# FIRE BEHAVIOR IN EXPERIMENTAL GRASS FIRES

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# AUTHORIZATION TO SUBMIT THESIS

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# ABSTRACT

Grasslands and other types of grass dominant ecosystems account for the majority of global fire events. Under climate change towards less humid and extended hot and dry periods, vulnerability of grass dominated ecosystems to a fire is projected to increase. Fire behavior is one of the key factors for understanding fire patterns and effects. This small-scale grass-fire experiment sought to explain how fire behavior properties of two bunchgrass species respond to increase in fuel density and composition. Although the results confirmed that higher fuel load and increased percentage of cheatgrass abundance leads to the increase in total mass consumption, rate of consumption and flame length, the relation with the decrease in the burning time is less defined. The burning properties of Idaho fescue were less influenced by increase in cheatgrass presence. These results highlight that changing fire behavior due to the increase in cheatgrass abundance is species specific and that more research is needed to understand the dynamics of both cheatgrass and other invasive species on fire behavior in grass dominated ecosystems.

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# DEDICATION

This work is dedicated to one who purchased a ticket for this journey to me, my wife Milena Rangelov, for her selfless love, help, belief, support, and push whenever it was necessary and much more often. Additionally, I would like to dedicate this work to my lovely fellows with whom I shared glorious and dark moments for last three years, especially to Nuria, Andrea, Joseph, Janire, Brooke, Austin, Michael, Devi, Filip, Dunja, Branimir, Sasa, and all other Balkans friends.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# CHAPTER 1. INTRODUCTION

Globally, >2.5 million $km^2$ of savannas, pure grasslands, shrublands, and croplands are estimated to burn annually (1, 2). Within the United States, these ecosystems serve important roles in sustaining a myriad of ecosystem goods and services including agriculture, avian habitats, wildlife habitats, grazing of ungulates, in addition to products associated with the maintenance of healthy woodlands (3). In the western United States, these systems are increasingly vulnerable to climate change, with projected shifts in plant species distributions, water availability, as well as an increased frequency of droughts coupled with increased frequency of large and high intensity wildfires (3, 4). The length of the fire season is also predicted to increase in western North America (5-7) and decreases in snow pack persistence has increased the vulnerability of fuels in these ecosystems (4, 5, 8).

The introduction or migration of invasive grass species can alter fire regimes (i.e. frequency, intensity, severity, extent, type, and seasonality of fire) by altering the fuel properties (i.e. continuity, quantity, horizontal and vertical arrangements), which may consequently alter the fire behavior (i.e. fire rate of spread, residence time, flame length, and flame depth) (1, 9-13). Historically, fire return intervals in native bunchgrass and sagebrush steppe communities, that represent the most common rangeland communities of western North America, were from 20 years to greater than 100 years (9, 14-17). Along with the introduction of cheatgrass (*Bromus tectorum*, hereafter BRTE), which is an annual invasive species, the mean fire return intervals decreased to less than 5 years (10, 11, 14, 16, 18). The impacts of BRTE infestation on fire regimes is similar to the influence of other invasive grass species on fire behavior properties (11, 12, 19). Often, invasive species accelerate fire cycles and create positive grass-fire cycle feedback by increasing the quantity and horizontal continuity of fine fuel (9, 11, 14, 18, 20). Increased continuity of fine fuel in turn makes the native plant community more vulnerable to fire, due to the acceleration of fire spread following ignition (9, 11, 14, 15, 17, 20). It has been observed that rangelands with an increased amount of invasive annual species, such as BRTE, burn more readily and at increased fire frequency in comparison to areas containing predominately native species (9-11, 14, 17). Consequently, it has been proposed that the main driver for variation in rangeland fire frequency is not fuel abundance, but rather fine fuel continuity (18, 21). Shorter periods between two fires are beneficial for annual grasses and forbs, while being detrimental for native grass and shrub species, which leads to associated changes in ecosystem structure and function (10, 17, 22). For example, bunchgrass and shrub-steppe communities (e.g. dominated by *Agropyron, Festuca, Pseudoroengeria, Hespelostipa, Poa* species) are characterized by infrequent fire return intervals caused by slow fuel accumulation and discontinuity in between the clumps. Consequently, BRTE provides a higher amount of fine fuels and higher horizontal fuel continuity by filing the gaps between native bunchgrass species, which in turn changes the fire behavior and makes the plant association more fire-prone (9, 11, 19, 20, 23). Repeated fire occurrence in short intervals in turn acts to decrease the vigor of native bunchgrass and sagebrush species and may eventually lead to dominance of the invasive species (10, 17, 22), resulting in insufficient time for native species to recover (9-11, 14, 22).

Fire behavior can be defined by numerous in-situ metrics. Common in-situ metrics include the rate of spread, residence time, flame length, metrics relating to the fire intensity, and flame depth of an individual fire (11). Flammability of grassland fuels has been proposed as a good predictor of fire behavior (23-25). Although the term flammability is defined in numerous ways, most definitions generally relate to the fuel load and type, fuel bulk density, fuel moisture content, an air temperature (23-

25). Flammability is often described by four main components: ignitability (easiness of ignition), sustainability (the ability of fire to thrive), combustibility (the rate in which fuel is consumed) and consumability (the proportion of fuel consumed) (23, 24, 26-30). There is some debate in the fire science community on the use of these metrics as although they have been widely adopted, limited studies exist that define or evaluate the suitability of these concepts (27-30). In this study, the concepts of flammability were used (rate of consumption and proportion of fuel consumed) in order to provide metrics for comparison of fire behavior between two bunchgrass species without any inclination for their deeper elucidation. Furthermore, the traditional components of flammability usage appeared to be very limited in small-scale burning experiments.

The likelihood of fire occurrence increases largely with the presence of BRTE, regardless of whether (or not) it is the dominant species in a given plant association, because of its highly flammable nature (9, 11, 20, 22, 31). Characteristics that distinguish BRTE flammability compared to other species are high seed production and formation of dense stands (16, 22, 32). The finely divided stems and panicles (branched inflorescence) that readily burn also rapidly respond to changes in atmospheric relative humidity (22, 32). Additionally, the growth of BRTE matches with zones characterized by severe fire weather (22, 32). The increase in the quantity of BRTE (increased fuel load and continuity) leads to greater fire intensity, flame length, the rate of fuel consumption, and ROS (9, 14, 20, 33). Overall, BRTE is considered a highly flammable grass species due to its physical properties and supports the rapid fire rates of spread (18, 22, 31, 34, 35). Stands invaded by BRTE are highly flammable after the plants' maturation (18, 22, 31, 34). Accordingly, BRTE encroachment into the sagebrush or bunchgrass region induces a shift in fire cycles and consequently lead to the species self-replacement (9, 10, 22, 31, 36).

### *1.1. Research questions*

In Link et al. 2006, fire frequency in *Artemisia tridentata – Poa secunda* shrub-steppe community has been observed. They observed that when BRTE cover was ~ 12 %, this lead to a 46 % probability of fire occurrence; whereas when BRTE cover exceeded 45 % the probability of fire occurrence approached 100 % (20). This study builds on Link et al. 2006 by conducting a controlled laboratory experiment to investigate how two bunchgrasses (*Pseudoroengeria spicata* (bluebunch wheatgrass) and *Festuca idahoensis* (Idaho fescue), hereafter PSSP and FEID) burn under varying degrees of BRTE abundance. This study seeks to answer the following questions:

(1) What are the fire behavior characteristics of pure PSSP and FEID assemblages?

(2) How do the fire behavior characteristics of pure PSSP and FEID differ?

(3) How do the fire behavior characteristics of pure PSSP and FEID change when associated with an increasing abundance of BRTE?

Based on Link et al. 2006, it is hypothesized that with the increasing percentage of the BRTE in native bunchgrass fuel abundance, the associated fire behavior metrics would increase (i.e. total consumption, flame length, and the rate of fuel consumption), while the burning time will decrease (20).

# CHAPTER 2. MATERIALS AND METHODS

## *2.1. Species Selection*

Bluebunch wheatgrass (*Pseudoroengeria spicata* (Pursh), A. Löve 1980) is a species of a temperate region, a cool-season (i.e. species that are growing in a cooler climate such as northern part of US and Canada), perennial bunchgrass native to western North America (36-38). It can grow up to 1.2 meters tall with extensive, deep root system and bunches with a diameter exceeding 25 cm (36, 37). The leaf blades of PSSP are approximately 4-6 mm wide, flat to inrolled, and green to blue in color (36). The common habitat of PSSP in the United States is along the northern Great Planes, northern Rocky Mountains, and Intermountain region (36, 38). PSSP is part of bunchgrass association with Idaho fescue (*Festuca idahoensis*, Elmer), Sandberg bluegrass (*Poa secunda*, Presl), bottlebrush squirreltail (*Elymus elymoides*, (Raf.) Swezey) and other annual and perennial bunchgrass species throughout the Pacific bunchgrass region, sagebrush grasslands, juniper woodlands, and open forests and foothills (37). PSSP is important species for livestock and wildlife forage, hay production, and it provides cover for birds and small mammals (36, 37). According to the literature, it is cold tolerant, moderately shade tolerant, and highly fire tolerant (36).

Idaho fescue (*Festuca idahoensis*, Elmer) is a temperate region species, perennial, cool season, bunchgrass with fine narrow leaves native to western North America (36, 37). The average height for this species is 0.3 to 1 meter (36). The root system is extensive and deep, which provides excellent erosion control (36). It is wide distributed forage for grazing livestock and wildlife, especially later in the season, because it stays green longer in the fall season than other bunchgrass species (36, 37). Together with the PSSP it is one of the most common and widespread grasses in the

Western United States. FEID is usually part of the same plant associations as a PSSP on a wide variety of soil types from Pacific bunchgrass region, through sagebrush bunchgrass region, juniper woodland region, to the coniferous forest region (37). Regarding the fire behavior, it is fairly tolerant and requires 2-3 years period for the full recovery (36).

Cheatgrass (*Bromus tectorum*, L.) is annual, cool season grass introduced and highly invasive in North America, but native to Europe, southwestern Asia and northern Africa (22, 36, 38). Because of its marked impact on fire cycles and its abundance in North American rangeland ecosystems, the significance of BRTE is unmatched by other species (18). The root system of BRTE is shallow, adapted to collect surface water when it is the most available at the end of the winter and early spring, which corresponds with the plant's main growth period (36). The plant height is between 0.1 and 0.6 m and it matures and senescence before the native perennial grasses are fully developed (36). During the late winter and early spring, before the seed production, BRTE can be used for grazing by livestock and wildlife (36, 37). Early development enables BRTE to produce seed earlier than neighboring native plants do. Accordingly, in the case of the early summer fire, the mature seed of BRTE positioned on the ground is more likely to survive than the aforementioned native plant neighbors (18, 22, 31, 39).

Species selected for this study are broadly present in the state of Idaho and throughout the western part of the USA (9-11, 14, 20). Additionally, the relationships between PSSP, FEID, and BRTE regarding grazing and fire regime are of tremendous importance in the existing ecosystems. Under favorable fire conditions (i.e. hot, dry, windy weather, and low fuel moisture) grass burning is characterized by a high rate of spread, high fire intensity, and low fire severity because of the low residence time of the fire (11, 12, 19, 40). The environmental conditions that support the initial development of grass fire are low relative humidity, high air temperature, and the presence of wind (11, 15, 39-41). The main plant-related characteristics influential to fire occurrence are the phenological stage of the plant, stand density (related to fuel porosity), and moisture content (14, 40, 42-44). The fully maturated, low moisture content plants are burning readily, especially if environmental conditions match with these favorable grass development stage (18, 19, 39, 45, 46). The longer and broader leaves, as well as less dense clumps, enable PSSP better fuel ventilation compared to FEID. Also, the assumption is that broader leaves respond faster to the changes in ambient relative humidity. The addition of BRTE provides higher fuel horizontal connectivity in fuel bed geometry.

High plant moisture content leads to more extended pre-heating and consequently delayed ignition and lower fire spread rates (18, 23, 40, 42, 46). Fuel porosity can play both ways, either as a fire promoter or as a fire extinguisher (12, 24). When the porosity is higher than a threshold value, convective cooling dampens the heat transfer mechanism and prevents fire spread; conversely, when porosity is below this threshold, the convective and radiant heat transfer from the flames overcomes the convective cooling from entrainment (12, 24). Post-fire composition and subsequent growth of the species can be significantly affected by the timing of burning (10, 16, 19, 39, 41). Late spring and early summer burnings, when the BRTE is already mature and dormant and PSSP and FEID are in the intensive growth stage, are causing the maximum tissue damage to former species (16, 18, 39, 41, 47). When the bunchgrasses are dormant during the late summer and fall, the low thermal conductivity of the soil and short residence time of fire enables a high rate of plant survival because their basal meristem is close to the soil surface or right below it (19, 41, 48-50).

*2.2. Growing and conditioning*

Grasses used in this laboratory burning experiment were grown in the University of Idaho Franklin M. Pitkin Forest Nursery located in Moscow, ID, USA. PSSP and FEID were seeded and grown in plastic trays sizing 27.9 cm W x 54.3 cm L 6.2 cm H (11" W x 21.37" L x 2.44" H), shown in Figure A. 1. in Appendix. Additionally, 1020 daisy trays were used to add more stability to the trays during the growth, particularly during the samples transfer from nursery to the combustion lab, shown in Figure A. 2. in Appendix. The biotype Anatone was used for PSSP and Chelan for FEID (BFI Native Seeds, Moses Lake, WA, USA). Implemented seeding rate for PSSP was 0.25 gr/tray (= 16 lbs/acre), and for FEID was 0.13 gr/tray (= 8 lbs/acre) as it corresponds to the density of a single species growth on harsh terrains (36). Seeds were applied over the area of the tray by hand. Growing medium (soil) was Professional Growing Mix: 40-50 % Canadian Sphagnum peat moss, vermiculite and aged fine bark – Custom Blend (79 L bags, Sun Gro Horticulture, Agawam, MA, USA). The total number of trays was 60, with 30 trays designated for each species (PSSP and FEID), as shown in Table 2. 1.. The grass was actively grown, from sowing until the last watering, for approximately 3.5 months (May 31$^{st}$, 2017 to September 22$^{nd}$, 2017) in an open-sided greenhouse under natural light conditions. Grass trays were watered once per week from the day of sowing to the last day of the growing season. During each watering period, water was supplied until the soil reached the saturation level observed when the water starts dropping evenly from entire bottom area of the tray. One month after sowing, all trays were fertilized with 18 gr per tray Osmocote smart-release plant food plus outdoor and indoor 15-9-12 NPK fertilizer (Scotts Miracle-Gro Company Corp., Marysville, OH, USA). After the 3.5-month growth period, the watering was terminated, and grass was left to senescence until the burning trials (for 7 months approximately).

*Table 2. 1. Experimental matrix; 5 trays were included for each series.*

| **Species** | **Role of the tray in the experiment** |
|---|---|
| PSSP | Clipped and dried |
| PSSP | Ignition trial |
| PSSP | 0%BRTE |
| PSSP | 20%BRTE |
| PSSP | 50%BRTE |
| PSSP | 80%BRTE |
| FEID | Clipped and dried |
| FEID | Ignition trial |
| FEID | 0%BRTE |
| FEID | 20%BRTE |
| FEID | 50%BRTE |
| FEID | 80%BRTE |

*2.3. Burning process*

All trays with grass were burned at the University of Idaho Combustion Lab during April 2018. Five representative trays per species were randomly chosen. All the aboveground plant parts from five random trays per species were clipped and oven dried on 65 $^{0}$C for 48 hours to provide an estimate of the pre-fire dry fuel loading, as presented in Table 2. 2. These pre-fire clipped trays were used to estimate the quantity of additional BRTE that had to be added on a mass balance basis. Additionally, five trays per species were used for ignition trials and identify the optimum ignition patterns. The initial fuel load expressed as the mass of dry biomass per tray for PSSP averaged 9.74 gr (= 779.2 kg/ha) and for FEID 8.02 gr (= 641.6 kg/ha) (see Table 2. 2.). At the time of burning the average fuel moisture for PSSP was 5 % and for FEID 6.2 %. The average soil (with the roots) moisture for PSSP was 10.1 % and FEID 8.7 %. The ambient relative humidity was measured on every hour and was averaging 55.8 % in the day of 80%BRTE burning trials. The average ambient relative humidity for the days when 0%BRTE, 20%BRTE, and 50%BRTE trials were performed were 27.1 % and 25.3 %. Air temperature in the room for the 80%BRTE burning trials was averaging 21.4 $^{0}$C, while for the other three group burning trials was averaging 22.0 $^{0}$C and 22.4 $^{0}$C.

The trays from both species were randomly divided in four groups of five trays. The four groups differentiated by the amount of BRTE that was added to promote the fire. The first group (group *0%BRTE*) of trays did not contain BRTE and thus served as a control group. In other groups (*20%BRTE*, *50%BRTE*, and *80%BRTE*), BRTE was added 20 %, 50 %, and 80 % by dry biomass, respectively. BRTE was collected during the previous fall and oven dried on 65 $^{0}$C for 48 hours prior to each burning day. The BRTE was placed upright, evenly in the gaps of original species, mimicking natural conditions, to provide spatial connectivity. Along with the addition of BRTE, the plant density – fuel load – increased accordingly for the groups 20%BRTE, 50%BRTE, and 80%BRTE to 11.69 gr/tray (= 929.6 kg/ha), 14.61 gr/tray (= 1168.8 kg/ha), 17.54 gr/tray (= 1403.2 kg/ha) for PSSP; and 9.62 gr/tray (= 769.6 kg/ha), 12.02 gr/tray (= 961.6 kg/ha), 14.42 gr/tray (= 1115.4 kg/ha) for FEID, respectively, as shown in Table 2. 2.

*Table 2. 2. Average dry mass fuel load per species per tray.*

| Percent of BRTE | PSSP fuel load | FEID fuel load |
|---|---|---|
| 0%BRTE | 9.74 gr/tray | 8.02 gr/tray |
| 20%BRTE | 11.69 gr/tray | 9.62 gr/tray |
| 50%BRTE | 14.61 gr/tray | 12.03 gr/tray |
| 80%BRTE | 17.54 gr/tray | 14.42 gr/tray |

All burn trials were performed with a low level of wind applied with a fan (~ 1.15 ± 0.11 m/s) to promote direction of fire spread Table 2. 3. The wind speed was measured with a Hot Wire Thermo-Anemometer (Extech Instruments, Waltham, MA, USA) at nine locations (the 3 locations evenly distributed over the width of the tray at 5 cm, 11cm, and 17 cm height) Table 2. 3. For each location, 8 measurements were performed. The average wind speed was reported as a mean of the totality of measurements. 10 gr of excelsior was used for ignition of each tray, laid in a horseshoe shape around the half of the tray to provide reliable ignition. The schematic of the burning setup with the horseshoe-shaped fuel configuration is given in Figure 2. 1.. The burning experiments were conducted on the table by using the hollow concrete board in which a tray was positioned, as shown in Figure 2. 2. To eliminate air flow from beneath the surface, the gaps between the grass trays and the concrete board were sealed with aluminum tape. After several test runs, it was determined that horseshoe shape of the ignition source provided the most consistent ignition patterns.

*Table 2. 3. Hot Wire Anemometer measurements. The sensor position regarding tray: BL- bottom left, ML- middle left, UL- upper left; BM- bottom middle, MM- middle (center of rectangle), UM- upper middle; BR- bottom right, MR- middle right, UR- upper right. M (1,2,3…) – the number of measurement.*

| **Position** | **M1** | **M2** | **M3** | **M4** | **M5** | **M6** | **M7** | **M8** | **Average** | **StDev** |
|---|---|---|---|---|---|---|---|---|---|---|
| **BL** | 0.9 | 0.7 | 0.8 | 0.9 | 0.7 | 1.1 | 0.8 | 0.9 | **0.85** | **0.13** |
| **ML** | 1.1 | 1.2 | 1.1 | 1.0 | 1.1 | 1.2 | 1.2 | 1.1 | **1.13** | **0.07** |
| **UL** | 0.9 | 0.8 | 1.0 | 1.1 | 0.8 | 0.9 | 0.7 | 0.8 | **0.88** | **0.13** |
| **BM** | 0.8 | 0.9 | 1.0 | 1.1 | 1.0 | 1.1 | 1.0 | 1.1 | **1.00** | **0.11** |
| **MM** | 1.3 | 1.4 | 1.3 | 1.4 | 1.2 | 1.6 | 1.4 | 1.2 | **1.35** | **0.13** |
| **UM** | 0.8 | 0.9 | 0.8 | 0.9 | 0.7 | 0.8 | 0.9 | 0.8 | **0.83** | **0.07** |
| **BR** | 1.6 | 1.7 | 1.7 | 1.6 | 1.7 | 1.6 | 1.5 | 1.6 | **1.63** | **0.07** |
| **MR** | 1.6 | 1.8 | 1.7 | 1.5 | 1.5 | 1.3 | 1.4 | 1.6 | **1.55** | **0.16** |
| **UR** | 0.6 | 1.1 | 1.3 | 1.1 | 1.2 | 1.3 | 1.2 | 1.3 | **1.18** | **0.14** |

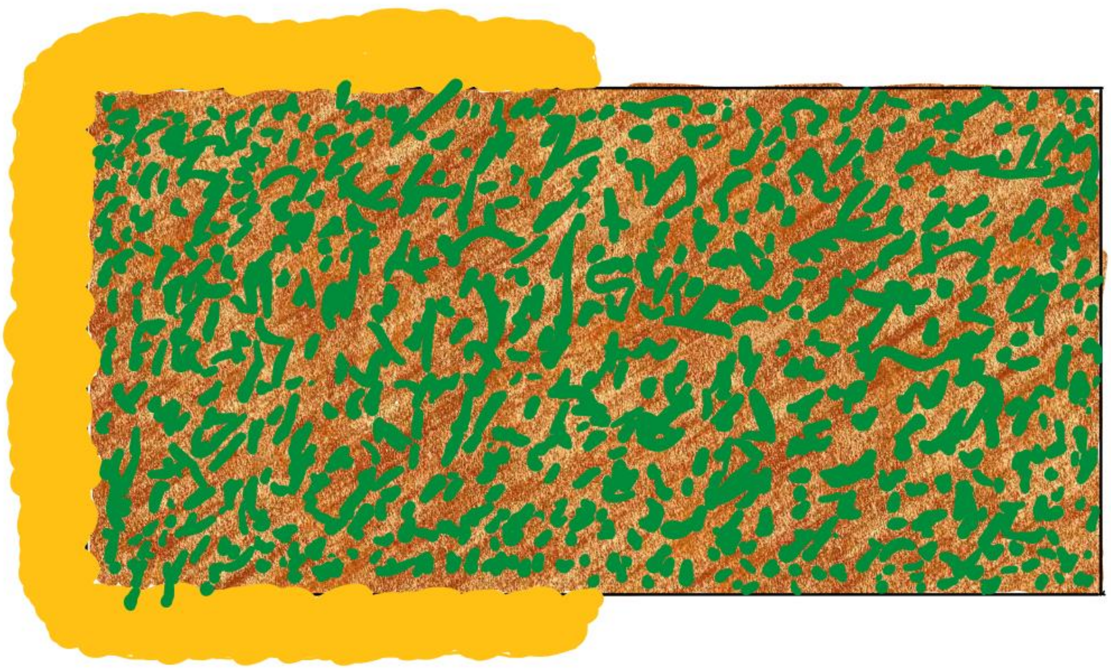


*Figure 2. 1. Schematic of the burning setup with the horseshoe-shaped ignition fuel configuration. Yellow- excelsior; brown- soil, green- grass (fuel load), black- tray edge.*

*Figure 2. 2. Experimental setup*

*2.4. Measured burning parameters*

The rate of consumption (hereafter ROC) is defined as the rate of biomass consumed (BC) over the entire burn (flaming, smoldering, glowing) duration ($T_T$, seconds), expressed in grams per second:

$$ROC = \frac{BC}{T_T} \qquad [1]$$

The entire burning duration, $T_T$, was calculated from temperature data collected from two thermocouples located on the soil surface. The fire was considered active when temperature data exceeded 50 °C.

Total consumption (i.e. BC) was measured as the mass of pre-fire trays minus the mass of the post-fire trays (grams).

$$BC = Mass_{Initial} - Mass_{Final} \qquad [2]$$

The pre-fire initial mass was measured by weighing each tray just prior to the burn trial and the post-fire final mass was measured by re-weighing each tray immediately following fire extinction.

The fuel bed height was measured at six positions for each tray using a ruler and reported as an average value, in centimeters (cm). The fuel bed height measurements were taken following BRTE addition.

Flame length was obtained from videography, as a ratio of flame height (FH) and sine of an angle ($\alpha$) formed by flame direction and soil surface, in centimeters (cm):

$$FL = \frac{FH}{\sin(\alpha)} \qquad [3]$$

Flame length is not a good measure of fire intensity as it mainly shows the degree of ventilation (or not) within the fuel bed. This study included flame length to evaluate whether ventilation is impacted as the abundance of BRTE increases.

The proportion of burned area compared to the complete area of a tray (%) will be calculated after image analysis. Here, it is reported on visual estimation base.

To characterize fire behavior characteristics (i.e. ROC, and duration of combustion) two thermocouples were used (aluminum-chrome type K thermocouples, Omega Engineering INC, Stamford, CT, USA). As the fires only took between 15-20 seconds from ignition until fire extinction, ROC calculation thermocouples were located on the soil surface. They were located 0.20 m apart following similar methodologies on small plots in savanna ecosystems (51). These two thermocouples were positioned in the second half of a tray to avoid the influence of edge effects. The rapid temperature increases on each of the thermocouples indicated the passage of the fire through the fuel bed. This time coincided with the observed time of the active flame progression and extinction from the videography. In addition, the Engauge Digitizer (free software available from: http://markummitchell.github.io/engauge-digitizer/) was used for more accurate calculation of time difference between the thermocouple readings. The data from thermocouples were transferred to the computer by using datalogger (TC08 USB thermocouple data logger, Omega Engineering INC, Stamford, CT, USA) and related software (Picolog recorder, PICO technologies LLC, Houston, TX, USA). The burns were video-recorded, which was the basis for the later flame length and burning time calculations (Microsoft LifeCam, Microsoft Corp. Redmond WA, USA). All trays were photographed before consumption, with BRTE added, and after the fire experiment. This enabled an evaluation of effective area burned, as can be seen in Appendix, Figure A. 3. and Figure A. 4.. The data about the fuel moisture content and air temperature were measured and recorded, presented in Table 2. 4.

*Table 2. 4. Relative humidity and air temperature in laboratory during the burning trials (hourly).*

| Specimen category | Burning time | RH @ burning time [%] | Temp. @ burning time [$^0$C] |
|---|---|---|---|
| **80%BRTE** | 10:00 | 66.8 | 20.1 |
| | 11:00 | 63.1 | 20.7 |
| | 12:00 | 56.5 | 21.3 |
| | 13:00 | 49.4 | 21.6 |
| | 14:00 | 48.7 | 22.1 |
| | 15:00 | 50.3 | 22.8 |
| **20%BRTE, 50%BRTE** | 09:00 | 33.1 | 20.2 |
| | 10:00 | 32.5 | 20.6 |
| | 11:00 | 30.8 | 21.1 |
| | 12:00 | 28.1 | 21.4 |
| | 13:00 | 25.0 | 21.8 |
| | 14:00 | 23.6 | 22.1 |
| | 15:00 | 22.5 | 22.4 |
| | 16:00 | 22.9 | 23.4 |
| | 17:00 | 23.9 | 23.8 |
| | 18:00 | 28.9 | 23.3 |
| **0%BRTE** | 10:00 | 32.5 | 21.0 |
| | 11:00 | 30.7 | 21.5 |
| | 12:00 | 28.0 | 21.9 |
| | 13:00 | 24.0 | 22.5 |
| | 14:00 | 22.3 | 22.9 |
| | 15:00 | 20.1 | 23.3 |
| | 16:00 | 19.8 | 23.8 |

### *2.5. Statistical Analysis*

The correlations between different parameters were evaluated using Correlation function in Minitab (commercially available software package on minitab.com). Linear correlations between parameters were assumed and corresponding goodness of the fit was evaluated based on coefficient of determination ($R^2$). To analyze the significance of changes introduced by increase in available fuel amount paired t-tests were conducted between the corresponding groups of parameters (e.g. ROC 0%BRTE vs ROC 20%BRTE, etc.). The significance was established at 95 % confidence interval. The significance was reported by means of p-values calculated in Minitab.

# CHAPTER 3. RESULTS

All the results refer to solely bunchgrass and mixed bunchgrass/BRTE experimental trials. In all trials, regardless of bunchgrass species, the portion of BRTE was completely charred or consumed. Incomplete burned area refers to the unburned share of either PSSP or FEID.

## *3.1. Proportion of Consumption, Total Consumption, and Rate of Consumption*

The proportion of fuel consumed (consumption) was obtained by visual estimation for both species. Figure A. 5. - Figure A. 8. in the Appendix shows the samples of PSSP after trials grouped by the percentage of BRTE used. Two of five trays of PSSP in the 0%BRTE group had incomplete burning. However, there was no difference in the relative amount of fuel consumed in other groups (i.e. 20%BRTE, 50%BRTE, 80%BRTE), as shown in Figure A. 5. - Figure A. 8. in Appendix. The trays in those three groups were burned completely and the entirety of the fuel was either charred or consumed. Therefore, the difference in proportion of combusted area among them cannot be identified and further image analyses should be performed. Figure 3. 1. presents total consumption for all the trays per species. Figure 3. 2 presents the rate at which fuel was consumed with increase in fuel percentage. As seen in Figure 3. 2, ROC showed a positive trend with an increase in the percentage of BRTE. However, the ROC of 80%BRTE group does not follow this trend. For FIED, results about proportion of consumption and rate of consumption showed more variation. The lowest percentage of combustion was in 20%BRTE group, followed by 50%BRTE, 0%BRTE, and 80%BRTE group, respectively (Figure A. 8. - Figure A. 12. in Appendix). In the group with 20%BRTE two trays burned incompletely as well as in the group with 50%BRTE. All trays in control group (0%BRTE) and 80%BRTE burned completely. As it could be seen from Figure 3. 2, the results for ROC are generally as expected that ROC will increase with increased amount of BRTE added.

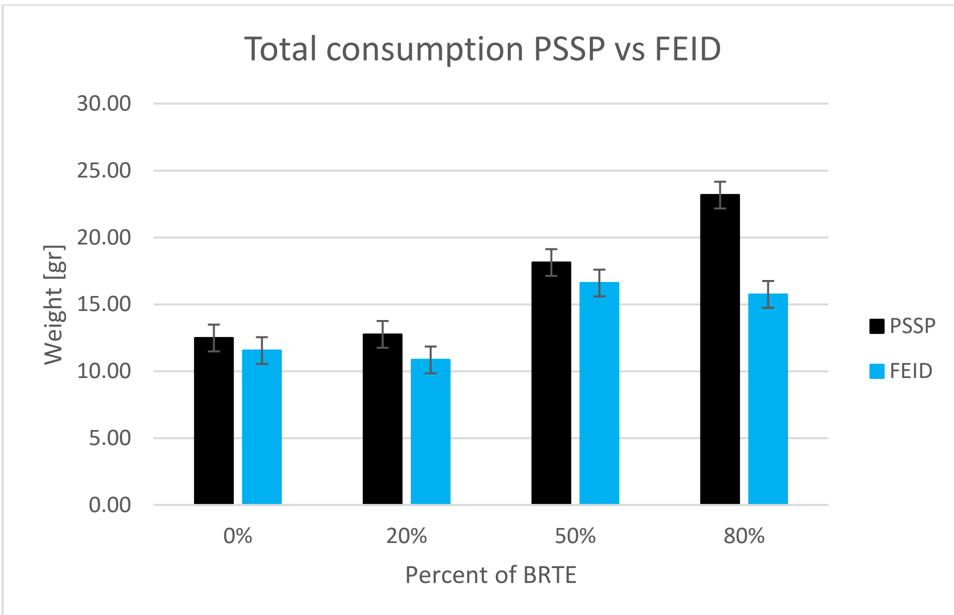



*Figure 3. 1. Mass loss as an average value of difference in trays weight before and after burning for PSSP and FEID.*

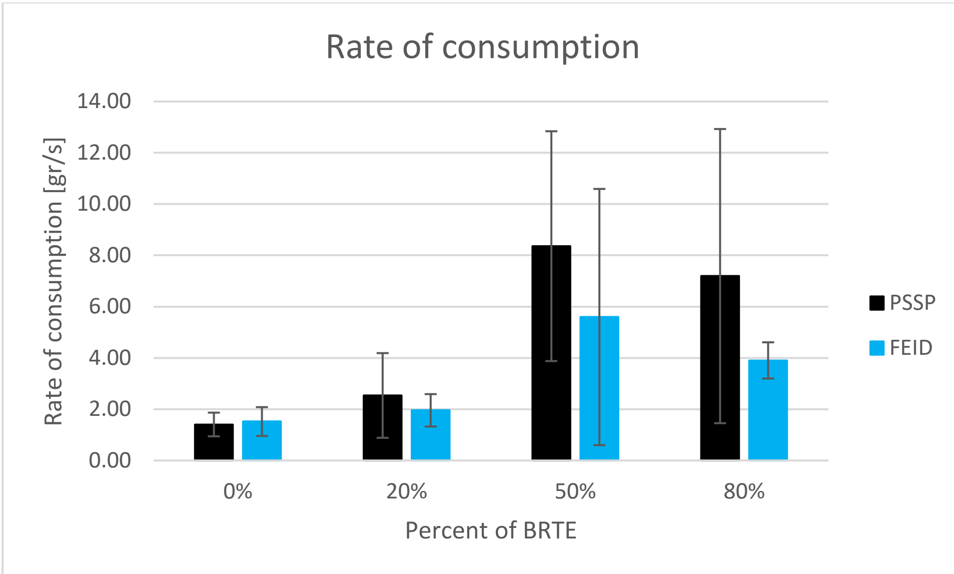



*Figure 3. 2. Average ROC for PSSP and FEID in relation to fuel addition in percent of BRTE added.*

### *3.2. Flame Length and Fuel Bed Height*

Figure 3. 3 and Figure 3. 4 present average flame length and fuel bed height for both species, respectively. Increase in flame length followed the increase in the percentage of BRTE, as seen in Figure 3. 3. It is interesting that the average height of fuel was also increasing with a higher percentage of BRTE despite the randomness in trays' grouping, especially expressed for FEID, based on Figure 3. 4. This can later blur the results about the relationship between flame length and fuel bed height. As it could be seen in Figure 3. 3 and Figure 3. 4, more clearly with PSSP, it seems that the percent of BRTE has more influence on flame length than the fuel bed height.

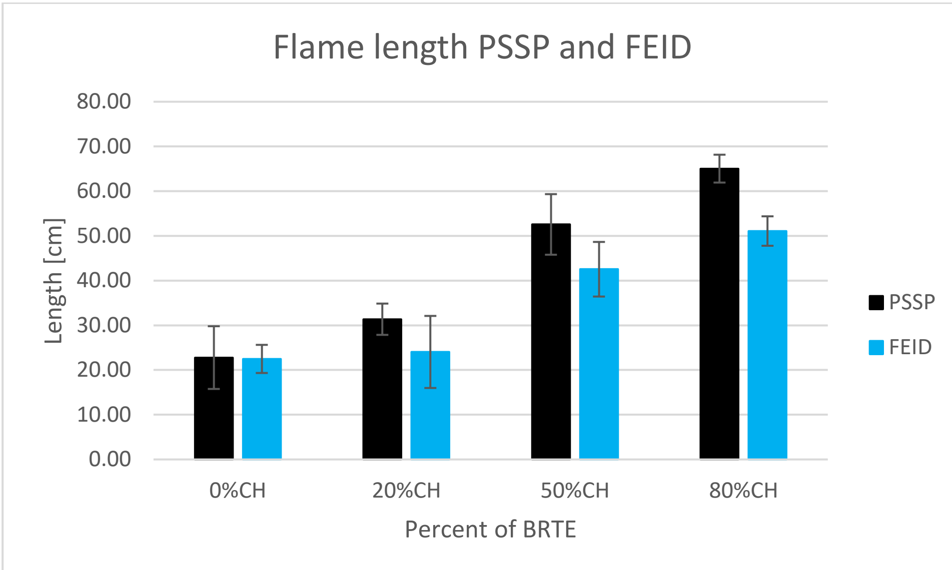



*Figure 3. 3. Average flame lengths for PSSP and FEID in relation to fuel addition in percent of BRTE added.*

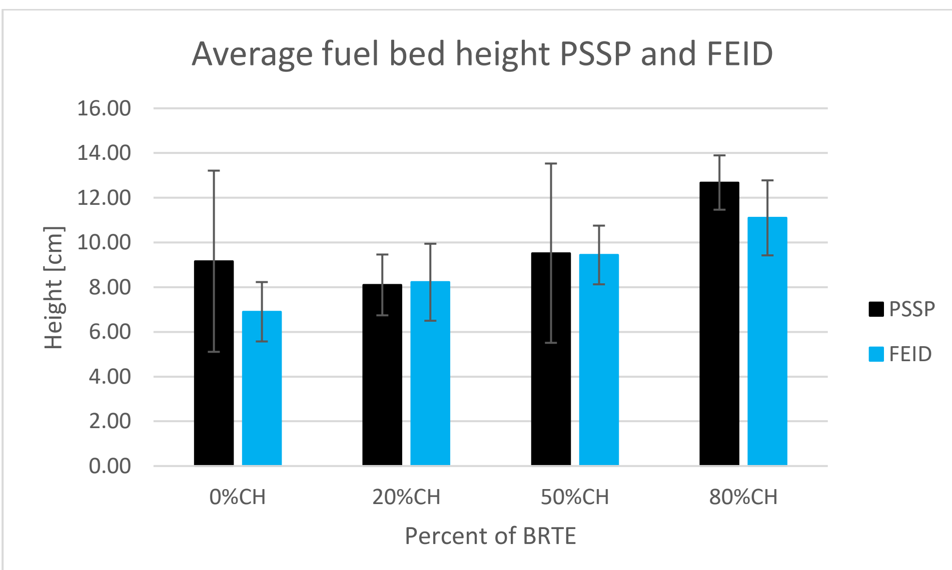



*Figure 3. 4. Average fuel height for PSSP and FEID in relation to fuel addition in percent of BRTE added.*

### *3.3. Burning time*

Figure 3. 5 shows the averaged burning time for each group of trays. As seen in Figure 3. 5, the decrease in burning time for PSSP was following the rise in the percentage of BRTE until the last group (80%BRTE) when it unexpectedly increased. FEID acted slightly different compared to PSSP in terms of burning time. Namely, the burning time was gradually increasing from 0%BRTE group to 80%BRTE group, as seen in Figure 3. 5.

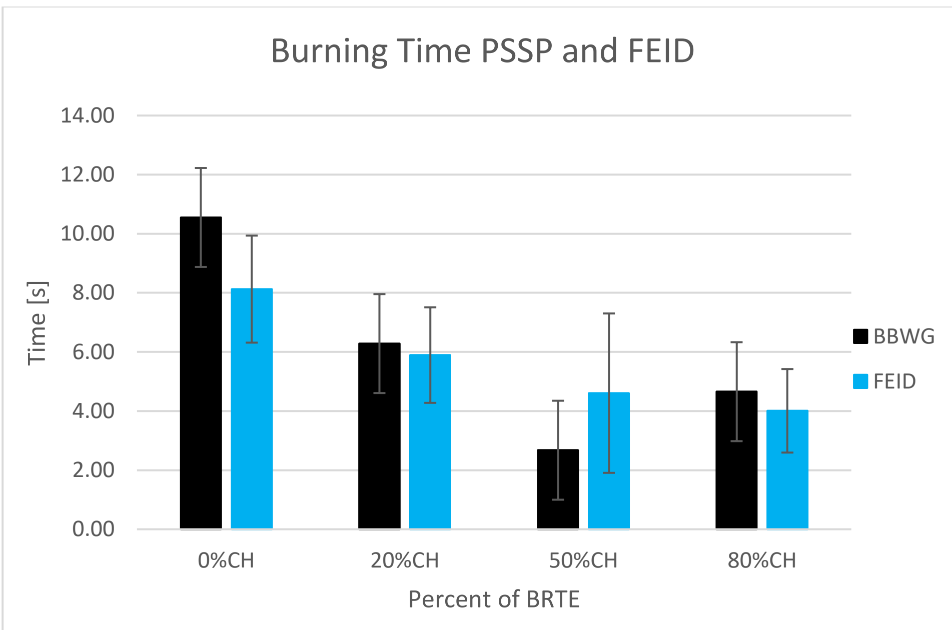


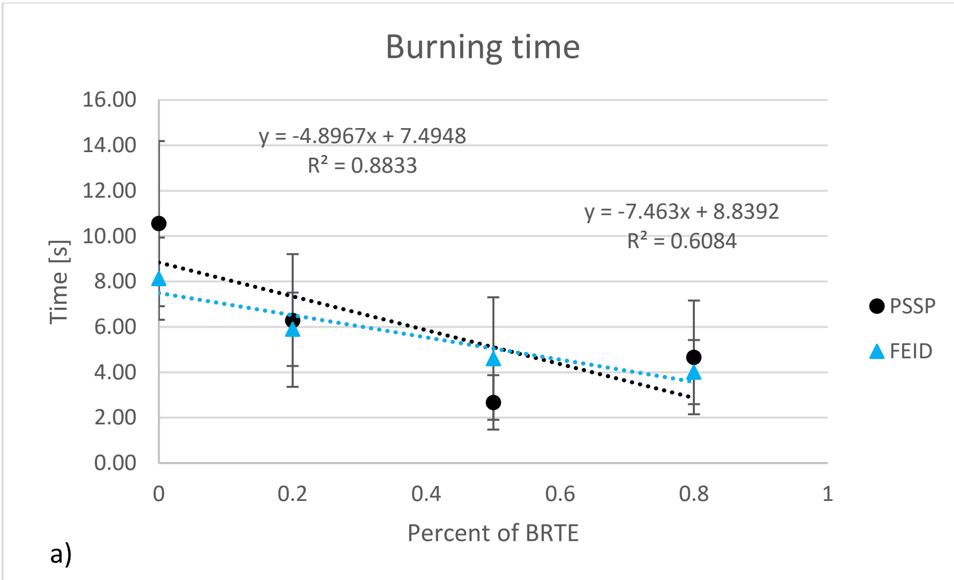

*Figure 3. 5. Average burning time for PSSP and FEID in relation to fuel addition in percent of BRTE added.*

# CHAPTER 4. DISCUSSION

All data that defines changes in fire behavior with an increase in the percentage of BRTE within bunchgrass species fuel load are presented in Table 4. 1.. The relationships between fire parameters (burning time, flame length, rate of consumption), plant properties (moisture content, developmental stage, stand density), and, in some cases, environmental conditions (wind, relative humidity) are systemized and presented in Figure 4. 1 - Figure 4. 6.. Visual observations from the pictures in Figure A. 5. - Figure A. 12. in Appendix did not reveal much information about burning patterns but they will be used for further analysis and proportion of burned area determination.

## *4.1. Burning Time*

The previous research, conducted in the natural environment, suggested that the rate of spread will increase with increasing presence of BRTE in sagebrush or bunchgrass associations (11, 18, 22, 23, 40). Along with the increase in the rate of spread, the burning time will decrease. Figure 4. 1.a is presenting the relations between burning time and increase in percentage of BRTE added. Results in Figure 4. 1.a reveal that increased amount of fuel results in a drop in burning time. To evaluate this conclusion and isolate the effect of fuel addition Figure 4. 1.b presents burning time normalized by fuel consumed versus the fuel addition percentage. The trends in Figure 4. 1.b confirms that decrease in burning time is due to the BRTE addition rather than increase in fuel mass. Nonetheless, 80% BRTE addition in PSSP resulted in relatively high burning time value. The reason for this discrepancy can be either too high fuel bed density or the difference in ambient relative humidity during combustion. In some cases, too high fuel bed density can cause fire extinction due to the lack of oxygen. However, in the case of 80% BRTE, where the grass is fully cured, and other burning conditions are satisfying, the oxygen depletion is unlikely (23, 24). The higher amount of BRTE provides higher stand density and horizontal continuity, which are favorable conditions for homogeneous fire movement (9, 11, 19, 20, 23). It can be, though, that there is a fuel load threshold after which the fire burning time increases again. Also, as an indicator of ventilation of the fire, flame length increases with the increase in fuel load demonstrate the sufficient presence of oxygen in 80%BRTE burn trials. However, the fuel loadings in this study are well below the amount of fine fuel that will support the burnings with lower wind, lower temperatures, and higher relative humidity values reported in the literature (41). Even in the highest density groups (i.e. 80%BRTE group), the fuel loads for PSSP and FEID were 1403.2 kg/ha and 1115.4 kg/ha, respectively. For reference, 1681.28 kg/ha is needed to provide the burning in harsh environmental conditions, as reported by Bunting et al. 1987 (41). As the fuel loads in this study were below this limit, the wind was used in the experiment to enhance burning. Still, the fuel load was higher than the needed amount which provides for readily fire burning in the sagebrush-grassland community (> 672 kg/ha) (15, 16, 52). Nevertheless, fire burning time values were higher for the 80%BRTE group for PSSP, while for FEID were almost the same as for 50%BRTE group Figure 4. 1.a. Namely, with the increase in BRTE percentage, burning time decreased until the 80%BRTE group when significantly increased for the PSSP. The burning time for FEID 80%BRTE group was lower than for 50%BRTE, as expected, which additionally blurs the results interpretation. All trays with 80%BRTE were completely burned or charred, as it can be seen in Figure A. 8. and Figure A. 12. in Appendix.



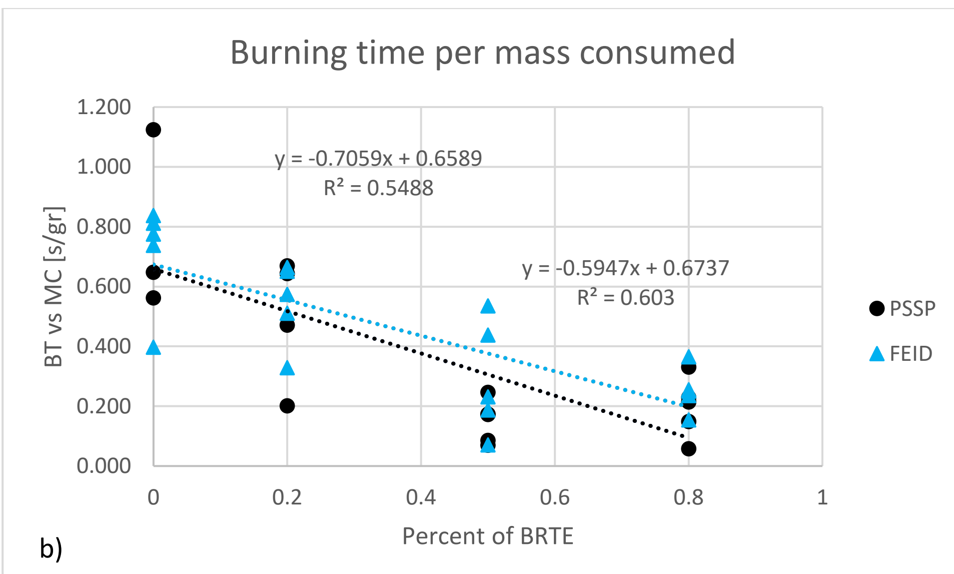




*Figure 4. 1. The relation between percent of fuel addition for PSSP and FEID and: (a) average burning time (b) burning time normalized by the mass consumed.*

*Table 4. 1. Fire behavior elements comparison for two bunchgrass species. Comparison of rate of consumption, flame length, and burning time for two bunchgrass species with the different percentage of BRTE added.*

| **BRTE [%] /Species** | **PSSP** | **FEID** |
|---|---|---|
| Rate of consumption (gr/s) for 0%BRTE | 1.4 | 1.5 |
| Rate of consumption (gr/s) for 20%BRTE | 2.1 | 1.7 |
| Rate of consumption (gr/s) for 50%BRTE | 6.1 | 2.6 |
| Rate of consumption (gr/s) for 80%BRTE | 4.6 | 2.5 |
| Flame length (cm) for 0%BRTE | 22.78 | 22.48 |
| Flame length (cm) for 20%BRTE | 31.36 | 24.04 |
| Flame length (cm) for 50%BRTE | 52.56 | 42.54 |
| Flame length (cm) for 80%BRTE | 65.04 | 51.08 |
| Burning time (s) for 0%BRTE | 1.93 | 2.34 |
| Burning time (s) for 20%BRTE | 4.04 | 3.39 |
| Burning time (s) for 50%BRTE | 9.92 | 5.59 |
| Burning time (s) for 80%BRTE | 3.5 | 4.82 |

Ambient relative humidity was higher during the 80%BRTE groups burning, 55.8 % relative to 27.1 % and 25.3 % (mean average values for the burning days) for the other burnings, which might have a negative influence on the burning time (18, 24). Low moisture content fuels are highly responsive to the change in relative humidity values (18, 24, 45). Part of the heat energy will be lost to water evaporation from the fuel which can increase the burning time (11, 18, 24). But, relative humidity and other environmental parameters were similar for both 80%BRTE burns because they were burned during the same day. Fluctuations in relative humidity on hour-to-hour basis were ranging from 48.7 % to 66.8 % in the time of burning. Accordingly, relative humidity can play a certain role in explaining the difference between 50%BRTE and

80%BRTE group fire behavior properties, but it is less influential in the explanation of differences between two bunchgrass species of the same group (i.e. 80%BRTE group). The correlation between the decrease in burning time with an increase in the percentage of BRTE for both species was observed; linear $R^2$ value for FEID was 0.88 and for PSSP 0.61, as seen in Figure 4. 1.a. Burning time decreased sharply in PSSP while the drop in FEID was more gradual. Therefore, BRTE percentage exhibits the higher influence on PSSP burning properties, as shown in Figure 4. 1.a.

### *4.2. Flame Length*

The results of this study show that increased percentage of BRTE in bunchgrass association will provide more fuel continuity and therefore higher flame length, which corresponds to the findings in the literature (24). Figure 4. 2.a presents the relation between flame length properties and increased amount of fuel. The flame length was unequivocally related to the higher amount of BRTE in fuel load. The positive linear correlations between the increase in BRTE and increase in the length of flame were identified, with $R^2$= 0.91 for PSSP and $R^2$= 0.82 for FEID, as shown in Figure 4. 2.a. To evaluate this conclusion and isolate the effect of fuel addition Figure 4. 2.b presents flame length normalized by fuel consumed versus the fuel addition percentage. The trends in Figure 4. 2.b confirm that increase in flame length is due to the BRTE addition rather than increase in fuel mass. Figure 4. 3. shows the relationship between the flame length and averaged fuel bed height for each group of five trays. Flame length correlated well with the plants' height too, however, relation factors were lower in comparison with the BRTE percentage increase ($R^2$= 0.67 for PSSP and $R^2$= 0.91 for FEID), as shown in Figure 4. 3.. Flame lengths noticeably increased in all PSSP groups with BRTE added, as shown in Figure 4. 2.a, which further confirms the higher influence of BRTE addition to the fire behavior properties of PSSP. The significance of fuel amount over initial fuel bed height for flame length increase is particularly highlighted for the PSSP where the average plant height did not follow the increase in BRTE percentage, which was the case with FEID, as it can be seen in Figure 4. 3.. The increase in fuel bed height and increase in percent of BRTE coincided in FEID but it did not hinder the results.

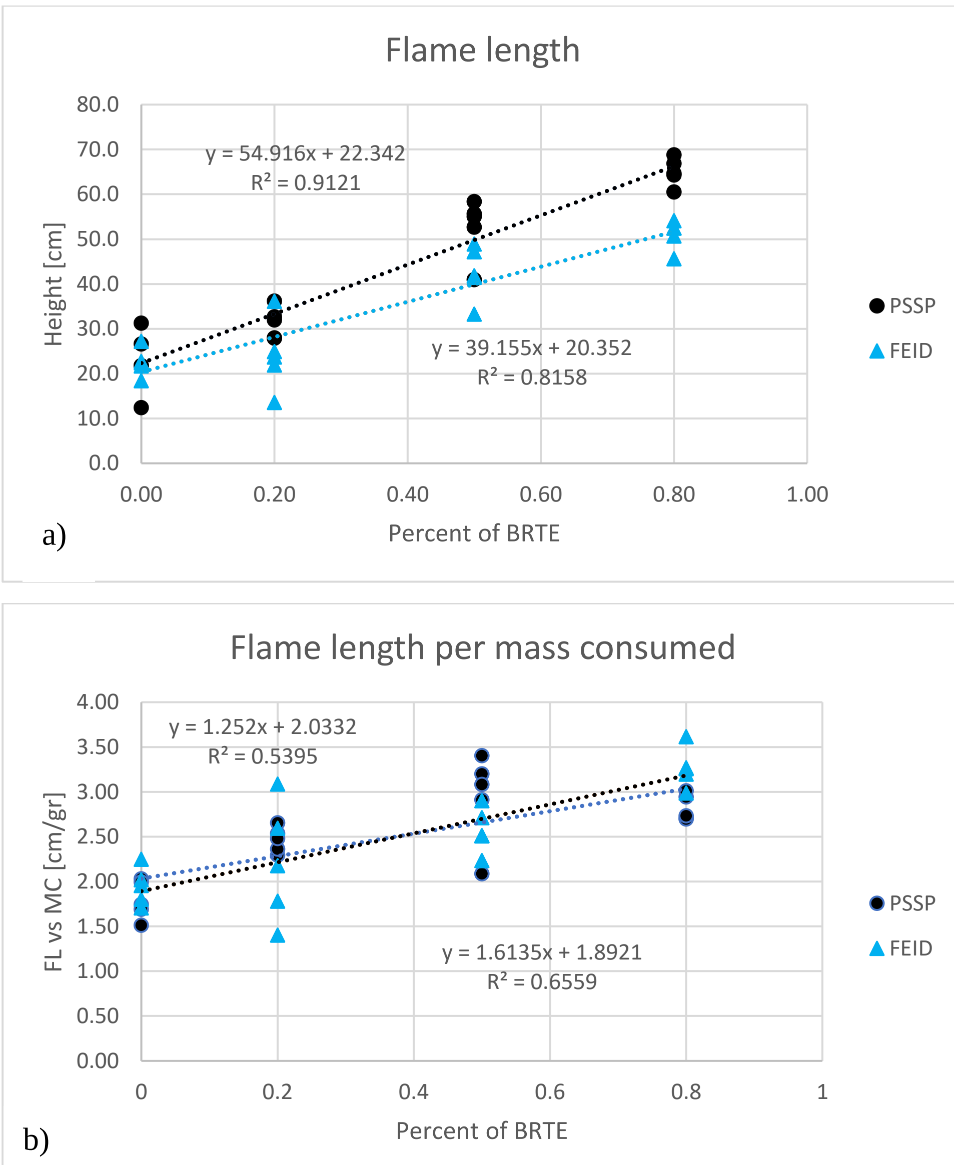



*Figure 4. 2. The relation between fuel addition for PSSP and FEID and: (a) average flame length, and (b) flame length normalized by the mass consumed (total consumption).*

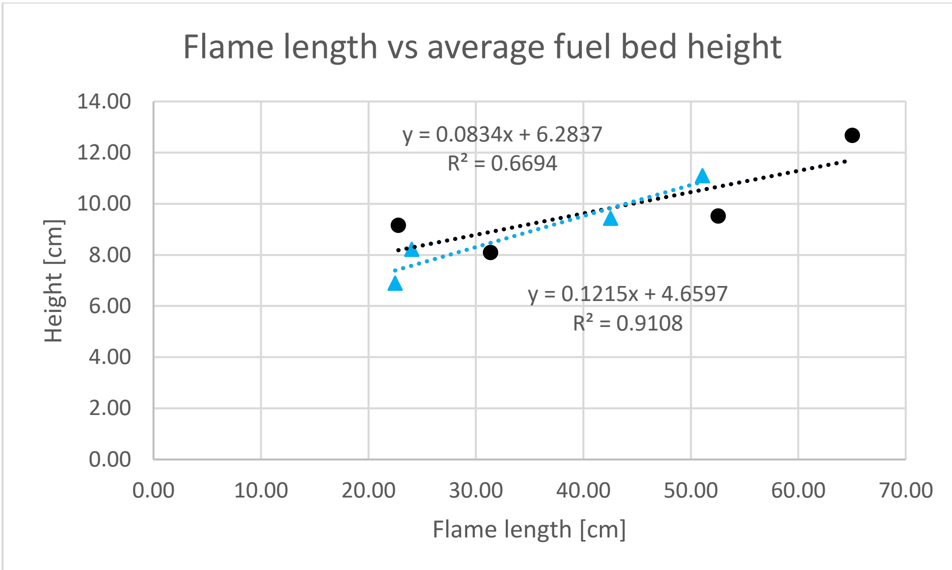



*Figure 4. 3. The relation between average flame length and average height for PSSP and FEID.*

### *4.3. Rate of consumption and total consumption*

Results indicated a correlation between the percentage of BRTE and the rate of consumption, except for 80% group for both bunchgrass species. Figure 4. 4. presents the relation between the rate of consumption and increase in the percentage of BRTE. Despite the lower values for 80%BRTE groups, the correlation between the rise in the percentage of BRTE and increase in the rate of consumption was positive for both species, with higher values for FEID ($R^2$=0.54 for FEID and $R^2$=0.76 for PSSP), as seen in Figure 4. 4.. Figure 4. 5. describes relationship between rate of consumption and average mass consumed by fire. The relationship between ROC and total consumption (the amount of fuel consumed) is also observed with much higher correlation for FEID compared to PSSP ($R^2$= 0.90 and $R^2$= 0.71 for FEID and PSSP, respectively), as could be seen in Figure 4. 5. The increase in fuel amount is followed by the speed that fuel was consumed. The results shown in Figure 4. 4. and Figure 4. 5. underlines that the species involved in grass fire and the amount of fuel are of similar importance in fire propagation. Presented in Figure 4. 6. is the relation between the increase in fuel consumption and increase in percent of BRTE added. The total consumption with increase in fuel load is highly linear correlated for the PSSP with $R^2$= 0.95, while for FEID linear correlation has lower value but still positive trend with $R^2$= 0.69, as seen in Figure 4. 6..

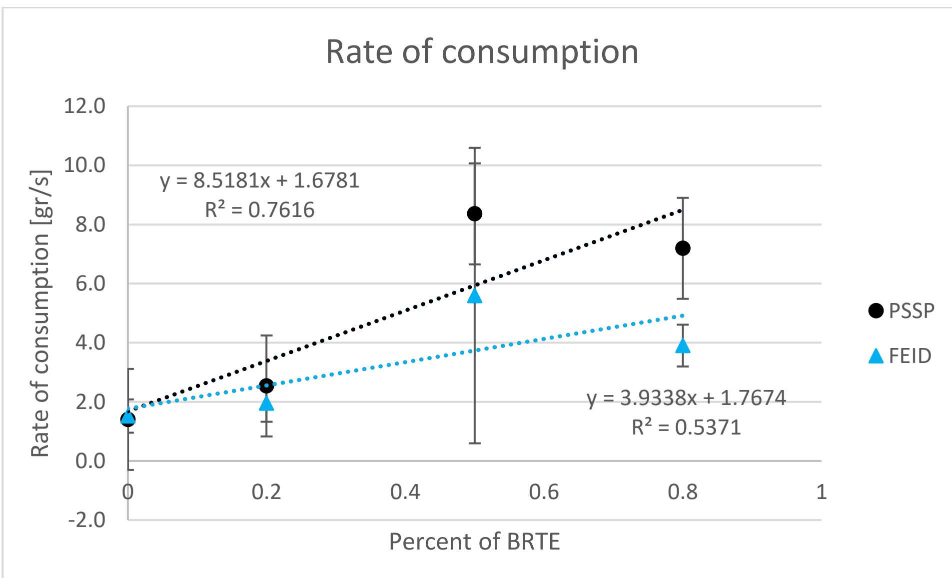



*Figure 4. 4. The relation between average combustibility and percent of fuel addition for PSSP and FEID.*

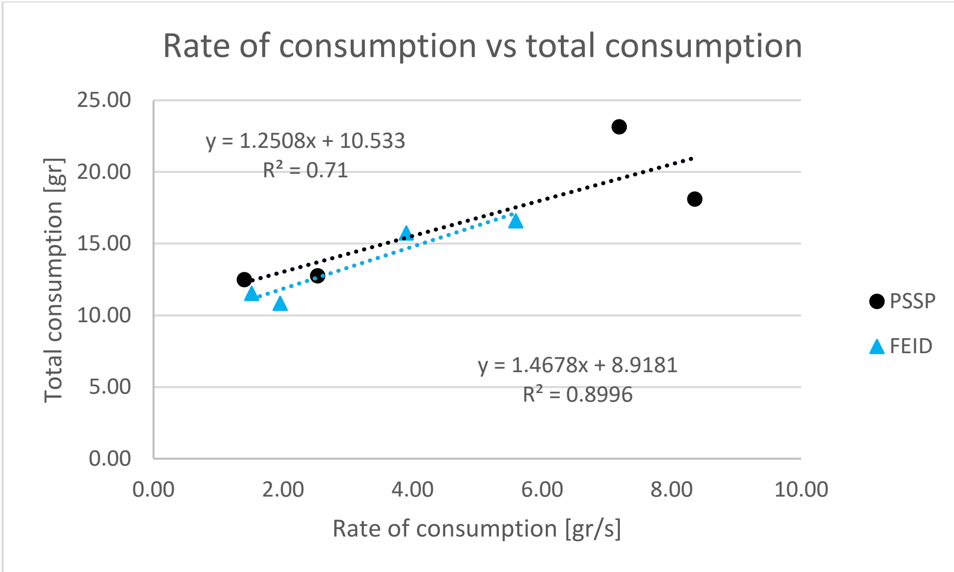



*Figure 4. 5. The relation between average combustibility and average mass consumed by fire for PSSP and FEID.*

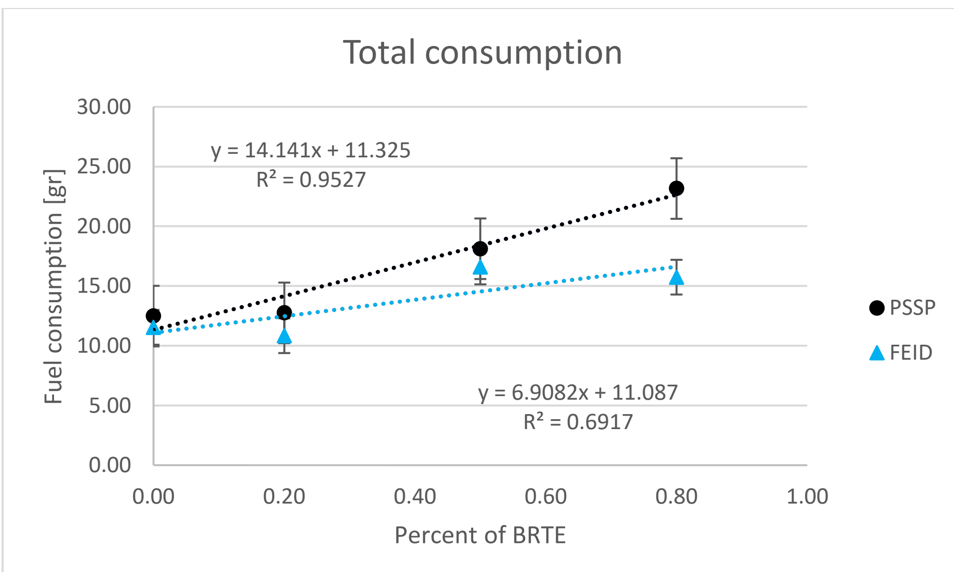



*Figure 4. 6. The relation between total consumption (mass loss) and percent of fuel addition for PSSP and FEID.*

The 80%BRTE addition corresponds to the BRTE cover of 45 %, while 50%BRTE and 20%BRTE groups suit 33 % and 17 % BRTE cover, respectively, in Link et al. 2006 (20). Despite the difference in plant community type (*Artemisia tridentata – Poa secunda* association, dominated by *Artemisia tridentata*, *Poa secunda*, and BRTE; vs mixture of PSSP or FEID with BRTE) and methodology (field burnings vs laboratory burnings), our 80%BRTE groups were completely charred and burned which was in line with their fire risk estimation. The burning results from other three groups (0%BRTE, 20%BRTE, and 50%BRTE) were harder to relate with findings of Link et al. 2006 because they are not so consistent among them as the results for 80%BRTE groups were. PSSP showed the difference in the rate of combustion and burning time with an increase in BRTE but not in area burned and overall total consumption. Namely, all trays in 20%BRTE and 50%BRTE were completely charred, while that was not the case with FEID. Further research is needed, with more samples in every group, to confirm and strength the results of the presented study.

The only significant differences (p-value < 0.05) between two bunchgrass species obtained by paired t-test are differences in flame length. The significant difference was identified for almost all combinations of flame lengths except between groups 0%BRTE and 20%BRTE for both bunchgrass species. Paired t-test did not show significant differences between the same groups (e.g. PSSP 0%BRTE versus FEID 0%BRTE, PSSP 20%BRTE versus FEID 20%BRTE, etc.) for the other tested parameters (total consumption, rate of consumption, and burning time) between PSSP and FEID.

# CHAPTER 5. CONCLUSIONS

An experimental study was designed and conducted aiming to show the effects of the increased amount of BRTE on two common bunchgrass species, namely PSSP and FEID. Main findings and conclusions are summarized as follows.

Overall, the results indicate that PSSP is characterized by more intensive fire behavior parameters compared to FEID (i.e. higher flame lengths, shorter burning times, increased rate of consumption, and total consumption) at the increased percentage of BRTE environment. Based on visual estimation, burnings in PSSP trays were more homogenous and fuel charring and consumption was complete in almost all cases (except two trays with 0%BRTE). Conversely, FEID burnings were mostly incomplete regardless of the quantity of BRTE added, excluding 80%BRTE group where all trays were burned completely. The rate of consumption is highly correlated with the burning time. Because the results for 80%BRTE failed to prove a high positive correlation between BRTE percentage increase and fire behavior properties, we have discrepancies in results for this parameter. By neglecting values for disputable group for a moment, the high linear correlation among given parameters will be established. The values of $R^2$ were approaching 1 for the rate of consumption and burning time linear correlations with the increase in fuel percentage, when the result for 80%BRTE was removed which emphasize the importance of the environmental conditions even in the lab environment.

The size of trays used for bunchgrass growing in this experiment was the main limitation in the study. The most affected was root growth. The trays were too shallow (only 6 cm) taking in consideration that main root development occurs in the first year of growth for bunchgrass species, precisely in the first couple of weeks. Low depth of the tray hinders the appropriate root system development. The length of growing period was another limitation. Burning after the second growth season would provide more realistic data about the fire in natural conditions. However, due to the limitations of the nursery facilities, the experiment could not be conducted over the two seasons.

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# APPENDIX: Supplemental Materials for Chapters 2,3, and 4

*Figure A. 1. 10-20 heavy weight tray with holes used for bunchgrass growing.*

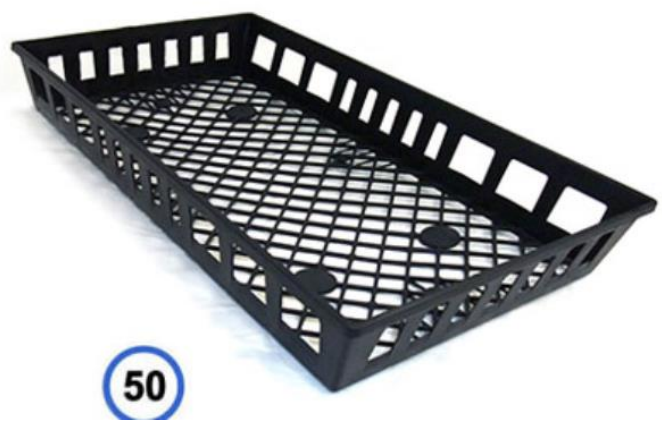


*Figure A. 2. 10-20 Daisy tray used to add more stability to the trays during the growth, and the samples transfer from nursery to the combustion lab.*

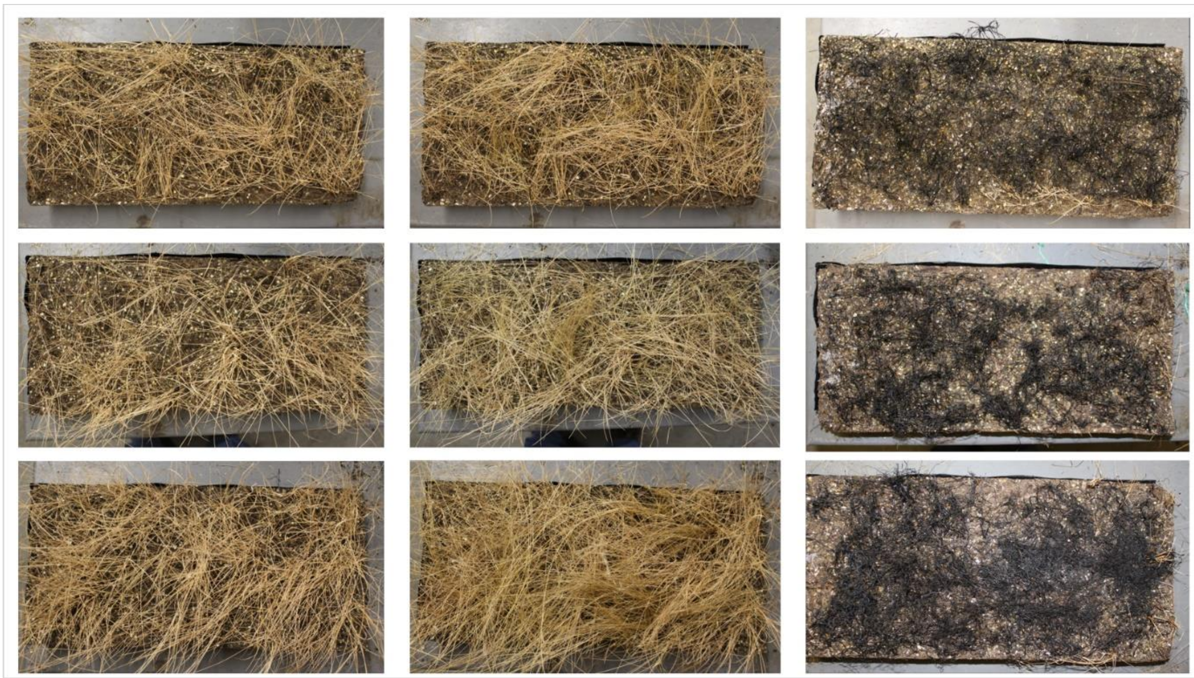

*Figure A. 3. PSSP burning patterns. From left to right: PSSP without BRTE (natural fuel load), PSSP with added BRTE, after burning. From up to the bottom: 20% BRTE added, 50% BRTE added, 80% BRTE added.*

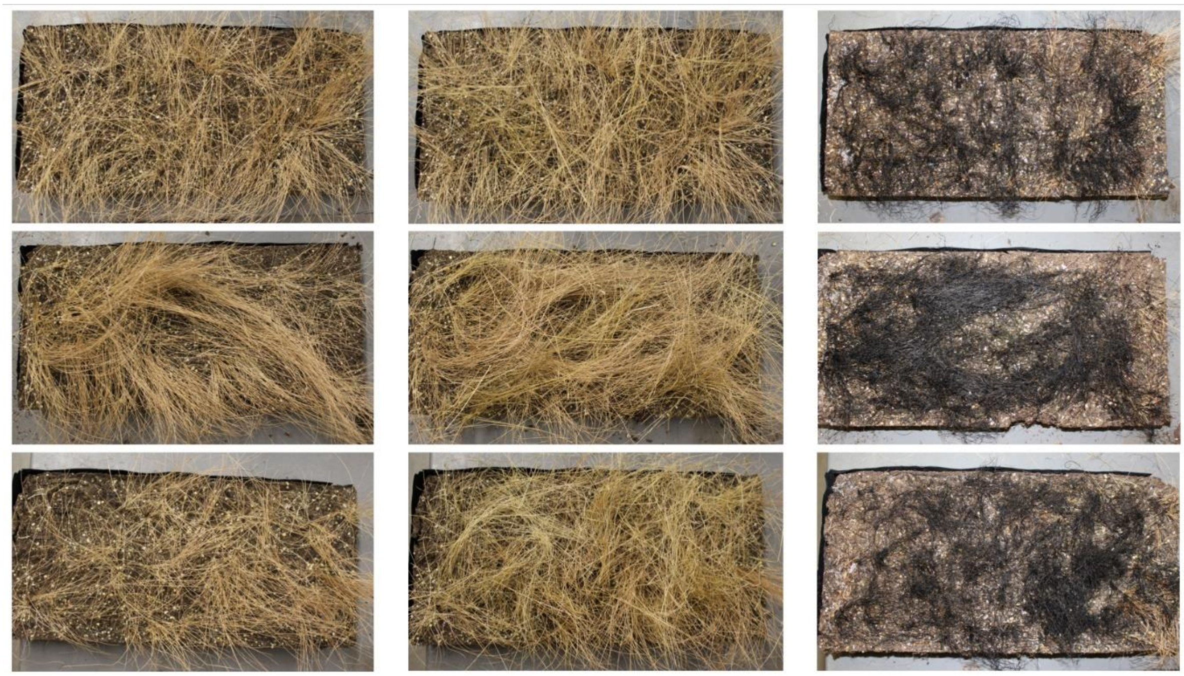

*Figure A. 4. FEID burning patterns. From left to right: FEID without BRTE (natural fuel load), FEID with added BRTE, after burning. From up to the bottom: 20 % of BRTE added, 50 % of BRTE added, 80 % of BRTE added.*

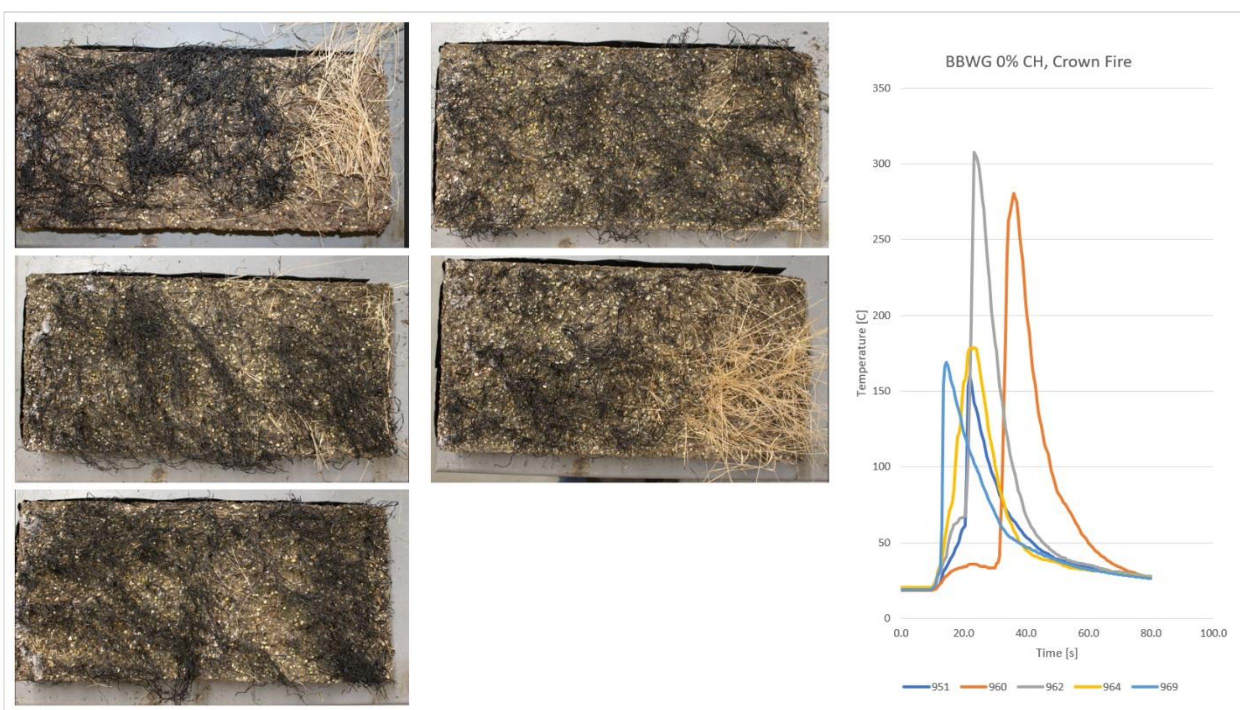


*Figure A. 5. PSSP after burning, natural fuel load (0%CH).*

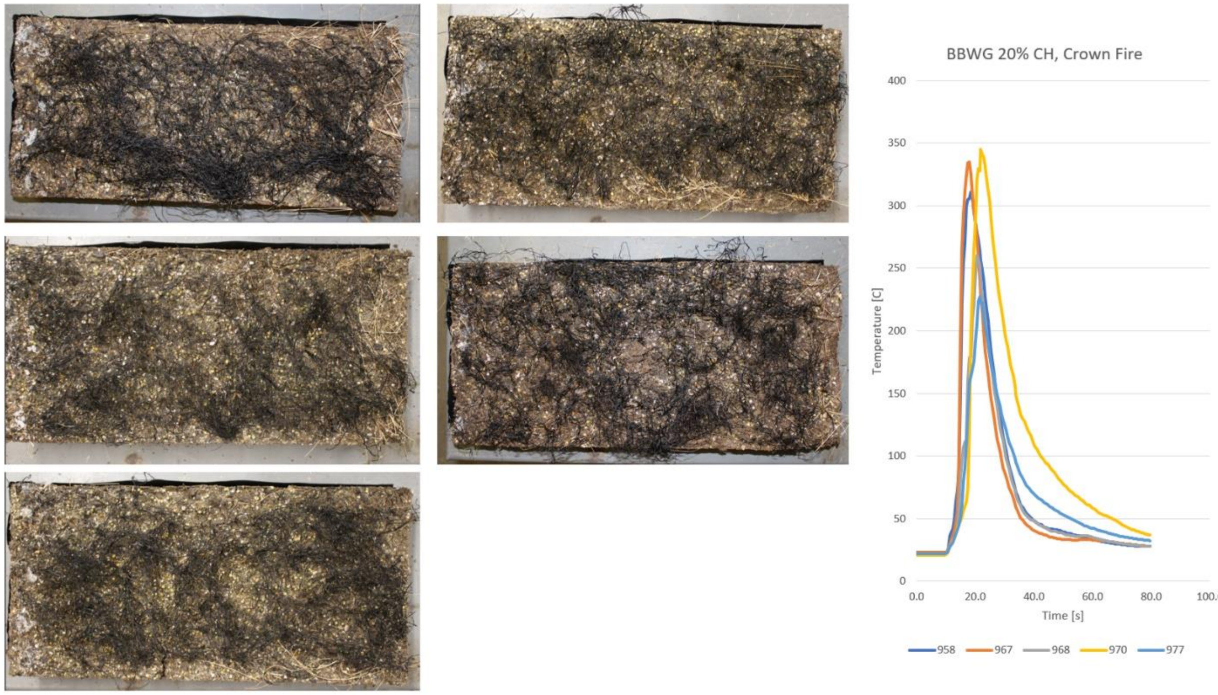


*Figure A. 6. PSSP with 20%CH after burning.*

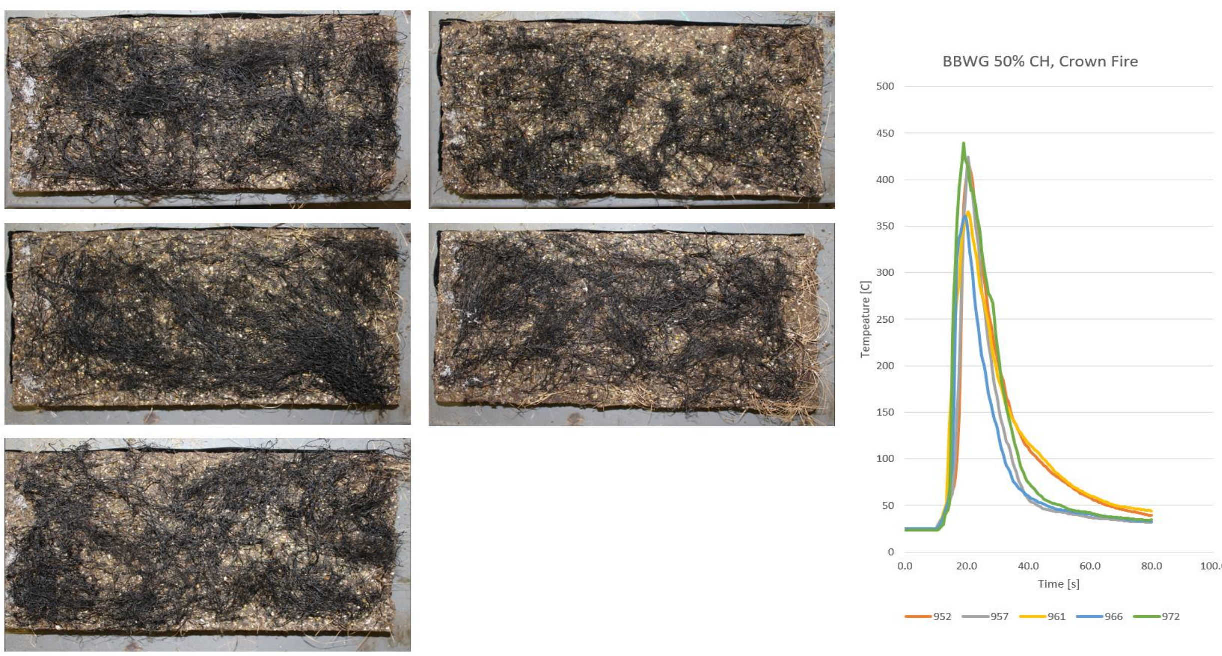


*Figure A. 7. PSSP with 50%CH after burning.*

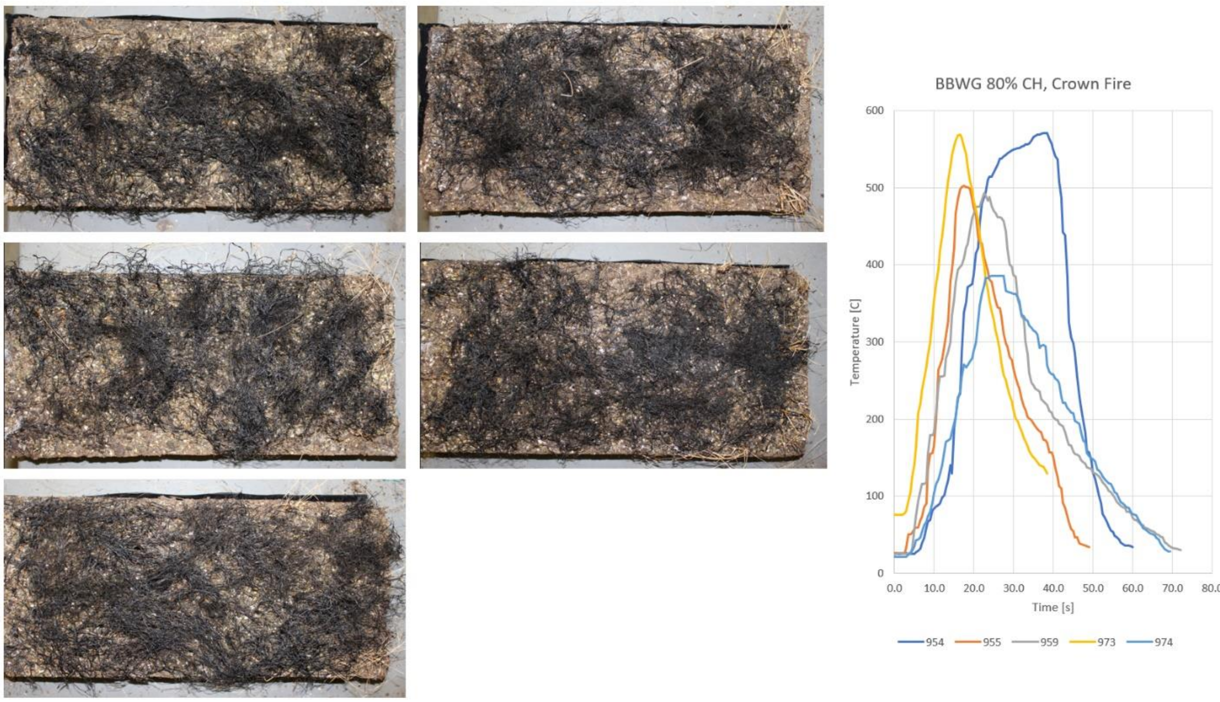


*Figure A. 8. PSSP with 80%CH after burning.*

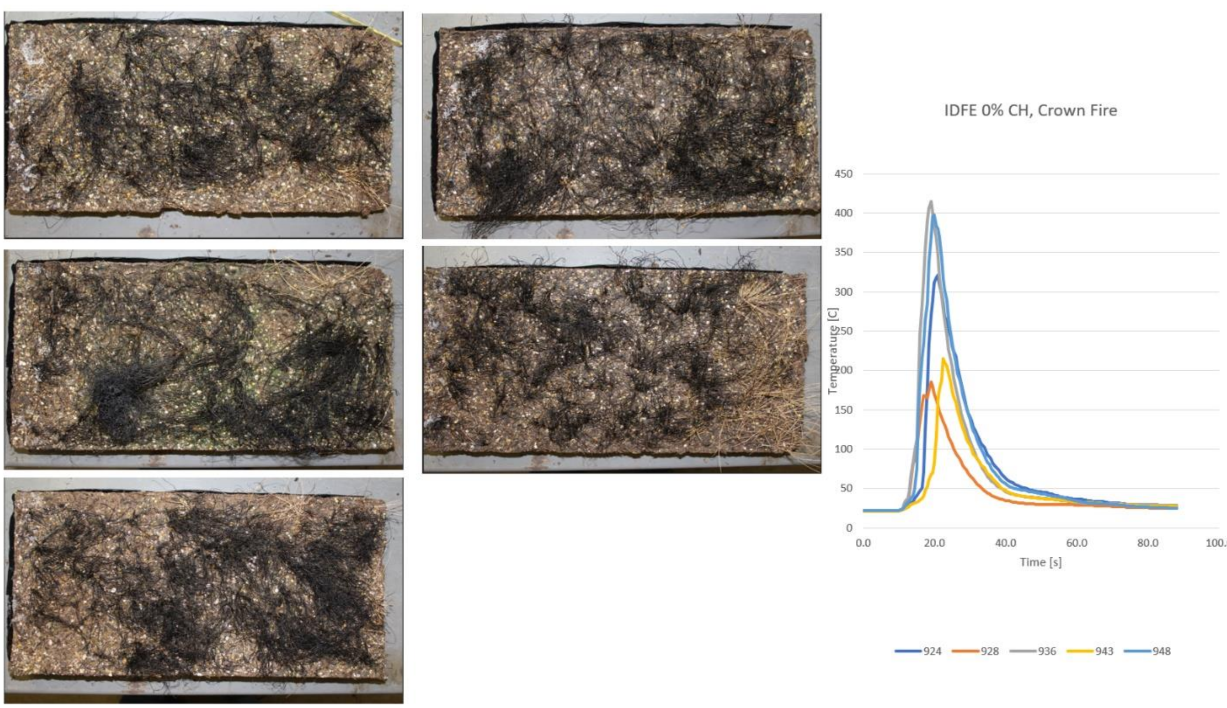


*Figure A. 9. FEID after burning, natural fuel load (0%CH).*

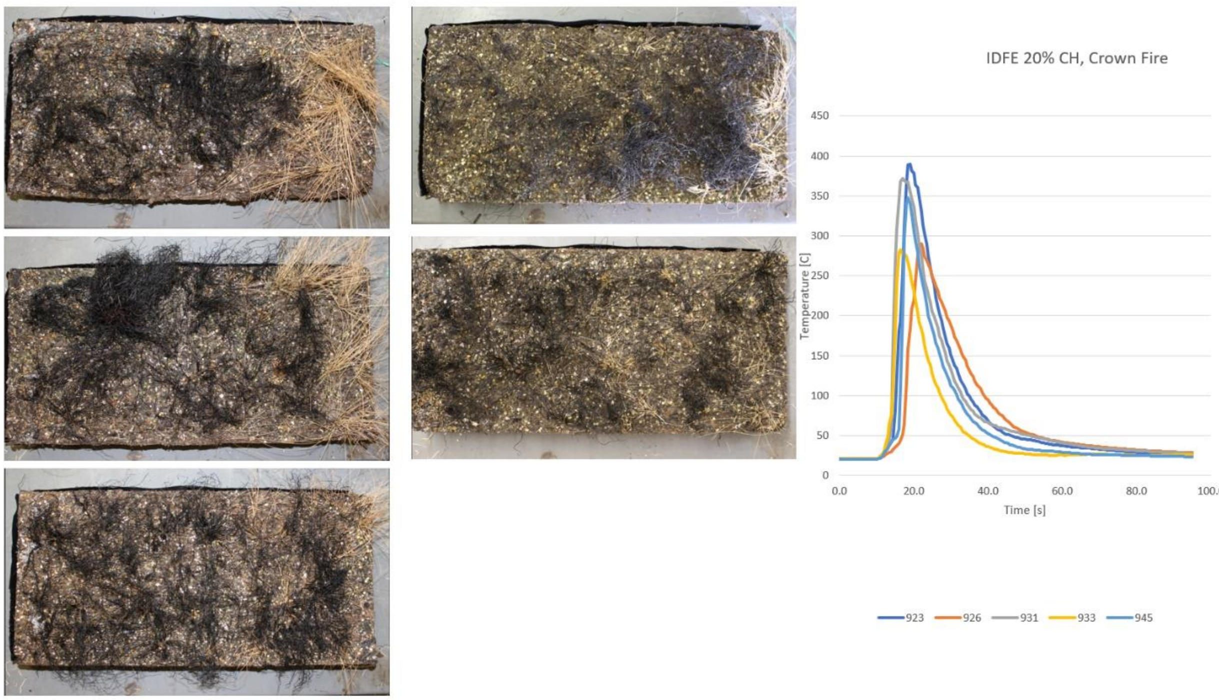


*Figure A. 10. FEID 20%CH after burning.*

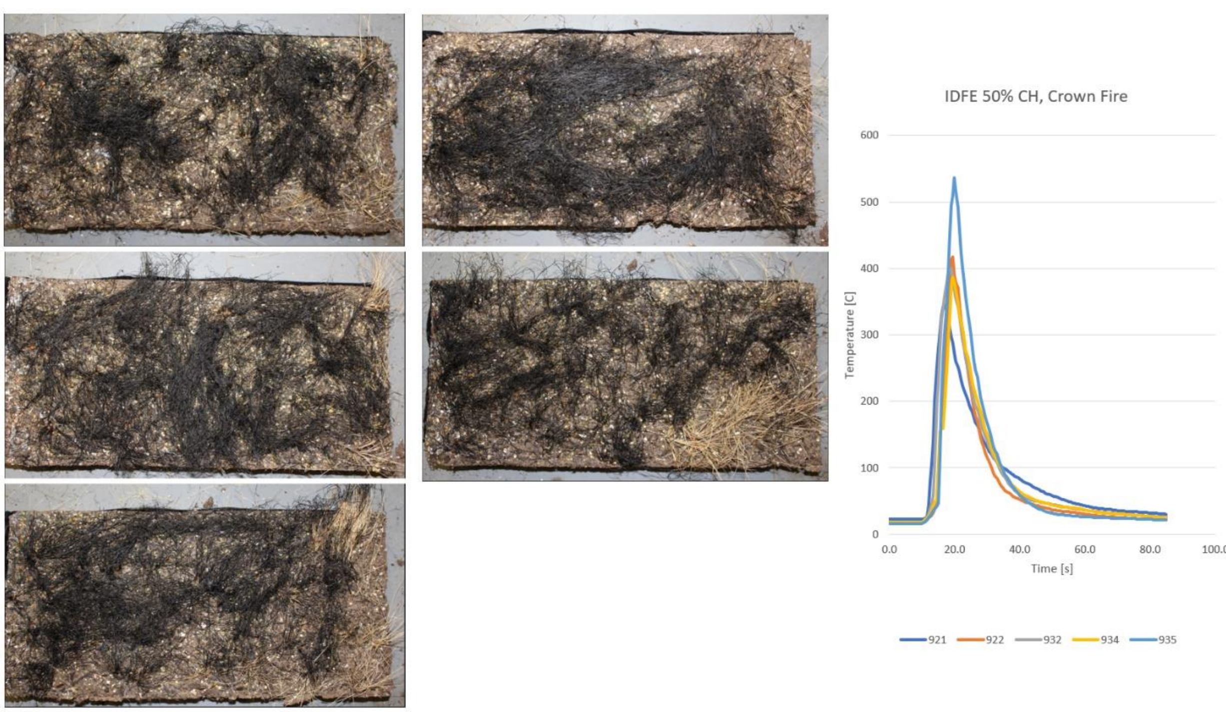


*Figure A. 11. FEID 50%CH after burning.*

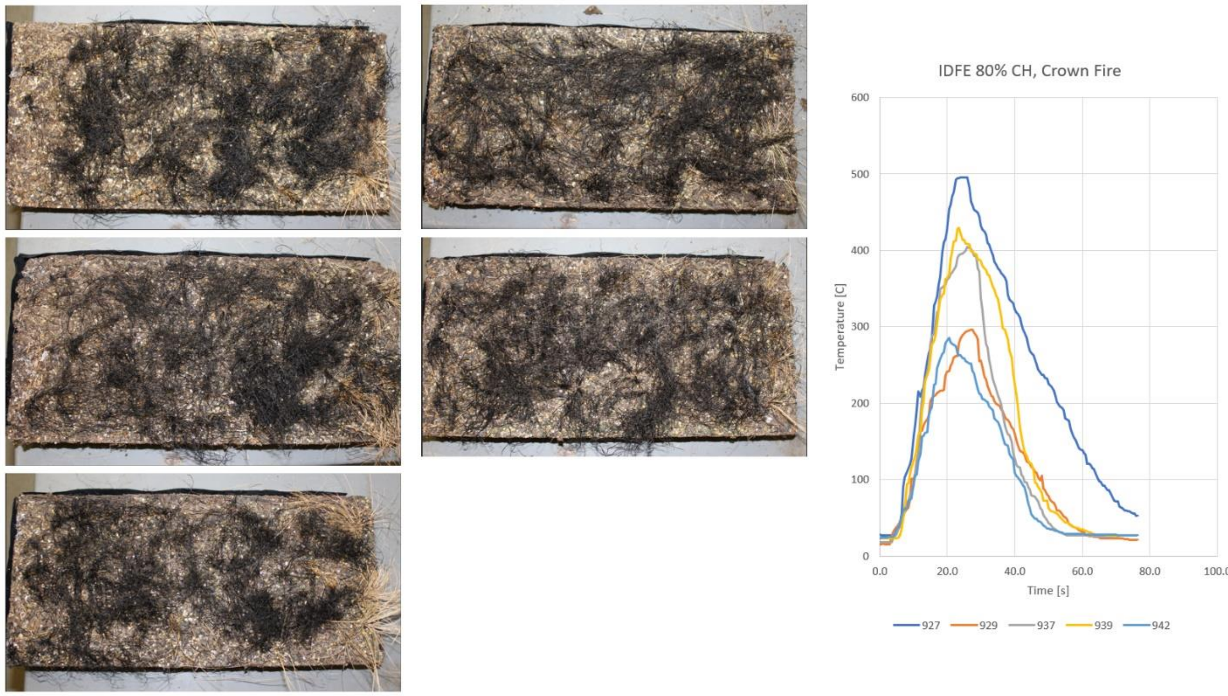


*Figure A. 12. FEID 80%CH after burning.*