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RESEARCH ARTICLE

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A Model to Identify Smooth Brome Elongation Using Correlation of Mean Stage Count and Accumulated Growing Degree Days

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ABSTRACT: The US Fish and Wildlife Service (USFWS) uses the five-leaf developmental stage as a signal to the initiation of elongation in smooth brome (*Bromus inermis* Leyss.). In areas where certain plant community criteria are met, conducting a prescribed burn at elongation onset has reduced smooth brome populations. However, leaf stage identification presents USFWS managers with challenges due to the variability of smooth brome development in tallgrass prairies of the Northern Great Plains. The objective of this research was to develop an alternative method to determine when smooth brome populations reach the targeted 50% elongation by linking accumulated growing degree days and population-level plant phenological stages (mean stage count). We determined smooth brome phenological stages at sites in North Dakota, South Dakota, and Minnesota and calculated the corresponding number of growing degree days (using the base temperature of 0 °C). Linear regression models, correlating phenological stage and growing degree days, determined onset of elongation in the smooth brome population, regardless of leaf stage variation. The average accumulated growing degree days (1256 AGDD) and corresponding standard deviation (±155 AGDD) can be used to predict when 95% of smooth brome populations in northern tallgrass prairies reach 50% elongation. As part of USFWS Native Prairie Adaptive Management program, results will be used to assist management decisions regarding the timing of defoliation in an effort to enhance native plant communities where smooth brome is the dominant invader.

Index terms: Bromus inermis, invasive grasses, native tallgrass prairie, phenological development, prescribed burning

INTRODUCTION

Smooth brome (*Bromus inermis* Leyss.) is a perennial cool-season grass (Newell and Keim 1943; Lamp 1952) introduced to North America from regions of Europe and Asia in the late 1800s for forage and erosion control (Newell and Keim 1943; Hitchcock 1950). Smooth brome's rapid rhizomatous growth (Stubbendieck et al. 2011) allows it to spread and increase above- and below-ground biomass (Piper et al. 2015), resulting in decreased plant species diversity (Fink and Wilson 2011; Piper et al. 2015). The effects of smooth brome invasion cascade through native prairie grasslands. Smooth brome can alter fundamental aspects of an ecosystem, including productivity and nutrient cycling (Vitousek et al. 1996; Vinton and Goergen 2006). Grassland managers, including US Fish and Wildlife Service (USFWS) personnel, employ grazing and fire as tools to maintain the health of grasslands (Grant et al. 2009; Gannon et al. 2013), the timing of which plays a critical role in achieving the desired management goals (Fuhlendorf and Engle 2004). Brueland et al. (2003) concluded that early grazing on smooth brome after the presence of one fully collared leaf per tiller, followed by a recovery period, would not be detrimental to the plant or have a negative effect on forage quality. Mitchell et al. (1998) suggested when tillers are in the elongation and reproductive stages, opening the canopy by grazing could recruit new tillers. Both of these situations would stimulate smooth brome growth. Thus, if controlling smooth brome is the objective, the opposite strategies could be employed to inhibit smooth brome's growth and spread.

Willson and Stubbendieck (1997) determined the most effective time to target smooth brome was during tiller elongation, and their model (Willson and Stubbendieck 2000) outlines a decision matrix. After verifying invaded tallgrass prairies include at least 20% warm-season native grasses, a requirement to support the competitive exclusion of smooth brome, it is necessary to identify the developmental stage of the smooth brome population (Willson and Stubbendieck 2000). Prescribed burning is recommended when more than 50% of the smooth brome population has begun elongation but not yet reached the inflorescence stage (Willson and Stubbendieck 2000). The recommended alternative is to begin prescribed burning when the majority of smooth brome has reached the five-leaf vegetative state, a benchmark that corresponds with the beginning of tiller elongation (Willson 1990), allowing prescribed burning to have maximum detrimental impact on smooth brome by destroying the carbohydrate reserves required for survival, especially over winter (Willson and Stubbendieck 2000). In an effort to reduce smooth brome in native tallgrass prairies and maintain diverse habitats that support a wide variety of species, the USFWS includes both grazing and prescribed burning in its management plans (Grant et al. 2009). The USFWS adopted Willson and Stubbendieck's (2000) provisional model to assist land managers in determining when prescribed burning should be applied to tallgrass prairies to target smooth brome.

The Native Prairie Adaptive Management program (NPAM) provides annual decision support for selecting management actions on USFWS lands in Montana, North Dakota, South Dakota, and Minnesota (Gannon et al. 2013). USFWS's current seasonal monitoring requires repeated field surveys during the spring to determine the developmental stage of smooth brome in order to initiate a prescribed burn. USFWS personnel (Sara Vacek, wildlife biologist, USFWS, pers. comm.) in the Northern Great Plains tallgrass prairies use the five-leaf method of Willson and Stubbendieck's (2000) provisional model but have found populations of smooth brome that appear to never reach the five-leaf stage. Following the USFWS NPAM program (Grant et al. 2009; Gannon et al. 2013), USFWS personnel are developing alternative methods to identify the appropriate timing for prescribed burning to target smooth brome that do not rely on the population reaching the five-leaf stage threshold or labor-intensive surveys with the goals of reducing smooth brome's prevalence on USFWS-managed prairies and better allocating resources.

The objective of our current research was to develop an alternative method to determine when smooth brome populations have reached the targeted 50% elongation using the phenological stages and population mean stage count developed by Moore et al. (1991), thereby providing for better accuracy in staging and minimizing the need for repeated field surveys. Moore et al. (1991) created a system to identify the developmental stage of forage grasses at the population level, with morphological descriptors for each stage and a corresponding numerical index (mean stage count, MSC) that can be employed to calculate various statistics on populations. The system uses five growth stages (germination, vegetative, elongation, reproductive, and seed-ripening) and was designed to be easily memorized for use in the field to support practical management decisions. In the vegetative stage, the number of fully collared leaves are counted (Moore et al. 1991) while leaves that are more than 50% dead (Lamp 1952) are excluded from the count. Once the first node is palpable, the plant is categorized in the elongation stage until the reproductive shoot can be observed (Moore et al. 1991).

Growing degree days (GDD), or heat units, are commonly used for agricultural purposes to identify developmental stages of crops (Romo and Eddleman 1995; Akyuz and Ransom 2015) to determine the appropriate timing of events such as fertilizer, pesticide, or herbicide application, and harvest. In these cases, GDD are accumulated (accumulated growing degree days, AGDD) beginning at the date of seed sowing. Different types of plants have different temperature requirements for growth to occur and this difference is accounted for by including the base temperature (minimum temperature for biological activity of that species) in the growing degree day equation (Hatfield et al. 2011). The relationship between growing degree days and phenological development has been used by other researchers (Frank et al. 1985; Hendrickson et al. 1998) to determine population developmental stages. Thus, we hypothesized that the number of accumulated growing degree days had the potential to serve as a cue to the onset of elongation within a smooth brome population in tallgrass prairies in the Northern Great Plains. We conducted field surveys of smooth brome populations at sites in North Dakota, South Dakota, and Minnesota in 2014 and 2015 and developed a model to assist land managers in timing their management activities to target smooth brome while reducing labor input in the spring.

METHODS

We selected sites throughout North Dakota, South Dakota, and Minnesota within the region's tallgrass prairies (Figure 1) based on the presence of smooth brome. While the majority of sites were located on USFWS managed land, six total transects were located at Bluestem Prairie (The Nature Conservancy, Glyndon, Minnesota), Minnesota State Parks (Minnesota Department of Natural Resources, near Crookston, Minnesota), Sheyenne National Grassland (US Forest Service, Milnor, North Dakota), and the Albert K. Ekre Grassland Preserve (North Dakota State University Development Foundation, Richland County, North Dakota). Transects (50 m) were situated at each site to intersect as much smooth brome as possible and GPS coordinates and compass bearings were recorded for each transect to ensure that repeated sampling

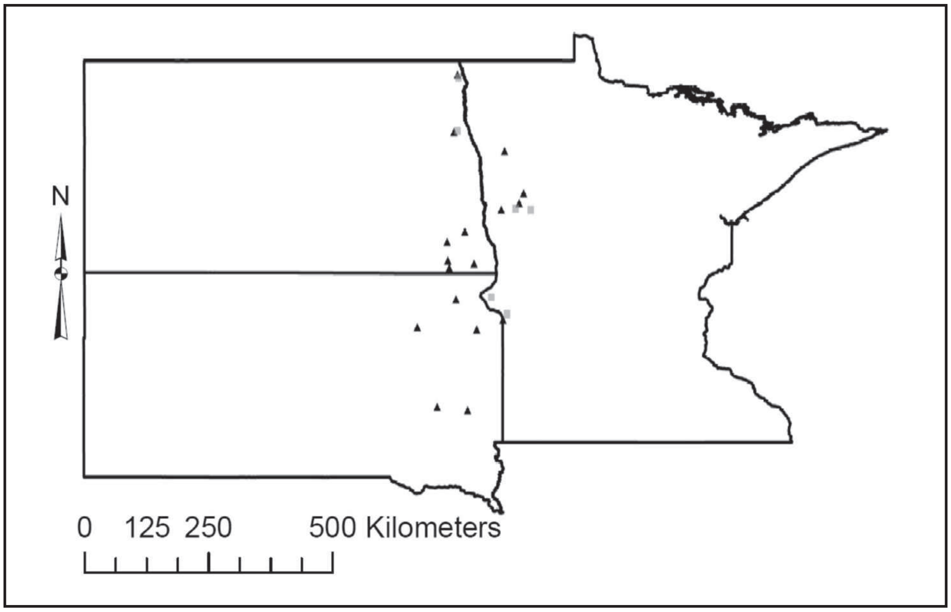

Figure 1. Locations of smooth brome transects sampled in 2014 and 2015 during model development (triangles) and model validation (squares) transects sampled in 2016.

was conducted at the same location. We placed each transect in areas of relatively uniform topography and soil structure to minimize variation attributable to changes in microhabitat. Multiple transects were placed at sites with topographical variation, such as obvious sloping, to account for smooth brome population dynamics across the landscape.

Five 1-m^2 quadrats were centered along each transect, using restricted randomization to determine the placement of a quadrat within each 10-m subsection of the 50-m transect. We divided each quadrat into 10 subplots of 20 cm × 50 cm. Each week, we sampled a single subplot to reduce the likelihood of evaluating the effects of repeated sampling. In 2014 data collection began in early May and continued for 6 wk or until at least 50% of the sample population reached the elongation stage. Sampling was repeated in 2015, using the same transects, and began early enough to ensure that each site was sampled before the population reached the 50% elongation benchmark. If a transect was located on a site that experienced a disturbance (i.e., grazing, burning) the data was collected up to the date of the disturbance and discontinued following the disturbance. In some cases, lack of sufficient data required transects be eliminated from the study, resulting in a total of 23 transects in 2014 and 17 transects in 2015.

Weekly sampling consisted of placing a 20 cm × 50 cm frame in one of the 10 subplots and identifying the phenological stage of each smooth brome tiller rooted within the frame. Phenological stage identification followed the Moore et al. (1991) method (Table 1). Subplot counts were tallied for each transect to obtain the number of tillers at each phenological stage within the transect sample. Each phenological stage was assigned an index value according to Moore et al. (1991). The values for germination have been omitted because, as a perennial grass, it is difficult to distinguish between a germinating seed and a new emergent tiller. The index values for seed ripening were also omitted because the sampling concluded prior to seed ripening. For each stage, the index value was calculated by multiplying the total number of tillers at that stage by its index value (Table 1). Mean stage count (MSC) was then determined according to the following equation (Moore et al. 1991):

MSC = (Σ Index Values for each stage encountered)/total sampled tillers.

AGDD was calculated using 0 °C as the base temperature because smooth brome is a cool-season grass, like those studied by Frank and Hofmann (1989), that will begin growing early in the season and does not necessarily require germination of seeds as it is perennial and rhizomatous. In addition, we used the base temperature of 0 °C to account for the possibility that photosynthesis could occur in existing plants when the temperature rises above freezing. Similar to Hendrickson et al. (1998), we chose to begin accumulating growing degree days on 1 January of each year. Targeting specific AGDD values allows for identification of the burn window no matter the severity of winter or spring conditions. AGDD were calculated using the following equation (Akyuz and Ransom 2015):

AGDD = Σ [(Daily maximum temperature + Daily minimum temperature)/2 − Base temperature)].

Maximum and minimum temperatures for each site were determined using the online Applied Climate Information System (ACIS) Query Builder (Regional Climate Centers 2017). GPS coordinates and desired output of maximum and minimum daily temperatures were entered into the

Table 1. Phenological development stage, index and description (Moore et al. 1991).

Stage	Index	Description
Vegetative-Leaf development		
Emergent or V_O	1	Emergence of first leaf
V_1	(1/N)+0.9	First leaf collared
V_2	(2/N)+0.9	Second leaf collared
V_n	(n/N)+0.9	Nth leaf collared
Elongation-Stem elongation		
E_O	2	Onset of stem elongation
E_1	(1/N)+1.9	First node palpable/visible
E_2	(2/N)+1.9	Second node palpable/visible
E_n	(n/N)+1.9	Nth node palpable/visible
Reproductive-Floral development		
R_O	3	Boot stage
R_1	3.1	Inflorescence emergence/1st spikelet visible
R_2	3.3	Spikelets fully emerged/peduncle not emerged
R_3	3.5	Inflorescence emerged/peduncle fully elongated
R_4	3.7	Anther emergence/anthesis
R_5	3.9	Post-anthesis/fertilization

query builder from 1 January through 31 July of each year for each transect. The ACIS Query Builder used GPS coordinates and interpolated data from National Oceanic and Atmospheric Administration (NOAA), increasing the accuracy of the maximum and minimum temperatures used for the AGDD equation, while maintaining consistent methodology.

Temperatures, maximum or minimum, lower than 0 °C were adjusted to the effective temperature of 0 °C, as described by Akyuz and Ransom (2015). Effective maximum and minimum daily temperatures were used to calculate AGDD with a base temperature of 0 °C. Because this model was developed to be used in the United States, actual GDD calculations were completed using Fahrenheit scale.

AGDD and MSC were regressed (Frank et al. 1985; Hendrickson et al. 1998) for each transect (Microsoft Excel 2013). Additionally, the percentage of each tiller stage was calculated for each sampling date to determine the approximate AGDD at which the sampled population reached 50% elongation. Using the slope of the line between two points that included 50% elongation, AGDD was calculated for each transect to determine the point at which the sample population reached this critical value of 50% elongation. Estimated AGDD at 50% elongation was calculated for each transect during both years and the average for all sites and both seasons was calculated with their corresponding standard deviations.

Following model development (field sampling in 2014 and 2015), we conducted a model validation trial in 2016. We selected six previously unstudied sites (Figure 1), placed transects at each site, and performed weekly phenological stage sampling from mid-May through early June using the same methods described above. Regression analysis was repeated on model validation data (Microsoft Excel 2013). We used the resulting AGDD at 50% elongation values from our sampling and model validation trials to calculate the range within which prescribed burning is most likely to be detrimental to smooth brome populations. These intervals were generated around the average AGDD at 50% elongation values by adding and subtracting two standard deviations. The resulting intervals serve as the basis for our recommendations to USFWS personnel to identify the appropriate burn window to be most detrimental to smooth brome.

RESULTS

Phenological development stages were tallied and used to determine the percentage of the smooth brome population at elongation phase or beyond. MSC was calculated for each transect and used in linear regression analysis with AGDD. Linear regression analysis indicated a positive linear relationship between MSC and AGDD for each transect in 2014 and 2015 (Table 2). Nonlinear regression analysis of AGDD and % > E1 for the combined years showed a polynomial relationship (R^2 = 0.8301; Figure 2), allowing for estimation of the number of AGDD elapsed when the population reached 50% elongation, even though sampling may not have occurred on the day of 50% elongation.

Using the extrapolated AGDD for each transect, the average number of AGDD when smooth brome populations reached 50% elongation was 1214 AGDD (SD = 182) in 2014. Thus, in 2014, the interval in which brome populations were most likely to be harmed by a prescribed burn occurred between 850 and 1578 AGDD. Based on the 2014 results, we expected populations to reach 50% elongation at roughly the same number of AGDD in 2015. Field sampling and data analysis confirmed that the average AGDD at which the population reached 50% elongation in 2015 was similar to that in 2014 and occurred well within the predicted interval (2015 average = 1309 AGDD, SD = 92). In 2015, the interval in which brome populations were most likely to be harmed by a prescribed burn occurred between 1125 and 1493 AGDD. The average AGDD for the combined 2014 and 2015 data was 1256 AGDD (SD = 155) and the resulting interval during which smooth brome populations are expected to reach 50% elongation was between 946 and 1566 AGDD.

Model validation sampling in 2016 confirmed our prediction that 50% of the smooth brome population would reach elongation at approximately 1250 AGDD (Table 3). There was a strong linear correlation between MSC and AGDD (R^2 = 0.8512; Figure 3). The average number of AGDD at which 50% of the smooth brome tillers at the validation sites reached elongation or higher was 1160 AGDD (SD = 35), well within the 95% interval predicted from the combined 2014 and 2015 data (946–1566 AGDD).

DISCUSSION

Opening the canopy in a smooth brome–invaded tallgrass prairie could encourage the recruitment of native species (Willson and Stubbendieck 2000) and restore the diversity of this threatened ecosystem (Murphy and Grant 2005). However, the timing of prescribed burning is an important consideration for tallgrass prairie managers. Burning early in the season, prior to elongation, removes litter from the young smooth brome plants, gives them better access to sunlight, and allows for increased growth of smooth brome (Willson and Stubbendieck 1997). Additionally, burning during this early season could deplete soil moisture (Willson and Stubbendieck 1997), affecting the growth of both smooth brome and the native plants. Late-season burning, following elongation, was found to have a negative impact on smooth brome but not as effectively as during elongation (Willson and Stubbendieck 1997). Waiting to burn until later in the season could also be detrimental to the native species. The USFWS, through the NPAM program, is attempting to identify the appropriate period in which to conduct a prescribed burn to harm smooth brome populations while improving native plant community components on USFWS-managed tallgrass prairies.

Our research confirmed that the linear relationship between MSC and AGDD allows us to determine the average number of accumulated growing degree days required for smooth brome populations in our study area to reach 50% tillers in the elongation stage. With this average (1256

Table 2. Results of linear regression analysis and calculated accumulated growing degree days when sampled populations reached at least 50% elongation for 2014 and 2015.

Transect #	Transect name	State	County	R^2 (2014)	R^2 (2015)	AGDD @ 50%>E1 (2014)	AGDD @ 50%>E1 (2015)
1	Tewaukon/Wyum A	ND	Sargent	0.8354	0.7788	1279	1298
2	Tewaukon/Wyum B	ND	Sargent	0.7533	0.6661	1250	1258
3	Tewaukon/Wyum C	ND	Sargent	0.7736	0.6166	1221	1237
4	Ekre/NDAWN	ND	Richland	0.9271	0.6916	1235	1250
5	Sheyenne National Grasslands A	ND	Ransom	0.7064	0.7308	1232	1286
6	Sheyenne National Grasslands B	ND	Ransom	0.8670	0.6861	1271	1419
7	Tewaukon/Pool 4 A	ND	Sargent	0.5724	0.6792	1146	1266
8	Tewaukon/Pool 4 B	ND	Sargent	0.6229	0.7441	1042	1134
10	Hartleben C B	ND	Richland	0.6586	0.5827	1342	1231
11	Helliksen	MN	Becker	0.8051	0.7726	1242	1286
12	Marks	MN	Becker	0.7248	NA	1276	NA
13	Mekinock	ND	Grand Forks	0.9301	0.9130	1209	1299
14	Pembina Prairie	ND	Pembina	0.6583	0.9167	970	1239
16	Hepner	SD	Miner	0.7592	NA	1386	NA
17	Wolfe A	SD	Lake	0.7106	0.5063	1348	1358
18	Wolfe B	SD	Lake	0.5744	0.4781	1163	1531
19	Sanderson	SD	Spink	0.6766	0.9205	1285	NA
20	Overland	SD	Covington	0.6166	0.8266	1270	1398
21	Gerber	SD	Marshall	0.6887	0.8204	1169	1322
22	Big Stone NWR	MN	Big Stone	0.5055	NA	788	NA
23	Tympanuchus WMA	MN	Polk	0.8932	0.8874	783	1325
26	Bluestem Prairie West A	MN	Clay	0.8077	NA	1502	NA
27	Bluestem Prairie West B	MN	Clay	0.9144	NA	1518	NA
	Annual average					1214	1309
	Standard deviation					182	92
	Combined average					1256	
	Standard deviation					155	

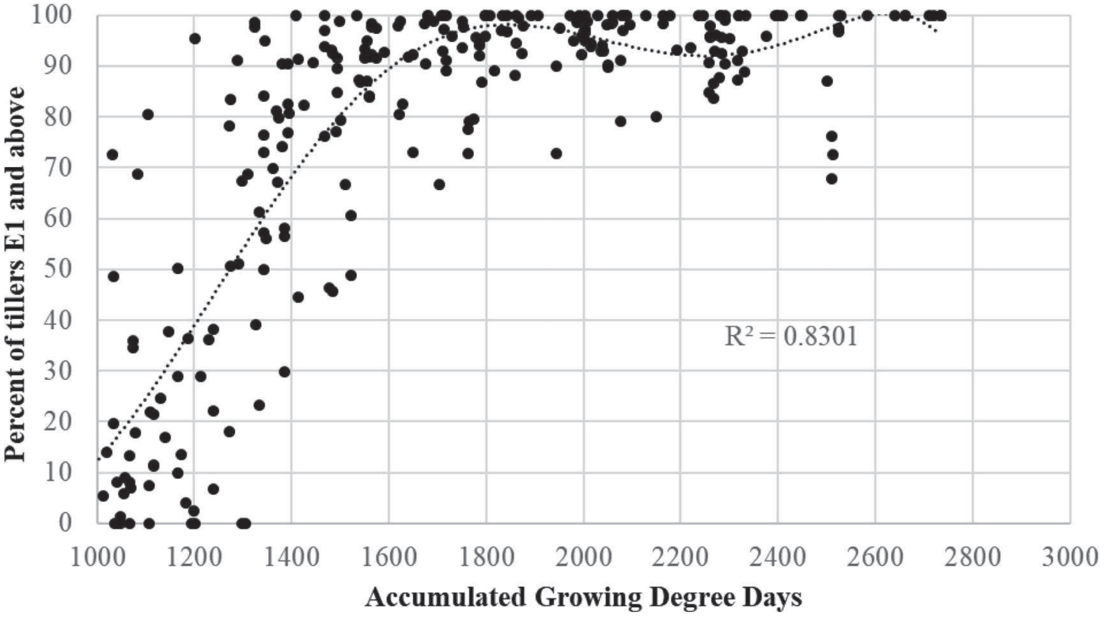

Figure 2. Nonlinear regression showing a polynomial relationship between the percent of tillers in elongation (% > E1) and the number of accumulated growing degree days (AGDD) of all sites for 2014 and 2015. The average AGDD at which the population reached 50% elongation was 1256 (SD = 155).

AGDD) and corresponding standard deviation (155 AGDD), we expect that 95% of smooth brome populations in northern tallgrass prairies will reach 50% elongation between 946 AGDD and 1566 AGDD. This interval can be identified as the window in which to expect smooth brome populations to best respond to prescribed burning as described in Willson and Stubbendieck's (2000) provisional model for controlling smooth brome.

During sampling, we noted that the percentage of tillers that had begun elongation could jump significantly from one week to the next, progressing from no sampled tillers in elongation to greater than 50% tillers in elongation in the period between sampling. Additionally, the sample population was rarely observed to achieve five-leaf stage before beginning elongation (determined by the Moore et al. 1991 staging method), more commonly elongating when the tillers had only three or four leaves, supporting the USFWS's reported difficulty in identifying five-leaf stage and complicating management decisions tied to the recognition of this phenological stage. Thus, by focusing on elongation and not on leaf stage, uncertainty in timing of proper management will be circumvented. Also, management resources could be allocated more effectively by adapting Willson and Stubbendieck's (2000) model to use AGDD and elongation to determine the appropriate timing of prescribed burning rather than labor-intensive field surveys.

Utilizing our method of monitoring sites for the target window via temperature reports and calculating AGDD can be completed quickly in the office on a daily or weekly basis, without relying on the valuable resources required to perform labor-intensive phenological staging in the field.

Table 3. Summary of R^2 values and the number of accumulated growing degree days calculated when the sampled population reached at least 50% elongation for each of the model validation sites.

Transect name	State	County	R^2 (2016)	AGDD @ 50%>E1 (2016)
Arneson	MN	Becker	0.8976	1179
Olson	MN	Clay	0.9546	1111
Kelly Slough	ND	Grand Forks	0.9716	1137
Kemp	ND	Pembina	0.9797	1214
Kiekmann	MN	Traverse	0.7854	1157
Twin Lakes	MN	Big Stone	0.7854	1159
Annual average				1160
Standard deviation				35

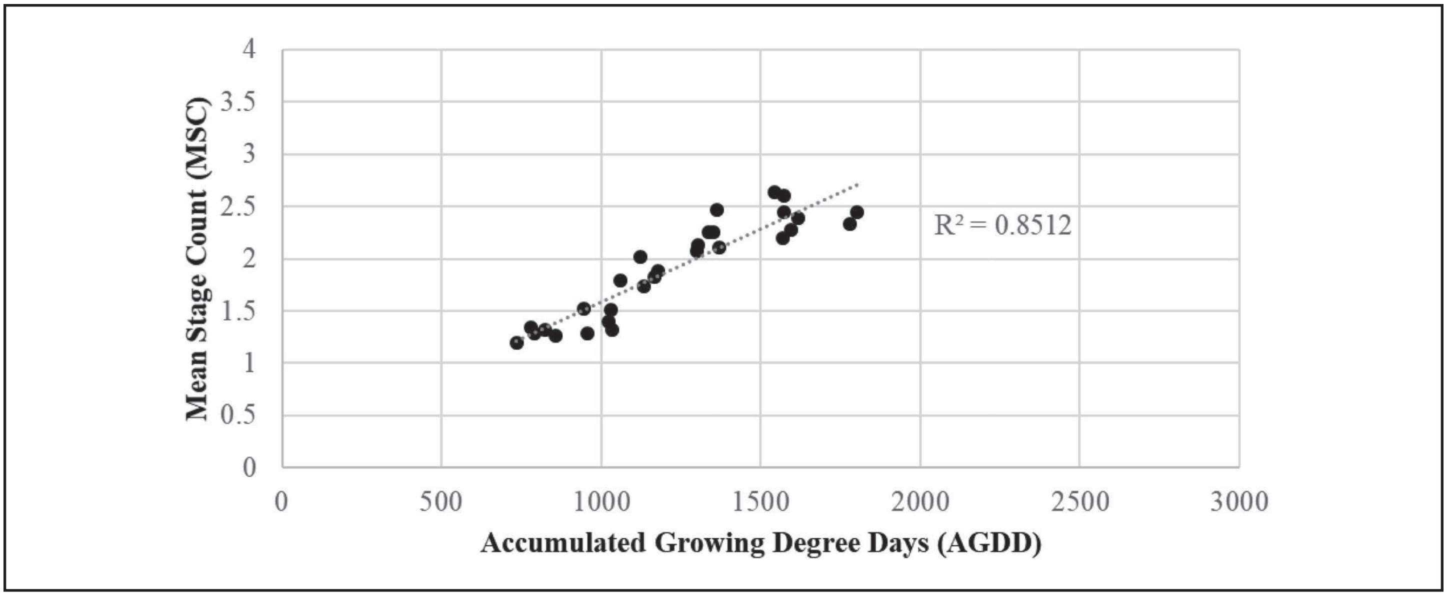

Figure 3. Linear regression of Mean Stage Count and Accumulated Growing Degree Days for 2016 model validation sites. The average AGDD at which the population reached 50% elongation was 1160 (SD = 35) for the validation sites. Model validation confirmed our prediction that 50% of the smooth brome population would reach elongation at approximately 1250 AGDD.

When AGDD nears the beginning of the recommended burn interval (946 AGDD), USFWS personnel could confirm that the smooth brome population is approaching the targeted development of 50% or greater elongation through a single field survey and time their prescribed burning prior to the anticipated end of the recommended interval (1566 AGDD). Thus, our model will help USFWS personnel time their prescribed burning to be most detrimental to smooth brome populations while conserving resources, both important objectives of the USFWS NPAM program (Gannon et al. 2013).

In the future, additional ad hoc analysis could be applied to historical USFWS burn data by calculating elapsed AGDD of previous burns, to strengthen the accuracy of our AGDD model and its usefulness to USFWS personnel as part of the NPAM program. Our model could also be made more precise through narrowing the recommended burn interval or incorporating other variables that affect smooth brome growth (e.g., moisture, nitrogen). Continued evaluation of our model's effectiveness and adaptability will be crucial for successful management of smooth brome populations and fits well with the USFWS NPAM program goals.

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The views expressed in this article are the authors' own and do not necessarily represent the views of the US Fish and Wildlife Service.

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