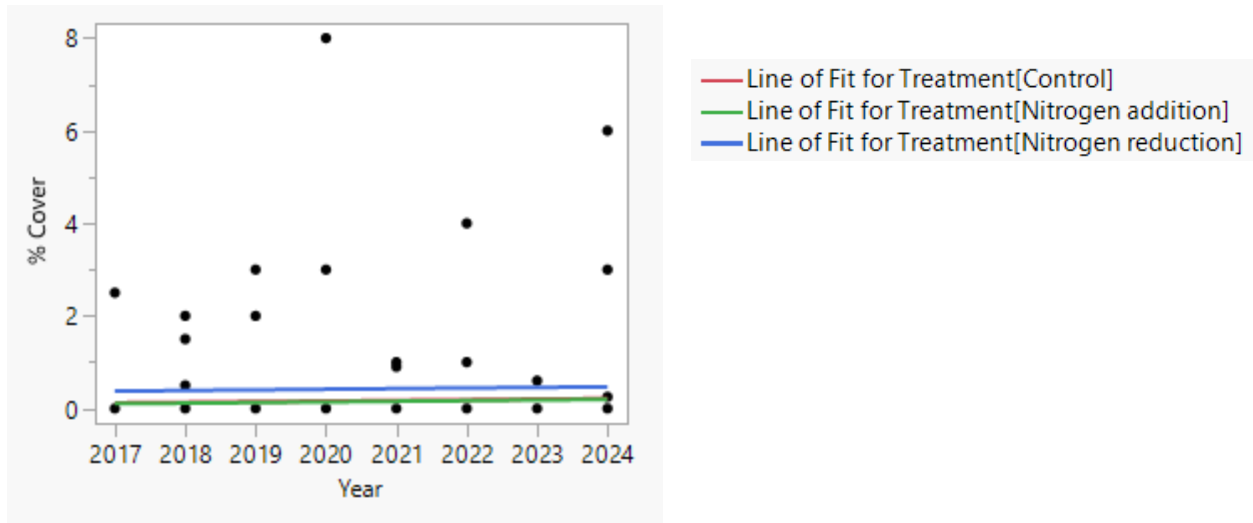


Figure 23. Effect of treatment and time on percent cover of *Helianthella* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

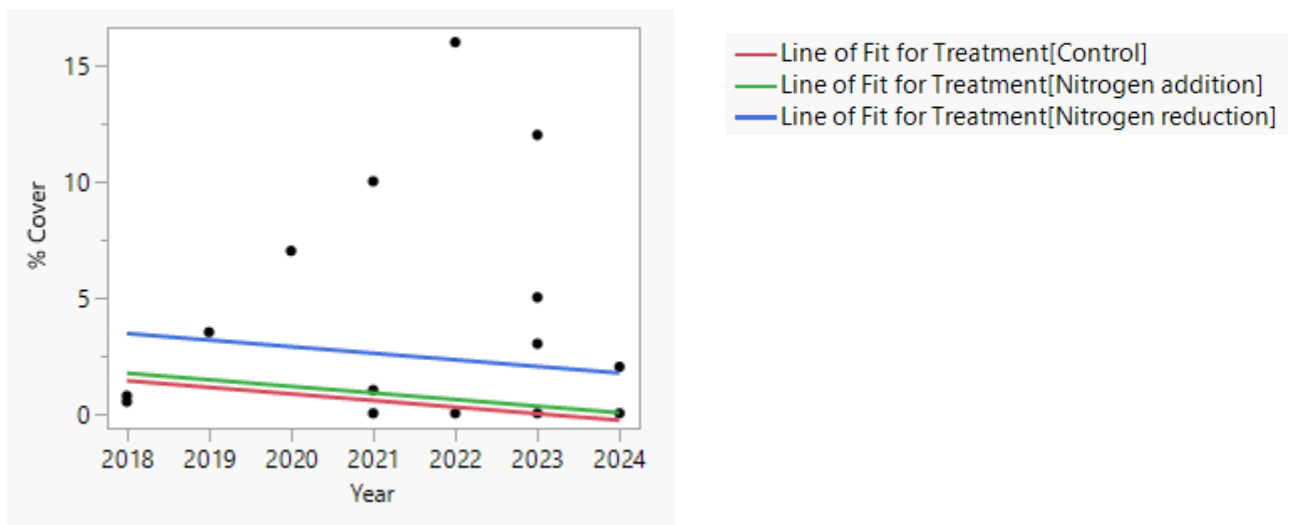


Figure 24. Effect of treatment and time on percent cover of *Heterotheca* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

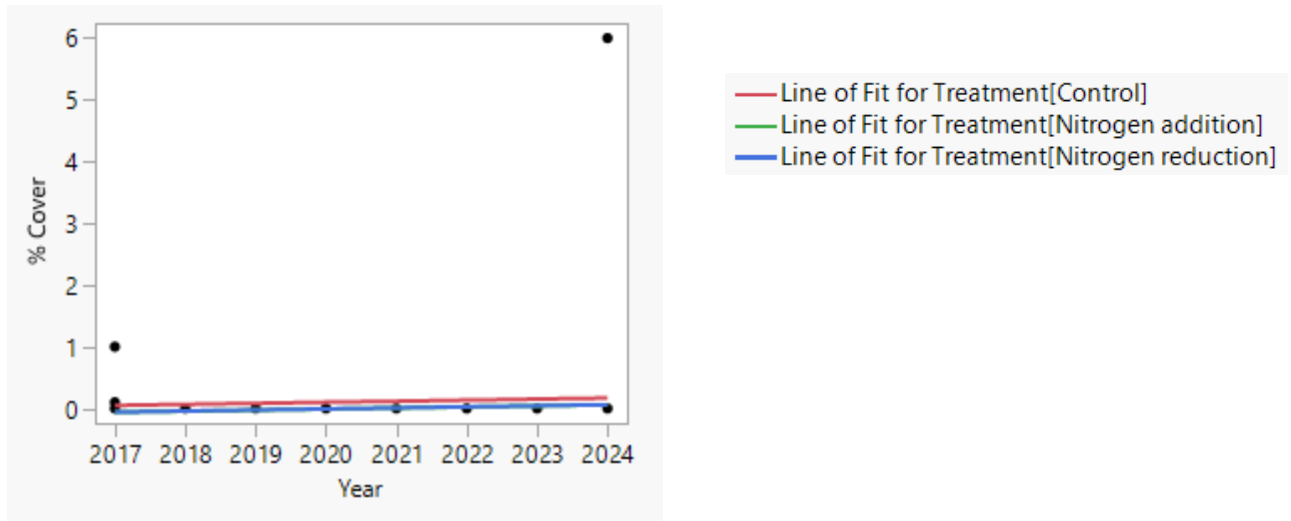


Figure 25. Effect of treatment and time on percent cover of *Hymenoxys hoopesii* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

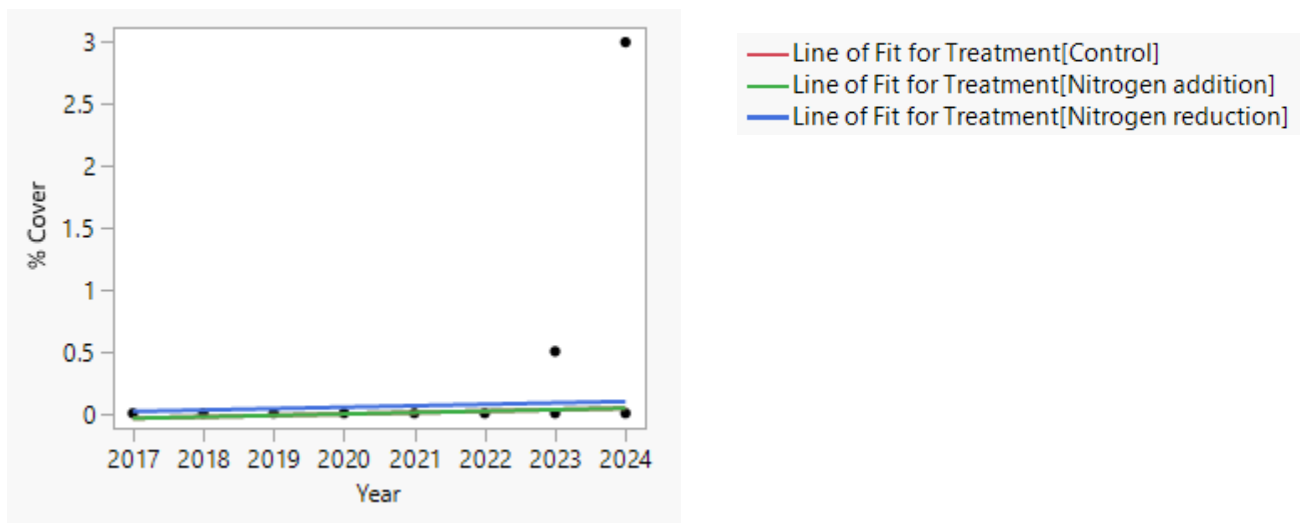


Figure 26. Effect of treatment and time on percent cover of *Ipomopsis aggregata* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

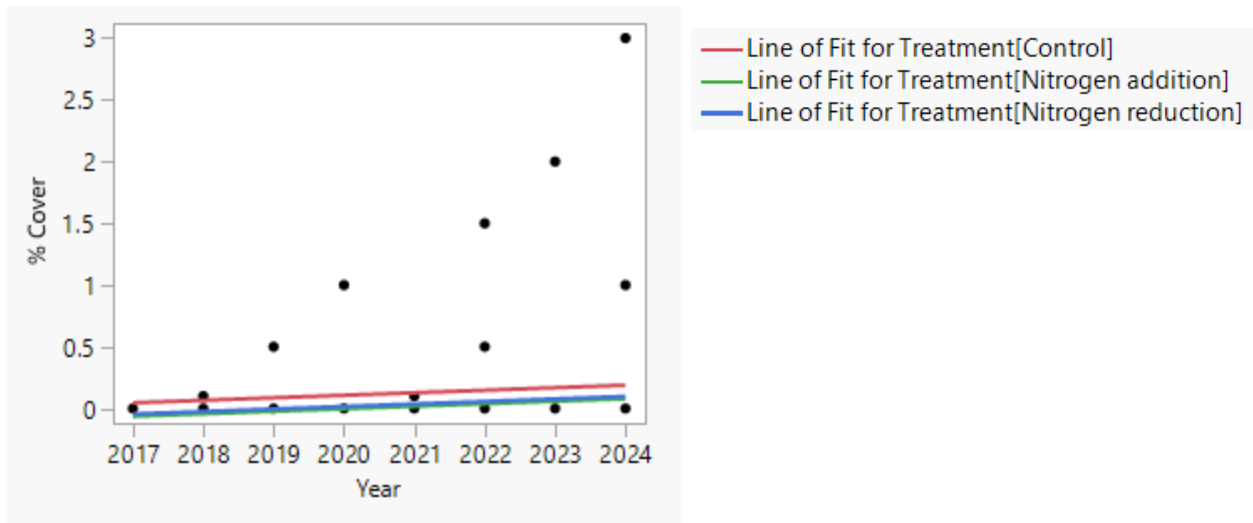


Figure 27. Effect of treatment and time on percent cover of *Lathyrus leucanthus* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 4.80$, $P = 0.0298$).

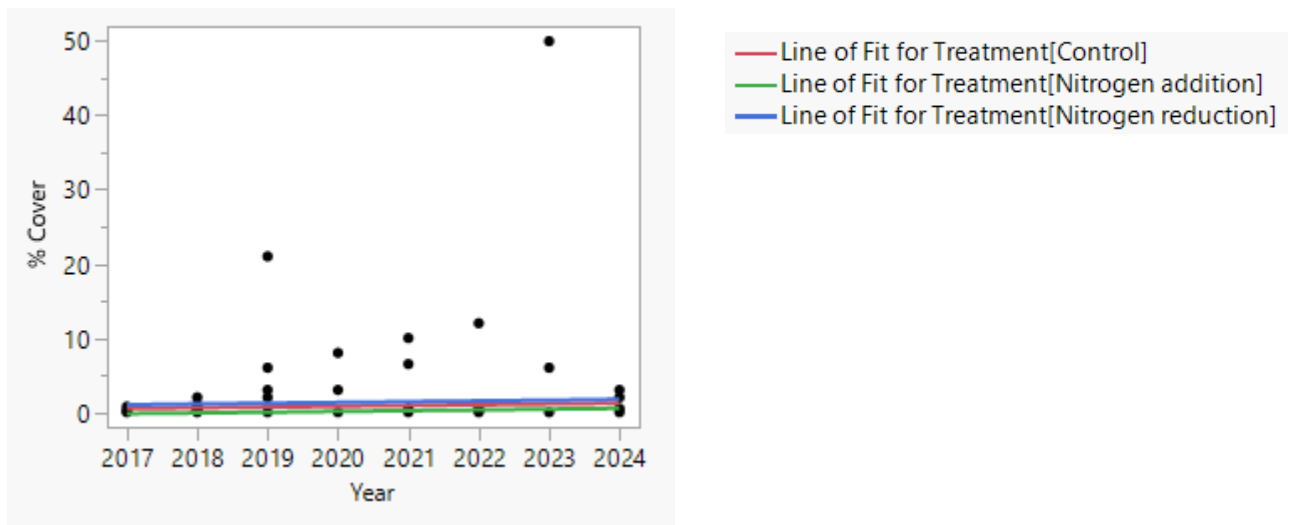


Figure 28. Effect of treatment and time on percent cover of *Linum lewisii* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

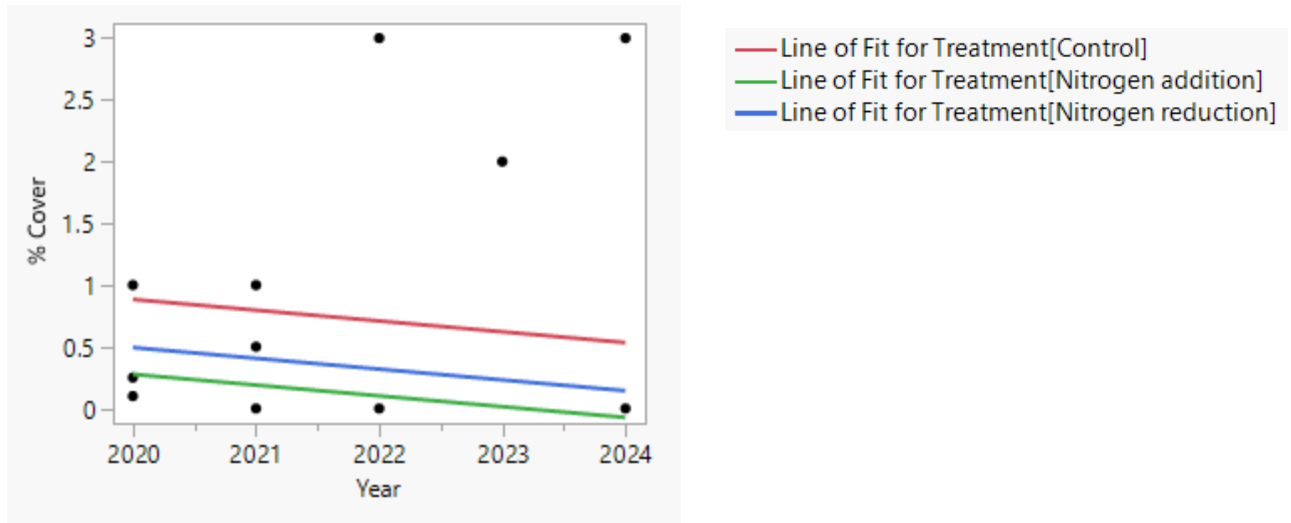


Figure 29. Effect of treatment and time on percent cover of "needle seed grass" from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

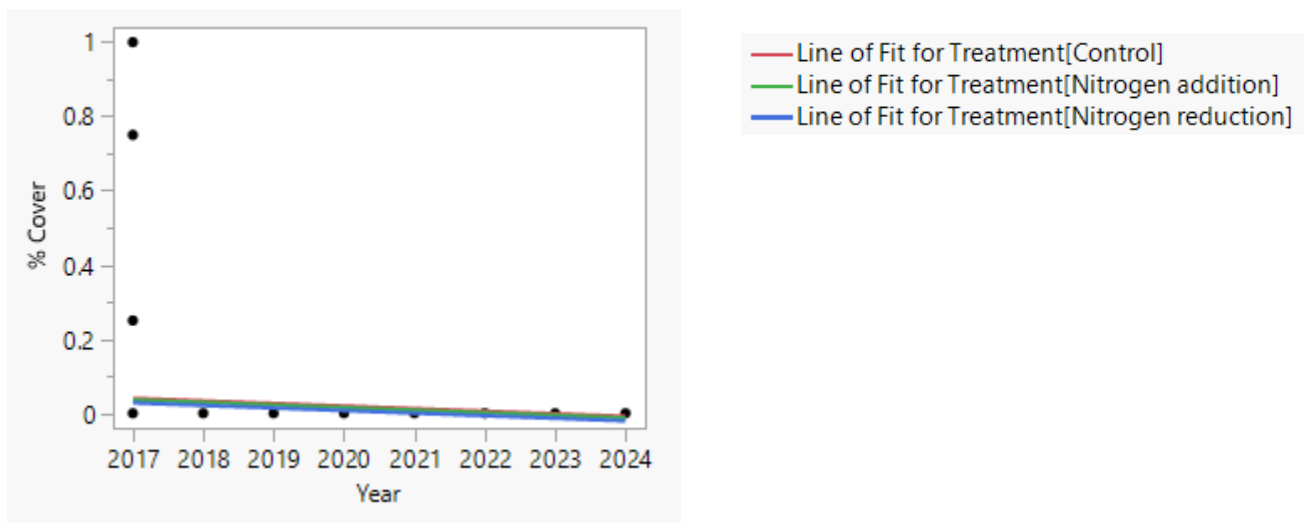


Figure 30. Effect of treatment and time on percent cover of *Oenothera flava* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 5.89$, $P = 0.0162$).

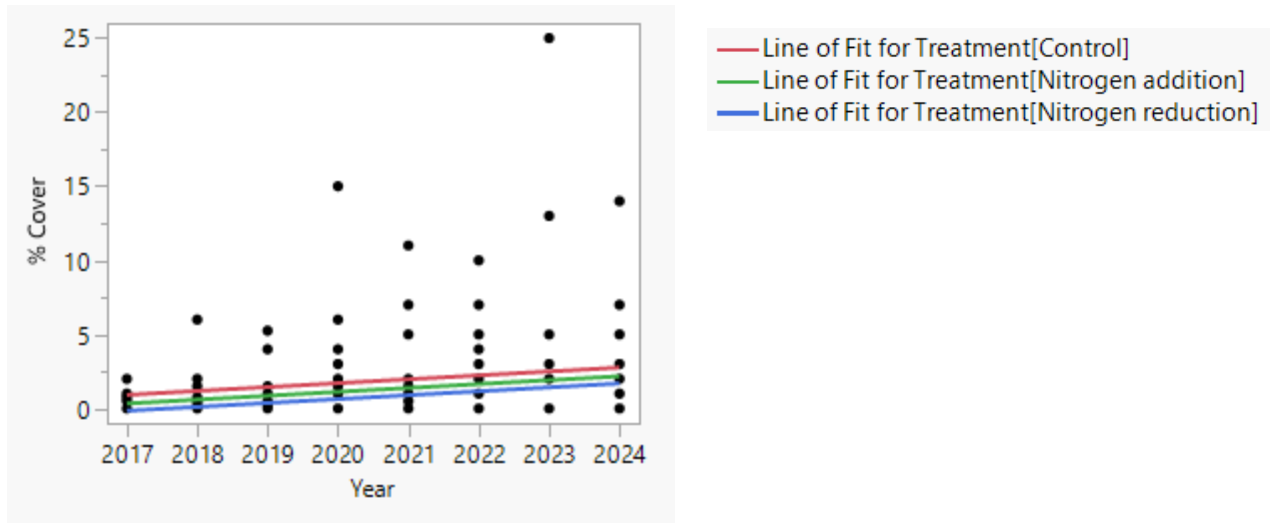


Figure 31. Effect of treatment and time on percent cover of *Oligosporus* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 7.67$, $P = 0.0062$).

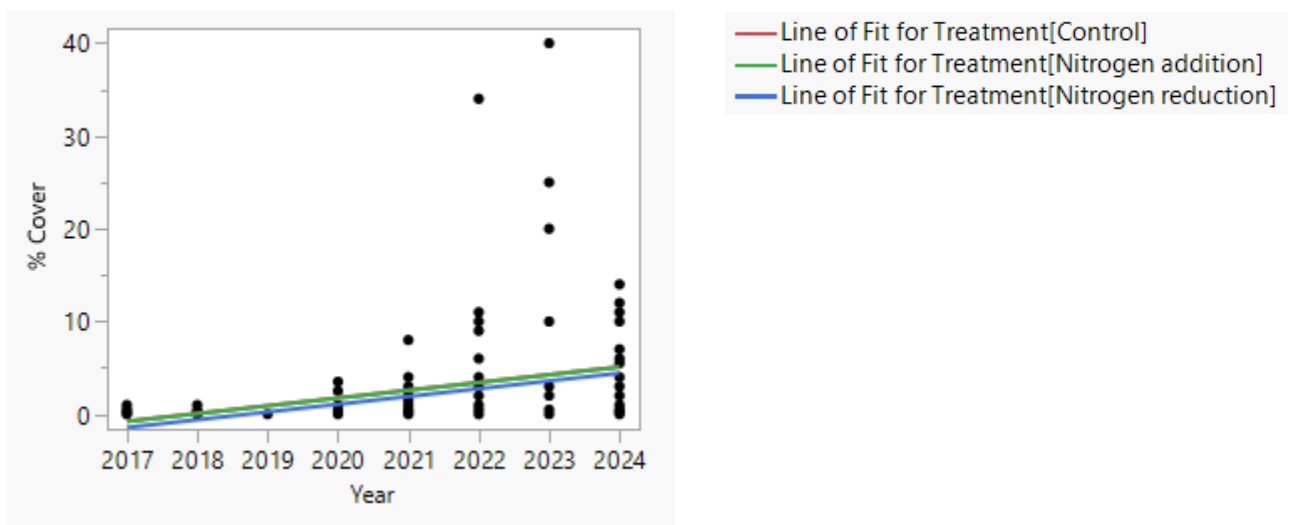


Figure 32. Effect of treatment and time on percent cover of *Poa* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 31.53$, $P < 0.0001$).

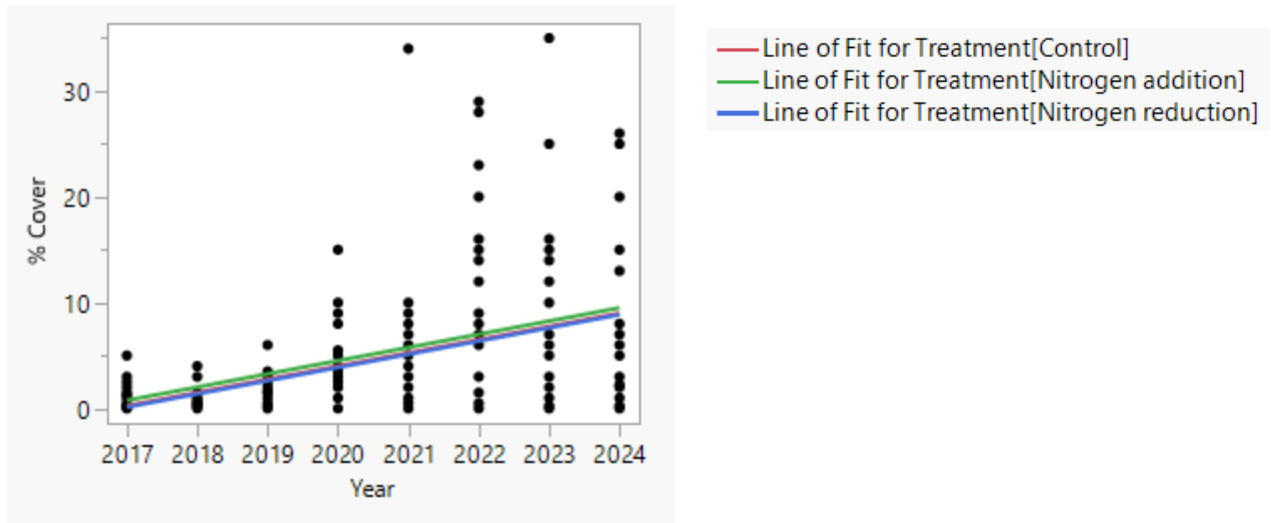


Figure 33. Effect of treatment and time on percent cover of *Polemonium foliosissimum* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 41.19$, $P < 0.0001$).

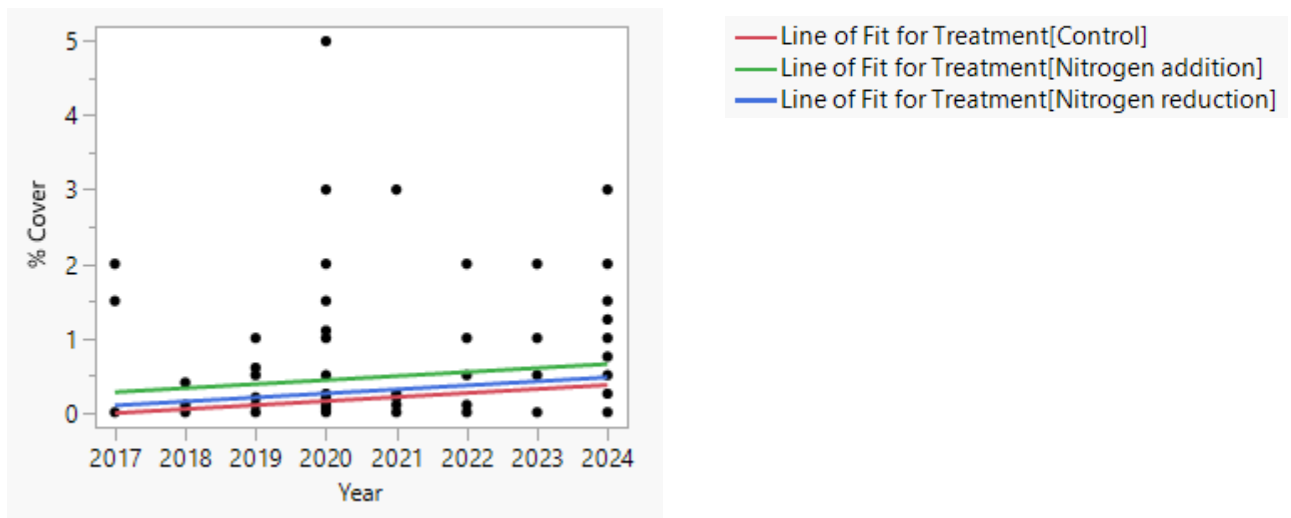


Figure 34. Effect of treatment and time on percent cover of *Polygonum douglasii* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 6.25$, $P = 0.0133$).

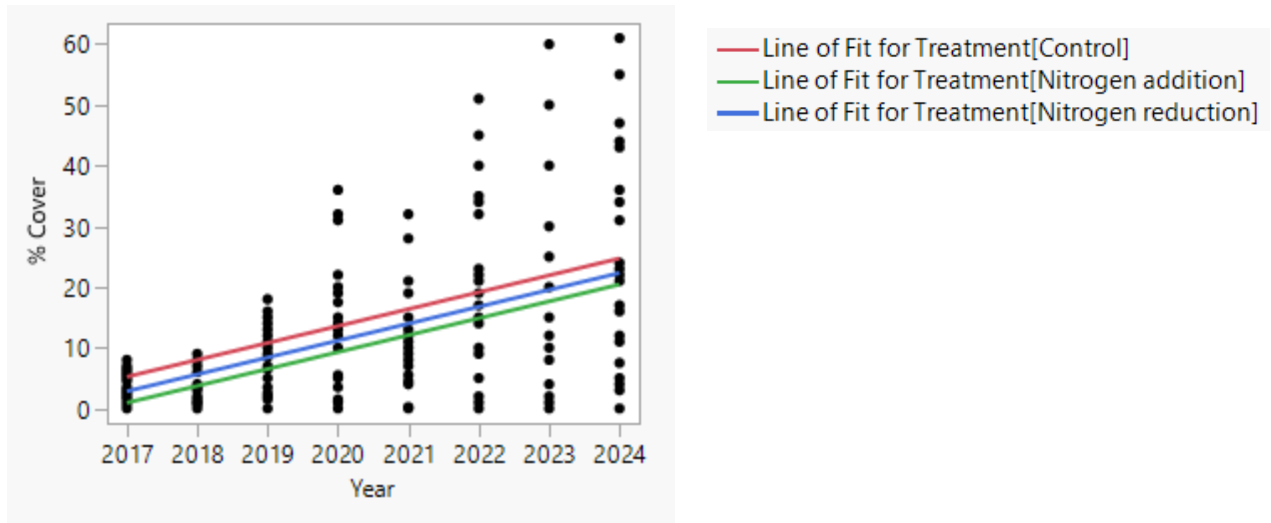


Figure 35. Effect of treatment and time on percent cover of *Potentilla pulcherrima* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 58.21$, $P < 0.0001$).

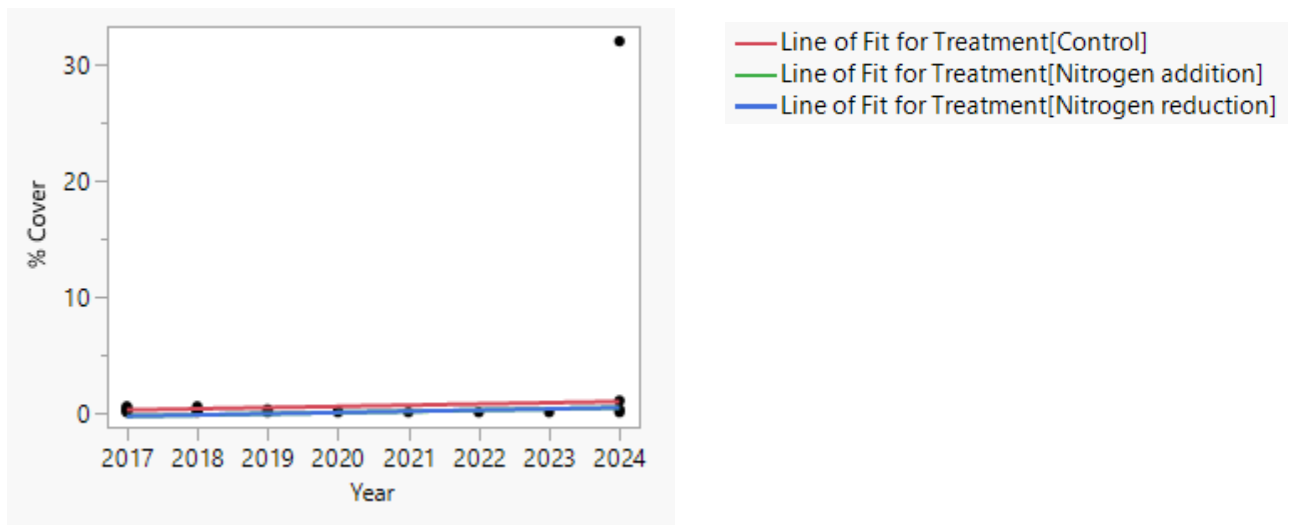


Figure 36. Effect of treatment and time on percent cover of *Ranunculus* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

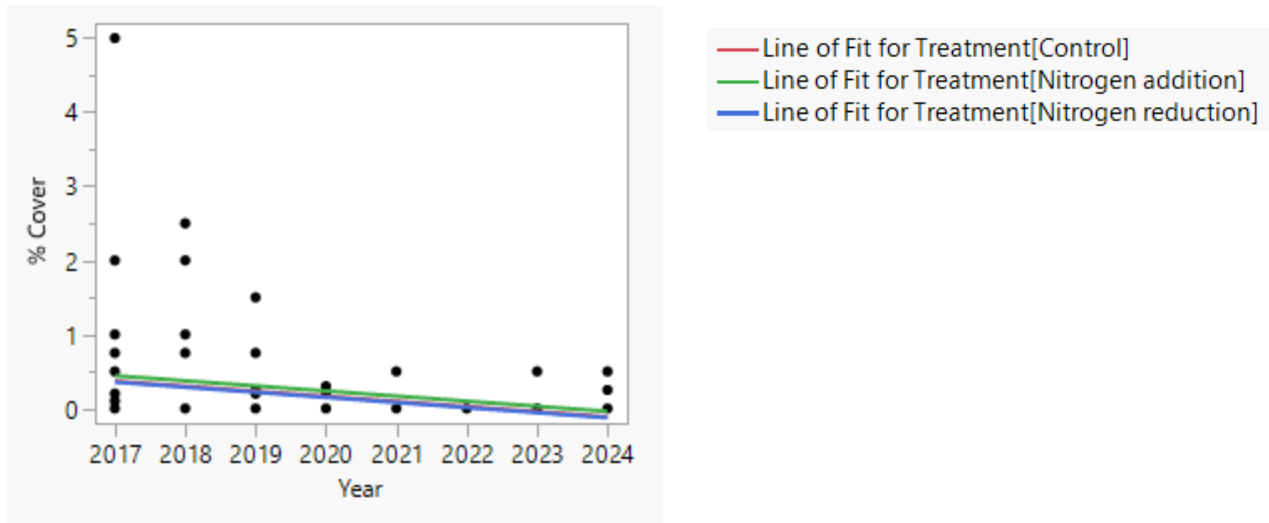


Figure 37. Effect of treatment and time on percent cover of *Rumex triangulivalvis* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 18.19$, $P < 0.0001$).

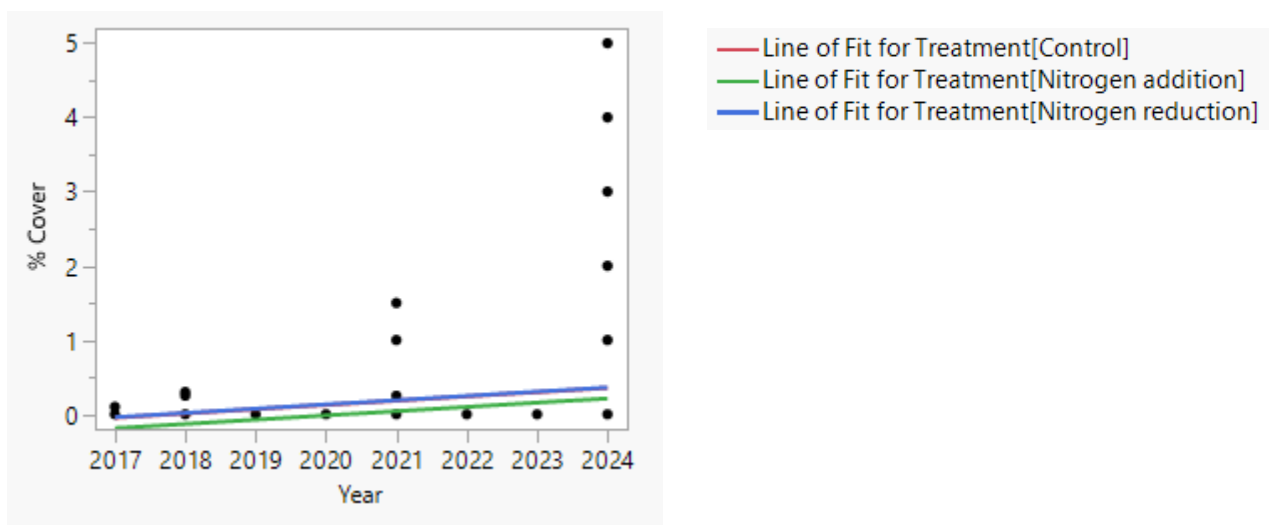


Figure 38. Effect of treatment and time on percent cover of *Sa/sify* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 11.50$, $P = 0.0008$).

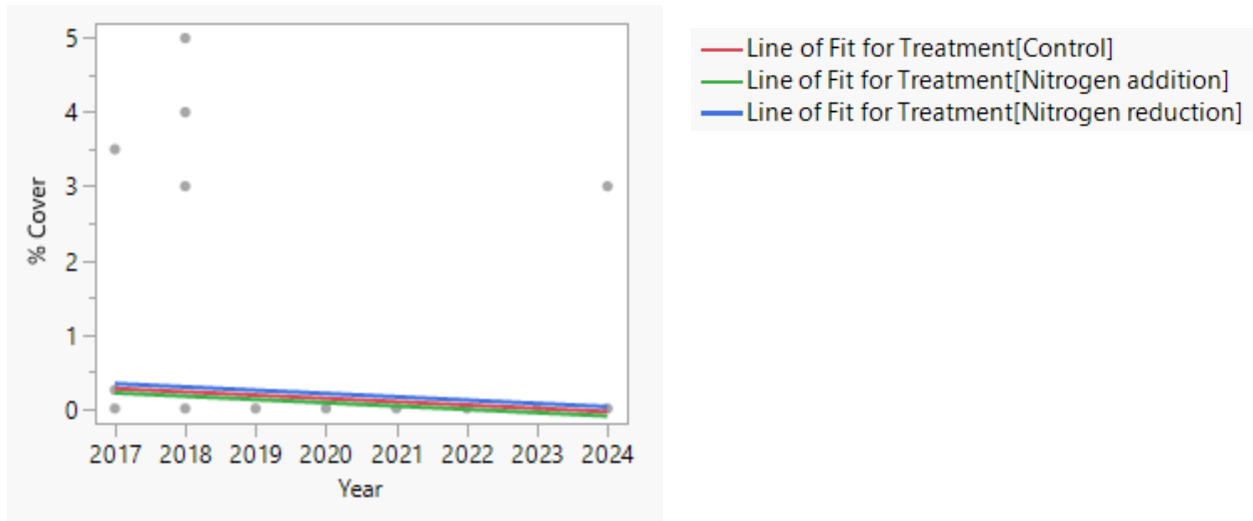


Figure 39. Effect of treatment and time on percent cover of *Taraxacum* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 4.79$, $P = 0.0299$).

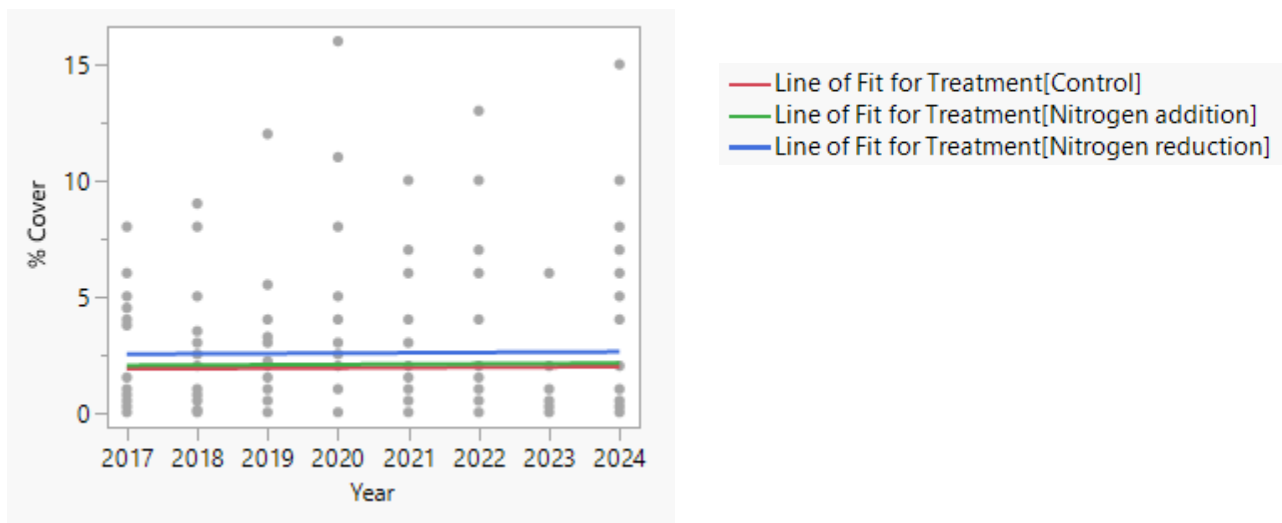


Figure 40. Effect of treatment and time on percent cover of *Taraxacum officinale* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = \text{ns}$).

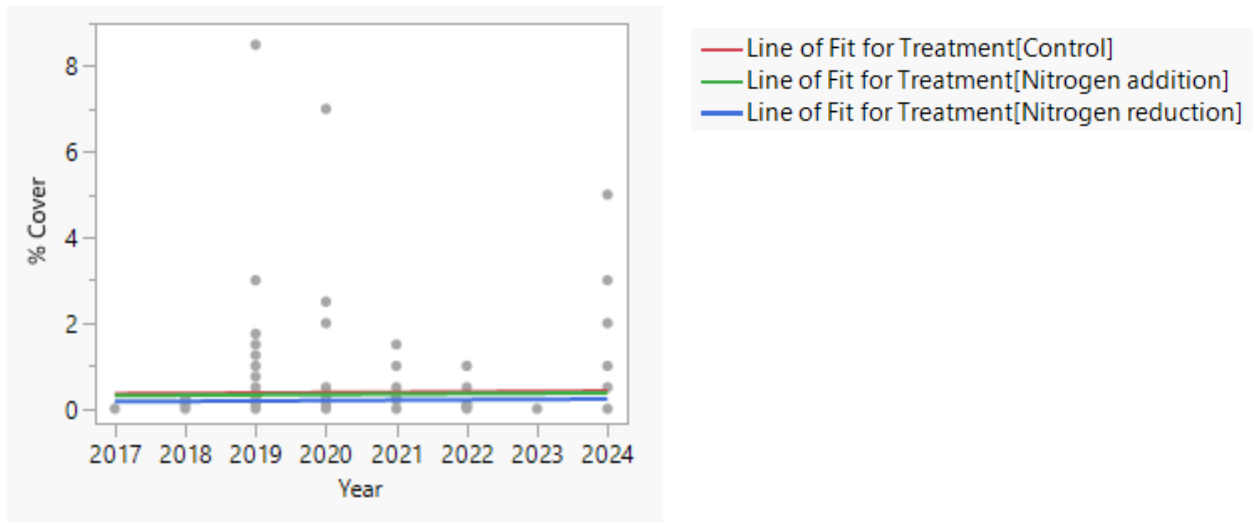


Figure 41. Effect of treatment and time on percent cover of *Thlaspi arvense* from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 41.19$, $P < 0.0001$).

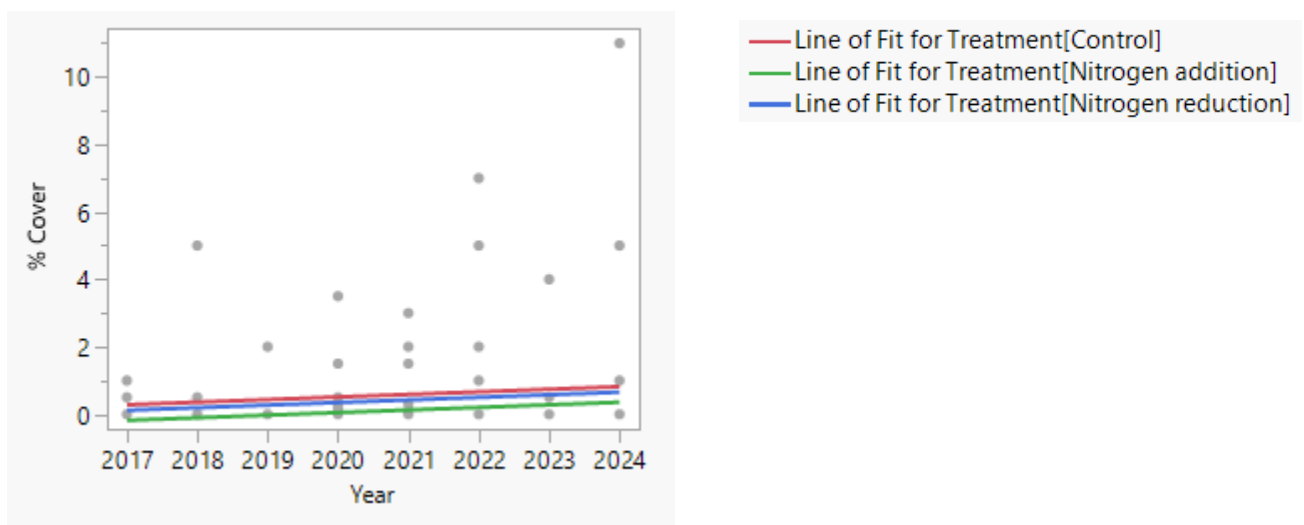


Figure 42. Effect of treatment and time on percent cover of *Timothy* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 4.01$, $P = 0.0468$).

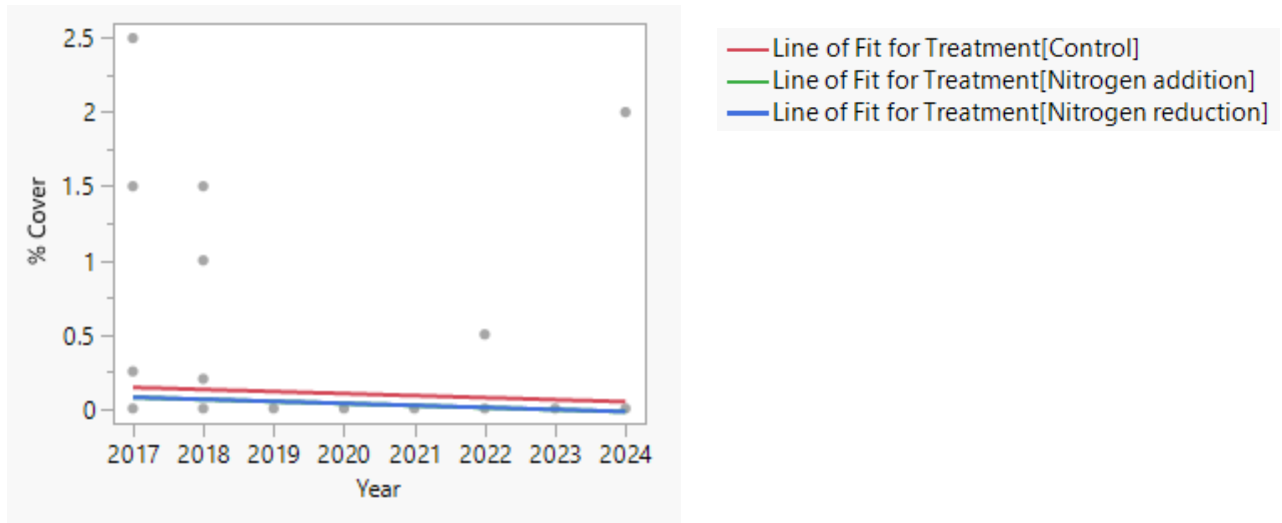


Figure 43. Effect of treatment and time on percent cover of *Trifolium* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

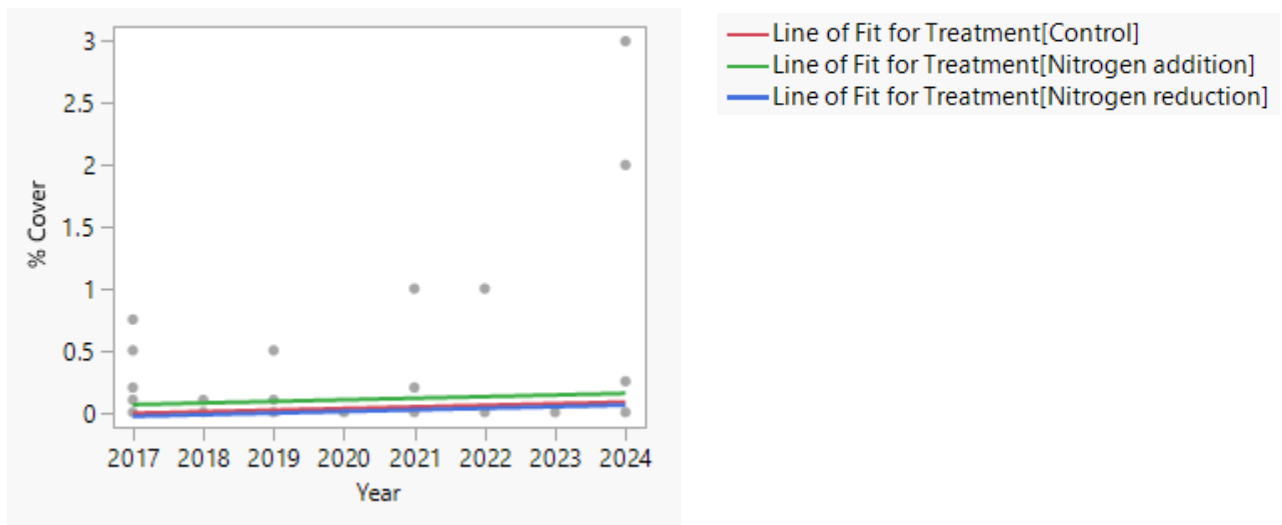


Figure 44. Effect of treatment and time on percent cover of *Vicia* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

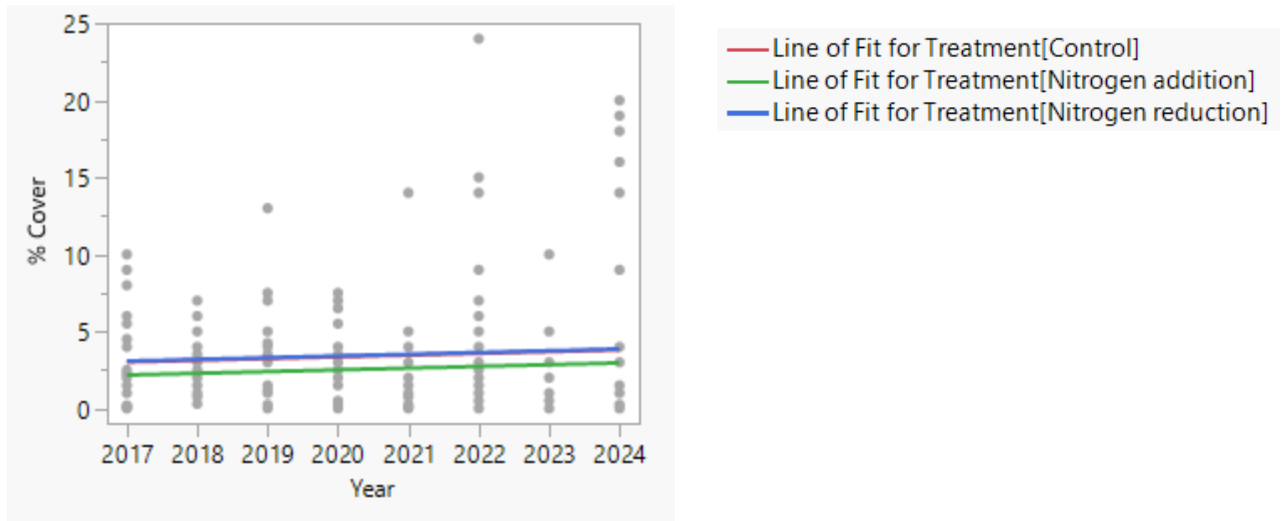


Figure 45. Effect of treatment and time on percent cover of *Viguera* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: ns).

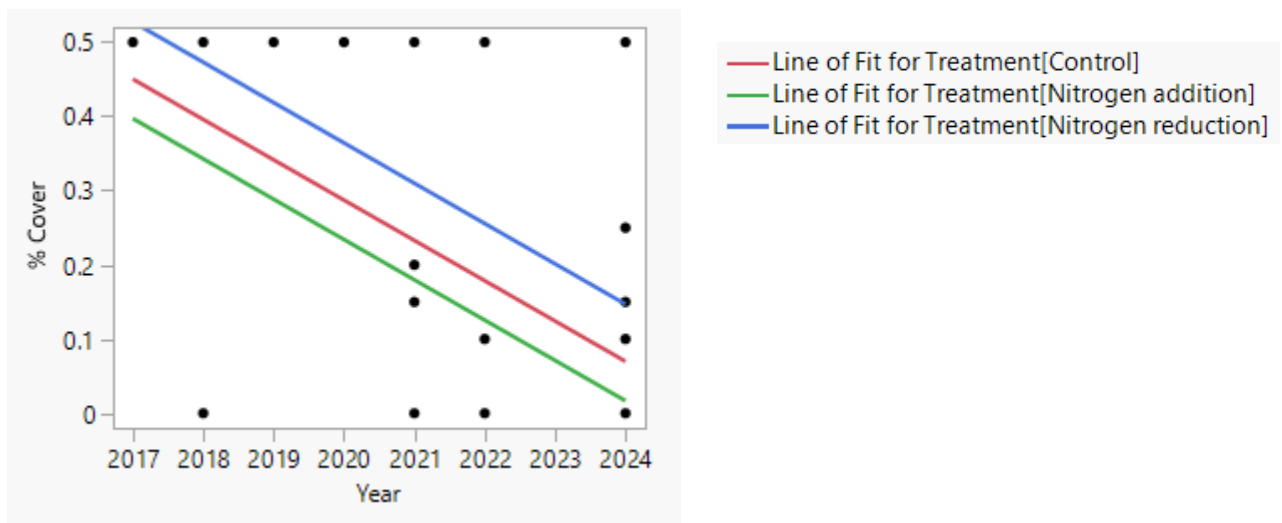


Figure 46. Effect of treatment and time on percent cover of *Viola* spp. from 2017 to 2024 (Multiple linear regression; Treatment effect: ns; Year effect: $F = 21.10$, $P < 0.0001$).

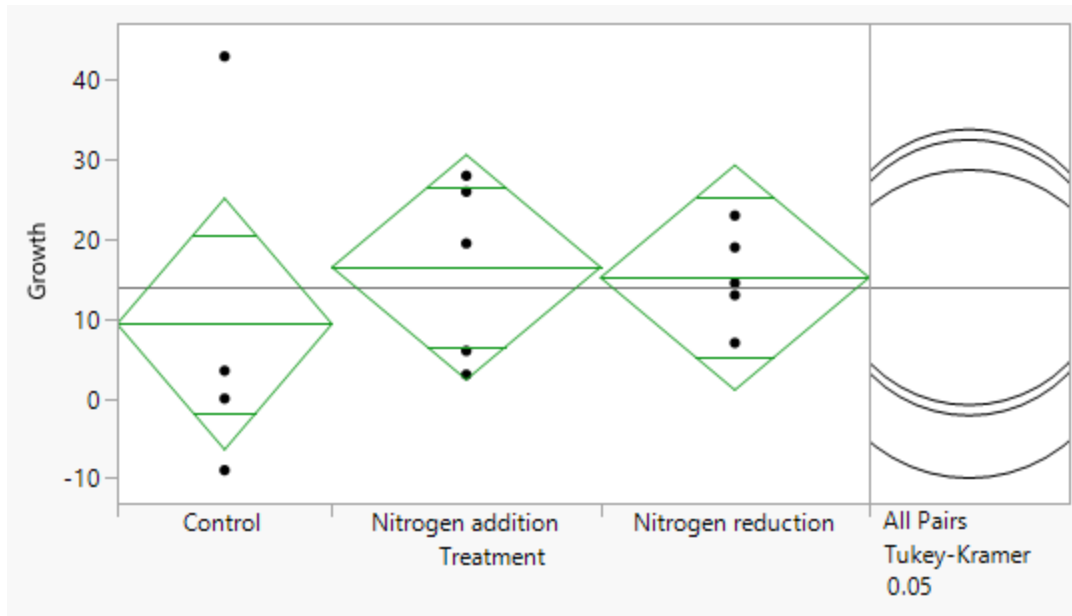


Figure 47. Plant growth of *Linaria vulgaris* in 2024. (ANOVA & Tukey-Kramer, ns).

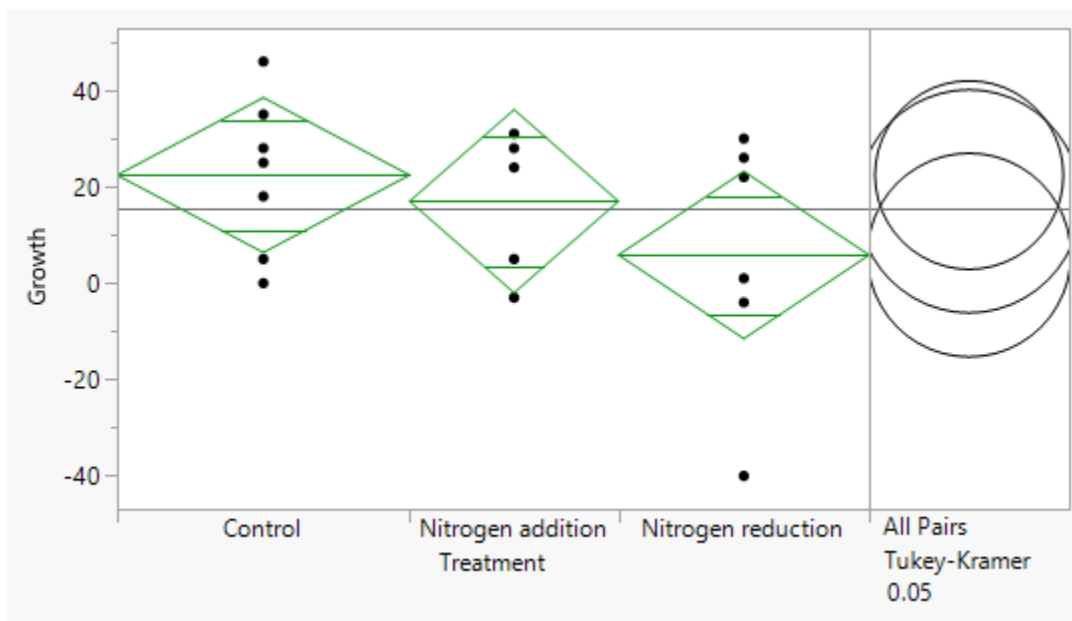


Figure 48. Plant growth of *Brome* spp. in 2024. (ANOVA & Tukey-Kramer, ns).

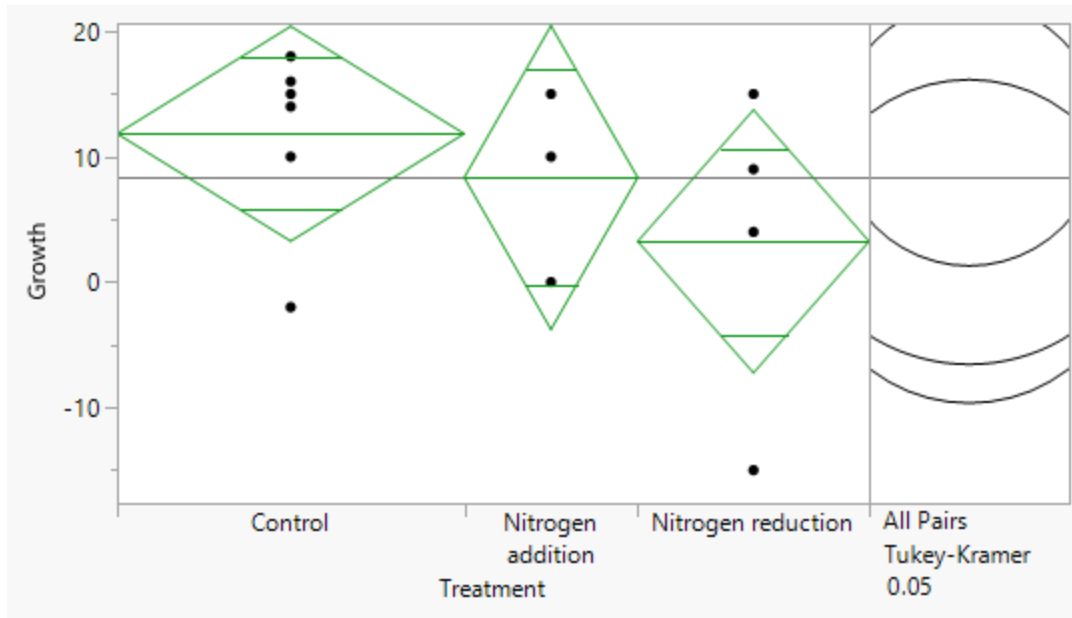


Figure 49. Plant growth of *Erigeron speciosus* in 2024. (ANOVA & Tukey-Kramer, ns).

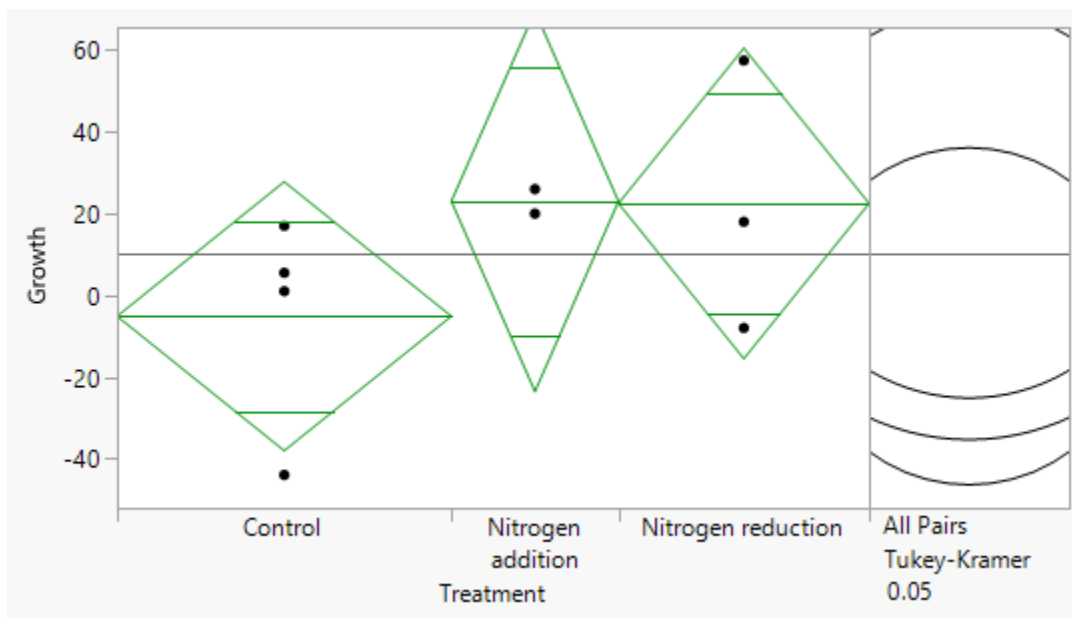


Figure 50. Plant growth of *Poa* spp in 2024. (ANOVA & Tukey-Kramer, ns).

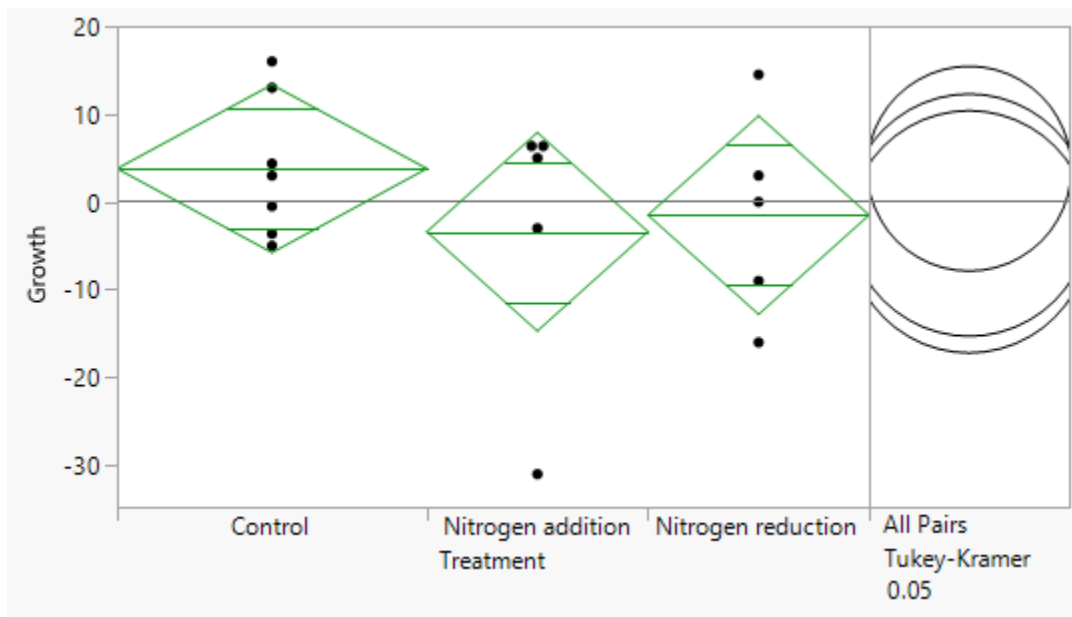


Figure 51. Plant growth of *Polemonium foliosissimum* in 2024. (ANOVA & Tukey-Kramer, ns).

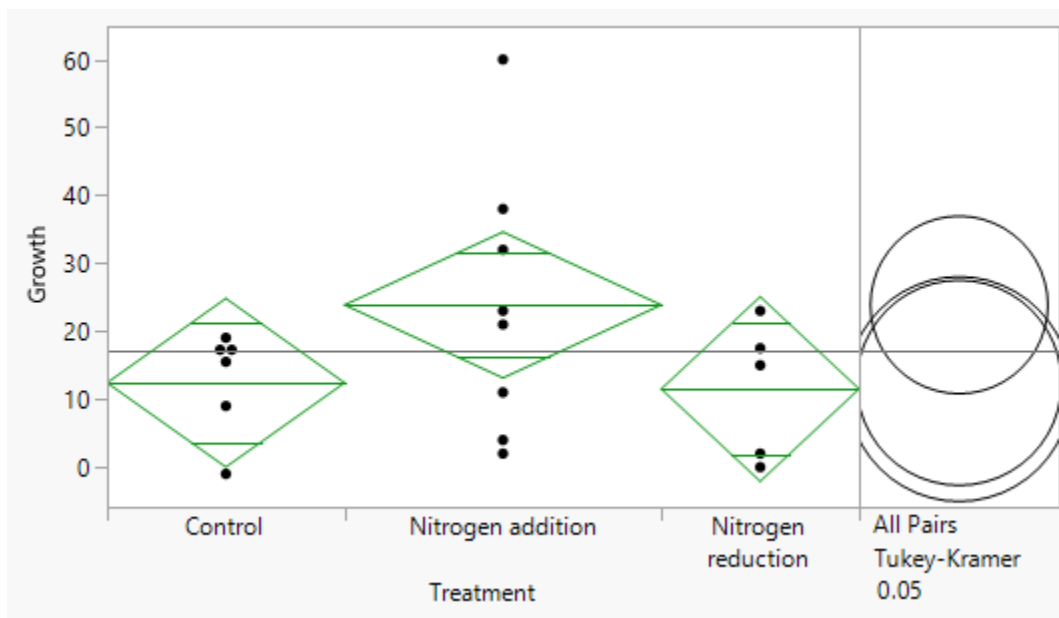


Figure 52. Plant growth of *Potentilla pulcherirma* in 2024. (ANOVA & Tukey-Kramer, ns).

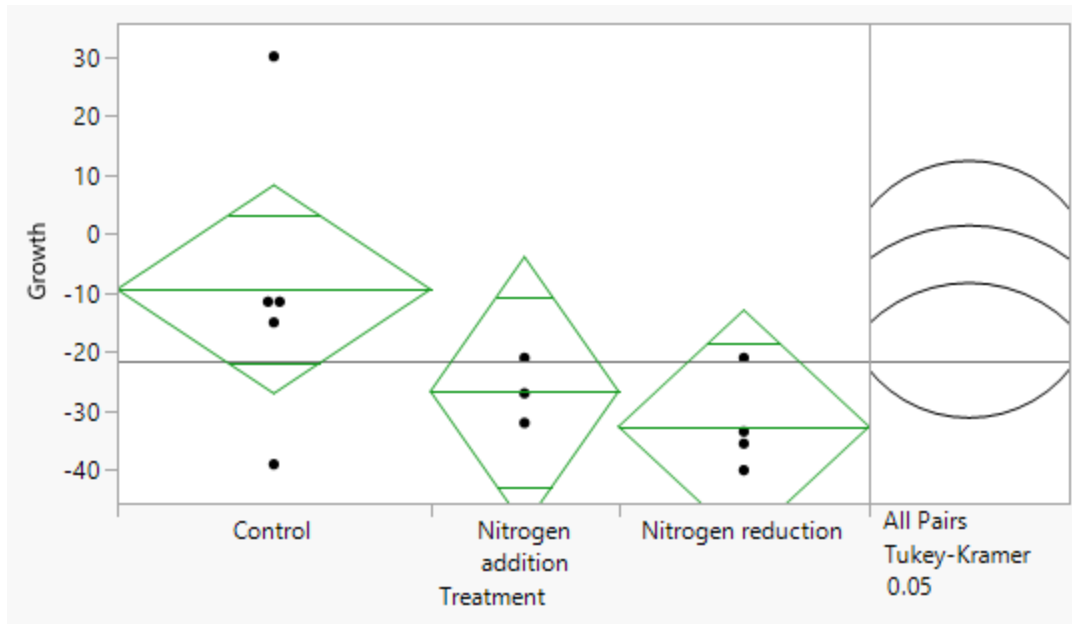


Figure 53. Plant growth of *Taraxacum officinale* in 2024. (ANOVA & Tukey-Kramer, ns).

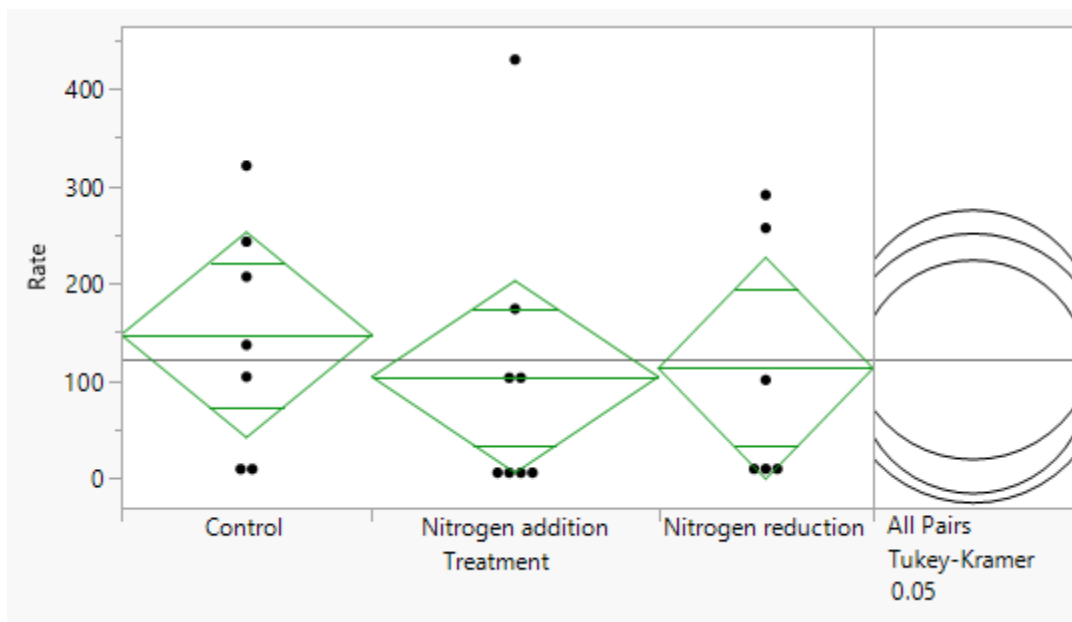


Figure 54. Photosynthetic rate of *Brrome* spp. in 2024. (ANOVA & Tukey-Kramer, ns).

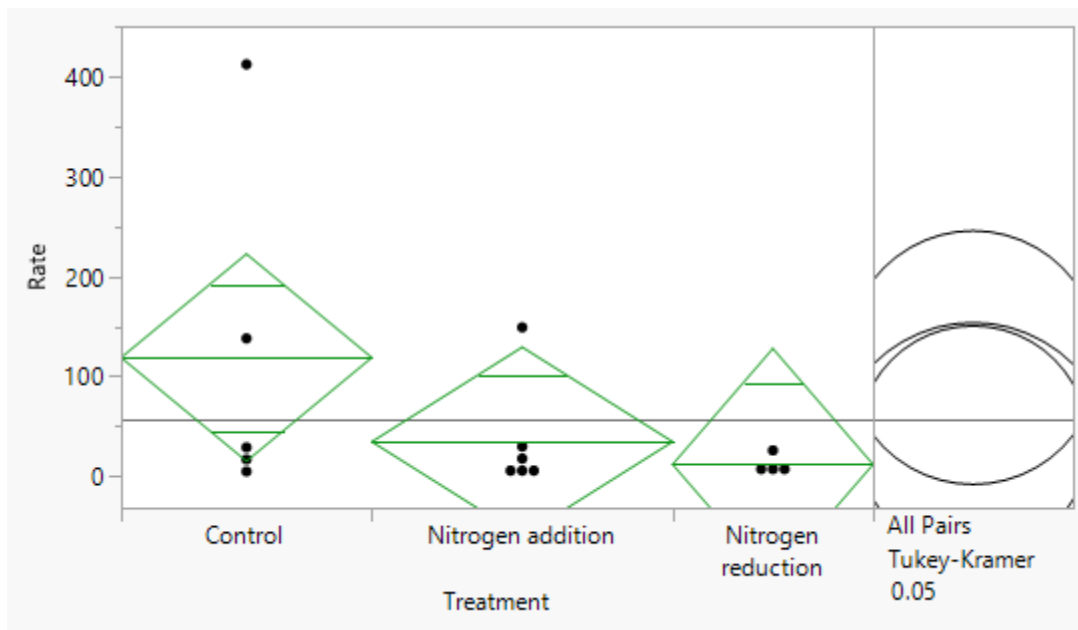


Figure 55. Photosynthetic rate of *Linaria vulgaris* in 2024. (ANOVA & Tukey-Kramer, ns).