Controls on Black Carbon Production and Loss in Masticated Fuels: An Experimental Approach

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Outline

- Forests, Fire, and Carbon Storage
- Experiment #1: Fuel Moisture and Black Carbon
  - Methods
  - Results and Discussion
- Experiment #2: Repeated Burning
  - Methods
  - Results and Discussion
- Conclusions

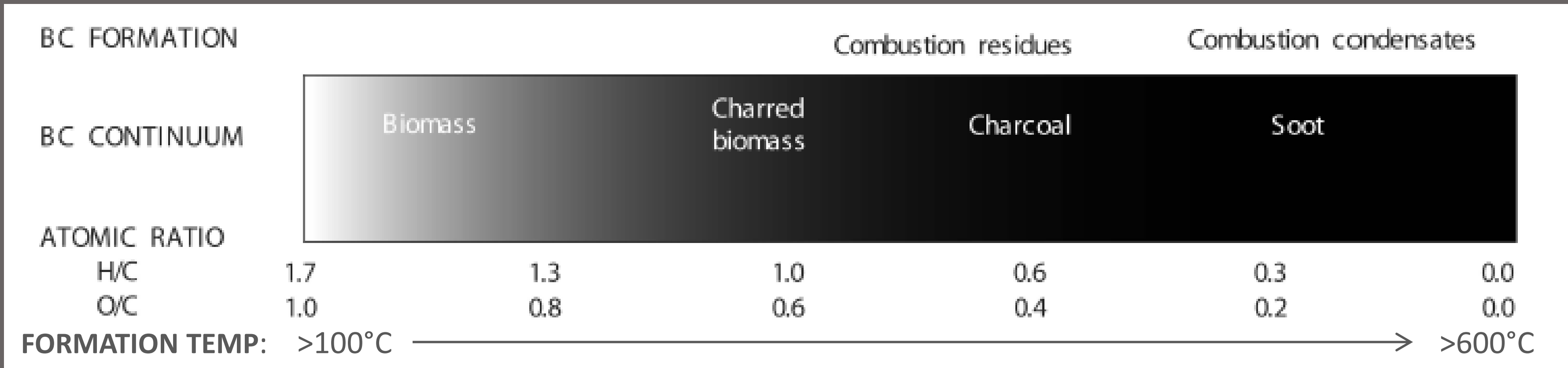
Forests, Fire, and Carbon Storage

- Fire-affected forests, carbon sinks?
- Fire frequency is expected to increase with climate change.
- Forest management in fire-affected ecosystems and its role in carbon sequestration.

Forests, Fire, and Carbon Storage

- Results have been mixed regarding the role of fuels reduction and carbon storage.
- The take-home: Carbon storage is an "ancillary benefit" to proper ecology-based forest management.
- Mastication and its application
- Above-ground carbon, but what about black carbon?

Black Carbon: A Conceptual Model



To date, most black carbon studies have been limited to either strictly controlled laboratory combustion or observational soil studies.

Figure adapted from Preston and Schmidt 2006

Black Carbon and Forest Carbon Storage

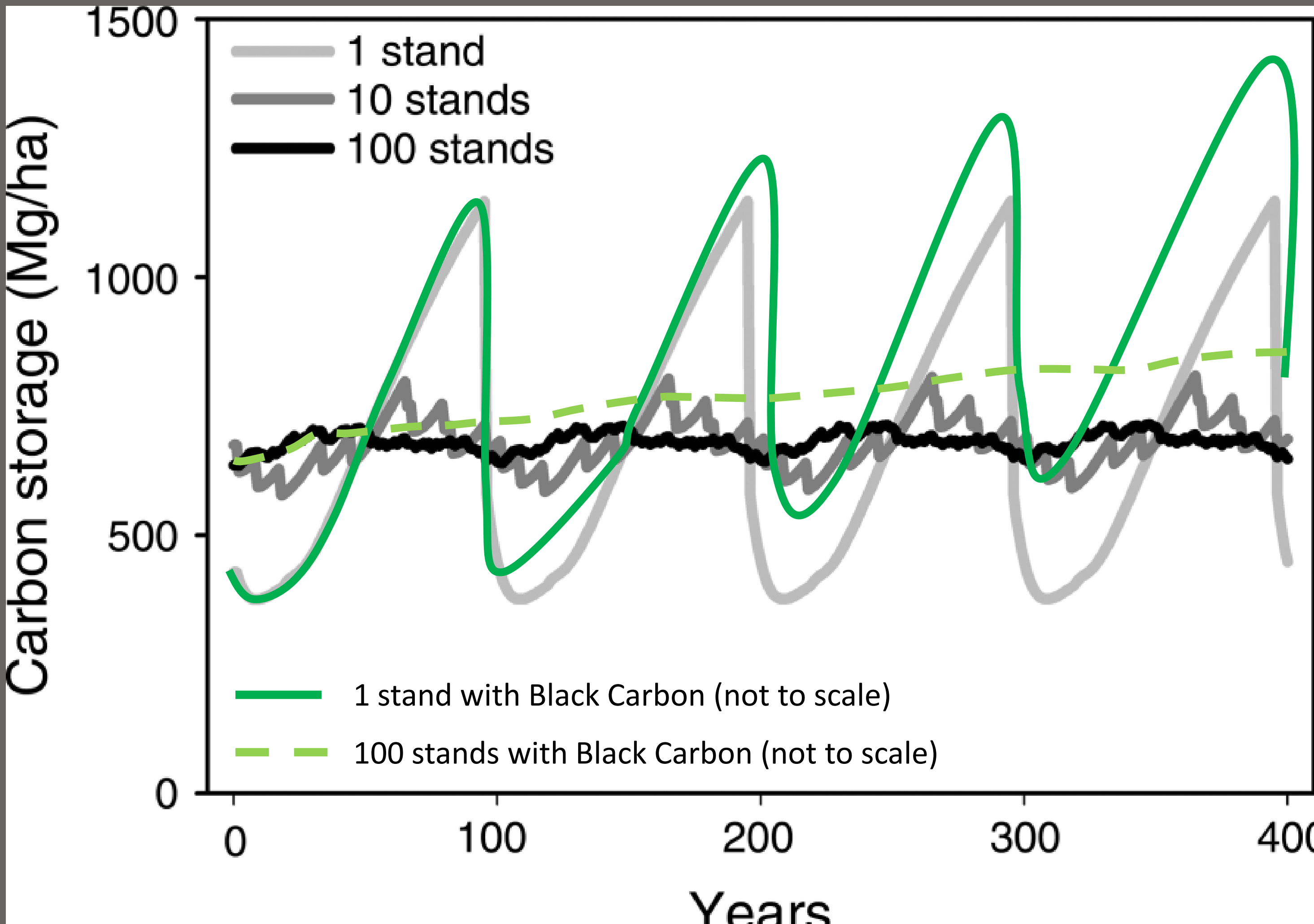


Figure adapted from McKinely et al. 2011

Controls on Black Carbon in Soils

Is it Refractory or Dynamic?

- Radio-carbon ^{14}C dating has identified carbon on the order of 1-10k years.
- Requires Fire!

But…there isn’t as much black carbon as there should be.

- Degradation mechanisms: presence of micro-organisms, chemical, and U.V. oxidation mechanisms
- More Fire?

My Research Questions:

1) How does fuel moisture influence the quantity and “quality” of black carbon in masticated fuels?

2) How does repeated burning influence the black carbon generated from an “initial” burn?

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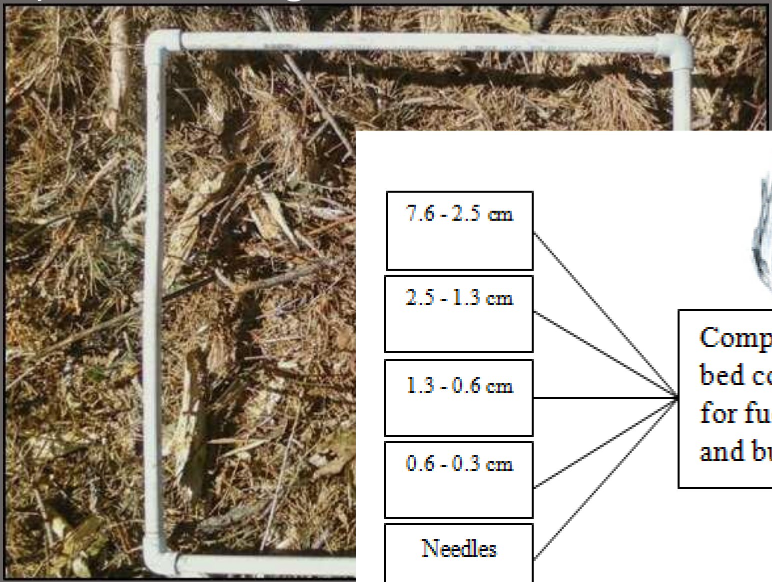
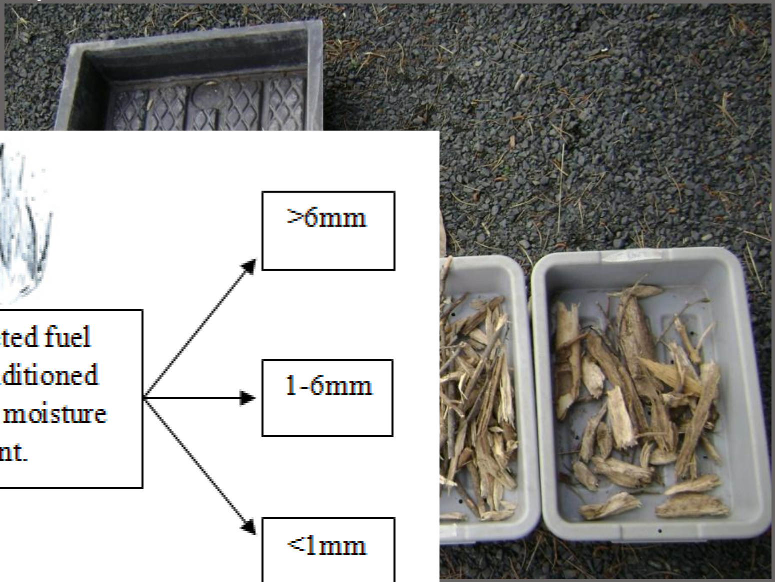
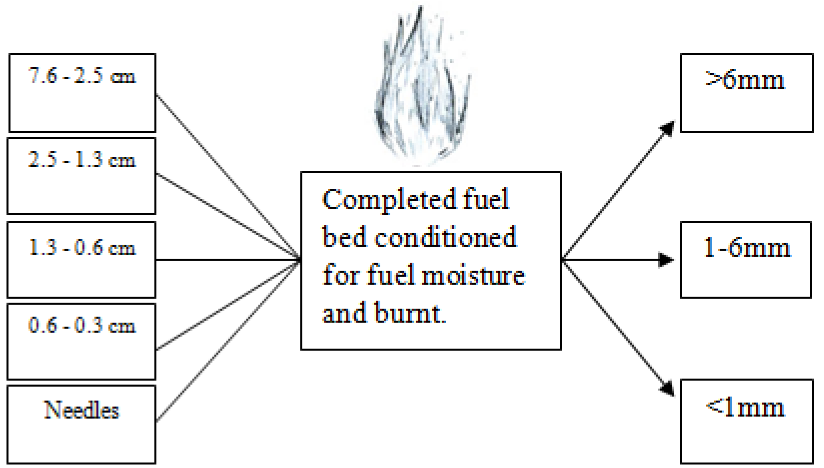
Methods/Study Design

A) Fuel Loading Determination



B) Fuel Bed Characterization

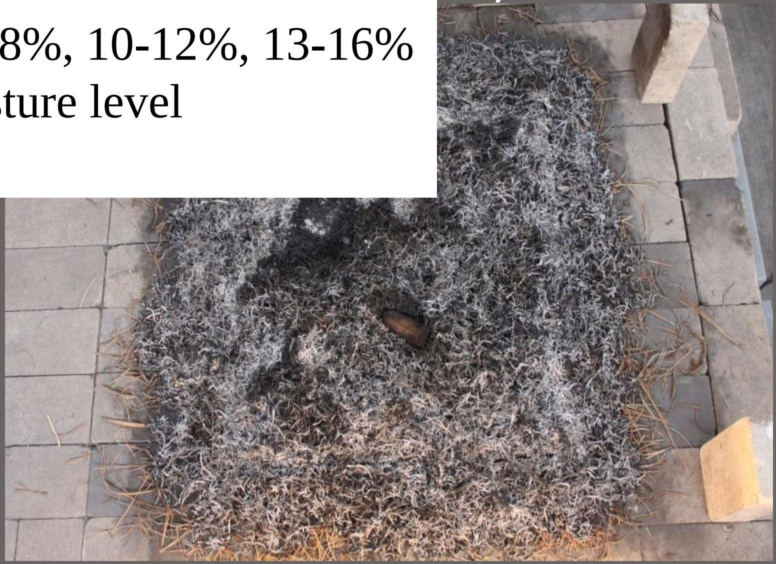




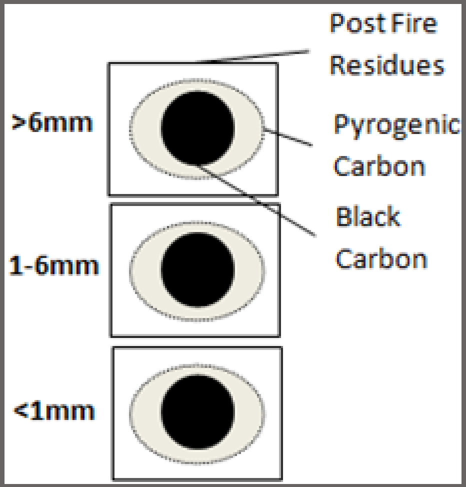
- 3 moisture levels: 4-8%, 10-12%, 13-16%
- 5 replicates per moisture level
- 15 burn trials total

C) Experimental B

nalysis



Methods/Study Design



Carbon Analysis Output Variables:

– Pyrogenic Carbon: Elemental analysis
– Black Carbon: Methods adapted from CTO375 (Gustoffson 1997).
– Ratio: Black C - to - Pyrogenic C

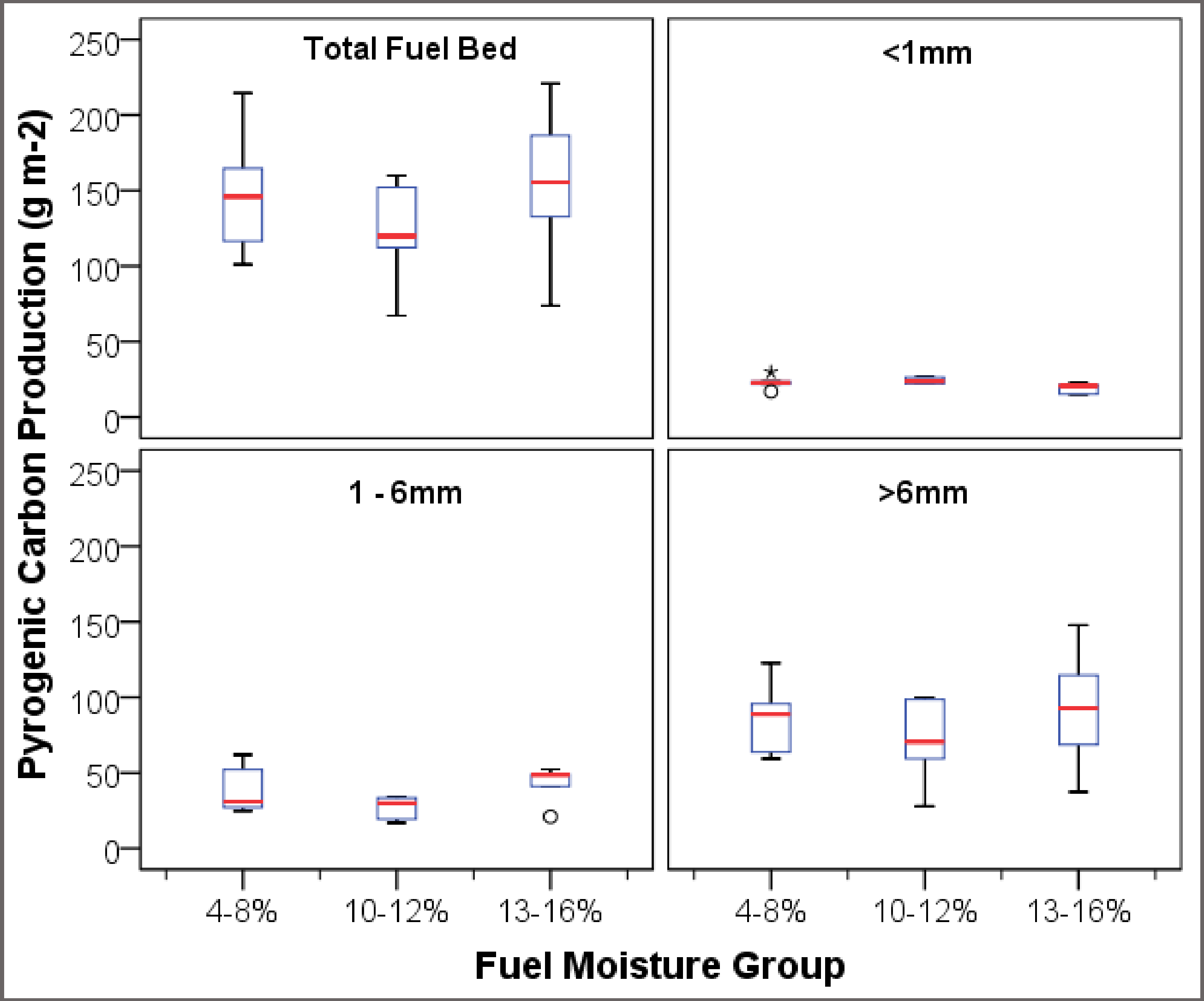
Active Fire Measurements:

– Fire Radiative Energy (FRE) flux points were recorded every 5 seconds during trials.

Statistical Analysis:

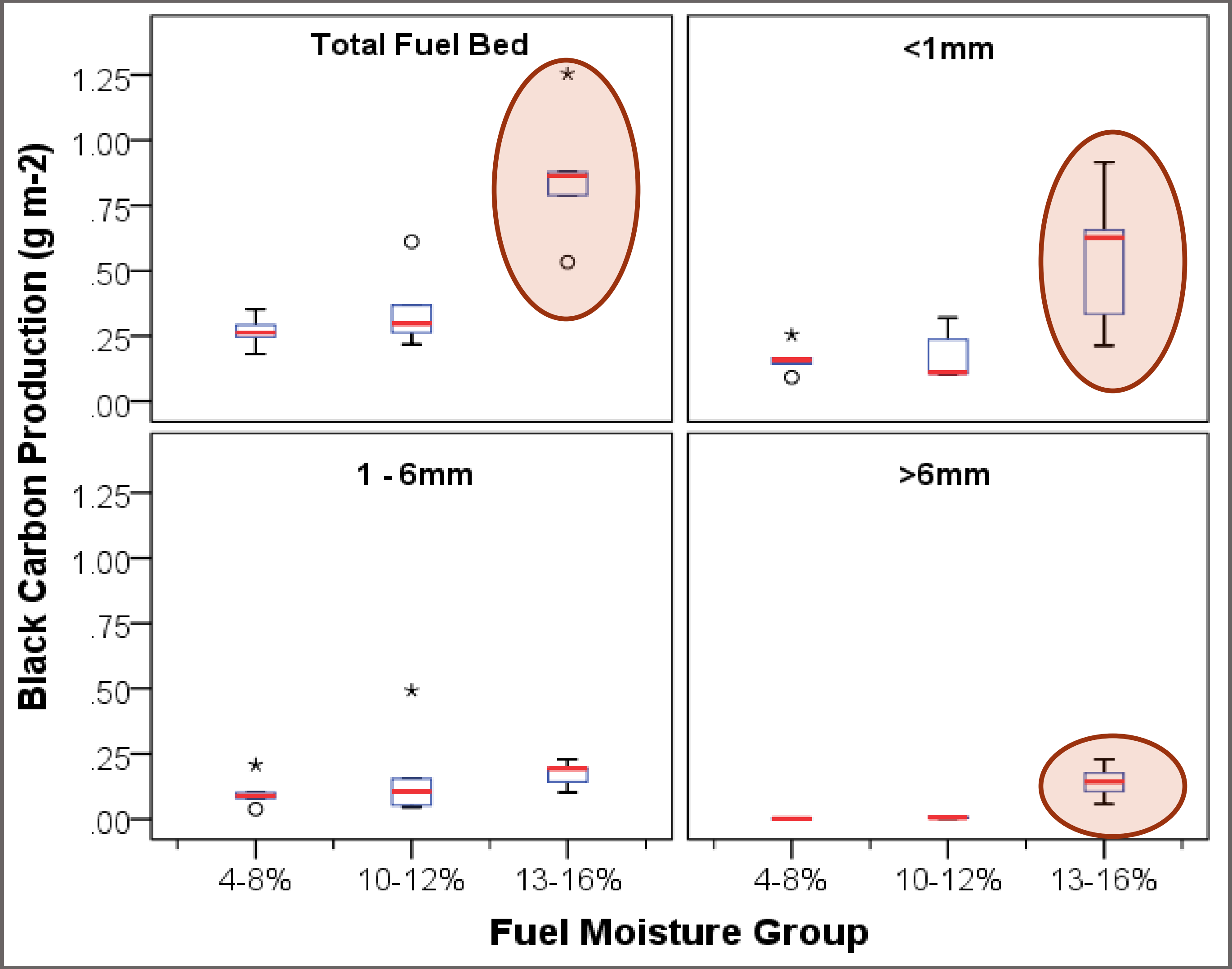
– One-way ANOVA's were used to compare means of pyrogenic carbon, black carbon and the BC:PyrC ratio between moisture levels.

Results: Pyrogenic Carbon



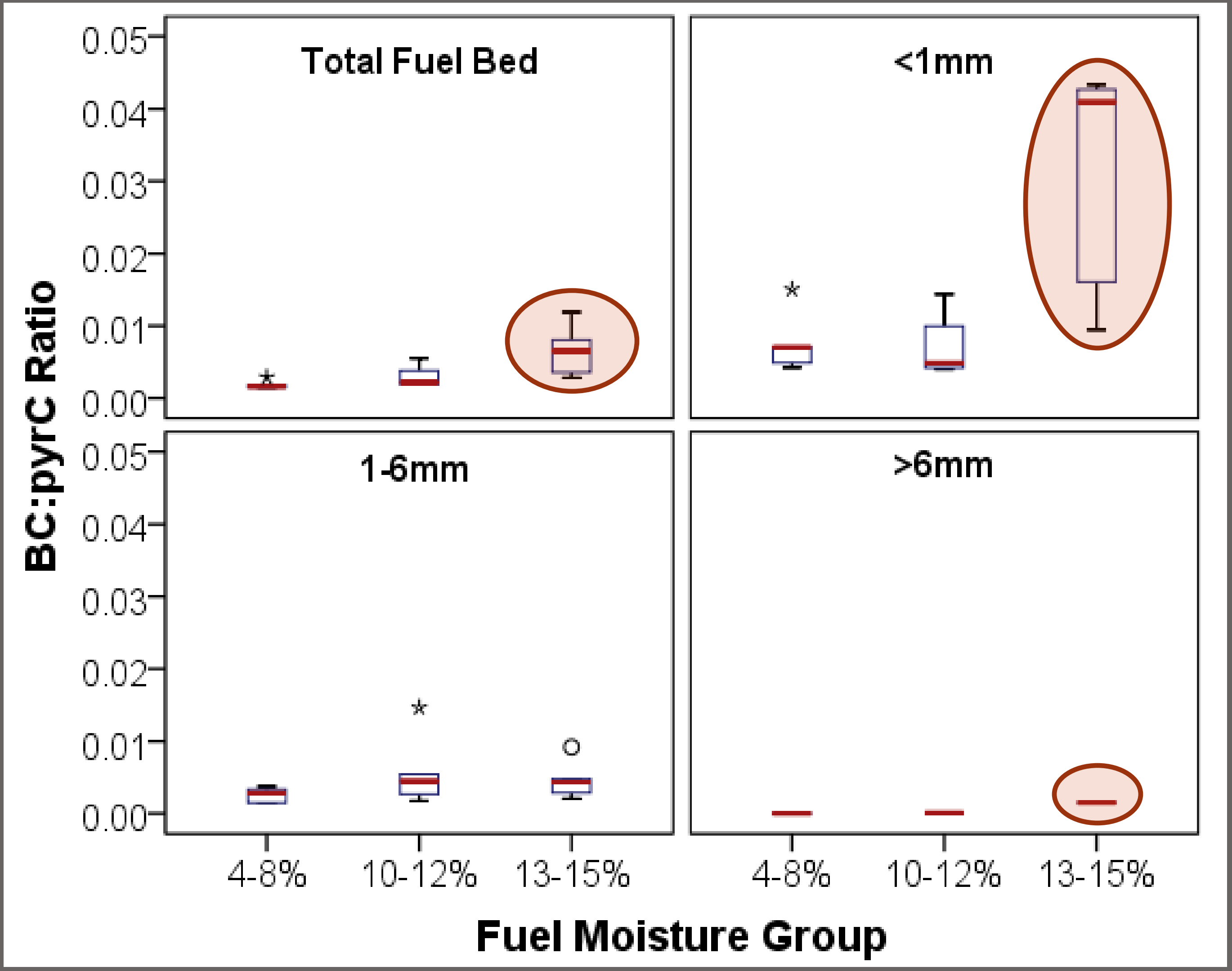
- Rates ranged from 7.23- 8.67% relative to pre-fire organic carbon content.

Results: Black Carbon

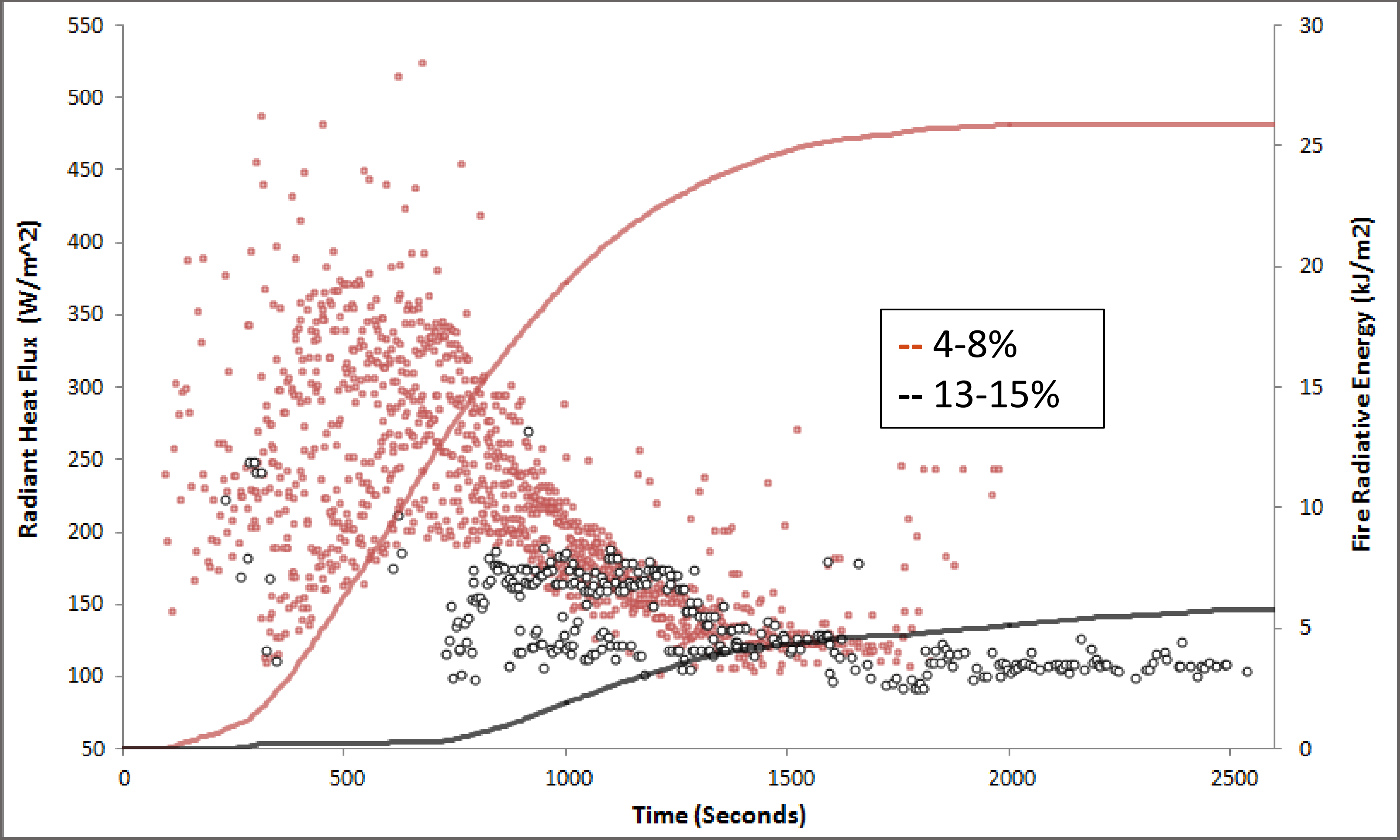


- Rates ranged from 0.02 to 0.05%.

Results: BC:PyrC Ratio

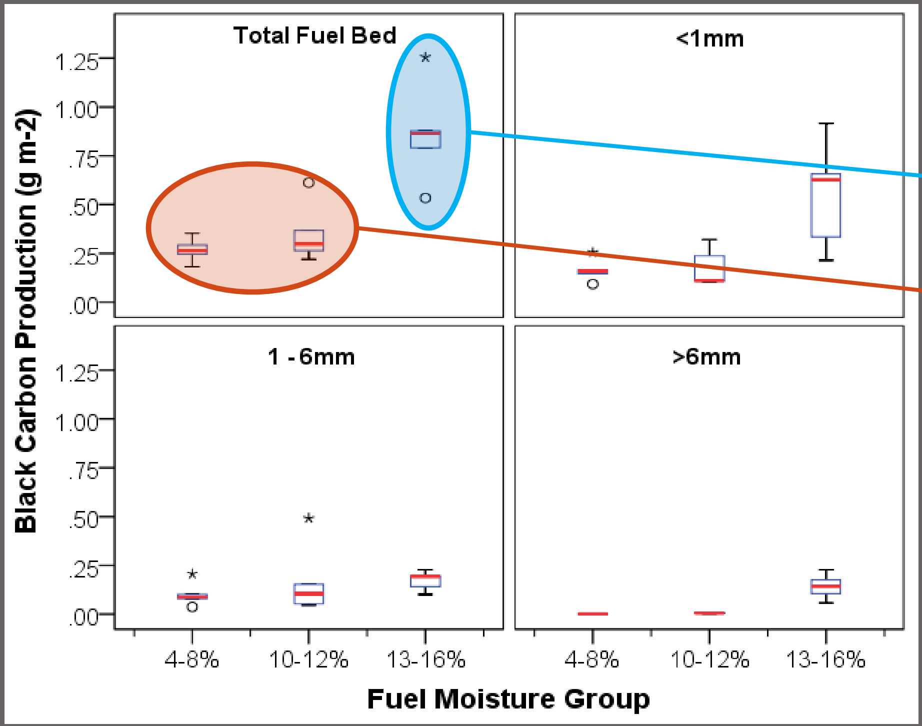


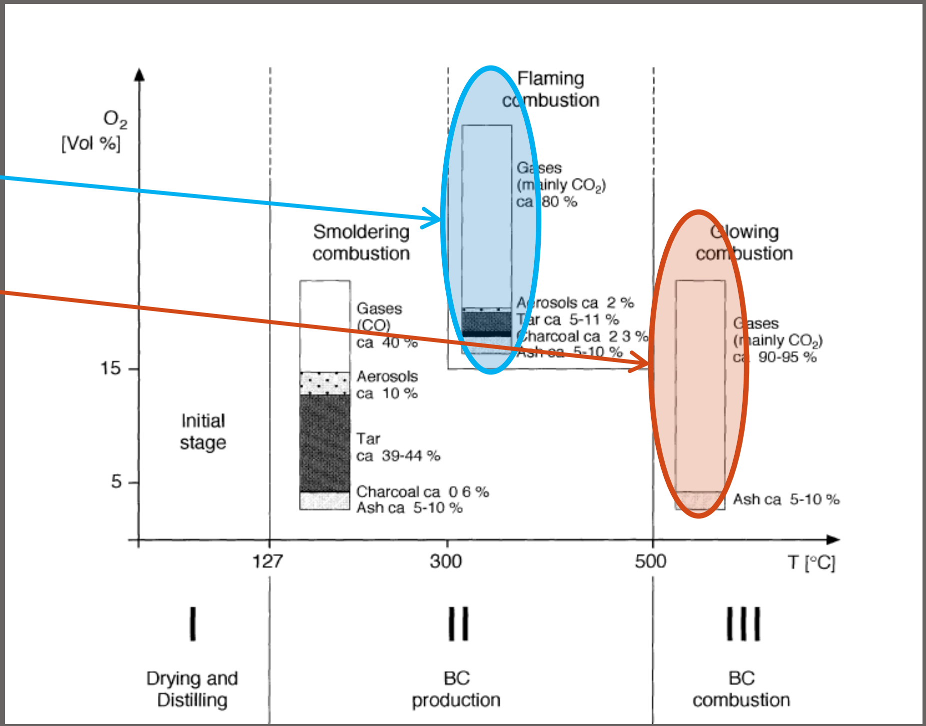
Results: FRE



550
500
450
400
350
300
250
200
150
100
50
Radiant Heat Flux (W/m^2)
30
25
20
15
10
5
0
Fire Radiative Energy (kJ/m2)
0
500
1000
1500
2000
2500
Time (Seconds)
-- 4-8%
-- 13-15%

Fuel Moisture Discussion





From Gleixner et al. 2009

- Not only is this a story of black carbon generation, but also indiscriminate volatilization of the pre-cursors to black carbon.
- C:N and d13C data corroborate the story of indiscriminate volatilization.

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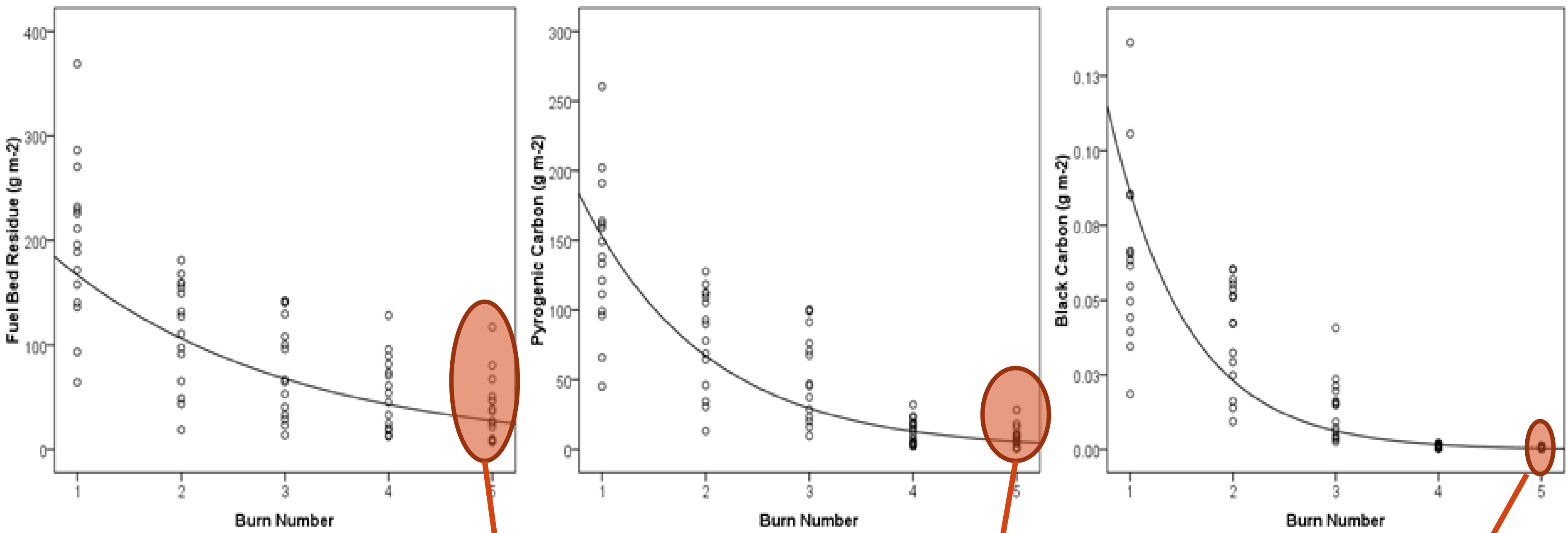
Methods/Study Design: Repeated Burns

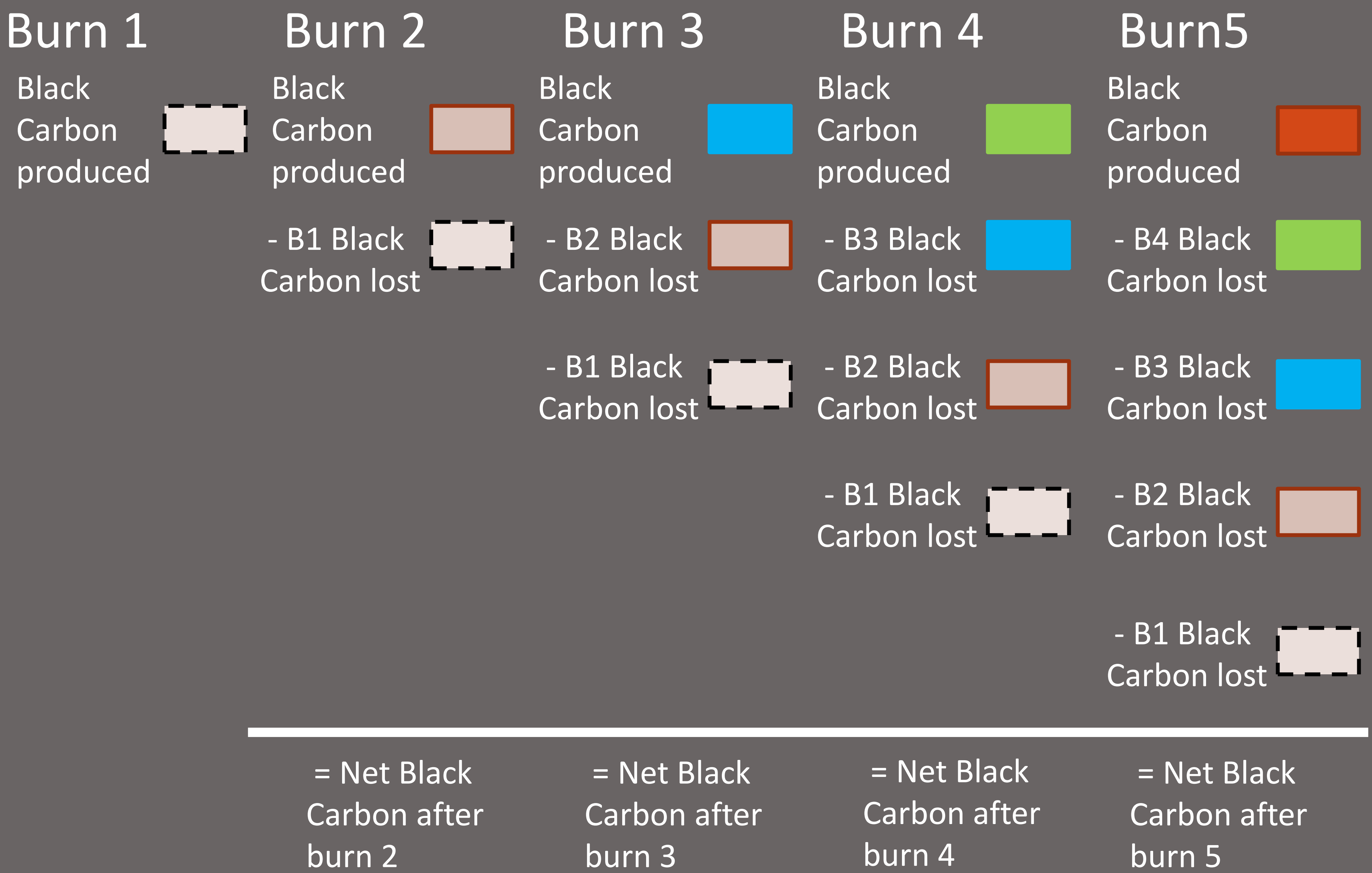
- Macro charcoal particles >6mm in size were carried forward to be re-burnt 4 times in a pine needle fuel bed.
- 15 burn trials for each burn number, a total of 60 trials.
- Similar methods for PyrC and BC sampling as above, but limited to >6mm charred particles.
- Fuel Moisture levels ranged from 3-16%, not considered an ‘effect’ or ‘factor’ in repeated measures ANOVA.

Results: Effects of Repeated Burning

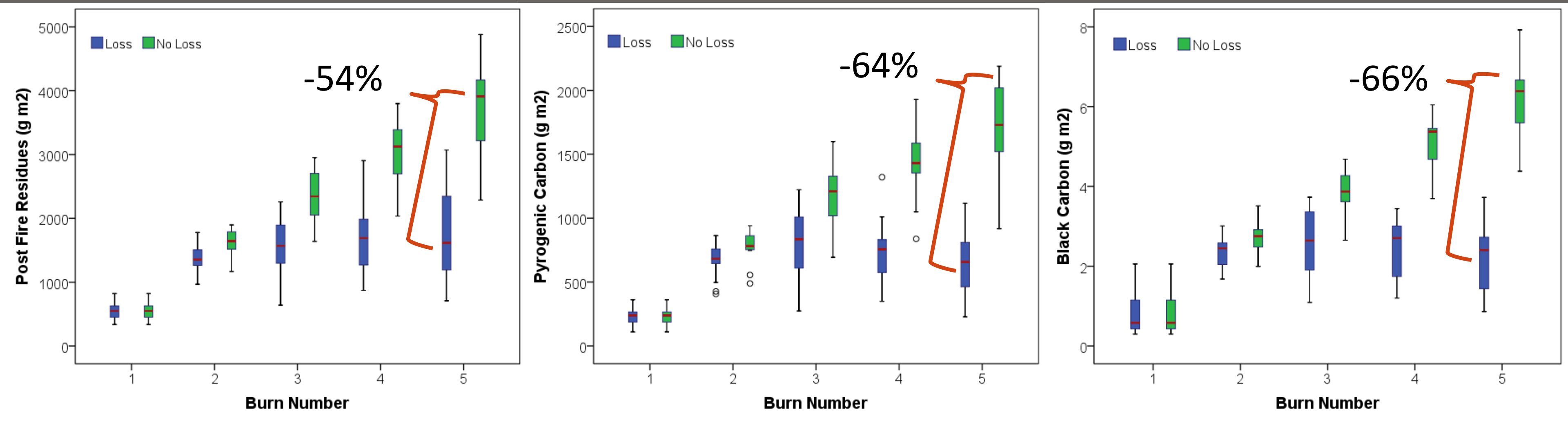


Burn Number	Residues	Percent Remaining	Pyrogenic Carbon	Percent Remaining	Black Carbon	Percent Remaining
1	198.07 (77.29) [a]	100.00	139.86 (54.58) [a]	100.00	6.51E-02 (2.94E-02) [a]	100.00
2	113.74 (50.93) [b]	56.59 (17.08)	80.25 (35.93) [b]	56.54 (17.06)	3.99E-02 (1.77E-02) [b]	63.40 (22.97)
3	78.78 (46.58) [c]	37.63 (14.97)	55.56 (32.86) [c]	37.59 (14.95)	1.36E-02 (1.02E-02) [c]	20.45 (13.42)
4	54.79 (34.92) [d]	26.60 (13.31)	13.38 (8.9) [d]	9.09 (4.87)	1.00E-03 (6.22E-04) [d]	1.56 (0.82)
5	39.46 (30.68) [e]	19.46 (13.32)	8.73 (7.62) [e]	5.94 (4.79)	6.58E-04 (3.61E-04) [d]	1.06 (0.57)
p-value	*<0.001*	-	*<0.001*	-	*<0.001*	-
ß	-0.451 (0.057)	-	-0.822 (0.066)	-	-1.315 (0.067)	-
R^2	0.464	-	0.681	-	0.840	-

A proposed black carbon budget as a function of repeated burning



A proposed black carbon budget as a function of repeated burning



- Including loss rates there is a >50% difference in remaining amounts after burn #5.
- Fuel loading and consumption play a large role in determining sink/source potential of black carbon over time.

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Conclusions

- Management implications: Burning masticated fuels under “prescribed fire” conditions will produce greater amounts of black carbon.
- Methods of using FRE can easily be applied to future wildland fire/prescribed fire scenarios. Temperature data?
- Repeated burning might be the primary mechanism for degradation in high fire frequency regimes.
- Future carbon budgets should include loss of previously created black carbon.
- Fire return interval should be greater than the incorporation rate.

Conclusions

- Built in assumptions on repeated burns.
  - Fine particle loss rates (isotopic marker?)
  - Incorporation Rates?
- Other degradation and transport mechanisms acting on the black carbon.
- Extrapolation to stands and landscapes.

Questions?

Fuel Moisture Tables (1-3)

Residue Type	Moisture Group	<1mm	1-6mm	>6mm
Pyrogenic Carbon Concentration (%)	4-8%	17.94 (2.73)	40.13 (8.82)	71.66 (4.66) [a]
	10-12%	17.95 (2.17)	42.02 (3.55)	74.45 (0.63) [a, b]
	13-16%	15.37 (3.59)	36.93 (8.52)	65.73 (0.83) [b]
p-value:		*0.495*	*0.708*	*0.021*
Black Carbon Concentration (%)	4-8%	0.14 (.07) [a]	0.30 (0.15)	0.03 (0.00) [a]
	10-12%	0.13 (0.08) [a]	0.45 (0.50)	0.22 (0.14) [a]
	13-16%	0.49 (0.27) [b]	0.51 (0.37)	2.65 (0.15) [b]
p-value:		*0.006*	*0.654*	*<0.001*

Material Type	Moisture Group	<1mm	1-6mm	>6mm	Total	Consumption (%)	Production (%)
Post-fire residues ($g\ m^{-2}$)	4-8%	210.06 (42.23)	154.00 (64.80)	189.74 (56.75)	571.65 (155.93)	90.39 (2.73)	9.60 (2.73)
	10-12%	220.98 (19.72)	109.56 (33.14)	163.30 (68.43)	493.84 (107.34)	91.31 (1.85)	8.78 (1.95)
	13-16%	203.68 (38.21)	188.42 (56.29)	230.37 (105.51)	622.47 (183.94)	89.71 (2.93)	10.22 (3.38)
p-value		*0.735*	*0.103*	*0.433*	*0.904*	*0.622*	*0.623*
Pyr C Production ($g\ m^{-2}$)	4-8%	39.65 (3.54)	43.96 (13.3)	117.02 (49.04)	200.63 (60.64)	91.33 (2.73)	8.67 (2.63)
	10-12%	37.7 (7.58)	64.72 (27.23)	141.26 (42.26)	243.68 (72.81)	92.77 (2.13)	7.23 (2.13)
	13-16%	31.31 (5.87)	69.58 (20.79)	151.42 (69.35)	252.32 (91.4)	91.46 (3.00)	8.54 (3.00)
p-value		*0.105*	*0.171*	*0.607*	*0.533*	*0.667*	*0.638*
BC Production ($g\ m^{-2}$)	4-8%	0.27 (0.10) [a]	0.17 (0.10)	1.73E-03 (5.18E-04) [a]	0.44 (0.10) [a]	100 (0.00) [a]	0.02 (0.00) [a]
	10-12%	0.29 (0.16) [a]	0.28 (0.30)	1.07E-02 (4.47E-03) [a]	0.58 (0.25) [a]	100 (0.00) [a]	0.02 (0.01) [a]
	13-16%	0.9 (0.46) [b]	0.28 (0.08)	2.34E-01 (1.07E-01) [b]	1.42 (0.42) [b]	99.99 (0.00) [b]	0.05 (0.01) [b]
p-value		*0.006*	*0.580*	*<0.001*	*<0.001*	*<0.001*	*<0.000*
BC:pyrC	4-8%	7.65E-03 (4.33E-03)	2.59E-03 (1.03E-03)	1.23E-05 (2.07E-21)	1.88E-03 (5.80E-04)	-	-
	10-12%	7.48E-03 (4.57E-03)	5.80E-03 (5.16E-03)	9.12E-05 (1.66E-20)	4.31E-03 (2.54E-03)	-	-
	13-16%	3.05E-02 (1.64E-02)	4.66E-03 (2.76E-03)	1.54E-03 (1.57E-21)	6.59E-03 (3.65E-03)	-	-
p-value		*0.005*	*0.356*	*<0.001*	*0.019*	-	-

Residue Type	Moisture Group	C:N <1mm	C:N 1-6mm	C:N >6mm	δ13 C Isotope <1mm	δ13 C Isotope 1-6mm	δ13 C Isotope >6mm
Unburnt Carbon	na	na	103.13 (16.21)*	477.64 (52.37)†	na	-26.74 (0.11) *	-27.16 (0.09)†
Pyrogenic Carbon	4-8%	25.98 (0.53) [a]	39.26 (5.38)	371.32 (20.52) [a]	-27.69 (0.04) [a]	-27.86 (0.14)	-27.17 (0.14)
	10-12%	21.6 (0.5) [b]	39.84 (0.31)	227.45 (42.18) [a]	-27.71 (0.05) [a]	-27.92 (0.41)	-27.31 (0.98)
	13-16%	21.29 (1.02) [b]	36.89 (3.44)	187.36 (18.40) [b]	-27.36 (0.21) [b]	-27.93 (0.27)	-26.44 (0.04)
p-value		*<0.001*	*0.611*	*0.001*	*0.023*	*0.948*	*0.214*
Black Carbon	4-8%	4.47 (1.05)	4.51 (0.88)	0.37	-24.63 (1.33) [a]	-23.03 (0.27) [a]	-27.57
	10-12%	3.92 (1.45)	4.95 (1.41)	2.91	-24.16 (0.39) [a]	-23.07 (0.31) [a]	-23.54
	13-16%	10.05 (6.28)	4.52 (0.96)	12.16	-25.3 (0.88) [b]	-23.63 (0.3) [b]	-21.17
p-value		*0.086*	*0.805*	-	*0.013*	*0.184*	-

1) C:N in pyrogenic carbon indicates that C was preferentially consumed to N.
2) N plays an important role in C stability!
3) The low C:N ratio with higher fuel moistures suggests that the pyrolysis products of the Maillard reaction were preserved by burning, and that low N-containing OM is being consumed.
4) The lack of a trend in isotope data suggest that both lignin and cellulose were preferentially consumed over N-containing compounds.
5) For BC:BN, more BN may be available to react and form BC – selective preservation of N at higher fuel moistures may cause increased formation of BC.

Repeated Burns Tables

Table 1 Mean (sd) fuel bed characteristics and burn conditions for the repeated burns (n=15).

Repeated Burn	Bulk Density (kg m^{-3})	Fuel Loading (kg m^{-2})	Consumption (%)	Fuel Moisture (%)	Temperature (°C)	Relative Humidity (%)
2	58.74 (6.34)	783.02 (90.16)	45.5 (13.07)	9.66 (3.85)	16.69 (2.66)	36.07 (10.98)
3	48.81 (8.37)	658.43 (74.93)	57.41 (18.14)	11.03 (3.28)	21.54 (2.9)	34.26 (5.24)
4	45.87 (4.39)	651.23 (36.32)	57.28 (15.44)	9.49 (4.59)	25.41 (5.18)	30.17 (6.88)
5	52.53 (16.84)	655.24 (47.72)	61.76 (18.05)	10.22 (4.68)	21.48 (2.3)	33.61 (6.41)

Table 3: Pyrogenic (n=9) and black carbon (n=3) characteristics through 5 repeated burns and p-values associated with the repeated measures ANOVA (α = 0.05). Homogenous subsets marked by: [a,b,c] as identified by the Bonferonni post-hoc test.

	Pyrogenic Carbon			Black Carbon		
Burn Number	$\delta^{13}C$	%C	C:N	$\delta^{13}BC$	%BC	BC:BN
1	-26.96 (0.64)	70.61 (4.53)	262.04 (87.48)	-23.54 (3.51)	0.97 (1.46)	5.14 (6.21)
2	-26.99 (0.44)	70.55 (2.38)	277.72 (166.89)	-20.78 (1.01)	1.06 (0.14)	8.77 (3.86)
3	-27.08 (0.28)	70.53 (1.24)	239.47 (113.26)	-22.37 (0.77)	0.95 (0.11)	3.95 (2.89)
4	-26.75 (0.64)	68.00 (2.03)	167.89 (33.9)	-22.86 (0.46)	0.05 (0.02)	0.73 (0.53)
5	-26.92 (0.40)	67.53 (2.53)	237.87 (64.06)	-25.86 (3.46)	0.40 (0.58)	4.06 (5.60)
p-value	*0.67*	*0.17*	*0.23*	*0.15*	*0.54*	*0.32*