GMR
The Original

ASSESSING THE INFLUENCE OF ENVIRONMENTAL POLLUTION ON PLANT DIVERSITY AND ECOSYSTEM STABILITY USING ECOLOGICAL MODELING

Dr. Biju Sidharthan[1], Praveen Kumar[2], Dr. Akanksha Dubey[3], Dr. Rashmi Nagesh[4], Dr. Jaya Sharma[5], Dipak K. Koche[6]

[1]Scientist, Kerala Agricultural University, Thrissur, 680656, Email Id- biju.s@kau.in, Orcid Id- 0009-0008-9775-7670
[2]Consultant & Sr Chemist, Specialization in Environmental monitoring, Raj Envirocare Pvt Ltd,
Email Id: pkanuragi003@gmail.com
[3]Assistant Professor, School of Biological and Forensic Sciences, Department of Life Sciences, Kristu Jayanti (Deemed to be University), Email Id-dubeyakanksha3004@gmail.com, Orcid Id- 0009-0001-2036-0041
[4]Assistant Professor, School of Biological and Forensic Sciences, Department of Life Sciences, Kristu Jayanti (Deemed to be University), Email Id- rashmi.nagesh1689@gmail.com, Orcid Id-0000-0002-4817-4929
[5]Associate Professor, Faculty of Agriculture Science, Specialization in Botany & Plant breeding, SAM Global University Raisen, Email Id-jayasharma.sub@gmail.com, Orcid Id-0009-0008-2778-7970
[6]Professor Department of Botany, Shri Shivaji College of Arts, Commerce and Science, Akola (MS), Specialization in Cytology and Genetics, Sant Gadge Baba Amravati University, Amravati (MS) India,
Email Id- kochedeepak77@gmail.com Orcid Id: https://orcid.org/0000-0001-8403-9460

ABSTRACT:
Nitrogen enrichment is a critical type of environmental contamination that may influence post-fire vegetation recovery, plant diversity, community structure and ecosystem stability. This study evaluated how contrasting nitrogen treatments influenced plant diversity, native–nonnative vegetation structure, community composition, and temporal stability across three post-fire sampling years. Plot-level observations were repeatedly analyzed with diversity indices, mixed-effects models, temporal stability metrics, PERMANOVA, PERMDISP and non-metric multidimensional scaling. The analyses included nitrogen treatment, year, invasion status and relevant interactions. Significant nitrogen × year interactions were detected for total richness, native richness, Shannon diversity, Simpson diversity, and Pielou evenness. High nitrogen was associated with lower native vegetation cover and greater nonnative cover, while native and nonnative vegetation components exhibited significant temporal responses. Community composition differed significantly among nitrogen treatments (PERMANOVA, $p = 0.006$), with significant pairwise differences involving the high-nitrogen treatment. The evaluated temporal stability metrics were not significantly affected by nitrogen treatment, but invasion status did affect some of the stability outcomes. Overall, the post-fire plant diversity and community composition changed in a highly time-dependent way as a result of the nitrogen enrichment, especially through shifts in the native–nonnative vegetation balance, while temporal stability was relatively unaffected.

KEYWORDS: nitrogen enrichment, plant diversity, ecosystem stability, community composition, post-fire vegetation

1. INTRODUCTION

The ecological impacts of the pollution caused by human activities have become a significant force in driving ecological changes, as pollution levels have risen and human impacts on physical and chemical conditions that affect ecological communities have increased. Agriculture, industry, transportation, energy production and land use change all have the potential to alter nutrient cycles, soil properties and biological interactions, which can have effects within species to ecosystem processes (Ukaogo et al., 2020). These pressures are harder to manage in the presence of natural disturbances and other environmental stressors, and when combined with natural disturbances (Rathod et al., 2024). Human activities have significantly altered the transport of biologically available nitrogen to terrestrial ecosystems, and reactive nitrogen plays a special role. Nitrogen deposition from the atmosphere has undergone significant changes over the past few decades, and there are significant regional differences in deposition rates linked to agricultural emissions, fossil-fuel combustion, industrialization and environmental regulation by policy (Ackerman et al., 2019). When enrichment takes place in systems with limited nutrient supplies, it may also stimulate productivity, but long-term enrichment could change the nature of the competition, nutrient levels, soil conditions and/or species coexistence. Nitrogen deposition also plays a role in the climate, which means that ecological responses are not only to nitrogen but to several environmental drivers (Borer & Stevens, 2022). The assessment of nitrogen enrichment thus needs to take into account biodiversity, structure of vegetation, composition of communities and temporal responses.

Nutrient enrichment has especially high sensitivity for plant diversity. The previous studies from around the world suggest that N enrichment often has a negative effect on plant species richness, and it alters the abundance and dominance of species (Midolo et al., 2019). The extent of biodiversity declines in ecosystems due to chronic N

deposition has since been linked to the process of competitive exclusion, changes in soil structure, nutrient imbalances, and enhanced species dominance, which are better able to exploit available resources quickly (Payne et al., 2017). Vegetation responses to enrichment vary through time as changes in community composition, environmental parameters, disturbance history and species' ecological strategies affect the response. The complexity of these relationships is increased by fire. Resource availability, recruitment, competition and community assembly are in a state of change following fire. Climatic conditions can hinder establishment and regeneration, leading to altered post-fire trajectories, which can constrain vegetation recovery (Nolan et al., 2021). Fire is also a significant ecological driver of plant traits, species distribution, community structure and terrestrial biodiversity (He et al., 2019). Plant life forms and ecological context also vary in their post-fire recovery, leading to significant differences in plant responses following fire (Sapkota et al., 2025). Nitrogen enrichment during this time could thus alter successional processes and have effects that shift with recovery years.

The responses of native and non-native vegetation to nutrient enrichment may be different. More nutrients can lead to improved performance of the alien plant and influence resource allocation and growth related to invasion success (Shan et al., 2024). In addition, there are also functional trait differences in the acquisition of resources and in competition between dominant native and non-native plants (Broadbent et al., 2020). Biotic resistance can limit the success of invasive plants in nutrient-rich environments, even in the presence of these effects (Teixeira et al., 2017). It is therefore crucial to be able to separate native from nonnative vegetation responses in order to detect changes that could be hidden in vegetation cover aggregate measures. Another aspect of the evaluation of nitrogen-induced ecological change is temporal stability. Average richness or vegetation cover can be the same in communities, but they can vary significantly in variability over time. Nitrogen enrichment can impact several aspects of grassland stability, including composition, which can lead to altered ecosystem stability (Xu et al., 2022). Following fire, species composition and vegetation structure may change very rapidly as the system recovers, making this an important concern.

Although there is a large body of work that correlates nitrogen enrichment to vegetation change, there is some doubt about the relative impact of nitrogen enrichment during post-fire succession. Past studies have tended to focus on richness or productivity, or individual invasion responses, and fewer studies try to include plant diversity, native and non-native vegetation structure, community composition, and temporal stability in the same experimental context. The effect of treatment on nitrogen and how these effects have changed over time should also be considered and compared with invasion status, as it may not reflect future community dynamics.

The purpose of this study was to assess the temporal ecological response of post-fire plant communities to opposing N treatments. The goals were to quantify the effect of nitrogen treatment and year on plant richness, diversity, and vegetation structure; quantify changes in native and non-native vegetation cover and composition; and to determine if nitrogen treatment and invasion status affect the temporal stability of plant diversity and vegetation cover.

2. METHODOLOGY

2.1 Research Design

To quantify the effects of nitrogen enrichment on plant diversity, vegetation composition and ecosystem stability, a longitudinal ecological modelling design was used. Four nitrogen treatments (control, low, medium and high) were used in the experimental structure and sampled over the three consecutive years. Temporal responses were identified by repeating observations at the plot level, allowing to separate temporal from treatment-related variation. Ecological heterogeneity and the structured field design were incorporated by adding invasion status and experimental block, where appropriate.

2.2 Data Source

Ecological data were collected from the publicly available data from Valliere et al. (2023). The data included multiple vegetation measurements taken on the experimental plots that were subjected to different nitrogen treatments. Records included species-level and plot-level data, which were used to describe plant diversity, vegetation cover, the composition of plant communities, status of species as invaders, and responses to changes in time.

2.3 Ecological Variables and Diversity Assessment

Total species richness, native species richness, Shannon diversity, Simpson diversity and Pielou evenness were used to quantify plant diversity. Vegetation structure was described with the cover of the species as the total species cover, the cover of native species, the cover of nonnative species, the proportion of nonnative cover, cover of functional groups, bare ground cover, litter cover, and shrub cover (if present). Prior to calculating community-level measures, species-level observations were categorized as native or nonnative. The continuous ecological variables were summarized by means and standard deviations, and treatment-specific and year-specific estimates were calculated to describe spatial and temporal variability.

2.4 Longitudinal Mixed-Effects Modeling

Repeated measurements were taken within experimental plots and these were accounted for by fitting mixed-effects regression models to diversity and vegetation-cover outcomes separately. Nitrogen treatment, sampling

year and the interaction between N and year were included as fixed effects, whereas the plot identity was added as a random effect. Invasion status was added as an extra ecological covariate when appropriate. Likelihood-ratio tests were used to assess the overall contribution of temporal treatmSchool of Biological and Forensic Sciencesent interactions, by fitting full interaction models and reduced models. Model fit was also compared by AIC and parameter estimates were presented with standard errors, probability values and 95% confidence intervals.

2.5 Temporal Stability Analysis

The temporal ecosystem stability for each experimental plot was estimated independently by dividing the temporal mean by the temporal standard deviation. Three years of sampling were used to calculate stability indices for each of the following: total richness, native richness, Shannon diversity, total species cover, native species cover, and nonnative species cover. Since some of the outcomes did not have normal stability distributions, the differences between the nitrogen treatments were tested with Kruskal–Wallis tests. To assess the effects of ecological context and treatment effects, and to mitigate sensitivity to non-normal residual distributions, complementary robust models were used that include nitrogen treatment, invasion status, experimental block, and the interaction of nitrogen with invasion status.

2.6 Community Composition and Ordination

Species abundance data were organized into a sample-by-species community matrix and analyzed with multivariate procedures based on permutations. Permutational multivariate analysis of variance (PERMANOVA) with 999 permutations was used to evaluate differences in community composition due to nitrogen treatment, year and invasion status. PERMDISP was used to assess the homogeneity of multivariate dispersion separately. If a general nitrogen effect was found, a pairwise PERMANOVA was performed between the treatment groups, and the family-wise error rate was controlled for using the Holm correction. Reduced-dimensional ordination space was used to represent the variation in the community composition by non-metric multidimensional scaling (NMDS). We considered 2- and 3-dimensional solutions and we used the ordination stress to evaluate dimensionality. Treatment-specific centroids were computed from the NMDS coordinates to provide a summary of the relative position of each treatment for each nitrogen group in the multivariate community space.

2.7 Statistical Analysis

A p-value of < 0.05 was considered to be statistically significant and multiplicity-adjusted probabilities were used when pairwise comparisons were made. The bounded Simpson diversity and Pielou evenness indices were also analysed using sensitivity analyses to evaluate the robustness of the estimated nitrogen × year effects. Depending on the structure and distribution of each outcome, statistical procedures were chosen that included mixed-effects modeling, nonparametric testing, robust factorial analysis, multivariate inference based on permutations and ecological ordination, all within an integrated analytic framework.

3. RESULTS

3.1 Plant Diversity Responses to Nitrogen Treatment

Nitrogen treatments and sampling years also had some variation in plant diversity. The mean total species richness was 15.68 ± 4.11 under high nitrogen and 17.72 ± 4.80 under low nitrogen. Native species richness was highest in the control treatment (11.38 ± 3.47) and the low nitrogen treatment (11.32 ± 3.91), while the high nitrogen treatment had the lowest native species richness (9.70 ± 3.65). Shannon diversity ranged from 1.78 ± 0.35 to 1.90 ± 0.39, while Simpson diversity ranged from 0.75 ± 0.11 to 0.78 ± 0.12. The highest native cover was found in the control (32.09 ± 20.12%), while the highest non-native cover was found under high nitrogen (43.04 ± 22.44%). Descriptive ecological characteristics by nitrogen treatment are given in Table 1.

Table 1. Descriptive ecological characteristics by nitrogen treatment

Ecological variable	Control	High nitrogen	Low nitrogen	Medium nitrogen
Total species richness	17.17 ± 4.43	15.68 ± 4.11	17.72 ± 4.80	15.97 ± 3.69
Native species richness	11.38 ± 3.47	9.70 ± 3.65	11.32 ± 3.91	9.85 ± 3.31
Shannon diversity	1.90 ± 0.36	1.82 ± 0.28	1.90 ± 0.39	1.78 ± 0.35
Simpson diversity	0.78 ± 0.10	0.77 ± 0.08	0.78 ± 0.12	0.75 ± 0.11
Pielou evenness	0.68 ± 0.11	0.67 ± 0.10	0.67 ± 0.12	0.65 ± 0.11
Native species cover (%)	32.09 ± 20.12	21.99 ± 12.27	28.79 ± 15.83	25.72 ± 16.03

Nonnative species cover (%)	27.73 ± 15.60	43.04 ± 22.44	37.32 ± 19.80	38.25 ± 22.73
Nonnative cover proportion	0.48 ± 0.18	0.64 ± 0.18	0.56 ± 0.18	0.58 ± 0.20

The temporal patterns varied between the nitrogen treatments. Total richness had relatively high values in 2014 and 2015, but decreased in all treatments in 2016. Treatment-related differences with time were also observed for Shannon diversity. The total number of species varied with time as indicated in Figure 1A by nitrogen treatment. Figure 1B shows the corresponding temporal variation in Shannon diversity across nitrogen treatments.

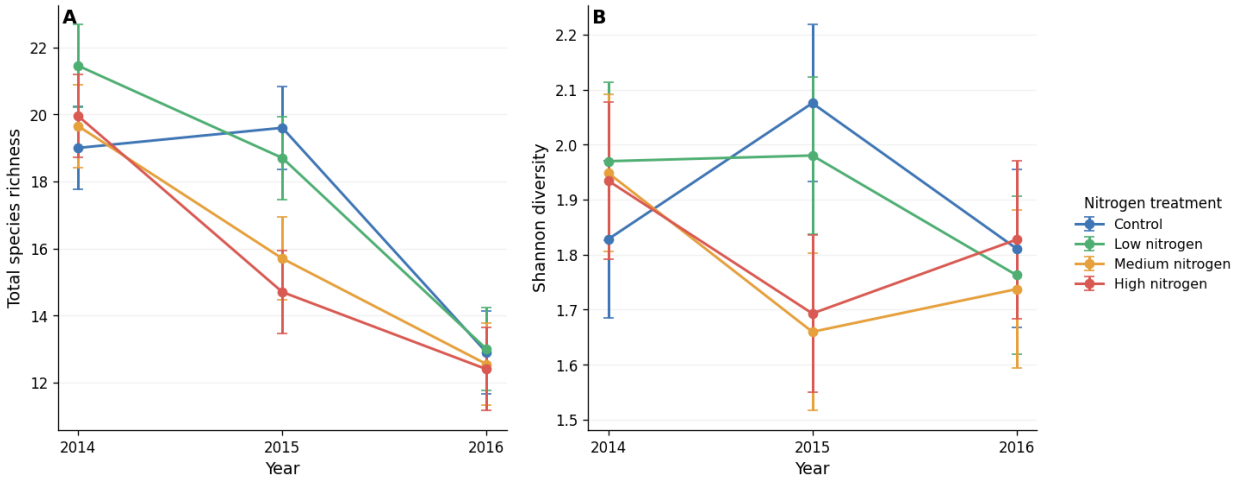

Figure 1. Temporal patterns of plant diversity across nitrogen treatments. (A) Total species richness across sampling years. (B) Shannon diversity across sampling years.

Nitrogen × year was significant in all five diversity outcomes for omnibus likelihood-ratio tests. The interaction was significant for total richness ($\chi^2 = 39.919$, $p < 0.001$), native richness ($\chi^2 = 55.082$, $p < 0.001$), Shannon diversity ($\chi^2 = 30.944$, $p < 0.001$), Simpson diversity ($\chi^2 = 16.896$, $p = 0.010$), and Pielou evenness ($\chi^2 = 14.618$, $p = 0.023$). The models generated by the interaction also had lower AIC values, compared with their reduced counterparts. Table 2 shows the omnibus tests for the nitrogen × year interaction.

Table 2. Omnibus mixed-effects model tests for the nitrogen × year interaction

Outcome	Likelihood-ratio χ^2	df	p-value	Interaction model AIC	Reduced model AIC
Total richness	39.919	6	<0.001	1180.53	1208.44
Native richness	55.082	6	<0.001	1073.45	1116.54
Shannon diversity	30.944	6	<0.001	140.75	159.69
Simpson diversity	16.896	6	0.010	-413.80	-408.91
Pielou evenness	14.618	6	0.023	-393.11	-390.49

Sensitivity analyses of the bounded diversity indices identified significant interactions for Simpson diversity under high nitrogen × 2015 ($\beta = -0.623$, $p = 0.0017$) and medium nitrogen × 2015 ($\beta = -0.698$, $p = 0.0004$). For Pielou evenness, significant coefficients occurred for high nitrogen × 2015 ($\beta = -0.394$, $p = 0.0400$) and medium nitrogen × 2015 ($\beta = -0.548$, $p = 0.0043$).

3.2 Vegetation Structure and Cover Dynamics

The amount of vegetation cover varied from one nitrogen treatment to another. The mean native species cover was 32.09% in control, 28.79% with a low amount of nitrogen, 25.72% with a medium amount of nitrogen and 21.99% with a high amount of nitrogen. Corresponding nonnative cover values were 27.73%, 37.32%, 38.25%, and 43.04%, respectively. The distribution of native and nonnative species cover by nitrogen treatment is shown in Figure 2A. The percentage of nonnative cover is presented by treatment time in Figure 2B.

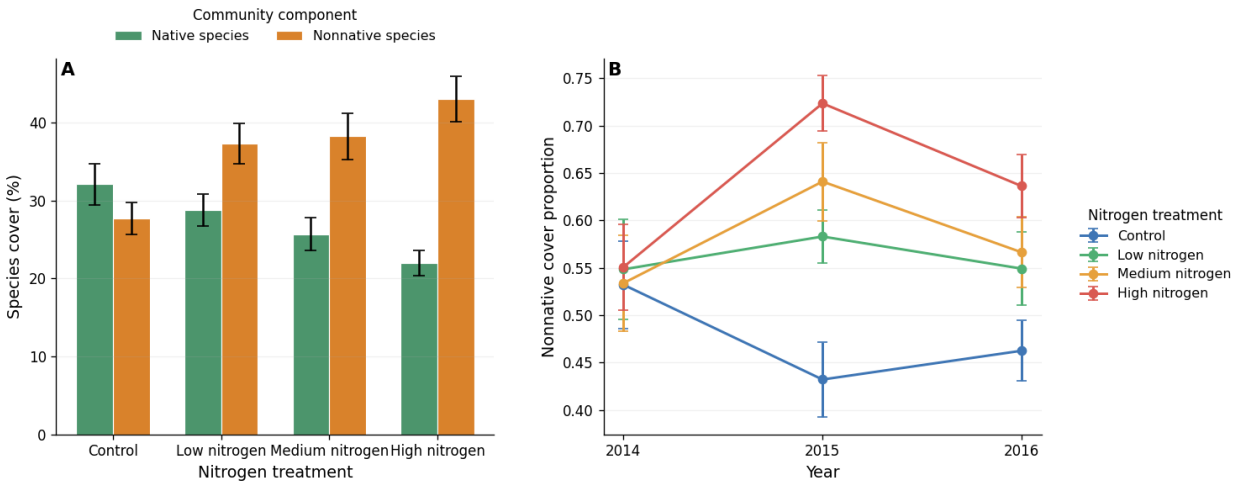

Figure 2. Vegetation cover responses to nitrogen treatment. (A) Native and nonnative species cover across nitrogen treatments. (B) Temporal variation in nonnative cover proportion across nitrogen treatments.

Mixed-effects analyses identified significant nitrogen × year interactions for native species cover ($\chi^2 = 28.056$, $p < 0.001$), nonnative species cover ($\chi^2 = 23.617$, $p < 0.001$), nonnative cover proportion ($\chi^2 = 19.486$, $p = 0.003$), native forb cover ($\chi^2 = 34.974$, $p < 0.001$), and nonnative forb cover ($\chi^2 = 18.612$, $p = 0.005$). No significant interactions were detected for total species cover ($p = 0.904$), bare ground ($p = 0.698$), litter cover ($p = 0.625$), shrub cover ($p = 0.889$), or nonnative grass cover ($p = 0.689$). For native species cover, significant negative interaction coefficients were observed in 2015 for high nitrogen ($\beta = -26.34$, $p < 0.001$), low nitrogen ($\beta = -15.03$, $p = 0.0025$), and medium nitrogen ($\beta = -19.23$, $p < 0.001$). Nonnative species cover showed positive interactions in 2015 for high nitrogen ($\beta = 23.57$, $p < 0.001$), low nitrogen ($\beta = 12.24$, $p = 0.0177$), and medium nitrogen ($\beta = 20.04$, $p < 0.001$). Uninvaded plots had higher native species cover ($\beta = 8.29$, $p < 0.001$) and lower nonnative species cover ($\beta = -13.10$, $p < 0.001$).

3.3 Community Composition

The community composition was found to vary extremely with regard to nitrogen treatment, year and invasion status. PERMANOVA produced test statistics of 1.732 for nitrogen ($p = 0.006$), 21.110 for year ($p = 0.001$), and 23.499 for invasion status ($p = 0.001$). There were no PERMDISP significant differences for nitrogen ($p = 0.452$), but significant differences in dispersion were found for year ($p = 0.009$) and invasion status ($p = 0.001$). The multivariate community-composition tests are presented as well as the temporal-stability comparisons in Table 3.

Table 3. Community composition and temporal stability results

Analysis	Outcome/factor	Statistic	df	p-value
PERMANOVA	Nitrogen	1.732	—	0.0060
PERMANOVA	Year	21.110	—	0.0010
PERMANOVA	Status	23.499	—	0.0010
PERMDISP	Nitrogen	0.851	—	0.4520
PERMDISP	Year	4.224	—	0.0090
PERMDISP	Status	16.074	—	0.0010
Kruskal–Wallis stability test	Total richness	0.530	3	0.9122
Kruskal–Wallis stability test	Native richness	4.469	3	0.2151
Kruskal–Wallis stability test	Shannon diversity	2.771	3	0.4283
Kruskal–Wallis stability test	Total species cover	1.476	3	0.6879
Kruskal–Wallis stability test	Native species cover	6.161	3	0.1040
Kruskal–Wallis stability test	Nonnative species cover	2.642	3	0.4502

Significant differences between control and high nitrogen (Holm-adjusted p = 0.006) and high and low nitrogen (Holm-adjusted p = 0.035) were detected by pairwise PERMANOVA. All other pairwise comparisons were not significant after Holm adjustment.

3.4 Temporal Stability and Community Ordination

Temporal stability was evaluated across 80 plots observed over three years; 79 plots contributed to the native richness stability analysis because one stability estimate was unavailable. The mean stability values were 5.51 for total richness, 3.26 for native richness, 12.61 for Shannon diversity, 2.51 for total species cover, 2.79 for native species cover, and 3.82 for nonnative species cover. All p values in the Kruskal–Wallis analyses were greater than 0.10 for any stability metric used, indicating that treatment with nitrogen did not significantly affect any. No significant main effect of nitrogen was found for any of the robust stability models (RSM) in total richness, native richness, Shannon diversity, total species cover, native species cover, or nonnative species cover (p = 0.605, 0.204, 0.920, 0.642, 0.099, 0.426, respectively). For all six outcomes, there was no significant interaction between nitrogen and invasion status. Invasion status was significant for total richness stability (F = 4.633, p = 0.035), native richness stability (F = 5.469, p = 0.023), and nonnative species cover stability (F = 4.084, p = 0.048). The distributions of temporal stability for total richness, native richness and total species cover are presented in Figure 3A for the nitrogen treatments. The NMDS ordination of the plant community according to nitrogen treatment was performed (Figure 3B), and treatment centroids are shown in the ordination space.

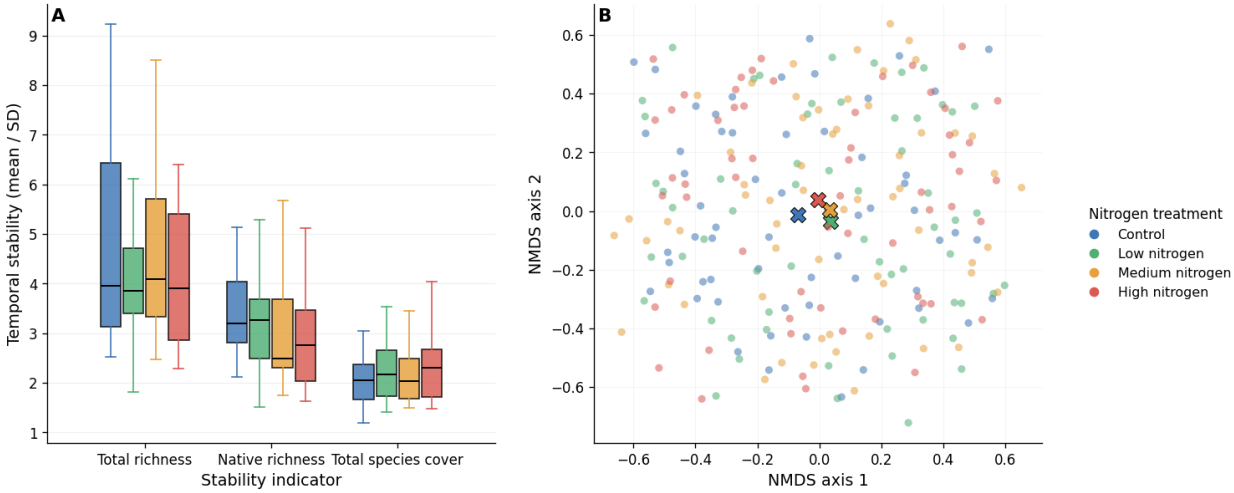

Figure 3. Temporal stability and multivariate community structure across nitrogen treatments. (A) Temporal stability of total richness, native richness, and total species cover. (B) NMDS ordination of plant-community composition with nitrogen-treatment centroids.

The stress value for the 2-D NMDS solution was 0.299 and the 3-D solution reduced stress to 0.241. The treatment centroids on NMDS axes 1 and 2 were approximately −0.068 and −0.012 for control, −0.004 and 0.038 for high nitrogen, 0.036 and −0.035 for low nitrogen, and 0.032 and 0.004 for medium nitrogen, respectively.

4. DISCUSSION

Enriching with nitrogen resulted in very different temporal responses in post-fire plant communities, as opposed to consistent responses throughout the monitoring period. Significant nitrogen × year interactions were found for total richness, native richness, Shannon diversity, Simpson diversity and Pielou evenness. The greatest differences in treatment were found in 2015, with the medium and high nitrogen generally having less diversity than the control and low nitrogen treatments. Richness declined throughout treatments and the magnitude of treatment separation was reduced by 2016. The time pattern suggests the influence of nitrogen on the ecology was related to the phase of post-fire vegetation growth. There was a clear shift in vegetation structure towards a greater proportion of non-native vegetation. Native species cover was greatest in the control and least in the high N, and nonnative cover was greatest in the high N and least in the control. The significant interactions between nitrogen and year for native species cover, nonnative species cover, nonnative cover proportion, native forb cover, and nonnative forb cover also indicated variation in these species' responses over time. There was no significant nitrogen × year interaction for total species cover, suggesting that nitrogen primarily modified vegetation composition rather than total vegetation abundance. The N treatment, year, and invasion status also significantly influenced community composition. The large nitrogen PERMANOVA and lack of significant differences in dispersion for nitrogen indicate that the treatment effect was due to a compositional separation, rather than to a change in within-group variance. Pairwise comparisons showed that there were significant differences between the control and high nitrogen and between high and low nitrogen. No significant differences in the six-stability metrics were found for temporal stability. Selected stability measures were more relevant to invasion status, such as total richness, native richness, and nonnative species cover stability.

The temporal diversity responses agree with evidence that enrichments of nutrients can gradually influence plant diversity and ecosystem productivity, and that the ecological impacts increase over time (Seabloom et al., 2021). This is consistent with other evidence from herbaceous communities indicating that the impact of nitrogen on the richness of plant species is widespread and can be more pronounced than the impact of phosphorus enrichment (Soons et al., 2017). Year was an important component of the environmental variability, as evidenced by the strong contribution. Nitrogen effects have been found to interact with water availability to influence annual plant diversity and community composition, indicating that nitrogen effects can be highly dependent on environmental conditions during the particular years (Wheeler et al., 2021). Post-fire situations can exacerbate this temporal dependence as a result of changes in resource availability, establishment opportunities, and competitive relationships caused by fire. Other changes in plant diversity and soil nitrogen dynamics after controlled burning have also been linked to vegetation recovery and resilience of grasslands (Azpilicueta, 2021).

Comparative plant species' responses are consistent with the evidence that N deposition can affect competitive interactions between native and non-native plant species (Ren et al., 2021). Species that are able to quickly take advantage of enriched resource conditions might be favored by an increase in nitrogen availability. Nitrogen deposition has been simulated to impact growth and resource-use strategies during invasive plant range expansion, which may improve competitive performance under nutrient enrichment (Huang et al., 2022). The community-level response also suggests that the impacts of nitrogen went beyond the changes to the single diversity measures. In other soil microbial communities, it has also been reported that changes in bacterial and fungal community composition could be different in response to nutrient enrichment (Wang et al., 2021). The presence of non-native vegetation is more important because of the potential for invasive annual plants to have phenological and physiological benefits at higher N levels (Valliere et al., 2022). These responses give ecological advantages to the increased non-native cover and decreased native representation seen with increased N enrichment.

Results indicate that the assessment of the effects of nitrogen based on the total percentage of vegetation cover can overlook important ecological changes. Nitrogen enrichment changed the native-non-native balance, diversity and composition even when the total species cover did not change significantly over time as a function of the treatments. Native and nonnative vegetation measures and multivariate community assessments should be used along with richness and diversity indices to monitor programs. The significant interaction between N and year also indicates that repeated monitoring throughout post-fire succession is important. The results from one sampling year alone could be misleading with regard to the treatment effects, since the responses to nitrogen varied considerably as vegetation recovery was achieved. The recovery stage of the community should therefore be taken into account as well as the nutrient exposure when managing the effects of nitrogen on post-fire ecosystems.

There are a few restrictions that need to be taken into account. It takes three years of monitoring to get an assessment of long-term ecological stability, and stability estimates were made from three observations per plot in the three-year monitoring period. Some of the response variables were non-normally distributed, but robust and sensitivity analyses were used as appropriate. The two-dimensional NMDS solution also had relatively high stress and therefore should be interpreted with care.

Monitoring should be expanded to later successional stages to assess the persistence, reduction, or enhancement of nitrogen associations at later successional stages in the future. Considering the availability of soil nitrogen, moisture, climatic variations, and plant functional traits would further elucidate the mechanisms underlying the measured temporal responses. Extended monitoring would also contribute to the estimates of ecosystem stability and to determining whether short-term shifts in native/non-native composition led to long-term shifts in ecosystem resilience in response to fire.

5. CONCLUSION

Enrichment with nitrogen resulted in clear, although highly time-dependent, shifts in post-fire vegetation communities, especially for species richness, diversity, and native–non-native balance of vegetation. Larger exposures to nitrogen led to lower native species richness and cover and higher abundance of exotic species, and there was a significant interaction between nitrogen and year, indicating that this response varied across recovery stages. Nitrogen treatment also had significant differences in community composition, with the largest differences between the high nitrogen treatment. The response pattern for temporal stability was different. Nitrogen treatment did not significantly change the stability of richness, diversity, or vegetation-cover metrics, although invasion status influenced selected stability outcomes. These results suggest that compositional restructuring can take place without an immediate reduction in ecosystem stability in the short term. Using diversity indices, vegetation composition, invasion status, and temporal stability gives a more comprehensive picture of environmental change due to pollution than does using vegetation cover alone. It is important to monitor this site for a long period of time to see if the compositional post-fire changes continue and whether short-term changes in composition influence ecosystem resiliency.

REFERENCES

1. Ackerman, D., Millet, D. B., & Chen, X. (2019). Global estimates of inorganic nitrogen deposition across four decades. Global Biogeochemical Cycles, 33(1), 100-107.

2. Azpilicueta, L. M. (2021). Plant diversity patterns and soil nitrogen dynamics after controlled burnings applied to restore mountain grasslands and create resilient landscapes (Doctoral dissertation, Universidad Pública de Navarra).
3. Borer, E. T., & Stevens, C. J. (2022). Nitrogen deposition and climate: an integrated synthesis. Trends in Ecology & Evolution, 37(6), 541-552.
4. Broadbent, A. A., Firn, J., McGree, J. M., Borer, E. T., Buckley, Y. M., Harpole, W. S., ... & Stevens, C. J. (2020). Dominant native and non-native graminoids differ in key leaf traits irrespective of nutrient availability. Global Ecology and Biogeography, 29(7), 1126-1138.
5. He, T., Lamont, B. B., & Pausas, J. G. (2019). Fire as a key driver of Earth's biodiversity. Biological Reviews, 94(6), 1983-2010.
6. Huang, F. F., Zhou, G. H., Liao, H. X., Fan, Z. X., & Chen, B. M. (2022). Simulated nitrogen deposition induces shifts in growth and resource-use strategies during range expansion of an invasive plant. Biological Invasions, 24(3), 621-633.
7. Midolo, G., Alkemade, R., Schipper, A. M., Benítez-López, A., Perring, M. P., & De Vries, W. (2019). Impacts of nitrogen addition on plant species richness and abundance: A global meta-analysis. Global ecology and Biogeography, 28(3), 398-413.
8. Nolan, R. H., Collins, L., Leigh, A., Ooi, M. K., Curran, T. J., Fairman, T. A., ... & Bradstock, R. (2021). Limits to post-fire vegetation recovery under climate change. Plant, cell & environment, 44(11), 3471-3489.
9. Payne, R. J., Dise, N. B., Field, C. D., Dore, A. J., Caporn, S. J., & Stevens, C. J. (2017). Nitrogen deposition and plant biodiversity: past, present, and future. Frontiers in Ecology and the Environment, 15(8), 431-436.
10. Rathod, S. V., Saras, P., & Gondaliya, S. M. (2024). Environmental pollution: Threats and challenges for management. In Eco-restoration of polluted environment (pp. 1-34). CRC Press.
11. Ren, G. Q., Zou, C. B., Wan, L. Y., Johnson, J. H., Li, J., Zhu, L., ... & Du, D. L. (2021). Interactive effect of climate warming and nitrogen deposition may shift the dynamics of native and invasive species. Journal of Plant Ecology, 14(1), 84-95.
12. Sapkota, D. P., Edwards, D. P., Massam, M. R., & Evans, K. L. (2025). A Pantropical Analysis of Fire Impacts and Post-Fire Species Recovery of Plant Life Forms. Ecology and Evolution, 15(2), e71018.
13. Seabloom, E. W., Adler, P. B., Alberti, J., Biederman, L., Buckley, Y. M., Cadotte, M. W., ... & Borer, E. T. (2021). Increasing effects of chronic nutrient enrichment on plant diversity loss and ecosystem productivity over time. Ecology, 102(2), e03218.
14. Shan, L., Oduor, A. M., Huang, W., & Liu, Y. (2024). Nutrient enrichment promotes invasion success of alien plants via increased growth and suppression of chemical defenses. Ecological Applications, 34(1), e2791.
15. Soons, M. B., Hefting, M. M., Dorland, E., Lamers, L. P., Versteeg, C., & Bobbink, R. (2017). Nitrogen effects on plant species richness in herbaceous communities are more widespread and stronger than those of phosphorus. Biological Conservation, 212, 390-397.
16. Teixeira, M. C., Bini, L. M., & Thomaz, S. M. (2017). Biotic resistance buffers the effects of nutrient enrichment on the success of a highly invasive aquatic plant. Freshwater Biology, 62(1), 65-71.
17. Ukaogo, P. O., Ewuzie, U., & Onwuka, C. V. (2020). Environmental pollution: causes, effects, and the remedies. In Microorganisms for sustainable environment and health (pp. 419-429). Elsevier.
18. Valliere, J. M., Flores, R. G., Cason, B. J., & Hernández, M. J. (2022). Phenological and physiological advantages of invasive annuals are strengthened by nitrogen enrichment. Functional Ecology, 36(11), 2819-2832.
19. Valliere, J., Irvine, I., & Allen, E. (2023). Data from: Nitrogen deposition suppresses ephemeral post-fire plant diversity [Dataset]. Dryad. https://doi.org/10.5061/DRYAD.ZS7H44JG9
20. Wang, J., Shi, X., Zheng, C., Suter, H., & Huang, Z. (2021). Different responses of soil bacterial and fungal communities to nitrogen deposition in a subtropical forest. Science of the Total Environment, 755, 142449.
21. Wheeler, M. M., Collins, S. L., Grimm, N. B., Cook, E. M., Clark, C., Sponseller, R. A., & Hall, S. J. (2021). Water and nitrogen shape winter annual plant diversity and community composition in near-urban Sonoran Desert preserves. Ecological monographs, 91(3), e01450.
22. Xu, Q., Yang, X., Song, J., Ru, J., Xia, J., Wang, S., ... & Jiang, L. (2022). Nitrogen enrichment alters multiple dimensions of grassland functional stability via changing compositional stability. Ecology Letters, 25(12), 2713-2725.