Agriculture Development Fund (ADF)
Project Final Report

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Project Title:	Combining Fertilizers and Herbicides to Enhance *Artemisia absinthium* Control in Pastures and Rangelands
ADF File Number:	20220052
Project Duration:	Start Date: May 2023 End Date: May 2026

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Abstract *(maximum 500 words)*

Detail an outline on overall project objectives, methods, key findings and conclusions for use in publications and in the ministry's database. The abstract should address the following (usually 1–2 sentences per topic):

- Key aspects of the literature review
- Problem under investigation or research question(s)
- Clearly stated hypothesis or hypotheses
- Methods used (including brief descriptions of the study design, sample, and sample size)
- Study results
- Conclusions

Absinthe wormwood (*Artemisia absinthium* L.) is an invasive perennial forb that threatens pasture productivity, forage availability, and forage recovery in the Canadian Prairies. Its unpalatable to cattle, persists in disturbed sites, and suppresses desirable forage species. Management is challenging, particularly where effective weed control must be balanced with maintaining productive grass-legume communities, where herbicide can damage desirable broadleaf forage species. Therefore, integrated management strategies are needed to suppress absinthe while supporting recovery of grasses, legumes, forage quality, and pasture diversity.

This project evaluated how herbicide choice, fertilizer addition, and temporary rest interact to influence absinthe suppression and pasture recovery in Saskatchewan rangelands. We hypothesized that fertilizer application following herbicide treatment would increase grass vigor and reduce absinthe regrowth; that phosphorus fertilizer combined with a less persistent herbicide would support legume re-establishment; and that temporary rest from cutting or grazing would improve recovery of grass-legume mixtures and strengthen absinthe suppression.

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A multi-year field experiment was conducted from 2023 to 2025 at four absinthe-invaded pasture sites in southern Saskatchewan. Treatments were factorial and included four herbicide treatments - unsprayed control, 2,4-D, Navius Flex, and ReClaim II - crossed with four fertilizer treatments - unfertilized control, nitrogen, phosphorus, and nitrogen plus phosphorus - and a one-year rest treatment compared with continued cutting. The study was established as a randomized complete block design with 384 plots initially across the four sites; however, two sites were lost after the first year, and a third after the second year due to factors beyond our control. Plant biomass, species richness, and forage quality measurements were collected to evaluate treatment effects on absinthe control and recovery of grasses and legumes. Additionally, an economic analysis was conducted to determine the most cost-effective treatment.

Herbicide treatment was the strongest and most consistent driver of absinthe suppression and pasture community change. Residual herbicides, particularly ReClaim II, provided the greatest and most persistent reduction in absinthe biomass, whereas 2,4-D provided shorter-term suppression. Fertilizer effects were most evident after herbicide reduced absinthe competition, suggesting that weed suppression increased resource availability and allowed fertilizers, particularly nitrogen, to support grass biomass recovery. Phosphorus showed some potential to support legume recovery under certain conditions, especially where herbicide effects were less persistent. Temporary rest had limited overall effects and did not consistently improve absinthe suppression or forage recovery. From an economic perspective, the best return on investment was for 2,4-D ($646/ha) followed by ReClaim II ($528/ha); however, treatment costs were only recouped after three years. Fertilizer was not cost effective.

Overall, results show that absinthe management requires balancing strong weed suppression with recovery of desirable forage species. Residual herbicides may be most appropriate where long-term absinthe control is the main objective, but they may also delay legume and diversity recovery and are moderately less cost effective over the short term. Less persistent options such as 2,4-D may be more suitable where maintaining legumes and pasture diversity is a management priority, although follow-up monitoring may be needed. Fertilizer and rest should be considered supporting tools rather than stand-alone absinthe control methods.

Extension Messages *(3 to 5 bullet point in plain language)*

Provide key outcomes and their importance for producers/processors and the relevant industry sector.

- Herbicide, specifically ReClaim II, gave the strongest and most persistent absinthe control, but also reduced legumes and species richness.
- 2,4-D provided shorter-term absinthe suppression but was most cost effective over the study duration, and may allow better recovery of legumes and plant diversity over time.
- Nitrogen fertilizer can improve grass recovery after absinthe suppression, but it should be used carefully where legume retention is a priority.
- Phosphorus shows some ability to aid legume recovery, but requires sufficient legumes to be present to work.

- Fertilizer and temporary rest alone did not reliably control absinthe; they are best considered supporting tools after effective weed suppression.

Introduction *(maximum 1,500 words)*

Provide a brief project background and rationale.

Absinthe wormwood (*Artemisia absinthium* L.) is an invasive perennial forb that has become a management concern in Saskatchewan pastures and rangelands. It is commonly associated with disturbed pastures, roadsides, field edges, and other managed grassland systems. Its low palatability, strong aromatic compounds, high seed production, and persistence in disturbed habitats allow it to spread and remain competitive in forage systems. Dense infestations can reduce forage availability, alter pasture composition, and create challenges for producers who need to control absinthe while maintaining productive grass-legume communities.

Long-term pasture weed management requires more than short-term suppression of the target weed. Successful long-term management also depends on recovery of desirable forage species that can compete with the invader and reduce reinvasion. In Saskatchewan pastures, maintaining grasses and legumes is especially important because these functional groups contribute to forage yield, forage quality, nitrogen cycling, and pasture resilience. However, management tools that suppress invasive broadleaf weeds may also damage desirable broadleaf forage species, especially legumes, resulting in declines in forage productivity and quality.

Herbicides remain an important tool for absinthe control, but different herbicides vary in persistence, efficacy, and non-target impacts. Non-residual herbicides such as 2,4-D can provide short-term suppression but may require repeated applications. Residual herbicides such as ReClaim II (aminopyralid based) or Navius Flex (aminocyclopyrachlor based; i.e., TruRange) may provide longer-lasting control, but they may also increase risk of legume injury and delayed recovery of plant diversity. While aminopyralid-based herbicides are known to be effective, less data is available for aminocyclopyrachlor. Consequently, use of Navius / TruRange for absinthe control is currently off-label and more data is needed to understand its efficacy.

Fertilizer application may also influence recovery after absinthe suppression by changing the competitive balance among plant functional groups. Nitrogen may stimulate grass growth and help grasses capture resources released after weed suppression, whereas phosphorus may support legume recovery. However, fertilizer could also favor undesirable species, including absinthe if herbicide control is incomplete, or reduce legume recovery if nitrogen stimulates grasses too strongly. Therefore, fertilizer needs to be evaluated as part of an integrated management strategy with herbicides rather than as a stand-alone solution.

Because absinthe is generally avoided by livestock while grasses and legumes are preferentially grazed, continuous defoliation may weaken forage competitors and indirectly favor absinthe. Temporary rest from cutting or grazing may also allow desirable forage species to recover after weed control, especially if fertilized. There is limited data, however, about the efficacy of short-term rest for forage recovery following absinthe control.

This project tested how herbicide, fertilizer, and temporary rest interact to influence absinthe suppression, forage recovery, forage quality, and species richness in Saskatchewan pastures. The overall goal was to identify management approaches that reduce absinthe while supporting productive and diverse forage communities.

Objectives and Progress *(add additional lines as needed)*

Please list the original objectives and/or revised objectives if ministry-approved revisions have been made to original objectives. A justification is needed for any deviation from original objectives.

Objective	**Progress** *(i.e., completed/in progress)*
Determine if fertilizer can augment herbicide control of absinth and improve legume recovery	Completed.
Determine if a short rest following herbicide can increase legume recovery while improving absinth control	Completed.
Determine if fertilizer plus 2,4-D provides cost effective control relative to residual herbicides and improve legume regrowth	Completed

Methodology *(maximum of five pages)*

Specify project activities undertaken during this reporting period. Include approaches, experimental design, tests, materials, sites, etc. Please note that any significant changes from the original work plan will require written approval from the ministry.

The field experiment was conducted from 2023 to 2025 at four absinthe-invaded pasture sites in southern Saskatchewan: Lanigan, Parkbeg, Francis, and Wawota. These sites represented different pasture histories and disturbance conditions, including newly seeded pasture, older grazed pasture, occasionally hayed pasture, and a heavily disturbed grazed site. The experiment was arranged as a 4 * 4 * 2 randomized complete block design (32 plots per block) with three blocks per site. Each site initially contained 96 plots, for a total of 384 plots across all four sites. Each plot measured 9 m^2 and all plots within the block were separated by at least 1 m in all directions from the nearest plot to minimize any drift effects. As much as possible, plots were arranged in a grid; however, areas lacking absinthe were avoided.

Treatments included four herbicide levels: unsprayed control, 2,4-D, Navius Flex, and ReClaim II. All herbicides were applied in accordance with the label: 2,4-D Ester 700 was applied at the maximum recommended pasture and rangeland rate of 3.4 L/ha; Navius Flex was applied at the weed control rate of 167 g/ha with Merge surfactant at 1% v/v; and ReClaim II was applied at 135g/ha ReClaim IIA and 1.7L/ha ReClaim IIB with 20 mL Agral 90 surfactant per 10L of water. At Lanigan and Francis, herbicides were applied with 700 L/ha of water; however, at Wawota and Parkbeg this water was doubled (1400 L/ha) to ensure even coverage. All herbicides were applied using separate Field King PROMAX Battery-powered backpack sprayers fitted with an adjustable brass nozzle. Herbicide applications took place between June 8 and June 20, depending on the weather.

The herbicide treatments were crossed with four fertilizer treatments: unfertilized control, nitrogen, phosphorus, and nitrogen plus phosphorus. Nitrogen was applied as coated urea at 112 kg N/ha, and phosphorus was applied as triple superphosphate at 67 kg P/ha. As we were uncertain whether spring or flal fertilizer application would be more effective, half the fertilizer was applied immediately before spraying and half between August 24 and 31 the same year. Each herbicide × fertilizer combination was also paired with a harvest/rest treatment to compare continued cutting with temporary rest. For this treatment, only half the plots were cut in the first year. All plots were cut to 10 cm stubble height. Alfalfa seed was also broadcast across plots during the fall fertilizer application to support consistent evaluation of legume recovery as the sites varied in the degree of legume they supported.

Each year, vegetation data were collected using both cover estimates and biomass harvests at peak biomass in early July. Plant cover was estimated in a 0.5 m × 0.5 m subplot. Biomass was clipped to a 10 cm stubble height, separated into absinthe, grasses, legumes, and other weeds, dried at 60°C for 48–72 hours, and weighed. Grass and legume biomass samples were also analyzed for forage quality. Crude protein was estimated from total nitrogen using a LECO elemental analyzer. Neutral detergent fiber and acid detergent fiber were measured using an Ankom fiber analyzer. Relative feed value was calculated from acid detergent fiber and neutral detergent fiber using the following equations:

$$DDM = 88.9 - (0.779 \times ADF)$$
$$DMI = 120/NDF$$
$$RFV = (DDM \times DMI)/1.29$$

Where DDM is digestible dry matter, DMI is dry matter intake, and ADF and NDF represent acid detergent fiber and neutral detergent fiber, respectively.

Due to field setbacks, not all sites were available in all years. In 2024, Lanigan was excluded because plots were destroyed by an unknown party, and Parkbeg was excluded because absinthe disappeared even in control plots, likely due to drought. In 2025, only Francis remained available for full sampling after plot infrastructure was damaged by intense grazing at Wawota. Analyses were therefore structured to use the strongest available comparisons: 2023 across all four sites, 2023–2024 at Francis and Wawota, and 2023–2025 at Francis.

Treatment effects were analyzed using linear mixed-effects models in R. Fixed effects included herbicide, fertilizer, harvest/rest, site, year, and their interactions, depending on the dataset. Block and plot were included as random effects where appropriate. Response variables included absinthe biomass, grass biomass, legume biomass, species richness, relative feed value, and crude protein. Model assumptions were checked using residual diagnostics, and transformations were applied where needed. Estimated marginal means and Tukey-adjusted pairwise comparisons were used to interpret treatment differences.

For the economic analyses, aimed to determine the most cost-effective combination of fertilizer and herbicide application. We only include the cost of the herbicide and fertilizer applied. Costs to apply the products, surfactant and alfalfa seed are excluded. However, custom spraying herbicide can range from $22.23/ha ($9/ac) for high clearance spraying to $370/ha ($150+/ac) for certified custom application using an UTV-mounted sprayer. Fertilizer was hand spread on each plot in the current small-plot study. Granular fertilizer is usually broadcasted with a spreader with suggested custom rates of $25-49/ha based on rates incurred for recent ADOPT projects. Each plot was mowed to 10-cm height to simulate haying, which would cost approximately $62/ha ($25/acre).

Herbicides were provided in-kind for use in the study. We contacted sales representatives at Envu and Corteva for the suggested retail price of Navius Flex ($925 per 1.361 kg) and ReClaim II ($1,170.63 for 1.84 kg A + 2 × 6.84 L of B), respectively. Online pricing was used 2,4-D ($166.24 per 20 L jug). We used the actual prices paid at Early's Farm and Garden for Super Triple Phosphate fertilizer ($55 per 25 kg bag = $2.20/kg) and 46-0-0 urea ($53 per 25 kg= $2.12/kg); however, bulk fertilizer prices from agricultural distributors would be notably less. Each treatment cost was assumed to be the same across all four sites.

Of the four sites in the study, only Francis had biomass (yield) collected for all three years of the study (2023-2025). We calculated 3-yr cumulative net returns for Francis. For Lanigan and Parkbeg, we calculated 1 yr net returns and 2 yr net returns for Wawota. We only report analysis for the cut treatments because yield data was not available in 2023 for the rested plots.

The mass of grass, legumes, absinthe and other weeds were measured in grams per m2. To calculate returns, we summed the mass of grass and legumes together, multiplied by 10 to convert to kg/ha and multiplied by an estimated market price for grazing/standing hay ($0.09/kg). Returns were then calculated as Grass & Legume DM Yield ×Price of DM Forage.

Published rental rates for private pasture are not currently available. The Saskatchewan Forage Council used to publish prices for standing hay and private pasture rent, but has not done so for the last few years. Rates of $1.25-1.50/cow/d are commonly noted by cattle producers who share rates they pay/charge for grazing on deeded land on social media (e.g. 306 Ranchers on Facebook). A 1350 lb cow will consume ~35 lb DM forage per day; therefore $1.50 / 35 lb DM consumed per day = $0.04 per lb DM forage ($0.09/kg).

Costs were only incurred in year one of the study and were assumed to be the same across all sites. Net returns were calculated as the cumulative market value of grass + legume biomass minus the input costs incurred in Year 1 (2023). While results are shown for all sites, return values for sites harvested for less than three years are an underestimate and likely do not represent the true return on investment.

We also calculated the cost per unit decrease in absinthe presence (% of total biomass) to identify the most cost-effective weed control treatment. The Francis site had measures taken 26 MAT (months after treatment; June 2023 treatment, last biomass measured August 2025), Wawota's final biomass was collected 14 MAT and Lanigan and Parkbeg had one biomass measurement five weeks after treatment.

For each site and treatment we calculated the percent of absinthe present by dividing the absinthe mass by the total biomass (grass + legume + absinthe + weed). The absinthe presence (% of total mass) in the No Herbicide + No Fertilizer (Control) treatment in 2023 serves as the baseline that the herbicide treatments were compared to.

$$\text{Absinthe Presence } \% = \frac{\text{Absinthe mass } (g/m2)}{\text{Total Mass } (g/m2)} \times 100$$

Where Total Mass is the sum of grass, legume, absinthe and weeds in grams per m2.

We subtracted the absinthe presence from the final year of biomass measured at each site (Francis 2025, Lanigan/Parkbeg 2023, Wawota 2024) with the absinthe presence measured in August 2023 for the No Herbicide + No Fertilizer treatment to determine an absolute change in absinthe presence.

Results and Discussions *(maximum of 30 pages (not including figures or tables))*

Describe research accomplishments during the reporting period under relevant objectives listed under "Objectives and Progress" section. Please accompany a written description of results with tables, graphs and/or other illustrations. Provide discussion necessary to the full understanding of the results. Where applicable, results should be discussed in the context of existing knowledge and relevant literature. Detail any major concerns or project setbacks.

Absinthe responses

Over the three years, herbicide application consistently reduced absinthe biomass, whereas fertilizer effects were generally weak and only became apparent at Francis in the final year. When years were analyzed separately, absinthe biomass was strongly affected by herbicide in both 2023 and 2024 (both $p < 0.001$), with no significant herbicide × fertilizer interactions. Site differences in mean biomass were detected in 2023 ($p = 0.004$), but site did not modify the treatment effects in that year. In 2023, all three herbicides (2,4-D, Navius, and Reclaim) substantially reduced absinthe biomass relative to the untreated control (all $p < 0.001$; Fig. A1; Table A1). Among the herbicide treatments, Reclaim produced lower absinthe biomass than 2,4-D and Navius ($p = 0.001$), whereas 2,4-D and Navius did not differ significantly.

In 2024, the overall pattern was similar and all herbicides reduced biomass relative to the control (all $p < 0.001$), and Reclaim again showed the greatest suppression (both $p < 0.001$; Fig. A2; Table A2). Neither fertilizer nor harvest, nor any interactions involving these factors, were significant.

A combined analysis of 2023-2024 data for Francis and Wawota confirmed strong effects of herbicide, year, and site, and revealed that herbicide efficacy depended on year and differed between sites with a significant three-way interaction of Herbicide × Year × Site ($F = 2.71$, $p = 0.048$; Fig. 1; Table A3). At Francis in 2023, all three herbicides reduced biomass relative to the control (all $p < 0.001$), whereas in 2024 Reclaim produced the lowest biomass and was significantly more effective than both 2,4-D ($p = 0.01$) and Navius ($p < 0.001$). At Wawota, only Reclaim reduced biomass relative to the control in 2023 ($p = 0.003$), but by 2024 all three herbicides significantly suppressed absinthe (all $p < 0.001$; Fig. 1).

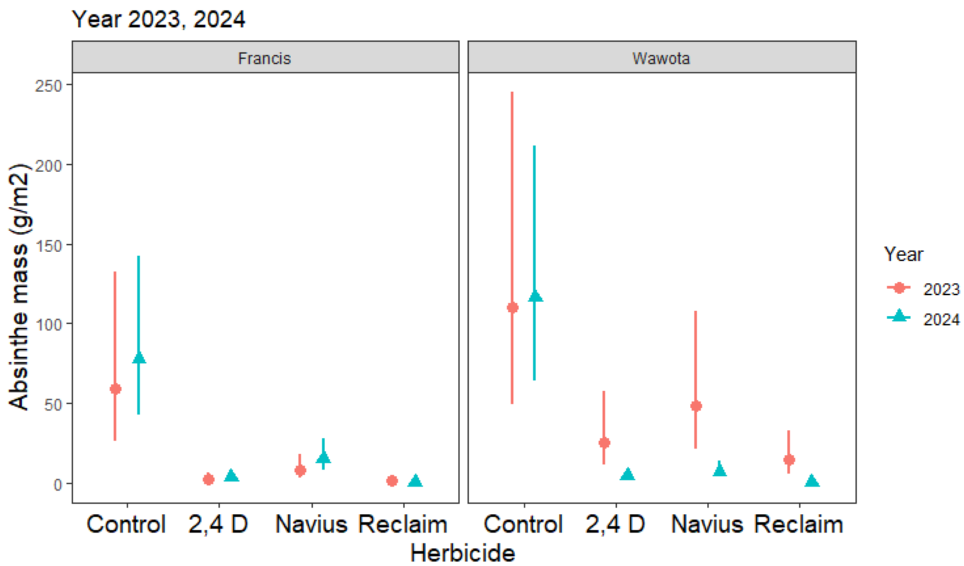


Figure 1 *Linear mixed model predicting the effects of herbicide treatments on absinthe mass (g/m²) in 2023 and 2024 at the Francis and Wawota sites (bottom).*

When we focused on Francis (only Francis remained in the experiment by 2025) across all three years (2023-2025), the mixed model again detected significant Herbicide × Year and Fertilizer × Year interactions, with a marginal herbicide by fertilizer by year interaction (Table 1). Because each herbicide × fertilizer × year combination was represented by only three plots (n = 3), this three-way interaction should be interpreted cautiously, but it suggests that treatment effects were not fully consistent across years. Across all three years at Francis, Reclaim consistently produced the greatest absinthe suppression and was significant in every year, while 2,4-D also strongly reduced biomass in 2023 and 2024 (Fig. 2). Fertilizer treatments generally had little effect on absinthe, with a single notable exception: in 2025, the NP treatment reduced absinthe biomass relative to the unfertilized control ($p = 0.01$). No other fertilizer contrasts were significant. When year 3 was analyzed separately to evaluate harvest treatment, no significant harvest effect was detected on absinthe biomass ($p > 0.45$). Herbicide remained the strongest predictor of absinthe biomass ($p < 0.001$), whereas fertilizer had no significant main effect ($p = 0.11$).

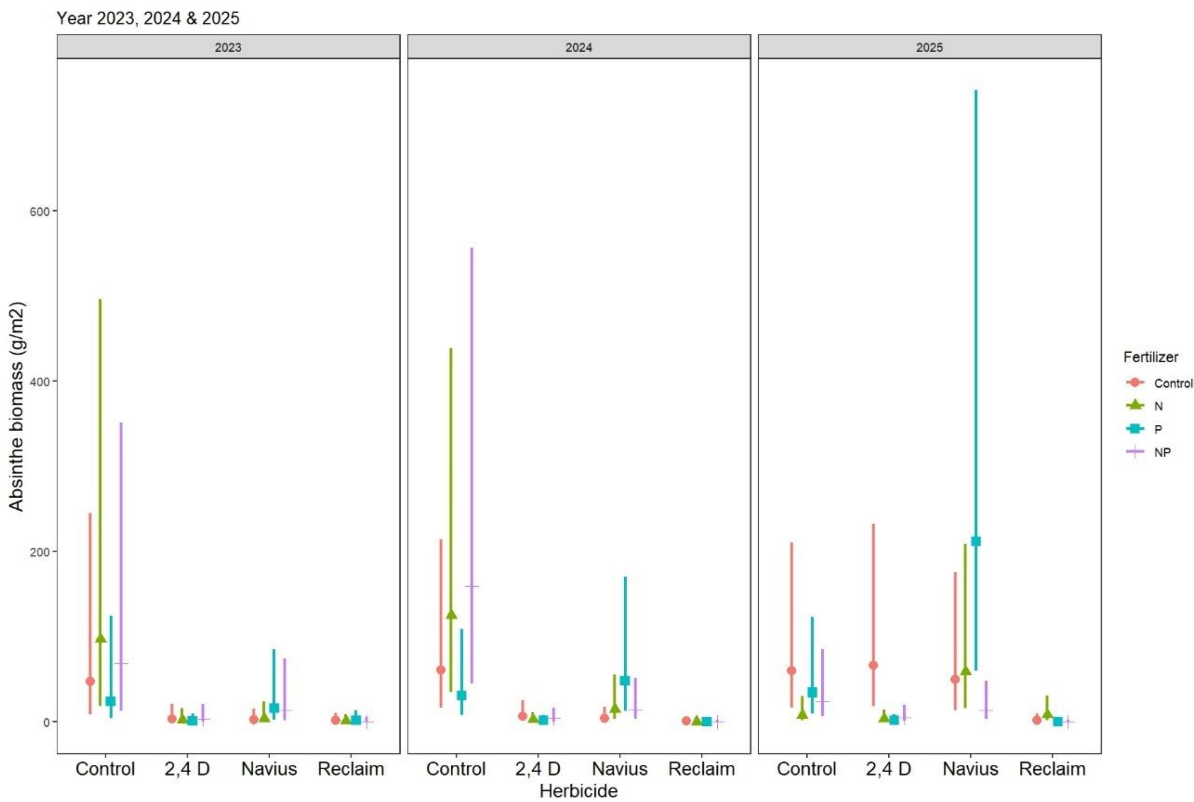


Figure 2 *Linear mixed model predicting the effects of herbicide and fertilizer treatments on absinthe biomass (g/m²) at the Francis site in 2023, 2024, and 2025; panels show model-predicted means (± SE) by year.*

Table 1. Mixed model results testing treatment effects on absinthe biomass (type III analysis of variance table with Satterthwaite's method).

Years 2023–2025 – log(Absinthe.mass + 1) ~ Herbicide*Fertilizer*Year + (1|Plot)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 81.183	29.182	**< 0.001**
Fertilizer	3, 81.183	0.190	0.903
Year	2, 115.740	4.750	**0.010**
Herbicide: Fertilizer	9, 81.183	1.472	0.172
Herbicide: Year	6, 115.740	6.975	**< 0.001**
Fertilizer: Year	6, 115.740	2.876	**0.012**
Herbicide: Fertilizer: Year	18, 115.740	1.642	0.060

Grass responses

In the first year, when comparing among all sites, there were no significant herbicide or fertilizer effects on grass biomass, although there were differences among sites (Table A4). In the second year, however, there was a significant interaction among herbicide and harvest treatment that varied among sites ($F = 3.22$, $p = 0.024$; Fig. 3; see Table 2 for full statistical results). At Francis, all herbicides resulted in greater grass biomass when the plots were cut (all $p < 0.001$), although Navius treated plots produced less grass than either the 2,4-

D or Reclaim treatments (all p <0.05). When Francis was rested, however, 2,4-D and Reclaim again exceeded the control (both $p < 0.05$), whereas Navius did not differ from the control. At Wawota, under the cut treatment, Navius and Reclaim were higher than the control (both $p < 0.05$), but 2,4-D did not differ from the control ($p = 0.471$); however, all three herbicides increased grass biomass relative to the control when the plots were rested initially (all $p < 0.05$), with Reclaim showing the largest increase.

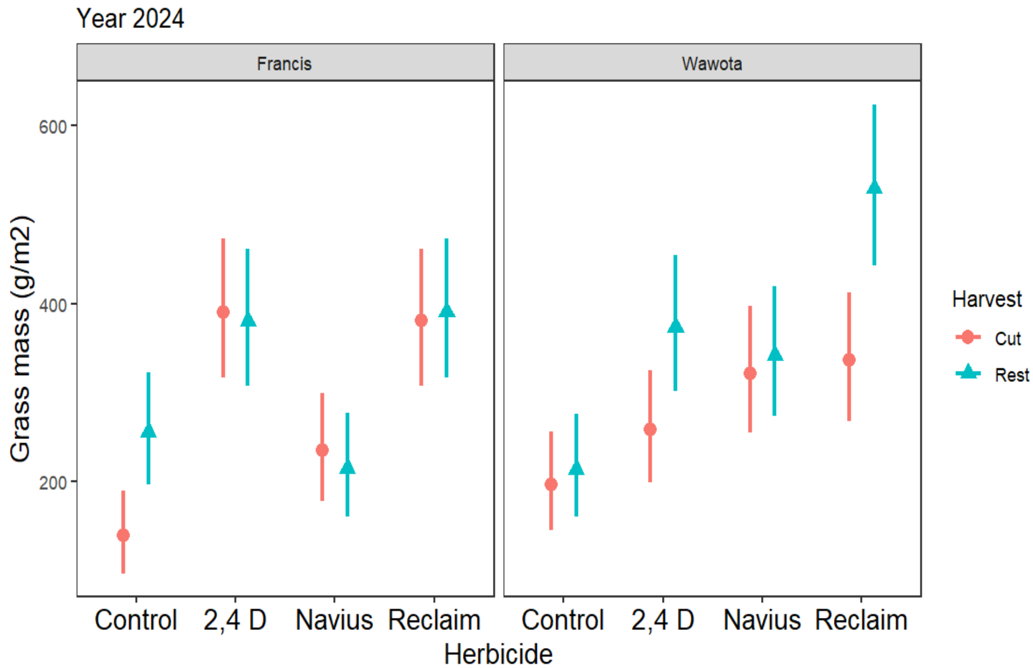


Figure 3 *Linear mixed model predicting the effects of herbicide and harvest treatments on grass mass (g/m²) in 2024 at the Francis and Wawota sites.*

Table 2. Mixed model results testing treatment effects on grass biomass (type III analysis of variance table with Satterthwaite's method).

Year 2 – sqrt(Grass.mass) ~ Herbicide*Fertilizer + Fertilizer*Site +Herbicide*Harvest*Site + (1|Block)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 161	27.615	**< 0.001**
Fertilizer	3, 161	9.395	**< 0.001**
Site	1, 161	1.888	0.171
Harvest	1, 161	9.993	**0.002**
Herbicide: Fertilizer	9, 161	2.048	**0.037**
Fertilizer: Site	3, 161	2.467	0.064
Herbicide: Harvest	3, 161	1.386	0.249
Herbicide: Site	3, 161	4.538	**0.004**
Site: Harvest	1, 161	1.958	0.164
Herbicide: Site: Harvest	3, 161	3.216	**0.024**

When testing for changes between years 1 & 2, there were significant herbicide × fertilizer ($F = 2.15$, $p = 0.028$) and herbicide × year interactions ($F = 5.02$, $p = 0.003$), although the three-way interaction was not significant ($p = 0.207$; Table A5). Nitrogen based fertilizer treatments (N & NP) increased grass biomass, but only in the herbicide treatments (all $p < 0.05$; Fig. A3). Consistent with the year specific models results, the herbicides had limited effect initially, but all three herbicides showed significant promotion of grass biomass by year two relative to the control (all $p < 0.01$; Fig. A3).

When focusing on the Francis site for the three-year comparison (Fig. 4; Table 3), we found similar results, with a significant Herbicide × Year interaction ($F = 3.37$, $p = 0.004$), although the effect of Navius relative to the control was lessened in the second year ($p = 0.741$) and the benefits of 2,4-D were largely lost by the final year ($p = 0.057$). Fertilizer effects at Francis were independent of any other treatment, but followed the same pattern found when comparing among sites with the nitrogen containing fertilizers (N & NP) promoting grass growth (all $p < 0.05$). When year 3 was analyzed separately to evaluate harvest treatment, no significant harvest effect was detected on grass biomass ($p > 0.17$).

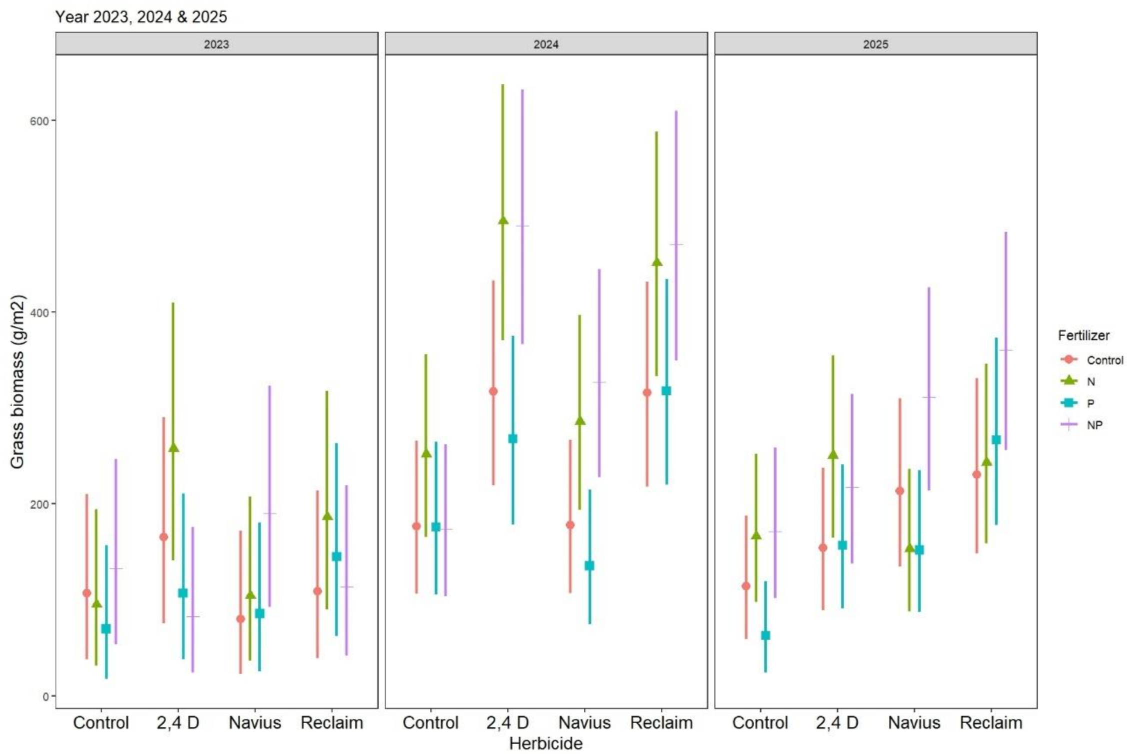


Figure 4 Linear mixed model predicting the effects of herbicide and fertilizer treatments on grass biomass (g/m²) at the Francis site in 2023, 2024, and 2025; panels show model-predicted means (± SE) by year.

Table 3. Mixed model results testing treatment effects on grass biomass (type III analysis of variance table with Satterthwaite's method).

2023-2025 – sqrt(Grass.mass) ~ Herbicide*Fertilizer*Year + (1|Plot)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 84.444	11.170	**< 0.001**
Fertilizer	3, 84.400	6.850	**< 0.001**
Year	2, 126.200	53.130	**< 0.001**
Herbicide: Fertilizer	9, 84.400	1.030	0.426
Herbicide: Year	6, 126.200	3.370	**0.004**
Fertilizer: Year	6, 126.200	1.410	0.217
Herbicide: Fertilizer: Year	18, 126.200	0.940	0.533

Legume responses

Herbicide effects on legume biomass were statistically significant in every year of the experiment, but the magnitude and direction of those effects varied strongly among sites and fertilizer treatments. In 2023, the legume biomass model detected a significant three-way Herbicide × Fertilizer × Site interaction (*p* = 0.022; Table 4). Herbicide and fertilizer effects on first-year legume biomass seem to have depended on each site's initial legume density. In the unfertilized treatment, only at Wawota, herbicide effects and their interactions with fertilizers were not significant, likely because legumes were already very sparse there, whereas at the other sites all herbicides significantly reduced legume biomass ($p < 0.05$). When fertilizer was applied with herbicide, site-specific patterns emerged. At Lanigan, P fertilization partially offset the negative effect of 2,4-D on legume biomass (*p* = 0.03; Fig. 5). This specific response at Lanigan may reflect the fact that it was a newly seeded field with a substantial alfalfa population. In contrast, when NP was applied to Navius treated plots, legume biomass was significantly reduced (*p* = 0.002). At Francis, NP fertilization also reduced legume biomass relative to the unfertilized treatment, regardless of herbicide (*p* = 0.02). No other interaction terms were significant. At Parkbeg, under the unfertilized control treatment all herbicides reduced legume biomass significantly (*p* = 0.023), and the absence of fertilizer effects likely reflects that legumes were largely absent in the herbicide-treated plots, leaving little legume biomass for fertilization to influence.

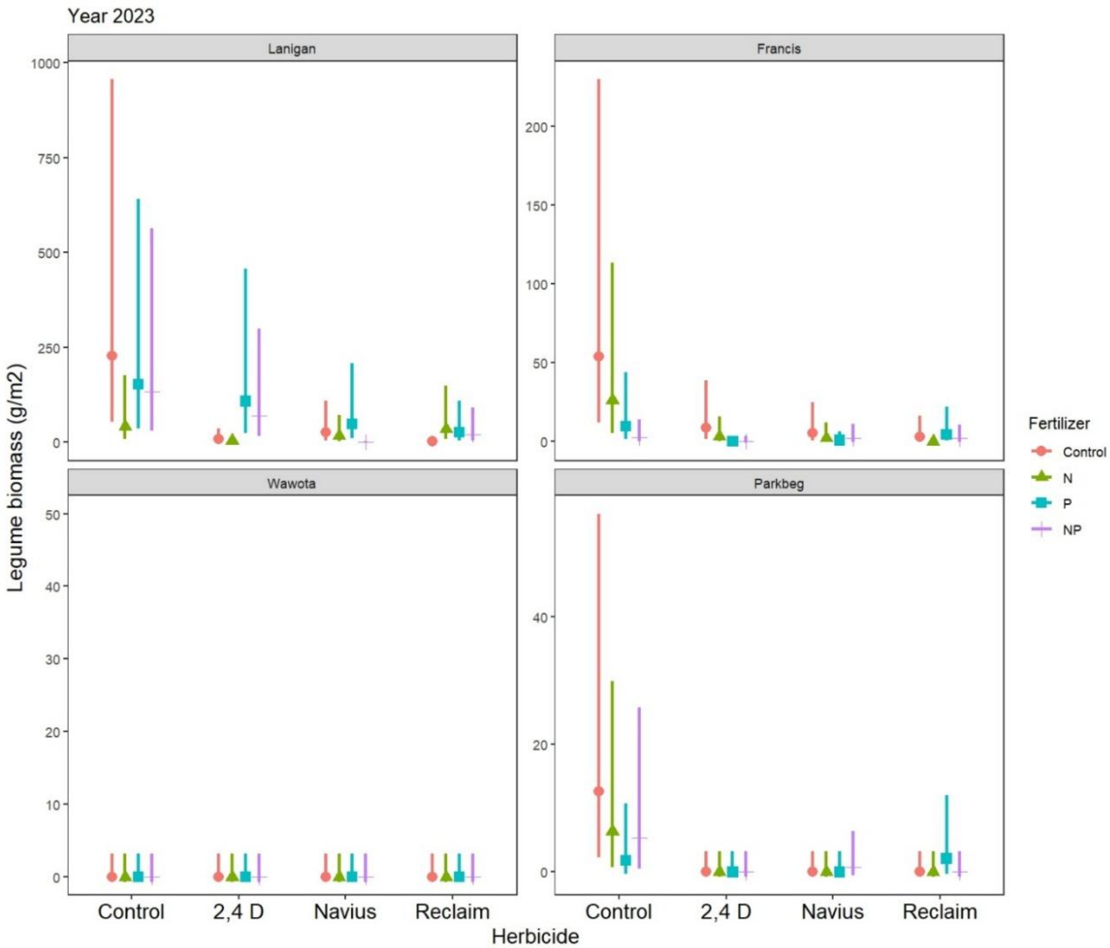


***Figure 5** Linear mixed model predicting the effects of herbicide and fertilizer treatments on legume biomass (g/m²) in 2023 across the four study sites; values shown are model-predicted means (± SE) averaged over random effects.*

Table 4. Mixed model results testing treatment effects on legume biomass in 2023 (type III analysis of variance table with Satterthwaite's method).

Year 1 – log(Legume.mass + 1) ~ Herbicide*Fertilizer*Site + (1|Block)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 120	17.820	**< 0.001**
Fertilizer	3, 120	1.506	0.216
Site	3, 8	15.420	**0.001**
Herbicide: Fertilizer	9, 120	1.177	0.315
Herbicide: Site	9, 120	2.281	**0.021**
Fertilizer: Site	9, 120	2.150	**0.030**
Herbicide: Fertilizer: Site	27, 120	1.748	**0.022**

In year 2 (Fig. A4; Table A6), at Francis, all herbicide treatments significantly reduced legume biomass relative to the unsprayed control ($p < 0.001$); however, legume biomass was greater in the 2,4-D plots than the other two herbicides ($p < 0.01$). The pattern was similar at Wawota, but only Navius and Reclaim were significantly different from the unsprayed control ($p = 0.026$) and no herbicide treatments differed from the others. Neither the fertilizer main effect nor any fertilizer interactions were significant. By 2024, the negative effect of 2,4-D at Francis had weakened but remained statistically significant. Although significant fertilizer terms emerged in the two-year model (Table 5), it reflected differences between years at Francis (significant N and P effects) driven by an overall decline in legume biomass in year 2 (Fig. 6, A5), rather than a consistent fertilizer effect on legumes.

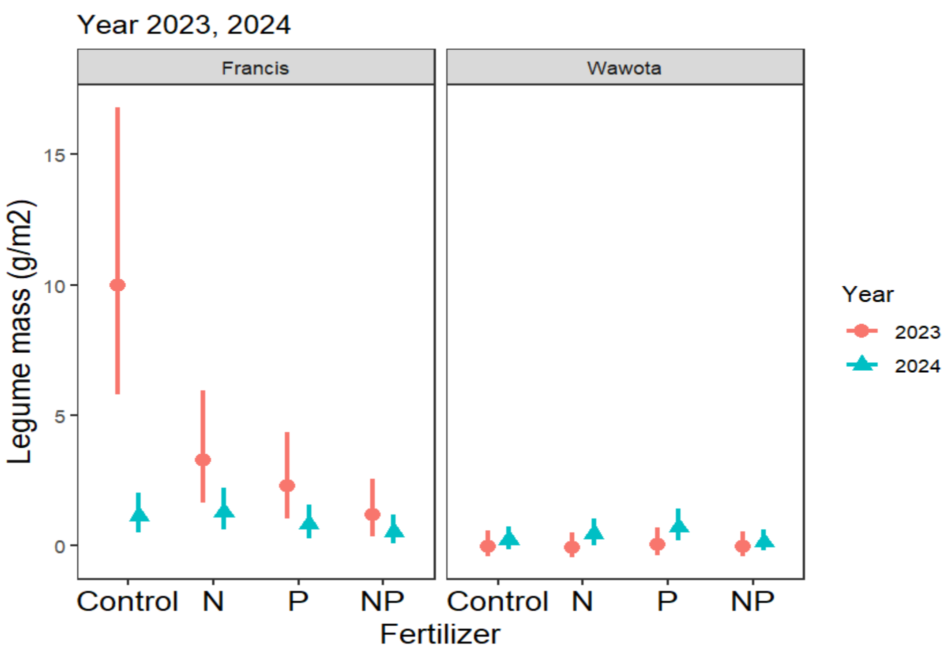


***Figure 6** Linear mixed model predicting the effects of fertilizer treatments on legume mass (g/m²) in 2023 and 2024 at the Francis and Wawota sites.*

Table 5. Mixed model results testing treatment effects on legume biomass (type III analysis of variance table with Satterthwaite's method).

Years 2023-2024 – log(Legume.mass + 1) ~ Herbicide*Year*Site + Fertilizer*Site*Year + (1|Plot)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 180.450	17.344	**< 0.001**
Year	1, 129.540	6.181	**0.014**
Site	1, 180.450	61.215	**< 0.001**
Fertilizer	3, 180.450	3.209	**0.024**
Herbicide: Year	3, 129.540	3.752	**0.013**
Herbicide: Site	3, 180.450	8.720	**< 0.001**
Year: Site	1, 129.540	36.229	**< 0.001**
Site: Fertilizer	3, 180.450	3.378	**0.019**
Year: Fertilizer	3, 129.540	2.750	**0.045**
Herbicide: Year: Site	3, 129.540	0.886	0.450
Year: Site: Fertilizer	3, 129.540	2.061	0.109

By 2025, in Francis (the only remaining site), Navius and Reclaim significantly reduced legume biomass (Fig. 7; Table 6), but only under the unfertilized control (p = 0.006) and P fertilization (p < 0.001) because nitrogen fertilizer kept legume biomass minimal across all treatments. Interestingly, legume biomass within the 2,4-D treatment increased under P fertilization across years as the negative effect of this non-residual herbicide weakened, with the strongest increase occurring between 2024 and 2025 (p < 0.001). As a result, legumes had recovered to the same level as the control by year 3 (p > 0.307). When year 3 was analyzed separately to evaluate harvest treatment, no significant harvest effect was detected on legume biomass (p > 0.15).

Table 6. Mixed model results testing treatment effects on legume biomass (type III analysis of variance table with Satterthwaite's method).

Years 2023–2025 – log(Legume.mass + 1) ~ Herbicide*Fertilizer*Year + (1|Plot)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 86.293	18.884	**< 0.001**
Fertilizer	3, 86.293	3.415	**0.021**
Year	2, 124.358	11.552	**< 0.001**
Herbicide: Fertilizer	9, 86.293	0.869	0.556
Herbicide: Year	6, 124.358	3.144	**0.007**
Fertilizer: Year	6, 124.358	2.857	**0.012**
Herbicide: Fertilizer: Year	18, 124.358	2.092	**0.010**

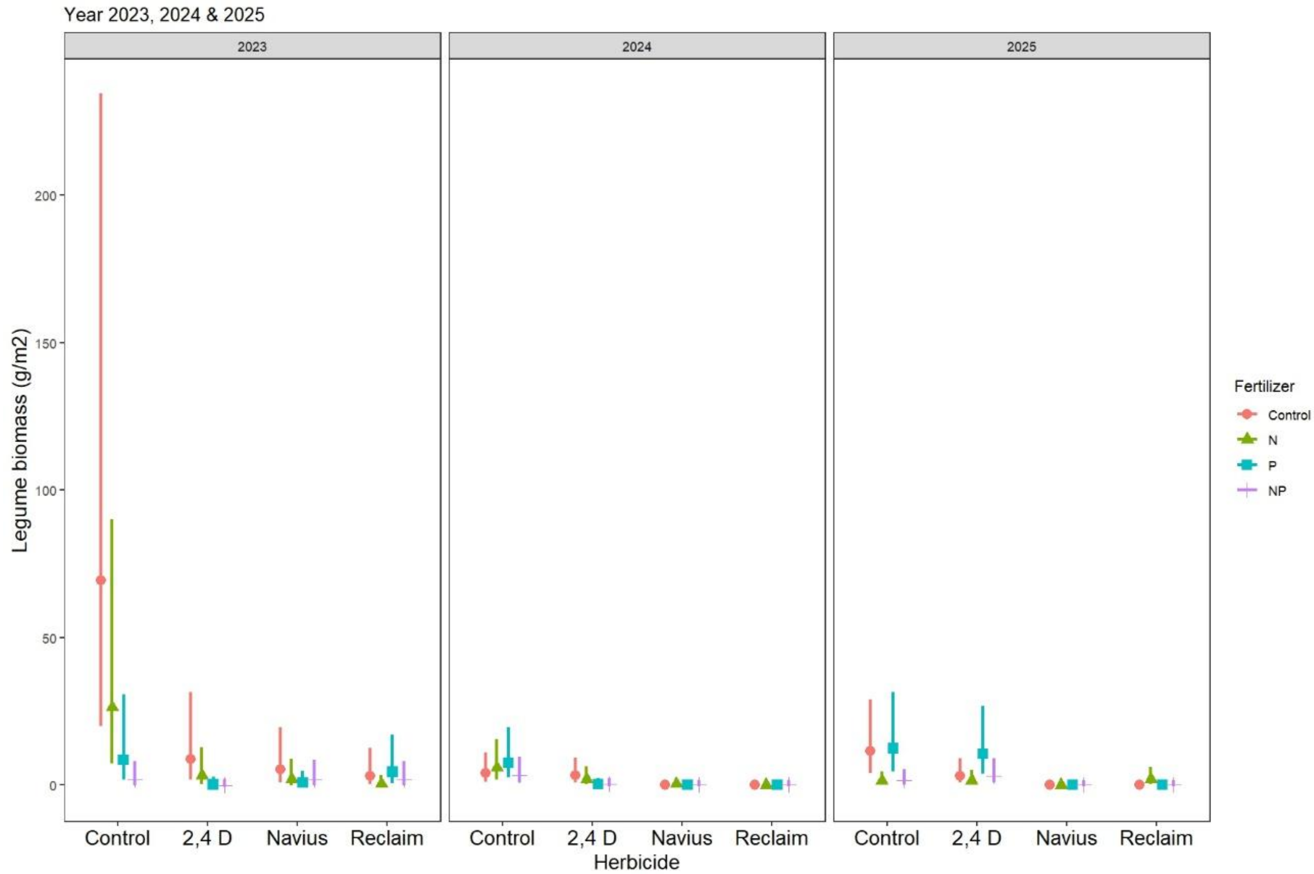


Figure 7 *Linear mixed model predicting the effects of herbicide and fertilizer treatments on legume biomass (g/m²) at the Francis site in 2023, 2024, and 2025; panels show model-predicted means (± SE) by year.*

Species richness

Based on Year 2023 species richness model, no significant interactions were found (Fig. A6; Table A7). Only Herbicide strongly affected species richness (F = 22.02, p < 0.001). All herbicides reduced species richness significantly (p < 0.001). Across 2023 and 2025, there was a significant Herbicide × Year interaction (F= 7.43, p < 0.001, Fig. 8; Table 7) where species richness under the non-residual herbicide (2,4-D), but not the residual herbicides (both p < 0.05) recovered to the same level as the control. There were no significant fertilizer or rest treatment effects.

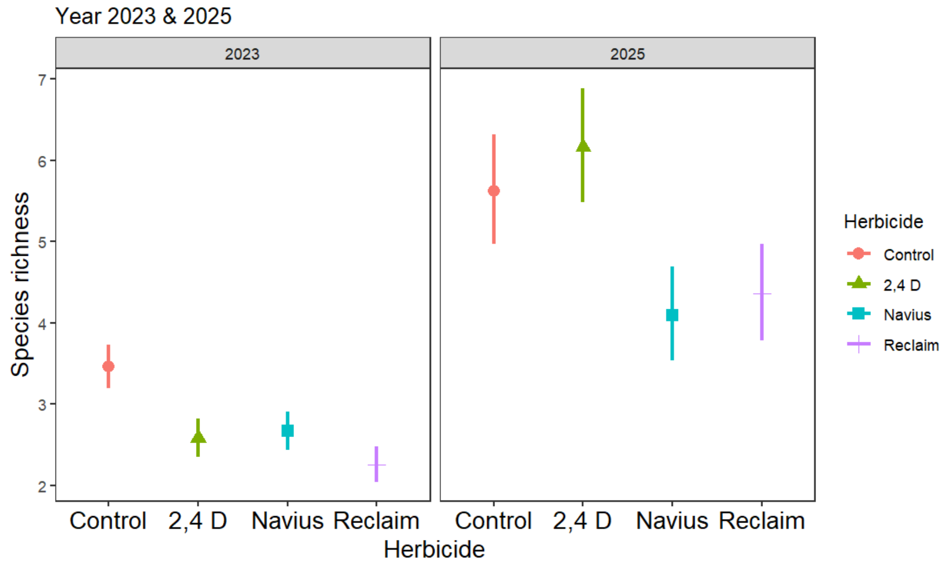


Figure 8 *Linear mixed model predicting the effects of herbicide treatments on species richness in 2023 and 2025; panels show model-predicted means (± SE) by year.*

Table 7. Mixed model results testing treatment effects on species richness (type III analysis of variance table with Satterthwaite's method).

Years 2023 & 2025 – sqrt(Species.richness) ~ Herbicide*Fertilizer*Year + Harvest + (1|Plot)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 404.910	13.856	**< 0.001**
Fertilizer	3, 404.910	1.065	0.364
Year	1, 151.650	243.006	**< 0.001**
Harvest	1, 301.020	0.103	0.749
Herbicide: Fertilizer	9, 404.910	0.970	0.465
Herbicide: Year	3, 151.650	7.435	**< 0.001**
Fertilizer: Year	3, 151.650	0.173	0.915
Herbicide: Fertilizer: Year	9, 151.650	1.346	0.218

Relative feed value

We detected a significant Herbicide × Site interaction for 2023 ($F = 2.49$, $p = 0.013$; Table 8). At Lanigan, Navius and Reclaim significantly reduced relative forage quality compared with the unsprayed control ($p < 0.001$; Fig. 9), although the three herbicide treatments did not differ significantly from one another. At Francis, Parkbeg, and Wawota, no herbicide contrasts were detected (all $p \geq 0.25$), indicating no clear RFV differences among herbicide treatments at those sites. Fertilizer had no detectable effect and did not modify herbicide or site response (Table 8).

Table 8. Mixed model results testing treatment effects on plants relative feed value (type III analysis of variance table with Satterthwaite's method).

Year 1 – log(RFV + 1) ~ Herbicide*Fertilizer*Site + (1|Block)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 107.281	5.431	**0.002**
Fertilizer	3, 107.446	0.683	0.564
Site	3, 7.869	27.032	**< 0.001**
Herbicide: Fertilizer	9, 107.369	1.173	0.319
Herbicide: Site	9, 107.249	2.482	**0.013**
Fertilizer: Site	9, 107.388	1.449	0.176
Herbicide: Fertilizer: Site	27, 107.278	0.874	0.645

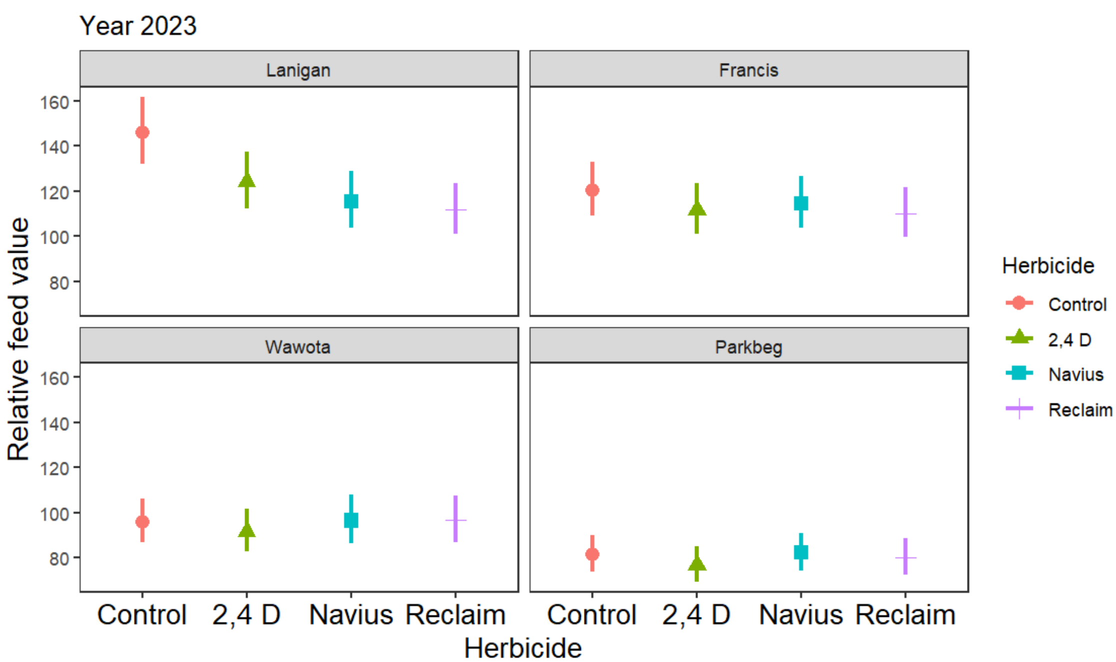


***Figure 1** Linear mixed model predicting the effects of herbicide treatments on relative feed value (RFV) in 2023 across the four sites (Lanigan, Francis, Wawota, and Parkbeg); points show model-predicted means (± SE).*

There was a significant Herbicide × Fertilizer interaction in 2024 (Table 9). Overall, nitrogen-based fertilizers (N and NP) tended to reduce RFV (both $p < 0.01$; Fig. 10); however, when N fertilizer was applied with either Navius or Reclaim, RFV increased significantly ($p < 0.01$). In contrast, P fertilization combined with Reclaim significantly reduced RFV ($p = 0.001$). RFV also varied with harvest management: cut plots had higher RFV than rested plots ($p = 0.01$). No other interaction terms were significant.

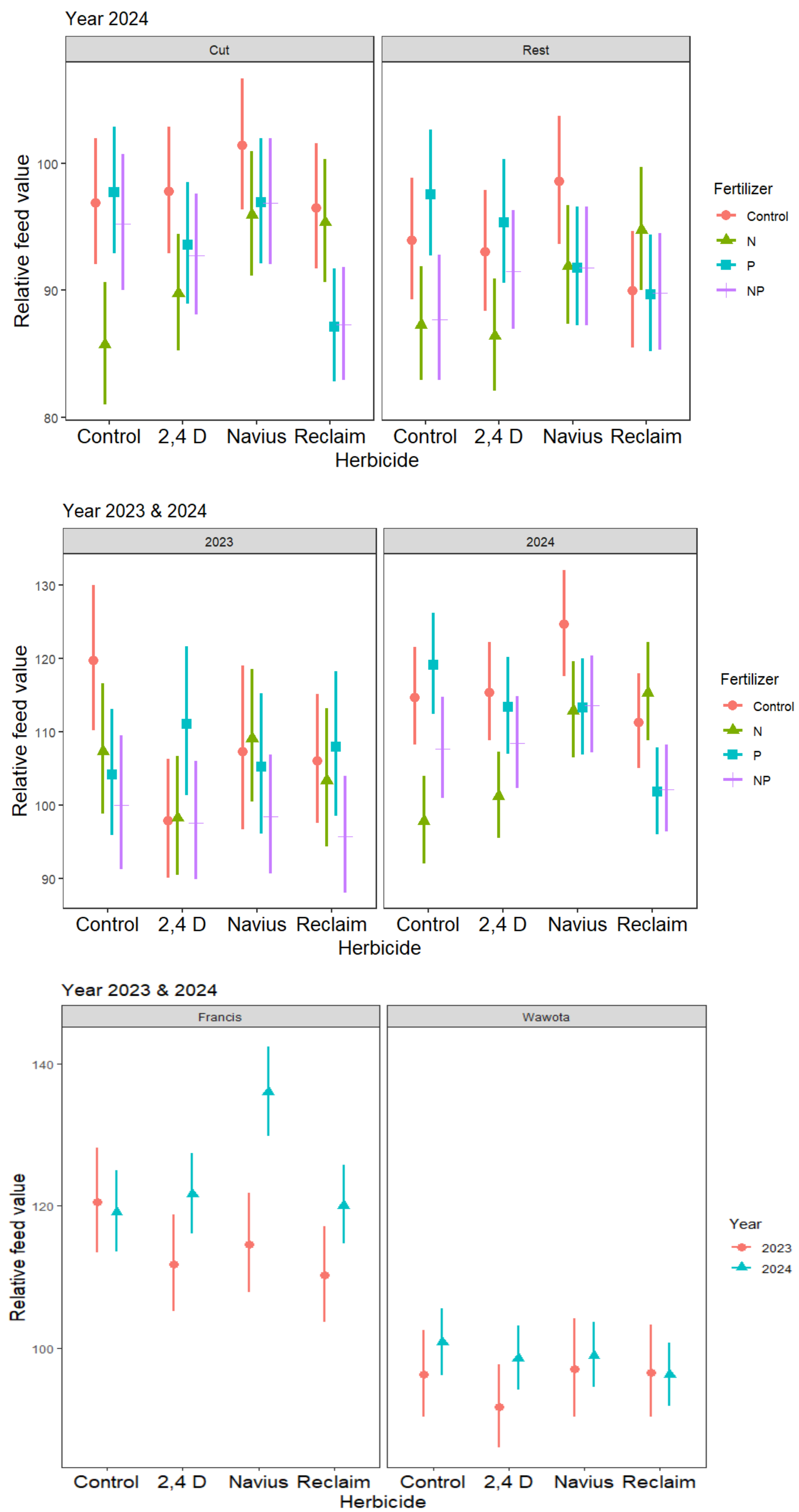


Figure 10 *Linear mixed model predicting the effects of herbicide and fertilizer treatments on relative feed value (RFV) in 2024 under Cut and Rest harvest regimes (top); Linear mixed model predicting the effects of herbicide and fertilizer treatments on relative feed value (RFV) in 2023 and 2024 (middle); Linear mixed model predicting the effects of herbicide treatments on relative feed value (RFV) in 2023 and 2024 at the Francis and Wawota sites (bottom).*

Table 9. Mixed model results testing treatment effects on plants relative feed value (type III analysis of variance table with Satterthwaite's method).

Year 2 – $\log(RFV + 1) \sim Herbicide*Fertilizer*Harvest + Fertilizer*Site*Harvest + (1|Block)$

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 145.190	4.810	**0.003**
Fertilizer	3, 145.120	7.440	**< 0.001**
Harvest	1, 145.190	6.820	**0.010**
Site	1, 4.060	118.450	**< 0.001**
Herbicide: Fertilizer	9, 145.120	3.960	**< 0.001**
Herbicide: Harvest	3, 145.190	0.830	0.477
Fertilizer: Harvest	3, 145.120	1.020	0.387
Fertilizer: Site	3, 145.120	0.670	0.570
Harvest: Site	1, 145.190	0.040	0.844
Herbicide: Fertilizer: Harvest	9, 145.120	0.930	0.501
Fertilizer: Harvest: Site	3, 145.120	0.740	0.530

Table 10. Mixed model results testing treatment effects on plants relative feed value in 2023 & 2024 (type III analysis of variance table with Satterthwaite's method).

Years 2023–2024 – $\log(RFV + 1) \sim Herbicide*Fertilizer*Year + Herbicide*Year*Site + (1|Plot)$

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 150.310	2.950	**0.035**
Fertilizer	3, 149.890	7.580	**< 0.001**
Year	1, 131.280	21.640	**< 0.001**
Site	1, 150.180	227.320	**< 0.001**
Herbicide: Fertilizer	9, 149.250	1.970	**0.047**
Herbicide: Year	3, 131.180	2.060	0.109
Fertilizer: Year	3, 130.900	1.880	0.136
Herbicide: Site	3, 150.040	1.030	0.379
Year: Site	1, 130.900	3.600	0.060
Herbicide: Fertilizer: Year	9, 130.330	2.420	**0.014**
Herbicide: Year: Site	3, 130.800	3.020	**0.032**

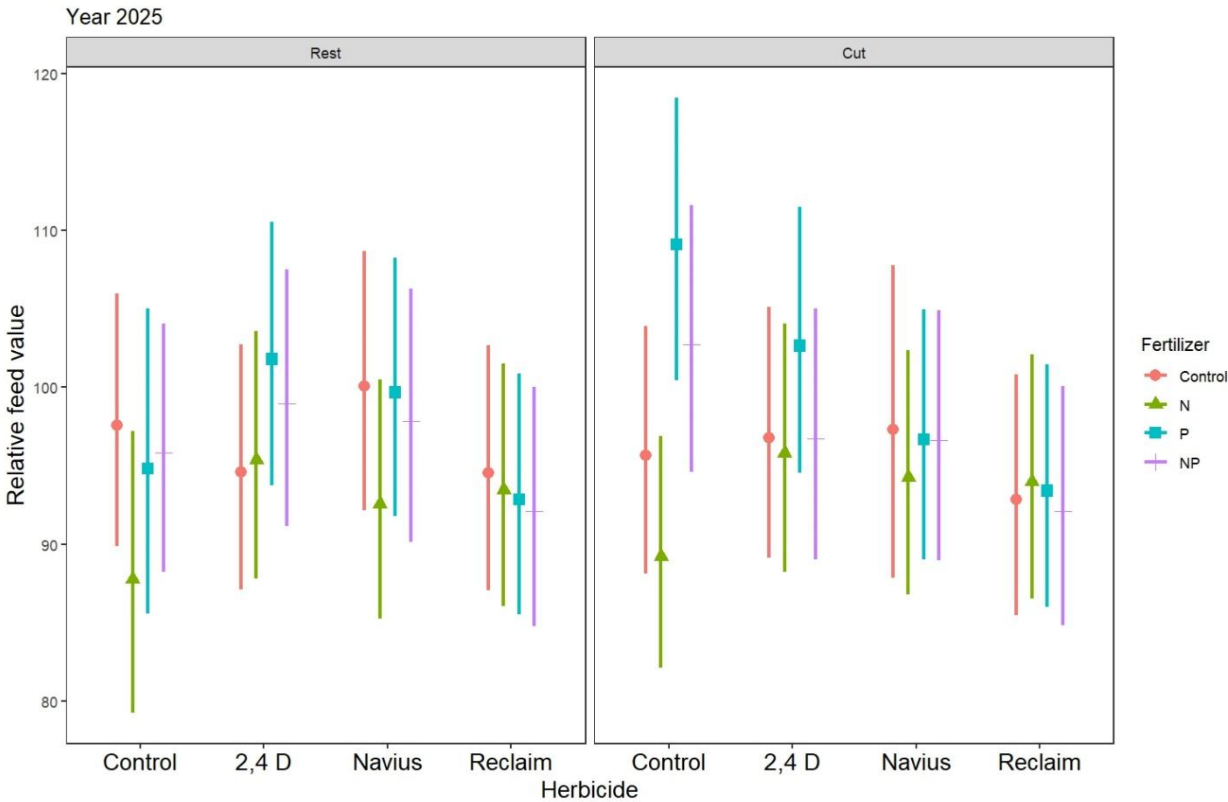


Figure 10 *Predicted relative feed value (RFV) in 2025 at the Francis site as influenced by herbicide, fertilizer, and harvest treatments. Points represent estimated marginal means ± SE from the mixed-effects model.*

In 2025, RFV was significantly affected by fertilizer treatment (F = 2.95, p = 0.039), whereas herbicide (p = 0.112), harvest treatment (p = 0.507), and all interactions were not significant (Table 11). RFV values generally ranged from approximately 90 to 110 across treatments. Phosphorus fertilization tended to produce the highest RFV values, whereas nitrogen alone generally resulted in lower RFV values. Herbicide treatments showed little influence on RFV, and responses were consistent between rested and cut plots (Fig. 10). The significant fertilizer effect suggests that forage quality responded more strongly to nutrient availability than to absinthe management treatments in the final year of the study. The tendency for phosphorus-treated plots to exhibit higher RFV may reflect improved forage quality associated with enhanced legume performance or shifts in plant community composition. In contrast, herbicide treatments primarily affected weed suppression and forage biomass recovery rather than forage quality. The absence of harvest effects indicates that a single year of rest did not substantially alter forage nutritive value under the conditions of this study.

Table 11. Mixed model results testing treatment effects on relative feed value (RFV) in 2025 at the Francis site (Type III analysis of variance table with Satterthwaite's method).

Effect	**DF (num, den)**	**F value**	***Pr(>F)***
Herbicide	3, 61	2.082	0.112
Fertilizer	3, 61	2.954	**0.039**
Harvest	1, 61	0.445	0.507
Herbicide × Fertilizer	9, 61	0.951	0.489

Herbicide × Harvest	3, 61	0.876	0.458
Fertilizer × Harvest	3, 61	0.323	0.808
Herbicide × Fertilizer × Harvest	9, 61	0.418	0.921

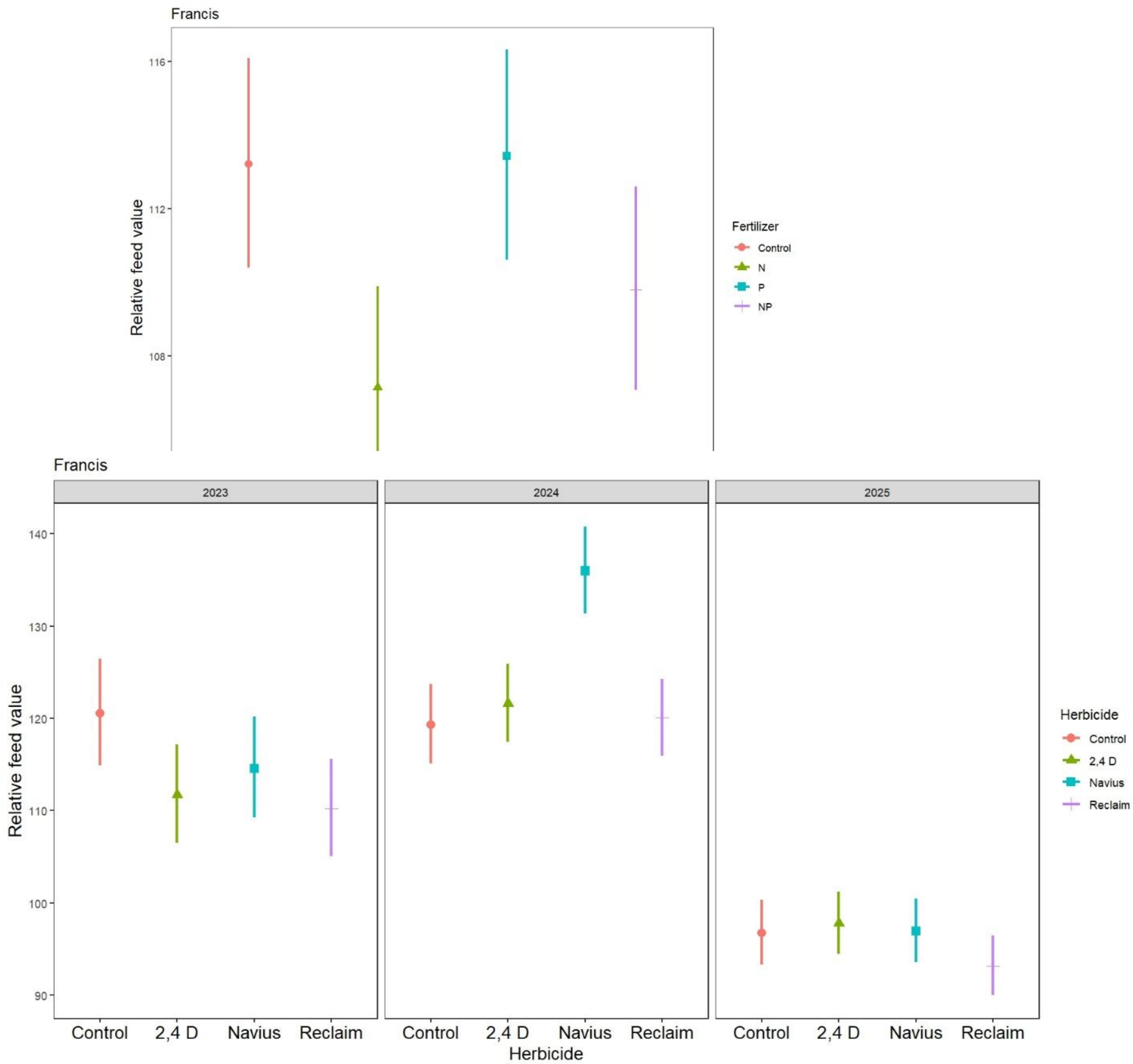


Figure 11 *Predicted relative feed value (RFV) at the Francis site from 2023 to 2025 as influenced by fertilizer treatments (top panel) and herbicide treatments across years (bottom panel). Points represent estimated marginal means ± SE.*

Across the three-year study period at Francis, RFV was significantly affected by herbicide treatment ($F = 6.36$, $p < 0.001$), fertilizer treatment ($F = 5.76$, $p < 0.001$), year ($F = 227.43$, $p < 0.001$), and the Herbicide × Year interaction ($F = 4.74$, $p < 0.001$; Table 12). RFV declined substantially over time, with values generally exceeding 110 in 2023 and 2024 but falling below 100 in 2025 (Fig. 11). Phosphorus fertilizer tended to maintain the highest RFV values across years, while nitrogen alone often resulted in lower values. Herbicide effects varied among years, with Navius producing relatively high RFV values in 2024 but showing little difference from other herbicides in 2025.

The strong year effect indicates that environmental conditions and annual variation were major determinants of forage quality. The decline in RFV observed in 2025 may reflect changes in weather conditions, plant maturity, or community composition. Fertilizer effects were consistent with the hypothesis that nutrient availability can influence forage quality, particularly when phosphorus promotes the contribution of higher-quality forage species. The significant Herbicide × Year interaction suggests that herbicide effects on forage quality were context dependent and likely mediated through changes in vegetation composition rather than direct treatment effects.

Table 12. Mixed model results testing treatment effects on relative feed value (RFV) at the Francis site from 2023 to 2025 (Type III analysis of variance table with Satterthwaite's method).

Effect	**DF (num, den)**	**F value**	***Pr(>F)***
Herbicide	3, 185.070	6.358	**< 0.001**
Fertilizer	3, 185.060	5.760	**< 0.001**
Year	2, 185.070	227.429	**< 0.001**
Herbicide × Fertilizer	9, 185.060	1.579	0.124
Herbicide × Year	6, 185.040	4.738	**< 0.001**
Fertilizer × Year	6, 185.030	1.088	0.371
Herbicide × Fertilizer × Year	18, 185.040	0.746	0.760

Protein content

Protein content showed strong spatial structure and site-specific treatment responses. The three-way interaction (Herbicide × Fertilizer × Site) was not significant (Table 13). Two two-way interactions were significant: Herbicide × Site ($F = 2.13$, $p = 0.033$) and Fertilizer × Site ($F = 1.97$, $p = 0.049$). At Parkbeg, 2,4-D and Reclaim significantly reduced protein content relative to the unsprayed control ($p < 0.05$; Fig. 12, although it did not differ significantly among the three herbicide treatments. None of the fertilizer pairwise comparisons were significant, likely owing to the complexity of the contrasts and the small sample size, but, at Lanigan under NP fertilization and at Wawota under N fertilization, protein content showed a positive trend, but these increases were not statistically significant ($p = 0.256$ and $p = 0.147$, respectively). In contrast, at Francis, P fertilization tended to decrease protein content, with a marginal effect ($p = 0.056$).

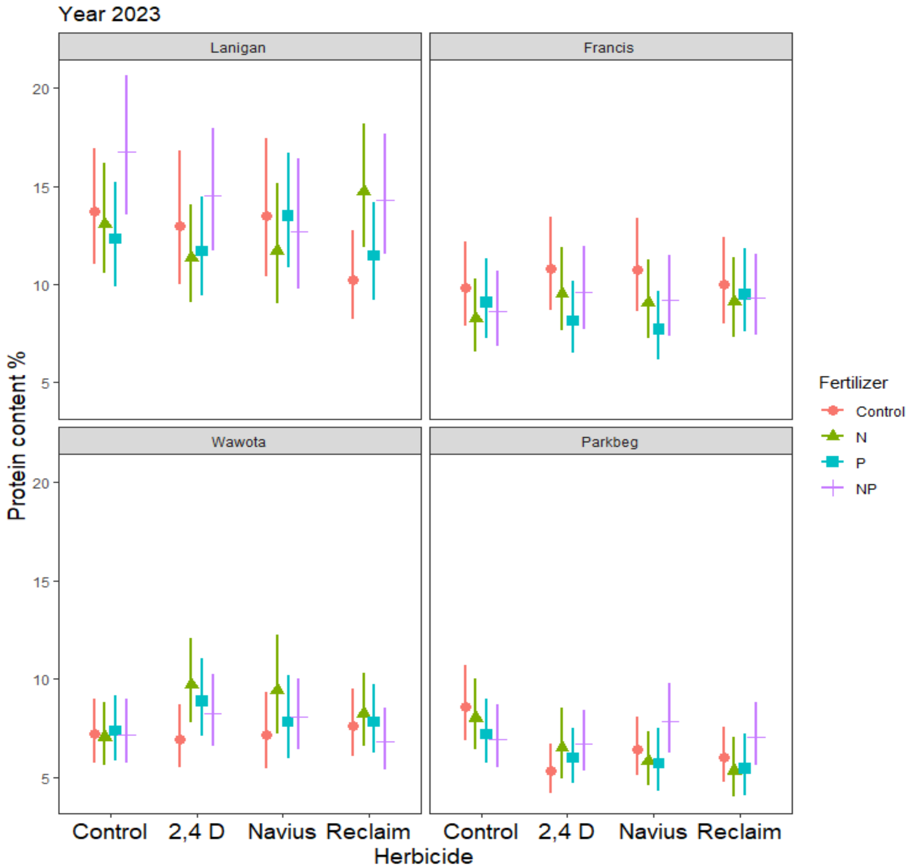


***Figure 12** Linear mixed model predicting the effects of herbicide and fertilizer treatments on forage protein content (%) in 2023 across the four sites (Lanigan, Francis, Wawota, and Parkbeg); points show model-predicted means (± SE).*

Table 13. Mixed model results testing treatment effects on plants protein content (type III analysis of variance table with Satterthwaite's method).

Year 1 – log(protein.percent + 1) ~ Herbicide*Fertilizer*Site + (1|Block)

Effect	**Df (num, den)**	**F value**	***Pr(>F)***
Herbicide	3, 109.350	0.847	0.471
Fertilizer	3, 109.530	1.815	0.149
Site	3, 7.970	35.664	**< 0.001**
Herbicide: Fertilizer	9, 109.370	0.378	0.943
Herbicide: Site	9, 109.320	2.131	**0.033**
Fertilizer: Site	9, 109.500	1.972	**0.050**
Herbicide: Fertilizer: Site	27, 109.340	0.955	0.535

Comparing year 2023 and 2024 (Table 14), the three-way interaction Herbicide × Year × Site was significant ($F = 3.31$, $p = 0.022$). Navius produced higher protein than all other herbicides, but only at Francis and only in 2024 ($p < 0.001$; Fig. 13). Fertilizer had no detectable effect.

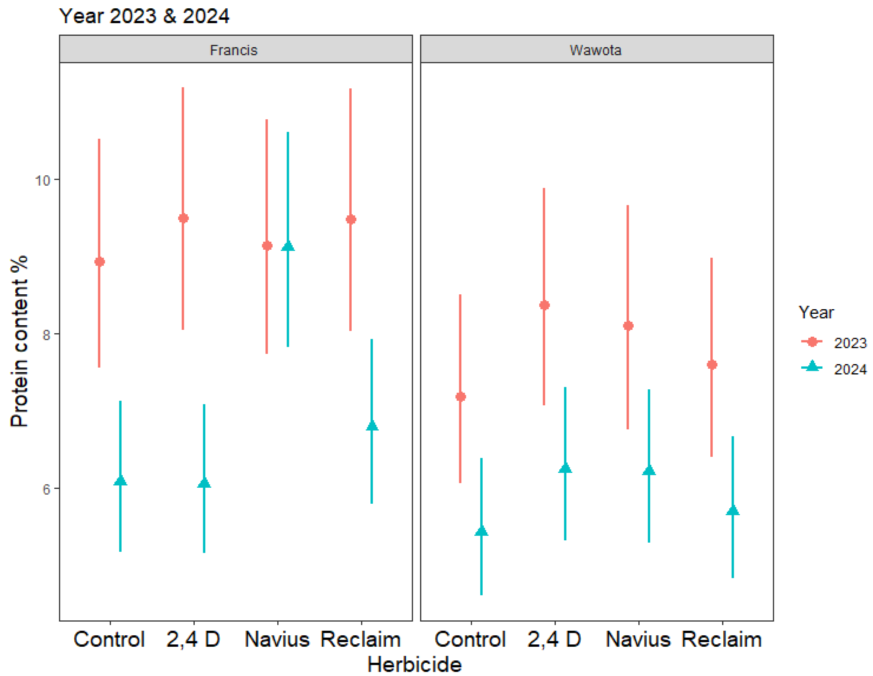


Figure 23 *Linear mixed model predicting the effects of herbicide treatments on forage protein content (%) in 2023 and 2024 at the Francis and Wawota sites.*

Table 14. Mixed model results testing treatment effects on plants protein content (type III analysis of variance table with Satterthwaite's method).

Years 2023–2024 – log(protein.percent + 1) ~ Herbicide*Year*Site + Fertilizer*Site*Year + (1|Plot)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 171.860	5.412	**0.001**
Year	1, 117.700	138.432	**< 0.001**
Site	1, 172.130	29.599	**< 0.001**
Fertilizer	3, 171.280	1.084	0.357
Herbicide: Year	3, 117.560	4.406	**0.006**
Herbicide: Site	3, 171.860	2.132	0.098
Year: Site	1, 117.700	0.018	0.893
Site: Fertilizer	3, 171.280	0.705	0.551
Year: Fertilizer	3, 117.190	0.297	0.827
Herbicide: Year: Site	3, 117.560	3.315	**0.022**
Year: Site: Fertilizer	3, 117.190	2.484	0.064

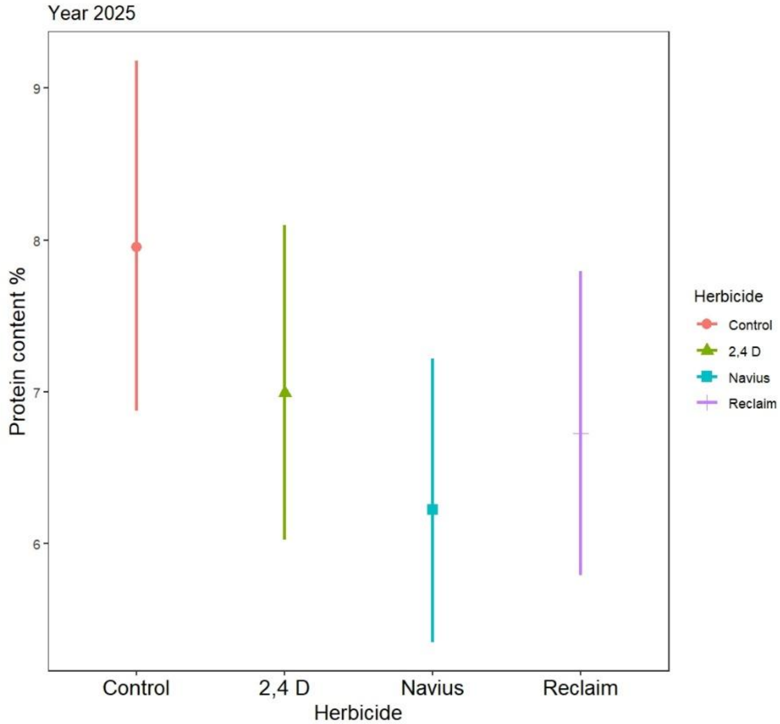


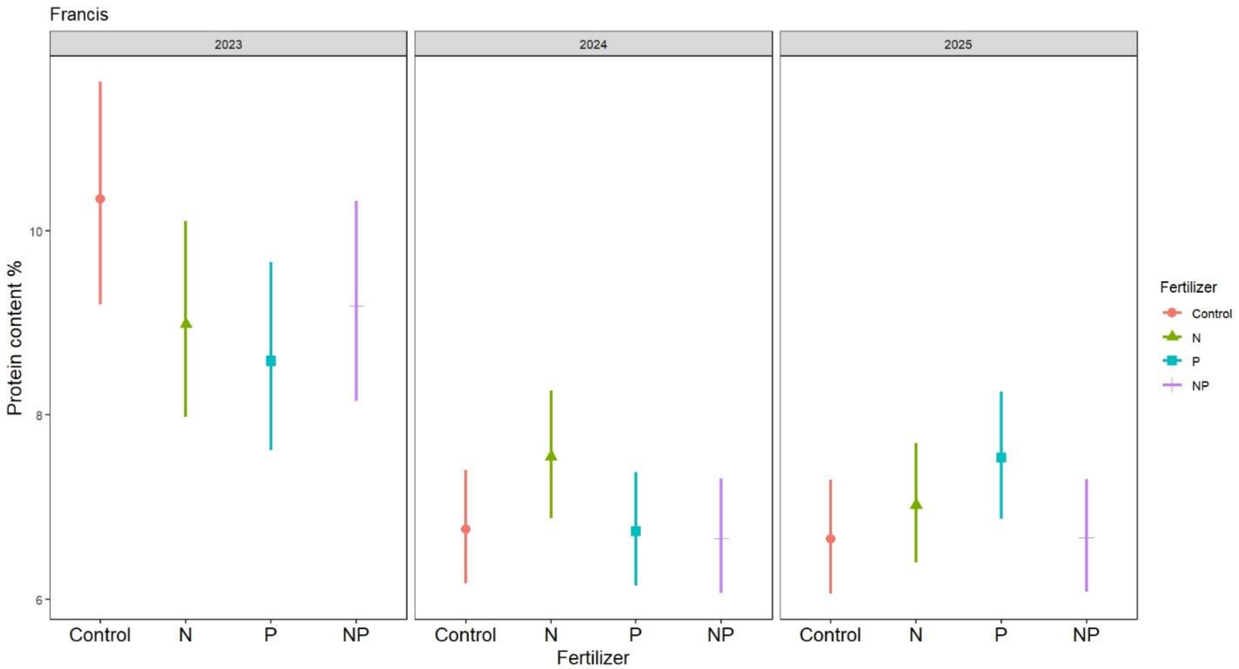
Figure 14 *Predicted crude protein concentration (%) in 2025 at the Francis site as influenced by herbicide treatments. Points represent estimated marginal means ± SE from the mixed-effects model.*

Crude protein concentration in 2025 was significantly influenced by herbicide treatment ($F = 6.89$, $p < 0.001$), whereas fertilizer ($p = 0.087$), harvest treatment ($p = 0.254$), and their interactions were not significant (Table 15). Mean protein concentrations ranged from approximately 6 to 8%. The untreated control tended to have the highest crude protein concentration, whereas Navius-treated plots had the lowest values. ReClaim and 2,4-D produced intermediate responses (Fig. 14).

Differences in crude protein among herbicide treatments likely reflect changes in plant community composition following absinthe suppression rather than direct effects of herbicides on forage quality. Herbicide treatments that promoted grass recovery may have altered the relative abundance of plant functional groups contributing to harvested biomass. However, the magnitude of these differences was relatively small, indicating that herbicide selection had a greater influence on vegetation composition and biomass production than on forage protein concentration.

Table 15. Mixed model results testing treatment effects on crude protein concentration (%) in 2025 at the Francis site (Type III analysis of variance table with Satterthwaite's method).

Effect	**DF (num, den)**	**F value**	***Pr(>F)***
Herbicide	3, 59.014	6.890	**< 0.001**
Fertilizer	3, 59.028	2.296	0.087
Harvest	1, 59.007	1.329	0.254
Herbicide × Fertilizer	9, 59.029	1.976	0.058
Herbicide × Harvest	3, 59.020	0.131	0.941
Fertilizer × Harvest	3, 59.035	2.291	0.087
Herbicide × Fertilizer × Harvest	9, 59.027	0.569	0.817



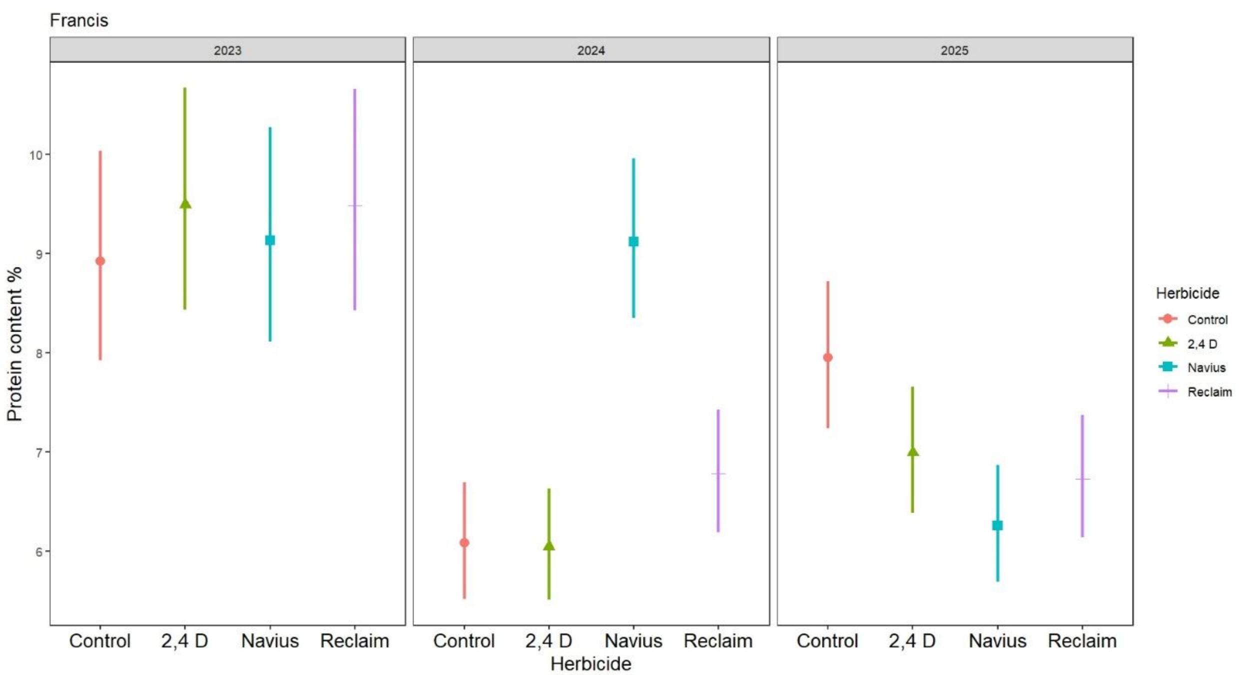


Figure 15 *Predicted crude protein concentration (%) at the Francis site from 2023 to 2025 as influenced by fertilizer and herbicide treatments. Points represent estimated marginal means ± SE.*

Across the three-year period, crude protein concentration was strongly affected by year ($F = 39.17$, $p < 0.001$), whereas herbicide ($p = 0.147$) and fertilizer ($p = 0.548$) main effects were not significant (Table 16). A significant Fertilizer × Year interaction was detected ($F = 2.36$, $p = 0.032$), indicating that fertilizer responses varied among years. Protein concentrations were highest in 2023, declined substantially in 2024, and remained relatively low in 2025 (Fig. 15). Fertilizer treatments produced only modest differences within individual years. Year-to-year environmental variation had a much stronger influence on crude protein concentration than any management treatment. The decline in protein concentration after 2023 likely reflects differences in growing conditions and forage composition among years. Although fertilizer effects varied slightly across years, these responses were inconsistent and relatively small compared with annual variation. Overall, forage quality metrics appeared less responsive to management treatments than biomass responses, suggesting that herbicide and fertilizer treatments primarily influenced productivity and community composition rather than nutritive value.

Table 16. Mixed model results testing treatment effects on crude protein concentration (%) at the Francis site from 2023 to 2025 (Type III analysis of variance table with Satterthwaite's method).

Effect	DF (num, den)	F value	*Pr(>F)*
Herbicide	3, 185.030	1.809	0.147
Fertilizer	3, 185.030	0.709	0.548
Year	2, 185.040	39.166	**< 0.001**
Herbicide × Fertilizer	9, 185.030	0.939	0.492
Herbicide × Year	6, 185.020	11.765	**< 0.001**
Fertilizer × Year	6, 185.010	2.356	**0.032**
Herbicide × Fertilizer × Year	18, 185.020	0.935	0.538

Economic analysis

In Francis, Control (No Herbicide + No Fertilizer) had a net return of $382/ha (rounded to nearest whole dollar). Three treatments had net returns exceeding Control: 2,4-D + No Fertilizer ($646/ha) > Reclaim + No Fertilizer ($528/ha) > 2,4-D + N ($387/ha). In Lanigan, Control had a 1 yr net return of $281/ha. None of the treatments exceeded control; 2,4-D + No Fertilizer ($33/ha) and ReClaim II + No Fertilizer ($18/ha) were the only two treatments with a positive net return. In Parkbeg, Control had a 1 yr net return of $47/ha. No herbicide treatments exceeded control. Only 2,4-D + No Fertilizer had a positive 1 yr net return ($19/ha). In Wawota, Control had a 2 yr net return of $366/ha. No herbicide treatments had net returns exceeding control. Herbicide treatments with positive net returns included: 2,4-D + No Fertilizer ($343/ha) > Reclaim II + No Fertilizer ($253/ha) > Navius Flex + No Fertilizer ($139/ha).

Table 17. Cumulative net returns ($/ha) by site and absinthe treatment method (Cut Treatment)†

Herbicide	***Fertilizer***	***Francis***	***Lanigan***	***Parkbeg***	***Wawota***
# of Years		**3**	**1**	**1**	**2**
No Herbicide	**No Fertilizer (Control)**	**381.88**	**280.76**	**46.88**	**365.60**
	N	141.45	-224.55	-454.44	-265.29
	P	-403.93	-528.42	-699.10	-422.21
	N + P	-930.93	-1104.64	-1207.10	-918.69
2,4-D	No Fertilizer	645.83	33.44	18.78	342.64
	N	387.33	-346.04	-489.99	-47.19
	P	-292.39	-587.26	-750.85	-491.22
	N + P	-447.63	-1159.83	-1205.98	-915.84
Navius Flex	No Fertilizer	273.20	-2.07	-76.37	138.93
	N	-125.71	-543.85	-537.11	-83.32
	P	-472.42	-743.93	-827.72	-474.94
	N + P	-536.26	-1292.61	-1308.90	-838.09
ReClaim II	No Fertilizer	528.30	17.92	-45.90	252.78
	N	300.38	-455.62	-537.56	-126.69
	P	-132.27	-609.83	-783.15	-369.11
	N + P	-425.18	-1268.30	-1297.28	-690.45

† Cumulative grass + legume biomass (kg/ha) valued at $0.09/kg; Francis had 3 yr biomass data, Lanigan and Parkbeg 1 yr, and Wawota 2 yr.

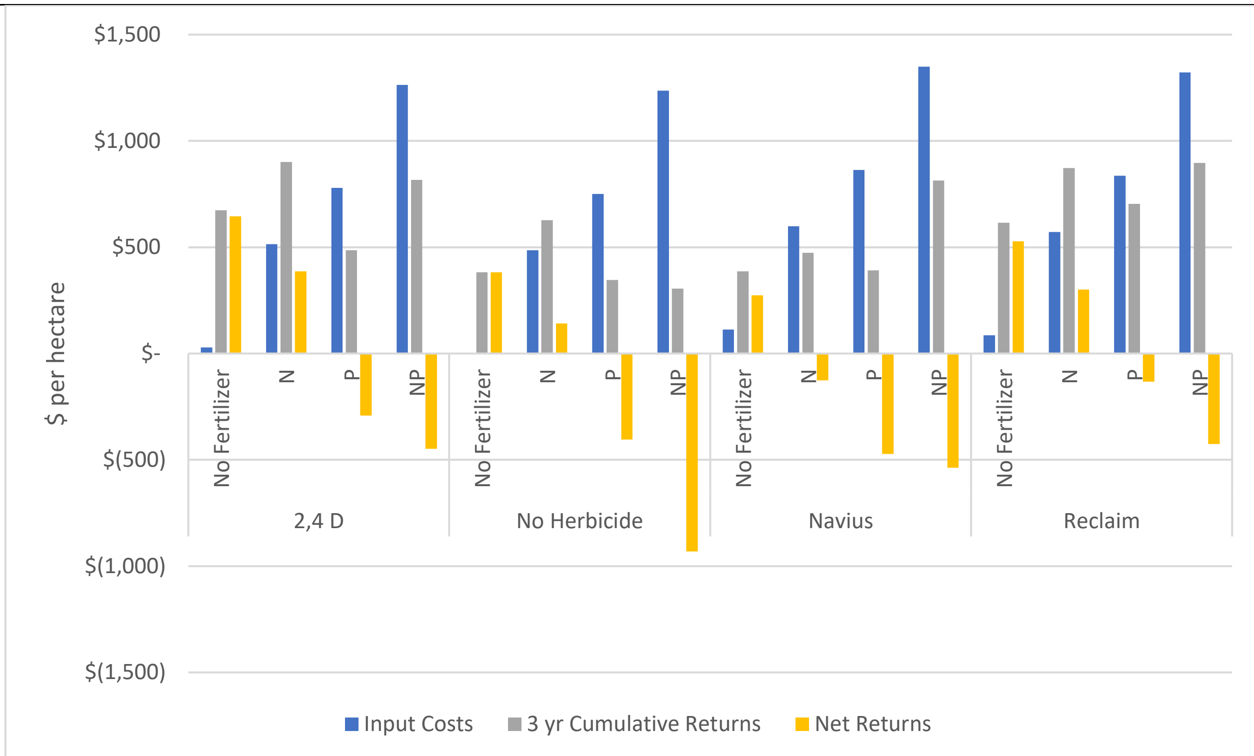


Figure 16. 3 Yr Cumulative Net Returns by Absinthe control treatment at Francis†

†Herbicide applied June 8-22, 2023. Biomass clips taken early August 2023, 2024 and 2025. Grass and legume biomass valued at $0.09/kg. Cost of application excluded.

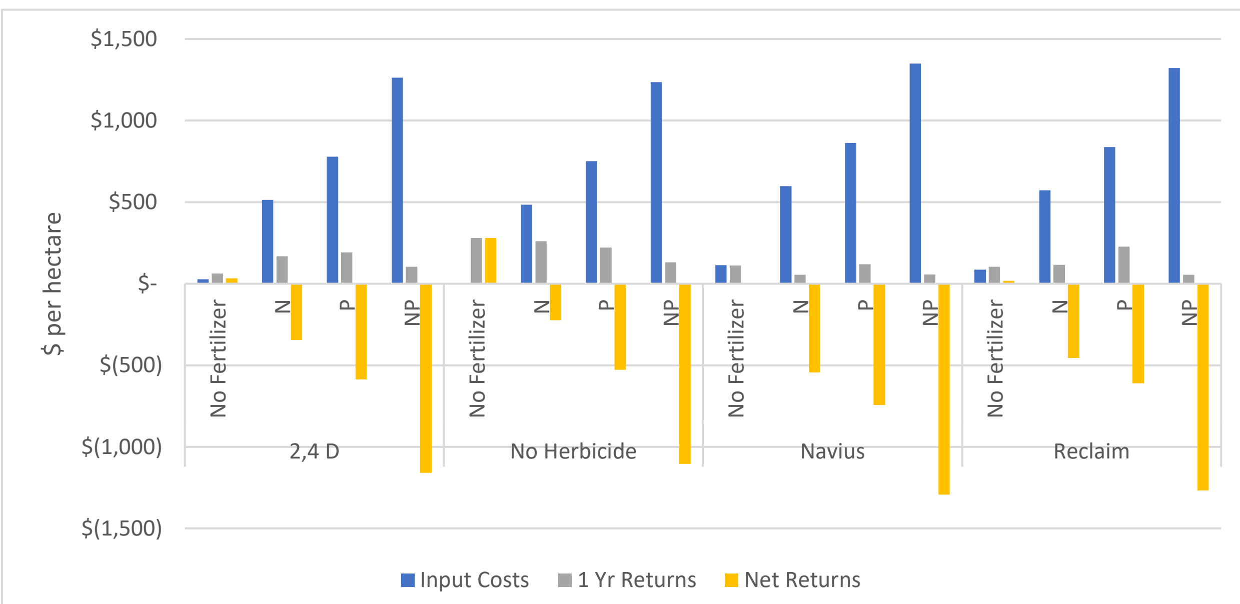


Figure 17. *Net Returns by Absinthe control treatment at Lanigan 5 weeks after application †*

† Herbicide applied June 8-22, 2023. Biomass clips taken early August 2023. Grass and legume biomass valued at $0.09/kg. Cost of application excluded.

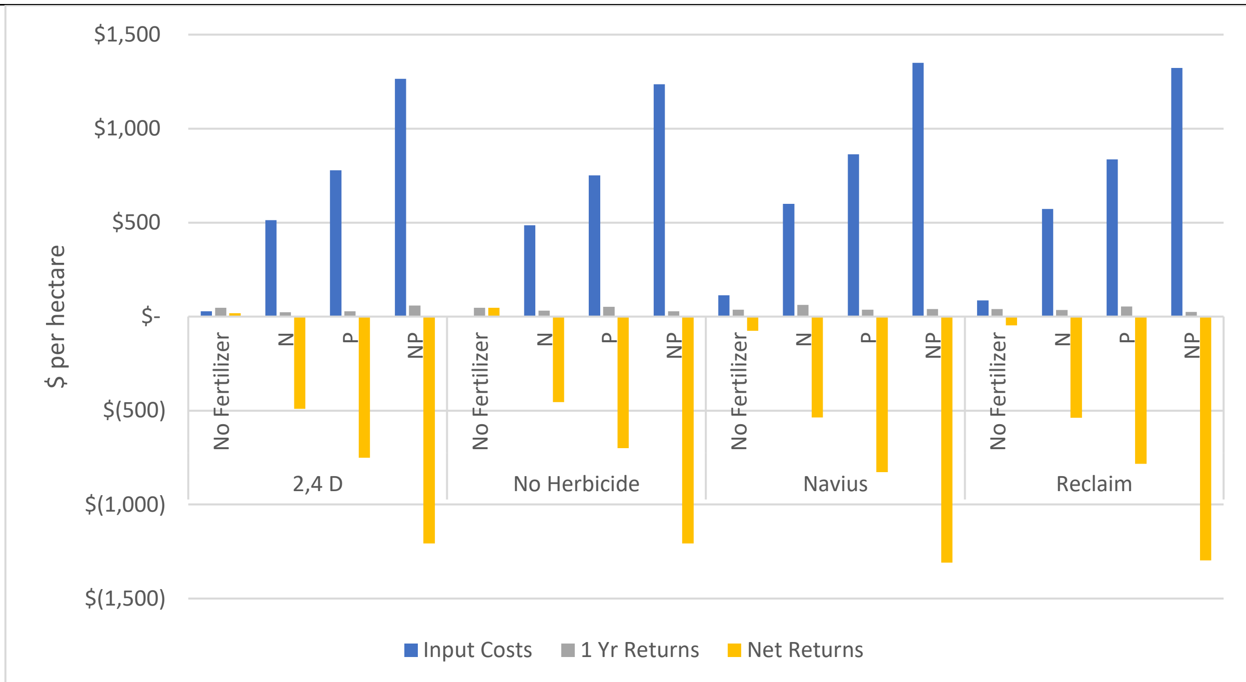


Figure 18. *Net Returns by Absinthe control treatment at Parkbeg 5 weeks after application* †

† Herbicide applied June 8-22, 2023. Biomass clips taken early August 2023. Grass and legume biomass valued at $0.09/kg. Cost of application excluded.

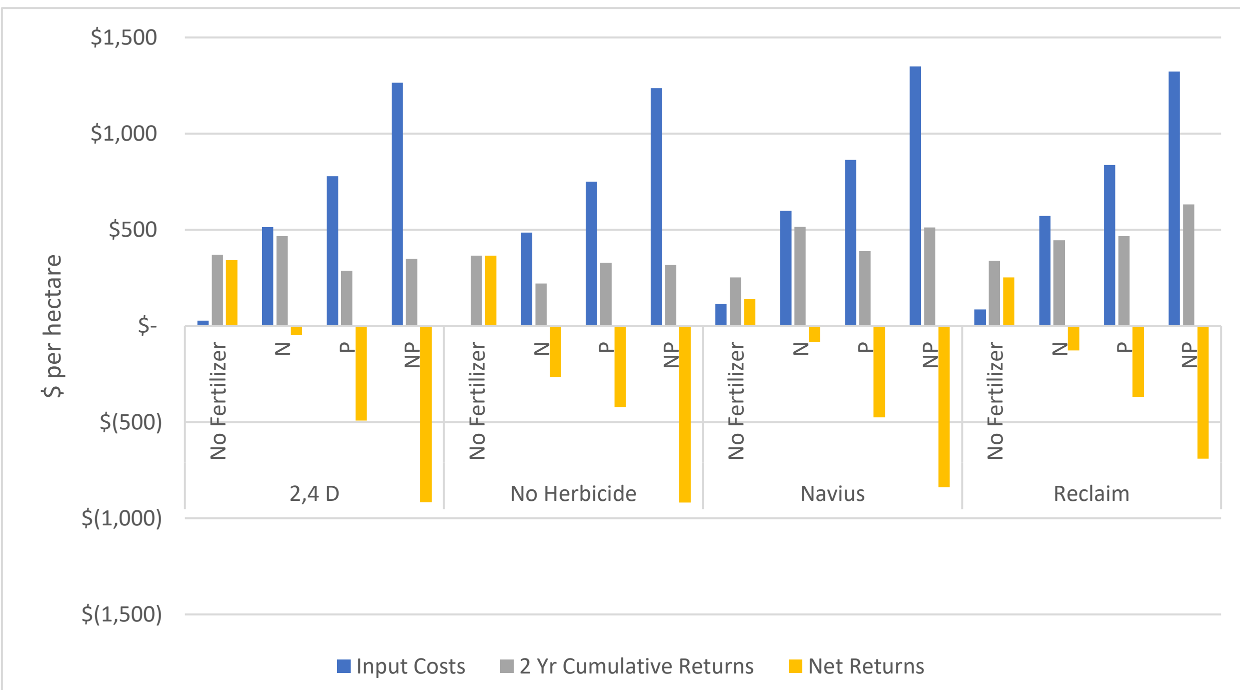


Figure 19. *2 Yr Cumulative Net Returns by Absinthe control treatment at Wawota* †

† Herbicide applied June 8-22, 2023. Biomass clips taken early August in 2023 and 2024. Grass and legume biomass valued at $0.09/kg. Cost of application excluded.

The observations above were calculated using the average yield from each treatment at each site. Using RStudio V. 2025.05.01+513, we analyzed if there was a significant difference in revenue across the treatments at each site using the Kruskal-Wallis test.[1] If $P \le 0.05$ there is a statistical difference between the groups. We tested the difference in net returns across treatments for all sites pooled together, and then each site individually. Results are reported in Table 4. There was a significant difference in cumulative net returns across treatments for all sites.

Table 18. Results for the Kruskal-Wallis test statistics and associated P-value for testing the difference in net returns across treatments for each site.

Net returns by site	No. of years	P-Value
Francis	3	0.000
Wawota	2	0.000
Lanigan	1	0.000
Parkbeg	1	0.000

As shown in Table below, absinthe in the harvested/cut Control (no herbicide + no fertilizer) ranged by plot (n=3) and site, averaging 14 to 31%. At Francis, absinthe in the control plots ranged from 9% to 43% of total biomass with a mean of 27%. Total weeds (absinthe + other weeds) averaged 31 to 46% across the four sites. If a herbicide treatment had a lower absinthe presence than the 2023 Baseline (No Treatment + No Fertilizer), the herbicide treatment was considered effective at reducing absinthe and the treatment cost (**Error! Reference source not found.**) incurred in Year 1 was divided by the absolute change in absinthe to calculate a cost per unit decrease in absinthe presence. For example, if the 2023 Baseline was 30% and a herbicide treatment costing $100/ac had 5% absinthe in the final biomass sample taken, the absinthe decreased 25 percentage points and the cost per unit decrease would be $4/ac ($100/25).

Table 19. Absinthe presence (g/m^2 as % of total biomass) in control plots (n=3) (no herbicide + no fertilizer + cut) by site in 2023

Absinthe presence, %	Francis	Lanigan	Parkbeg	Wawota
Min	9%	2%	0%	18%
Max	43%	30%	61%	45%
Mean	27%	14%	25%	31%
SD	0.17	0.15	0.32	0.13

At Francis, eight of the treatments had absinthe presence below Control (27.5%) at Francis (Table). The most cost-effective herbicide treatment at Francis was ReClaimII + No Fertilizer ($3.38 per unit of decrease achieved or $0.93 per percent). The ReClaim II + No Fertilizer treatment measured 2% absinthe in 2025 biomass clips for a decrease of 93% (-25.6 points), followed by 2,4-D + N ($6.91 per % decrease) and 2,4-D + P ($8.13 per % decrease).

[1] The Kruskal-Wallis test is appropriate when determining if there are differences among three or more groups, and the data is not normally distributed (McClenaghan, 2024).

Table 20. Change in absinthe presence (2023 Control vs 2025 treatments) and the associated cost per percent decrease in absinthe presence for Francis site.

Herbicide	Fertilizer	Absinthe Presence in 2025	Absolute Change†	Percent Change	Cost per point decrease	Cost per % decrease
No Herbicide	**No Fertilizer**	49%	+21.7	+78%	Baseline	
	N	5%	-22.2	-81%	21.91	6.01
	P	38%	+8.8	+56%		
	N + P	46%	+15.8	+31%		
2,4-D	No Fertilizer	32%	+4.9	+17%		
	N	7%	-20.4	-74%	25.20	6.91
	P	2%	-26.3	-96%	29.60	8.13
	N + P	14%	-15.0	-55%	84.14	22.99
Navius Flex	No Fertilizer	48%	+20.8	+75%		
	N	52%	+25.0	+90%		
	P	64%	+36.9	+133%		
	N + P	28%	0.0	-1%		
ReClaim II	No Fertilizer	2%	-25.6	-93%	3.38	0.93
	N	15%	-12.2	-45%	47.06	12.82
	P	0%	-27.5	-100%	30.46	8.37
	N + P	0%	-27.5	-100%	48.12	13.22

† Baseline (No Herbicide + No Fertilizer) averaged 27.5% absinthe biomass in Aug 2023. A positive number indicates absinthe increased (undesirable outcome), a negative value indicates absinthe as a percent of biomass decreased (desirable outcome). If absinthe presence decreased, the treatment cost per hectare was divided by the decrease to calculate a cost per unit decrease (right-most column).

At Lanigan, six treatments had lower absinthe presence than control (14%) when biomass was measured five weeks after application. The most cost-effective herbicide for Lanigan (Table 7) was ReClaim II + No Fertilizer ($0.86 per % decrease) with no absinthe measured in August 2023 plots (5 weeks after treatment).
At Parkbeg, eight herbicide treatments had no absinthe detected in biomass clips 5 weeks after treatment (e.g. 100% control). Three treatments with the lowest cost per percent decline in absinthe were: 2,4-D + No Fertilizer ($0.28) > ReClaim II + No Fertilizer ($0.86) > Navius + No Fertilizer ($2.30) (

Table).

Table 21. Change in absinthe presence (Control vs Herbicide treatments) and the associated cost per unit decrease in absinthe presence for Lanigan site.

Herbicide	Fertilizer	Absinthe Presence in Aug 2023	Absolute Change†	Percent Change	Cost per point decrease	Cost per % decrease
No Herbicide	**No Fertilizer**	**14%**	**Baseline**	0%		
	N	32%	+18.6	+135%		
	P	16%	+2.6	+19%		
	N + P	36%	+22.5	+165%		
2,4-D	No Fertilizer	47%	+33.2	+242%		
	N	10%	-3.2	-24%	158.47	21.37
	P	5%	-9.1	-67%	85.43	11.62
	N + P	16%	+2.6	+19%		
Navius Flex	No Fertilizer	14%	-0.1	-1%	1744.98	142.86
	N	35%	+21.4	+157%		
	P	6%	-7.1	-53%	120.88	16.42
	N + P	46%	+32	+236%		
ReClaim II	No Fertilizer	0%	-13.6	-100%	6.35	0.86
	N	3%	-10.3	-76%	55.55	7.56
	P	16%	+2.1	+15%		
	N + P	27%	+13.0	+94%		

† Baseline (No Herb/Fert) had 14% absinthe biomass in Aug 2023. A positive number indicates absinthe increased (undesirable outcome), a negative value indicates absinthe as a percent of biomass decreased (desirable outcome). If absinthe presence decreased, the treatment cost per hectare was divided by the decrease to calculate a cost per unit decrease (right-most column).

Table 22. Change in absinthe presence (Control vs Herbicide treatments) and the associated cost per unit decrease in absinthe presence for Parkbeg site.

Herbicide	Fertilizer	Absinthe Presence in Aug 2023	Absolute Change†	Percent Change	Cost per point decrease	Cost per % decrease
No Herbicide	**No Fertilizer**	**25%**	**Baseline**			
	N	54%	+28.45	+112%		
	P	9%	-16.73	-66%	44.84	11.37
	N + P	35%	+9.89	+39%		
2,4-D	No Fertilizer	0%	-25.35	-100%	1.11	0.28
	N	0%	-25.35	-100%	20.27	5.14
	P	0%	-25.35	-100%	30.72	7.79
	N + P	0%	-25.35	-100%	49.87	12.64
Navius Flex	No Fertilizer	13%	-12.53	-49%	9.06	2.30
	N	0%	-25.35	-100%	23.63	5.99
	P	3%	-22.83	-90%	37.84	9.59
	N + P	10%	-15.42	-61%	87.51	22.19
ReClaim II	No Fertilizer	0%	-25.35	-100%	3.41	0.86
	N	0%	-25.35	-100%	22.56	5.72
	P	0%	-25.35	-100%	33.01	8.37
	N + P	3%	-21.89	-86%	60.41	15.32

† Baseline (No Herb/Fert) had 25% absinthe biomass in Aug 2023. A positive number indicates absinthe increased (undesirable outcome), a negative value indicates absinthe as a percent of biomass decreased (desirable outcome). If absinthe presence decreased, the treatment cost per hectare was divided by the decrease to calculate a cost per unit decrease (right-most column).

Table 23. Change in absinthe presence (2023 Control vs Herbicide treatments) and the associated cost per decrease in absinthe presence for Wawota site.

Herbicide	Fertilizer	Absinthe Presence in Aug 2024	Absolute Change†	Percent Change	Cost per point decrease	Cost per % decrease
No Herbicide	**No Fertilizer**	**29.6%**	**-1.65**	**-5%**	**Baseline**	
	N	55.7%	+24.46	+80%		
	P	40.6%	+9.34	+31%		
	N + P	23.4%	-7.81	-24%	158.19	50.59
2,4-D	No Fertilizer	1.3%	-29.92	-96%	0.94	0.30
	N	12.9%	-18.34	-58%	28.02	8.80
	P	16.0%	-15.27	-48%	50.98	16.06
	N + P	9.0%	-22.22	-71%	56.90	17.83
Navius Flex	No Fertilizer	34.7%	+3.49	+12%		
	N	3.1%	-28.17	-90%	21.26	6.65
	P	9.1%	-22.11	-71%	39.07	12.24
	N + P	0.0%	-31.24	-100%	43.20	13.49
ReClaim II	No Fertilizer	3.4%	-27.85	-89%	3.10	0.97
	N	0.0%	-31.24	-100%	18.31	5.72
	P	0.0%	-31.24	-100%	26.79	8.37
	N + P	0.2%	-31.05	-99%	42.59	13.30

† Baseline (No Herb/Fert) had 31% absinthe biomass in Aug 2023. A positive number indicates absinthe increased (undesirable outcome), a negative value indicates absinthe as a percent of biomass decreased (desirable outcome). If absinthe presence decreased, the treatment cost per hectare was divided by the decrease to calculate a cost per unit decrease (right-most column).

At Wawota, 2,4-D + No Fertilizer achieved a 96% reduction in absinthe mass (Baseline had 31% absinthe in Aug 2023 vs 1.3% in 2,4-D + No Fertilizer in Aug 2024) which works out to $0.30 per percent decrease. ReClaim II + No Fertilizer cost $0.97 per percent decrease (89% decrease with 3.4% absinthe in total biomass 14 months after treatment).

ReClaim was found to provide effective herbicide for absinthe control 12 months after treatment in a ADOPT study with four sites ranging in absinthe canopy cover of 4 to 12.5% (Lardner et al, 2014). In that study Reclaim cost $105/ha ($42.50/ac) and reduced absinthe canopy cover 13.2 points or 99% (from 13.3% to 0.1%). The Control treatment had 8.2% absinthe in its canopy cover at pre-treatment and 15.1% after 12 months.

To test if there was a significant difference in the cost per unit decrease in absinthe coverage across the treatments for each site, we use the Kruskal-Wallis test. The cost per unit decrease was calculated for each treatment block individually. The amount of absinthe present for each treatment was subtracted from the control (No Herbicide + No Fertilizer) for its corresponding block (i.e. Francis: 2024 Block F1 Plot 126 Reclaim II + P subtracted from 2022 Block F1 Plot 187 No Herbicide + No Fertilizer). There were 384 plots (4 sites x 3 replicates x 32 treatment plots), although we only tested plots that were cut. Each site was tested separately. Results can be found in Table . There was a significant difference in treatment cost per unit decrease in absinthe coverage for Wawota and Parkbeg, but not for Francis and Lanigan.

Table 24. Results for the Kruskal-Wallis test statistics and associated p-value for testing the difference in cost per unit decrease in absinthe coverage across treatments for each site.

Location	No. of years	P-Value
Francis	3	0.066
Wawota	2	0.027
Lanigan	1	0.595
Parkbeg	1	0.001

Note: Significance Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.'; - : missing value.

Discussion

Herbicide treatment was the primary driver of community reassembly, as it directly affected many species and altered competitive hierarchies within the plant community. By reducing absinthe abundance, herbicide applications released resident species from competitive suppression, which increased grass biomass; however, this release came with trade-offs, as non-target effects also reduced legume biomass and overall species diversity. Reclaim provided the strongest absinthe control, but differences among herbicides were largely attributable to residual longevity, which prolonged suppression but also extended non-target impacts. In contrast, fertilizer and rest did not directly suppress absinthe; instead, they which species increased in abundance. This indicates that these tools can still help achieve specific management goals such as promoting grass production or facilitating legume recovery when paired with a herbicide whose efficacy and non-target effects align with those objectives.

Herbicide effects

Herbicide treatment was the most consistent mechanism for reducing absinthe biomass, with residual herbicides producing stronger and more persistent suppression than non-residual herbicides. Residual products such as aminopyralid provide extended control of broadleaf weeds through both post-emergence activity and residual soil activity (Bork et al., 2023; Enloe et al., 2007). This persistence prolonged the period during which absinthe was suppressed, effectively extending the window of opportunity for establishment by other species in the plant community.

Ecologically, the extended disturbance caused by residual herbicides facilitated competitive release for grasses. When dominant invaders are suppressed, previously limited resources such as light, nutrients, and space become available to the remaining community (Catford et al., 2009; Davis et al., 2000). In our system, according to the fluctuating resource hypothesis, herbicide-induced mortality likely reduced resource uptake by absinthe, creating a temporary increase in resource availability that grasses could exploit (Davis et al., 2000; McIver et al., 2014). Residual herbicides therefore appear to have influenced community assembly by allowing grasses more time to pre-empt resources and occupy physical space before absinthe could re-establish, strengthening their competitive position and reducing reinvasion risk.

In contrast to residual herbicides, the non-residual herbicide 2,4-D produced shorter suppression periods. Although it is effective at reducing absinthe initially, its lack of persistence means that reinvasion risk is higher because the invader can recover once the chemical disturbance pulse ends (DiTomaso, 2000; Rinella et al., 2009). Shorter disturbances may therefore require repeated applications to maintain control (Gaskin et al., 2021; Malis, 2023).

Although residual herbicides have a definite advantage for controlling absinthe, there are important trade-offs because desirable broadleaf species are also lost. In pasture systems, legumes are particularly relevant non-targets. Previous work has shown that aminopyralid-based control of spotted knapweed (*Centaurea maculosa*) reduced non-target forb abundance for multiple years in Montana grasslands (Rinella et al., 2009). Even 2,4-D can cause substantial suppression desirable legumes, although often less severely than more aggressive mixtures or herbicides (Davy et al., 2015; Greene et al., 2022; McCurdy et al., 2013), consistent with our results. The difference between residual and non-residual herbicides in this experiment can therefore be interpreted primarily as a difference in disturbance duration affecting all aspects of the community and its ability to recover. Consequently, use of non-residual herbicides may still be the best option when minimizing non-target effects.

Herbicide effects also varied across sites and years, suggesting that abiotic factors (local site conditions and time since application) also influenced the strength of outcomes. For absinthe, herbicide efficacy differed between Francis and Wawota and changed from 2023 to 2024. For grasses, herbicide had little effect on biomass in the first year, but by the second year grasses responded positively to herbicide treatments. The magnitude of this increase varied across sites and harvest contexts, reflecting differences in local conditions and competitive environments. Wawota had greater initial absinthe abundance, almost no legumes, and a history of disturbance associated with nearby gravel extraction, which may have altered both the degree of invader suppression and the capacity of grasses to respond following release from competition.

Fertilizer effects

Fertilizer treatments generally had limited direct effects on absinthe suppression. Nutrient addition alone rarely eliminates established perennial invaders: When an invasive species already occupies space and captures resources efficiently, increasing nutrient supply does not necessarily alter competitive interactions. Instead, fertilization often increases total productivity of the community rather than selectively disadvantaging the invader (Lardner et al., 2014; Tognetti et al., 2021). Vegetation responses were more apparent after herbicide reduced absinthe, consistent with the idea that nutrient additions are more likely to influence community recovery once competitive release has already occurred. Established perennial forbs often possess deep or extensive root systems that allow them to access resources beyond the primary rooting zone of grasses, which may reduce the ability of fertilization to alter competitive balance (Casper & Jackson, 1997; Kulmatiski & Beard, 2013).

Nitrogen fertilizer functioned primarily as an amplifier of grass recovery. Grass biomass increased most strongly when nitrogen was applied after herbicide treatments had already reduced absinthe abundance, consistent with Aulakh (2020) and You et al. (2017). This pattern suggests a two-phase process involving competitive release followed by nutrient-driven canopy expansion. In the first year, grasses responded weakly to nitrogen, likely because the plant community had not yet fully capitalized on the release of resources following absinthe suppression. This delayed response may also reflect the timing of fertilizer application and seasonal moisture constraints if limited moisture reduced plant capacity to capitalize on added nutrients. However, herbicide effects on absinthe were modest overall, and nitrogen did not intensify that suppression, indicating that nitrogen acted mainly to support post-treatment grass recovery rather than to improve weed control directly. Nitrogen addition also may have contributed to legume decline through indirect competitive mechanisms. This is directly relevant to our original objective of evaluating whether fertilizer could aid pasture recovery following absinthe suppression without compromising desirable functional groups. In grassland systems nitrogen enrichment often shifts competition toward grasses. For example, experimental nitrogen addition in temperate grasslands increased grass biomass and canopy height, intensifying light competition and reducing the abundance of legumes and other low-stature species (Hautier et al., 2009). Conversely, many legumes rely on symbiotic nitrogen fixation and may be disadvantaged because nitrogen fixation is a costly process and the nitrogen they produce is relatively less valuable when the resource is added in abundance (Vitousek & Howarth, 1991). Therefore, our results suggest that nitrogen-based fertilization may have undermined the goal of legume retention.

Although nitrogen may reduce legume recovery, legume biomass was higher in some phosphorus-containing treatments during later years, particularly following 2,4-D. This pattern suggests that phosphorus may have supported legume recovery where herbicide effects were shorter-lived and legumes were able to re-establish. Because biological nitrogen fixation of legumes requires substantial phosphorus for nodule formation and energy transfer, legumes often respond positively to phosphorus additions when soil phosphorus is limiting (Vitousek et al., 2002; Lüscher et al., 2014). Thus, phosphorus may facilitate legume growth; however, under residual herbicide regimes, phosphorus alone may not be sufficient to restore legume populations if there is active herbicide suppression.

The effectiveness of fertilization may depend strongly on the initial abundance of different functional groups within the community, as nutrient additions often amplify the growth of already dominant species rather than altering competitive structure. Because Lanigan was newly seeded and initially contained higher legume biomass than the other sites, its removal likely reduced our ability to evaluate whether legumes can recover more effectively in communities with greater initial legume abundance. The partial mitigation of 2,4-D effects by phosphorus at Lanigan in 2023 suggests that, if this site had remained in the dataset, later-year patterns may have shown greater evidence of legume recovery under short-lived herbicide pressure. This interpretation also highlights the importance of initial community composition in shaping treatment responses.

While we found little evidence of co-limitation in the experiment, combined nitrogen and phosphorus fertilization produced a detectable absinthe suppression effect at Francis 2025. As grasses did not show any biomass response suggesting co-limitation of their growth, the mechanism behind this enhanced absinthe suppression is unclear. It is possible, however, that the addition of phosphorus allowed for more diffuse competitive suppression of absinthe, mediated through both the grasses and any other broadleaf species that recovered (Bennett et al., 2014). It seems unlikely that legumes contributed to this suppression, however, as their abundance was reduced in all treatments that included nitrogen fertilizer.

Rest treatment effects

The one-year rest treatment had minimal effects on vegetation dynamics. This result indicates that short-term cessation of biomass removal did not alter processes governing competition between absinthe and neighboring vegetation. With their basal meristems, grasses are well adapted to periodic defoliation and most tame forage grasses have been selected for regrowth capacity (Rauf et al., 2016) and a single additional defoliation event is unlikely to reduce their abundance significantly. In fact, plots that continued to be cut tended to maintain higher grass biomass. This may reflect reduced accumulation of standing dead material and litter under continued defoliation, as well as maintaining the forage in a younger, more vegetative state. More targeted defoliation strategies such as repeated defoliation during vulnerable phenological stages, may influence invasive perennial forbs, but these approaches were outside the scope of this experiment. It is also unclear whether grazing would have a different effect than the cutting treatment. Grazing can influence plant communities through multiple mechanisms, including selective defoliation, trampling, canopy opening, and redistribution of nutrients (Milchunas & Lauenroth 1993). However, these processes depend strongly on grazing intensity, timing, and duration. A more fulsome understanding of the potential impacts of grazing would require consideration of each of these aspects.

Forage quality responses

Forage quality responses were less consistent than biomass and species richness responses. Relative feed value (RFV) and crude protein were influenced mainly by year and site conditions rather than by a consistent treatment effect. At Francis, where data were available across all three years, RFV declined substantially by 2025. Fertilizer affected RFV in 2025, with phosphorus tending to maintain higher RFV values, while nitrogen generally produced lower values. Herbicide and rest treatments had little direct effect on RFV in 2025.

Crude protein also varied strongly among years. Protein concentrations were highest in 2023 and declined in 2024 and 2025. In 2025, crude protein differed among herbicide treatments, with the untreated control tending to have the highest protein concentration and Navius the lowest. However, these differences were relatively small compared with the year-to-year variation.

Overall, forage quality metrics were less responsive to management treatments than biomass. This suggests that herbicide and fertilizer treatments primarily affected absinthe suppression, grass recovery, legume retention, and species richness, rather than consistently improving forage nutritive value. Phosphorus may help maintain forage quality under some conditions, likely by supporting higher-quality forage components such as legumes, but this response was not consistent enough to make fertilizer a stand-alone tool for improving forage quality.

Economic considerations

Among the treatments, herbicides applied alone generally provided the best return on investment. The best return on investment was for 2,4-D, followed by ReClaim II. This was especially obvious at the Francis site where three years of forage data was available, but similar patterns were found at the other sites. There was no obvious economic value to the fertilizer applications; however, these calculations do not account for any potential changes in legumes and are limited by the fact that fertilizer effects took time to accrue and three years of data were only available for one site. With respect to the cost per degree of absinthe control. ReClaim II tended to be more favorable than 2,4-D, likely owing to it persisting longer. In these scenarios, however, the fertilizers improved 2,4-D efficacy, but their value was lessened by the high cost of the fertilizer. Using bulk fertilizer pricing may improve the value of these treatments somewhat, although not likely to the extent that it matches ReClaim II applied without fertilizer.

Conclusions and Recommendations *(maximum 500 words)*

Highlight significant conclusions based on the findings of this project, with emphasis on the project objectives specified above. Provide recommendations for the application and adoption of the project findings.

Overall, the results suggest that herbicide duration determines how effectively the invader is suppressed, with residual herbicides providing longer term control. ReClaim II provided the most effective absinthe control but also limited the recovery of legumes, whereas 2,4-D provided less control but also more limited non-target effects. Fertilizers only slightly altered the effect of herbicides, as the exclusion of the absinthe provided competitive release, allowing other species to exploit newly available resources. Nitrogen functioned mainly as an amplifier of grass recovery after suppression, but also suppressed legumes, potentially reducing functionality and long-term productivity within pastures. Phosphorus, however, may help promote legume recovery if timed properly and a short-lived herbicide is used. Fertilizer usage, however, is unlikely to be economical.

From a management perspective, herbicide should remain the primary tool for absinthe control, but the choice of herbicide should depend on the restoration goal. Where absinthe densities are high and sustained suppression is the priority, Reclaim is the most reasonable option because it provided the most stable control across years at a cost only marginally greater than when using 2,4-D; however, managers should expect greater ecological costs, including reduced legume biomass, and slower recovery of plant diversity. Where the goal is to retain legumes and restore a more diverse pasture, 2,4-D is the better option because its effects were shorter lived and community recovery was faster, even though absinthe suppression was less persistent and follow-up treatment may therefore be required. Nitrogen should not be applied routinely after spraying when legume retention is a priority, because in this experiment it mainly amplified grass recovery and likely contributed to legume decline without clearly improving absinthe control. If fertilizer is used to support legume recovery, phosphorus is the more appropriate choice, particularly after short-lived herbicide treatment and at sites where legumes are already present. Thus, successful management depends not only on removing the invader but on anticipating how the plant community will reorganize afterward, ensuring that interventions support the desired ecological outcomes rather than unintentionally reinforcing new competitive imbalances.

Follow-up Research

Please identify if there is a need to conduct further research. Detail any further research, development and/or communication needs arising from this project.

Further research is needed to better evaluate longer-term recovery after herbicide treatment, especially at multiple sites, as the retention of only one site in this study is a major limitation. It is especially important that such work include sites where legumes are already present in reasonable quantities to better evaluate the potential for using phosphorus as a legume recovery tool. Such work should also better evaluate the timing of fertilizer application, as it is likely possible to apply fertilizer to better enable legume recovery.

Patents/ IP generated/ Commercialized Products

List any products developed from this research.

No patents, intellectual property, or commercialized products were generated from this project.

Sustainable Canadian Agricultural Partnership (Sustainable CAP) Performance Indicators

a) List of performance indicators for the entire lifespan of the project

Sustainable CAP Indicator	Total Number
Scientific publications from this project (List the publications under section b)	
• Published	0
• Accepted for publication	0 (One in review though)
Highly Qualified Personnel (HQP) trained during this project	
• Master's students	1
• PhD students	0
• Post docs	1
Knowledge transfer products developed based on this project (presentations, brochures, factsheets, flyers, guides, extension articles, podcasts, videos)[1]	2

[1] Please only include the number of unique knowledge transfer products.

b) List of scientific journal articles published/accepted for publication from this project. Please ensure that each line includes the following: **Title, Author(s), Journal, Date Published or Accepted for Publication and Link to Article (if available).** *Add additional lines as needed*.

1.
2.
3.
4.

Technology Transfer Activities

List any technology transfer activities. Include presentations to conferences, producer groups or articles published in magazines except scientific journals.

Results from this experiment have been included in an undergraduate class on invasive plant management, reaching ~ 60 students per year.

Results from this experiment have been summarized in a one-page infographic that will be distributed to producer groups upon revision.

Contributions and Support

List any industry contributions or support received.

In-kind support of herbicides and surfactants provided by Envu and Corteva.

Cash support of approximately $70,000 from Envu also enabled the hiring of an MSc student to work on the project.

Acknowledgements

Include actions taken to acknowledge support by the Ministry of Agriculture, the Canadian Agriculture Partnership (for projects approved between 2017 and 2023) and the Sustainable Canadian Agriculture Partnership (for projects approved between 2023 and 2028).

Acknowledgement of funding has been included in the acknowledgements section of the manuscript currently under review.

Appendices

Include any additional materials supporting the previous sections, e.g. detailed data tables, maps, graphs, specifications, literature cited (Use a consistent reference style throughout).

Table A1. Mixed model results testing treatment effects on absinthe biomass (type III analysis of variance table with Satterthwaite's method).

Year 1 – log(Absinthe.mass + 1) ~ Herbicide*Fertilizer*Site + (1|Block)

Effect	**Df (num, den)**	**F value**	***Pr(>F)***
Herbicide	3, 120	35.143	**2.257e-16**
Fertilizer	3, 120	1.219	0.306
Site	3, 8	10.248	**0.004**
Herbicide: Fertilizer	9, 120	0.762	0.652
Herbicide: Site	9, 120	1.021	0.428
Fertilizer: Site	9, 120	0.505	0.868
Herbicide: Fertilizer: Site	27, 120	1.055	0.405

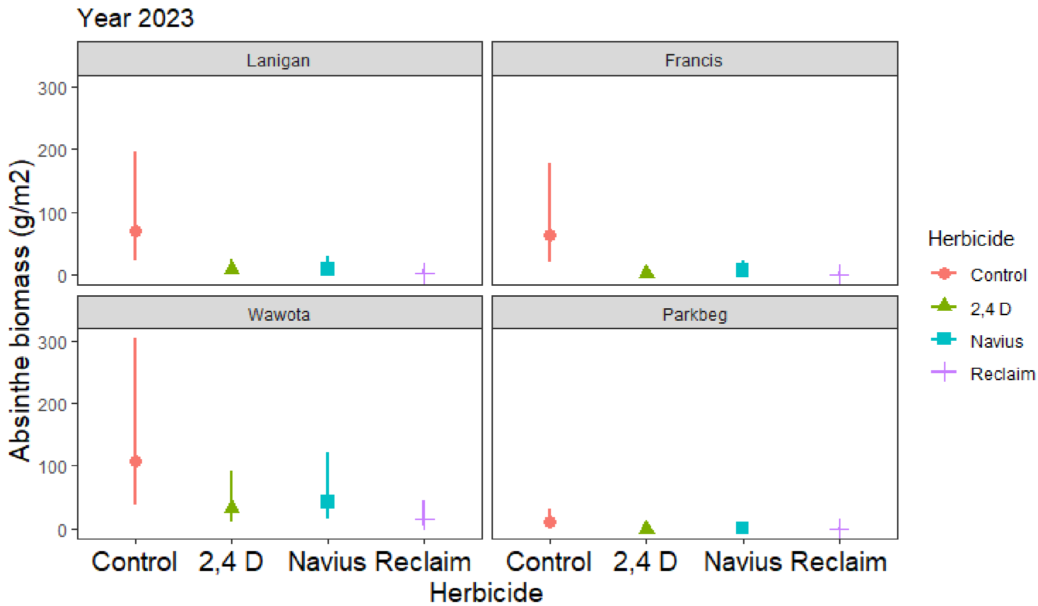


Figure A3 *Linear mixed model predicting the effects of herbicide treatment on absinthe biomass (g/m²) in 2023 across the four study sites; values shown are model-predicted means (± SE) averaged over random effects.*

Table A2. Mixed model results testing treatment effects on absinthe biomass (type III analysis of variance table with Satterthwaite's method).

Year 2 – log(Absinthe.mass + 1) ~ Fertilizer*Site*Harvest +Herbicide*Site*Harvest + Herbicide*Fertilizer*Harvest + (1|Block)

Effect	**Df (num, den)**	**F value**	***Pr(>F)***
Fertilizer	3, 142	0.189	0.904
Site	1, 4	0.001	0.984
Harvest	1, 142	0.060	0.806
Herbicide	3, 142	77.522	**< 0.001**
Fertilizer: Site	3, 142	0.672	0.570
Fertilizer: Harvest	3, 142	0.294	0.830
Site: Harvest	1, 142	0.413	0.521
Site: Herbicide	3, 142	1.313	0.273
Harvest: Herbicide	3, 142	0.144	0.933
Fertilizer: Herbicide	9, 142	1.374	0.205
Fertilizer: Site: Harvest	3, 142	1.712	0.167
Site: Harvest: Herbicide	3, 142	1.430	0.236
Fertilizer: Harvest: Herbicide	9, 142	1.700	0.094

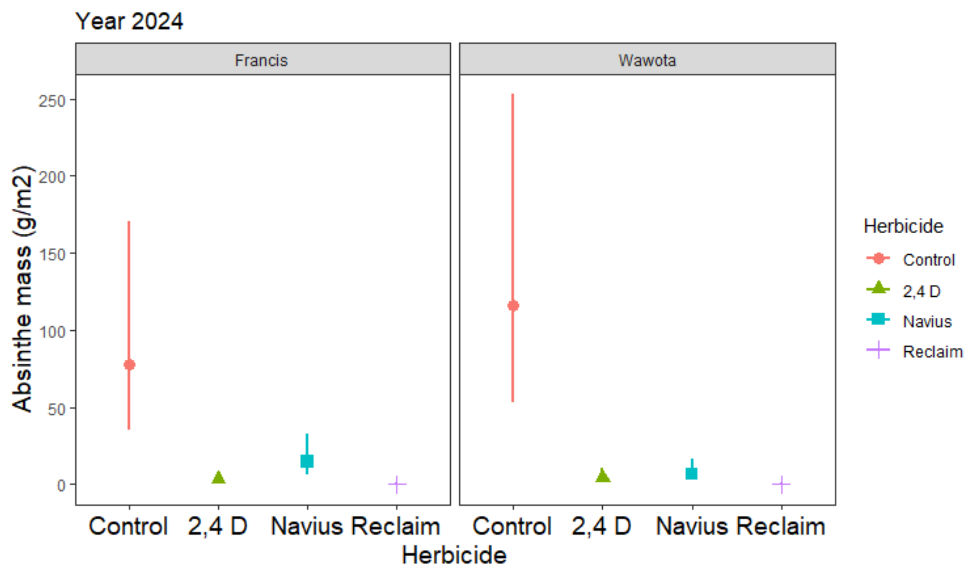


Figure A2 *Linear mixed model predicting the effects of herbicide treatments on absinthe mass (g/m²) in 2024 (top);*

Table A3. Mixed model results testing treatment effects on absinthe biomass (type III analysis of variance table with Satterthwaite's method).

Years 2023–2024 – log(Absinthe.mass + 1) ~ Herbicide*Year*Site+ Fertilizer + (1|Plot)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 185.110	53.710	**< 0.001**
Year	1, 113.020	21.378	**< 0.001**
Site	1, 185.110	15.353	**< 0.001**
Fertilizer	3, 167.590	0.404	0.750
Herbicide: Year	3, 113.020	5.872	**< 0.001**
Herbicide: Site	3, 185.110	0.658	0.579
Year: Site	1, 113.020	30.149	**< 0.001**
Herbicide: Year: Site	3, 113.020	2.711	**0.048**

Table A4. Mixed model results testing treatment effects on grass biomass (type III analysis of variance table with Satterthwaite's method).

Year 1 – sqrt(Grass.mass) ~ Herbicide*Fertilizer*Site + (1|Block)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 120	2.323	0.078

Fertilizer	3, 120	1.280	0.284
Site	3, 8	14.825	**0.001**
Herbicide: Fertilizer	9, 120	1.533	0.144
Herbicide: Site	9, 120	0.574	0.816
Fertilizer: Site	9, 120	1.134	0.344
Herbicide: Fertilizer: Site	27, 120	0.940	0.556

Table A5. Mixed model results testing treatment effects on grass biomass (type III analysis of variance table with Satterthwaite's method).

Years 2023–2024 – sqrt(Grass.mass) ~ Herbicide*Fertilizer*Year + (1|Plot)

Effect	**Df (num, den)**	**F value**	***Pr(>F)***
Herbicide	3, 160.090	12.423	**< 0.001**
Fertilizer	3, 160.090	5.456	**0.001**
Year	1, 116.900	204.660	**< 0.001**
Herbicide: Fertilizer	9, 160.090	2.152	**0.028**
Herbicide: Year	3, 116.900	5.024	**0.003**
Fertilizer: Year	3, 116.900	1.488	0.221
Herbicide: Fertilizer: Year	9, 116.900	1.375	0.207

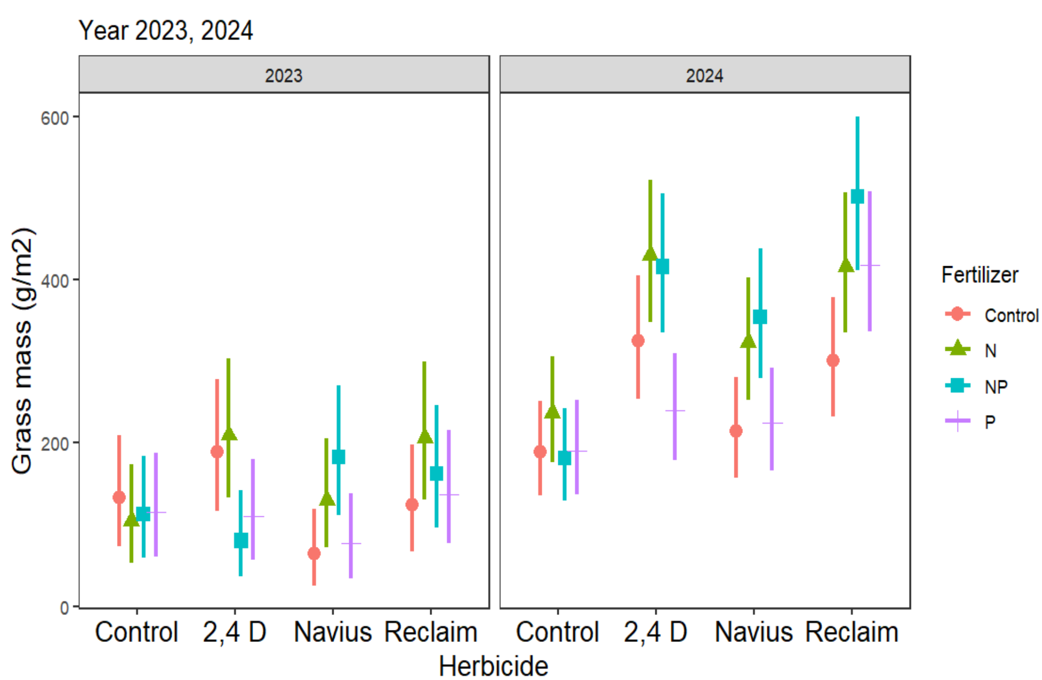


***Figure A3** Linear mixed model predicting the effects of herbicide and fertilizer treatments on grass mass (g/m²) in 2023 and 2024.*

Table A6. Mixed model results testing treatment effects on legume biomass (type III analysis of variance table with Satterthwaite's method).

Year 2 – log(Legume.mass + 1) ~ Fertilizer+ Herbicide*Site + Harvest + (1|Block)

Effect	**Df (num, den)**	**F value**	***Pr(>F)***

Fertilizer	3, 176	1.466	0.225
Herbicide	3, 176	24.84	**< 0.001**
Site	1, 4	4.236	0.109
Harvest	1, 176	0.102	0.749
Herbicide: Site	3, 176	4.979	**0.002**

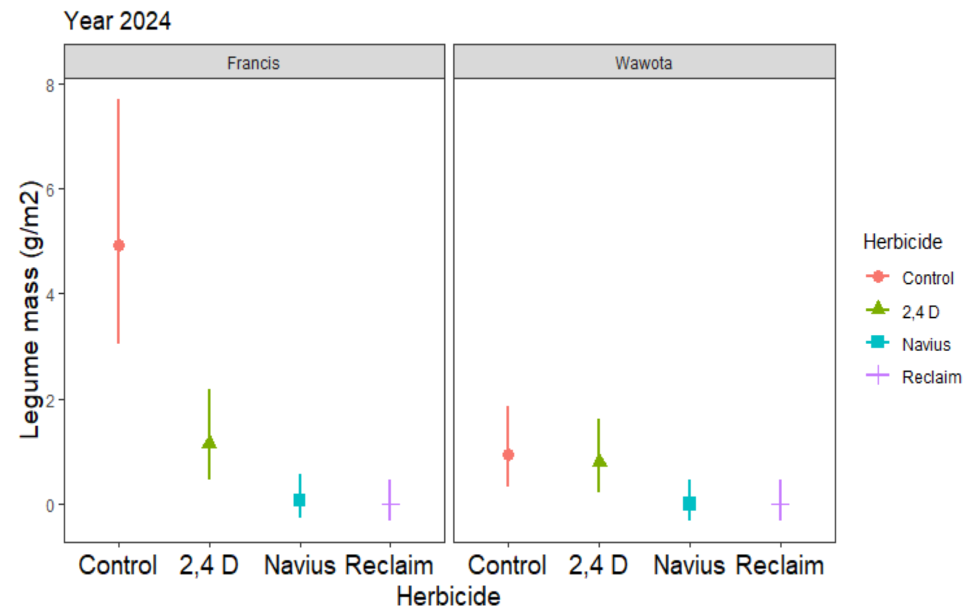


Figure A4. *Linear mixed model predicting the effects of herbicide treatment on legume mass (g/m²) in 2024 at the Francis and Wawota sites.*

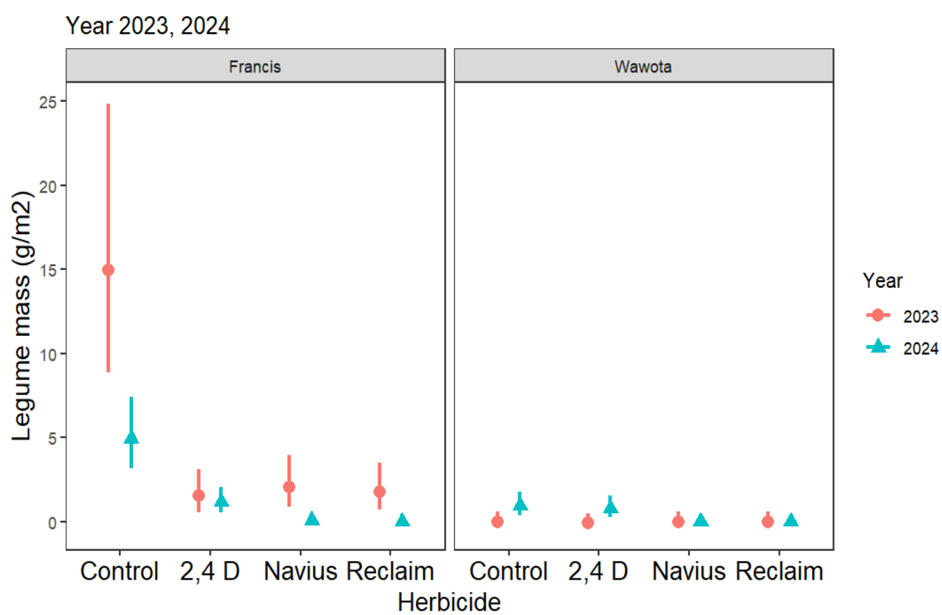


Figure A5. Linear mixed model predicting the effects of herbicide treatments on legume mass (g/m²) in 2023 and 2024 at the Francis and Wawota sites.

Table A7. Mixed model results testing treatment effects on species richness (type III analysis of variance table with Satterthwaite's method).

Year 1 – sqrt(Species.richness) ~ Herbicide*Fertilizer*Site + (1|Block)

Effect	Df (num, den)	F value	*Pr(>F)*
Herbicide	3, 312	2.105	**< 0.001**
Fertilizer	3, 312	3.255	0.099
Site	3, 8	1.276	0.081
Herbicide: Fertilizer	9, 312	1.515	0.249
Herbicide: Site	9, 312	1.486	0.141
Fertilizer: Site	9, 312	1.154	0.152
Herbicide: Fertilizer: Site	27, 312	2.105	0.277

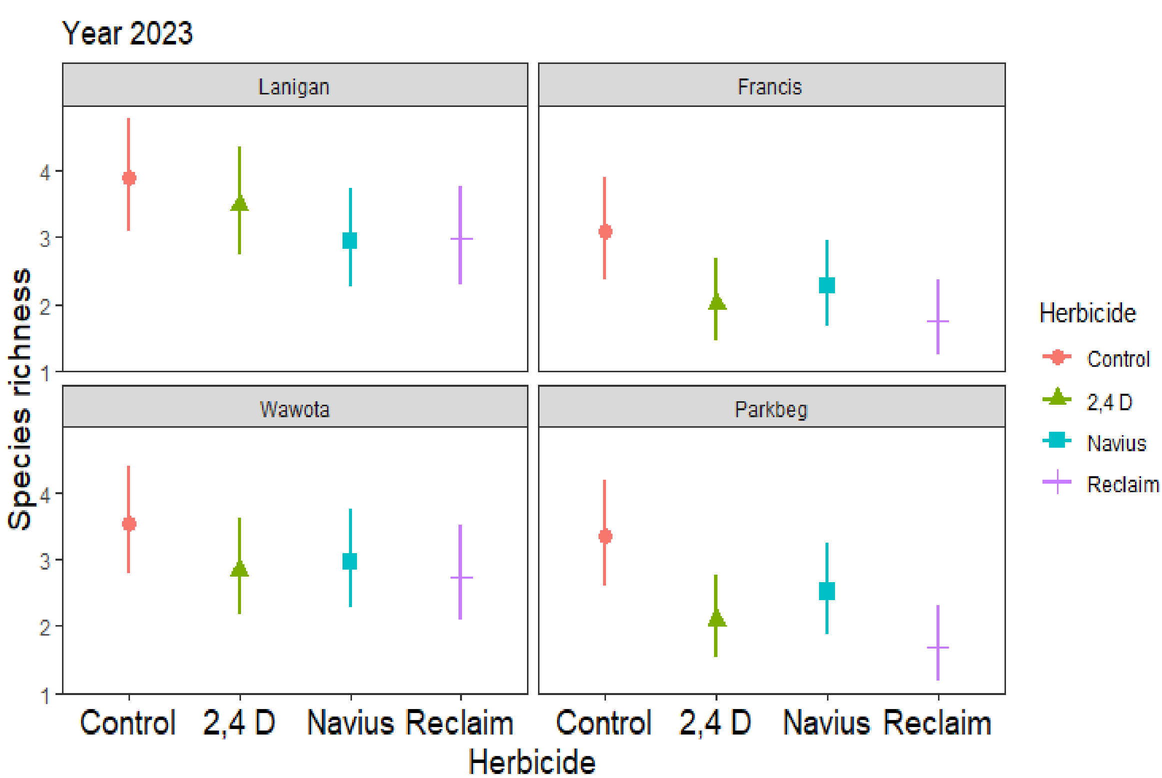


Figure A6 *Linear mixed model predicting the effects of herbicide treatment on species richness in 2023 across the four sites (Lanigan, Francis, Wawota, and Parkbeg); points show model-predicted means (± SE).*

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