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Evaluation of 20 Years of Vegetation Change in Big Meadows, Shenandoah National Park

Identification of Best Practices for Future Meadow Management

The western section of Big Meadows, Shenandoah National Park in June 2022.
NPS / WENDY CASS

Evaluation of 20 years of vegetation change in Big Meadows, Shenandoah National Park: Identification of best practices for future meadow management

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Contents

Figures

Tables

Abstract

The Big Meadows landscape is an open habitat that supports unique biodiversity not found elsewhere in Shenandoah National Park. To support this biodiversity and to maintain the Meadow's historic landscape characteristics, Park staff have managed the meadows using prescribed burns, mowing, and the targeted cutting and removal of woody plants since 1998. To assess the impacts of these management actions on the plant community in Big Meadows and to guide future land management recommendations, we visualized changes in the plant community composition between 1998 and 2022 using non-metric multidimensional scaling and used generalized linear mixed-effects regression to model the impacts of climate and land management actions on eight plant community composition variables. Ordination revealed that the plant community across Big Meadows has moved in the direction of undesired increases in *Rubus* and *Celastrus* presence between 2004 and 2022 (*stress* = 0.13, *non-metric* R^2 = 0.98, *linear* R^2 = 0.91), a direction correlated with longer intervals between prescribed burns (R^2 = 0.36, P = 0.01). Our models suggest that changes in the plant community were correlated with both changes in climate and changes in management frequency, providing strong evidence that longer intervals between prescribed burns were associated with undesired increases in woody plant cover (*estimate* ± *SE* = 0.19 ± 0.06, P < 0.001) and decreases in desired forb cover (*estimate* ± *SE* = −0.20 ± 0.04, P < 0.001 and moderate evidence that later spring freezes were associated with increases in desired graminoid cover (*estimate* ± *SE* = 0.11 ± 0.04, P = 0.01) and decreases in undesired *Celastrus* cover (*estimate* ± *SE* = −1.02 ± 0.48 , P = 0.04). Overall, though targeted experimentation will be needed to identify a management interval that balances the costs and effects of changes in management frequencies, our results suggest that increases in the frequency of prescribed burns and other management actions may assist in the maintenance of desired landscape conditions in Big Meadows.

List of Acronyms

AICc: Akaike Information Criterion corrected for small sample size

CI: 95% confidence interval

GLMER: generalized linear mixed-effects regression

LMER: linear mixed-effects regression

NMDS: non-metric multidimensional scaling

Acknowledgments

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Project Motivation

Big Meadows is a 134-acre meadow in Shenandoah National Park that is rich in natural resources and cultural history. Located along the crest of the Blue Ridge Mountains at an elevation of 3,500 ft, the Meadow is the largest open area in the Park. The Big Meadows landscape is predominantly an open meadow, and it contains two globally critically rare Blue Ridge Mafic Fen wetlands (NatureServe Element Code CEGL006249). Though it is only about 0.01% of the park's area, it supports populations of 18% of the park's state and globally rare plant species, a rare snake, a rare insect, and several birds and amphibians that are not found elsewhere in the Park (Ludwig et al. 1993, Fleming and Patterson 2021, NatureServe 2025). The landscape is a popular visitor destination and is the site of one of the park's two visitor centers.

The origins of the open habitat at Big Meadows are unclear as its topography, edaphic conditions, and plant community are distinct from naturally occurring grassy balds elsewhere in the Blue Ridge and Appalachians. Fires, set by both lightning and indigenous peoples, and the deliberate clearing of trees by indigenous inhabitants are likely factors in the Meadow's creation and persistence (Wilhelm 1969, Wilhelm 1972). Big Meadows was a grassy pasture maintained by livestock grazing before the establishment of Shenandoah National Park in 1935, and continuous efforts have been made to preserve the historic open landscape since the Park's founding (Shenandoah National Park 1986). The Meadow was mowed annually in the late fall between 1936 and 1975 when an experiment was implemented to test the effects of prescribed burns on encroaching *Robinia pseudoacacia* (black locust) and *Rubus* (blackberries, raspberries, and brambles) (Christensen 1976, Cocking et al. 1976). After this experiment ended in 1982, an intensive program of mowing, targeted burning, cutting, and herbicide application was initiated to control the spread of *Robina* saplings. After recording a 98% reduction in *Robinia* saplings in 1984, the intensive program was ended and management was minimal until 2000, when burning and mowing treatments were resumed to maintain the open landscape and preserve rare resources. While initially successful, these recent management actions appear to have become less effective over time. Park staff are unsure of how to adjust the mowing and burning regimen to achieve desired landscape conditions.

To assess changes in management effectiveness and make future management recommendations, this project examined changes in vegetation data collected in Big Meadows over the past 20 years. Changes in the overall plant community were visualized using non-metric multidimensional scaling (NMDS) ordination, and the responses of several vegetation community characteristics to changes in management and climate were modeled using generalized linear mixed-effects regression (GLMER). The results of these analyses were interpreted to produce land management recommendations.

The desired landscape conditions of Big Meadows have been defined by the 1985 Management Plan objectives, which aim to preserve the Meadows as an open grassland representative of its historic appearance for visitor use and to encourage natural vegetation diversity (Shenandoah National Park 1986). Additional landscape condition objectives developed since 2000 aim to preserve the presence of rare meadow and wetland plants. Overall, the desired landscape conditions of Big Meadows include:

1. The maintenance or net increase in cover of rare plant species.
2. The maintenance or net increase in cover of native graminoids and forbs.
3. The prevention of net increases in the cover of woody plants.
4. The prevention of net increases in non-native species.
5. The prevention of the establishment of invasive species not previously reported on site.
6. The prevention of net increases in established non-native species such as *Celastrus orbiculatus* (oriental bittersweet).
7. Net decreases in the cover of *Robinia pseudoacacia* (black locust).

Methods

Study Area

Big Meadows is located along Skyline Drive in Shenandoah National Park. From the time of park establishment in 1935 until 1975, the Meadow was regularly mowed. Targeted efforts to control the spread of *Robina* and *Rubus* were conducted between 1975 and 1984, after which management actions were minimal, and the Meadow decreased in size and shrubs such as *Lyonia ligustrina* (maleberry), *Vaccinium pallidum* (early lowbush blueberry), and *Vaccinium stamineum* (deerberry) began to fill in the open habitat. In 2000, plant survey and management activities were implemented in Big Meadows to help restore the open landscape and encourage herbaceous plant cover and diversity. The meadow was divided into three main management zones defined by park infrastructure (Figure 1). The East zone is separated from the Central zone by a walking trail, and the West zone is divided from the Central zone by a road. A fourth zone, the Wetland, is delineated by the boundary of the Blue Ridge Mafic Fen habitat within the Meadow.

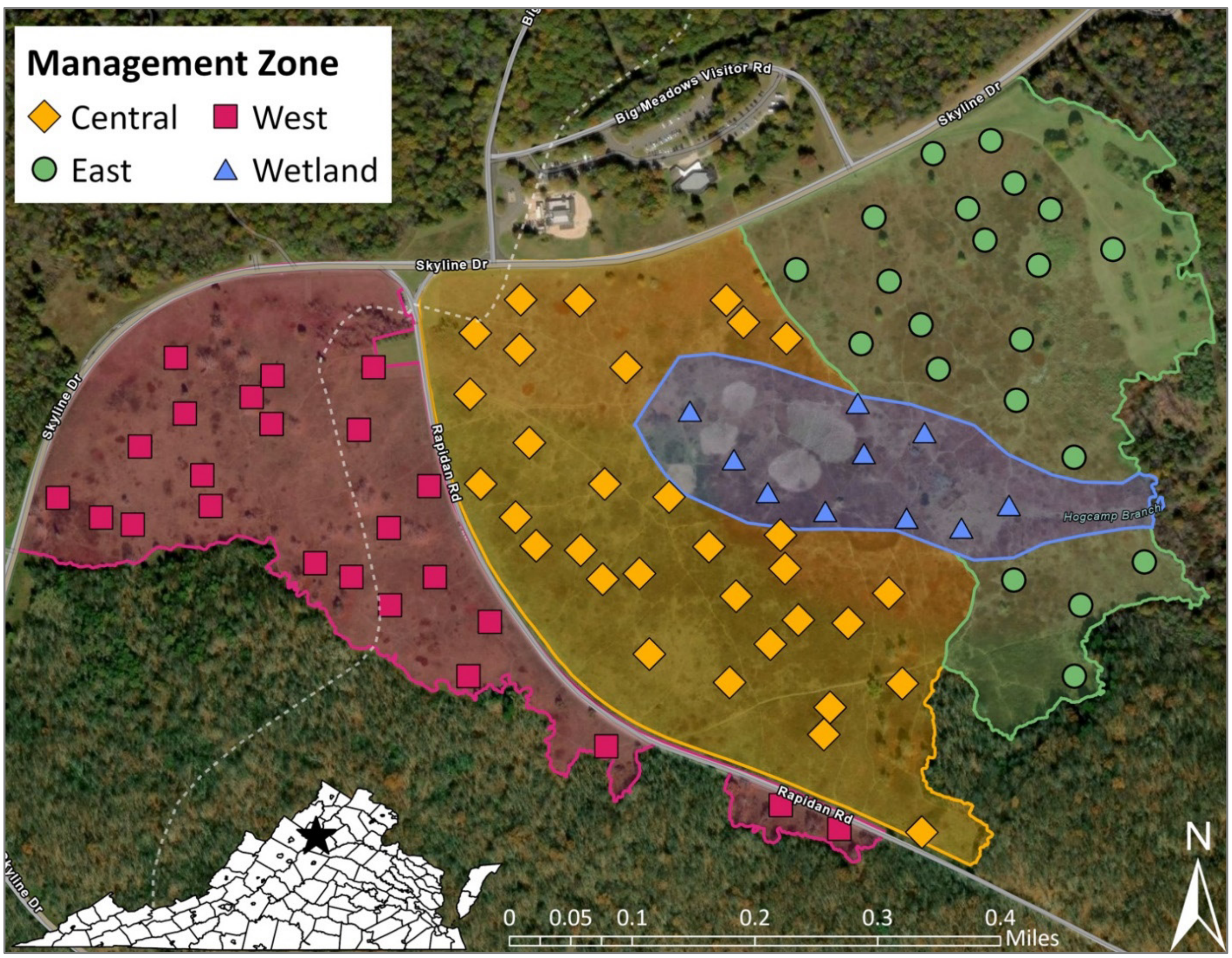

Figure 1. Map of the four management zones and 87 survey transects within Big Meadows, Shenandoah National Park.
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Data Collection and Variable Selection

Survey and Management History

Vegetation composition data have been collected in Big Meadows by The Inventory and Monitoring program at Shenandoah National Park since 1998. Vegetation monitoring in Big Meadows has been conducted along 79 permanent, randomly located 50-meter transects established in 1998 and 1999. Eight additional transects were added in the Western portion of the meadow in 2013, bringing the total number of transects to 87. These 87 transects are distributed across three management zones: the East, Central, and West meadows (Figure 1). Due to differences in management history and a small sample size, the Wetland transects were excluded from analysis.

In 2000, all four zones in Big Meadows were mowed in the dormant season and treated with prescribed burns conducted in the spring. From 2001 to 2003, all four zones were burned each spring. In 2004, the management schedule was revised with the goal of maintaining a three-year burn-mow-fallow cycle in each zone. This cycle was adaptively modified to accommodate "catch-up" management in zones that were unable to be burned or mowed in their scheduled years due to variations in weather, staff availability, or to accommodate special events. Between 2011 and 2019, small areas in the southern Central management zone were treated periodically with targeted *Robinia* cutting and herbicide application to control woody encroachment into the Meadows. Vegetation surveys were conducted annually between late June and early July across all four management zones between 1998 and 2010. In 2011, the vegetation survey schedule was modified to match the three-year management cycle, with vegetation surveys occurring in each zone in the years that they were left fallow.

Response Variables

Beginning in 2000, vegetation data were collected along each transect using point-intercept sampling methods on all herbs and woody vegetation less than 0.5 m in height and line-intercept sampling methods on all woody vegetation between 0.5 and 5 m in height with a diameter of less than 10 cm at breast height (Elzinga et. al. 1998, National Park Service 1998). Point-intercept sampling of low herbs and woody vegetation less than 0.5 m was conducted by recording all taxa found at each of 50 points located at 1 m intervals along each 50 m transect, resulting in a count of the number of times each plant taxon was encountered with a maximum possible value of 50. Line-intercept sampling of high woody vegetation between 0.5 and 5 m was conducted by recording the total length of the transect covered by each taxon, with a maximum possible value of 50 m. Data collected using these two methods were combined by converting the line-intercept lengths from the high vegetation data into a count of 1 m units covered by each taxa, allowing both the low and high vegetation data to be added into a count of the total number of times each plant taxon was encountered at each transect with a maximum possible value of 50 for each taxon. To calculate the percent of forbs, graminoids, and woody plants for each transect, the total number of woody, forb, and graminoid taxa found along each transect was divided by the total number of plants encountered along the transect. Preliminary analyses using only the high woody vegetation data were conducted to determine if separating the low herb and woody vegetation and the high woody vegetation data would aid in the ability to assess the impacts of management on woody plants, however, due to low sample sizes in the high woody vegetation data, only the combined low herb and woody vegetation and high woody vegetation data were used in the final analyses. Plant taxa that were inconsistently identified across survey years were grouped to the genus level, except for rare and exotic species of concern. A full list of taxa used in analysis and their characteristics is presented in the Appendix.

To assess changes in plant community composition in alignment with the desired future conditions of Big Meadows, the total counts of focal plant taxa and sets of plant taxa with selected characteristics encountered along each transect were used as response variables in model construction. The taxa and characteristics selected (e.g., woody plants, non-native plants) were chosen to reflect the desired landscape conditions of Big Meadows (Table 1). Changes in the average values of each response variable for each management zone between 2000 and 2022 are depicted in the Appendix.

Table 1. Response variables describing the structure and composition of vegetation at Big Meadows.

Response Variable	Units	Description
Woody Plants	% of Total Plants in Transect	Native and non-native trees, shrubs, and woody vines
Forbs	% of Total Plants in Transect	Native and non-native ferns and herbs
Graminoids	% of Total Plants in Transect	Native and non-native graminoids
Rare Plants	Count per Transect	Native species of conservation concern
Exotic Plants	Count per Transect	Non-native taxa
Robinia	Count per Transect	*Robinia pseudoacacia*
Rubus	Count per Transect	Native and non-native *Rubus* species
Celastrus	Count per Transect	*Celastrus orbiculatus*

Vegetation data from before the initiation of meadow management are available from surveys conducted in 1998 and 1999, however, these data were excluded from this analysis because they were collected using estimated percent cover of each species within a sampling plot rather than the point-intercept or point-line methods and are therefore not directly comparable with the transect data. Survey data collected in 2004 were also excluded from analysis, as plants were only identified to the genus level in that year while plants were identified to the species level in all other years.

Predictor Variables

The Inventory and Monitoring program at Shenandoah National Park has recorded the timing and type of management action (mowing, burning, and cutting of *Robinia*) taken within each of the three meadow management zones from 2000 through 2023. For analysis, predictor variables measuring the total number of years since the last management action was completed in each management unit were calculated to examine how changes in management schedules between 2000 and 2023 have impacted plant community structure composition (Table 2). The cumulative numbers of buns, mows, and cuttings were also considered as potential fixed effects, but were not modeled as they were strongly correlated with both each other and the year of sampling (see Appendix). Three climate metrics that are suspected to impact the quality of prescribed burns were included as predictor variables in model construction: the Julian date of the last spring freeze, the total amount of spring precipitation (ppt) between late February and early June in the year of each survey, and the total amount of summer precipitation (ppt) between early June and early September in the year before each survey (Table 2). Precipitation data was collected by the Big Meadows Air Quality Monitoring Station and were accessed through the National Atmospheric Deposition Program's National Trends Network Database (National Atmospheric Deposition Program (NRSP-3) 2024). Temperature data used to determine the date of the last spring freeze were accessed through the National Park Service Gaseous Pollutant & Meteorological Data Access (NPS 2024). The distributions of and correlation coefficients between each predictor variable are depicted in the Appendix.

Table 2. Predictor variables used to model changes in vegetation structure and composition over time at Big Meadows.

Predictor Variable	**Description**
Year	The year that the vegetation data were collected
Zone	The management unit in which vegetation data were collected
Transect	The transect along which vegetation data were collected
Spring Precipitation	Total spring precipitation (ppt) at the Big Meadows Meteorological Station
Previous Summer Precipitation	Total summer precipitation (ppt) at the Big Meadows Meteorological Station in the year before plant sampling was conducted
Last Freeze	Julian date of the latest spring freeze at the Big Meadows Meteorological Station
Years Since Burn	Total number of years since the last burn was conducted in the management unit
Years Since Mow	Total number of years since the management unit was last mown
Years Since Cut	Total number of years since *Robinia* was last cut in the management unit

Statistical Analyses

Ordination

To visualize the changes in the vegetation community over time in multidimensional space, a non-metric multidimensional scaling (NMDS) ordination of the total count of each plant taxa found across all three management zones was created using the R package vegan function "metaMDS" (Oksanen et al. 2022) using a Bray-Curtis distance metric and a maximum of 100 random starts. This ordination compresses a high-dimensional space with a separate axis for the number of each plant taxa encountered into a smaller number of dimensions for visualization. To determine the optimal number of dimensions, NMDS ordinations using 1 through 6 axes were conducted and compared in a scree plot, and the best solution was selected to balance low stress values with the ability to be visualized. Plots of the best solution were constructed using the R package plotly, and the response variables were projected as gradients onto these plots using the R package vegan function "envfit" using 100 permutations (Oksanen et al. 2022, Sievert 2020). The resulting plot depicts the location of the average plant community composition in each management zone as points, with changes in plant community composition over time depicted as the movement of points across the ordination space. While these movements are determined by changes in plant community composition alone, the movement of points in the direction of a response variable arrow indicates that the changes in community composition were correlated with an increase in the response variable.

Model Construction and Selection

Generalized linear mixed-effects regression (GLMER) was conducted using a two-step additive process. This additive process began with a simple model with no effects and iteratively added random and fixed effects to determine the most parsimonious model, or the model that achieves the highest explanatory power and the best fit to the data using the fewest effects. The predictor variables year of data collection, management zone, and sampling transect were modeled as random effects, or qualitative variables that represent only a random selection of all possible values. Sampling year was included as a random effect rather than a fixed effect because sampling was not conducted across all plots each year, and because we were interested in modeling the effects of inter-annual variability rather than the specific conditions of any given sampling year. The remaining predictor variables were modeled as fixed effects, or variables whose values are expected to predict changes in the response variable. The fixed effect predictor variables were divided into two groups for use in the model selection process: the climate variables spring precipitation, previous summer precipitation, and date of last freeze and the management variables years since last burn, years since last mow, and years since cut. The variable years since last cut was only incorporated into models of *Robinia* cover, as only *Robinia* species were targeted for removal during cutting treatments. To improve model convergence, the climate variables were re-scaled by dividing all values by 10. Therefore, when interpreting model coefficients, a one-unit increase in the precipitation represents a 10 ppt increase in rainfall and a one-unit increase in the Julian date of the last freeze represents a ten-day difference in the Julian date.

GLMER was conducted separately for each response variable listed in Table 2. All models were run in R using the package glmmTMB function "glmmTMB" (Brooks et al. 2017). Models of the percent of each transect covered by woody plants, graminoids, and forbs used an ordered beta family function, while models of rare plants, exotic plants, *Robinia*, *Rubus*, and *Celastrus* counts used a Poisson family function. At the end of each step, the model with the best fit was selected for use in the next step using the R package performance function "compare_performance", which computes a performance score for each model using multiple indices of model performance (Lüdecke et al. 2021). The three steps of the model selection process were:

1. Determine Random Effect Structure: Compared models with no fixed effects and four possible random effect structures based on the data sampling method: 1) intercept only, 2) year only, 3) both year and transect, and 4) both year and transect nested within zone.
2. Determine Fixed Effect Structure:
    a. Select Climate Variables: Compared models with twelve possible climate variable fixed effect structures: 1) no fixed effects, 2) spring precipitation only, 3) previous summer precipitation only, 4) last freeze only, 5) both spring precipitation and previous summer precipitation, 6) the interaction between spring precipitation and previous summer precipitation, 7) spring precipitation and last freeze, 8) the interaction between spring precipitation and last freeze, 9) previous summer

precipitation and last freeze, 10) the interaction between previous precipitation and last freeze, 11) spring precipitation, previous summer precipitation, and last freeze, and 12) the interaction between spring precipitation, previous summer precipitation, and last freeze.

b. Select Management Variables: Compared models with five possible management variable fixed effect structures: 1) no fixed effects, 2) years since burn only, 3) years since mow only, 4) both years since burn and years since mow, and 5) the interaction between years since burn and years since mow. In the models of *Robinia* only, the management variable years since cut and all its possible combinations and interactions with the other two management variables were added, resulting in a total of 12 possible fixed effect structures.

c. Select Final Fixed Effect Structure: Compared models with five possible fixed effect structures: 1) no fixed effects, 2) best climate variable or climate variable interaction only, 3) best management variable or management variable interaction only, 4) both the best climate variable or variable interaction and the best management variable or management interaction, and 5) the interaction between the best climate and management variables or variable interactions.

Once the overall best model for each response variable was selected at the end of step 2, standardized parameters were obtained using a standardized version of the dataset, and 95% confidence intervals (*CI*) and *P*-values were calculated using a Wald z-distribution approximation using the R package performance function "report" (Lüdecke et al. 2021). Model coefficients were visualized using the R package parameters function "parameters" (Lüdecke et al. 2020). Model performance was assessed using diagnostic tests (i.e., distribution of scaled residuals, dispersion, outliers, uniformity of direction of simulated residuals versus predictors) within the R package DHARMa function "simulateResiduals" (Hartig 2022).

Results

Ordination

The selected NMDS solution was built on two axes to balance stress and the ability to be visualized (*stress* = 0.13, *non-metric* R^2 = 0.98, *linear* R^2 = 0.91; Figure 2). Of the five predictor variables fit to this ordination, the only variable with strong statistical support was years since burn (R^2 = 0.36, P = 0.01), while last freeze (R^2 = 0.14, P = 0.14), previous summer precipitation (R^2 = 0.05, P = 0.50), spring precipitation (R^2=0.04, P = 0.60), and years since mow (R^2 = 0.04, P = 0.63) had poor fit to the ordination. As illustrated in Figure 2, the ordination indicates that the overall vegetation communities in all three management zones moved roughly in the direction correlated with an increase in time between prescribed burns and increases in *Rubus* and *Celastrus* presence between 2005 and 2022. The timing of this change in plant community composition mirrors the transition from annual prescribed burns to a three-year burn rotation implemented in 2004.

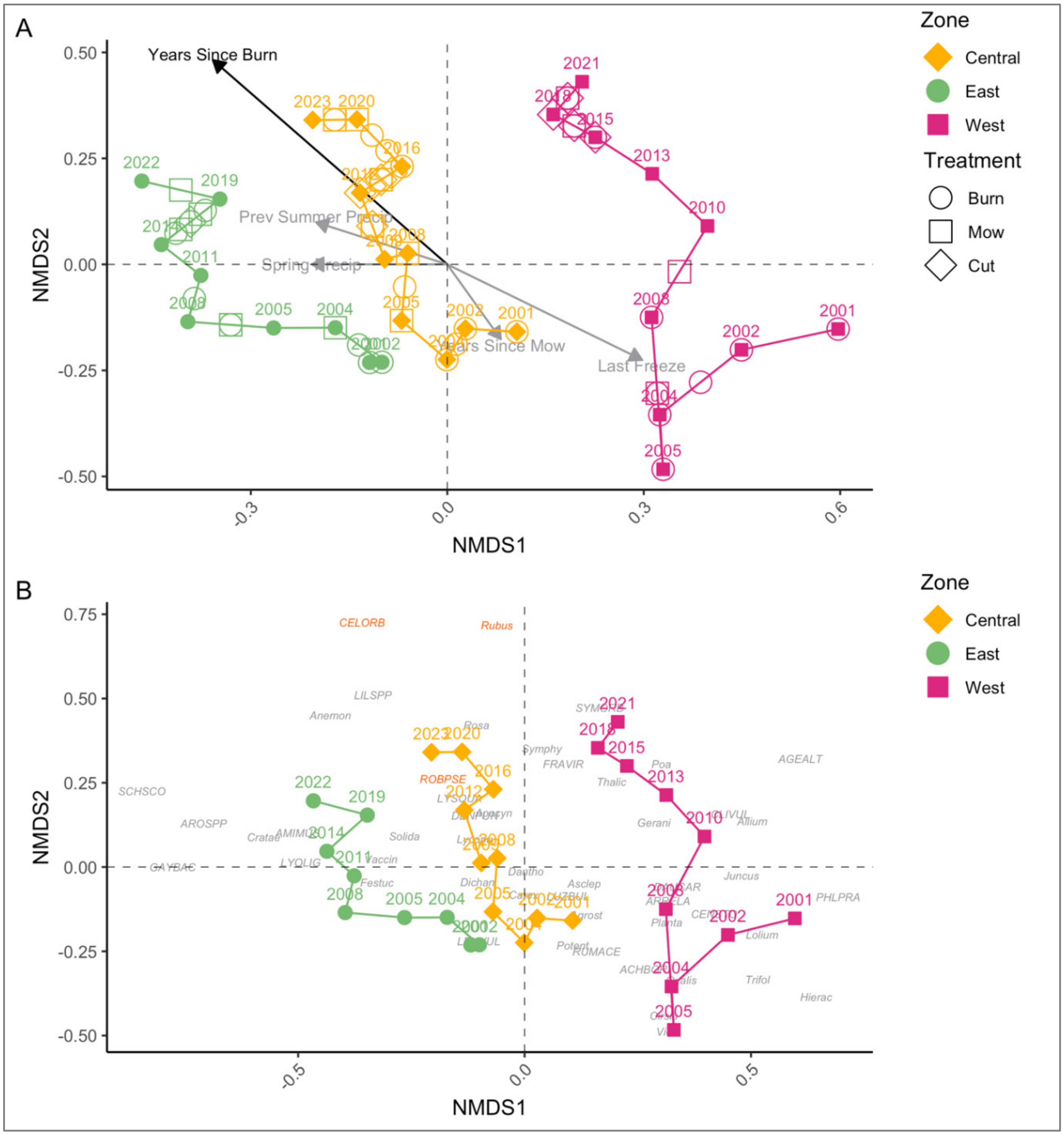

Figure 2. Scatterplot of the NMDS ordination of the vegetation communities in each of the three Big Meadows management zones from 2001 to 2022 in two dimensions (*stress* = 0.13, *non-metric* R^2 = 0.98, *linear* R^2 = 0.91). Solid-colored symbols indicate the average community composition each year, while the lines between each point indicate movement in multidimensional space over time. A) Hollow symbols indicate the timing of land management treatments in each zone. Overlaid arrows depict the directions correlated with an increase in each response variable gradient, with statistically significant variables illustrated in black and all other variables illustrated in grey. The lengths of the arrows are scaled by the strength of their correlation to the ordination plot. B) Six-letter taxa codes indicate the locations of the 50 most abundant plant taxa in the ordination space. Taxa codes highlighted in orange text are taxa chosen as response variables: CELORB for *Celastrus orbiculatus*, *Rubus* for *Rubus* species, and ROBPSE for *Robinia pseudoacacia*). A full list of taxa codes and their corresponding characteristics is presented in Table 4 in the Appendix.

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Response Variable Models

The overall structure, fit, and explanatory power of the best models for each of the response variables are summarized in Table 3. Simulated residual diagnostic plots for each response variable model are depicted in the Appendix. We were unable to select a suitable final model for two variables, the number of rare plants and the number of *Rubus*, as the “best” models identified at the end of our model selection process did not contain any fixed effects, likely due to the high number of zeros in the rare plant data and the lack of intermediate values in the *Rubus* data. The fixed effect coefficients and 95% confidence intervals are illustrated for the remaining six response variables in Figure 3.

Management variables were found in all six of the models that contained fixed effects. The number of years since the last prescribed burn was the most prevalent fixed effect, with a presence in five models (for woody plants, forbs, graminoids, exotic plants, and *Celastrus*) and very strong statistical evidence in two models. There was strong evidence that the number of years since the last burn had a positive effect on woody plant cover and a negative effect on forb cover, and a non-significant negative effect on graminoid cover and a non-significant positive effect on exotic plants and *Celastrus*. The number of years since the last mow was found in four models (forbs, graminoids, exotic plants, and *Robinia*), and it only had moderate statistical evidence in one model. There was moderate evidence that the number of years since the last mow had a negative effect on forb cover, and non-significant positive effects on graminoid cover, exotic plants, and *Robinia*. The best model for *Robinia* did include the number of years since the last cut, which had a non-significant negative effect alone but moderate evidence for a positive interaction with the number of years since the last mow.

Climate variables were only found in the models for graminoid cover, exotic plants, and *Celastrus*. There was strong evidence that later Julian dates for the last spring freeze had a positive effect on graminoid cover, and moderate evidence that later last freezes had a negative effect on *Celastrus*. The precipitation of the previous summer was only found in the model of exotic plants, where it was found to have a non-significant positive effect alone and non-significant interactions with burning and mowing. Spring precipitation was not found as a fixed effect in any of the selected models.

Table 3. Model structure, explanatory power, and fixed effect coefficients ± standard error for each response variable. Fixed effect coefficients supported by moderate evidence (*P* < 0.05) are indicated by single asterisks, strong evidence (*P* < 0.01) with double asterisks, and very strong evidence (*P* < 0.001) by triple asterisks.

	Ordinal Beta			**Poisson**				
Model Family	**Woody Plants**	**Forbs**	**Graminoids**	**Rare Plants**	**Exotic Plants**	***Robinia***	***Rubus***	***Celastrus***
Conditional R^2	0.93	0.88	0.78	0.42	0.87	0.87	0.97	0.95
Marginal R^2	0.08	0.15	0.13	0.00	0.02	0.4	0.00	0.20
Random Effects	Year + Zone/Transect	Year + Zone/Transect	Year + Transect	Year + Transect	Year + Zone/Transect	Year + Transect	Year + Transect	Year + Transect
Fixed Effects	Years Since Burn	Years Since Burn × Years Since Mow	Last Freeze + Years Since Burn + Years Since Mow	–	Previous Summer Precipitation × Years Since Burn × Years Since Mow	Years Since Mow × Years Since Cut	–	Last Freeze + Years Since Burn
Intercept	−1.30 ± 0.34**	−0.27 ± 0.18	−2.00 ± 0.52***	−3.90 ± 0.43***	2.06 ± 0.98*	−0.77 ± 0.23**	1.07 ± 0.33**	7.36 ± 5.8
Last Freeze	–	–	0.12 ± 0.04**	–	–	–	–	−1.02 ± 0.45*
Previous Summer Precipitation	–	–	–	–	0.19 ± 0.26	–	–	–
Years Since Burn	0.19 ± 0.06***	−0.20 ± 0.04***	−0.04 ± 0.03	–	0.32 ± 0.46	–	–	0.51 ± 0.31
Years Since Mow	–	−0.05 ± 0.02*	0.03 ± 0.01	–	0.26 ± 0.46	0.01 ± 0.07	–	–
Years Since Cut	–	–	–	–	–	−0.12 ± 0.07	–	–
Years Since Burn × Years Since Mow	–	0.02 ± 0.01*	–	–	−0.08 ± 0.09	–	–	–
Years Since Mow × Years Since Cut	–	–	–	–	–	0.19 ± 0.07**	–	–
Previous Summer Precipitation × Years Since Burn	–	–	–	–	−0.07 ± 0.13	–	–	–
Previous Summer Precipitation × Years Since Mow	–	–	–	–	−0.06 ± 0.04	–	–	–
Previous Summer Precipitation × Years Since Burn × Years Since Mow	–	–	–	–	0.02 ± 0.02	–	–	–

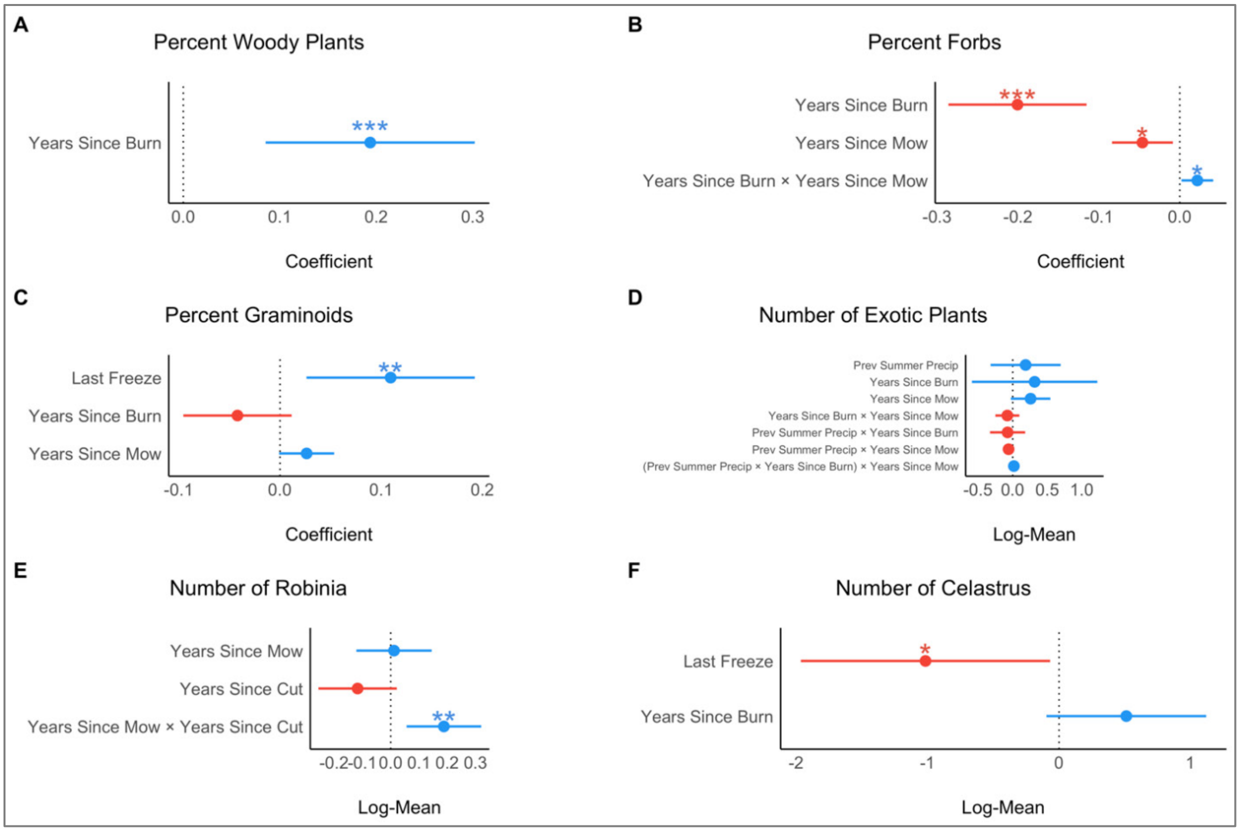

Figure 3. Effects plots summarizing the coefficients for all fixed effects and interaction terms included in the selected models for each response variable. Points indicate coefficient values and bars indicate 95% confidence intervals. Fixed effects supported by moderate evidence ($P < 0.05$) are indicated by single asterisks, strong evidence ($P < 0.01$) with double asterisks, and very strong evidence ($P < 0.001$) by triple asterisks. The selected models for the numbers of rare plants and *Rubus* are not included, as they did not contain any fixed effects.

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Discussion

Model Interpretation and Limitations

Model structure and fit varied across all eight response variables, with some models providing strong evidence for the impact of climate and/or management on the plant community in Big Meadows and others providing weak evidence for the impact of any predictor variable and/or displaying poor fit. Data distributions and variance, as well as the choice of model link function and the specification of model structures, can have large effects on model results. Therefore, a lack of model evidence for the impacts of selected management actions does not necessarily indicate that management has no effects, as model results must be interpreted within the context of model fit. For example, there was evidence for patterns in the simulated residuals when plotted against the expected values in the models of forbs, graminoids and exotic plants that may indicate that important variables are missing from these models or that some fixed effects may have non-linear relationships with the response variables (Hartig 2022). In addition, all models contained variance that was not explained by either climate or management, providing further support that variables with important effects on plant community composition are not included in our models. While this study was limited to climate and management variables, other factors such as changes in deer and rabbit herbivory, fluctuations in the water table, or changes in levels of human use at Big Meadows may also have important impacts on the plant community and should be explored in future analyses. Response variables such as rare and exotic plant numbers may also be influenced by the idiosyncratic responses of individual rare and exotic taxa to different management actions, and more targeted monitoring protocols and analyses may improve the ability to model changes in these taxa.

Recommendations for Future Management

Our models provide evidence that both climate change and management actions were impacting plant community composition across Big Meadows. There was moderate to strong evidence that later springs (as indicated by increases in the Julian date of the last freeze) were correlated with increases in graminoids and decreases in *Celastrus*. As climate change is expected to bring milder winters with fewer frost days to Shenandoah National Park (Shenandoah National Park 2024), these models suggest that graminoid cover may decrease while *Celastrus* numbers increase, directly counteracting the desired conditions in Big Meadows.

Fortunately, these negative climate-mediated effects may potentially be counteracted by the positive effects of increased management frequencies on other desired conditions. More frequent burns may prevent the unwanted increases in woody plant cover and decreases in forb cover correlated with longer intervals between prescribed burns. Likewise, more frequent mowing may prevent the unwanted decreases in forb cover associated with longer mowing intervals. The positive interactions between the number of years between burning and mowing on forb cover and between mowing and cutting on *Robinia* cover suggest that the negative impacts of longer mowing intervals are strengthened when other management intervals are longer, providing further evidence for the need for more frequent management overall.

While experimentation is needed to determine a management schedule that balances costs and effects of each management action, our models indicate that overall increases in management frequency, especially in prescribed burns, can assist in maintaining the desired landscape conditions in Big Meadows. In addition to these increases in management frequency, targeted management of *Rubus* and *Celastrus* may be considered, however, extreme care will need to be taken to distinguish the state-listed *Rubus setosus* from similar non-threatened *Rubus* species to avoid damage to the rare species' population. Finally, we recommend changing the annual plant survey methods to sample a subset of transects in each of the four management zones each year rather than sampling each zone separately in a multi-year rotation. This will allow for more detailed assessment of the year-to-year impacts of management across the entire Big Meadows landscape.

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Appendix

Table 4 and Figures 4–6 include the plant taxa list, response variable plots, predictor variable correlations, and model diagnostic plots supporting the analysis of vegetation changes in response to land management in Big Meadows, Shenandoah National Park. Species with a status of "N" are native to Virginia, while species with a status of "Ex" are exotic and not native to Virginia. Global and state ranks follow those assigned by the Virginia Department of Conservation and Recreation, with ranks G1 through G3 denoting globally rare species and ranks S1 through S2 denoting species that are rare in the state of Virginia (https://www.dcr.virginia.gov/natural-heritage/infoservices#lists).

Table 4. Plant taxa and taxa groupings used in the analysis of vegetation at Big Meadows.

Code	Scientific Name	Lifeform	Status	Global Rank	State Rank
ACERUB	*Acer rubrum*	Tree	N	G5	S5
ACHBOR	*Achillea borealis*	Herb	N	G5	S5
ACTRAC	*Actaea racemosa*	Herb	N	G4	S4
Actaea	*Actaea* sp.	Herb	–	–	–
AGEALT	*Ageratina altissima*	Herb	N	G5	S5
Agrost	*Agrostis* sp.	Herb	–	–	–
Allium	*Allium* sp.	Herb	–	–	–
Ambros	*Ambrosia* sp.	Herb	–	–	–
AMIMUS	*Amianthium muscitoxicum*	Herb	N	G4G5	S5
AMPBRA	*Amphicarpaea bracteata*	Vine	N	G5	S5
ANDGER	*Andropogon gerardii*	Graminoid	N	G5	S5
ANDVIR	*Andropogon virginicus*	Graminoid	N	G5	S5
Anemon	*Anemone* sp.	Herb	–	–	–
Antenn	*Antennaria* sp.	Herb	–	–	–
ANTODO	*Anthoxanthum odoratum*	Graminoid	Ex	GNR	SNA
Apocyn	*Apocynum* sp.	Herb	–	–	–
AQUCAN	*Aquilegia canadensis*	Herb	N	G5	S5
ARNATR	*Arnoglossum atriplicifolium*	Herb	N	G4G5	S4S5
AROMEL	*Aronia melanocarpa*	Shrub	N	G5	S5
AROSPP	*Aronia* sp.	Shrub	–	–	–
ARRELA	*Arrhenatherum elatius*	Graminoid	Ex	GNR	SNA
Asclep	*Asclepias* sp.	Herb	–	–	–
ASPPLA	*Asplenium platyneuron*	Fern	N	G5	S5
Aster	*Aster* sp.	Herb	–	–	–
ATHFIL	*Athyrium filix-femina*	Fern	N	–	–
AVEFLE	*Avenella flexuosa*	Graminoid	N	G5T5?	S5
BAPTIN	*Baptisia tinctoria*	Herb	N	G5	S5

Table 4 (continued). Plant taxa and taxa groupings used in the analysis of vegetation at Big Meadows.

Code	Scientific Name	Lifeform	Status	Global Rank	State Rank
BARVUL	*Barbarea vulgaris*	Herb	Ex	GNR	SNA
Betula	*Betula* sp.	Tree	–	–	–
BOTVIR	*Botrypus virginianus*	Fern	N	G5	S5
BROINE	*Bromus inermis*	Graminoid	Ex	G5	SNA
CALCAN	*Calamagrostis canadensis*	Graminoid	N	G5	S4
Calyst	*Calystegia* sp.	Herb	–	–	–
Carduu	*Carduus* sp.	Herb	–	–	–
CARBUX	*Carex buxbaumii*	Graminoid	N	G5	S2
CARCON	*Carex conoidea*	Graminoid	N	G5	S1S2
Carex	*Carex* sp.	Graminoid	–	–	–
Carya	*Carya* sp.	Tree	–	–	–
CELORB	*Celastrus orbiculatus*	Vine	Ex	GNR	SNA
CENSTO	*Centaurea stoebe* ssp. *micranthos*	Herb	Ex	GNR	SNA
Cerast	*Cerastium* sp.	Herb	–	–	–
CHALUT	*Chamaelirium luteum*	Herb	N	G5	S5
Cirsiu	*Cirsium* sp.	Herb	–	–	–
CLACLA	*Claytosmunda claytoniana*	Fern	N	G5	S5
CLEVIR	*Clematis virginiana*	Vine	N	G5	S5
CLIVUL	*Clinopodium vulgare*	Herb	N	G5	S5
COMPER	*Comptonia peregrina*	Shrub	N	G5	S5
CONARV	*Convolvulus arvensis*	Vine	Ex	GNR	SNA
CORRAC	*Cornus racemosa*	Shrub	N	G5	S5
Corylu	*Corylus* sp.	Shrub	–	–	–
Cratae	*Crataegus* sp.	Tree	–	–	–
CYNOFF	*Cynoglossum officinale*	Herb	Ex	GNR	SNA
DACGLO	*Dactylis glomerata*	Graminoid	Ex	GNR	SNA
Dantho	*Danthonia* spp.	Graminoid	–	–	–
DAUCAR	*Daucus carota*	Herb	Ex	GNR	SNA
DENPUN	*Dennstaedtia punctilobula*	Fern	N	G5	S5
DIAARM	*Dianthus armeria*	Herb	Ex	GNR	SNA
Dichan	*Dichanthelium* sp.	Graminoid	–	–	–
DIOSPP	*Dioscorea* sp.	Vine	–	–	–
DOEUMB	*Doellingeria umbellata*	Herb	N	G5	S5
Eleoch	*Eleocharis* sp.	Graminoid	–	–	–
ELETEN	*Eleocharis tenuis*	Graminoid	N	G5	S5

Table 4 (continued). Plant taxa and taxa groupings used in the analysis of vegetation at Big Meadows.

Code	Scientific Name	Lifeform	Status	Global Rank	State Rank
ELYREP	*Elymus repens*	Graminoid	Ex	GNR	SNA
Epilob	*Epilobium* sp.	Herb	–	–	–
Eriger	*Erigeron* sp.	Herb	–	–	–
EURRAD	*Eurybia radula*	Herb	N	G5	S1
Eurybi	*Eurybia* sp.	Herb	–	–	–
EUTGRA	*Euthamia graminifolia*	Herb	N	G5	S5
Fallop	*Fallopia* sp.	Herb	–	–	–
Festuc	*Festuca* sp.	Graminoid	–	–	–
FRAVIR	*Fragaria virginiana*	Herb	N	G5	S5
FRAAME	*Fraxinus americana*	Tree	N	G5	S5
Galium	*Galium* sp.	Herb	–	–	–
GAYBAC	*Gaylussacia baccata*	Shrub	N	G5	S5
Gerani	*Geranium* sp.	Herb	–	–	–
GEUSPP	*Geum* sp.	Herb	–	–	–
GLEHED	*Glechoma hederacea*	Herb	Ex	GNR	SNA
GLYSTR	*Glyceria striata*	Graminoid	N	G5	S5
Gnapha	*Gnaphalium* sp.	Herb	–	–	–
GNAULI	*Gnaphalium uliginosum*	Herb	N	G5	S1
Helian	*Helianthus* sp.	Herb	–	–	–
HELHEL	*Heliopsis helianthoides*	Herb	N	G5	SNA
Hierac	*Hieracium* sp.	Herb	–	–	–
Housto	*Houstonia* sp.	Herb	–	–	–
Hyperi	*Hypericum* sp.	Herb	–	–	–
HYPHIR	*Hypoxis hirsuta*	Herb	N	G5	S5
Ilex	*Ilex* sp.	Shrub	–	–	–
IPOPAN	*Ipomoea pandurata*	Vine	N	G5	S5
Juncus	*Juncus* sp.	Graminoid	–	–	–
Lactuc	*Lactuca* sp.	Herb	–	–	–
LEEORY	*Leersia oryzoides*	Graminoid	N	G5	S5
LEUVUL	*Leucanthemum vulgare*	Herb	Ex	GNR	SNA
LILSPP	*Lilium* sp.	Herb	–	–	–
LINVUL	*Linaria vulgaris*	Herb	Ex	GNR	SNA
LOLPER	*Lolium perenne*	Graminoid	Ex	GNR	SNA
LOLPRA	*Lolium pratense*	Graminoid	Ex	GNR	SNA
LUZBUL	*Luzula bulbosa*	Graminoid	N	G5	S5
Lycopu	*Lycopus* sp.	Herb	–	–	–

Table 4 (continued). Plant taxa and taxa groupings used in the analysis of vegetation at Big Meadows.

Code	Scientific Name	Lifeform	Status	Global Rank	State Rank
LYOLIG	*Lyonia ligustrina*	Shrub	N	G5	S5
LYSQUA	*Lysimachia quadrifolia*	Herb	N	G5	S5
MAIRAC	*Maianthemum racemosum*	Herb	N	G5	S5
MEDLUP	*Medicago lupulina*	Herb	Ex	GNR	SNA
Melant	*Melanthium* sp.	Herb	–	–	–
MELALB	*Melilotus albus*	Herb	Ex	GNR	SNA
MICVIM	*Microstegium vimineum*	Graminoid	Ex	GNR	SNA
MONFIS	*Monarda fistulosa*	Herb	N	G5T5	S5
MUHGLO	*Muhlenbergia glomerata*	Graminoid	N	G5	S2
Muhlen	*Muhlenbergia* sp.	Graminoid	–	–	–
ONOSEN	*Onoclea sensibilis*	Fern	N	G5	S5
OPHVUL	*Ophioglossum vulgatum*	Fern	N	–	–
OSMCLA	*Osmorhiza claytonii*	Herb	N	G5	S5
OSMCIN	*Osmundastrum cinnamomeum*	Fern	N	G5	S5
Oxalis	*Oxalis* sp.	Herb	–	–	–
OXYRIG	*Oxypolis rigidior*	Herb	N	G5	S5
PACAUR	*Packera aurea*	Herb	N	G5	S5
PARQUI	*Parthenocissus quinquefolia*	Vine	N	G5	S5
PEDCAN	*Pedicularis canadensis*	Herb	N	G5	S5
PHLPRA	*Phleum pratense*	Graminoid	Ex	GNR	SNA
PHYHET	*Physalis heterophylla*	Herb	N	G5	S5
Picea	*Picea* sp.	Tree	–	–	–
Pinus	*Pinus* sp.	Tree	–	–	–
Planta	*Plantago* sp.	Herb	–	–	–
POACOM	*Poa compressa*	Graminoid	Ex	GNR	SNA
POAPRA	*Poa pratensis*	Graminoid	Ex	G5	SNA
Poa	*Poa* sp.	Graminoid	–	–	–
POLCAE	*Polygonum caespitosum*	Herb	N	–	–
Polygo	*Polygonum* sp.	Herb	–	–	–
PORTRI	*Porteranthus trifoliatus*	Herb	N	–	–
Potent	*Potentilla* sp.	Herb	–	–	–
Prenan	*Prenanthes* sp.	Herb	–	–	–
PRUVUL	*Prunella vulgaris*	Herb	Ex	G5	S5
Prunus	*Prunus* sp.	Tree	–	–	–
PTEAQU	*Pteridium aquilinum*	Fern	N	G5	S5
PYCINC	*Pycnanthemum incanum*	Herb	N	G5	S5

Table 4 (continued). Plant taxa and taxa groupings used in the analysis of vegetation at Big Meadows.

Code	Scientific Name	Lifeform	Status	Global Rank	State Rank
Quercu	*Quercus* sp.	Tree	–	–	–
Ranunc	*Ranunculus* sp.	Herb	–	–	–
RHOSPP	*Rhododendron* sp.	Shrub	–	–	–
Rhus	*Rhus* sp.	Shrub	–	–	–
RIBROT	*Ribes rotundifolium*	Shrub	N	G5	S5
ROBPSE	*Robinia pseudoacacia*	Tree	N	G5	S5
Rosa	*Rosa* sp.	Shrub	–	–	–
Rubus	*Rubus* sp.	Shrub	–	–	–
RUDHIR	*Rudbeckia hirta*	Herb	N	G5	S5
RUDLAC	*Rudbeckia laciniata*	Herb	N	G5	S5
RUMACE	*Rumex acetosella*	Herb	Ex	GNR	SNA
SAGCAN	*Sanguisorba canadensis*	Herb	N	G5	S2
SANCAN	*Sanicula canadensis*	Herb	N	G5	S5
SASALB	*Sassafras albidum*	Tree	N	G5	S5
SCEMUL	*Sceptridium multifidum*	Fern	N	G5	S1
Sceptr	*Sceptridium* sp.	Fern	N	–	–
SCHARU	*Schedonorus arundinaceus*	Graminoid	Ex	–	–
SCHSCO	*Schizachyrium scoparium*	Graminoid	N	G5	SNR
SCRLAN	*Scrophularia lanceolata*	Herb	N	G5	S5
SILCAR	*Silene caroliniana*	Herb	N	G5	S5
SILSTE	*Silene stellata*	Herb	N	G5	S5
SISANG	*Sisyrinchium angustifolium*	Herb	N	G5	S5
Smilax	*Smilax* sp.	Vine	N	G5	S5
SOLCAR	*Solanum carolinense*	Herb	N	G5	S5
Solida	*Solidago* sp.	Herb	–	–	–
SPIALB	*Spiraea alba*	Shrub	N	G5	S4
Spiran	*Spiranthes* sp.	Herb	–	–	–
STECIL	*Steironema ciliatum*	Herb	N	G5	S5
Stella	*Stellaria* sp.	Herb	–	–	–
SYMORB	*Symphoricarpos orbiculatus*	Shrub	U	G5	S5
Symphy	*Symphyotrichum* sp.	Herb	–	–	–
TAROFF	*Taraxacum officinale*	Herb	Ex	G5	SNA
Thalic	*Thalictrum* sp.	Herb	–	–	–
THATHA	*Thalictrum thalictroides*	Herb	N	G5	S5
THENOV	*Thelypteris noveboracensis*	Fern	N	–	–
Tragop	*Tragopogon* sp.	Herb	–	–	–

Table 4 (continued). Plant taxa and taxa groupings used in the analysis of vegetation at Big Meadows.

Code	Scientific Name	Lifeform	Status	Global Rank	State Rank
TRACAR	*Trautvetteria caroliniensis*	Herb	N	G5	S5
Trifol	*Trifolium* sp.	Herb	–	–	–
Uvular	*Uvularia* sp.	Herb	–	–	–
Vaccin	*Vaccinium* sp.	Shrub	–	–	–
VERTHA	*Verbascum thapsus*	Herb	Ex	GNR	SNA
VEROFF	*Veronica officinalis*	Herb	Ex	G5	S5
VIBPRU	*Viburnum prunifolium*	Shrub	N	G5	S5
Viola	*Viola* sp.	Herb	–	–	–
ZIGELE	*Zigadenus elegans* ssp. *glaucus*	Herb	N	–	–
ZIZAPT	*Zizia aptera*	Herb	N	G5	S5

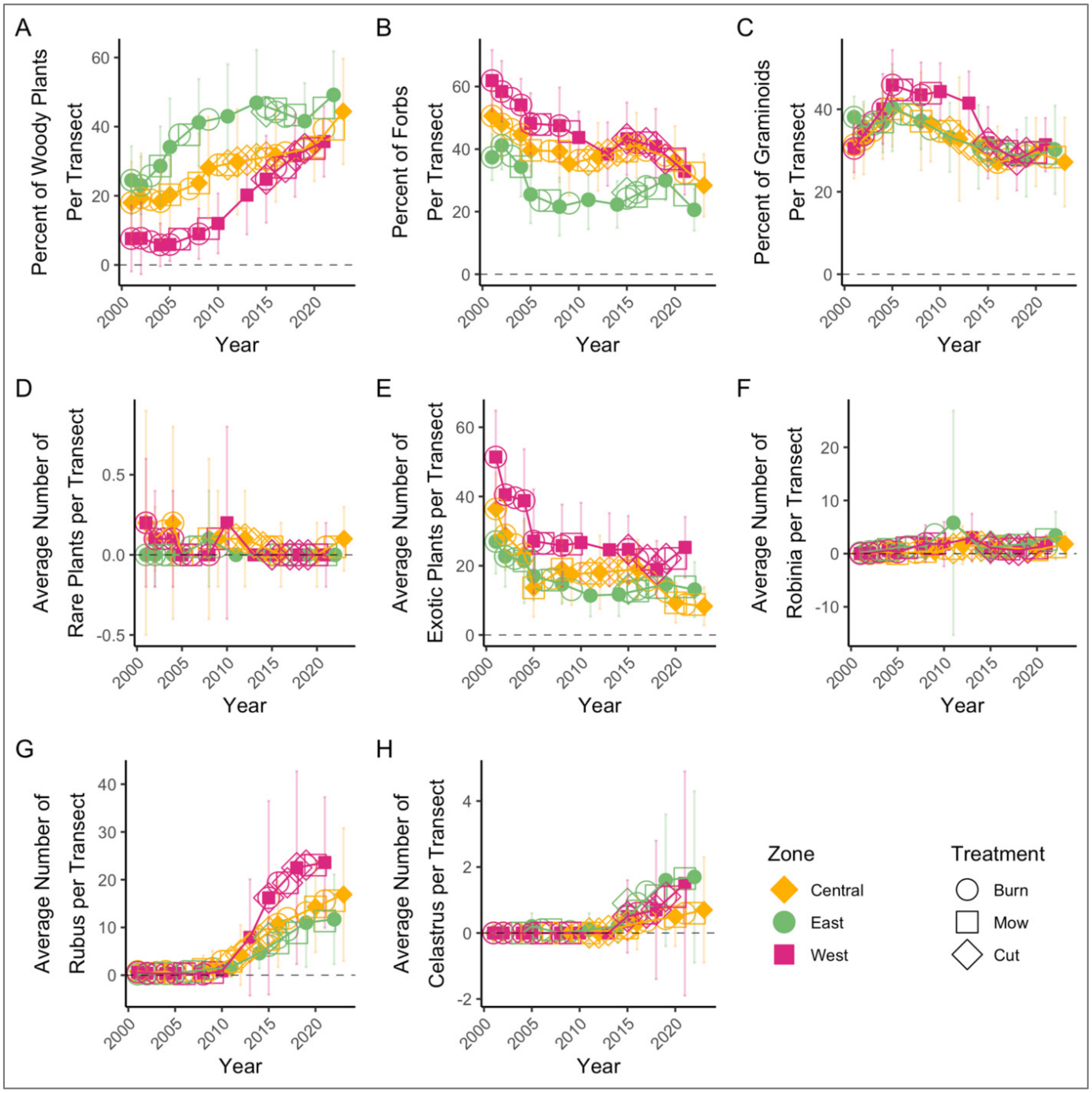

Figure 4. Change in each response variable across the three Big Meadows management zones between 2000 and 2023. Solid-colored symbols indicate the average community composition each year, which are surrounded by bars indicating the standard deviation from the mean. Hollow symbols indicate the timing of land management treatments in each zone.

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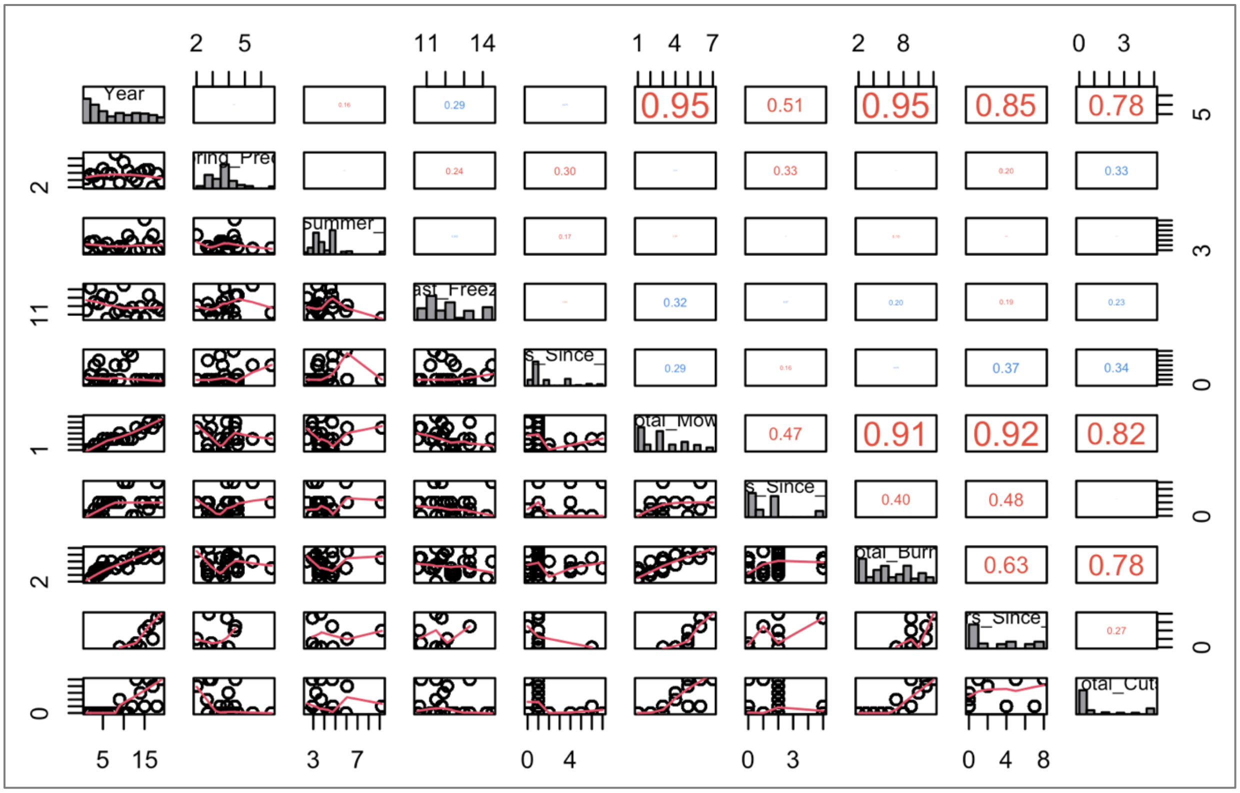

Figure 5. Scatter plots (lower left), distributions (central diagonal), and correlation coefficients (upper right) between each pair of predictor variables.

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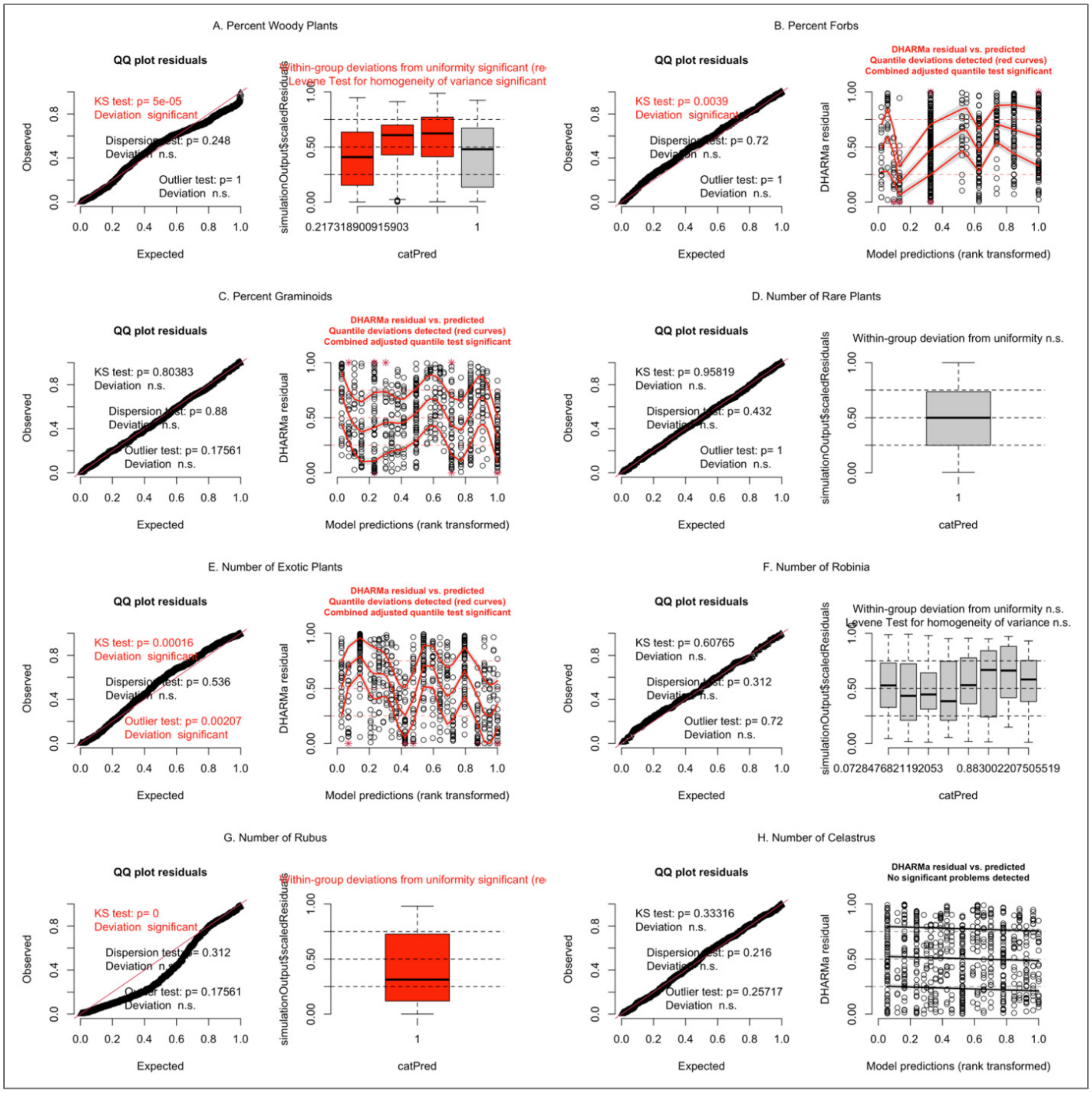

Figure 6. Simulated residual QQ plots (left in each pair) and simulated residuals vs predicted values plots (right in each pair) for each response variable model produced using the R package DHARMa (Hartig 2022). The results of tests of correct distribution, dispersion, and outliers are printed on the QQ plots. Test results highlighted in red failed to meet model assumptions.

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