Live Fuel Moisture: A new look at the combustion of living plants

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Motivation: A paradox

Fires in live fuels are common throughout the world

They often pose the greatest risk to life and property and resist control efforts

These fires fill a valuable ecological role but can rarely be managed effectively

Fire is bad

Fire is good

Understanding

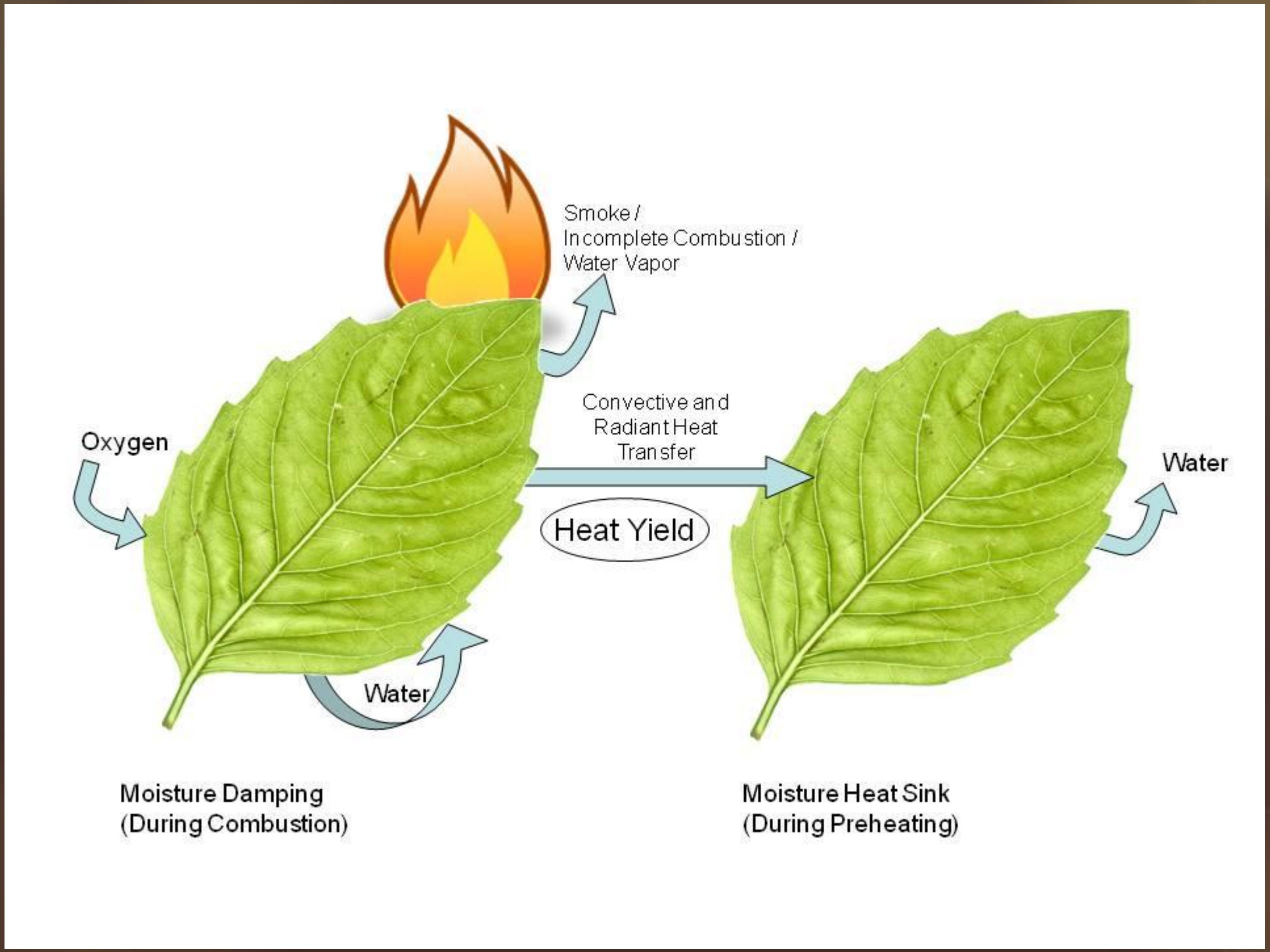
Our history shapes our perceptions

From Byram 1959

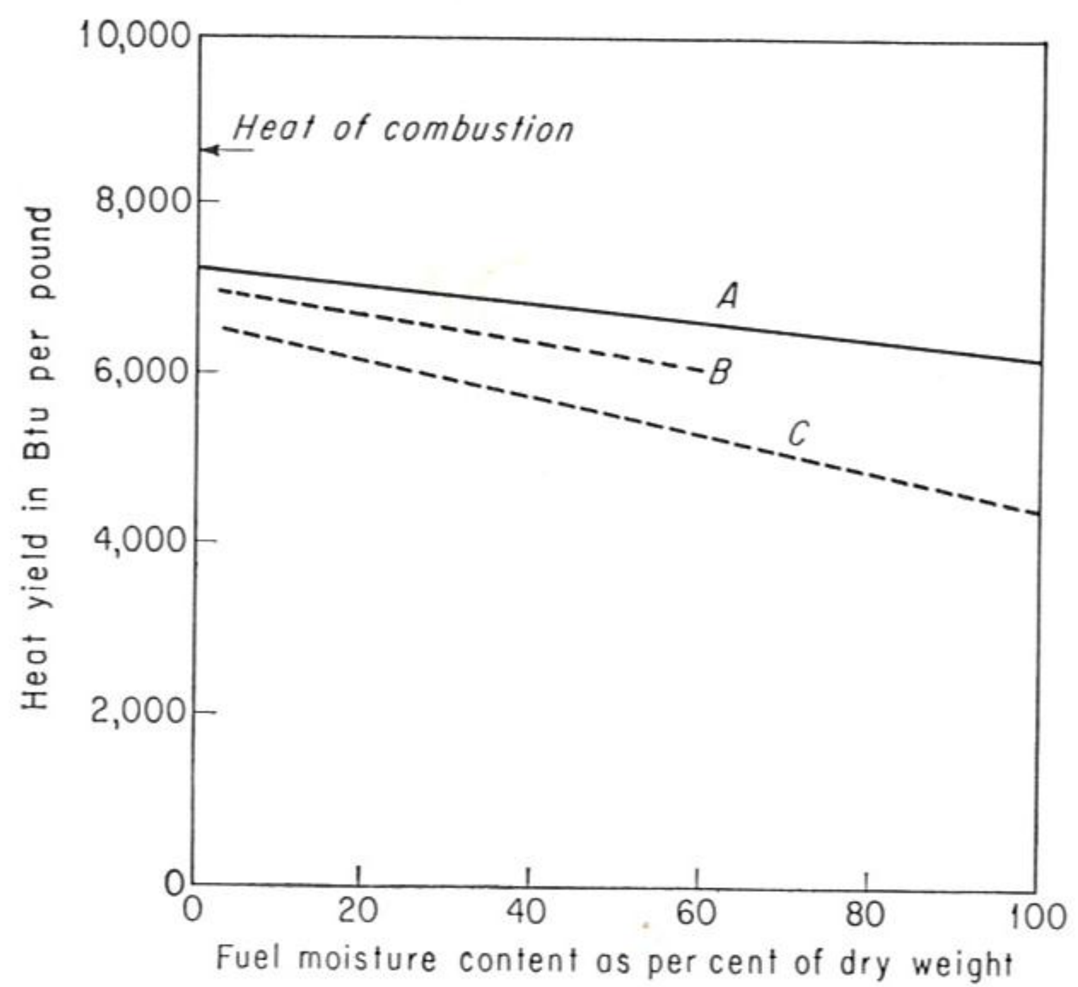
- “The effect of fuel moisture on the burning rate of wood fuel is pronounced and so obvious that no measurements are needed to illustrate its over-all effect”

These types of statements lead to the ‘natural’ conclusion that live fuels were just really wet dead fuels

Combustion of living plants



Byram 1959

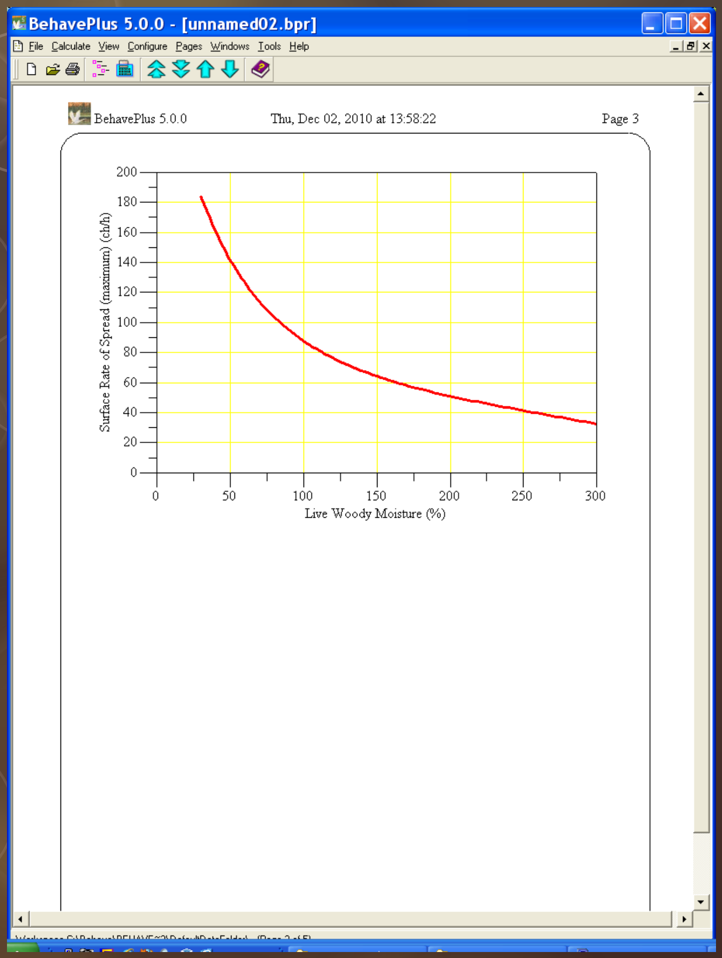


Heat yield of combustion as a function of fuel moisture content.

A – Complete combustion
B – Estimate for small fires
C – Estimate for large fires

- It takes heat to evaporate moisture

Moisture content is used to predict how fires spread



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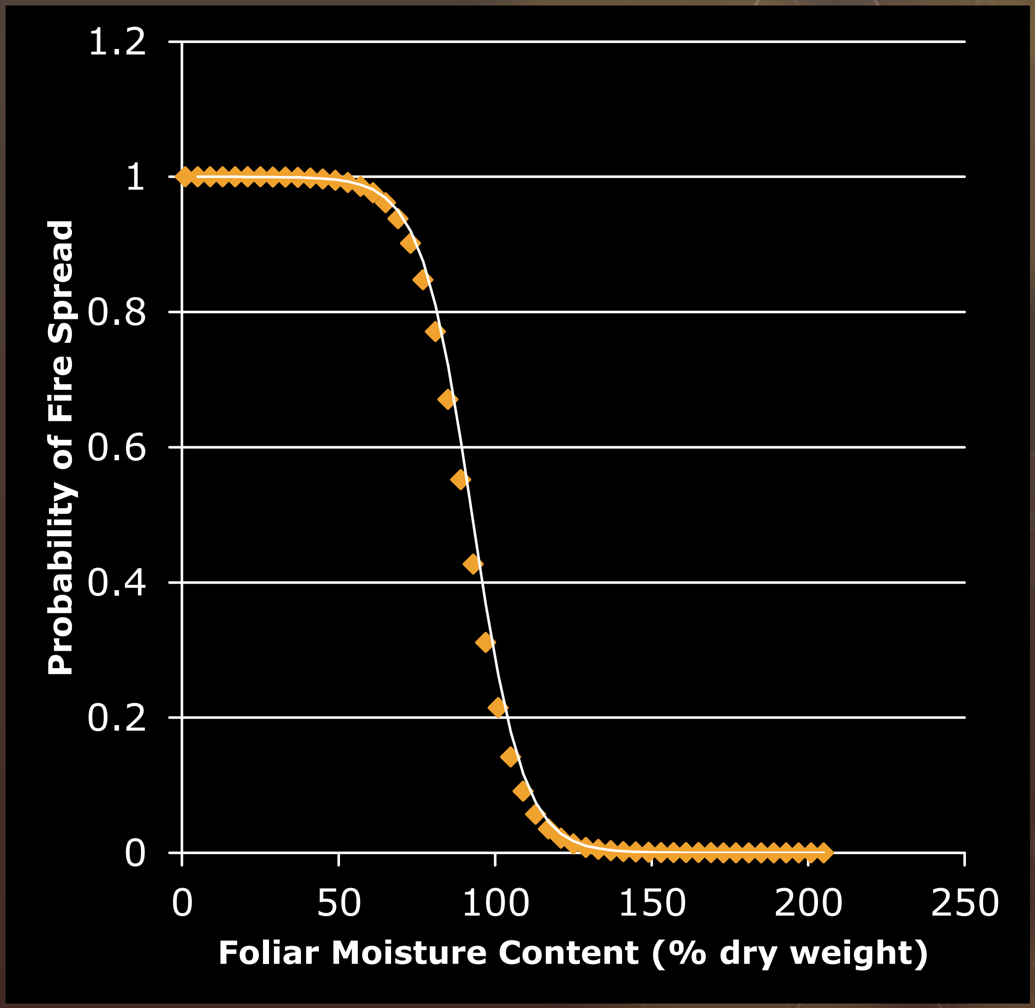


Weise et. al. IJWF 2005
Assuming 5 mi/hr winds, no slope
1.5 kg m^{-2} fuel loading

Many studies have shown a relationship between ignition delay time and foliar moisture content

Xanthapoulos and Wakimoto 1993

TABLE 2. Time to ignition – temperature – moisture relationships for three western conifer species using original variables

Test species	Equation coefficients*: Constant	Temp. (°C)	Moisture (%)	SEE†	CV‡	*F*-ratio	Adj. R^2§
Ponderosa pine	78.112 54 (4.045 60)	−0.148 16 (0.006 85)	0.189 71 (0.014 94)	6.210	0.281	310.365	0.665
Lodgepole pine	110.888 31 (6.099 54)	−0.211 18 (0.011 56)	0.162 32 (0.019 30)	6.381	0.287	190.221	0.655
Douglas-fir	157.769 83 (13.231 35)	−0.275 69 (0.026 35)	0.090 57 (0.031 98)	18.879	0.820	54.969	0.346

*The numbers in parentheses are the standard errors of the coefficients.
†Standard error of the estimate.
‡Coefficient of variation about regression.
§Adjusted squared multiple correlation coefficient.

- Extensive work has been done throughout the world looking at the combustion characteristics and fire spread through live vegetation

What don’t we understand?

- Fires will rarely spread in dead fuels when their moisture content is greater 20% but fires readily spread through living plants when their moisture content is 100% or more.
  - Sometimes referred to the moisture of extinction
- We don’t understand the inter-relationships between moisture, chemistry, thermal / physical properties and combustion of living plants
  - Always looking for the “Smoking Gun”: that magic variable that explains Life, the Universe and Everything
- Considerable time and money is spent by fire personnel measuring live fuel moisture but little is know about the utility of these measurements for fire management operations

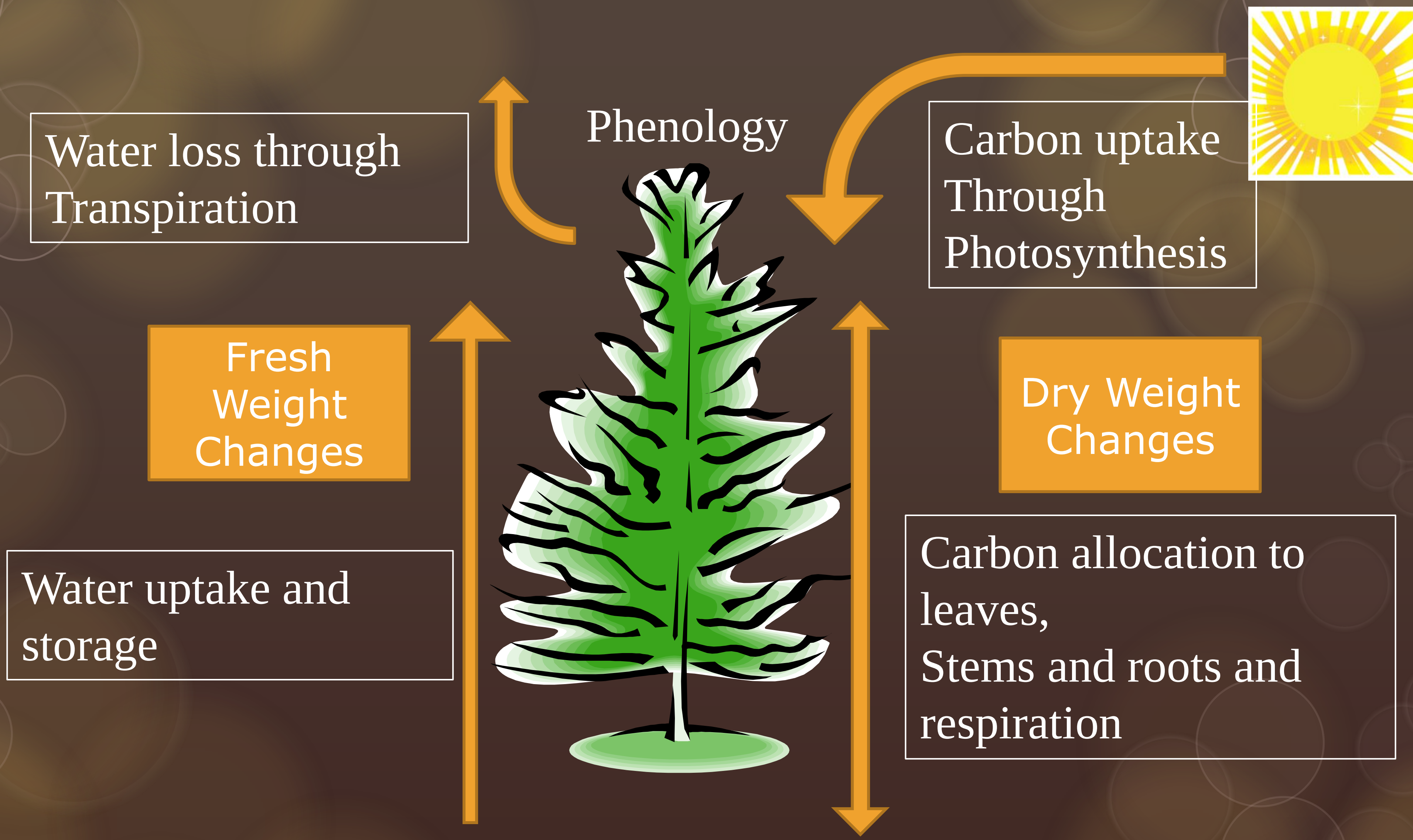
This all assumes that we know what live fuel moisture is quantifying

Difference in moisture content dynamics of live and dead fuels

$$Live\ Fuel\ Moisture = \frac{Fresh\ Wt\ (g) - Dry\ Wt\ (g)}{Dry\ Wt\ (g)}$$

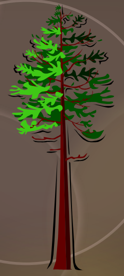
We have always assumed that live plants burn like really wet dead plants

Physiological processes that alter live foliar moisture content



$$Live\ Fuel\ Moisture = \frac{Fresh\ Wt\ (g) - Dry\ Wt\ (g)}{Dry\ Wt\ (g)}$$

Study Description

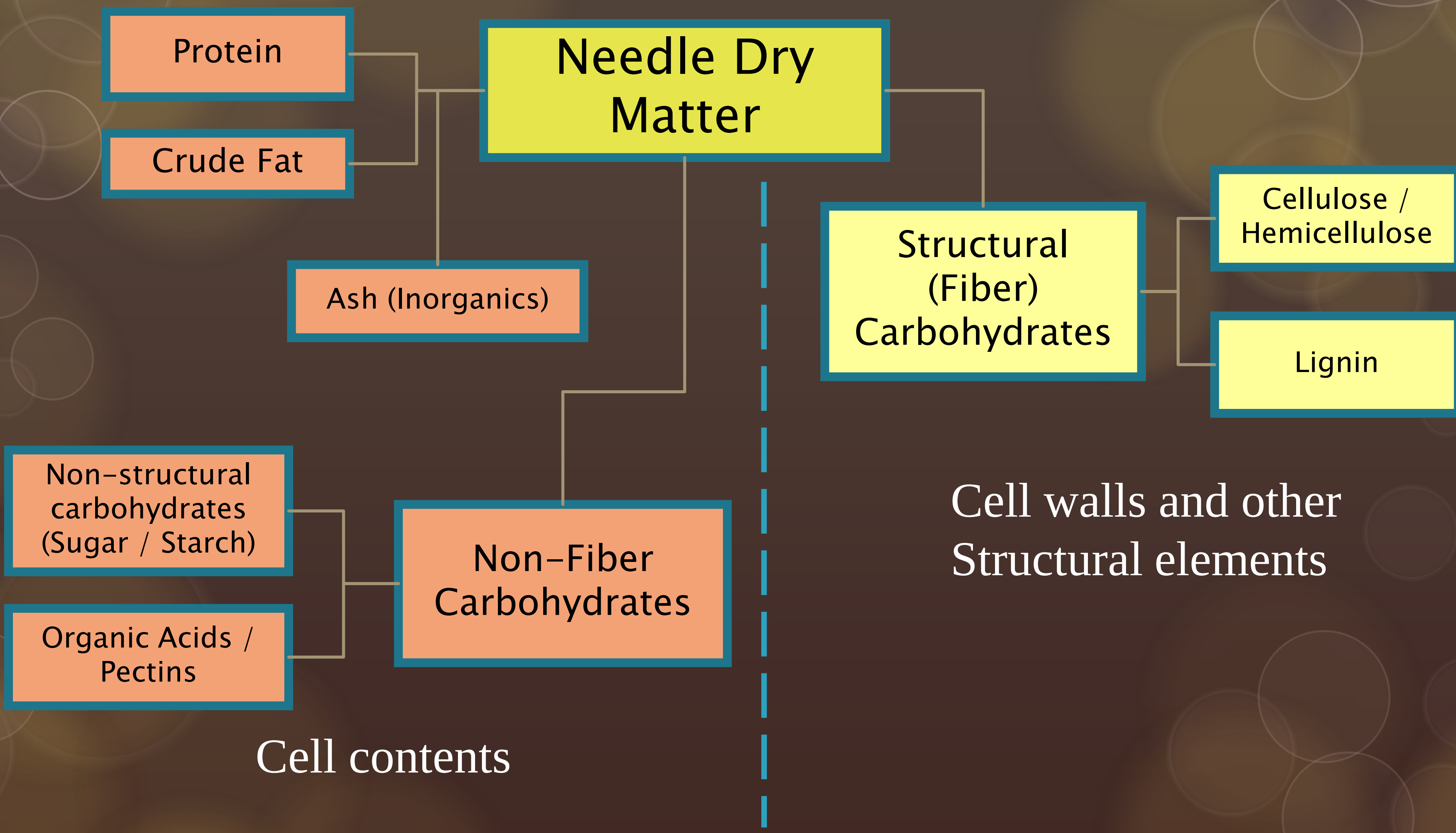


- Collected conifer foliar samples weekly from Lodgepole pine (*Pinus contorta*) for four sites for three years
  - Lubrecht Experimental Forest, Garnet Ghost town Road, Spring Gulch and Lolo Pass
  - Separated new and old needles
- Oven-dried subsample for **live fuel moisture content**, **relative water content**, needle density and heat content
- Analyzed subsample for foliar chemistry
  - Based on broad categories
- Ignited samples two ways:
  - Radiant panel
  - Open flame burner
    - Moisture loss at ignition with Nitrogen Quenching chamber

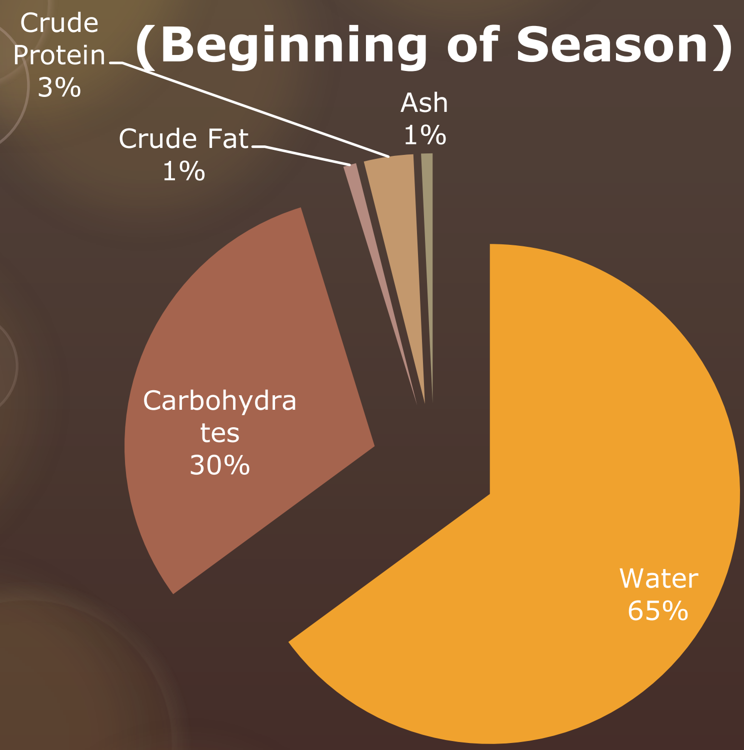
http://www.malton.n-yorks.sch.uk/TreeWeb/key/pi

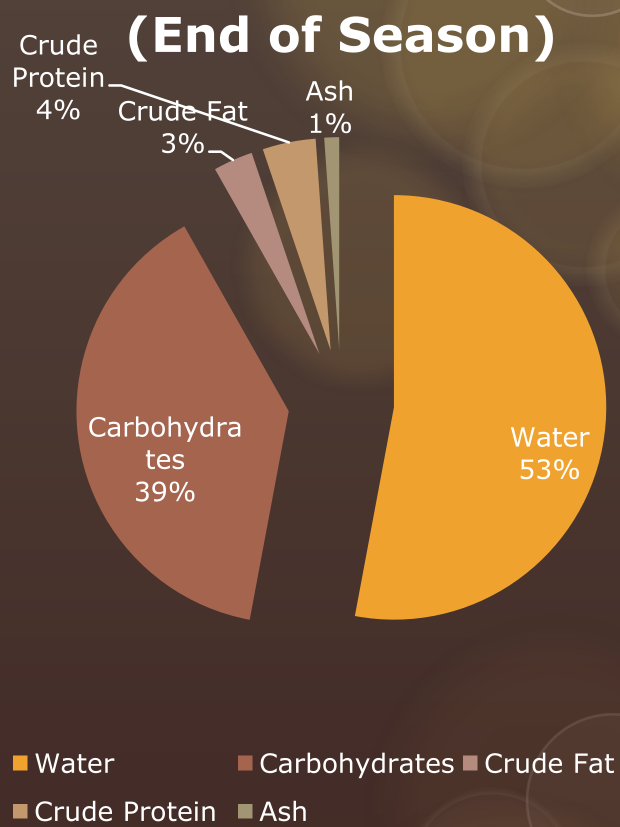
Fuel Chemistry

Dry matter partitioning from chemical analysis

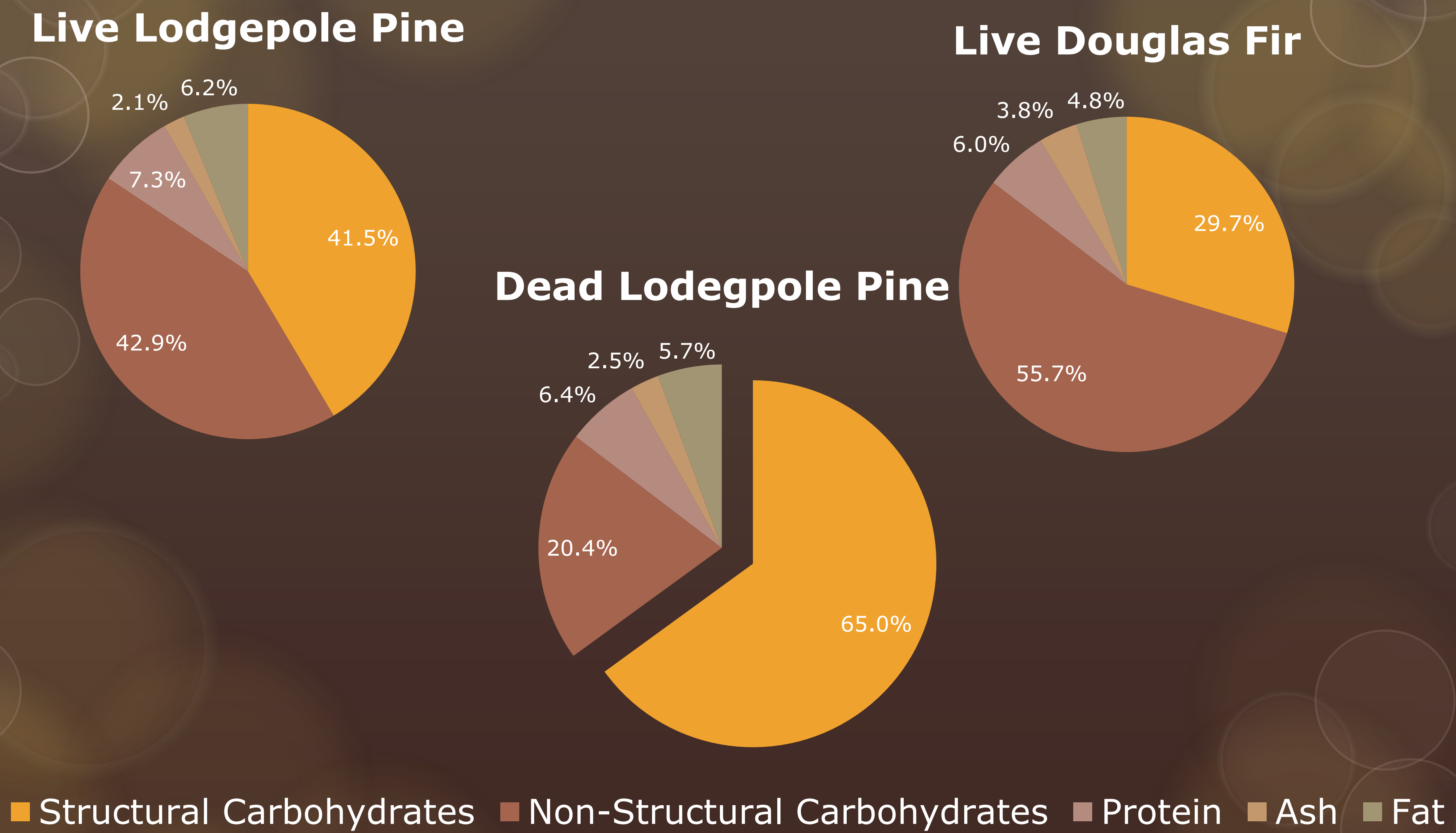


New Lodgepole Pine Needle Chemical Composition



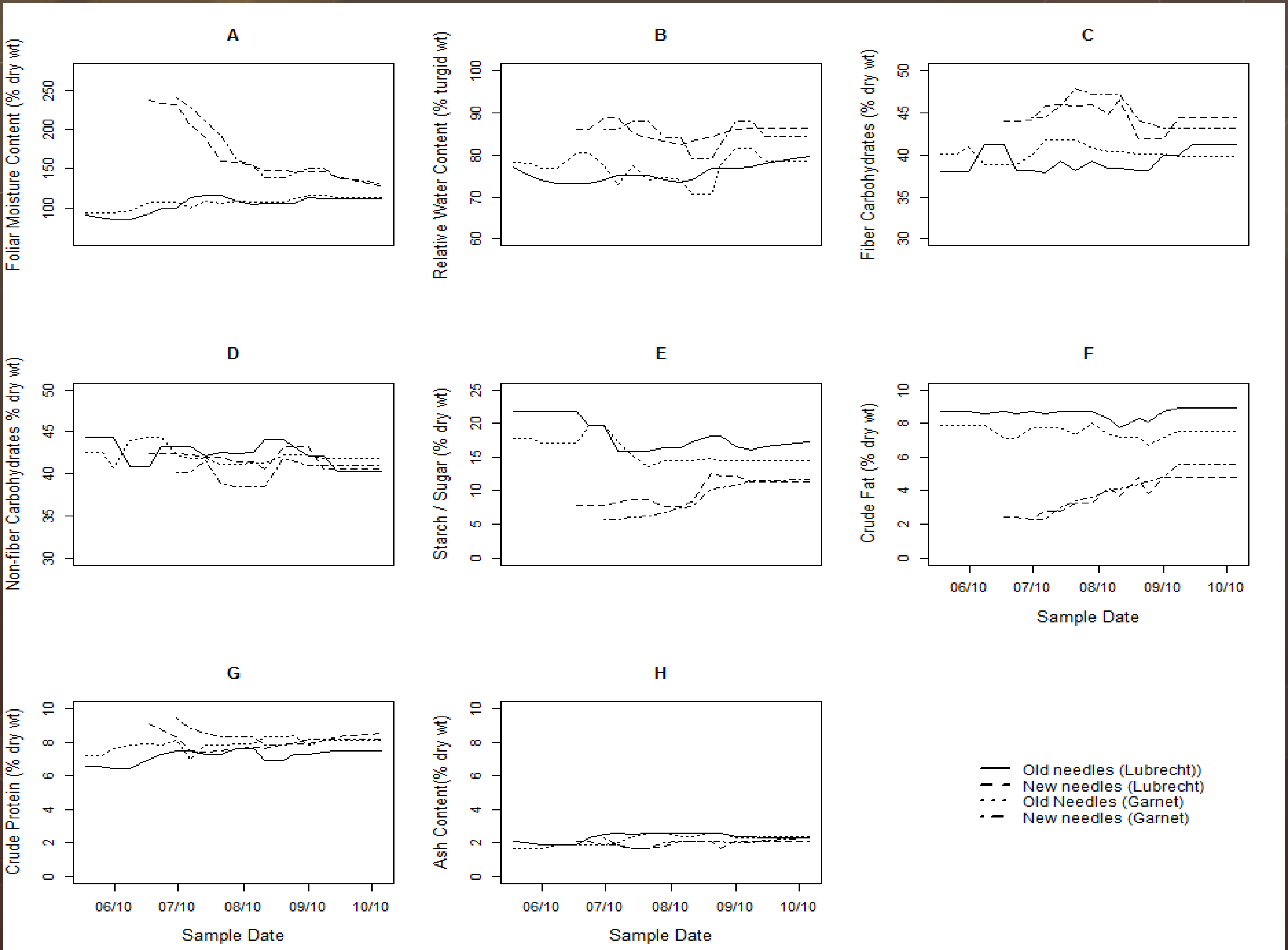


Components of the dry weight of some common conifer needles



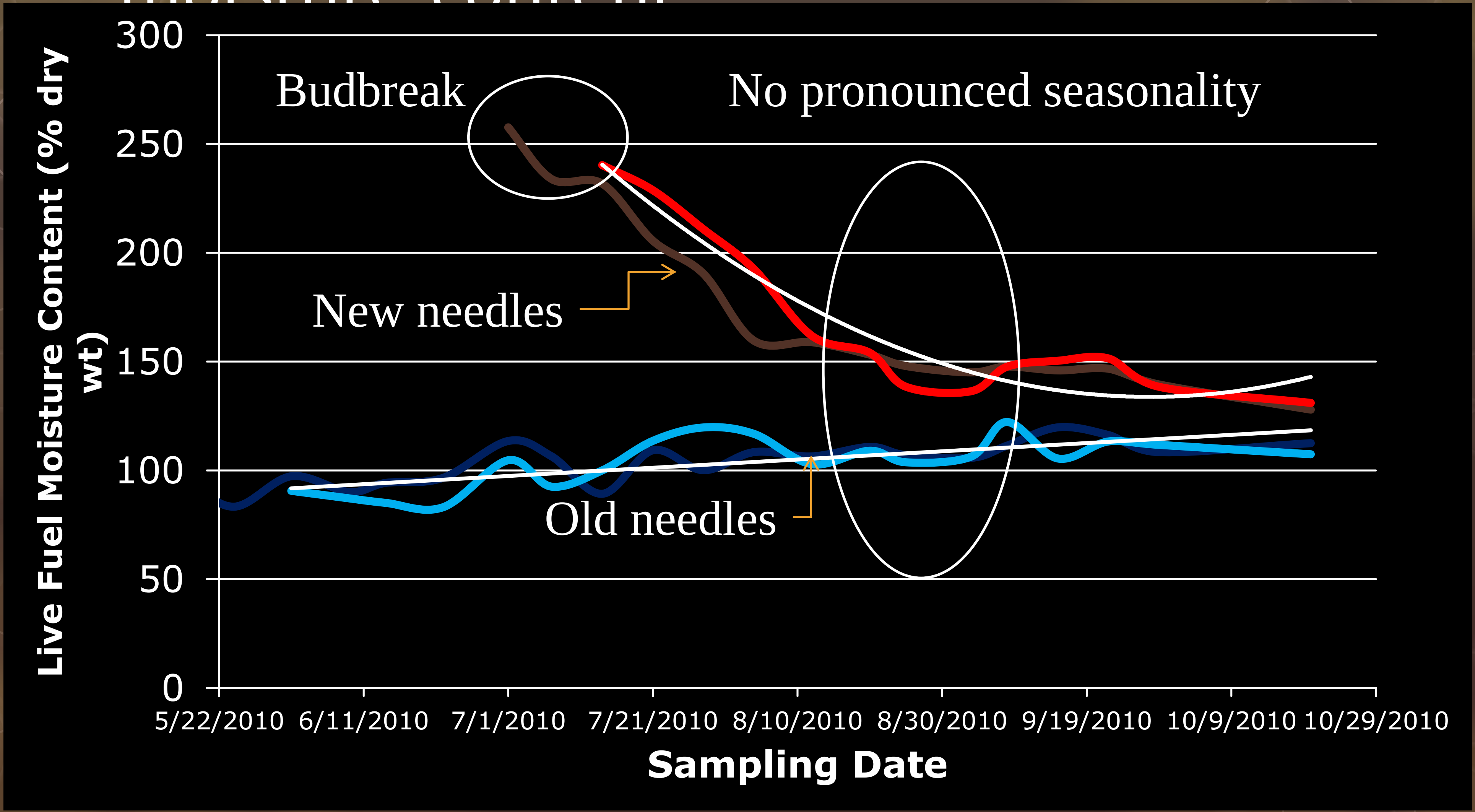
Live needles are chemically different than dead needles

And neither are similar to wood

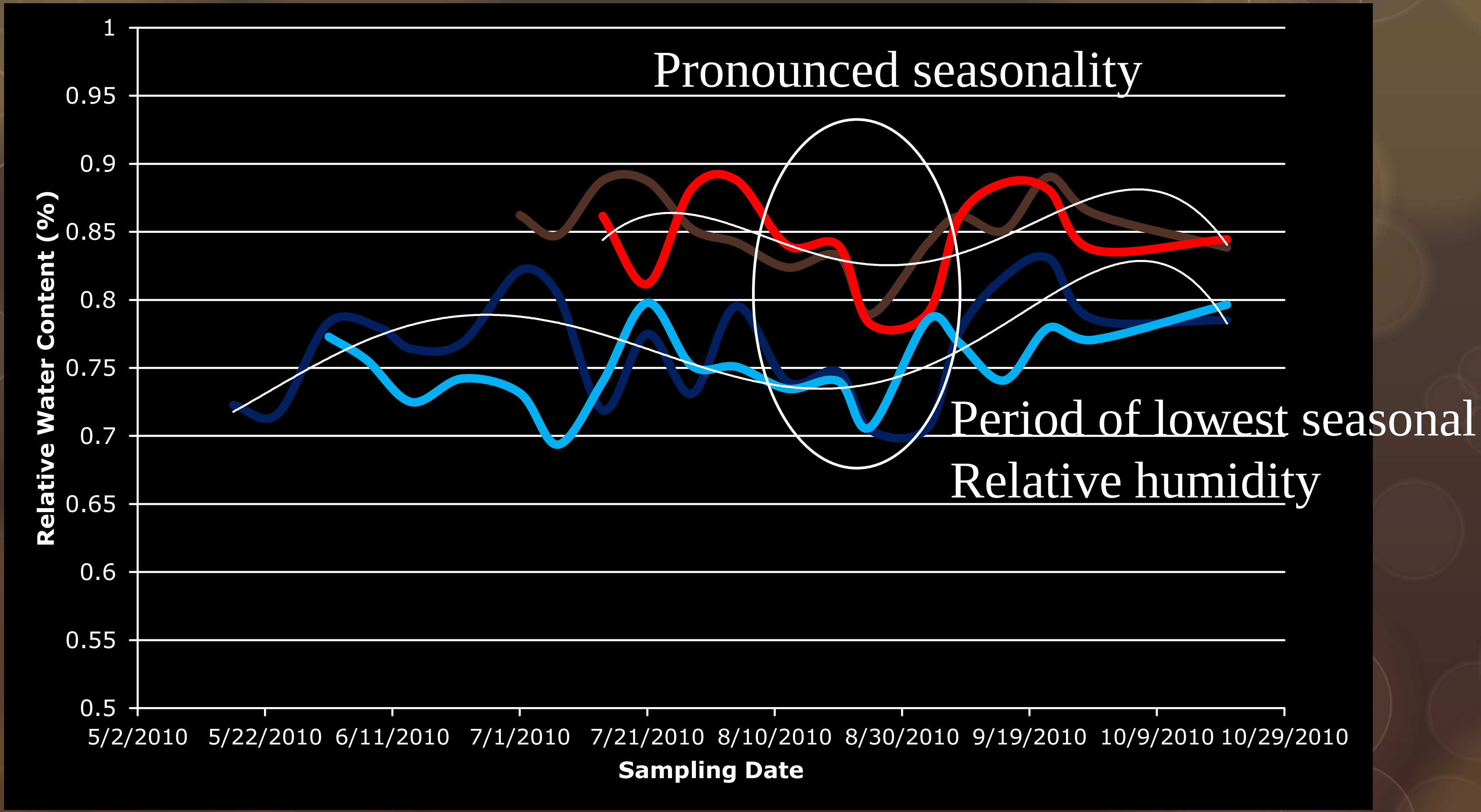


A
Foliar Moisture Content (% dry wt)
B
Relative Water Content (% turgid wt)
C
Fiber Carbohydrates (% dry wt)
D
Non-fiber Carbohydrates % dry wt)
E
Starch / Sugar (% dry wt)
F
Crude Fat (% dry wt)
G
Crude Protein (% dry wt)
H
Ash Content(% dry wt)
06/10
07/10
08/10
09/10
10/10
Sample Date
Old needles (Lubrecht))
New needles (Lubrecht)
Old Needles (Garnet)
New needles (Garnet)

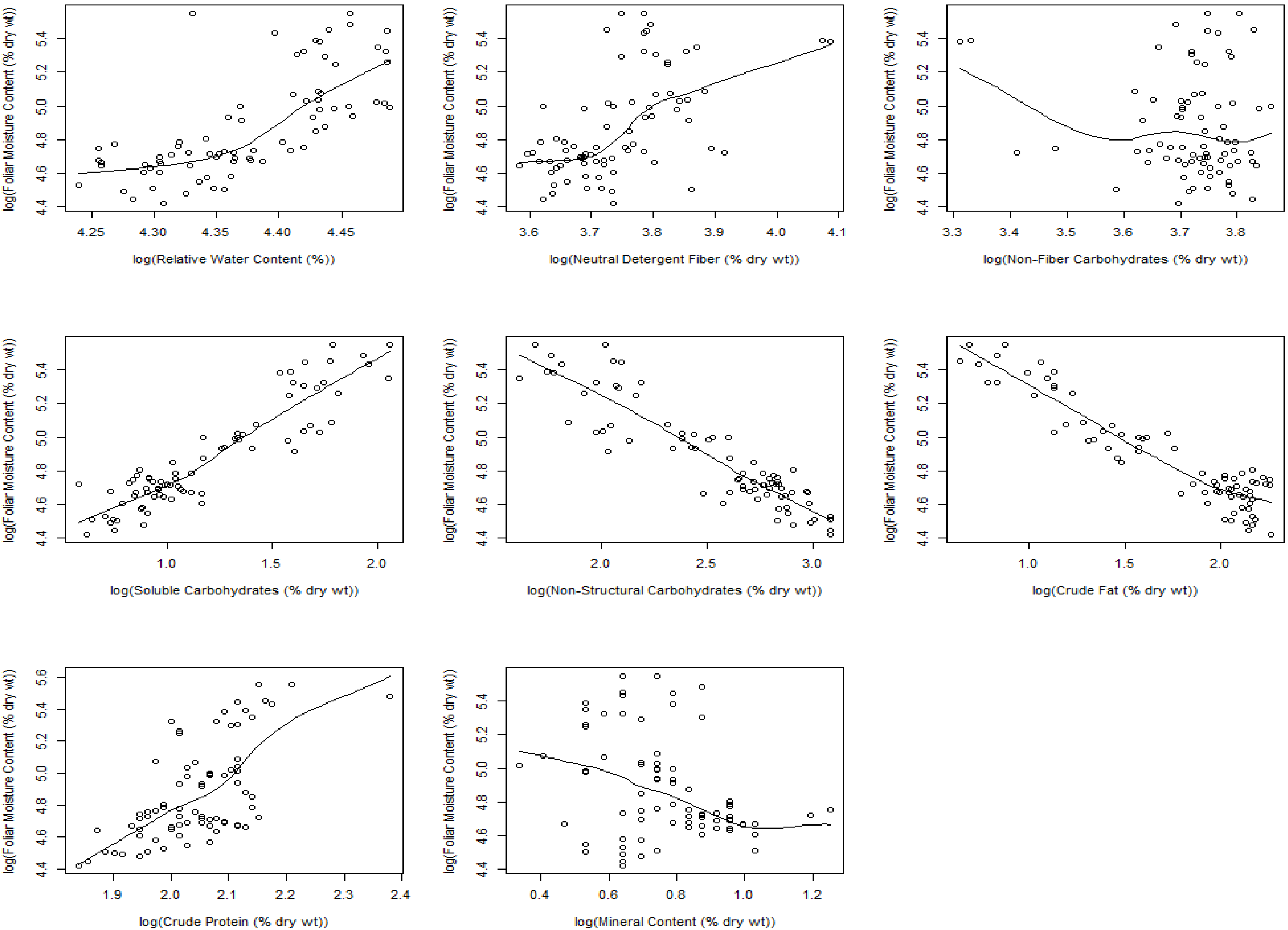
Seasonal changes in live fuel moisture content



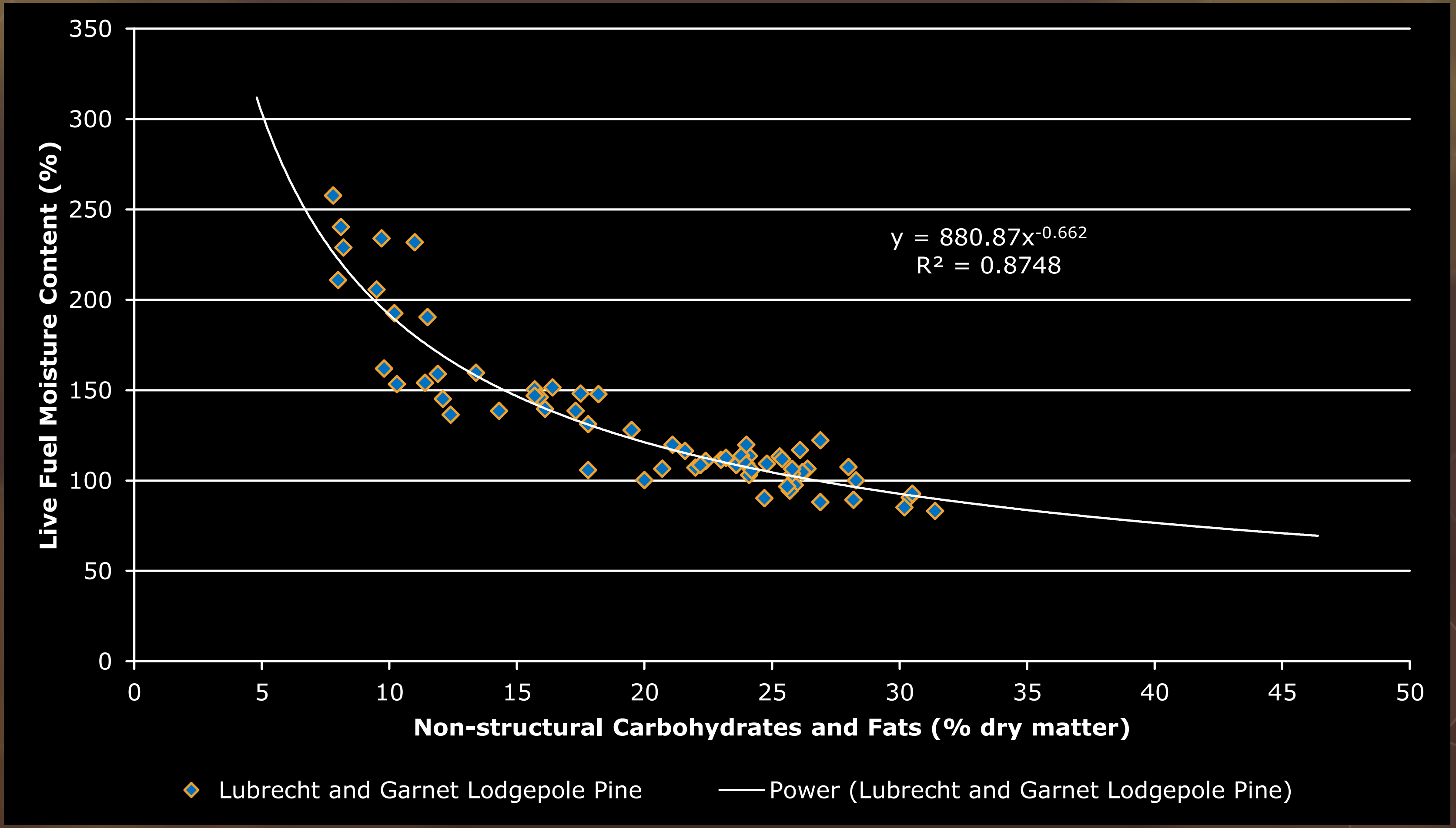
Seasonal changes in Relative Water Content



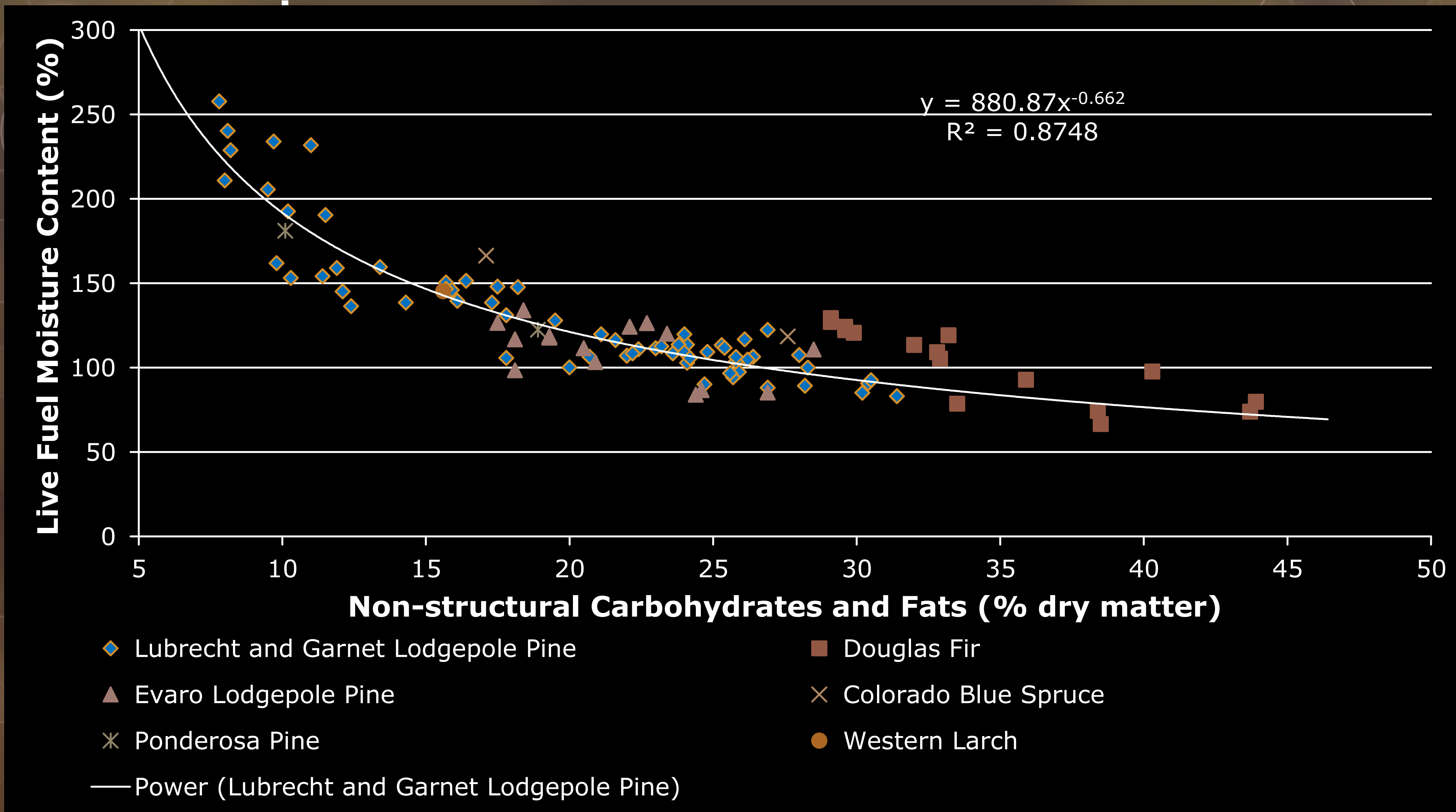
Modest changes in the relative water content throughout the season (~10%)


log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4
4.25 4.30 4.35 4.40 4.45
log(Relative Water Content (%))
log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4
3.6 3.7 3.8 3.9 4.0 4.1
log(Neutral Detergent Fiber (% dry wt))
log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4
3.3 3.4 3.5 3.6 3.7 3.8
log(Non-Fiber Carbohydrates (% dry wt))
log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4
1.0 1.5 2.0
log(Soluble Carbohydrates (% dry wt))
log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4
2.0 2.5 3.0
log(Non-Structural Carbohydrates (% dry wt))
log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4
1.0 1.5 2.0
log(Crude Fat (% dry wt))
log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4 5.6
1.9 2.0 2.1 2.2 2.3 2.4
log(Crude Protein (% dry wt))
log(Foliar Moisture Content (% dry wt))
4.4 4.6 4.8 5.0 5.2 5.4
0.4 0.6 0.8 1.0 1.2
log(Mineral Content (% dry wt))

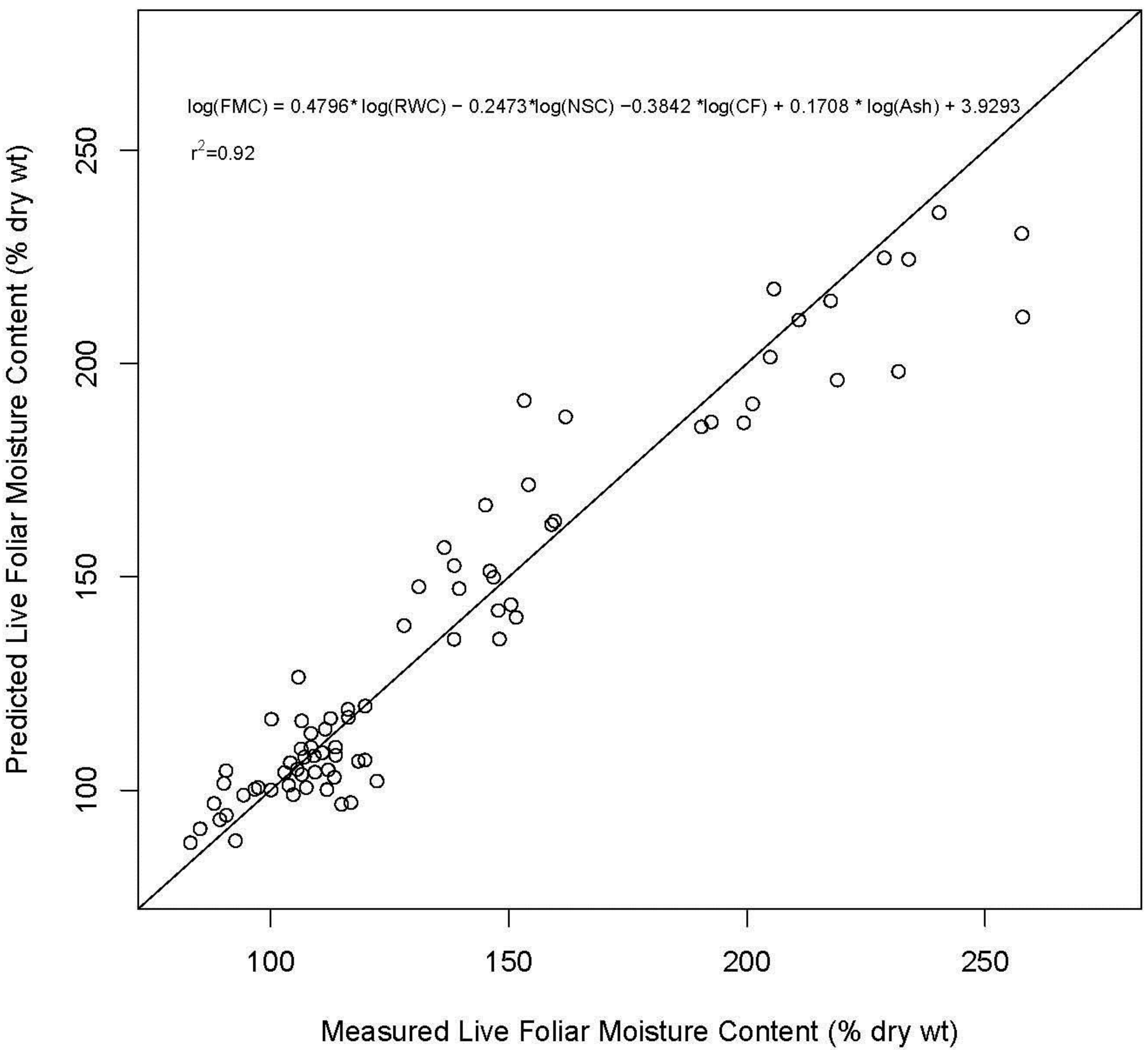
Non-structural carbohydrates, fats and live fuel moisture content for *Pinus contorta*



Non-structural carbohydrates, fats and live fuel moisture content across



Model predictions were improved when we included relative water content.


log(FMC) = 0.4796* log(RWC) − 0.2473*log(NSC) −0.3842 *log(CF) + 0.1708 * log(Ash) + 3.9293
r2=0.92
Predicted Live Foliar Moisture Content (% dry wt)
Measured Live Foliar Moisture Content (% dry wt)
100
150
200
250

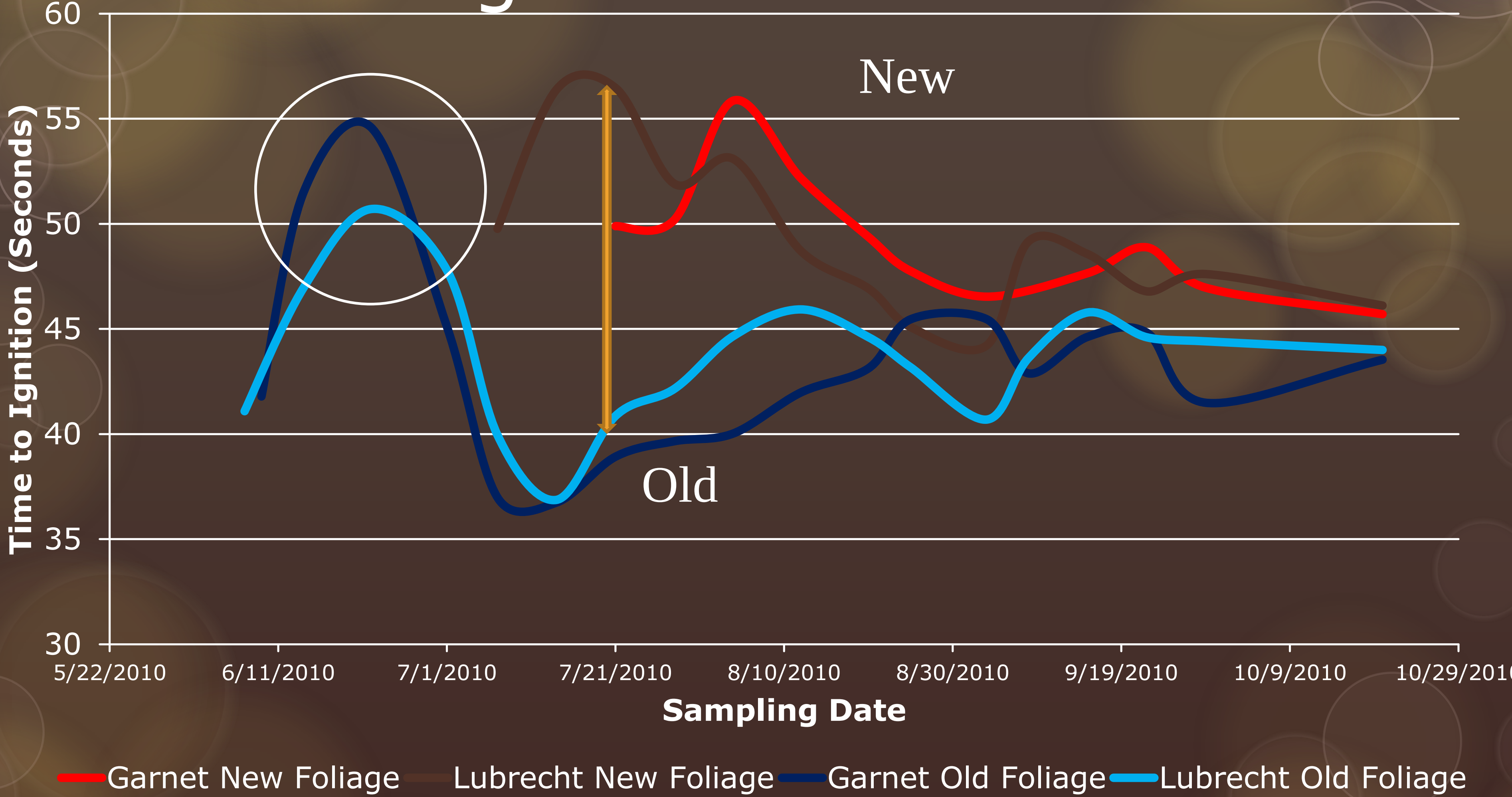
Live Fuel Ignition

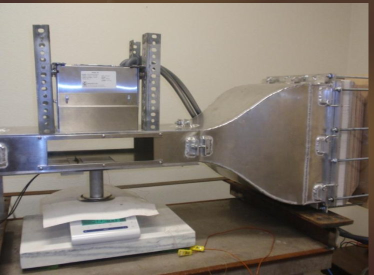
Ignition Appartus

Cordova, J., D. Walther, J. Torero, and A. Fernandez-Pello. 2001. Oxidizer flow effects on the flammability of solid combustibles. Combustion Science and Technology 164:253-278.

- Forced Ignition and Flamespread Test (Cordova et al. 2001)
  - Small-scale wind tunnel
  - Infrared heater
  - Coiled wire igniter
  - High precision mass balance
- Produces a uniform radiant heat flux of 50 kW/m^2 over the sample surface.
- All tests were performed with a fixed airflow velocity of 1 m/s
- **Time to ignition was measured for each sample**

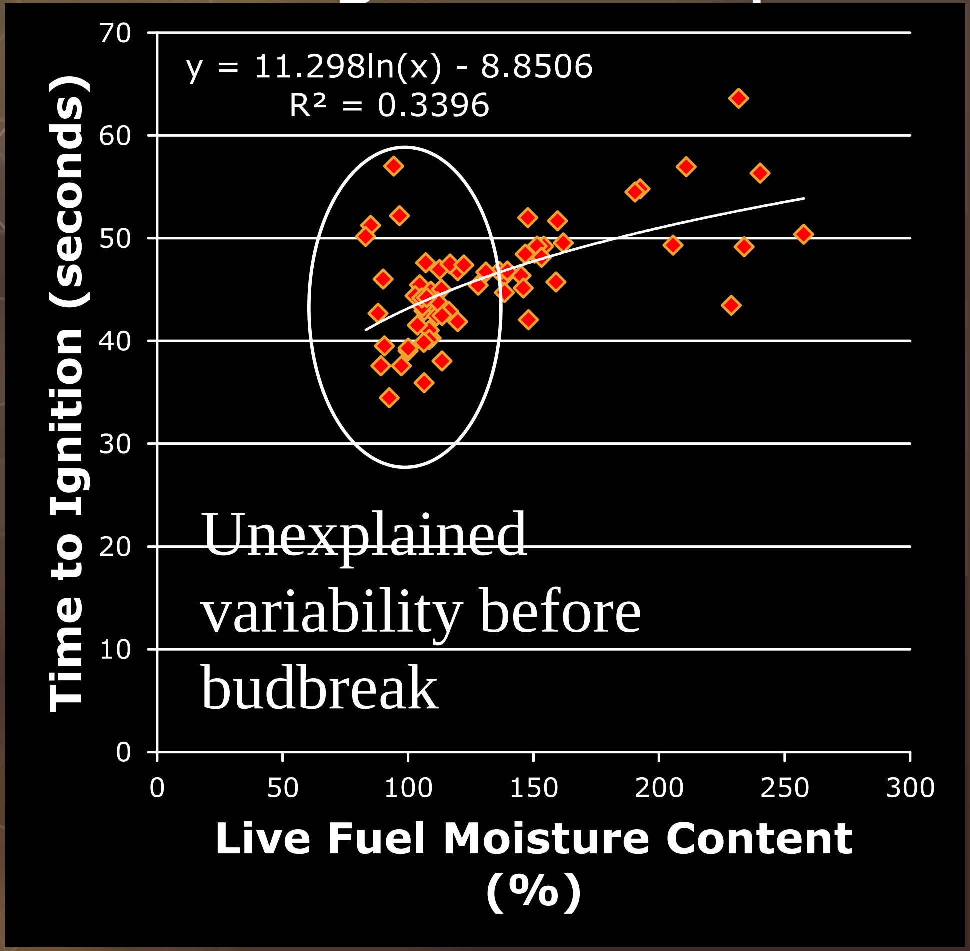
Time to ignition results



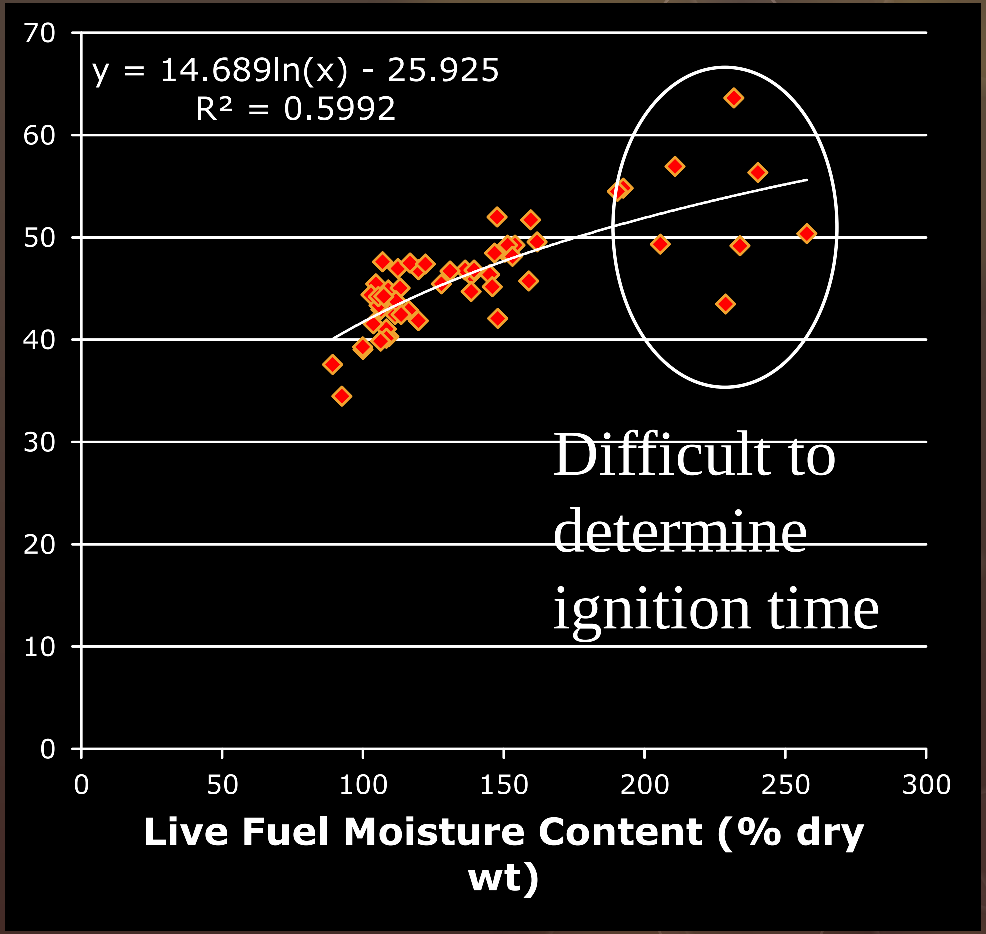


Moisture content explained about 34% of the variation in ignition timing and 60% after budbreak

Time to ignition versus moisture content for Lubrecht and Garnet using radiant panel



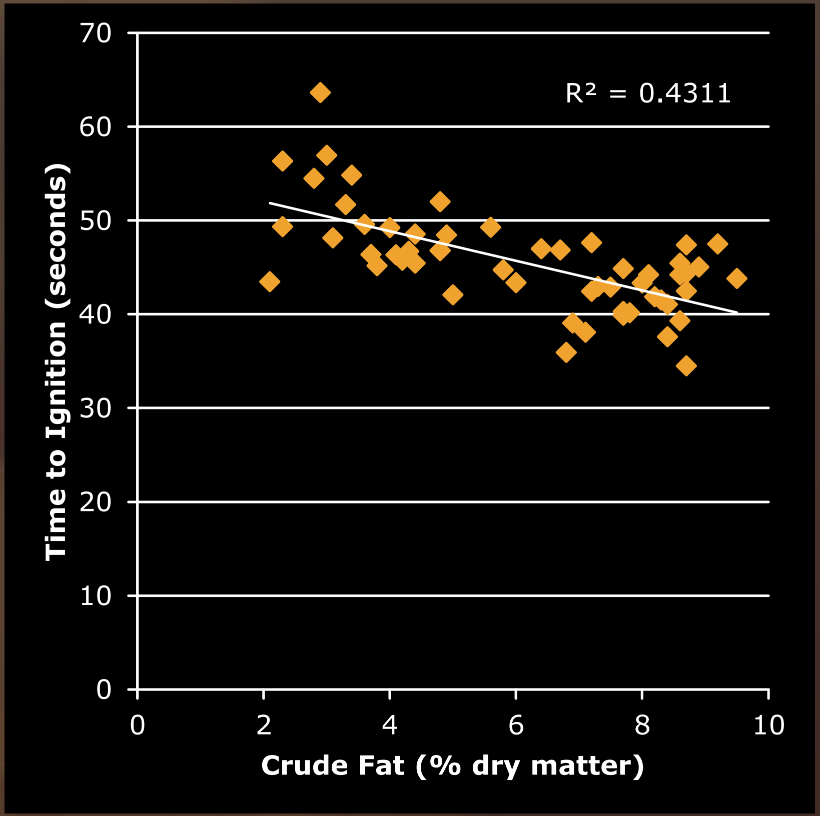
All data

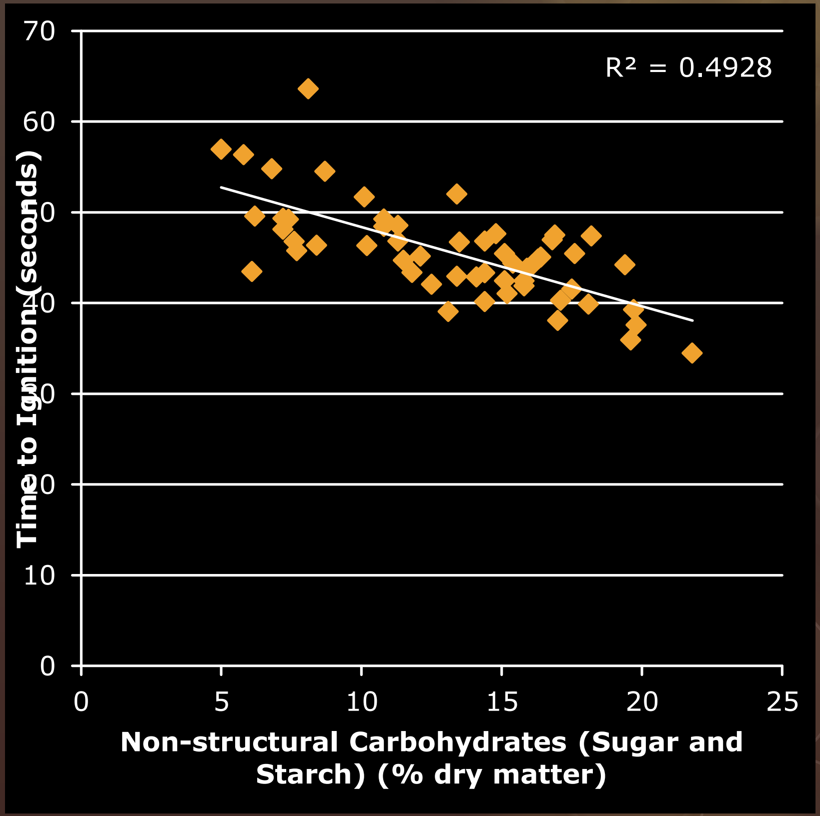


Post-budbreak Only

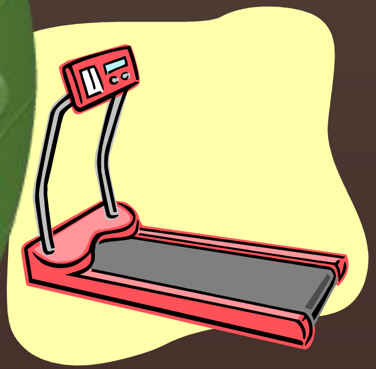
But…. Fat and NSC also explain a lot of the variability

Slopes are negative





Put our fuels on a low fat and low carbohydrate diet to make them less flammable



Nutrition Facts

Serving Size 5 Crackers (16g)
Servings Per Container About 28

Amount Per Serving

Calories 80	Calories from Fat 40
	% Daily Value*
Total Fat 4.5g	**7%**
Saturated Fat 1g	**5%**
Trans Fat 0g	
Polyunsaturated Fat 1.5g	
Monounsaturated Fat 2g	
Cholesterol 0mg	**0%**
Sodium 140mg	**6%**
Total Carbohydrate 9g	**3%**
Dietary Fiber less than 1g	**1%**
Sugars 1g	
Protein 1g	

Vitamin A 0% • Vitamin C 0%
Calcium 0% • Iron 2%

*Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs:

	Calories	2,000	2,500
Total Fat	Less than	65g	80g
Sat Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg
Sodium	Less than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g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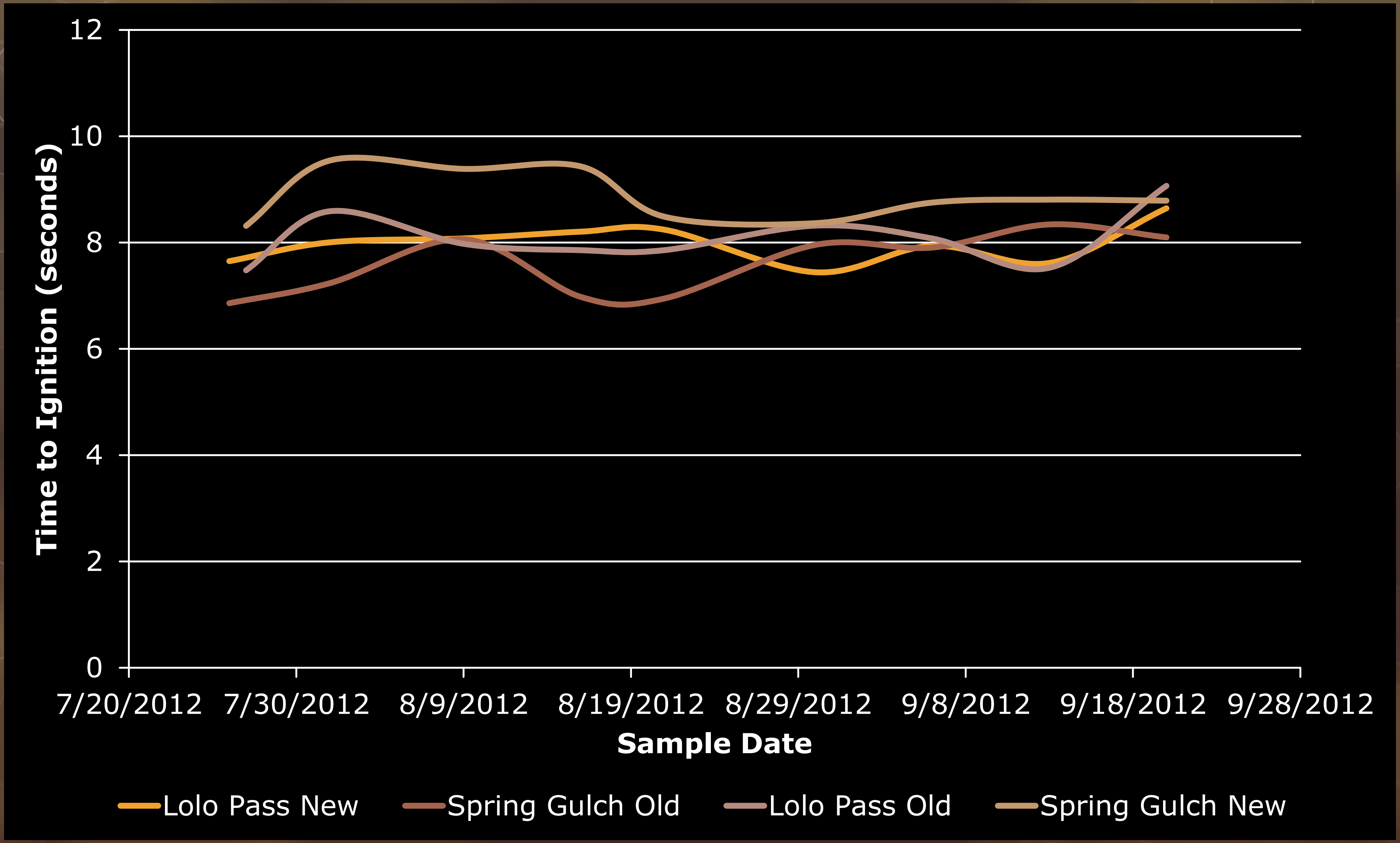
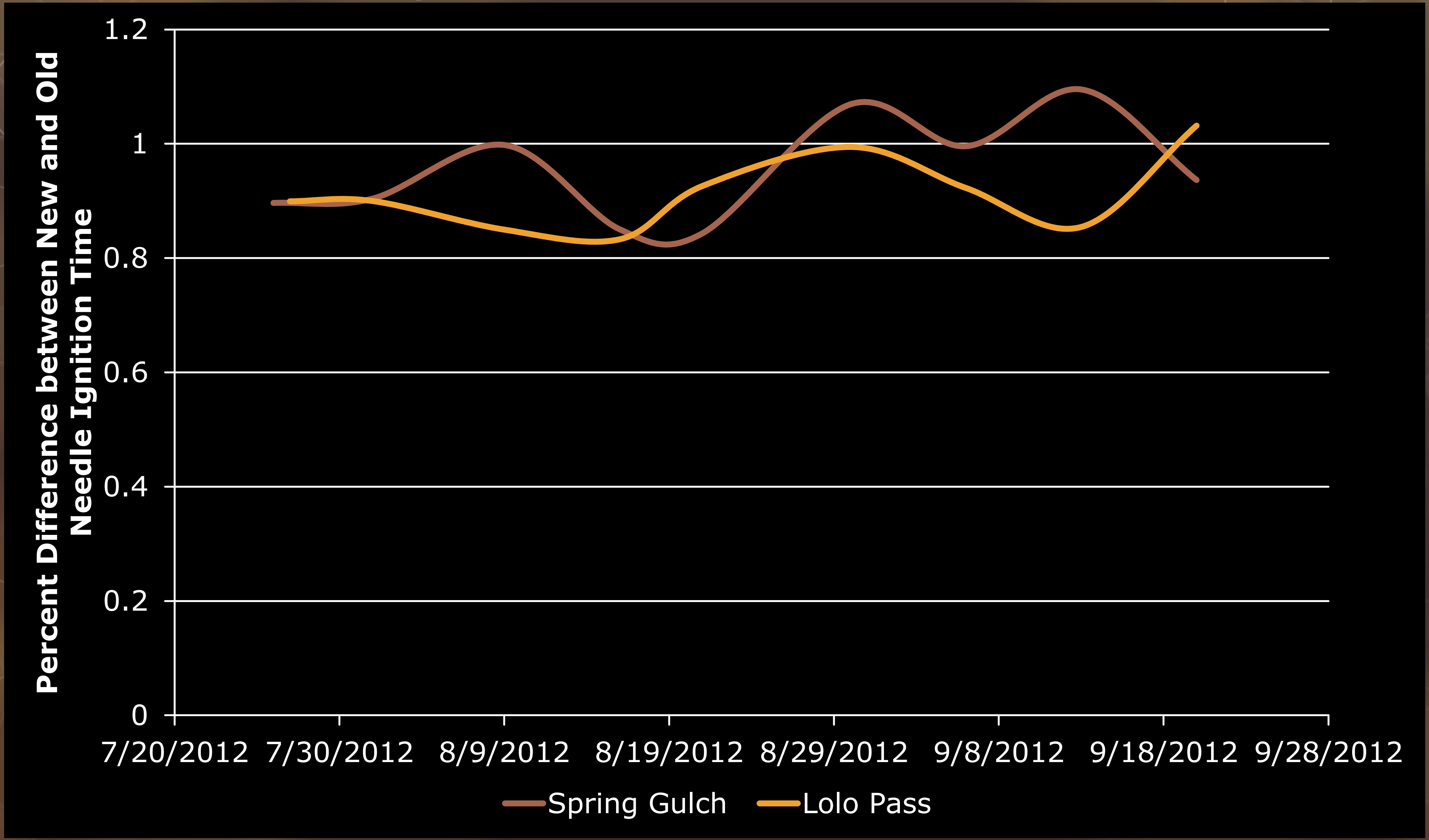
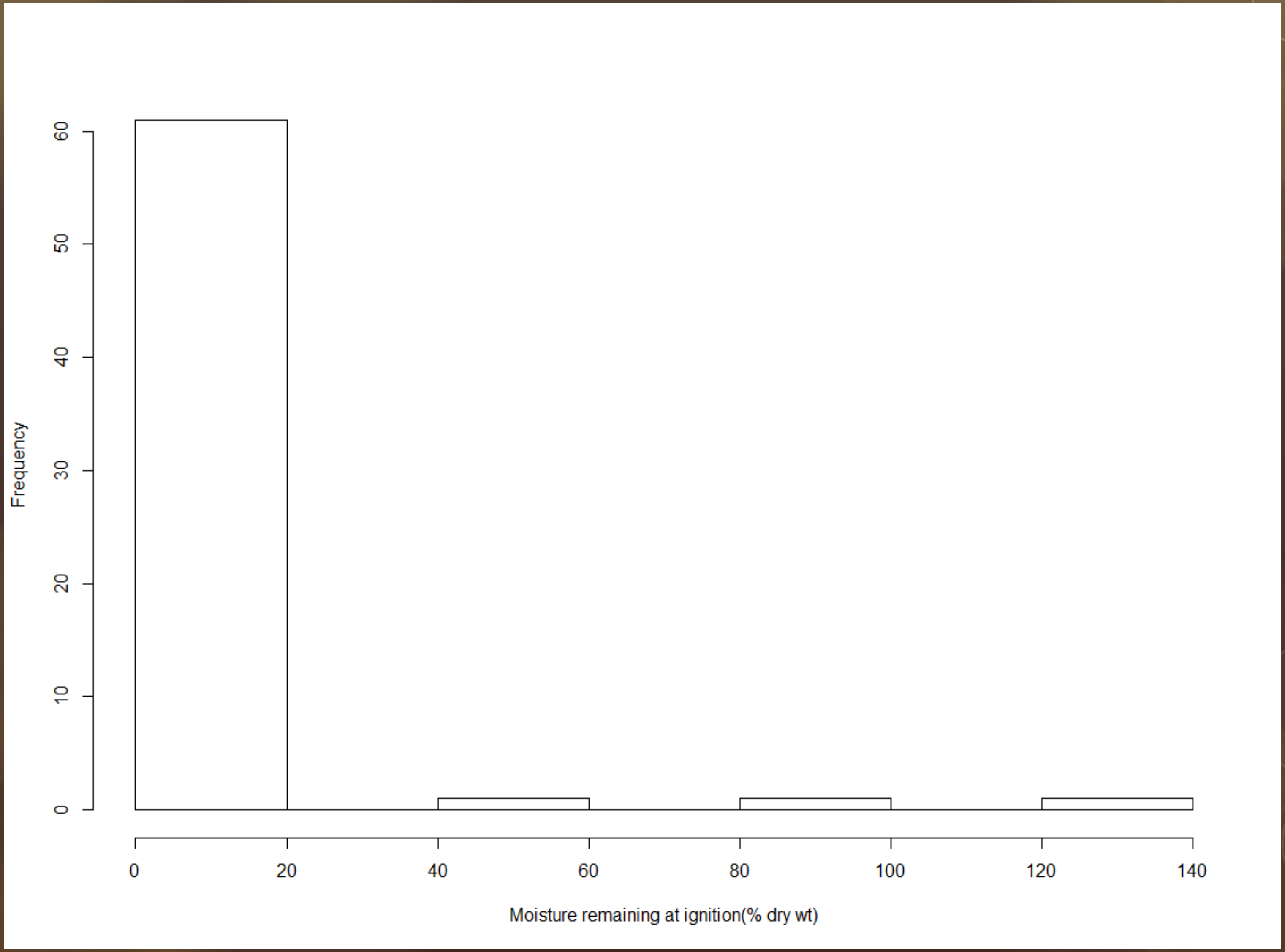
Open Flame Burner Ignition



Difference between new and old needle ignition



How much moisture is left at ignition?

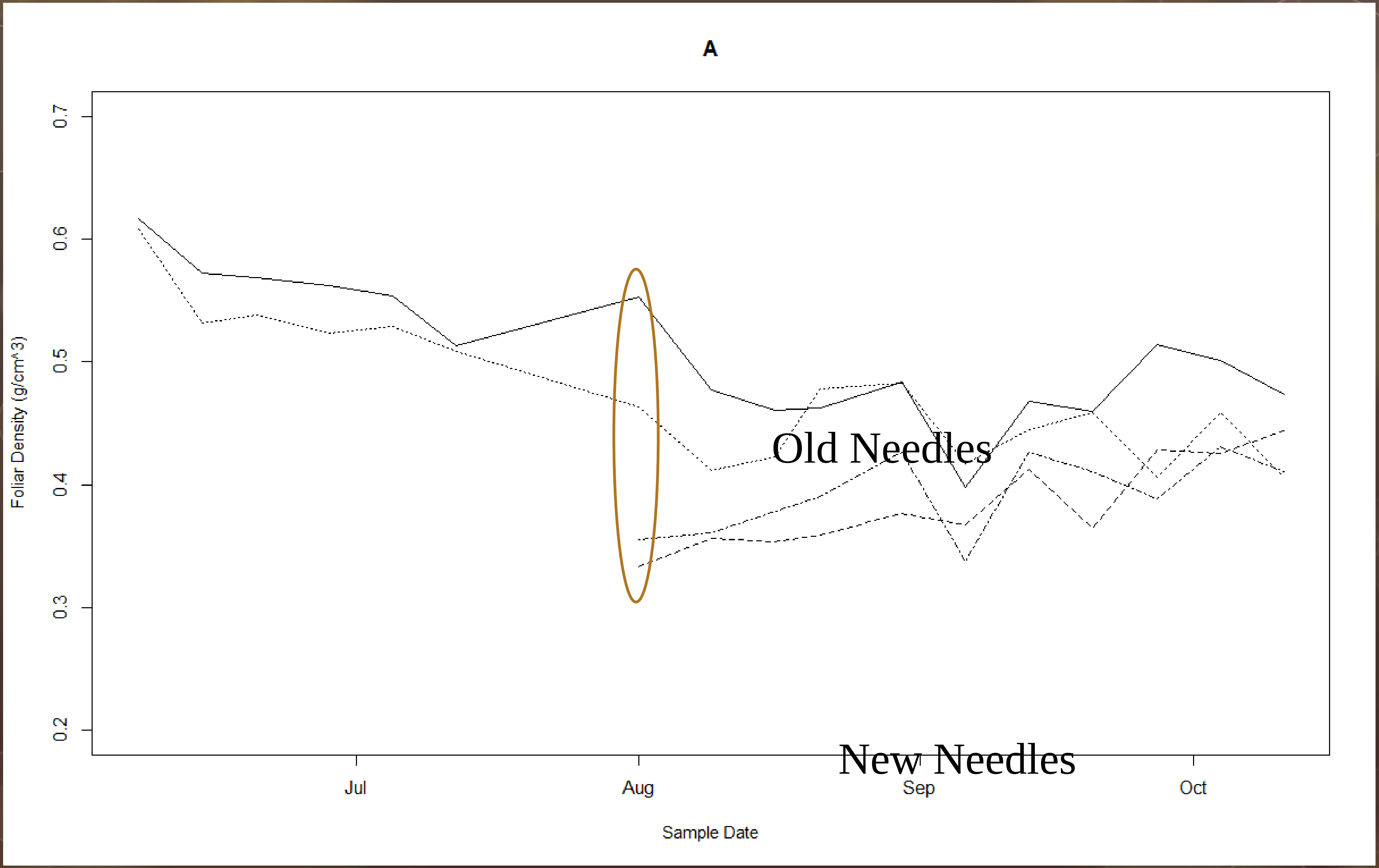


How does fuel chemistry affect the fuels physical and thermal properties?

Fuel Density

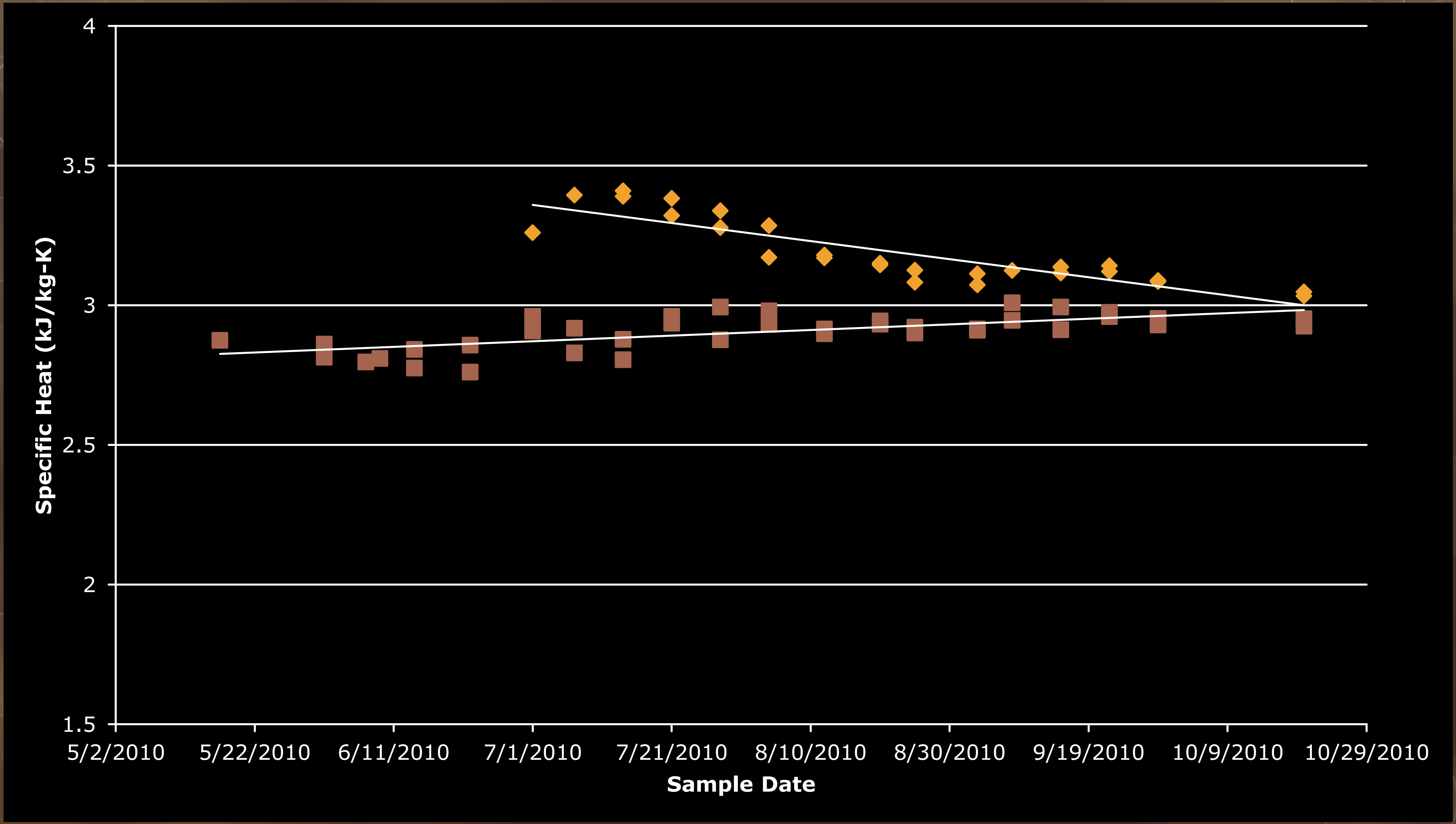
- Most models assume that fuel density is equal to that of wood
  - 520 kg/m^3
- Live fuel particle densities receive little thought


Foliar Density (kg/m^3)
700
600
500
400
300
200
Wood

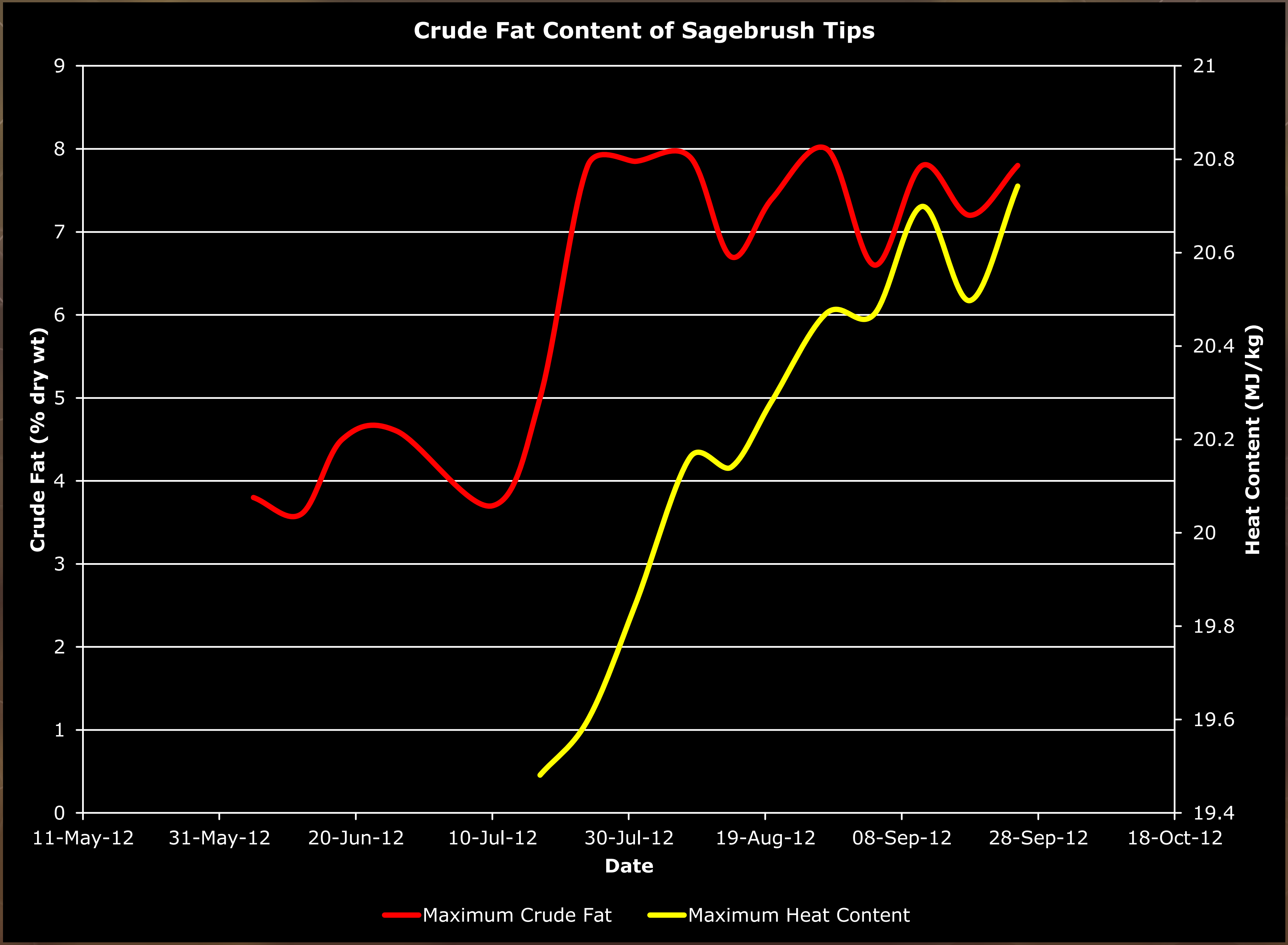


Ignition time is directly proportional to particle density

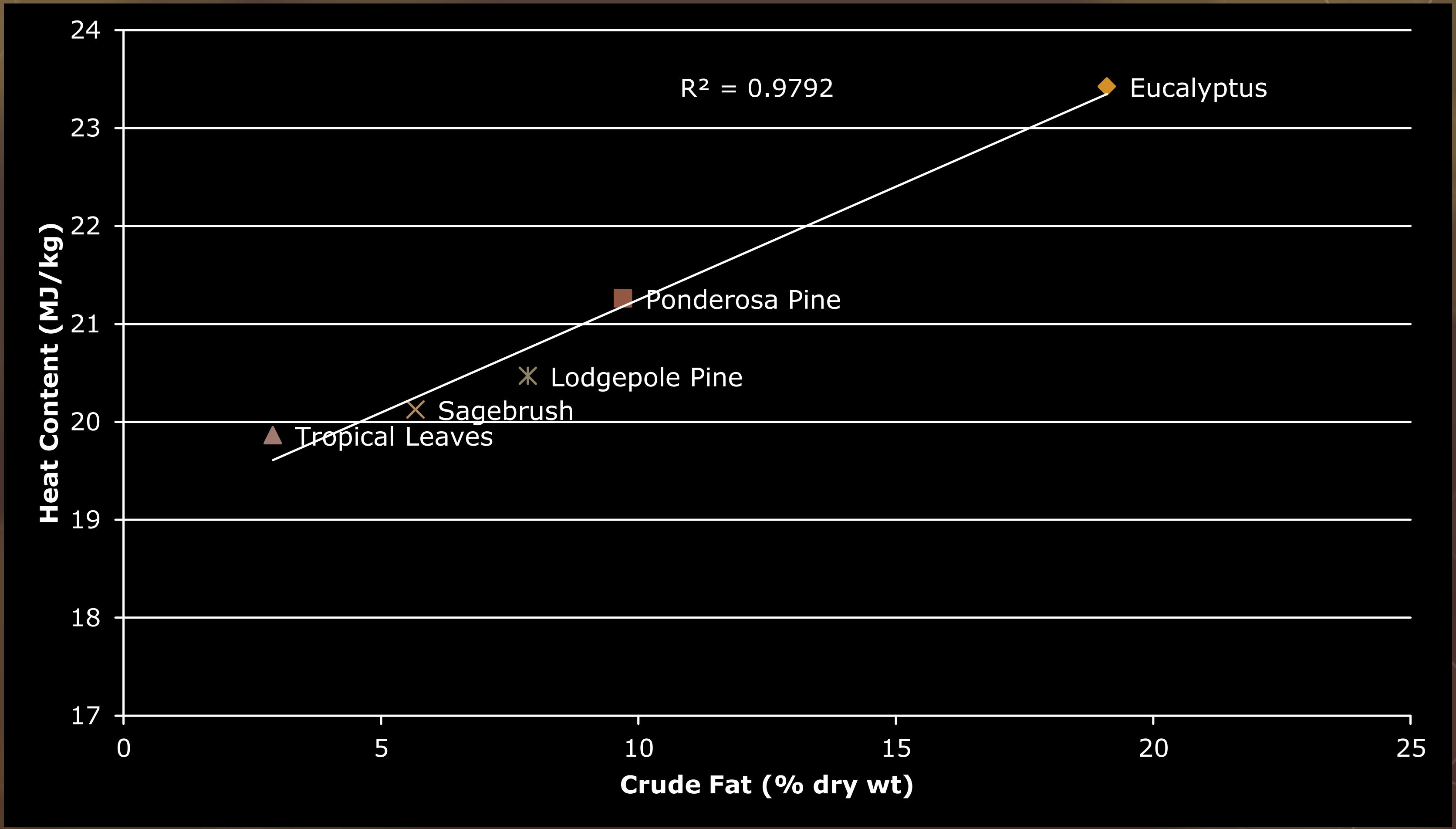
Specific Heat



$c_p = 4.180X_w + 1.711X_p + 1.928X_f + 1.547X_c + 0.908X_a$


Crude Fat Content of Sagebrush Tips
Crude Fat (% dry wt)
Heat Content (MJ/kg)
0
1
2
3
4
5
6
7
8
9
19.4
19.6
19.8
20
20.2
20.4
20.6
20.8
21
11-May-12
31-May-12
20-Jun-12
10-Jul-12
30-Jul-12
19-Aug-12
08-Sep-12
28-Sep-12
18-Oct-12
Date
Maximum Crude Fat
Maximum Heat Content

Crude Fat is closely related to heat content



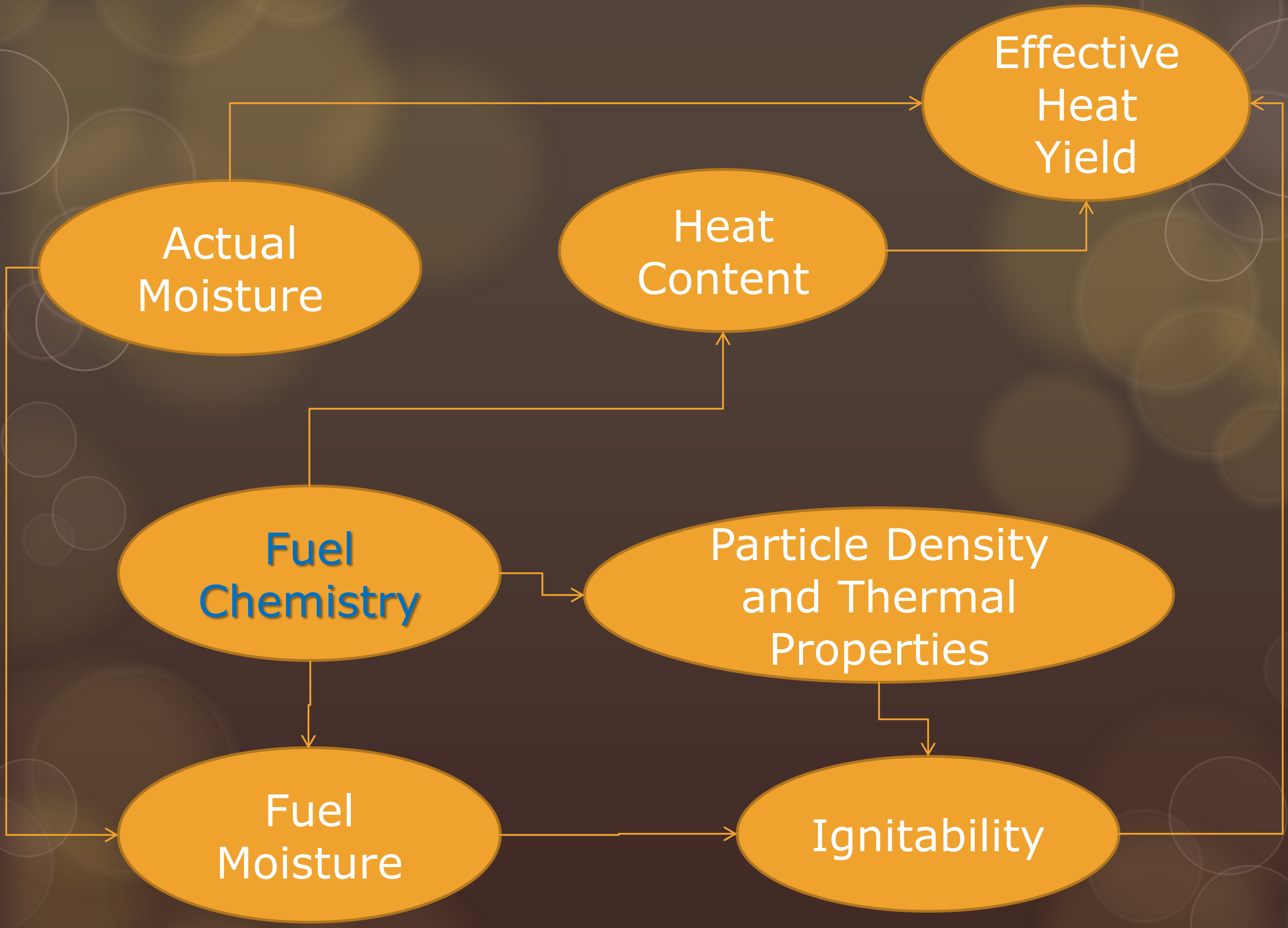
Putting it together

Decomposing the factors that regulate live fuel moisture content

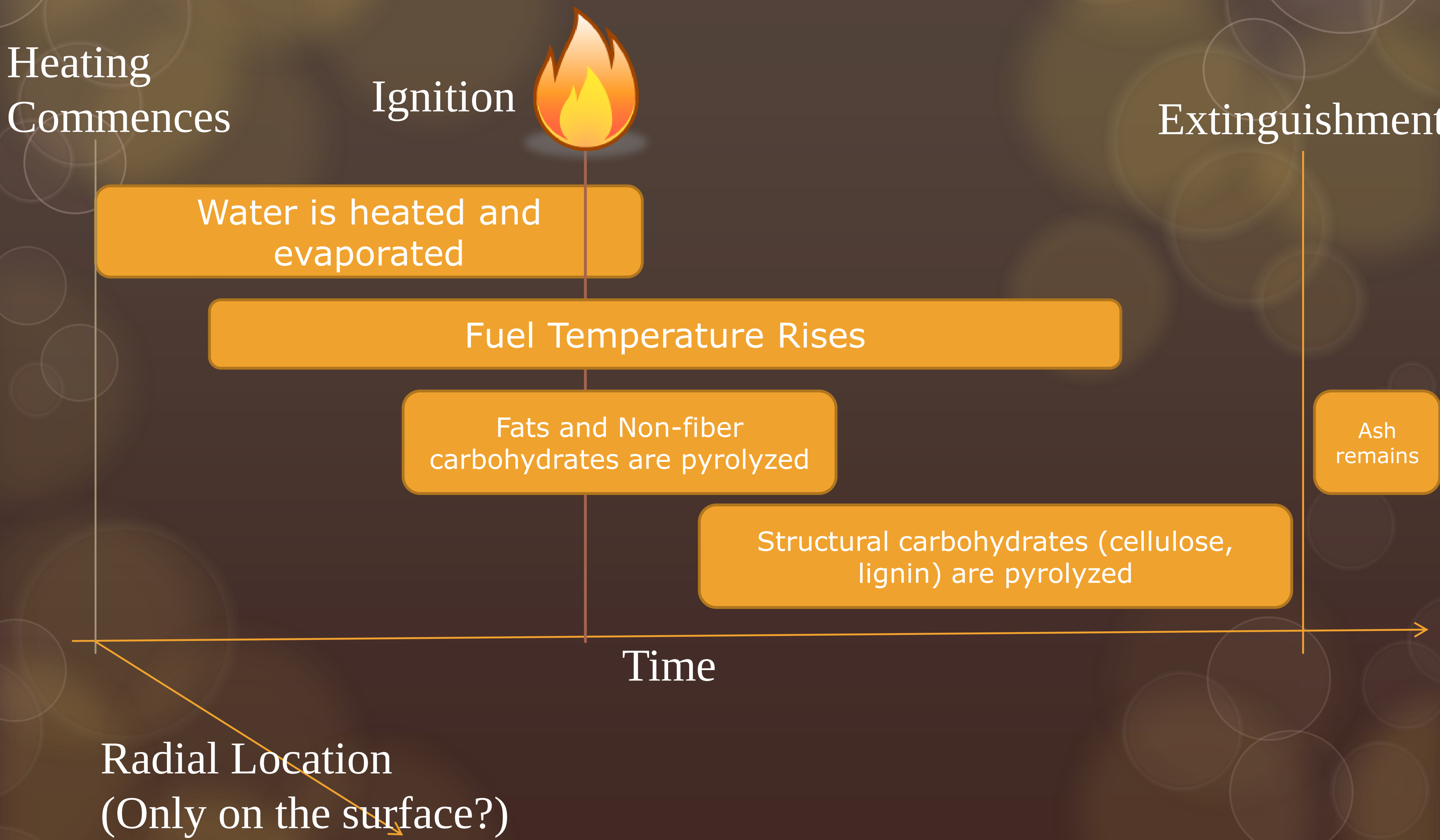
Related to transpiration and the plant water balance → **Relative Water Content / Leaf Water Potential**

$$Live\ Fuel\ Moisture\ Content\ (\%) = \frac{Fresh\ Weight\ (g) - Dry\ Weight\ (g)}{Dry\ Weight\ (g)}$$

Related to photosynthesis and carbon allocation → **Non-structural Carbohydrates and Fats**


Effective Heat Yield
Heat Content
Actual Moisture
Fuel Chemistry
Particle Density and Thermal Properties
Fuel Moisture
Ignitability

Theoretical heating model of a live fuel



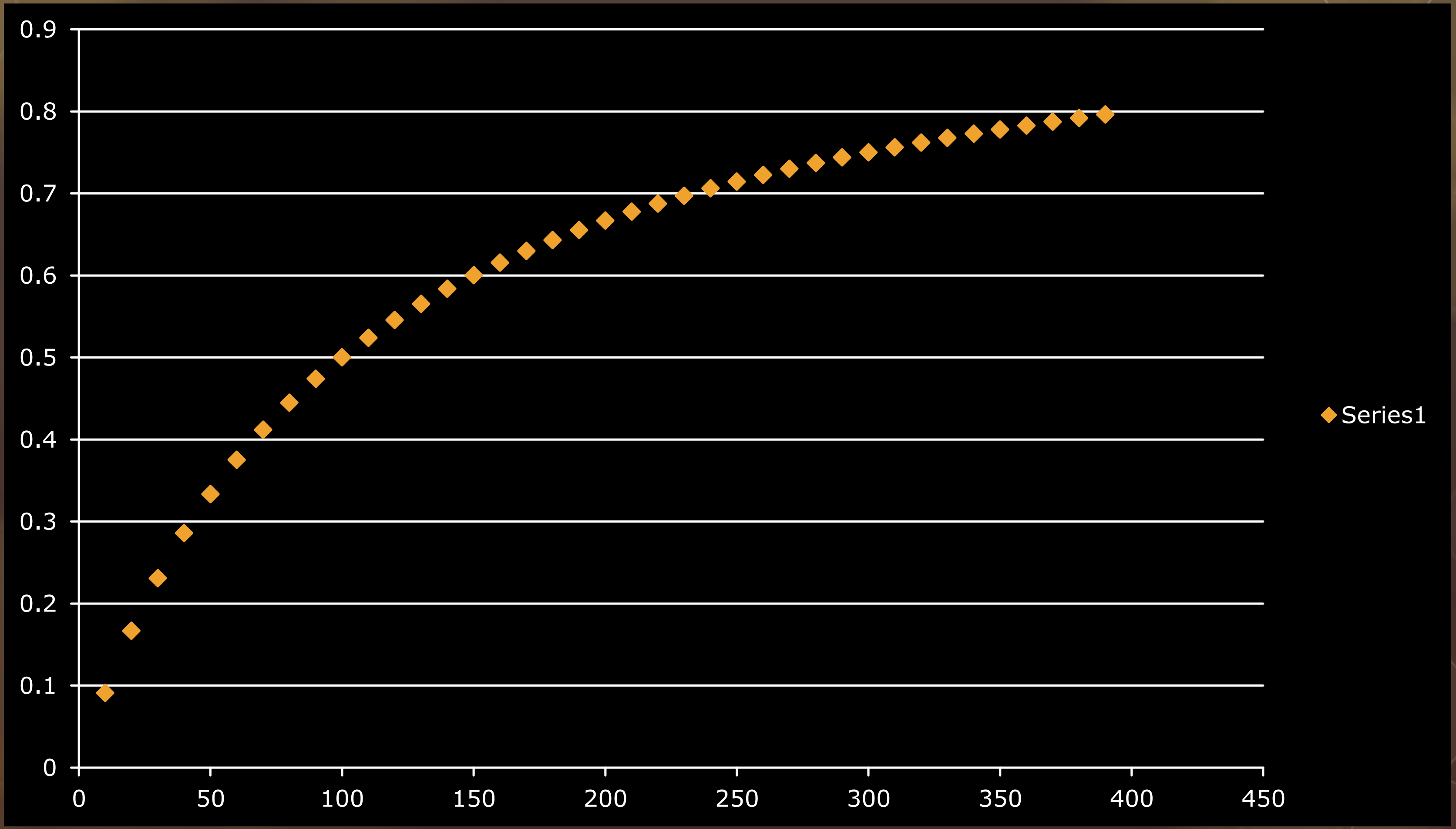
Summary

- There is no 'Smoking Gun'
- A higher percentage of conifer needles is allocated to non-fiber compounds than fiber compounds
  - *Not* cellulose, hemicellulose and lignin
- Seasonal live fuel moisture content variations are more closely related to dry weight partitioning than changes in water availability
  - Can be modeled using standard physiological metrics of plant functions
- Under rapid heating, we cannot assume that fuels are thermally thin
- Everything is correlated! The fundamental question is still "What is burning" and "When is it burning"
  - What is the least combustible mixture and what compounds are decomposing first to provide initial ignition?

Special Thanks

United States Joint Fire Science Program and the United States National Fire Decision Support Center for providing funding and other support for this study.

Questions?


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
Series1