

Burning Questions: Synchronizing Prescribed Fire to *B. inermis* Phenology

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Abstract – The U.S. Fish and Wildlife Service manages over 18,000 ha of tallgrass native prairies in eastern North Dakota, South Dakota, and western Minnesota. High invasion levels of two cool season introduced grasses, *Bromus inermis* Leyss and *Poa pratensis* L., are well documented in this region and motivated development of the Native Prairie Adaptive Management (NPAM) program. NPAM evaluates restoration strategies following principles of adaptive management and provides annual management decision support with the objective to increase native plant cover by reducing the two introduced grasses. Existing research recommended timing prescribed fires to the *B. inermis* elongation stage to reduce *B. inermis* cover and increase native plant cover, which lead us to incorporate this targeted burn timing into NPAM as a restoration strategy. As NPAM data accrued, retrospective analyses did not show burning during the *B. inermis* elongation stage to be more effective at reducing its cover than burning at other times. Thus, we explored burn timing by season, expecting spring burns to have superior outcomes with respect to *B. inermis* cover when compared to burns implemented in other seasons. However, this prediction did not hold true. Lastly, we consulted grassland experts who recommended targeting the *B. inermis* elongation and reproduction stages, combined with the *Andropogon gerardii* Vitman vegetative stage, as the most advantageous burn period to achieve our objective of decreasing *B. inermis* and increasing native plant cover. We found that expert-elicited preferred burn times did not have better outcomes than the non-preferred burn times. Regardless of how we defined burn timing in the three analyses, the data did not support the commonly accepted notion that the elongation growth stage of *B. inermis* is the most effective time to burn to decrease *B. inermis* and increase native plant cover. Moreover, we found that the hypothesized best timeframes to burn in all three analyses were no more effective than rest treatments and showed a tendency to have inferior outcomes to burns that were implemented at the non-preferred time periods.

Introduction

The U.S. Fish and Wildlife Service (Service) manages over 400,000 ha of National Wildlife Refuge System lands in the Prairie Pothole Region (PPR) of North Dakota, South Dakota, Minnesota, and Iowa (Dixon et al. 2019). These public lands provide important wildlife habitat, including over 18,000 ha of remnant (i.e. native) tallgrass prairies. With less than 1% of the original tallgrass prairies remaining in North Dakota, Minnesota, and Iowa, and about 15% in South Dakota (Samson and Knopf 1994) – usually in small, isolated tracts – protecting and restoring these remnant prairies is a priority for the Service. Beyond the conversion and fragmentation of the once-vast prairie biome, remaining prairie plant communities are commonly threatened by invasive woody plants and introduced cool-season grasses (Dixon et al. 2019; Grant et al. 2009, 2020a, 2020b). Specifically, Grant et al. (2020a, 2020b) documented that the dominant invasive plants on Service

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prairies are the introduced cool-season grasses, *Bromus inermis* Leyss. (Smooth Brome) and *Poa pratensis* L. (Kentucky Bluegrass). These findings, first available in 2006 as unpublished data, spurred Service biologists and managers to convene and “sound the alert” (Grant et al. 2009). Prairies evolved alongside natural disturbances (such as fire and grazing). These disturbances were suppressed for many years on Service lands, leading to the high invasion levels observed (Grant et al. 2009). Managers and biologists sought to reintroduce disturbances to address these invasions in a manner that fostered learning and guided decision-making, with the objective of increasing native plant cover by reducing *B. inermis* and *P. pratensis*. The result was a 2008 embarkation to create what became the Native Prairie Adaptive Management (NPAM) program, a decision support framework that allows for transparent and scientifically-based prairie management decisions in the face of uncertainty regarding the effectiveness of various management actions and the biological response of the prairie to these actions. Uncertainties are formally reduced over time as we learn by way of a structured and iterative process of predicting and monitoring outcomes of management actions, thereby improving future decision making (Gannon et al. 2024).

Native prairie adaptive management program

The NPAM program includes two separate decision tools for remnant prairies, one for mixed-grass and one for tallgrass. The tallgrass decision tool uses management alternatives that specify timing of burns and grazes to target the tiller elongation growth stage of *B. inermis*. Although prescribed fire is a common prairie land management tool, there are few examples in the literature describing best practices for applying fire management to restore northern tallgrass prairies that have been invaded by *B. inermis* (Blankespoor 1987, Blankespoor and Larson 1994). Instead, managers have relied on their best professional judgement and past experiences, informed by data from other regions (e.g., Willson and Stubbendieck 1997, Willson and Stubbendieck 2000, Vinton and Goergen 2006).

At the time that NPAM was developed, many tallgrass prairie managers were following the provisional model provided by Willson and Stubbendieck (2000) to decrease the cover of *B. inermis* and stimulate competition by warm-season native grasses. This model outlines several considerations for managing *B. inermis* using prescribed burns, while emphasizing the importance of post-fire competition, burn timing, and burn frequency. Firstly, the model indicates that the presence of at least 20% native, perennial tall grasses is necessary to ensure adequate competition to limit secondary *B. inermis* tillers after a fire. Secondly, burning when the majority of *B. inermis* plants are elongating, but not yet developing an inflorescence, reduces *B. inermis* tiller density and biomass during a vulnerable time in its development. Lastly, the model advises that burning before elongation is only recommended if the area can be burned at that same time on an annual basis. When developing the tallgrass framework, we elected to focus specifically on burn timing; we knew from information provided by Service managers that most NPAM tallgrass units would have at least 20% cover of native plants and that consecutive annual burning, regardless of the timing of the burn, was not feasible. Managers used site visits to determine when each management unit had reached the specified Willson and Stubbendieck timeframe (hereafter, W&S timeframe). We defined the W&S timeframe as beginning when >50% of *B. inermis* tillers have developed five fully-formed leaves, which is a proxy for the elongation growth stage recommended by Willson and Stubbendieck (2000). We specified the ending as when >50% of *B. inermis* tillers have visible inflorescences, which is an indication that it has reached the reproductive growth stage (Moore et al. 1991).

Adapting to confront uncertainties and a shifting knowledge base

Within the first two years (2010–2012) of implementing the NPAM tallgrass framework, it became clear to the program coordinators that specifically timing burns to occur during the elongation stage of *B. inermis* had many challenges. We assumed that phenological stages would gradually progress from south to north, with southern (warmer) management units reaching more advanced growth stages sooner than northern (cooler) management units. This pattern was not found, despite the most extreme units being located over 480 km apart. Further, observers noticed that many *B. inermis* plants never reached inflorescence, which was our indicator for the end of the W&S timeframe. We associated these unexpected and inconsistent observations of *B. inermis* phenology with the fact that most NPAM participants did not have previous experience in identifying growth stages of grasses, which pinpointed the need for better guidance to reduce observer variability.

Our first step to increase consistency in observation was to refine methods for accurately identifying the start and end of the elongation stage of *B. inermis*. During 2013–2014, we collaborated with South Dakota State University to develop standard guidance for counting *B. inermis* leaves and recognizing the inflorescence (Dupey 2014). A photographic user guide for identifying these features was created and tested for accuracy across the tallgrass prairie region in North Dakota, South Dakota, and Minnesota. This study concluded with a training session to test the effectiveness of the guidance with Service staff.

Now confident that NPAM participants were consistently recording *B. inermis* growth stages, we continued to experience difficulties targeting management application to *B. inermis* phenology. Tiller elongation is typically recognized by the presence of above ground nodes (Moore et al 1991). However, we followed the advice of Willson (1991) and Willson and Stubbendieck (2000) that counting green leaves was a less tedious method to identify the elongation stage. Our observers noted regular inconsistencies between when their units reached the five-leaf stage and when above ground nodes were present. Some units never reached five fully-formed green leaves or never developed inflorescences, our indicators for the start and end of the W&S timeframe, respectively. Finally, participants were growing frustrated with the need to visit their (sometimes distant) management units every few days to check *B. inermis* phenology. To address these concerns, during 2014–2015 we partnered with North Dakota State University to explore the possibility of correlating *B. inermis* elongation to accumulated growing degree days (AGDD) in the northern tallgrass prairies of western Minnesota and eastern portions of North Dakota and South Dakota. Preister et al. (2019) determined that, on average, *B. inermis* elongates at 1256 cool-season (CS) AGDD (95% CI = 946–1566 CS AGDD). In 2017 we started to use the AGDD information, along with web-accessed weather data, to calculate real-time, management unit specific CS AGDD from the office. Once a management unit reached 946 CS AGDD, Service staff visited the unit to visually determine if >50% of *B. inermis* tillers were elongating. This method was more accurate and efficient than what we had used previously for identifying the start of the W&S timeframe.

Preister et al.'s (2019) study also provided insights into the biology of *B. inermis* that led us to change how we defined the start and end of the targeted W&S timeframe. Preister et al. (2019, 2021) suggested that identifying above ground nodes was a better method to determine the elongation stage of *B. inermis* than counting leaves. Based on this information, in 2017 we redefined the start of the W&S timeframe to occur when >50% of *B. inermis* plants on a management unit had reached tiller elongation based

on the presence of at least one above ground node. Additionally, Preister et al. (2019) corroborated previous observations by Service staff that many *B. inermis* tillers never reached the reproduction stage (i.e., visible inflorescences). Based on these findings, in 2019, rather than use inflorescences to identify the end of the targeted W&S timeframe, we modified the rule such that the W&S timeframe ended 15 days following its identified start. We based this number of days on limited data from Preister et al. (2019) and our observations from identifying *B. inermis* stages over the years.

Settling burning questions

With improved efficiency and consistency in identifying *B. inermis* growth stages, we were confident that we could optimally target the timing of our management actions to the W&S timeframe, and we proceeded to apply this method within our NPAM tallgrass framework. By 2020, we had accrued sufficient data through the NPAM program to conduct retrospective analyses of the data and assess whether targeting our management within the specified timeframe was working as we had initially hypothesized.

In this paper we start by examining whether burning within the W&S specified timeframe results in the expected reduced cover of *B. inermis* and increased cover of native plants. Based on these findings, we then explore two additional methods of relating burn timing and phenology: a season-based timeframe and an expert elicited timeframe. Although the NPAM framework includes additional management actions (e.g., grazing), our focus for these analyses was strictly the effect of burn timing on plant community outcomes.

Methods

Study area

Tallgrass remnant prairies enrolled in the NPAM program are located within the PPR of eastern North Dakota, eastern South Dakota, and western Minnesota. Approximately 40 units are annually managed (using burning, grazing, haying, or resting) and monitored as part of the NPAM program (Fig. 1). Management units were voluntarily enrolled in the NPAM program by local management offices and are not meant to be a representative sample of tallgrass prairies on Service lands. Management units average 25.3 ha in size, with a range of 3.1 ha to 58.1 ha.

Data

Data for the retrospective analyses include annual monitoring and management data from tallgrass units enrolled in the NPAM program, during 2009–2021. Belt transects were used to measure the vegetation cover, with a 25 m transect every 2.0 ha (Grant et al. 2004). The vegetation cover data were summarized across transects per unit as the proportion of the unit composed of four vegetation components: native plants, *B. inermis*, *P. pratensis*, and other undesirable vegetation (hereafter, remainder). The native category is comprised of both native cool-season and warm-season grasses and forbs. The remainder category consists of non-native plants other than *B. inermis* and *P. pratensis*, as well as trees and shrubs. Management data consist of rest and burn treatments that occurred between the annual monitoring events. Rest treatments are defined as no defoliation activity on the unit for the entire year. When burn treatments were applied, participants recorded the date and the estimated growth stage of the majority of observed *B. inermis* plants (determined by a meandering walk through the unit). Data points included units

that were either rested or received a single burn treatment in a given year. A single data point consisted of paired consecutive years of monitoring data that include pre- and post-monitoring events with an intervening management action on a given unit.

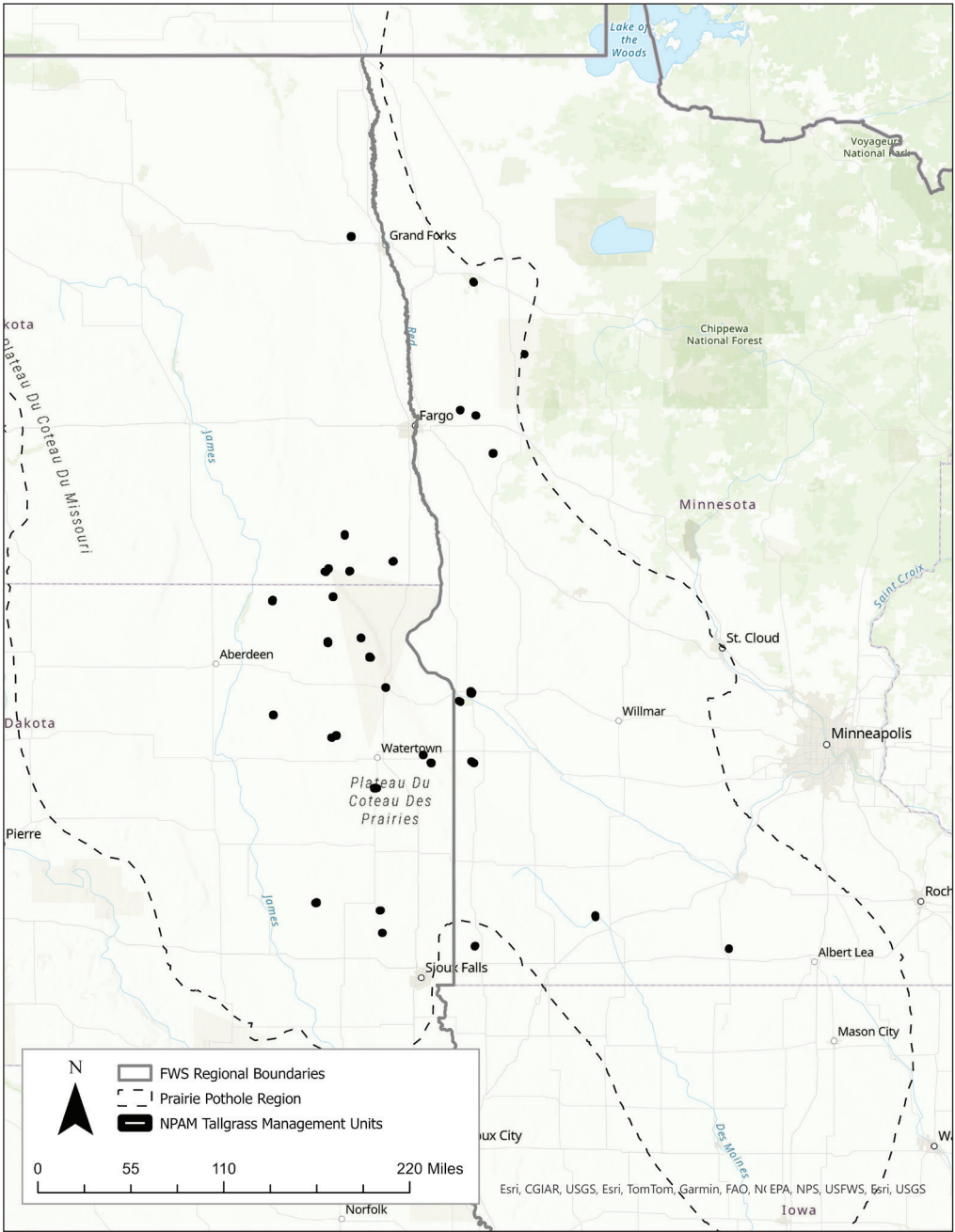


Figure 1. Map of Native Prairie Adaptive Management program tallgrass management units that are distributed throughout the Prairie Pothole Region of North Dakota, South Dakota, and Minnesota.

Analyses

Predictive models estimated the response of three vegetation components, *B. inermis*, *P. pratensis*, and remainder, at time $t+1$ given their respective cover at time t and the annual management action applied at time t as predictor variables. We completed three different analyses, each with a different categorization of burn times (Table 1), to assess the predicted change in cover of the three vegetation components following each treatment. The response of native cover was not modeled; rather, we calculated it as the remaining proportion cover of the unit after modeling the predicted changes in the three vegetation components. All analyses were performed using R Statistical Software (v4.3.0; R Core Team 2023). We used linear mixed-effects regression models with unit included as a random effect for intercept (*lmer* function, R package lme4; Bates et al. 2015). We used the *bootMer* R function with 10,000 replicates to bootstrap confidence intervals for each of the estimated treatment effects (R package lme4; Bates et al. 2015).

Table 1. The three ways in which we assessed timing of burning. The Willson and Stubbendieck (W&S) timeframe broke burn timing into two categories: occurring during *Bromus inermis* elongation ('Burn_Elongation') or occurring during a growth stage other than *B. inermis* elongation ('Burn_Other'). The Season-based timeframe broke burn timing into three categories relative to seasons: winter/early spring, spring, and summer/fall. The expert elicited timeframe used expert opinion to break burn timing into two categories based on the growth stages of *B. inermis* and *Andropogon gerardii*; these two timeframes are indicated as simply the best ('Burn_Best') and worst ('Burn_Worst') time to burn to achieve the desired impact of decreased cover of *B. inermis* and increased cover of native plants. Within each timeframe, we show how we defined each burn category for the analyses. CS AGDD = cool-season accumulated growing degree days. WS AGDD = warm-season accumulated growing degree days. Sample size is indicated per timeframe as the total number of paired pre- and post-treatment monitoring events on a given unit, summed across years; within each timeframe, we provide the sample size for each classified burn. Total sample sizes per the three timeframes were 271, 271, and 306, respectively. The difference between the total sample size and the sum of the burn treatment sample sizes is comprised of rest treatments. The expert elicited timeframe analysis contains more overall samples because it used data collected during 2009–2021, whereas the first two approaches used data gathered during 2009–2020.

Timeframe	Burn categories	Definition	Sample size
W&S	Burn_Elongation	Start: CS AGDD 1256 End: 15 days from start	19
	Burn_Other	Any time other than that indicated as 'Burn_Elongation'.	56
Season-based	Burn_Winter/Early Spring	CS AGDD 0–945	28
	Burn_Spring	CS AGDD 946–1566	34
	Burn_Summer/Fall	CS AGDD >1566	13
Expert elicited	Burn_Best	During <i>B. inermis</i> elongation and reproductive growth stages (CS AGDD 1256–2862) <u>and</u> before <i>A. gerardii</i> elongation growth stage (WS AGDD <1302).	22
	Burn_Worst	Any time other than that indicated as 'Burn_Best'.	60

To demonstrate the effect of each of the treatments on the response variables (that is, cover of *B. inermis*, *P. pratensis*, and remainder) we created boxplots showing the effect of each of the treatments. Plotted values include a box that shows the median of the bootstrapped predictions, the 25–75% quantile of bootstrapped predictions, and whiskers that contain the 95% confidence interval of the bootstrapped predictions. We interpreted non-overlapping 95% confidence intervals (i.e., the full box and its whiskers) among treatments as a significant difference in treatment effects, whereas overlapping 95% confidence intervals were considered a non-significant difference among the treatment effects. If the 25–75% portion of treatment predictions did not overlap, we interpreted them as having a *tendency* to result in different outcomes than another treatment. Per boxplot we indicated the starting state of the vegetation component (SBt = *B. inermis* cover at time t , KBt = *P. pratensis* cover at time t , or RMt = remainder cover at time t) as a dashed horizontal line. These starting states are based on the calculated means across all units. The y-axis of the boxplots is the corresponding state of the vegetation component at time $t+1$. Boxplots and whiskers fully above the horizontal starting state indicate a predicted increase in the vegetation component, whereas boxplots and whiskers fully below the horizontal starting state indicate a predicted decrease in the vegetation component. If the 25–75% portion of the prediction is fully above or below the horizontal line, we interpreted them as having a *tendency* to increase or decrease the vegetation component. We created these plots for each of three response variables (i.e., SBt1 = *B. inermis* cover at time $t+1$, KBt1 = *P. pratensis* cover at time $t+1$, and RMt1 = remainder cover at time $t+1$). We then calculated and plotted the predicted cover of native plants at time $t+1$ (i.e., NPt1) as 100 minus the sum of the three modeled vegetation components.

W&S timeframe. The first analysis focused on the W&S specified timeframe and compared the percent cover of *B. inermis*, *P. pratensis*, remainder vegetation, and native plant cover following three management treatments: rest, burn during the *B. inermis* elongation growth stage ('Burn_Elongation'), and burn at growth stages other than during the elongation of *B. inermis* ('Burn_Other') (Table 1, Fig. 2a). For this analysis, the elongation growth stage was defined per unit and year as starting when CS AGDD had reached 1256 (based on Preister et al. 2019) and lasting 15 days from this point onward. To be burned outside of the elongation timeframe included any time before or after the defined elongation period, specific to each unit and year. We retroactively applied this single rule to define the W&S timeframe to all years of data, despite the various methods (described in the introduction) that were used at the time of actual data collection.

Season-based timeframe. To gain further insight into the effects of burn timing, we conducted a second analysis where we identified three seasons to analyze based on CS AGDD from Preister et al. (2019): winter/early spring, spring, and summer/fall (Tables 1 and 2a, Fig. 2b). 'Burn_Winter/Early Spring' is a burn that occurs between CS AGDD 0 and 945, which correlates to calendar dates of 1 January to approximately mid-May. This season captures the time period that *B. inermis* is in its dormant and vegetative growth stages. 'Burn_Spring' is a burn that is applied during CS AGDD 946–1566, which corresponds to approximately mid-May to early-June and encompasses the full 95% CI for the *B. inermis* elongation growth stage (based on Preister et al. 2019). 'Burn_Summer/Fall' is a burn that is applied any time after CS AGDD has exceeded 1566. This time period corresponds to approximately mid-June through 31 December, including the summer and fall seasons, and encompasses the *B. inermis* reproductive stage through the first portion of its dormant stage.

Expert elicited timeframe. For our third and final analysis, we gathered a group of experts in grassland ecology, range science, and botany to elicit their current understanding of the optimal burn timing that would reduce *B. inermis* and increase native plant cover, particu-

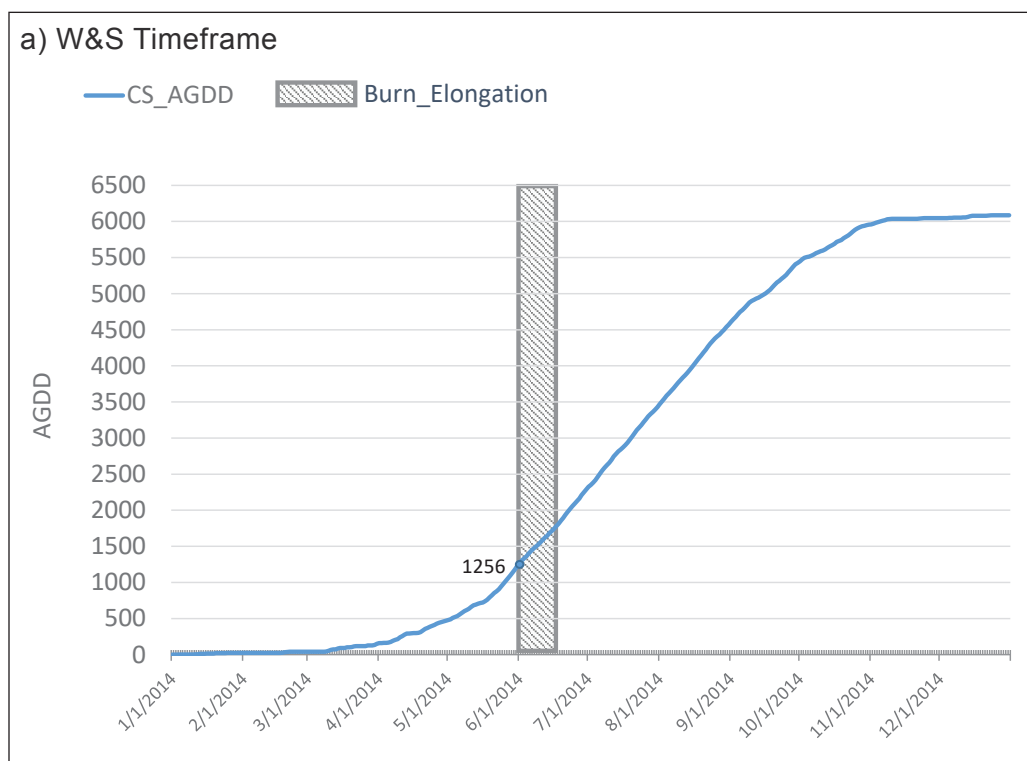


Figure 2. Identification of the burn times used in the analyses of the three different timeframes: a) Willson and Stubbendieck (W&S) timeframe, b) Season-based timeframe, and c) expert elicited timeframe (Table 1). CS AGDD = cool-season accumulated growing degree days. WS AGDD = warm-season accumulated growing degree days. The relationship between calendar month, CS AGDD, and WS AGDD is dynamic, varying from year-to-year and from location-to-location within a year. For each of the three timeframes, we show the relationship for one select location and year: Big Stone National Wildlife Refuge Laskowske unit in Minnesota (which is central to our tallgrass region), during 2014 (the first of the two years of the Preister et. al. (2019) field study). a) For the W&S timeframe, 'Burn_Elongation' is identified as beginning when CS AGDD reaches 1256 and continuing for 15 calendar days. 'Burn_Other' are burns that occur before or after the 15-day elongation period. b) The Season-based timeframe classifies burns according three partitions of the seasons, identified by CS AGDD. Burns that occur during CS AGDD 0–945 are classified as occurring during the winter/early spring season. Burns that occur during CS AGDD 945–1566 are classified as occurring during the spring season. Burns that occur after CS AGDD 1566 are classified as occurring during the summer/fall season. c) For the expert elicited timeframe, the best timeframe to burn is based on the relationship between the CS and WS AGDD that define the growth stages of *Bromus inermis* and *Andropogon gerardii* (Table 2). The best timeframe within which to burn (i.e., 'Burn_Best') is defined as when *B. inermis* is in the elongation or reproductive growth stages (CS AGDD 1256–2862) and before *A. gerardii* begins its elongation stage (WS AGDD < 1302). Note that in this particular instance, *B. inermis* completes its reproductive stage before *A. gerardii* starts its elongation stage (i.e., when CS AGDD reached 2862, the WS AGDD had not yet reached 1302); due to the dynamic nature of the relationship between CS and WS AGDD, this situation will not always be the case. Burns that occur outside of this timeframe (before or after) are classified as 'Burn_Worst'.

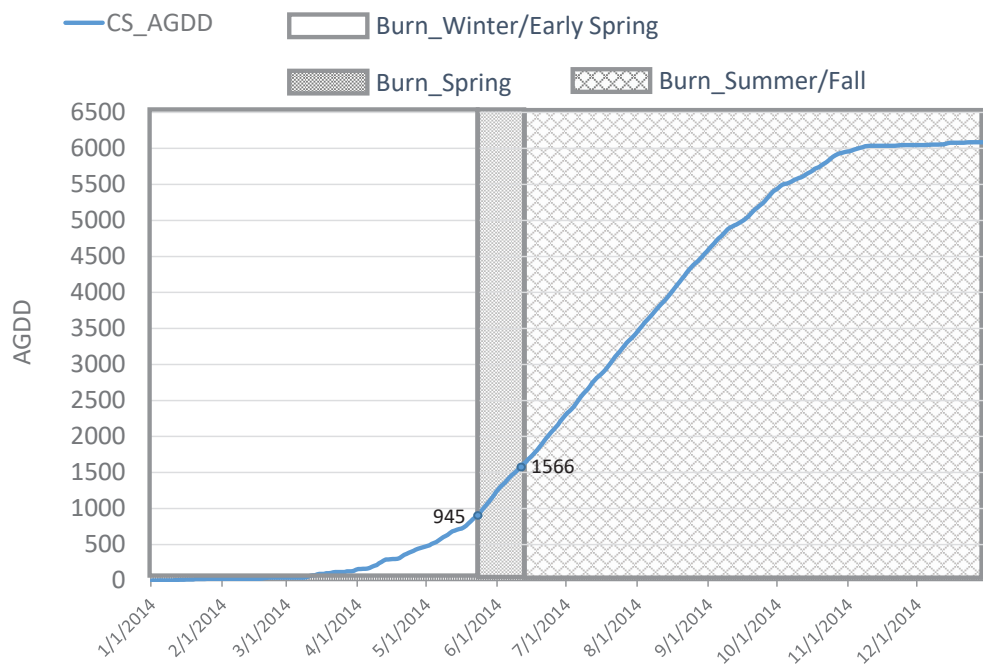
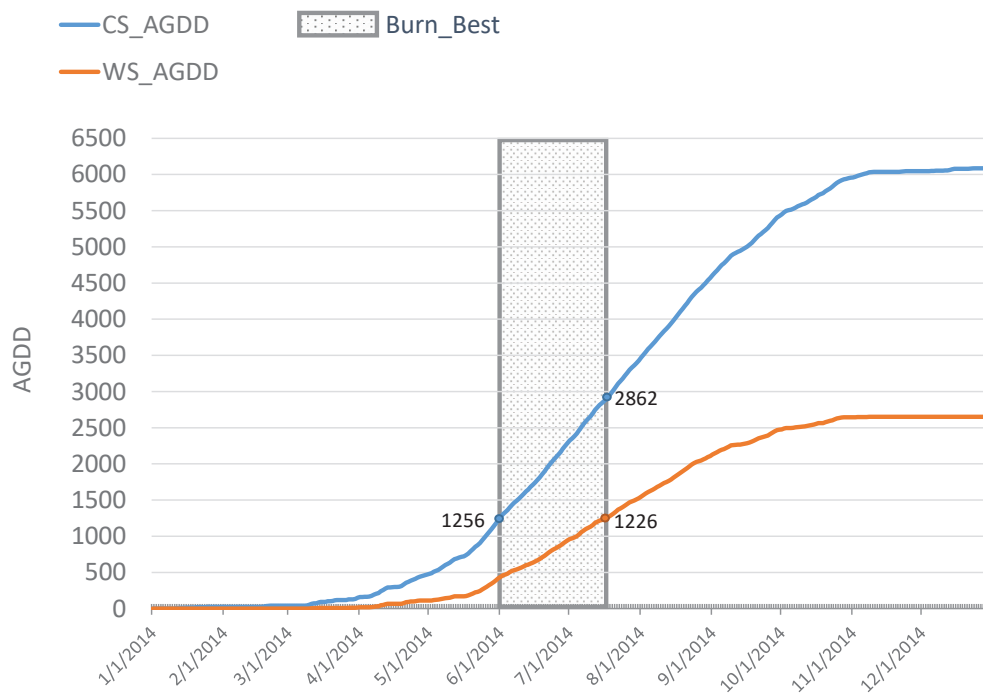
b) Season-Based Timeframe**c) Expert Elicited Timeframe**

Figure 2, continued.

larly warm-season grasses. For the elicitation, we used *Andropogon gerardii* Vitman (big bluestem) as a surrogate for native warm-season grasses. Despite variability among expert responses, there was consensus around elongation and reproduction stages of *B. inermis* and the vegetative stage of *A. gerardii* as an optimal time to burn to achieve the desired effect (J. Gannon, U.S. Fish and Wildlife Service, Fort Collins, CO, 2024 upubl. data). We determined the relationship between the mean stage count and warm-season (WS) AGDD for *A. gerardii* using the data and associated formulas and figures in Mitchell et al. (1997; see their Table 1 formulas and Fig. 3), where mean stage count is a method developed by Moore et al. (1991) to measure the developmental stage of grasses at the population level. These data, in conjunction with the Preister et al. (2019) site-specific data for *B. inermis* described earlier, allowed us to estimate the CS and WS AGDD for the growth stages of *B. inermis* and *A. gerardii* that the experts indicated were the best and worst times to burn to achieve the desired effect (Tables 1 and 2, Fig. 2c). Specifically, we defined the best timeframe to burn ('Burn_Best') as when a unit is within CS AGDD 1256–2862 (*B. inermis* elongation and reproductive growth stages; Table 2a) and WS AGDD <1302 (*A. gerardii* has not yet reached the elongation stage; Table 2b). 'Burn_Worst' is a burn that occurs at any other time.

In theory, the 'Burn_Best' and 'Burn_Worst' timeframes of the expert elicited method differ from the 'Burn_Elongation' and 'Burn_Other' timeframes of the W&S method, respectively. The basis of the difference is the expansion of the expert elicited targeted time-

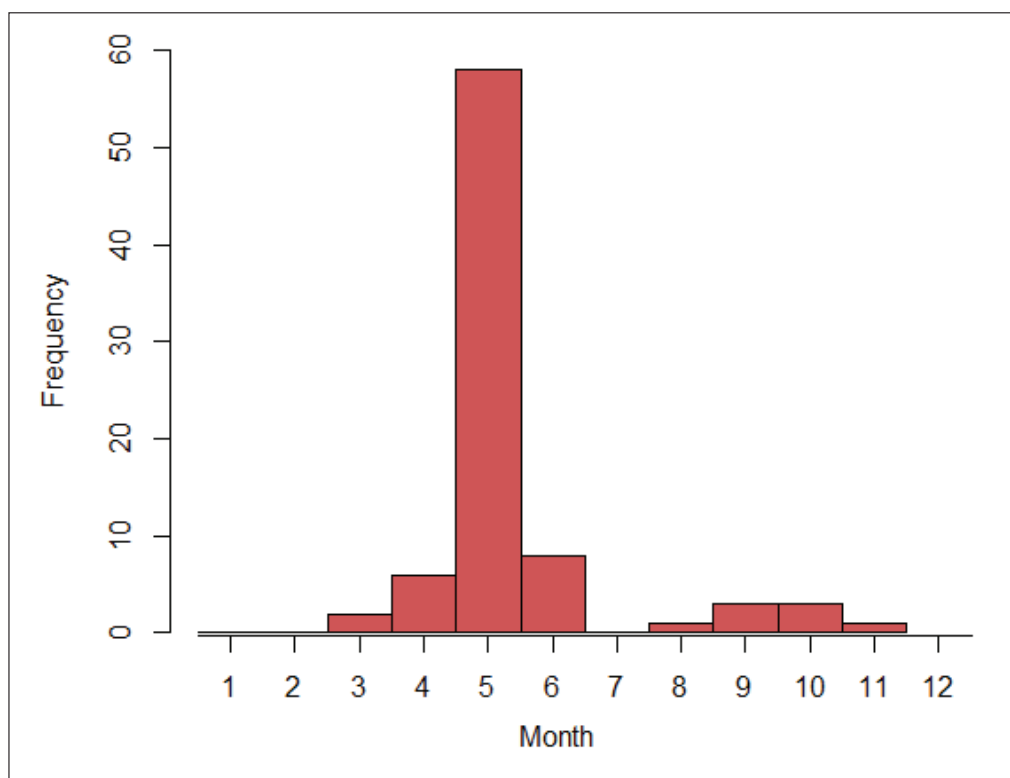


Figure 3. Frequency of burn treatments throughout the 12 months of the year, from January (month 1) through December (month 12). Treatment data are combined from 2009–2021 for U.S. Fish and Wildlife Service tallgrass prairies enrolled in the Native Prairie Adaptive Management program and include 82 burn treatments.

Table 2. Relationship between season, calendar month, accumulated growing degree days (AGDD), and growth stage for a) *Bromus inermis* and b) *Andropogon gerardii*. The relationship between calendar month and AGDD is dynamic, varying from year-to-year and from location-to-location within a year, whereas the relationship between season and calendar month and between AGDD and growth stage is static. We show the relationship for one select location and year: Big Stone National Wildlife Refuge Laskowske unit in Minnesota (which is central to our tallgrass region), during 2014 (the first of the two years of the Preister et. al. (2019) field study). CS AGDD = cool-season accumulated growing degree days. WS AGDD = warm-season accumulated growing degree days.

a) *B. inermis*

Season	Month	CS AGDD	Growth stage
Winter	January	0 - 23	Dormant
	February	23 - 40	
	March	40 - 150	
Spring	April	150 - 471	Vegetative
	May	471 - 1226	
	June	1226 - 1256	
		1256 - 1670	
Summer	July	1670 - 2287	Reproductive
		2287 - 2862	
		2862 - 3431	
	August	3431 - 4570	
Fall	September	4570 - 5427	Undefined
	October	5427 - 5956	
	November	5956 - 6048	
	December	6048 - 6086	

b) *A. gerardii*

Season	Month	WS AGDD	Growth stage
Winter	January	0	Dormant
	February	0	
	March	0 - 15	
Spring	April	15 - 111	Vegetative
	May	111 - 378	
		378 - 419	
	June	419 - 942	
Summer	July	942 - 1302	Elongation
		1302 - 1527	
		1527 - 1784	
	August	1784 - 2109	
Fall	September	2109 - 2163	Reproductive
		2163 - 2472	
		2472 - 2643	
	October	2643 - 2651	
Fall	November	2651 - 2651	Seed
	December		

frame beyond the elongation growth stage of *B. inermis* to include its reproductive growth stage, up to the onset of the *A. gerardii* elongation growth stage. This extended time period could include an additional 30 days (e.g., compare Fig. 2a and 2c). Based on CS and WS AGDDs, this additional timeframe would occur, on average, during the latter half of June and the first half of July (see Table 2). In practice, however, this extended time period did not result in augmented samples for the ‘Burn_Best’ time period (expert elicited method) over the ‘Burn_Elongation’ time period (W&S method) because the burns in our dataset tended to be clumped during May rather than distributed evenly over the months (Fig. 3). In fact, our data included no burns during the latter half of June or the first half of July. Consequently, there is extensive overlap between the 2009–2020 samples of the ‘Burn_Best’ and ‘Burn_Elongation’ timeframes (89% overlap) and the ‘Burn_Worst’ and ‘Burn_Other’ (95% overlap) timeframes.

Results

During 2009–2021 our data include 82 burn treatments and 224 rest treatments. The vast majority of the burn treatments occurred in May (Fig. 3). For this reason, we do not have well represented burn treatments across the various growth stages and have limited sample sizes for the distinct burn categories we used in our three timeframes (Table 1). Sample sizes within the timeframes that were hypothesized to be beneficial (e.g., during the *B. inermis* elongation period) are particularly sparse (Table 1).

For each of the three analyses conducted, we show the results using four box plots – one for each of the three modeled vegetation components of *B. inermis* (SB), *P. pratensis* (KB), and remainder (RM), and one for the derived native cover component (NP). Though our hypotheses focus on the effect of treatments on *B. inermis* and native cover, we show the *P. pratensis* and remainder plots because the native cover component is a derived value from the other three modeled vegetation components. Despite showing all four plots, we focus our assessment on the *B. inermis* and native cover plots; *P. pratensis* and remainder plots are only addressed in so much as they are necessary to explain the native cover outcome.

W&S timeframe

Our data did not show a decrease in *B. inermis* cover (Fig. 4a) with the application of burns timed to occur during the *B. inermis* elongation growth stage. In fact, we saw a tendency for the opposite relationship, meaning that burns that were applied at times other than the *B. inermis* elongation growth stage tended to have a more desirable effect (that is, ‘Burn_Other’ showed a tendency to decrease *B. inermis* cover while ‘Burn_Elongation’ showed a tendency to increase *B. inermis* cover). Despite these tendencies, there was not a significant difference in the effect of the two burn treatments on *B. inermis* (Fig. 4a). Though burns applied outside of the elongation growth stage tended to be better than rest treatments, neither of the burn treatments, regardless of time, were significantly different than the effect of the rest treatment on the cover of *B. inermis* (Fig. 4a).

We did not see an increase in native plant cover with the application of burns timed to occur during the *B. inermis* elongation growth stage (Fig. 4d). Instead, we saw that burns applied outside of the *B. inermis* elongation growth stage were predicted to significantly increase the cover of native plants. Despite this predicted increase, the ‘Burn_Other’ treatment outcome was not significantly different than the predicted outcome of burns timed during the elongation growth stage (Fig. 4d). The significant predicted increase in native cover with the ‘Burn_Other’ treatment was bolstered by the significant predicted decrease of *P. pratensis* cover (Fig. 4b) and

the tendency of a decrease of remainder cover (Fig. 4c). In terms of native plant cover, a burn applied outside of the *B. inermis* elongation growth stage is significantly more effective than a rest treatment (Fig. 4d). Note that the wide 95% confidence intervals for the predicted cover of all vegetation components after the application of a burn during the elongation growth stage are in part due to the small sample size of only 19 data points (Table 1).

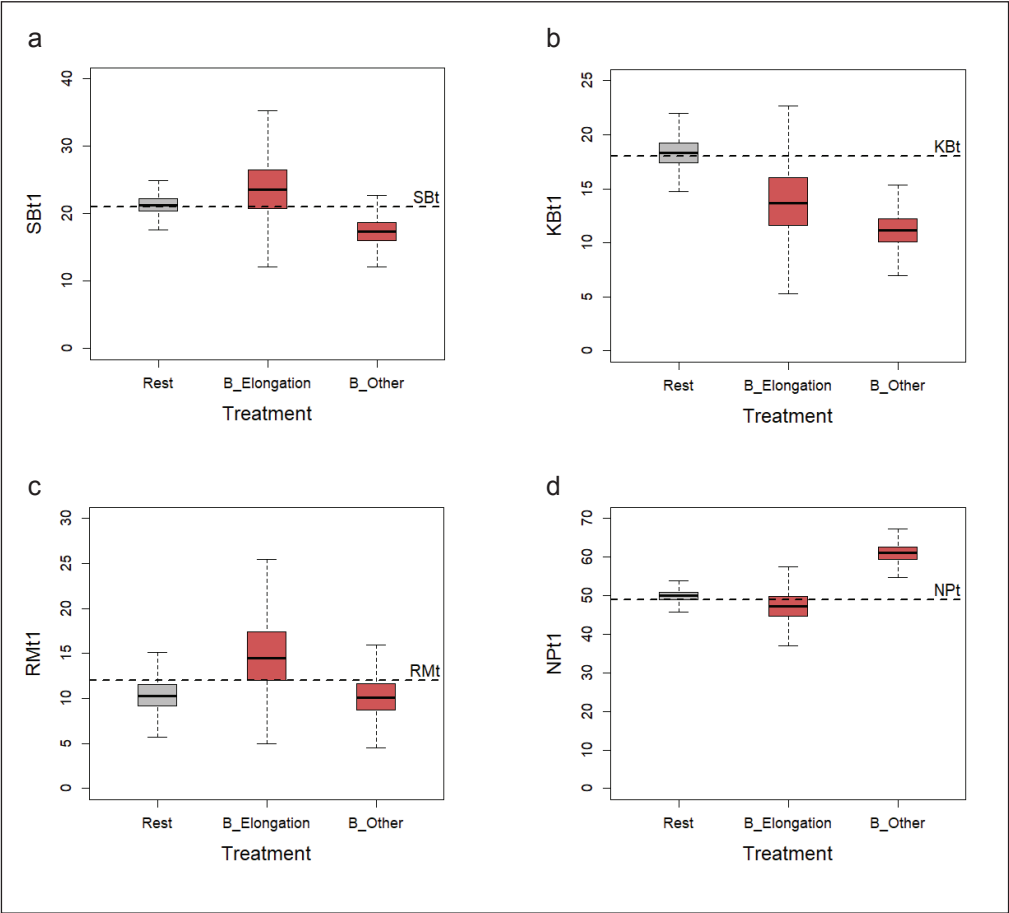


Figure 4. Willson and Stubbendieck timeframe. Box plots showing the predicted change in cover of a) *Bromus inermis*, b) *Poa pratensis*, c) remainder, and d) native plants one year after application of respective management treatments. The x-axis shows the treatment. Rest indicates no active defoliation treatment, ‘B_Elongation’ is a burn that occurred during the *B. inermis* elongation growth stage, and ‘B_Other’ is a burn that occurred anytime outside of the *B. inermis* elongation growth stage (Table 1). Per panel (a–d), the y-axis shows the predicted percent cover of the focal vegetation component at time $t+1$, after the implementation of the indicated treatment. The horizontal dashed line within each panel is the mean starting cover for the respective vegetation component at time t . Plotted values include a box that shows the median of the bootstrapped predictions, the 25–75% quantile of bootstrapped predictions, and whiskers that contain the 95% confidence interval of the bootstrapped predictions. SBT = starting cover of *B. inermis* at time t . SBT1 = predicted cover of *B. inermis* at time $t+1$. KBt = starting cover of *P. pratensis* at time t . KBt1 = predicted cover of *P. pratensis* at time $t+1$. Rmt = starting cover of the undesired remainder at time t . Rmt1 = predicted cover of the undesired remainder at time $t+1$. NPt = starting cover of native plants at time t . NPt1 = derived cover of native plants at time $t+1$ (i.e., $100 - \text{SBt1} - \text{KBt1} - \text{Rmt1}$).

Season-based timeframe

In terms of *B. inermis* cover, we did not see any significant differences among the effects of the three burn seasons nor between rest and any of the burn treatments (Fig. 5a). Burns applied during the winter/early spring and summer/fall seasons tended to decrease *B. inermis* cover and to be better than rest, whereas burns applied during the spring season did not show either of these tendencies (Fig. 5a).

For native plant cover, winter/early spring burns are predicted to result in a significant increase in native plant cover, while spring and summer/fall burns show a tendency to increase native plant cover (Fig. 5d). The overall positive effect of the three seasonal burns on

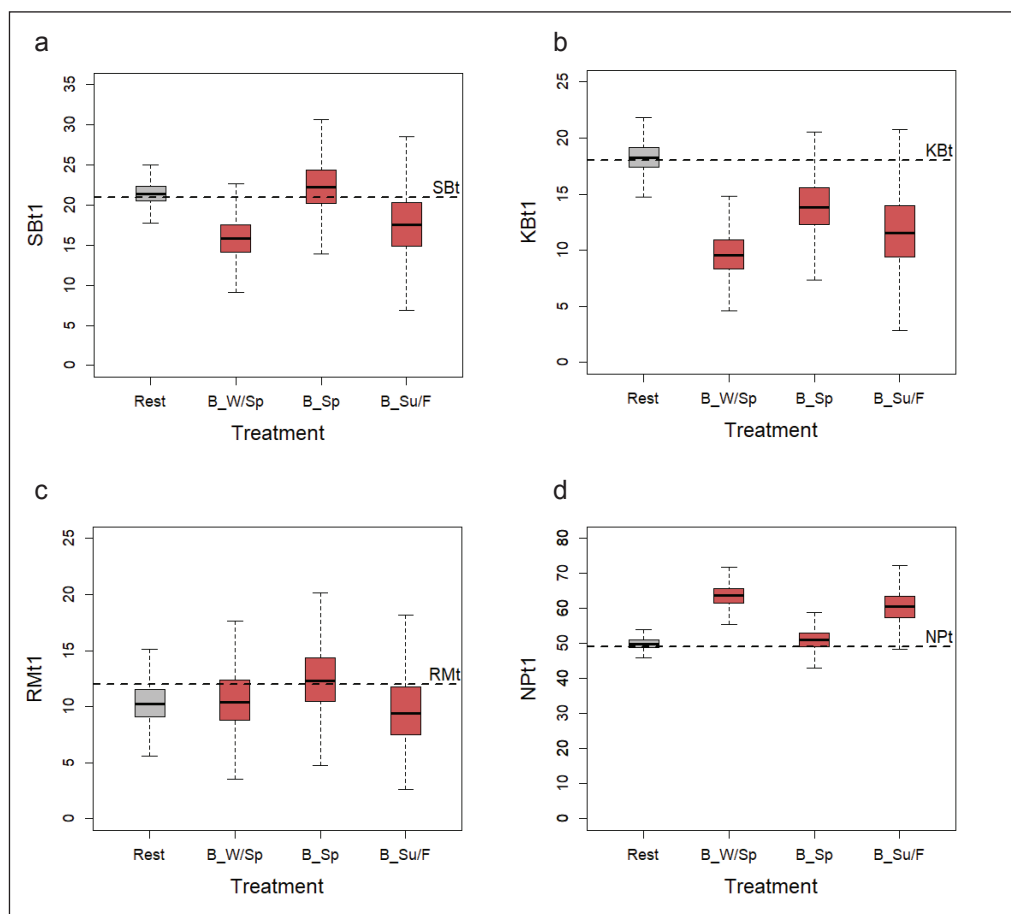


Figure 5. Season-based timeframe. Box plots showing the predicted change in cover of a) *Bromus inermis*, b) *Poa pratensis*, c) remainder, and d) native plants one year after application of the respective treatments. The x-axis shows the treatment. Rest indicates no active defoliation treatment, ‘B_W/Sp’ is a burn that occurred in the winter or early spring season when cool-season accumulated growing degree days (CS AGDD) ≤ 945 , ‘B_Sp’ is a burn that occurred in the late spring season between CS AGDD 946–1566, and ‘B_Su/F’ is a burn that occurred during the summer or fall seasons when CS AGDD > 1566 (Table 1). Per panel (a–d), the y-axis shows the predicted percent cover of the focal vegetation component at time $t+1$, after the implementation of the indicated treatment. Refer to the Figure 4 caption for a full explanation of the figure components.

native plant cover is bolstered by the significant decrease in *P. pratensis* with winter/early spring burns and the tendency to decrease *P. pratensis* cover with spring and summer/fall burns (Fig. 5b). Winter/early spring burns tended to be better at increasing native cover than did spring burns, showed no difference compared to summer/fall burns, and were predicted to be significantly more effective than rest treatments (Fig. 5d). Summer/fall burns tended to be better at increasing native plant cover than did spring burns or rest treatments (Fig. 5d). Spring burns and rest treatments showed no difference in effects (Fig. 5d).

Expert elicited timeframe

In terms of *B. inermis* cover, while burns applied during the ‘worst’ timeframe show a tendency to decrease *B. inermis* cover, we see no difference between the two burn treatments, nor between the burn treatments and rest (Fig. 6a). Burns applied during the ‘worst’ timeframe are predicted to significantly increase native plant cover and tend to be better at doing so than burns applied during the elicited ‘best’ timeframe (Fig. 6d). Burns applied during the ‘worst’ timeframe also tend to be more effective than rest at increasing native plant cover, whereas the effect of burns applied during the ‘best’ timeframe shows no difference from rest (Fig. 6d). These results in native plant cover are driven by the significant decreases in *P. pratensis* cover that are predicted to occur under both burn treatments (Fig. 6b), where the beneficial effect of the burns during the ‘best’ timeframe on resultant native plant cover is tempered by a tendency for increases in remainder plant cover (Fig. 6c). Note that the outcomes for the expert elicited timeframes (Fig. 6) are similar to those seen for the W&S timeframes (Fig. 4). This similarity is to be expected given the extensive overlap in the partitioning of the data into the classified timeframes (as described in the methods section).

Discussion

The NPAM program provides annual decision support to land managers in the PPR, with the tallgrass prairie management recommendations including specific timing relative to *B. inermis* phenology. When issues with tracking *B. inermis* phenology emerged, we explored the source of those issues through targeted research and retrospective analyses of our data. The Dupey (2014) and Preister et al. (2019, 2021) research provided valuable insights and practical guidance to improve our ability to efficiently and consistently identify the growth stages of *B. inermis*. However, a retrospective analysis of tallgrass NPAM data using the W&S timeframe caused us to rethink the whole concept of timing our burns to target the elongation growth stage of *B. inermis*.

Hypotheses and analyses

We expected that burns completed during the *B. inermis* elongation growth stage would substantially decrease *B. inermis* cover and show a commensurate increase in native plant cover compared to burns applied outside of this growth stage. This expectation was based on the literature (Bennett et al. 2019, Casler et al. 2020, Grace et al. 2001, Willson and Stubbendieck 2000), as well as on our anecdotal observations. However, our W&S timeframe analysis showed that burning during the *B. inermis* elongation growth stage was not a superior time period to burn our tallgrass units to reduce *B. inermis* or to increase native plant cover. In fact, we saw a tendency for the opposite relationship: burning outside the *B. inermis* elongation stage tended to be a more advantageous period to meet our plant cover objectives. While our sample size for the targeted timeframe was low, the results were compelling enough to cause

us to rethink our hypothesis. These results led us to explore the data in different ways to gain further insights into the effects of burn timing.

While the W&S timeframe analysis compared burning during a narrowly defined elongation period to burning at other times of the year, our Season-based analysis expanded the length of the elongation period and differentiated multiple seasons. We defined spring to include the entire 95% confidence interval of the CS AGDD range identified by Preister et al. (2019) for the *B. inermis* elongation growth stage. Additionally, we distinguished between earlier (winter/early spring) and later (summer/fall) burns. We hypothesized that spring burns

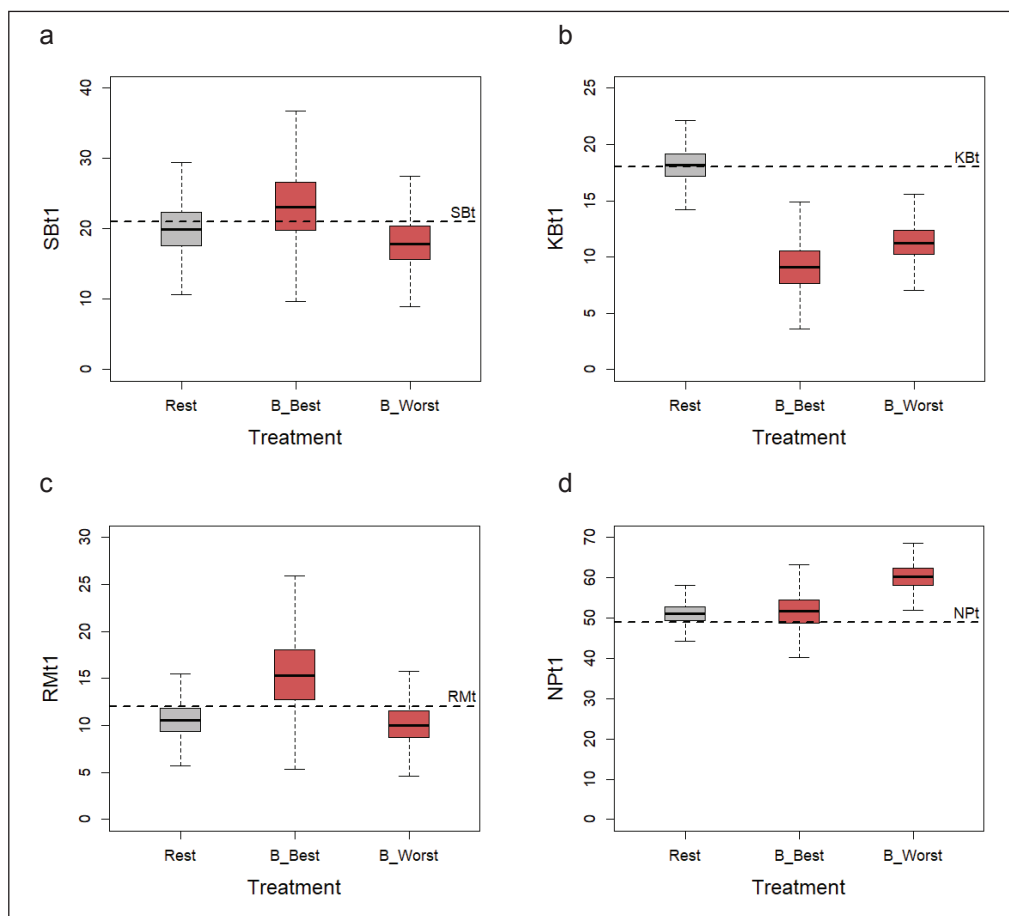


Figure 6. Expert elicited timeframe. Box plots showing the predicted change in cover of a) *Bromus inermis*, b) *Poa pratensis*, c) remainder, and d) native plants one year after application of the respective treatments. The x-axis shows the treatment. Rest indicates no active defoliation treatment. The burn treatments are based on the expert elicited timings of the ‘best’ and ‘worst’ times to apply a burn to achieve the desired impact of decreased *B. inermis* and increased native plant cover. ‘B_Best’ is a burn that occurs during *B. inermis* elongation or reproductive growth stages but ends before the start of the *Andropogon gerardii* elongation growth stage, while ‘B_Worst’ is a burn that occurs any other time (Tables 1 and 2; Figure 2). Per panel (a–d), the y-axis shows the predicted percent cover of the focal vegetation component at time $t+1$, after the implementation of the indicated treatment. Refer to the Figure 4 caption for a full explanation of the figure components.

would result in decreased cover of *B. inermis*, with a corresponding increase in native plant cover, and that burns occurring in the seasons before and after this period would have distinct outcomes from each other, with at least one of them being inferior to the spring burn outcome. Contrary to our hypotheses, the spring burn treatments did not result in a superior outcome; rather, we saw a tendency for the burns that were implemented before and after the spring timeframe to perform similarly to each other and better than the spring burns in terms of reducing *B. inermis* cover and increasing native plant cover.

With these results, we decided to query experts about burn timing. The seven individuals who provided input for the expert elicited timeframe analysis indicated their lack of confidence in the information they provided. This sentiment was unexpected, because we considered burning at elongation for perennial rhizomatous grasses to be a well-accepted and proven concept among grassland experts (e.g., Casler et al. 2020). As with the earlier analyses, we did not find that the hypothesized preferred time resulted in better outcomes for *B. inermis* cover or the native plant cover, and instead saw a tendency for the alternative time to perform better. Also similar to the other analyses, we found that the hypothesized best timeframe to implement burn treatments had a similar outcome to rest treatments for *B. inermis* and native plant cover. Note that because of the temporal clumping of our burns and consequent lack of sampling during the expert identified ‘best’ time to burn, we were not able to adequately investigate the efficacy of burning during these timeframes. Most burns on our sites took place during May because of the NPAM program guidance to focus burns during *B. inermis* elongation and because of seasonal availability of fire staff. Further exploration of these expert-identified timeframes (e.g., through targeted research) is warranted before conclusions regarding their potential effectiveness can be drawn.

We followed up the W&S timeframe analysis with the subsequent Season-based and expert elicited timeframes because we expected to gain insights into why burning during *B. inermis* elongation contradicted our initial hypothesis. As we progressed through the latter analyses, with identified respective hypotheses for each, we found that the results again contradicted our expectations on burn timing. Regardless of how we defined burn timing, our data did not support the commonly accepted notion that the elongation growth stage of *B. inermis* is a superior time to burn to decrease *B. inermis* and increase native plant cover. Additionally, it was unexpected that the hypothesized best timeframes to implement burn treatments in all three analyses (i.e., ‘B_Elongation’, ‘B_Sp’, and ‘B_Best’) showed similar outcomes to rest treatments for *B. inermis* and native plant cover, as well as showed a tendency to have inferior outcomes to burns that were implemented at the hypothesized non-preferred time periods. We lack a clear explanation for these unpredicted findings; however, we outline several factors that may have influenced the observed results in the following paragraphs.

Deviations from the W&S provisional model

We recognize there are many factors that may have influence on our results. For example, though we targeted burns to occur during the *B. inermis* elongation stage, we did not require that management units have at least 20% composition of native perennial tall grasses. Willson and Stubbendieck’s (2000) provisional model for managing *B. inermis* with prescribed fire emphasizes the importance of interspecific interactions; in addition to the immediate effect of burning *B. inermis* at a vulnerable growth stage, native perennial tall grasses serve an important role in suppressing the growth of secondary *B. inermis* tillers later in the growing season. If native grasses are less than 20% of the plant composition on a treatment site, Willson and Stubbendieck (2000) suggest that managers consider other methods for treatment such as herbicides. From 2009 to 2021, an average of 75% of the tallgrass NPAM units had

at least 20% cover of native plants (J. Gannon, U.S. Fish and Wildlife Service, Fort Collins, CO, 2024 upubl. data). Although this generally met the requirements of the Willson and Stubbendieck (2000) model, they did specifically mention warm-season grasses (e.g., *A. gerardii* and *Sorghastrum nutans* [L.] Nash [Indiangrass]) as being important. Our monitoring protocol grouped all native prairie species (native warm- and cool-season grasses and forbs), so we cannot assess the specific role of native warm-season grasses in our results.

We also recognize that our results may have been influenced by the presence of invasive species other than *B. inermis*. Willson and Stubbendieck's (2000) management recommendations focused solely on reducing *B. inermis* and did not address other introduced cool-season grasses. In practice, however, it is common for tallgrass prairies to have a combination of non-native plants; during our study period (2009–2021), NPAM tallgrass management units comprised an average of 21% *B. inermis*, 18% *P. pratensis*, and 12% remainder plants (including *Elymus repens* [L.] Gould [quackgrass] and *Phalaris arundinacea* L. [reed canarygrass]). Guidance similar to that provided by Willson and Stubbendieck (2000) for *B. inermis* was not available for other introduced cool-season grasses, so we applied their recommendations broadly regardless of the most common introduced plant on any given management unit. Reductions in *P. pratensis* cover were observed following burns (regardless of timing), leading to an increase in the native plant cover as shown in figures 4–6. These results corroborate the findings of Murphy and Grant (2005) and Grant et al. (2009) regarding the differential effectiveness of fire for managing against *B. inermis* and *P. pratensis*, as well as add to the evidence that fire effectively reduces *P. pratensis*. Although we do not focus on *P. pratensis* outcomes, it is important to acknowledge these consistent results across studies.

Other considerations

Burn severity. Plant composition following a burn is the result of complex interactions among numerous factors including weather and climate, soil characteristics, topography, fuel load, and ignition patterns (see Pyke et al. 2010, DiTomaso et al. 2006), none of which were part of our analyses. We have data on burn severity, a factor worthy of assessing based on the potential that high severity burns may help reduce non-native plants (see examples in DiTomaso et al. 2006). Each burn treatment for NPAM was categorized as heavy (no unburned grasses above the root crown), moderate (unburned grass stubble was less than 2 inches), or light (unburned grass stubble was over 2 inches) (USDI 2003). Most burn treatments were of heavy (27%) or moderate (56%) severity, which gave us confidence that the severity of our burns was sufficient to affect *B. inermis*.

Grazing treatments. *B. inermis* is known to be one of the most aggressive introduced grasses in the Great Plains (see Palit and DeKeyser 2022). The prolific growth of above and below ground plant parts make it a highly competitive grass; it is also drought tolerant and able to alter soil properties to benefit itself (see Palit and DeKeyser 2022, Preister 2018). Some research (Coleman et al. 2023, Murphy and Grant 2005, Stacy et al. 2005) has shown a *B. inermis* sensitivity to grazing. In other efforts not described here, we explored targeting grazing on tallgrass prairies to occur during the *B. inermis* elongation growth stage, which proved challenging. Service managers rely on private producers to provide cattle, which limits the Service's control of exactly when cattle are on management units. Additionally, the fact that grazing treatments typically span several weeks required that we develop rules to classify graze treatments as occurring within or outside the *B. inermis* elongation growth stage; these rules were subjective and we lacked confidence in their accuracy and thus usefulness. Ultimately, we lack the control to perfectly synchronize grazing to the *B. inermis* elongation growth stage, and we lack the necessary information to confidently identify whether we prop-

erly timed the treatment. To this end, we are collaborating with North Dakota State University to assess the influence of graze timing on *B. inermis* tiller development, which will help inform time-based grazing management.

Restoration potential. Prairies managed by the Service typically experienced decades of little to no disturbance (e.g., fire or grazing defoliation) starting as far back as the 1930s (Dixon et al. 2019). Long-term idling profoundly influences a prairie's plant composition, including facilitating invasion of *B. inermis* and *P. pratensis* (DeKeyser et al. 2010; Grant et al. 2010; Grant et al. 2020a, b; Murphy and Grant 2005). Lack of defoliation disturbance can change ecosystem processes including hydrological cycle, energy capture, and nutrient cycle (DeKeyser et al. 2013, Palit et al. 2021, Printz and Hendrickson 2015) and may limit restoration potential (Printz and Hendrickson 2015). On average, once enrolled in the NPAM program, our tallgrass units were defoliated (i.e., burned or grazed) almost as frequently as they were rested. Tallgrass units showed an average 2% (95% Bayesian CI of 1–3%; Gannon et al. 2024) increase in native plant cover since 2010. In a separate analysis of tallgrass NPAM data, we examined the relative importance of multiple biotic and abiotic variables for explaining observed change in *B. inermis* and *P. pratensis* cover. Management action (i.e., burn, graze, or rest) was the most important explanatory variable for both species; it had far more influence on outcomes than other variables such as recent precipitation, long-term climate, or soils (J. Gannon, U.S. Fish and Wildlife Service, Fort Collins, CO, 2024 upubl. data). Ahlering et al. (2020) also documented the important role of management on native plant cover outcomes, particularly for low-quality (i.e., more heavily invaded) prairies. We expect improvements in native cover to be a long process as plant communities and ecological processes recover from decades of being under-managed. These findings should encourage prairie managers to continue using active management, even without detailed recommendations such as timing, to improve the conditions of our prairies.

Final thoughts

The tallgrass NPAM decision framework was built around the assumption that burning during the *B. inermis* elongation growth stage was the best way to reduce the cover of *B. inermis* and increase the cover of native plants. Given our findings, we plan to explore necessary modifications to the tallgrass NPAM decision framework, including revisiting our uncertainties associated with managing tallgrass prairies. While these analyses provided necessary information to guide the future direction of the tallgrass NPAM program, important questions remain around the effectiveness of timing of burns in relation to *B. inermis* growth stages (and potentially other native and invasive grasses). An experimental approach, as opposed to the adaptive management approach we used, would provide critical insight into the mechanisms driving the vegetative responses to burning. Such information would potentially help explain our unexpected results.

Management implications

Invasion by *B. inermis* and *P. pratensis* pose substantial risks to the integrity and biodiversity of prairies (see Palit and DeKeyser 2022, Palit et al. 2021). The NPAM program provided the necessary data to increase our understanding of tallgrass native prairies and, ultimately, to evaluate our paradigm of focusing burning to the *B. inermis* elongation stage. Removing the emphasis on a narrow timeframe in which to target burning increases flexibility and opportunities to conduct prescribed fires. These results highlight the necessity of questioning established beliefs and leveraging current scientific knowledge to inform management decisions, as well as the significance of long-term datasets that facilitate this

process. Prairies are highly complex systems that face new and persistent threats; continued study and innovative management will be required to meet prairie restoration goals.

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