An experimental method for testing effects of fine fuel structure on fire intensity

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Keywords: fine fuels, fire heterogeneity, fire intensity, fuel load, fuel structure, fire behavior

INTRODUCTION

Fine surface fuels play a major role in the ignition, spread, and intensity of fires. Fire behavior from ~1-m^2 to landscape (hectares) scales is driven by weather conditions and fuel characteristics, including fuel load, structure, moisture, and continuity. Understanding how fuel characteristics influence fire intensity, severity, and behavior is imperative for fire ecologists, modelers, and land managers where fire is an integral part of the landscape. However, specific information is know about relatively few species, and while valuable, this information is often obtained by studies conducted across a spectrum of realism. Methods range from *in situ* approaches where measurements are made before, during, and after prescribed fires (high realism, low replication), to laboratory bench approaches where small amounts of fuel are combusted in highly controlled settings (low realism, highly replicable) EXPAND ON GAPS & REALISM/REPLICATION TRADEOFF (Fernandes and Cruz (2012)).

Fire ecology experiments in the field often only manipulate the fuel load or type, necessarily sacrificing some realism in fuel structure. Fuels are often piled horizontally even though fuel complexes are typically more heterogeneous with subtantial vertical structure that affects fire behavior (Loudermilk et al. (2014)). For example, in a grass-savanna landscape Bowman et al. (2017) piled fuels horizontally for a field experiment examining how fine fuel loads of different types affected fire intensity and survival of tree saplings. They found that sapling mortality increased with fire intensity (maximum temperature at 5 cm). Fire intensity increased with fuel load, and grass-only and grass-litter fuel complexes produced greater fire intensities than litter-only fuels. Similarly, Thaxton and Platt (2006) altered fuel loads in a longleaf pine system to examine groundcover shrub survival. They added fixed amounts of fuel by piling either longleaf pine needles or pieces of pine wood, or removing a fixed amount of fine fuels from plots. The fuel addition treatments resulted in greater fire temperatures and shrub mortality compared to the removal and control treatments.

Each of these studies provide useful information that is applicable to the conditions of their study area and for the scale of the question, however, they also necessarily sacrifice some realism in fuel structure.

JAUREGUIBERRY et al. (2011), Simpson et al. (2016), Wyse et al. (2016)

In this paper we present an experimental apparatus that can bridge the gap between making measurements of flammability at the lab bench and the limited replication of prescribed fires. The Fine Aboveground Biomass Incineration Organizer (FABIO) enables experimental manipulation of fuel load and structure at a realtively small but realistic and relevant scale of 1-m^2. We expect our design will be most useful for grasses or grass-like fuels, but it could be used or adapted for other fuel types such as small shrubs and trees.

Fuel load has been shown to be a particularly important driver of combustibility, sustainability, and rate of spread.

Temperature metrics are influenced by fuel structure. In general, fuels with greater vertical arrangement will achieve higher maximum temperatures, but will also burn faster. Faster burning should result in less exposure to temperatures that cause plant tissue damage. We show these differences in maximum temperature and time above 100 ºC for standing and piled fuels.

Also, density, dead:live ratio - the more flammable dead fuels can disproportionately influence fire behavior.

Grasses in particular fuel lots of fires, fuel loads are often increased in landscapes invaded by non-native grasses.

We present a methodology for maintaining realism in fuel structure in experiments where fine fuels with typical vertical structure, e.g. grasses, are manipulated.

Using the exotic invasive cogongrass we illustrate how changing the fuel structure can substantially alter flammability characteristics.

It can be deployed in the field or in a more controlled “laboratory” setting.

METHODS

Study site

We harvested ~50 kg of standing cogongrass from an invasion at the Biven’s Arm Research Station (BARS), Florida, USA. The fuel was stored in a shed for 48-hours to protect it from rainfall, and then spread outside in a cleared area to dry for ~72 hours. We raked through the pile each day to increase drying, while carefully maintaining stem orientation in the same direction. We found that consistent stem orientation was more efficient for weighing and loading fuels vertically into the FABIO.

1. Study Species
    a. Collection of materials
    b. Drying to a “constant” fuel moisture
2. Burning Location
    a. BARS
    b. Weather measurements
        i. Kestrel data
3. Experimental treatments
    a. Piled vs Standing

b. Number of burns

    i. Blocked by day

4. Flammability measurements

    a. All fires were ignited with a drip torch (Brand XX style XX)

        i. All were lighted as head fires
        ii. If failed to burn, was attempted 3 times from 3 sides before deemed a failure.

    b. Fire temperature was measured every second with XX type thermocouples

        i. Locations of sensors
        ii. Determined maximum temperature
        iii. Determined time above 100C

    c. Rate of spread

        i. 50cm distance and stop watch

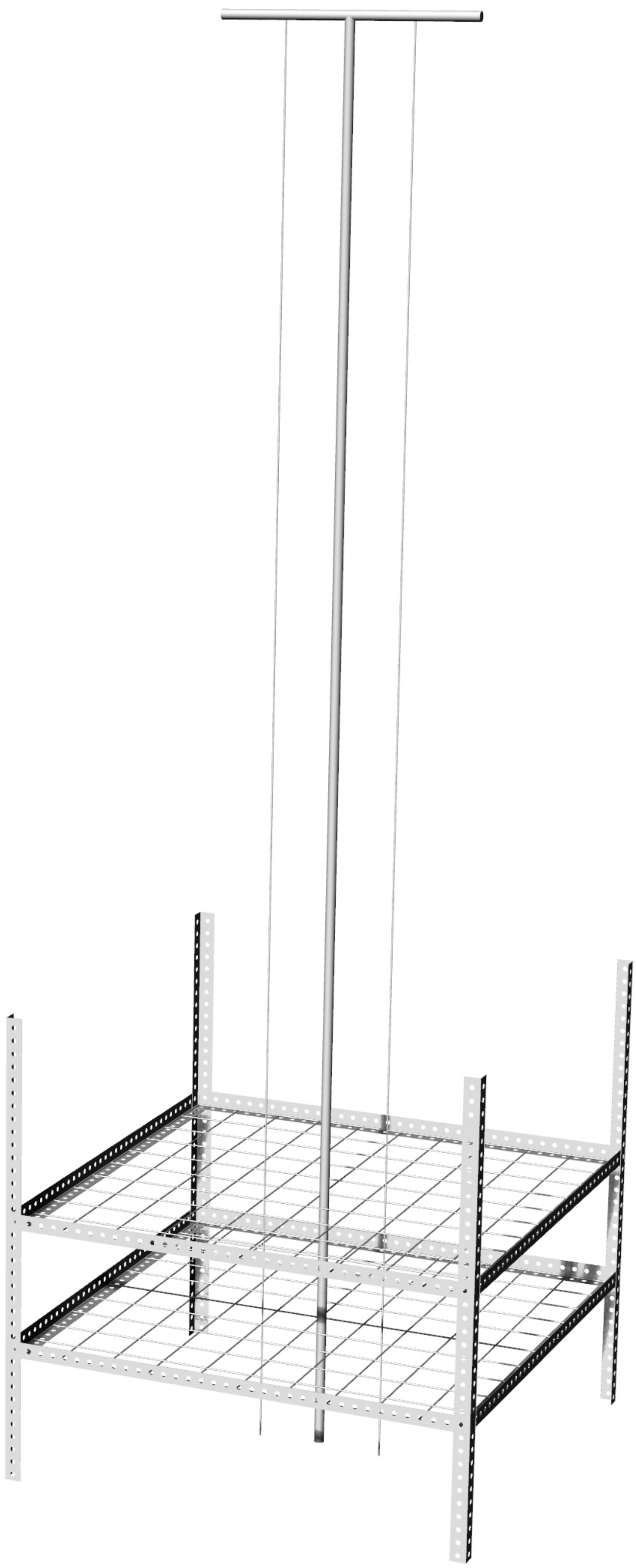
    d. Flame height

        i. String soaked in Foscheck

    e. Remaining biomass was collected to determine percent consumed

5. Statistical Analysis

Fine Aboveground Biomass Incineration Organizer (FABIO)



Data collection and analysis

Our experimental design was to conduct six burns, three piled and three standing, for each of five fuel loads (250 g, 500 g, 1000 g, 1500 g, 2000 g) spanning the range of cogongrass biomass observed from field measurements across Florida, USA.

Thermocouple sensor specs Thermocouple logger specs

Weather data was recorded at a two second interval during fires using a Kestrel 5500 Fire Weather Pro pocket weather tracker (Nielsen-Kellerman, Boothwyn, PA) mounted on a tripod to be ~1 m above the ground.

We used linear regression to model the average maximum temperature and time above 100 ºC at each probe height, and the average flame height, rate of spread, and percent consumed from each fire. Fuel load (mass) and fuel structure (piled vs. standing) were used as explanatory variables, with fuel load treated as continuous. We tested the main effects and interaction of these variables. If the interaction did not have a strong effect we fit a new model with only main effects. We report results from models that

We applied a linear model where

$$y_i = \alpha + \beta_1 * biomass_i + \beta_2 * biomass_i * structure_i$$

```
      date               fire_id         fabio_id      biomass
 Min.   :2017-12-01   Min.   :43.00   Min.   :1.0   Min.   : 250
 1st Qu.:2017-12-03   1st Qu.:50.75   1st Qu.:1.0   1st Qu.: 500
 Median :2017-12-04   Median :58.50   Median :1.5   Median :1000
 Mean   :2017-12-03   Mean   :58.50   Mean   :1.5   Mean   :1047
 3rd Qu.:2017-12-05   3rd Qu.:66.25   3rd Qu.:2.0   3rd Qu.:1500
 Max.   :2017-12-05   Max.   :74.00   Max.   :2.0   Max.   :2000

 litter_biomass   pct_green   biomass_type        structure
```

```
 Min.   :0      Min.   : NA   Length:32          Length:32
 1st Qu.:0      1st Qu.: NA   Class :character   Class :character
 Median :0      Median : NA   Mode  :character   Mode  :character
 Mean   :0      Mean   :NaN
 3rd Qu.:0      3rd Qu.: NA
 Max.   :0      Max.   : NA
                NA's   :32
 rate_of_spread_50cm f_litter_biomass    f_biomass         total_biomass
 Min.   : 0.000      Length:32          Length:32          Min.   : 250
 1st Qu.: 6.287      Class :character   Class :character   1st Qu.: 500
 Median :22.110      Mode  :character   Mode  :character   Median :1000
 Mean   :30.946                                            Mean   :1047
 3rd Qu.:48.797                                            3rd Qu.:1500
 Max.   :95.660                                            Max.   :2000

  pct_consumed    est_pct_fuel_moisture pct_fuel_moisture  max_flame_ht
 Min.   : 22.84   Min.   : 0.000        Min.   : 4.634    Min.   :  0.0
 1st Qu.: 96.90   1st Qu.: 7.171        1st Qu.: 9.453    1st Qu.: 54.5
 Median : 99.11   Median : 9.457        Median :10.947    Median : 75.5
 Mean   : 90.38   Mean   : 9.693        Mean   :11.494    Mean   :102.6
 3rd Qu.: 99.58   3rd Qu.:13.310        3rd Qu.:13.978    3rd Qu.:170.0
 Max.   :100.00   Max.   :18.399        Max.   :19.576    Max.   :256.0
                  NA's   :3
  avg_flame_ht     max_fuel_ht     avg_litter_depth  avg_green_ht
 Min.   :  0.00   Min.   :  7.00   Min.   :0        Min.   :  4.667
 1st Qu.: 38.12   1st Qu.: 15.75   1st Qu.:0        1st Qu.: 14.083
 Median : 64.00   Median : 82.00   Median :0        Median : 76.333
 Mean   : 87.31   Mean   : 84.22   Mean   :0        Mean   : 79.438
 3rd Qu.:138.25   3rd Qu.:151.25   3rd Qu.:0        3rd Qu.:143.833
 Max.   :248.00   Max.   :177.00   Max.   :0        Max.   :164.000
```

```
 avg_brown_ht  avg_fuel_ht
Min.   : NA   Min.   :  4.667
1st Qu.: NA   1st Qu.: 14.083
Median : NA   Median : 76.333
Mean   :NaN   Mean   : 79.438
3rd Qu.: NA   3rd Qu.:143.833
Max.   : NA   Max.   :164.000
NA's   :32
```

```
  location           structure             fire_id         max_temp
Length:96          Length:96          Min.   :43.00   Min.   : 40.26
Class :character   Class :character   1st Qu.:50.75   1st Qu.:244.32
Mode  :character   Mode  :character   Median :58.50   Median :366.70
                                      Mean   :58.50   Mean   :371.79
                                      3rd Qu.:66.25   3rd Qu.:540.18
                                      Max.   :74.00   Max.   :773.88

avg2_max_temp       s_abv100     heat_flux_abv100
Min.   : 40.13   Min.   :  2.0   Min.   :   206.3
1st Qu.:241.09   1st Qu.: 57.5   1st Qu.: 12995.4
Median :357.98   Median : 91.0   Median : 19776.9
Mean   :363.49   Mean   :131.4   Mean   : 32289.4
3rd Qu.:525.23   3rd Qu.:139.0   3rd Qu.: 36001.6
Max.   :749.66   Max.   :824.0   Max.   :295967.4
                 NA's   :13      NA's   :13
```

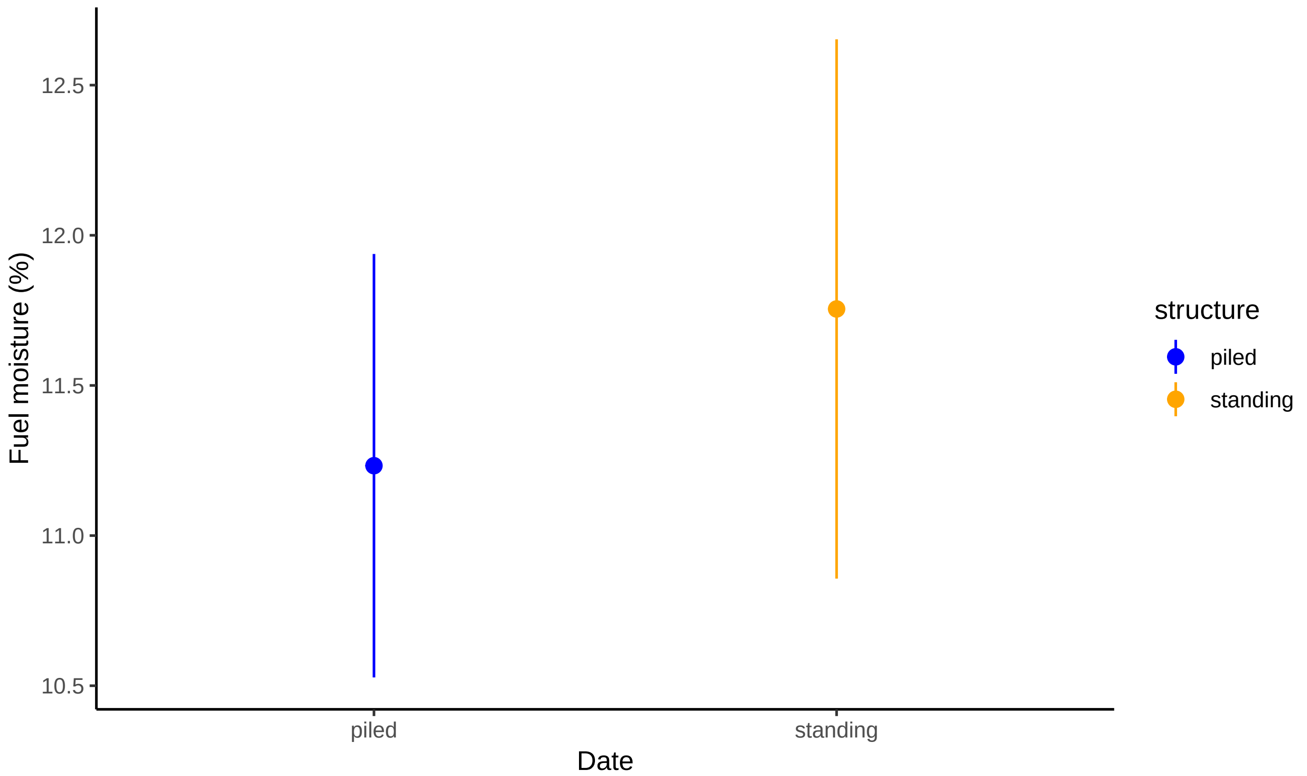
Table 1: Summary of weather for each fire (means ± SE). Fire IDs 54, 56, 70, & 74 were assigned values from their paired fires 53, 55, 69, & 73 due to missing data.

Fire ID	Date	Structure	Biomass	Air temperature (ºC)	RH (%)	Wind Speed (m s^{-1})
43	2017-12-01	piled	250	27.88 ± 0.08	36.8 ± 0.08	0.88 ± 0.08

Fire ID	Date	Structure	Biomass	Air temperature (ºC)	RH (%)	Wind Speed (m s^{-1})
44	2017-12-01	standing	250	28.11 ± 0.09	36.33 ± 0.1	0.84 ± 0.09
45	2017-12-01	piled	500	27.82 ± 0.09	37.51 ± 0.05	0.38 ± 0.09
46	2017-12-01	standing	500	27.82 ± 0.09	37.2 ± 0.06	0.43 ± 0.09
47	2017-12-01	piled	1000	22.81 ± 0.02	64.44 ± 0.06	0 ± 0.02
48	2017-12-01	standing	1000	26.08 ± 0.02	44.83 ± 0.12	0.35 ± 0.02
49	2017-12-01	piled	1500	22.27 ± 0.03	67.71 ± 0.05	0 ± 0.03
50	2017-12-01	standing	1500	22.76 ± 0.02	65.97 ± 0.06	0 ± 0.02
51	2017-12-04	piled	2000	26.69 ± 0.06	55.88 ± 0.13	0.58 ± 0.06
52	2017-12-04	standing	2000	28.21 ± 0.15	54.27 ± 0.23	0.44 ± 0.15
53	2017-12-04	piled	250	25.75 ± 0.04	55.15 ± 0.12	0.02 ± 0.04
54	2017-12-04	standing	250	25.75 ± 0.04	55.15 ± 0.12	0.02 ± 0.04
55	2017-12-04	piled	500	25.26 ± 0.06	57.39 ± 0.14	0.25 ± 0.06
56	2017-12-04	standing	500	25.26 ± 0.06	57.39 ± 0.14	0.25 ± 0.06
57	2017-12-04	piled	1000	24.25 ± 0.04	60.04 ± 0.1	0.37 ± 0.04
58	2017-12-04	standing	1000	23.57 ± 0.01	61.57 ± 0.1	0.77 ± 0.01
59	2017-12-04	piled	1000	25.38 ± 0.04	59.71 ± 0.09	0.1 ± 0.04
60	2017-12-04	standing	1000	25.79 ± 0.04	58.32 ± 0.15	0 ± 0.04
61	2017-12-04	piled	2000	24.3 ± 0.01	63.52 ± 0.15	0 ± 0.01
62	2017-12-04	standing	2000	24.2 ± 0	62.53 ± 0.01	0 ± 0
63	2017-12-05	piled	250	26.91 ± 0.05	60.61 ± 0.08	1.09 ± 0.05
64	2017-12-05	standing	250	27.08 ± 0.09	60.48 ± 0.06	1.1 ± 0.09
65	2017-12-05	piled	500	28.71 ± 0.09	56.63 ± 0.13	0.72 ± 0.09
66	2017-12-05	standing	500	29.28 ± 0.15	55.86 ± 0.2	0.69 ± 0.15
67	2017-12-05	piled	1000	28.22 ± 0.1	55.96 ± 0.21	0.49 ± 0.1
68	2017-12-05	standing	1000	27.72 ± 0.1	56.96 ± 0.14	0.59 ± 0.1
69	2017-12-05	piled	1500	27.11 ± 0.05	59.57 ± 0.08	1.02 ± 0.05
70	2017-12-05	standing	1500	27.11 ± 0.05	59.57 ± 0.08	1.02 ± 0.05
71	2017-12-05	piled	2000	28.47 ± 0.06	52.05 ± 0.11	0.71 ± 0.06

Fire ID	Date	Structure	Biomass	Air temperature (ºC)	RH (%)	Wind Speed (m s^{-1})
72	2017-12-05	standing	2000	28.35 ± 0.17	52.16 ± 0.09	0.43 ± 0.17
73	2017-12-05	piled	1500	30.33 ± 0.01	47.63 ± 0.02	0 ± 0.01
74	2017-12-05	standing	1500	30.33 ± 0.01	47.63 ± 0.02	0 ± 0.01

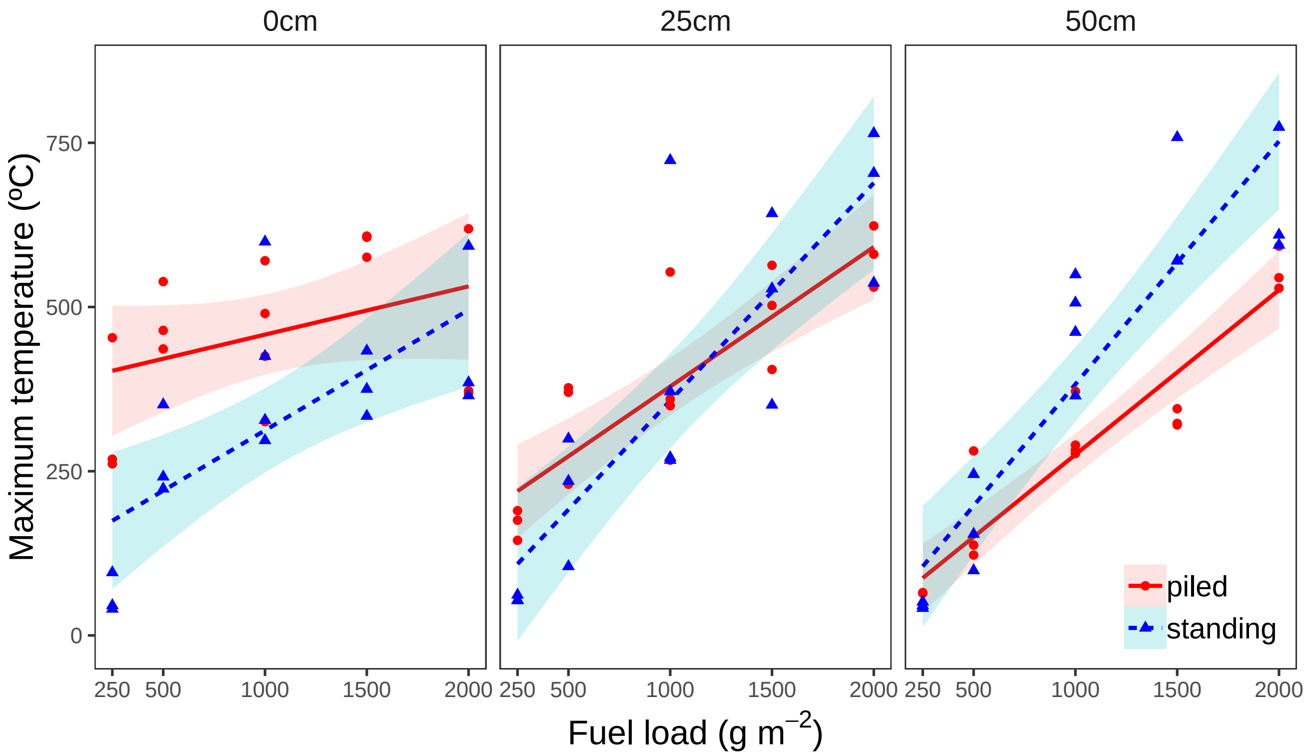
Fuel moisture



Across all fires fuel moisture content ranged from 4.6 to 19.6% (mean = 11.49±0.56%).

Linear models of maximum temperature

The “maximum temperature” at each height is the average of the maximum temperatures from the three temperature probes located at that height. For some of the fires with the lowest amount of biomass (250 g) the probe temperature did not deviate from near-ambient (Fig. 3).




```
Call:
lm(formula = max_temp ~ biomass * structure, data = fabio_fires_0cm)

Residuals:
    Min      1Q  Median      3Q     Max
-163.21 -115.29   15.26   90.02  287.15

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                384.52101   57.12710   6.731 2.62e-07 ***
biomass                      0.07345    0.04695   1.564   0.1290
structurestanding         -255.90652   80.78992  -3.168   0.0037 **
biomass:structurestanding    0.11008    0.06640   1.658   0.1085
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```

Residual standard error: 116.5 on 28 degrees of freedom
Multiple R-squared:  0.5122,	Adjusted R-squared:  0.4599
F-statistic:   9.8 on 3 and 28 DF,  p-value: 0.0001381


Call:
lm(formula = max_temp ~ biomass + structure, data = fabio_fires_0cm)

Residuals:
    Min      1Q  Median      3Q     Max
-215.66  -81.21    4.56   86.92  284.57

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)       326.90139   46.68516   7.002 1.06e-07 ***
biomass             0.12849    0.03419   3.759 0.000767 ***
structurestanding -140.66729   42.39658  -3.318 0.002451 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 119.9 on 29 degrees of freedom
Multiple R-squared:  0.4643,	Adjusted R-squared:  0.4274
F-statistic: 12.57 on 2 and 29 DF,  p-value: 0.0001173
```

Table 2: Max temperature at ground level

	Estimate	Std. Error	t value	Pr(>|t|)	2.5 %	97.5 %
(Intercept)	326.901	46.685	7.002	0.000	231.420	422.383
Biomass	0.128	0.034	3.759	0.001	0.059	0.198
Structure: standing	-140.667	42.397	-3.318	0.002	-227.378	-53.957

```

Call:
lm(formula = max_temp ~ biomass * structure, data = fabio_fires_25cm)

Residuals:
    Min      1Q  Median      3Q     Max 
-172.18  -64.49  -24.20   51.38  365.91 

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)    
(Intercept)                166.52310   54.42279   3.060  0.00484 ** 
biomass                      0.21240    0.04473   4.749 5.51e-05 ***
structurestanding         -140.67599   76.96544  -1.828  0.07826 .  
biomass:structurestanding    0.11911    0.06326   1.883  0.07013 .  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 110.9 on 28 degrees of freedom
Multiple R-squared:  0.735, Adjusted R-squared:  0.7066 
F-statistic: 25.88 on 3 and 28 DF,  p-value: 3.172e-08


Call:
lm(formula = max_temp ~ biomass + structure, data = fabio_fires_25cm)

Residuals:
    Min      1Q  Median      3Q     Max 
-145.20  -94.76  -13.18   56.47  363.11 

Coefficients:
```

```
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)       104.17636   45.04802   2.313    0.028 *
biomass             0.27195    0.03299   8.244 4.33e-09 ***
structurestanding -15.98250   40.90984  -0.391    0.699
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 115.7 on 29 degrees of freedom
Multiple R-squared:  0.7014,    Adjusted R-squared:  0.6808
F-statistic: 34.06 on 2 and 29 DF,  p-value: 2.447e-08
```

Table 3: Max temperature at 25cm

	Estimate	Std. Error	t value	Pr(>|t|)	2.5 %	97.5 %
(Intercept)	104.176	45.048	2.313	0.028	12.043	196.310
Biomass	0.272	0.033	8.244	0.000	0.204	0.339
Structure: standing	-15.982	40.910	-0.391	0.699	-99.653	67.688

```

Call:
lm(formula = max_temp ~ biomass * structure, data = fabio_fires_50cm)

Residuals:
     Min       1Q   Median       3Q      Max
-157.851  -54.343   -5.386   28.149  190.955

Coefficients:
                           Estimate Std. Error t value Pr(>|t|)
(Intercept)                24.65978   42.18178   0.585   0.5635
biomass                     0.25062    0.03467   7.229  7.2e-08 ***
structurestanding         -12.08180   59.65404  -0.203   0.8410
```

```
biomass:structurestanding   0.11922    0.04903   2.432   0.0217 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 85.99 on 28 degrees of freedom
Multiple R-squared:  0.8653,    Adjusted R-squared:  0.8508
F-statistic: 59.94 on 3 and 28 DF,  p-value: 2.631e-12
```

Table 4: Max temperature at 50cm

	Estimate	Std. Error	t value	Pr(>|t|)	2.5 %	97.5 %
(Intercept)	24.660	42.182	0.585	0.563	-61.746	111.065
Biomass	0.251	0.035	7.229	0.000	0.180	0.322
Structure: standing	-12.082	59.654	-0.203	0.841	-134.278	110.114
Biomass*Standing	0.119	0.049	2.432	0.022	0.019	0.220

Time above 100 ºC figure

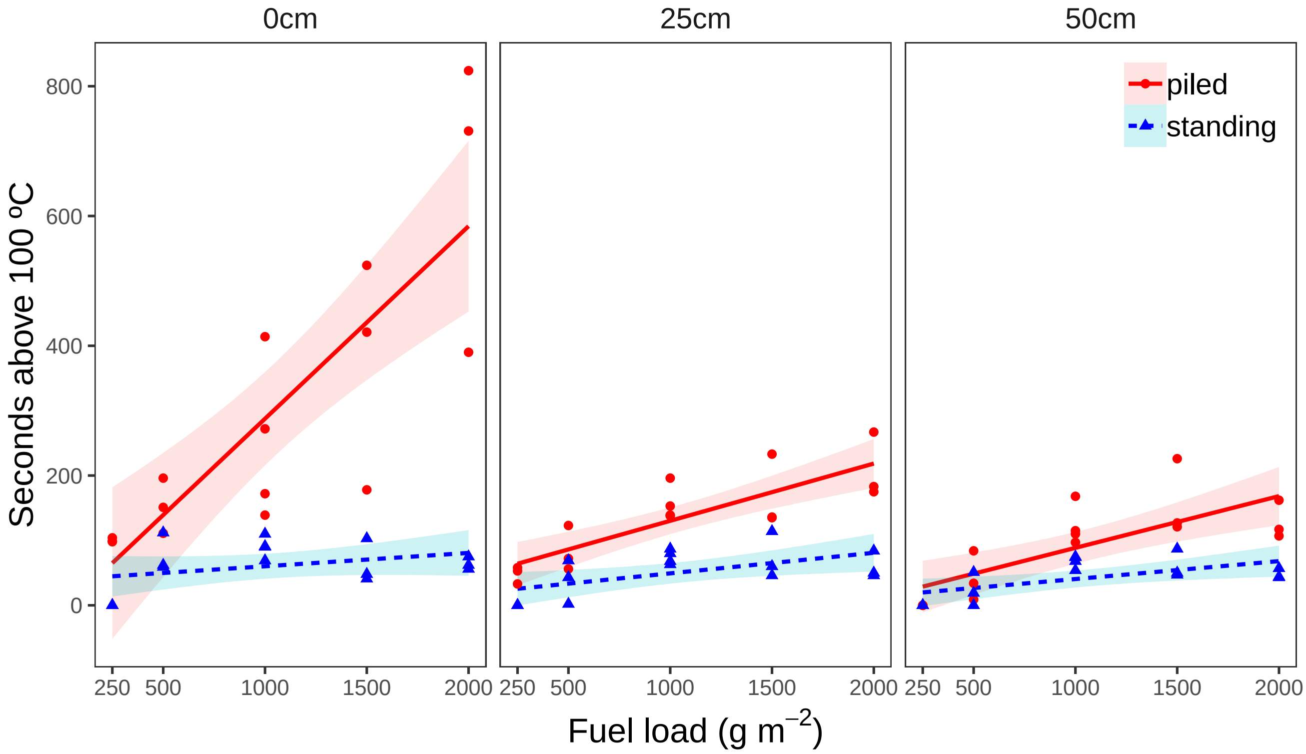


Table 5: Time above 100 ºC (seconds) at ground level

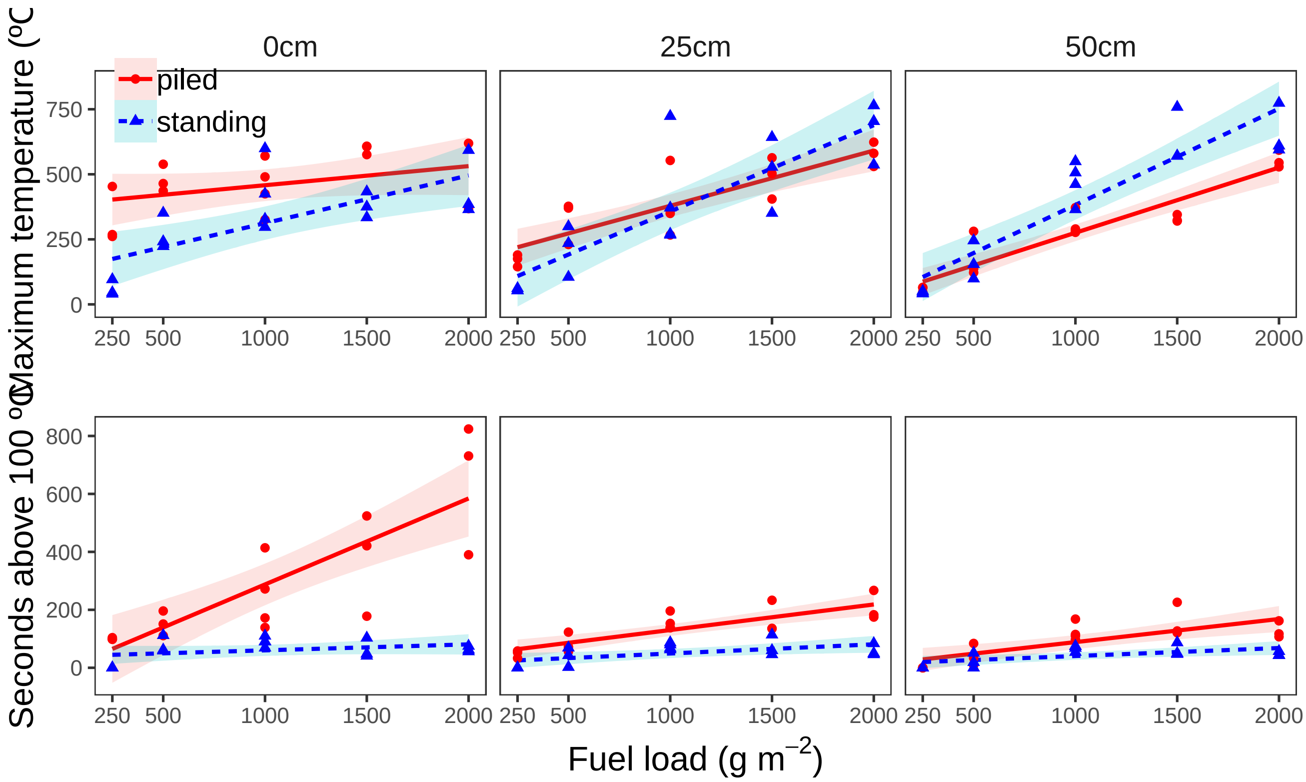
	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	135.401	51.289	2.640	0.013
Biomass	0.159	0.038	4.225	0.000
Strcture: standing	-240.375	46.578	-5.161	0.000

Table 6: Time above 100 ºC (seconds) at 25cm

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	71.616	14.910	4.803	0
Biomass	0.060	0.011	5.491	0
Strcture: standing	-83.625	13.541	-6.176	0

Table 7: Time above 100 ºC (seconds) at 50cm

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	36.168	15.452	2.341	0.026
Biomass	0.054	0.011	4.740	0.000
Strcture: standing	-50.500	14.033	-3.599	0.001



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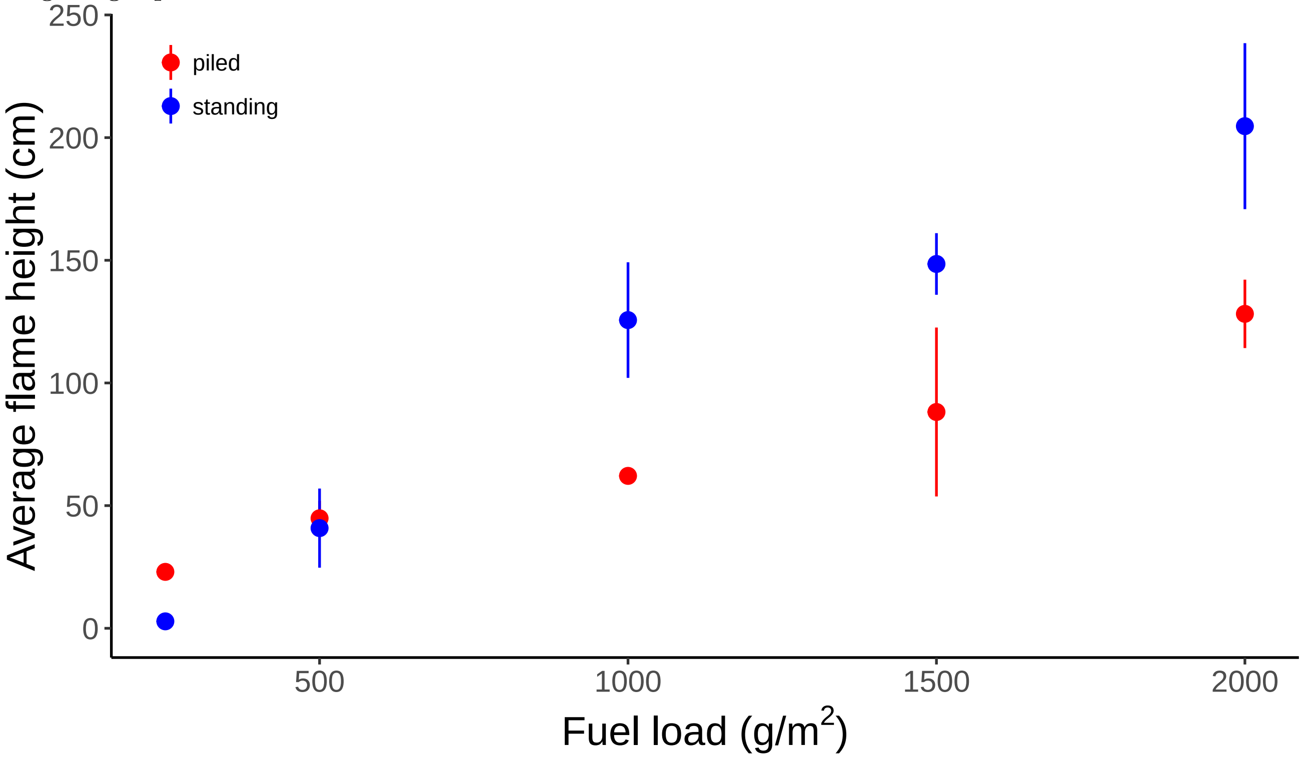
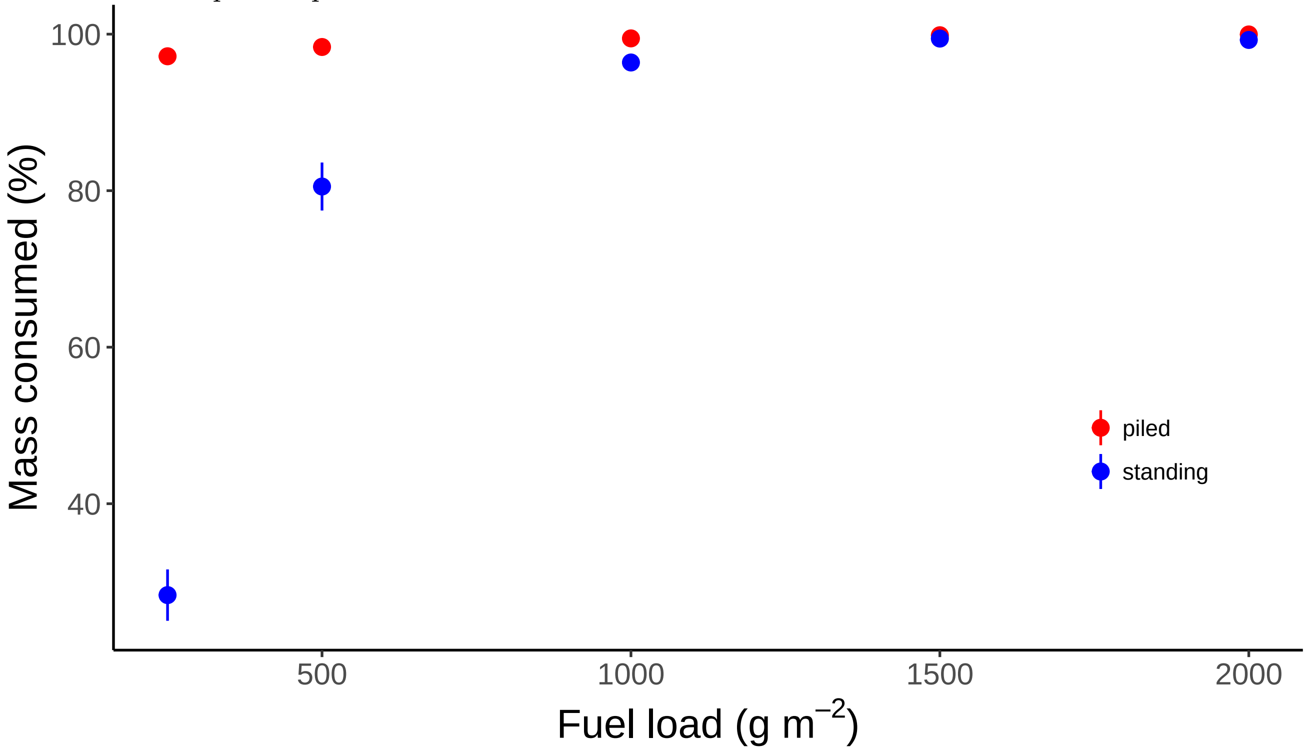
Flame height figure

height fig-1.pdf



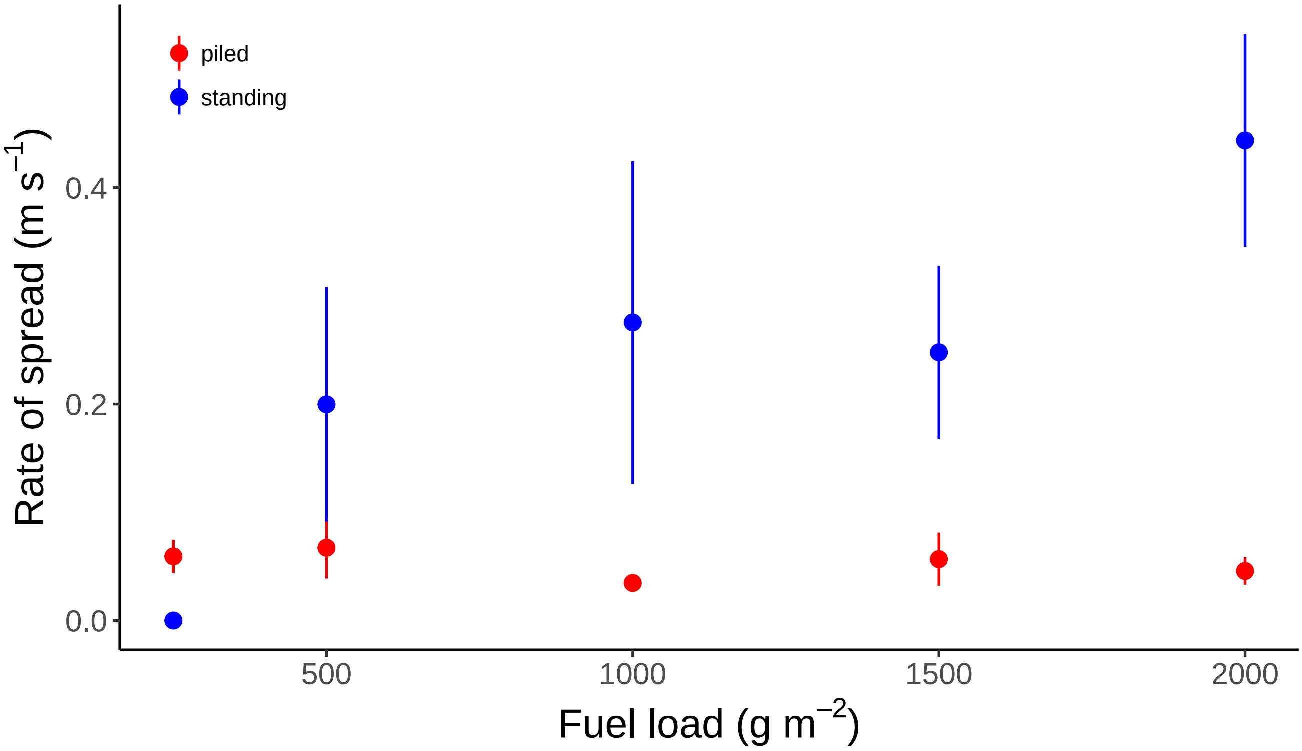
Biomass consumed figure

biomass consumption-1.pdf



Rate of spread figure

Rate of spread was measured by recording the number of seconds it took the fire-line to travel 50 cm and then converted to units of m s^{-1}.



We used the statistical language `R` (R Core Team 2018) for all our analyses. These were implemented in dynamic rmarkdown documents using `knitr` (Xie 2014, 2015, 2018) and `rmarkdown` (Allaire et al. 2018) packages. All the multilevel models were fitted with `lme4` (Bates et al. 2015).

RESULTS

Trees in forest A grew taller than those in forest B (mean height: 25 versus 13 m). And many more cool results that get updated dynamically.

DISCUSSION

Discuss.

CONCLUSIONS

ACKNOWLEDGEMENTS

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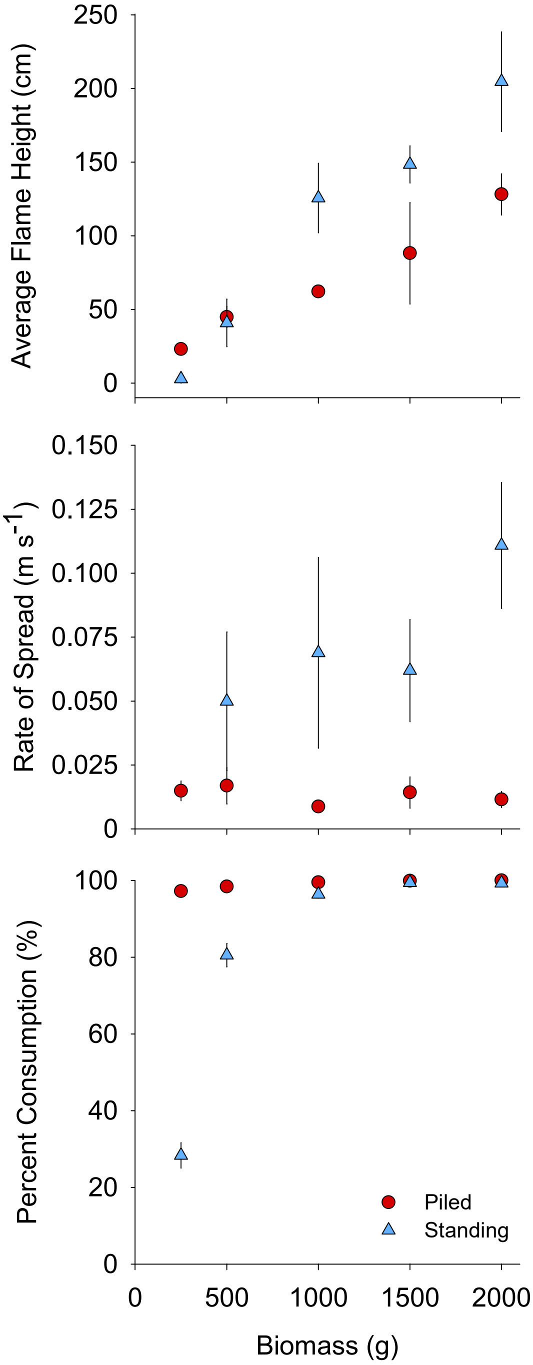
List of Tables

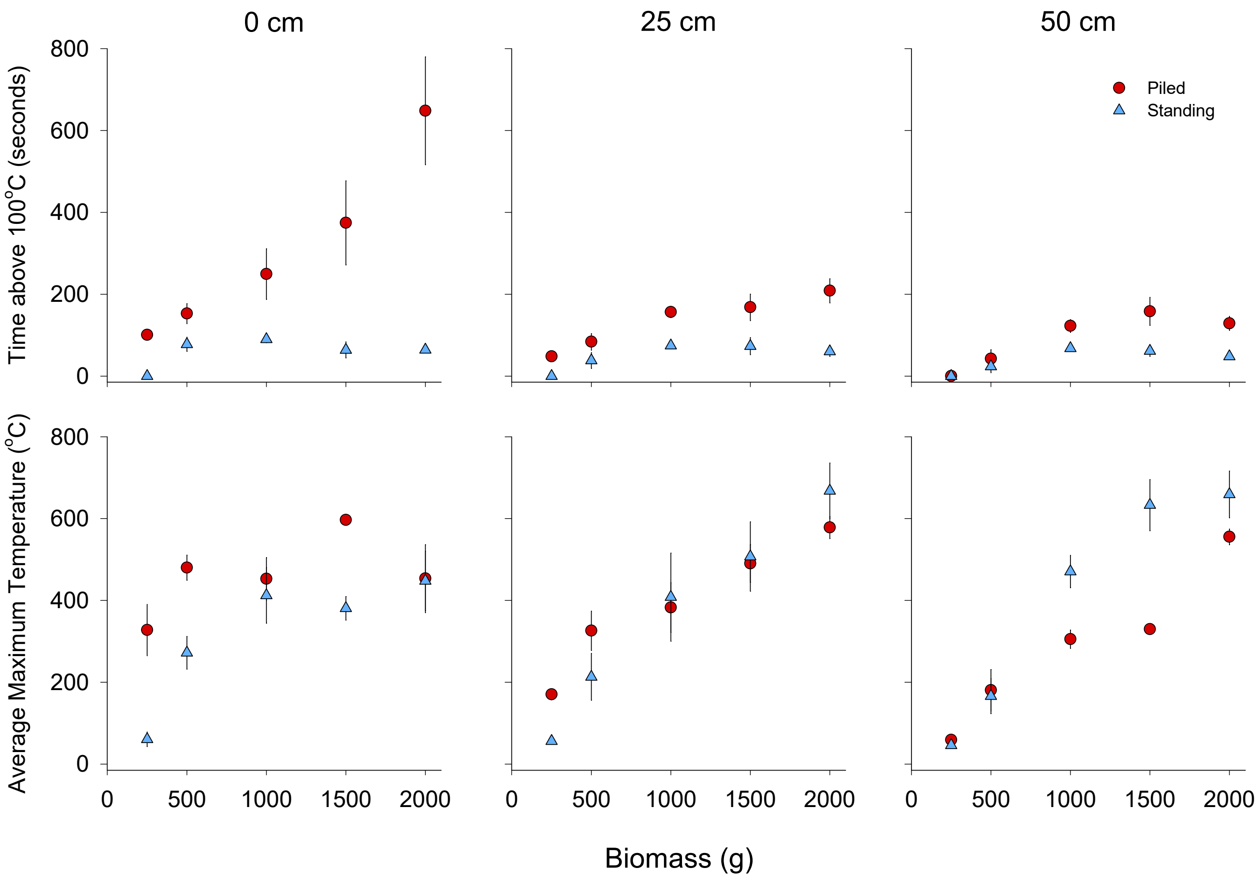
Table 8: A glimpse of the famous *Iris* dataset.

Sepal.Length	Sepal.Width	Petal.Length	Petal.Width	Species
5.1	3.5	1.4	0.2	setosa
4.9	3.0	1.4	0.2	setosa
4.7	3.2	1.3	0.2	setosa
4.6	3.1	1.5	0.2	setosa
5.0	3.6	1.4	0.2	setosa
5.4	3.9	1.7	0.4	setosa

List of Figures


Average Flame Height (cm)
250
200
150
100
50
0
Rate of Spread (m s-1)
0.150
0.125
0.100
0.075
0.050
0.025
0
Percent Consumption (%)
100
80
60
40
20
0
Piled
Standing
0
500
1000
1500
2000
Biomass (g)

341



0 cm
25 cm
50 cm
Piled
Standing
Time above 100°C (seconds)
Average Maximum Temperature (°C)
0
200
400
600
800
0
500
1000
1500
2000
Biomass (g)

342

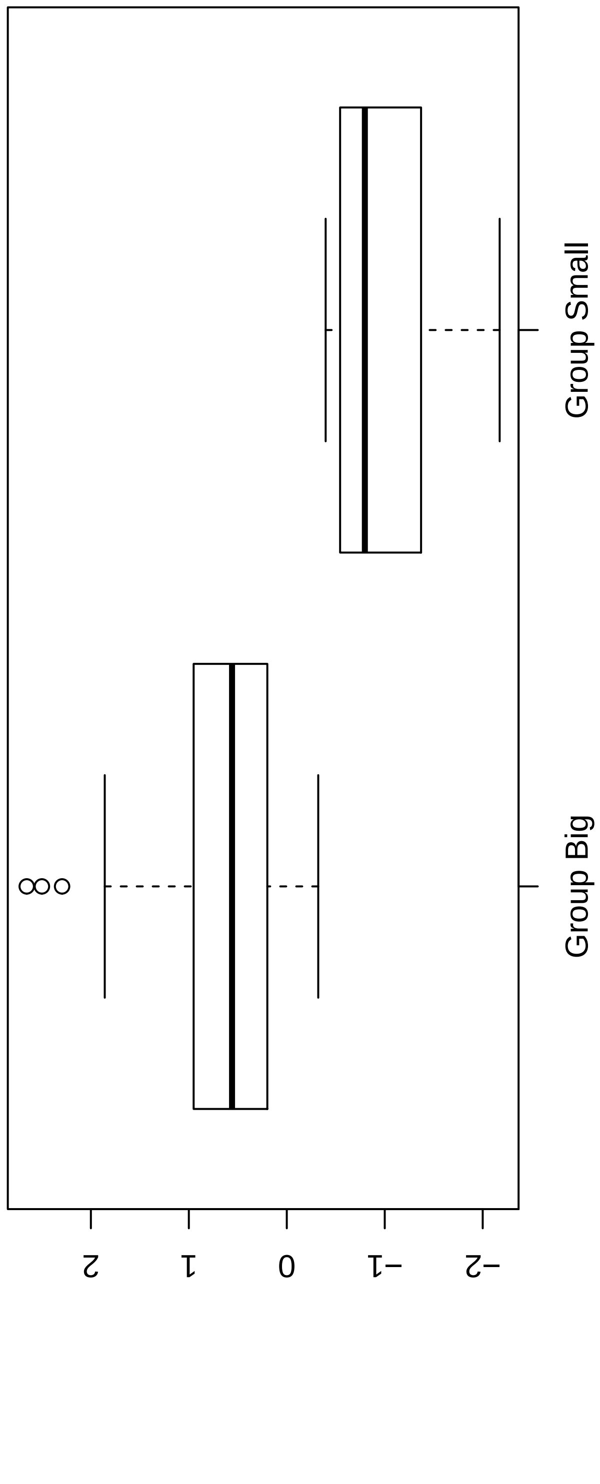


Figure 1: Second figure in landscape format.

Key experimental fire ecology studies for reference

(Bowman et al. 2017) *Differential demographic filtering by surface fires: How fuel type and fuel load affect sapling mortality of an obligate seeder savanna tree.*

In this study, “Grass fuels had to be laid horizontally rather than standing vertically.” The context provided is that the native sorghum grass flattens easily after it dries and does not remain vertical throughout the dry season.

- This reads like a response to a reviewer comment, which might indicate a gap that the FABIO methodology can fill.
- Average flame height was measured “when the fire was within 15cm of the tree stem using a metal grid placed verically against a steel picket placed next to the stem.”

Additional references given where fuels have been laid flat when testing flammability:

- **(???)**
  - Built the “Bar-B-Q”" apparatus to fill a need to quantify flammability of whole plants of many species
  - Quantified flammability characteristics of 34 species using “whole plant”
  - Fuels are still burnt horizontally, so no vertical structure
  - Length of fuel limited by size of burning surface
- **(Simpson et al. 2016)**
  - Assessed flammability of 25 savanna grass species
  - five plant traits: biomass quantity, biomass density, biomass moisture content, leaf surface-area:volume ratio, leaf effective heat combustion
  - related plant traits to three components of flammability: ignitability, sustainability, com-

bustibility at leaf and plant scales

  - Results: total above-ground biomass drove combustibility and sustainability - high biomass was more intense for longer; moisture content was main driver of ignitability and also reduced combustion rate; estimates of whole-plant combustion rates showed $>$20-fold variation; Showed that there was significant variation between species in flammability at the plant-level and leaf-level

- **(Wyse et al. 2016)**

All of these studies assessed flammability of multiple species, or multiple fuel complexes.