The Effect of Fuel Moisture Content on the Flammability of Goldenrod in Prairie Ecosystems

Honors Undergraduate Thesis

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Abstract:

Land use change across North America has greatly reduced the extent of prairies and grasslands and replaced them with agriculture. Grasslands and prairies provide biodiversity, habitat for many animals and pollinators, and ecosystem services. In Ohio, prairies did not have a large extent, but were known to exist in small patches representing the furthest reaches of western grasslands. Now, what is left of such prairies are small, remnants that lack resiliency and diversity, which makes restoring them necessary to conservation efforts.

Canadian goldenrod (*Solidago canadensis*) is a native species, but it can become invasive within restored prairies and old fields creating monocultures that reduce the species richness and diversity. Fire is likely a vital ecological disturbance within prairies, but goldenrod-dominated areas are may be difficult to ignite and burn. Goldenrod also greatly benefits from burns, due in part to suitable regeneration conditions created by fires and their early successional traits. To better understand fundamental controls on the potential for prescribed burning in restored prairies the flammability of goldenrod was investigated.

Field data was collected during spring and autumn 2019 to determine variation in fuel moisture content (FMC) with weather and how FMC varies vertically throughout the fuel bed. Weather data was taken on sampling days from Waterman Farm weather station and applied to the Canadian Forest Fire Danger Rating System to calculate the daily Fine Fuel Moisture Code (FFMC). Lab tests were conducted by heating samples of goldenrod of different FMCs in a quartz epiradiator and measuring ignitability, sustainability and combustibility. The impact of a pilot flame on ignition processes was also examined.

Goldenrod FMC was lowest at the top of the plants in spring, with greater fire danger ratings. Autumn FMC was not impacted by fire danger rating. Flammability tests showed that time to ignition was shortest at low FMCs. The duration of flaming and flame heights were greatest with lower FMCs. When comparing the flammability metrics to the FFMC values calculated from field data, there was a correlation between greater flammability and greater FFMC.

Overall, the results indicated that flammability was greatest at the lowest FMCs, specifically at around 15% and lower, which is a significant discovery. The flammability metrics determined that faster ignition, higher flame heights, and longer durations of flaming would likely lead to the spread of fire throughout fuels and greater consumption of goldenrod. Field data suggests that goldenrod has the lowest FMC in spring, at the top of the plant, which can alter fire behavior. Fine fuel moisture codes increased with decreasing FMCs and were positively correlated to flammability metrics. Fine fuel moisture codes of 70-74 and above strongly indicate increased flammability of goldenrod.

Introduction

Grasslands throughout North America protect the biodiversity of a variety of landscapes and provide valuable ecosystem services such as supporting endangered species, and acting as carbon sinks (Klimek et al., 2007; Soussana et al., 2010). Prairie grassland ecosystems vary in their size and extent across North America as a result of the capitalization by agriculture on their high nutrient value or being tillable for farming (Blair et al., 2014). Prairies have seen substantial losses between the early-colonial period and the present and restoring these systems can be difficult(Swab et al., 2020). The conversion of prairies to croplands has dwindled prairies in the United States by between 82 and 99% (Samson et al., 2004; Samson & Knopf, 1994). In Ohio, prairies were not known to be as historically extensive as the western United States, but they were apparent before colonization and represented the edge of the reach of the great wester grasslands (Lafferty, 1979). Losses of large swaths of prairie drives fragmentation and degrades patches, requiring significant restoration to replenish biodiversity and repair ecosystem structure (Berger et al., 2020). Restoring their current state prevents further degradation and conserves an ecologically important ecosystem (Blair et al., 2014). There has been a slow emergence of national recognition of the importance of this ecosystem, which has stalled their restoration efforts(Swab et al., 2020). Since 1985 though, the Conservation Reserve Program in the United States has promoted cropland restoration to prairie systems, and although program enrollment has waned, restoration of prairies has still grown (Berger et al., 2020). Government and private organizations have increased prairie restoration on reclaimed mine land and cropland as well (Camill et al., 2004; Swab et al., 2020). Restoration is a process that takes time and effort to return to an ecosystem to within the range of historical variability, such as the range of species compositions or diversities found in different prairies.

Implementing a disturbance regime that benefits the native species is a critical part of restoring prairies. The current state of an ecosystem, if they are an altered stable state, changes how it reacts to different disturbances, and using the current composition of an ecosystem to guide the process towards a disturbance regime will protect current diversity (Blair et al., 2014). Many ecosystems rely on maintenance of appropriate natural disturbance regimes to maintain biodiversity, control the abundance of invasive or invasive-like species (i.e. aggressively spreading native species with a tendency to become over-dominant), and prevent encroachment by woody species (Brooks et al., 2004). Historically, fire was a key disturbance process within prairies (He et al., 2019). Fires consume non-native, invasive-like and native species, while allowing native species potentially adapted to fire to maintain their dominance. Plots of prairie ecosystems burned frequently throughout decades have greater biodiversity and vegetation abundance than those unburned over decades (He et al., 2019). Certain introduced species such as *Alopecurus pratensis*, *Lotus corniculatus,* and *Bromus mollus* thrive without fire, and can outcompete native grasses and forbs leading to reduced biodiversity (Valkó et al., 2016). Fires are also responsible for remobilizing nutrients in the soil and frequent burns (5 year intervals) ensures that nutrients are returned to the soil that are necessary for the plants returning to populate the prairie, especially the resources most useful to native species (He et al., 2019; Valkó et al., 2016). Carbon and nitrogen levels are also specifically altered to the benefit of native species (Soong & Cotrufo, 2015). Although fire is beneficial to most native species, the initial changes it makes can create positive feedback loops that aid certain species more than others.

The goal of restoring a fire regime is to restore native species, diversity, species abundance and richness to an ecosystem. A fire regime describes the intervals, intensities and severities at which fires occur in a prairie ecosystem and were initially implemented by Native Americans for a variety of reasons such as hunting or clearing areas for sightlines(Roos et al., n.d.). Native prairie systems are filled with plants that foster ignition and sustain fires, such as C_4 grasses like big bluestem, Indian grass and switchgrass (Camill et al., 2004; Grman et al., n.d.). But these species can take longer to regenerate after a fire, even taking years to fully reestablish, and they are necessary for increased fire spread in later burns (Wragg et al., 2018). Canada goldenrod (*Solidago canadensis;* hereafter “goldenrod”) is a good example of an invasive-like species with the potential to alter fire regimes or a fire’s impact. Goldenrod regenerates quickly after a fire disturbance, due to soil rhizomes and seed dispersal if not consumed in fire (*Solidago Canadensis,* n.d.). As an early successional species, goldenrod establishes quickly after a disturbance and can spread over a site much faster than other native species (Medve, 1984). It can easily supplant other native species and become dominant (Marks, 1983). Although goldenrod is native to most mid-western prairies, it can become a monoculture (Lafferty, 1979). In Ohio, goldenrod can be found in a variety of ecosystems, but thrives in open prairie areas, especially those disturbed by human interactions (Lafferty, 1979). Removing a fire regime completely will not stop the spread of goldenrod or benefit other native species. For example, New Zealand study on the effects of removing a disturbance regime (Cubino et al., 2018) found that those that formerly had a fire regime experienced a shift from flammable, native grasses to fire-resistant forbs. Once an alternative stable state has been reached, achieving reoccurring fire can be problematic and requires taking into account the new fuel type, fuel load, and the altered structure of the plot (Brooks et al., 2004). Because fire regimes are necessary to protect ecosystem function and structure, other solutions to post-burn goldenrod spread must be found.

Although goldenrod monoculture may impact intensity or spread of a burn (Gusev, 2018), knowledge on its flammability in relation to certain plant traits is limited. Goldenrod burned during the dormant season is able to resprout before grasses while those burned during the fall are not fully consumed and can reseed the ground immediately after the burn (Ganteaume et al., 2013). Because goldenrod responds favorably to fire and post-fire conditions, it recovers from fire faster than other forbs and grasses, increasing its cover (Bieser & Thomas, 2019). Goldenrod's inherent flammability is important to investigate to discover potential ways to impact its regeneration after fire. Flammability is defined as the ability of a fuel to ignite and sustain a fire (Chuvieco et al., 2004). There are several other definitions of flammability, including the release of heat from a fire, consumption of mass and percent of sample consumed, but the definition used in this experiment is solely ignitability, sustainability and combustibility (Cubino et al., 2018; Santana & Marrs, 2014). Ignitability is how easily a plant catches fire and sustainability is the maintenance of flaming combustion (Cubino et al., 2018; Santana & Marrs, 2014). Combustibility is the intensity of a fire or combustion (Fernandes & Cruz, 2012; Santana & Marrs, 2014). There is typically an inverse relationship between Fuel moisture Content (FMC) and flammability; the lower the FMC of a fuel the more flammable it is likely to be (Santana & Marrs, 2016). If all other factors are the same, the water in a fuel must evaporate before ignition can occur, slowing down the time to ignition and requiring more energy. Water reduces the available oxygen, acts as a heat sink before evaporating and dilutes volatiles, which attacks all three parts of the fire triangle (fuel, heat, and oxygen) required for ignition (Chuvieco et al., 2004). A range of fuel moisture contents in which a specific fuel is known to ignite and sustain a fire is often used in fire danger rating and in predicting the potential for propagation of a fire (Jolly, 2016). Fire rating systems view FMC as one of the most important factors in predicting flammability and often attempt to define the moisture of extinction (ME) - the FMC at which a fire can no longer be sustained or thresholds of ignition at which above a specific FMC ignition is likely (Chuvieco et al., 2004; Wotton, 2009). This value defines a range of FMC values from

ME to oven dry (0% FMC) across which a fuel will burn. This range can be applied, with weather information to give a fire danger rating, and this is useful in management for determining whether conditions are in prescription.

The overall aim of this study is to find the link between weather, goldenrod fuel moisture content (FMC) and its flammability. Although flammability predictions for prairies are fairly accurate, goldenrod's flammability and the related fire behavior at specific FMC's are unknown. By gaining knowledge of the effects of FMC on goldenrod specifically, a barrier to biodiversity in prairies may be overcome. The objectives of this project were to 1) describe the variation in goldenrod FMCs within a season and between the potential burn seasons of fall and spring, 2) characterize the gradients of FMC in goldenrod and how their variation may influence fuel bed flammability 3) relate the variation in FMCs to fuel moisture indices that may be used in predicting flammability and 4) model multiple flammability metrics as a function of fuel moisture.

Methods:

Study Location

Field data was collected at the Ohio State University's research prairie at Chadwick Arboretum North (Lat 40.009948, Long -83.030989). Chadwick Arboretum North is a part of the Chadwick research gardens at the Ohio State University. It is located west of the Ohio State University's main campus in Columbus, OH and to the east of highway 315. Established in 1980 by SENR at The Ohio State University, it was intended as a buffer zone between the highway and athletic buildings being built nearby (*Arboretum North | Chadwick Arboretum & Learning Gardens*, n.d.). The research prairie was established on the western portion of the site, along a slight eastern facing hill in the late 1990's. It is frequently used in teaching ENR 4800 as a site to practice restoration techniques. Originally intended as an alternative ground cover to turf, the site now acts as a pollinator plant garden and hosts many native prairie species and flowering plants (*Prairie Plant Research & Monarch Butterfly Waystation | Chadwick Arboretum & Learning Gardens*, n.d.). When originally established, the soil at the site was a combination of silt loam and soil excavated from the construction of the lake at the site. The soil was placed into mounds and native prairie species were transplanted onto it from a lab experiment (Knee et al., 1998). The soil type is mostly Kendallville silt loam, with 2-6 percent slopes and well-drained, with some Miamian silt loam with slopes 6-12 percent (*Web Soil Survey*, n.d.). The current climate of the site is a moderate, continental climate with moderate extremes of weather (Lafferty, 1979).

Field Data Collection and Analysis:

Fuel samples for fuel moisture data were collected at Chadwick Arboretum research prairie in the spring and autumn of 2019. The prairie was divided into five units for the purposes of capturing intra-site variation in FMC. Samples were taken twice weekly around noon. Spring FMC sampling was completed between January 14th and April 16th, 2019. A single sample goldenrod stem was taken from each section and divided vertically into 10 cm strata. Depending on the season, the leaves and foliage were collected as well, with the top 10 cm often containing foliage in the autumn. In the autumn between September 12th and November 18th, 2019 this process was simplified with a 10 cm long sub-sample of each stem taken from the top third, middle and bottom of the plant. Samples were taken from the field in sealed containers and weighed the day of collection in tin trays. They were then dried at 60° C for 48 hours. They were weighed after drying and fuel moisture content was calculated following equation 1: FMC (%) =

(Original weight- Dry weight)/ Dry Weight *100. [Eq. 1]. Dried samples were then kept in the lab for use in subsequent flammability tests.

Weather data for the entire period over which field samples were collected, and the prior month, were also collected. Relative humidity, temperature, and wind speed at noon and the daily precipitation were taken from the Waterman Farm weather station, 2 km west of the sampling site, online database: https://www.oardc.ohio-state.edu/weather1/stationinfo.asp?id=14). These data were used to calculate the moisture codes of the Canadian Fire Weather Index System. Using the fwi function in R, the weather data for a month before sampling and throughout the study were applied to create outputs of the Canadian Forest Fire Weather Index (FWI) system. These included fine fuel moisture codes, duff fuel moisture codes and drought codes.(Ganteaume et al., 2013; Jolly, 2016; Wotton, 2009).

Flammability Tests

The flammability of samples of goldenrod was tested at 0, 5, 10, 15, 20, 25 and 30% FMC. For each FMC thirty, 10 cm long sticks of oven-dried goldenrod were weighed, and the mass of water needed to create the desired FMC calculated and added to each sample. Samples were left in a sealed container at ambient room temperature (ca 19°C) for one month, being turned occasionally to ensure even absorption. Once absorption was complete, and immediately before the flammability test, a stick was cut into two 5 cm pieces. One piece was used to determine the measured FMC of the sample and the other half was used in the flammability test. The wet mass of the first half was measured, and then placed in the oven at 60°C for 48 hours and the mass was again measured after and FMC calculated using Eq. 1.

Prior to the tests each goldenrod sample was measured in length in mm and the diameter of the stick was measured in mm with calipers. The mass of the sample was measured and its volume (assuming sticks were a cylinder) and density calculated from the mass and volume. Flammability tests broadly followed the methods described by Ganteaume et. al and were conducted in a fume hood (typical airflow rates through the hood were 101 FPM) (Ganteaume et al., 2013). A quartz epiradiator was set up and turned on an hour before the test to ensure even and maximum heating. A pilot flam was situated 4 cm above the epiradiator surface and was fueled by a portable propane gas tank. The pilot flame was created by turning a Bunsen burner on its site and attaching it to a pole, which resulted in a 3 cm long flame about 3 cm high in an L shape. Prior to flammability tests, pilot tests were conducted to determine the effects of the pilot flame on ignition time and sustained flaming time. The use of a pilot flame, and its height, were determined using tests, and in comparison to previous testing on ornamental plants (Ganteaume et al., 2013). Behind the flame and epiradiator a measuring stick was aligned with the bottom of the epiradiator's heated plate. The measuring stick showed increments of 10 cm, but because of its place behind the epiradiator, a calibration variable was calculated to account for distance and angle. To do so, the position of the camera for each video was set and marked with tape. Then, cardboard cutouts of 5cm, 10cm, and 15cmheights were placed on the unheated epiradiator and their picture taken with the camera in the pre-determined position. Using the known value of height on the measuring stick, and the known height of the cardboard cutouts, the calibration variable was calculated using the following equation 2:

Known height of cut out (cm) / measured height of cutout based on measuring stick (cm) (Eq. 2)

The calibration variable was 1.09 and each flame height was multiplied by it.

Once the epiradiator reached maximum heat and the set up was checked for accuracy, flame tests began. Half of the 30 samples for each FMC were tested with a pilot flame and half without. Ignitability and sustainability were, respectively, measured by quantifying time to ignition and duration of flaming. The ratio of flaming versus initial smoldering combustion was also estimated

The combustibility of the samples was quantified by measuring flame heights from the videos taken from the tests, as described in forest fuel tests (Essaghi et al., 2017). Ten flame heights were measured in each video, with the beginning and end of the flaming period excluded due to its greater variability. All heights were corrected based on the previously determined calibration.

The three flame metrics, ignitability, sustainability and combustibility, were measured because of their importance to overall flammability in prairie burns. Ignitability is a samples ability to transition from a smoldering burn to flaming combustion, while sustainability is a samples ability to maintain flaming combustion. Combustibility is the velocity or intensity of a burn (Santana & Marrs, 2014)

Data Analysis

All graphs were created in R. Field data was formed into boxplots using the boxplot function. Field data and FFMC data were merged via the merge function and a scatter plot of the points made using the plot function. Lm was used to create linear regressions for each height in the scatter plot.

The flame heights, ignition time, sustained flame time, and ratio of burn to smolder were compared to the FMC, mass and density of the sample. All statistical analyses were completed in R. Linear regressions were run using the lm function in R to predict how FMC, dry mass and whether or not a sample was piloted impact the flammability. Regressions were run to predict flame height, ignition time, sustained flame time, and the ratio of burn to smolder. Flame heights also included the influence of density on the model.

CFFDR package was used to calculate FFMC ratings in R using the weather data collected from Waterman Farm weather station. A linear regression model was also constructed using the lm function in R for the Canadian fire weather index values. The fine fuel moisture code ratings, height and season of field samples were used to create a linear regression model to predict FMC.

A generalized linear model was used to create an ignition variable using the glm function with a binomial family. The effect of FMC, dry mass and pilot flames were used to predict if samples ignited or not. This data was then converted from a prediction to a probability. A data frame of average FMC, piloted samples with randomly generated masses was created, as well as their potential for ignition to compare to the probability model. These points were graphed in a scatter along with the generalized linear regression.

For all graphs, a p value of 0.05 or smaller was used to define significance. R^2 values were used to determine the correlation and predictive abilities of linear regressions.

Results:

Spatial and temporal variation in fuel moisture content

Table 1: Results of a linear model comparing the effect of the Fine Fuel Moisture Code, sample height and season on FMC. There were 69 total degrees of freedom and the R^2 value was 0.68

Variable	**Degrees Freedom**	**Std. Error**	**F-value**	**P-value**
FFMC	1	6395	6.514	0.013
Height	1	11537	11.753	0.001
Season	1	111434	113.514	<0.001
FFMC: Height	1	7484	7.623	0.007
FFMC: Season	1	18509	18.854	<0.001
Height: Season	1	5216	5.313	0.024
FFMC: Height: Season	1	8031	8.181	0.006

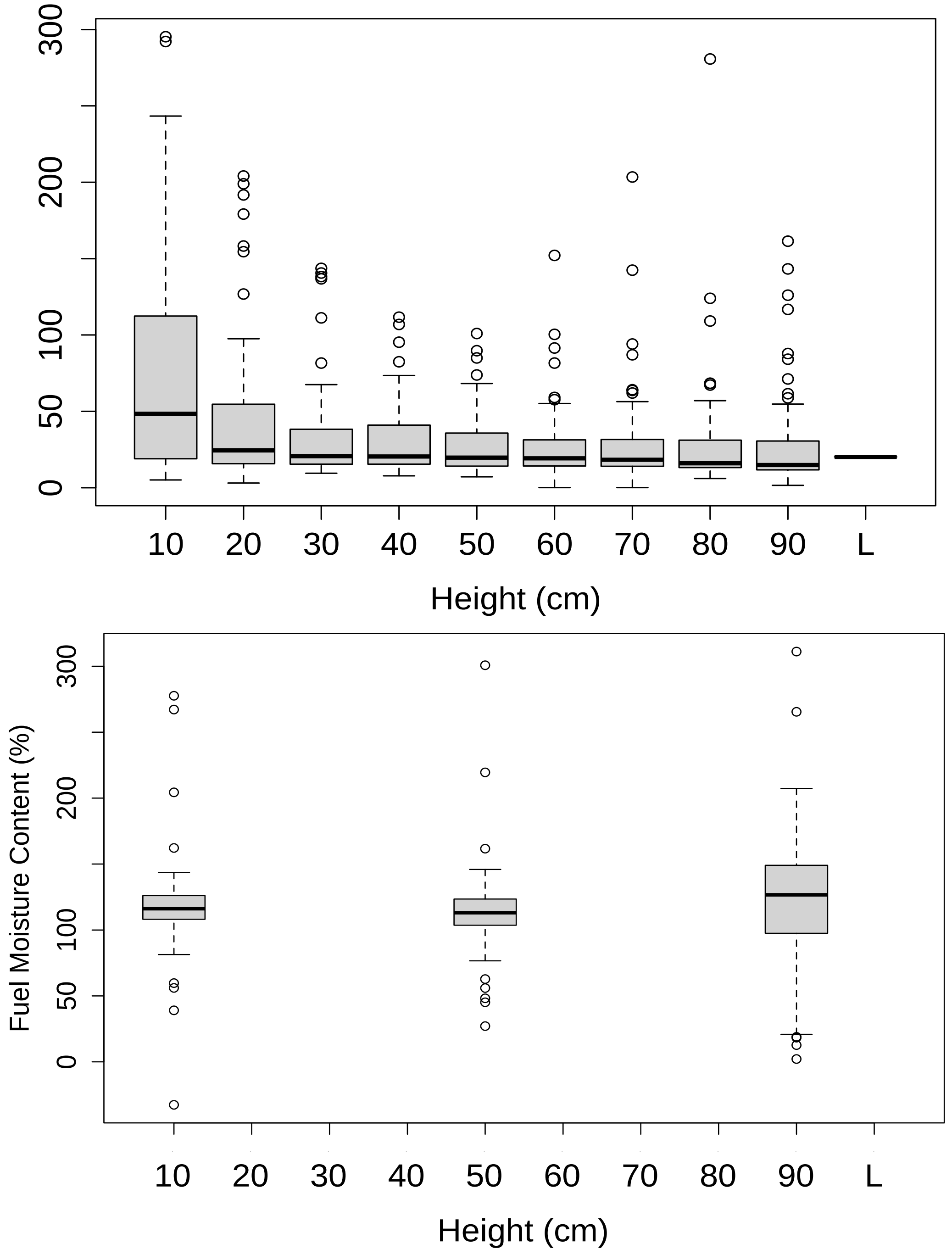

Figure 1: Graph A shows the FMC of goldenrod at heights of 10-90 cm in Spring 2019. Graph B is the FMC of goldenrod in Autumn 2019 at heights of 10, 50 and 90 cm. Measurements are the top of the sample's height from the bottom of the plant. L is the leaves of the plant.

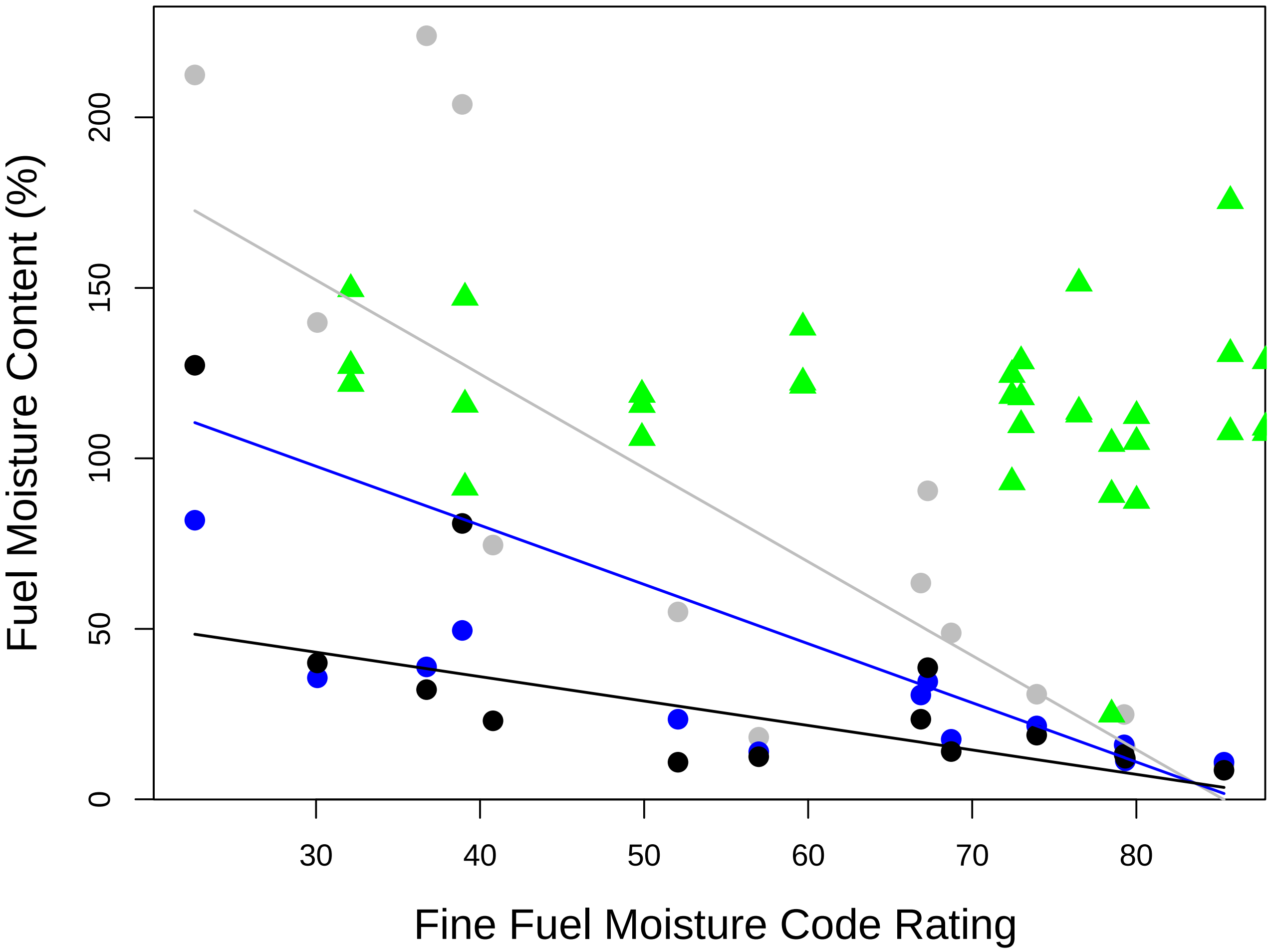

Figure 2: This graph shows the Fine Fuel Moisture Code (FFMC). Circles are samples taken in the spring. Black dots represent the top 10 cm of a golden rod stem, blue dots represent the middle 10 cm and grey dots represent the bottom 10 cm. Lines of the same color represent predicted trends for that height (Table 1). The green triangles represent samples from the autumn when the plants were alive.

There was a significant difference in mean FMC between seasons with values consistently higher in the fall (Table1). Season and height had a significant interaction in the model- in spring FMC decline substantially with increasing sample height but there was little evidence of such an effect in the fall (Figure 1). In spring, as sample height increased variability decreased in FMC, the opposite trend was apparent in the fall. FFMC (Fine Fuel Moisture Code) was significantly related to FMC, though it showed a significant interaction with both season and sample height (Figure 2). In spring there was a negative association between the FMC and FFMC. Higher FFMC means higher flammability, and lower FMC. In autumn there was little association between FMC and FFMC. The heights of samples influence FFMC so that for any given FFMC value, lower parts of the plant or sample will have higher FMCs and reduced flammability.

Variation of Lab Flammability Based on FMC

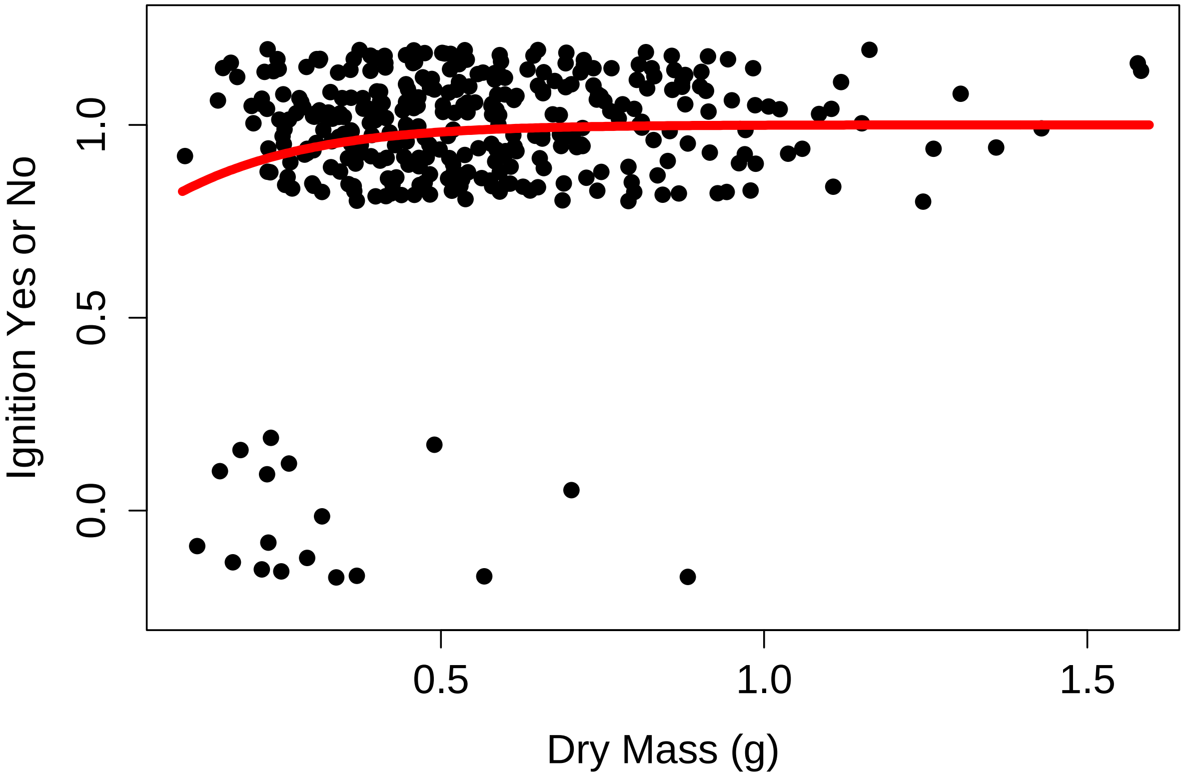

Figure 3: Ignition probability as a function of dry mass of a sample. The black dots are the dry masses of samples recorded in the flame experiments. 0 represents samples that did not ignite and 1 represents those that did. Numbers between 0 and 1 are simply a result of the applied jitter effect for clarity. The red line represents predicted ignition probability from a generalized linear model (Table 2).

Table 2: Ignition probability model variables. R^2= 0.203. This shows the variables used to predict ignition in the probability model

Variable	**Std. Error**	**Degrees of Freedom**	**P-value**
Fuel Moisture Content (%)	-6.9452	1	0.009
Dry Mass (g)	5.9886	1	>0.001
Pilot Flame	0.7064	1	0.181

The ignition probability model (Figure 3) revealed that sample dry mass has a significant effect on ignition probability. This model indicates that greater mass increases the probability that a sample will ignite and not smolder until charred. At sample masses above 0.5 g the probability that a sample will ignite is consistently close to one.

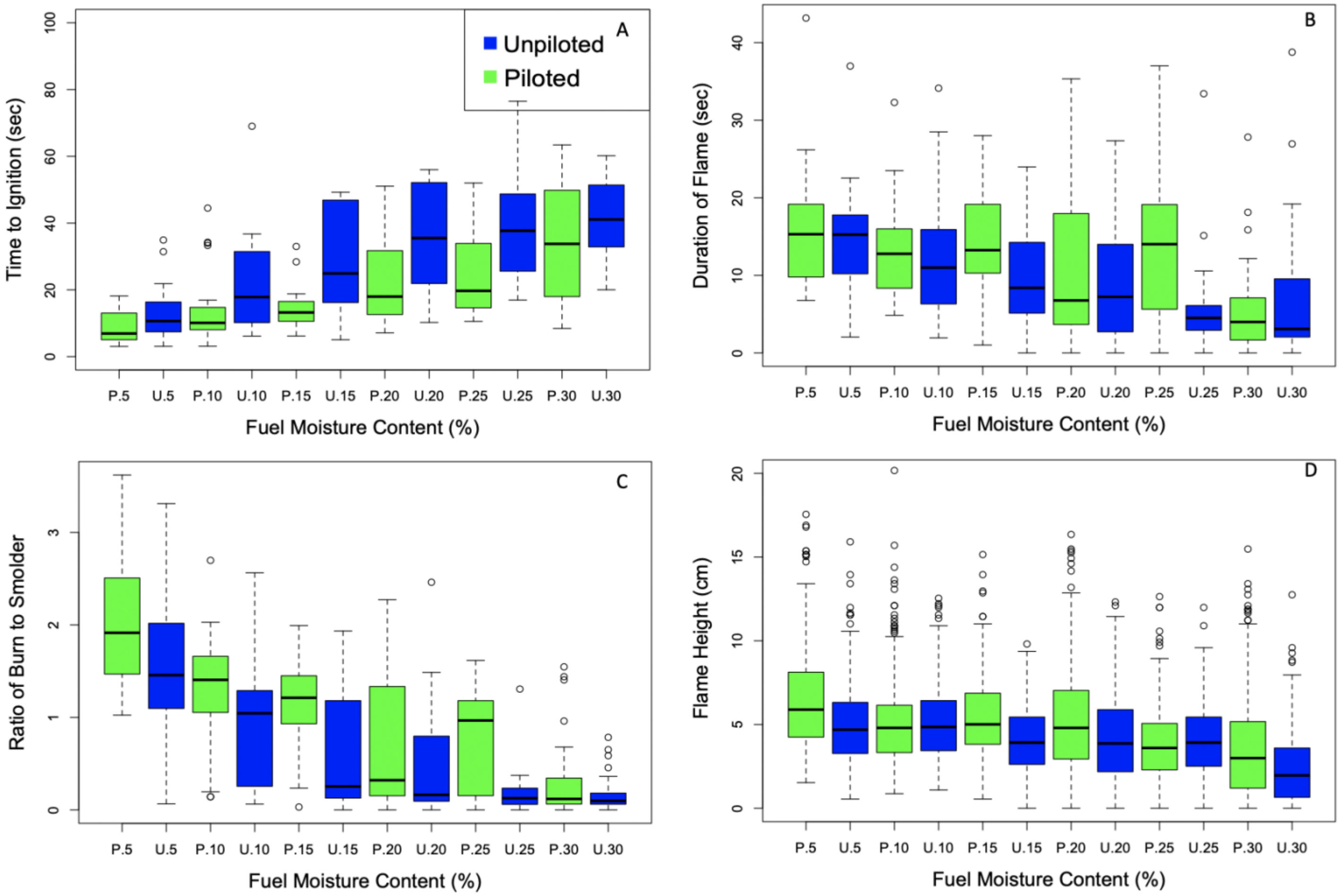

Figure 4: Flammability measurements comparing fuel moisture content to the measurements taken during flame tests. Blue boxes are piloted (P) samples and green boxes are unpiloted (U). Individual panes show time to flaming ignition (A), duration of flaming (B), the ratio of smoldering to flaming time (C), and flame height (D) in relation to target fuel moisture contents

Table 3: Linear regression models for flammability measures equations and r^2 value. 324 degrees of freedom.

Variable	**Equation**	**Adjusted R^2**
Flame Height (cm)	4.75+ -8. 63 × Fuel Moisture Content + 1.76 × Mass + -79.14 × Density+ 0.95 × Pilot	0.26
Time to Ignition (sec)	Intercept (4.25) +84.75 × Fuel Moisture Content +13.81 × Mass + -8.48 × Pilot	0.35
Flame Duration (sec)	Intercept (-0.3375) + -11.96 × Fuel Moisture Content + 22.62 × Mass + 3.10 × Pilot	0.523
Ratio of Flame Duration to Time to Ignition	Intercept (1.20) + -4.34 × Fuel Moisture Content + 0.41 × Mass + 0.42 × Pilot	0.36

The greater the FMC, the longer it took for samples to ignite. The pilot flame also decreased the time needed for a sample to ignite. Higher FMCs had the shortest duration of flaming, although piloted samples for 20 and 25% did have a large variability in duration of flaming (Figure 4). Lower FMCs had much larger flame: smolder ratios than higher FMCs. In piloted samples of 25 and 30%, the ratio was significantly smaller and less variable than any of the other FMCs, piloted or unpiloted. There is a slight trend towards lower fame heights at higher FMCs and higher flame heights when the samples were piloted. Overall, lower FMCs exhibited greater flammability across all metrics. Piloting samples increased their flammability. At FMC values of 15% and lower there was greater flammability across metrics on average. Greater than 15% had more variability and was consistently less flammable.

The linear regression model for flame duration was the strongest out of the four models, with an R^2 of 0.52 and flame height was the weakest (R^2=0.26) (Table 3). Stronger models have R^2 values closest to 1 showing the correlation between variables. Flame height varied greatly throughout burning samples an there were many high FMCs that had short duration of flames, with large flame heights (Figure 4).

Predictability of Flammability based on FFMC Rating

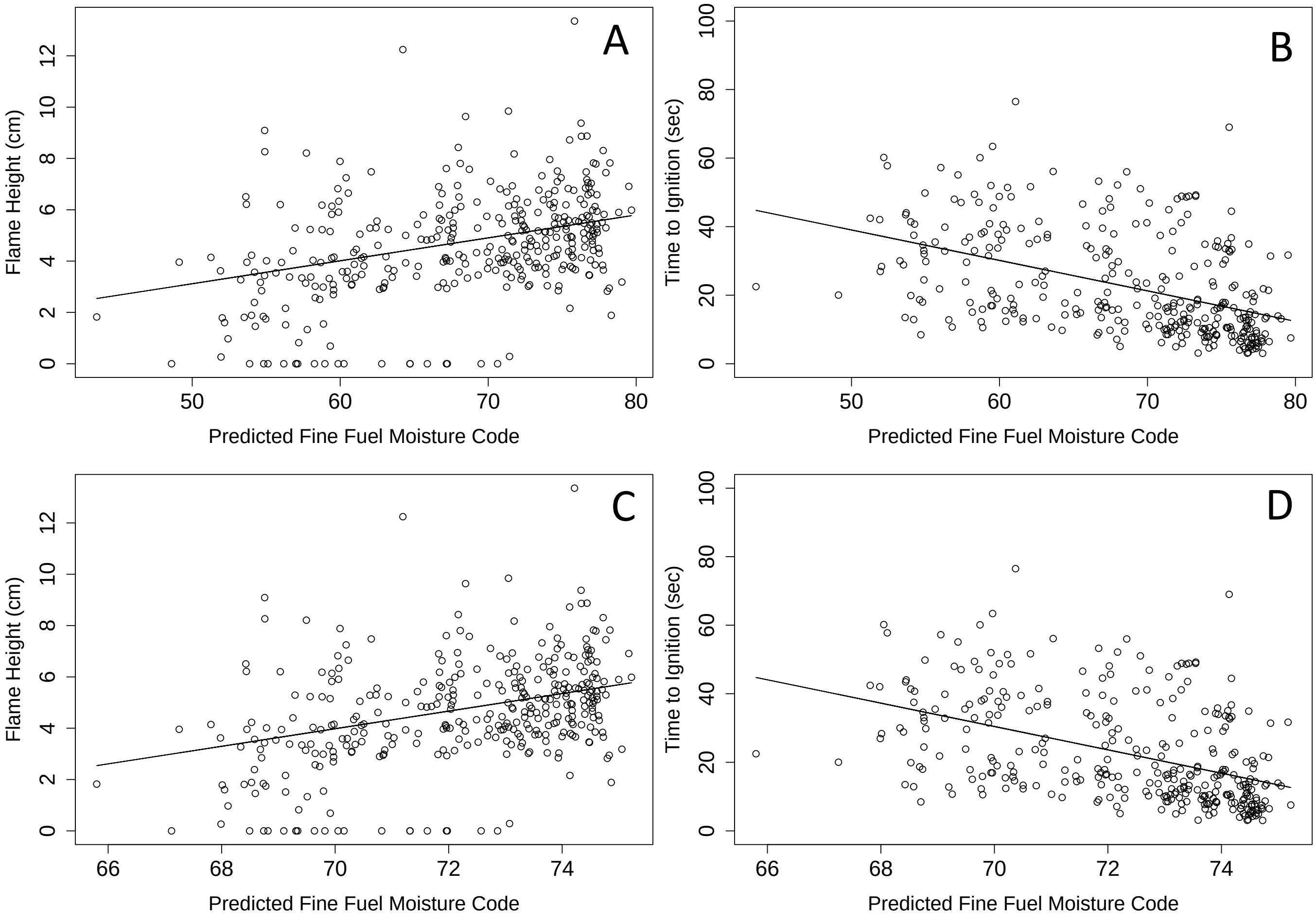

Figure 5: Predicted FFMC vs Flame height or ignition. Graphs A and C compare Flame height to predicted FFMC based on FMC. Graphs B and D do the same with time to ignition. Graphs A and B are the middle portion of a plant while C and D are the bottom. All lines are linear regression models

Flame height and predicted FFMC had a positive, weak correlation, with samples at the bottom of the plant having lower FFMC values. The greater a flame height, the greater the FFMC value should be, Time to ignition had a weak negative correlation with predicted FFMC. The shorter the time to ignition, the greater the FFMC value would be. The bottom samples also had lower predicted FFMC value for the same time to ignition as the middle.

Discussion:

The goals and objectives of this study were largely met after the initial analyses. We were able to determine a significant difference in FMC and Flammability dependent on season, and plant height. We also discovered the natural variation of FMC, and its relationship to FFMC. FFMC can now be used as a predictive tool for FMC and certain flammability metrics.

Predictability of FMC from FFMC

Field collection in the spring and autumn showed both temporal and spatial differences in FMCs. In the spring when the plant is dead and cured (dried out after death) there was greater variation in FMC at the bottom of the plant and higher FMCs on average, potentially because of moisture absorbed from snowfall that was on the ground for several of the sampling days. The bottom portion of the plant had protection from wind and solar radiation that leading to lower evaporative demand and slower rates of dying. Microclimates can form in tall-grass prairie systems or those with tall forbs because of the stratification of heat, sunlight and proximity to soil moisture (Blumenthal et al., 2020; Elmore et al., 2017). The steadier climate at the bottom of the plants surrounded by other plants and covered by snow would have retained more moisture. This was also the thickest portion of the plant with greater moisture capacity (Blumenthal et al., 2020). The chemical composition of goldenrod may also have impacted these findings. Older portions of the plant with greater lignin contents may have lower flammability, while larger sections may have greater cellulose contents and greater flammability (Li et al., 2014). FMC in autumn was significantly higher, likely a result of the plants being alive, though senescing. Live plants, especially leafy green plants, retain more moisture and require it for plant function (Blumenthal et al., 2020). They are actively up taking water through their roots and maintaining a consistent water status, unlike the cured plants in the spring. Variation in microclimate described above may explain why in autumn the top portion of the plants had the greatest variability in FMC, instead of the bottom. Plants senesce from the top of the plant to the bottom, so over the course of the fall data collection the top was likely more dead and dying faster than the bottom (Davies et al., 2010). As the plant dies, moisture control is lost creating greater variability is moisture, which may be exacerbated by greater drying (Davies et al., 2010)

The changing FMCs across the height of the plant show how goldenrod monocultures may change the fire regime of a prairie. High FMCs at the base of the goldenrod could prevent surface fire spread, while lower FMCs at the top of the plant may increase the spread of larger fires (Brooks et al., 2004). The FMCs of goldenrod found in both seasons were often higher than 50%, which would decrease the flammability and spread of fire throughout the prairie as well (Brooks et al., 2004).

High FFMC values denote higher flammability and lowest FMCs occurred on days with the highest FFMC values (Wotton, 2009). Based on the strong correlation between flammability and FFMC, FFMC should be a useful tool for predicting flammability in the field. The live samples showed no correlation between FMC and FFMC, or any real difference in samples. The FMC did not vary with FFMC. The FFMC ratings consider the weather conditions before and during the time a sample is collected. This has less of an effect on FMC during the fall because the plants are living and retain water for plant function, which can be seen by comparing the green leafy stalks in the fall to the dry brown stalks in the spring.

Implications of Lab Flammability

Lab flammability tests measured three aspects of flammability- ignitability, sustainability, and combustibility which were measured by time to ignition, flame duration and flame height respectively. Sample dry mass had a significant effect on ignitability, with larger samples having a greater probability of ignition. Larger samples also burned longer, with larger flames. Greater mass provided greater fuel for consumption. Greater mass of a sample increases the presence of pyrolysis gases, which effects the transition from a smoldering burn to flaming combustion (Santoso et al., 2019). Density of a sample, although not particularly significant in our results, also may impact flammability. As a significant factor of flame heights, higher density meant the amount of mass in a sample was greater, providing more fuel for flaming.

Fuel moisture content, dry mass and the presence of a pilot flame all had an effect on the flammability of goldenrod samples. Flammability metrics, including flame duration and time to ignition, were affected by FMC because of its ability to delay ignition while the sample smoldered, reducing the overall mass available for flaming ignition (Essaghi et al., 2017; Santana & Marrs, 2016). Higher FMCs increase the amount of heat needed to reach ignition, and provide greater pyrolysis gases for smoldering (Essaghi et al., 2017; Santoso et al., 2019).

Higher FMC led to longer ignition times, and pilot flame presence reduced ignition time as well. Time to ignition represented the ignitability of a sample, with shorter times indicating greater ignitability. Lower FMCs led to greater ignitability, which would allow for faster spread of fires (Santana & Marrs, 2014). Ignition of more biomass in a prairie fire creates larger, hotter fires that consume more of the plants in the stand (Livingston & Morgan Varner, 2016). While the pilot flame also could have added additional heat to the sample, it also provides a spark to ignite volatiles released during smoldering. Piloted ignition is contingent on the irradiance of a sample, how much radiation is applied to the surface area of the sample (Janssens, 1991). Pilot flames require higher temperatures to ignite than autoignition at the same minimum heat fluxes, but autoignition is considered to be when samples have glowing ignition not flaming (Babrauskas, 2002)

The ratio of flame duration to ignition was greatest at lower FMCs and it demonstrated the compounding effect of FMC on flammability. Ignitability and sustainability of a flame were greatest at lowest FMCs, making for exponentially larger ratios at low FMCs. Piloted flames also had greater ratios than unpiloted flames.

Sustainability, a key aspect of flammability was defined as the duration of flaming. The longer a goldenrod sample can sustain a flame, the greater the amount of plant consumed and the more likely the fire is to spread throughout the stand in an actual burn (Santana & Marrs, 2014). The longest durations of flaming were observed at the lowest FMCs. Lower FMCs had shorter ignition times, which decreased pyrolysis during smoldering and left volatiles behind to be burned, increasing duration of flaming (Santoso et al., 2019). The greater water content dilutes pyrrolic gases, which decreases the ability of them to burn or catch flame (McAllister et al., 2012). Piloted samples also had longer flame durations. This is potentially a result of piloted samples igniting faster and leaving more of the sample to be burned than the unpiloted samples. Unpiloted samples burned for shorter periods of time than their piloted counterparts, likely due to longer ignition times and greater loss of volatiles during the smoldering period.

Flame height represents combustibility of a sample, with higher flame heights indicating greater combustion of the plant (Essaghi et al., 2017). Higher flames also indicate greater spread of fire, creating a larger, higher intensity burn and increased fuel consumption (Wragg et al., 2018). Flame height was greatest where FMC was low. The linear regression model for flame duration was the strongest out of the four models but that for flame height was the weakest. Flame height varied greatly throughout sample combustion time, and there were many high FMC samples that had a short duration of flaming but large flame heights. Piloted flame heights were likely made larger by interaction with the pilot flame, although the set up was an attempt to decrease this interaction and measurements did not include the height of a pilot flame, past experiments with pilot flames at the same height still saw the influence (Essaghi et al., 2017; Ganteaume et al., 2013).

Overall, flammability as determined by ignitability, sustainability, and combustibility was greatest at the lowest FMCs (5-10%) and with the presence of a pilot flame. The presence of a pilot flame likely allowed for flammability predictions closer to that of an actual fire in which an ignition source would be present as the fire spread.

Applications of FFMC in the field to predict flammability

Fine Fuel Moisture Code ratings predict the flammability and spread of a fire based on weather conditions. The data we applied to determine the efficacy of the FFMC ratings were the flammability metrics measured in lab to test ignition, sustainability and combustibility of fire. The correlation between flammability metrics and FFMC was not very strong or straight, but clearly ignitability and combustibility could be predicted using the fine fuel moisture code. At code values between 70 and 74 the flammability of goldenrod became noticeably greater. This represents an ignition threshold at which a stand of goldenrod could be predicted to have greater potential to sustain flaming, and fire spread across the stand (Plucinski et al., 2010). The changing FMCs across the height of the plant show how goldenrod monocultures may change the fire regime of a prairie. Greater FMCs at the base of the goldenrod could prevent surface fire spread, while lower FMCs at the top of the plant may increase the spread of crown fires (Brooks et al., 2004). The FMCs of golden rod found in both seasons were often higher than 50%, which would decrease the flammability and spread of fire throughout the prairie as well (Brooks et al., 2004).

When attempting to plan a prescribed burn, weather conditions associated with an FFMC rating of 70 or greater are likely to have the greatest potential for lower FMCs, and higher flammability. Critically however, this relationship is only applicable to spring burns, because autumn FFMC ratings had no correlation with the FMC of goldenrod. FFMC and simplified models predict the fire danger, which is both the static and dynamic characteristics that predict the probability of ignition, and then the characteristics of that fire (Wotton, 2009). FFMC describes litter flammability by predicting FMC, and ranges in rating of 0-101, where 0 is 250% FMC and 101 is 0% or completely dry (Wotton, 2009). This ensures that goldenrod seeds are consumed, preventing further spread and establishment. By slowing this spread, slower growing species are given the opportunity to establish.

Efficacy of Flammability tests in predicting field results

Although this experiment combines both field research with flammability experiments, there is not a clear consensus on the efficacy of results measured in a controlled lab setting when applied to a field burn. Many flammability experiments have been conducted on small sample sizes or recreated fuel beds instead of prescribed burns in an attempt to control more variables (Ganteaume et al., 2013; Plucinski et al., 2010; Santana & Marrs, 2016). However, the application of the conclusions of such experiments in the field, and whether or not similar results could be measured is still unknown. The samples we measured were taken out of the context of a prairie ecosystem, where stand composition and structure may impact flammability. Because the surrounding structure of a prairie during a fire was removed, the simulated fire via epiradiator and pilot flame may not create results that actually transfer to the field (Fernandes & Cruz, 2012). Further investigation into the relationship between lab experiments and field results is necessary.

Conclusion:

Flammability of goldenrod is likely to be highest in spring, near the top of the plants. FFMC and flammability metrics predict greatest ignitability, sustainability and combustibility at lower FMCs. FFMC can fairly reliably be used to predict flammability of goldenrod starting at ratings of 70-74, depending on where the prescribed fire is intended to spread (ground fire vs crown fire). FMC below 15% correlates strongly with flammability, and should predict a more intense fire, capable of spreading throughout a prairie and consuming goldenrod, preventing larger monocultures after fire. This data can be used to predict the potential flammability of goldenrod for managers who wish to maintain or restore biodiversity in a prairie ecosystem. Restorationists can calculate the FFMC rating based on simple weather data to predict flammability of goldenrod. To ensure this can occur, further testing into the ability to translate lab results to the field needs to be completed. Lab results must actually predict field results for prairie managers to use them. If they do, this methodology could be applied to many fire resistant, prairie or invasive species, and used to create flammability predictions for specific species that either cause issues or create monoculture in prairies.

References:

Arboretum North | Chadwick Arboretum & Learning Gardens. (n.d.). Retrieved March 9, 2021, from https://chadwickarboretum.osu.edu/our-gardens/arboretum-north

Babrauskas, V. (2002). Ignition of Wood: A Review of the State of the Art. *Journal of Fire Protection Engineering*, *12*(3), 163–189. https://doi.org/10.1177/10423910260620482

Berger, H., Meyer, C. K., Mummert, A., Tirado, L., Saucedo, L., Bonello, H., Van Arsdale, D., & Williams, G. (2020). Land use dynamics within the tallgrass prairie ecosystem: The case for the Conservation Reserve Program (CRP). *Theoretical Ecology*, *13*(3), 289–300. https://doi.org/10.1007/s12080-020-00452-z

Bieser, J. M. H., & Thomas, S. C. (2019). Biochar and high-carbon wood ash effects on soil and vegetation in a boreal clearcut. *Canadian Journal of Forest Research*, *49*(9), 1124–1134. https://doi.org/10.1139/cjfr-2019-0039

Blair, J., Nippert, J., & Briggs, J. (2014). Grassland Ecology. In R. K. Monson (Ed.), *Ecology and the Environment* (pp. 389–423). Springer New York. https://doi.org/10.1007/978-1-4614-7501-9_14

Blumenthal, D. M., Mueller, K. E., Kray, J. A., Ocheltree, T. W., Augustine, D. J., & Wilcox, K. R. (2020). Traits link drought resistance with herbivore defence and plant economics in semi-arid grasslands: The central roles of phenology and leaf dry matter content. *Journal of Ecology*, *108*(6), 2336–2351. https://doi.org/10.1111/1365-2745.13454

Brooks, M. L., D'Antonio, C. M., Richardson, D. M., Grace, J. B., Keeley, J. E., DiTomaso, J. M., Hobbs, R. J., Pellant, M., & Pyke, D. (2004). Effects of Invasive Alien Plants on Fire Regimes. *BioScience*, *54*(7), 677–688. https://doi.org/10.1641/0006-3568(2004)054[0677:EOIAPO]2.0.CO;2

Camill, P., McKone, M. J., Sturges, S. T., Severud, W. J., Ellis, E., Limmer, J., Martin, C. B., Navratil, R. T., Purdie, A. J., Sandel, B. S., Talukder, S., & Trout, A. (2004). Community- and Ecosystem-Level Changes in a Species-Rich Tallgrass Prairie Restoration. *Ecological Applications*, *14*(6), 1680–1694.

Chuvieco, E., Aguado, I., & Dimitrakopoulos, A. P. (2004). Conversion of fuel moisture content values to ignition potential for integrated fire danger assessment. *Canadian Journal of Forest Research*, *34*(11), 2284–2293. https://doi.org/10.1139/x04-101

Cubino, J. P., Buckley, H. L., Day, N. J., Pieper, R., & Curran, T. J. (2018). Community-level flammability declines over 25 years of plant invasion in grasslands. *Journal of Ecology*, *106*(4), 1582–1594. https://doi.org/10.1111/1365-2745.12933

Davies, G. M., Legg, C. J., O'Hara, R., MacDonald, A. J., & Smith, A. A. (2010). Winter desiccation and rapid changes in the live fuel moisture content of *Calluna vulgaris*. *Plant Ecology & Diversity*, *3*(3), 289–299. https://doi.org/10.1080/17550874.2010.544335

Elmore, R. D., Carroll, J. M., Tanner, E. P., Hovick, T. J., Grisham, B. A., Fuhlendorf, S. D., & Windels, S. K. (2017). Implications of the thermal environment for terrestrial wildlife management: Thermal Ecology. *Wildlife Society Bulletin*, *41*(2), 183–193. https://doi.org/10.1002/wsb.772

Essaghi, S., Hachmi, M., Yessef, M., Dehhaoui, M., & El Amarty, F. (2017). Assessment of Flammability of Moroccan Forest Fuels: New Approach to Estimate the Flammability Index. *Forests*, *8*(11), 443. https://doi.org/10.3390/f8110443

Fernandes, P. M., & Cruz, M. G. (2012). Plant flammability experiments offer limited insight into vegetation–fire dynamics interactions. *New Phytologist*, *194*(3), 606–609. https://doi.org/10.1111/j.1469-8137.2012.04065.x

Ganteaume, A., Jappiot, M., Lampin, C., Guijarro, M., & Hernando, C. (2013). Flammability of Some Ornamental Species in Wildland–Urban Interfaces in Southeastern France: Laboratory Assessment at Particle Level. *Environmental Management*, *52*(2), 467–480. https://doi.org/10.1007/s00267-013-0067-z

Grman, E., Zirbel, C. R., Bauer, J. T., Groves, A. M., Bassett, T., & Brudvig, L. A. (n.d.). Super-abundant C4 grasses are a mixed blessing in restored prairies. *Restoration Ecology*, *n/a*(n/a). https://doi.org/10.1111/rec.13281

Gusev, A. P. (2018). The Invasion of Canadian Goldenrod (Solidago canadensis L.) into Anthropogenic Landscapes of Belarus. *Russian Journal of Biological Invasions*, *9*(1), 22–28. https://doi.org/10.1134/S2075111718010083

He, T., Lamont, B. B., & Pausas, J. G. (2019). Fire as a key driver of Earth's biodiversity. *Biological Reviews*, *94*(6), 1983–2010. https://doi.org/10.1111/brv.12544

Janssens, M. (1991). Piloted ignition of wood: A review. *Fire and Materials*, *15*(4), 151–167. https://doi.org/10.1002/fam.810150402

Jolly, W. M. (2016). *Development of fine dead fuel moisture field references for the Southeastern United States: SimpleFFMC*. 22.

Klimek, S., Richter gen. Kemmermann, A., Hofmann, M., & Isselstein, J. (2007). Plant species richness and composition in managed grasslands: The relative importance of field management and environmental factors. *Biological Conservation*, *134*(4), 559–570. https://doi.org/10.1016/j.biocon.2006.09.007

Knee, M., Brake, R., Cavender, N., & Thomas, L. (1998). Growth of Ornamental Plants in Compacted Soils and media. *Ohio Agricultural Reserach And Development Center, Ornamental plants: annual reports and research reviews,* 113–118.

Lafferty, M. (1979). *Ohio's Natural Heritage*. The Ohio Academy of Science.

Li, M., Pattathil, S., Hahn, M. G., & Hodge, D. B. (2014). Identification of features associated with plant cell wall recalcitrance to pretreatment by alkaline hydrogen peroxide in diverse bioenergy feedstocks using glycome profiling. *RSC Advances*, *4*(33), 17282–17292. https://doi.org/10.1039/C4RA00824C

Livingston, A. C., & Morgan Varner, J. (2016). Fuel Moisture Differences in a Mixed Native and Non-Native Grassland: Implications for Fire Regimes. *Fire Ecology*, *12*(1), 73–87. https://doi.org/10.4996/fireecology.1201073

Marks, P. L. (1983). On the Origin of the Field Plants of the Northeastern United States. *The American Naturalist*, *122*(2), 210–228.

McAllister, S., Grenfell, I., Hadlow, A., Jolly, W. M., Finney, M., & Cohen, J. (2012). Piloted ignition of live forest fuels. *Fire Safety Journal*, *51*, 133–142. https://doi.org/10.1016/j.firesaf.2012.04.001

Medve, R. J. (1984). The Mycorrhizae of Pioneer Species in Disturbed Ecosystems in Western Pennsylvania. *American Journal of Botany*, *71*(6), 787–794. https://doi.org/10.1002/j.1537-2197.1984.tb14143.x

Plucinski, M. P., Anderson, W. R., Bradstock, R. A., & Gill, A. M. (2010). The initiation of fire spread in shrubland fuels recreated in the laboratory. *International Journal of Wildland Fire*, *19*(4), 512. https://doi.org/10.1071/WF09038

Prairie Plant Research & Monarch Butterfly Waystation | Chadwick Arboretum & Learning Gardens. (n.d.). Retrieved March 9, 2021, from https://chadwickarboretum.osu.edu/our-gardens/arboretum-north/prairie-plants-monarch-waystation

Roos, C. I., Zedeño, M. N., Hollenback, K. L., & Erlick, M. M. H. (n.d.). *Indigenous impacts on North American Great Plains fire regimes of the past millennium*. 6.

Samson, F. B., Knopf, F. L., & Ostlie, W. R. (2004). Great Plains ecosystems: Past, present, and future. *Wildlife Society Bulletin*, *32*(1), 6–15. https://doi.org/10.2193/0091-7648(2004)32[6:GPEPPA]2.0.CO;2

Samson, F., & Knopf, F. (1994). Prairie Conservation in North America. *BioScience*, *44*(6), 418–421. https://doi.org/10.2307/1312365

Santana, V. M., & Marrs, R. H. (2014). Flammability properties of British heathland and moorland vegetation: Models for predicting fire ignition. *Journal of Environmental Management*, *139*, 88–96. https://doi.org/10.1016/j.jenvman.2014.02.027

Santana, V. M., & Marrs, R. H. (2016). Models for predicting fire ignition probability in graminoids from boreo–temperate moorland ecosystems. *International Journal of Wildland Fire*, *25*(6), 679. https://doi.org/10.1071/WF15126

Santoso, M. A., Christensen, E. G., Yang, J., & Rein, G. (2019). Review of the Transition From Smouldering to Flaming Combustion in Wildfires. *Frontiers in Mechanical Engineering*, *5*, 49. https://doi.org/10.3389/fmech.2019.00049

Solidago canadensis. (n.d.). Retrieved March 10, 2021, from https://www.fs.fed.us/database/feis/plants/forb/solcan/all.html

Soong, J. L., & Cotrufo, M. F. (2015). Annual burning of a tallgrass prairie inhibits C and N cycling in soil, increasing recalcitrant pyrogenic organic matter storage while reducing N availability. *Global Change Biology*, *21*(6), 2321–2333. https://doi.org/10.1111/gcb.12832

Soussana, J. F., Tallec, T., & Blanfort, V. (2010). Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal*, *4*(3), 334–350. https://doi.org/10.1017/S1751731109990784

Swab, R. M., Lorenz, N., Lee, N. R., Culman, S. W., & Dick, R. P. (2020). From the Ground Up: Prairies on Reclaimed Mine Land—Impacts on Soil and Vegetation. *Land*, *9*(11), 455. https://doi.org/10.3390/land9110455

Valkó, O., Deák, B., Magura, T., Török, P., Kelemen, A., Tóth, K., Horváth, R., Nagy, D. D., Debnár, Z., Zsigrai, G., Kapocsi, I., & Tóthmérész, B. (2016). Supporting biodiversity by prescribed burning in grasslands—A multi-taxa approach. *Science of The Total Environment*, *572*, 1377–1384. https://doi.org/10.1016/j.scitotenv.2016.01.184

Web Soil Survey. (n.d.). Retrieved February 26, 2019, from https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

Wotton, B. M. (2009). Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environmental and Ecological Statistics*, *16*(2), 107–131. https://doi.org/10.1007/s10651-007-0084-2

Wragg, P. D., Mielke, T., & Tilman, D. (2018). Forbs, grasses, and grassland fire behaviour. *Journal of Ecology*, *106*(5), 1983–2001. https://doi.org/10.1111/1365-2745.12980

Appendix:

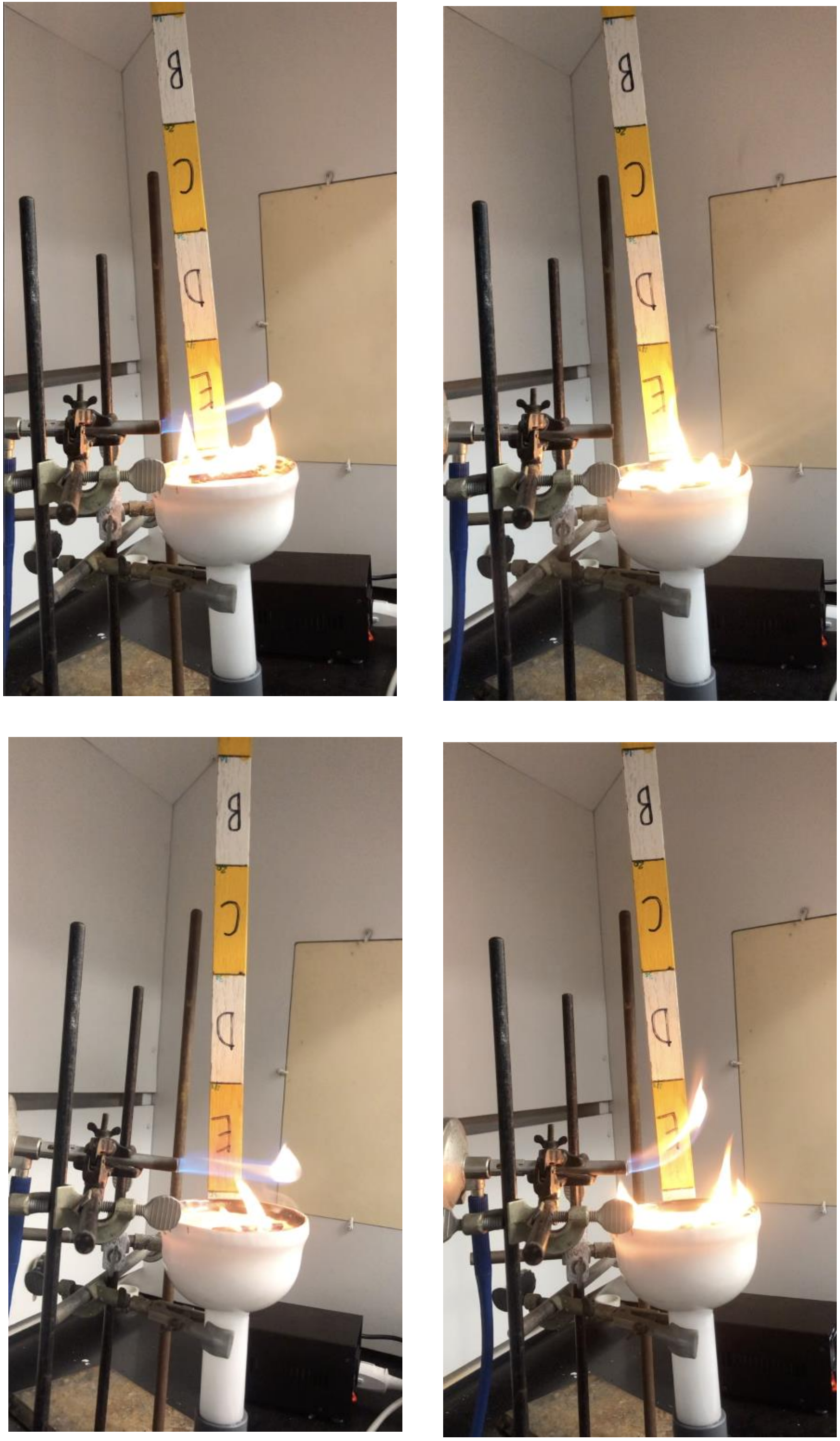

Image 1: Flame heights and burns at 10 and 15% FMC.

Image 2: The set up described in the flammability methods section for experiments. The left photo shows the set up and typical camera angle (which is more zoomed in on videos). And the right shows the set up with propane tank and converter, although the measuring stick was added later.

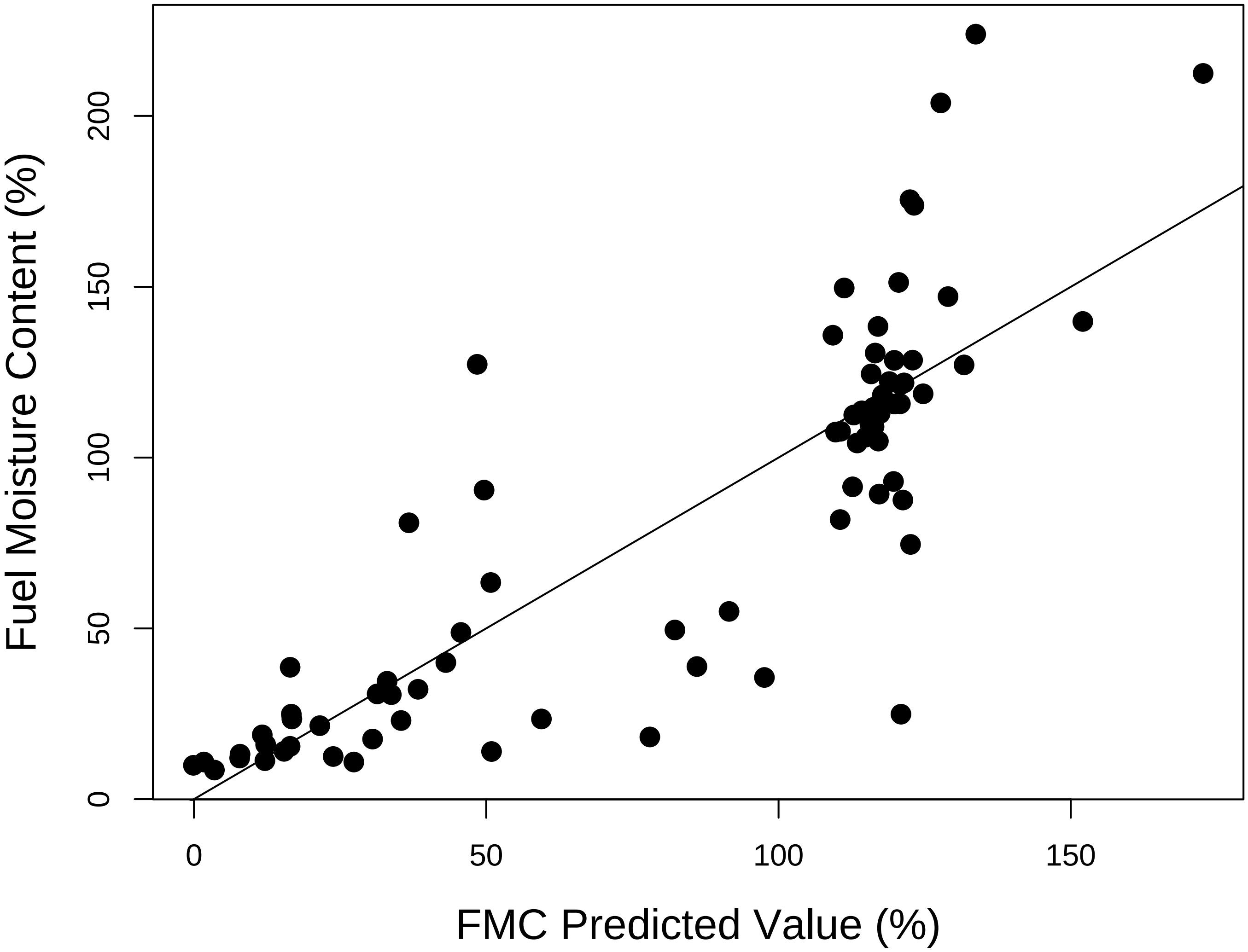

Figure 6: Linear Regression model of FMC and predicted FMC values based on FFMC calculations. P-value for this regression was <0.05, which was significant. The line is a (0,1) line, not the linear regression.

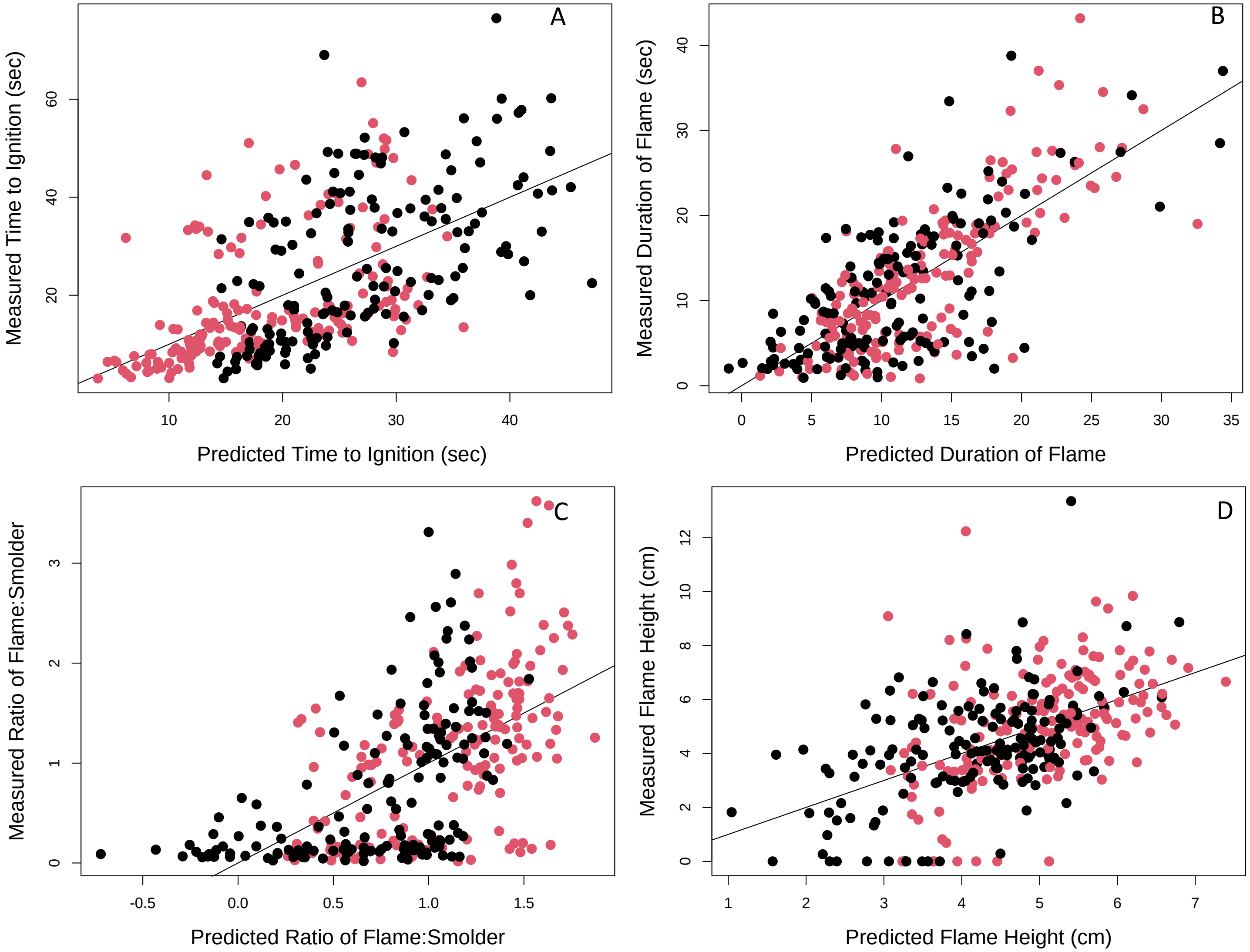

Figure 7: Linear Regression models from Table 3, plotted. Red dots represent piloted samples, while black dots are unpiloted. Flammability test data was used, and all linear regressions did not include non-ignitions, or samples that never caught flame. All lines are not regression lines, but simple (0,1) lines. The graphs compare the predicted flammability metrics vs. the actual metrics at the same FMC. The graphs show time to ignition (A), duration of flame (B), ratio of flame to smolder (C) and flame heights (D).

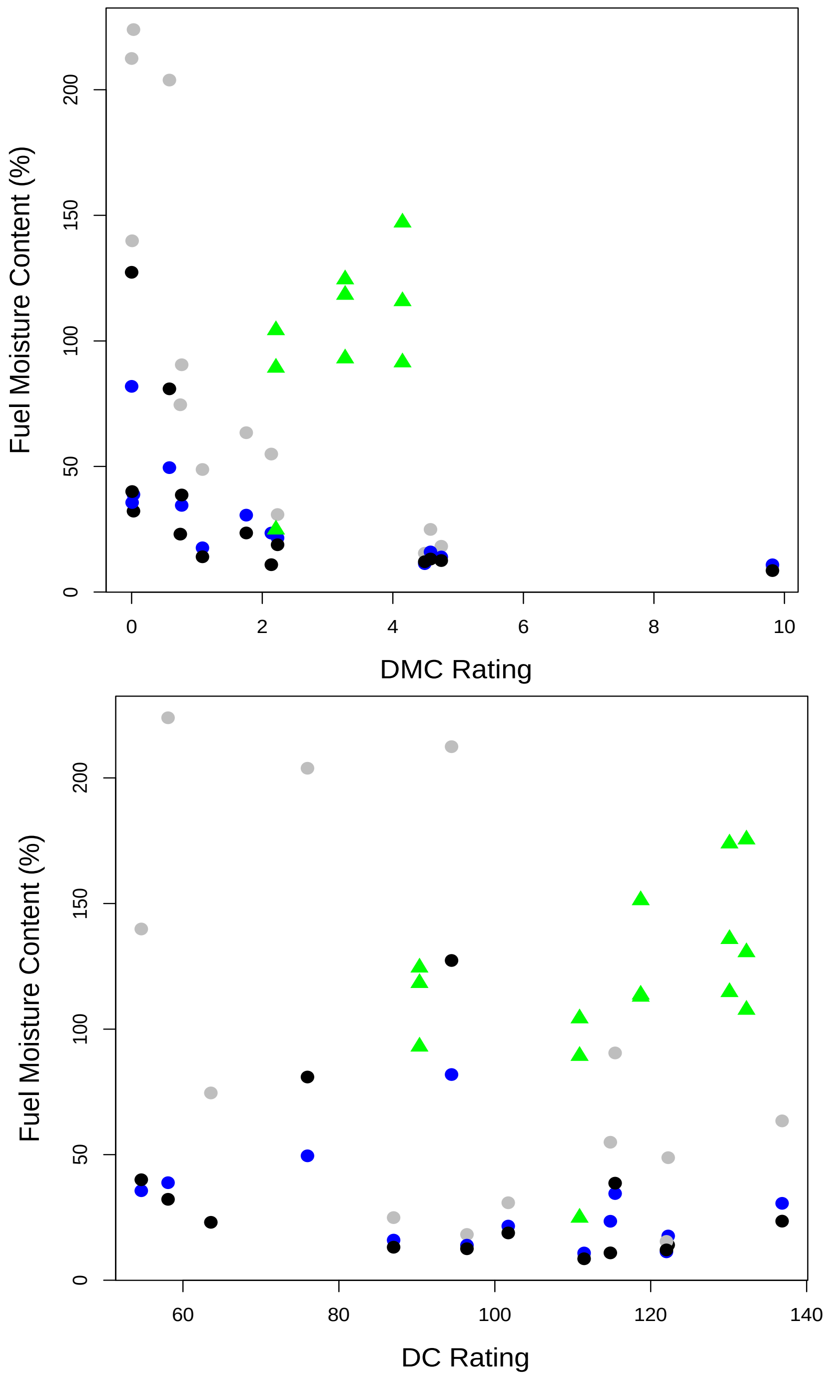

Figure 8: DMC and DC (Duff Moisture Code and Drought Code) plotted against measured FMC values in Spring (dots) and Autumn (Triangles). There was no significant difference in height or season in these code ratings. Green triangles are Autumn 2019 measurements, while all dots are Spring 2019. Black dots are the bottom of the of the plant, blue the middle and grey the top.