Time to ignition is influenced by both moisture content and soluble carbohydrates in live Douglas fir and Lodgepole pine needles

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Abstract
Living plants are often the primary fuels burning in wildland fire but little is known about the factors that govern their ignition behavior. Moisture content has long been hypothesized to determine the characteristics of fires spreading in live fuels but moisture content alone fails to explain observed differences in the ignition of various species at different times of the year. Furthermore, little concern has been given to balance between the moisture content and chemical composition of live fuels and how this balance of might affect the net energy required to produce the combustible mixture of gases that is necessary for flaming combustion. Here we examine the time to ignition of two species of live fuels, Douglas Fir (*Pseudotsuga menzeseii*) and Lodgepole Pine (*Pinus contorta*). Live fuels are collected throughout the season and their time to ignition quantified. Additionally, we assess the moisture content and carbohydrate composition of each sample. We found that time to ignition was significantly correlated with moisture content but that moisture content alone only explains about 46% of the variability in time to ignition for both species. However, when moisture content is combined with a simple metric of available carbohydrates, 85% of the variability in ignition timing was explained using the same model for both species. These results suggest that while moisture content plays an important role in determining the time to ignition of live plants, additional information about the distribution of carbon-based compounds in the foliage is equally as important. This metric may serve as a simple way to assess the flammability of foliage and to determine the characteristics that make some plants more easily ignited than others.

Keywords: live fuel, moisture content, carbohydrates, combustion, time to ignition

1. Introduction

Living plants comprise a large proportion of the fuels that are consumed in wildland fires each year but very little is known about what controls their ignition behavior. For decades, the amount of water held in living foliage has been assumed to determine its fire behavior (Fons 1946, Fosberg and Schroeder 1971, Rothermel 1972, Countryman 1974). However, vaporizing the moisture within a leaf represents only a portion of the total energy required to heat the fuel; it doesn't consider the variation of the specific heat of the fuel, the enthalpy of pyrolysis, and the specific heat of the char residues (Sussot 1982). Essentially, ignition of any wildland fuel depends on the ability of the heat source to raise the temperature of the fuel high enough to generate sufficient quantities of the gases that support flaming combustion. Intuitively, if some carbon-based compounds were more easily pyrolyzed and more readily available than others, there may be a pool of carbon compounds that could rapidly contribute pyrolyzates for flaming combustion even in the presence of higher moisture contents. This suggests that the ignition time may be a balance between the energy required to vaporize the moisture and the availability of compounds that can produce the necessary combustible gases. Both of these quantities are highly regulated by the physiology of the plants.

Seasonally, physiological processes can alter both the moisture content of leaves and the types chemical compounds found in them. Transpiration, or leaf water lost through small pores in its surface, and uptake of water from the plant's roots controls the moisture content of the vegetation. Water loss can be tightly regulated by the plant and the water balance of plants is highly seasonal, depending on external drivers such as precipitation and the moisture deficit of the air surrounding the leaves (Larcher 1995). Plants must balance controlling the loss of water with the need to take up carbon for photosynthesis. Photosynthesis fixes atmospheric carbon and provides the substrates and energy needed to create and maintain biomass. Various types of compounds are formed by the plant to meet the many needs of growth, respiration and defense. Nearly 50% of a leaf is composed of carbon, and most of this carbon is split equally between structural and non-structural carbohydrates. These compounds are the fundamental elements that are decomposed into the gases that support flaming combustion in both live and dead fuels but no work has been done at quantifying the potential impacts of seasonal changes in carbohydrate chemistry on the ignition of live fuels. Therefore, physiological processes might influence the seasonal changes in both the moisture content and the seasonal availability of pyrolyzates in live fuels.

In this study, we examine how foliar moisture content and leaf carbohydrates interact to regulate the time to ignition of two species of live fuels, Douglas Fir (*Pseudotsuga menzeseii*) and Lodgepole Pine (*Pinus contorta*). Moisture content and carbohydrate chemistry are quantified for samples of live fuels throughout the season. In addition, samples are ignited beneath a radiant heater and their time to ignition is quantified. We hypothesize that there is an interactive effect between leaf moisture and carbohydrate content and that the combination of both is a better predictor of flammability than simply moisture content alone.

2. Materials and Methods

An apparatus was built to measure the ignition time and critical mass flux (CMF) for sustained flaming ignition of woody materials for varying environmental conditions such as heat flux (heating rate) and airflow velocity (wind). Although the critical mass flux was not used for this analysis, future research will explore the relationship between CMF, moisture content, and leaf chemistry. This apparatus, based on the Forced Ignition and Flamespread Test (Cordova et al. 2001), consists of a small-scale wind tunnel, infrared heater, coiled wire igniter, and a high precision mass balance (see Figure 1). The tunnel is 9 cm tall, 25 cm wide, and 60 cm long. A fan at the entrance produces a laminar forced airflow through the tunnel with a velocity ranging from 0.8 to 1.6 m/s (corresponding to Reynold's numbers of $3\text{-}6{\cdot}10^4$, well under the transition to turbulent flow). The sample holder, measuring 9 cm by 9 cm with a depth of 2.5 cm, is a thin, lightweight aluminum box lined with Cotronix paper and a 1.27 cm thick Cotronix[1] board on the bottom. The sample holder is placed on top of the mass balance with the upper surface of the sample flush with the bottom of the tunnel. The sample is heated from above using an infrared heater capable of producing a uniform heat flux of 0 to 50 kW/m^2 over the sample surface. As the sample is heated, pyrolysis begins. The forced flow pushes the pyrolysis gases into the coiled Kanthal[1] wire igniter that initiates ignition. To remove the igniter location as a potential variable in the experiments, the 3.5 mm diameter igniter is fixed 1.2 cm downstream of the sample, centered 6 mm off the bottom, a position which covers the entire fuel concentration boundary layer. Additionally, the igniter consisted of a fixed number of coils and the supplied current was calibrated to keep the igniter above 1000°C. The time to ignition is recorded visually as the time from the initiation of heating until a flame is sustained over the surface of the sample. All tests were performed with a fixed airflow velocity of 1 m/s and an irradiance of 50 kW/m^2. All tests are repeated three times to provide an estimate of the experimental variability.

Tests were performed with two species: Lodgepole pine and Douglas fir. Each week the samples from both species were gathered and processed the same morning. Small branches were cut from the lower sections of the trees and brought into the laboratory. Care was taken to minimize transpiration losses by keeping the branches intact and out of the sun and heat. The needles were cut from the branch, only taking green needles from the previous year's growth. All needles were cut above the cuticle where the needle attaches to the branch. Once removed from the branches, seven samples of each species were weighed, three to be burned immediately ("live" samples) and four to be dried in the oven at 50°C for at least 48 hours prior to being burned ("dry" samples, results not reported here). The Lodgepole pine and Douglas fir samples were 6 g and 4 g, respectively, and were weighed within 0.05 g. An additional 40 g was weighed for the carbohydrate analysis. When placed into the sample holder, sheets of Cotronix[1] paper were used to support the needles such that they were flush with the surface of the sample holder and all samples were arranged to cover as much surface area as possible. For comparison purposes, photographs were taken of the arrangement of each sample. For example, see Figure 2.

Leaf chemical composition was determined using the wet reference method by an external forage testing laboratory (AgriAnalysis). The analysis provided measurements of neutral

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[1] Trade names used for information only and do not constitute a product endorsement.

detergent fiber (NDF), crude fat (CF), crude protein (CP) and ash content (AC). Non-fiber carbohydrates (NFC) were calculated by the difference method using the following equation:

NFC = 100 - NDF + CF + CP + AC

Neutral detergent fiber quanitifies the structural carbohydrates such as cellulose, hemicellulose and lignin, while non-fiber carbohydrates are generally water soluble and represent primarily sugars, starches, and other non-structural carbon compounds in the leaves.

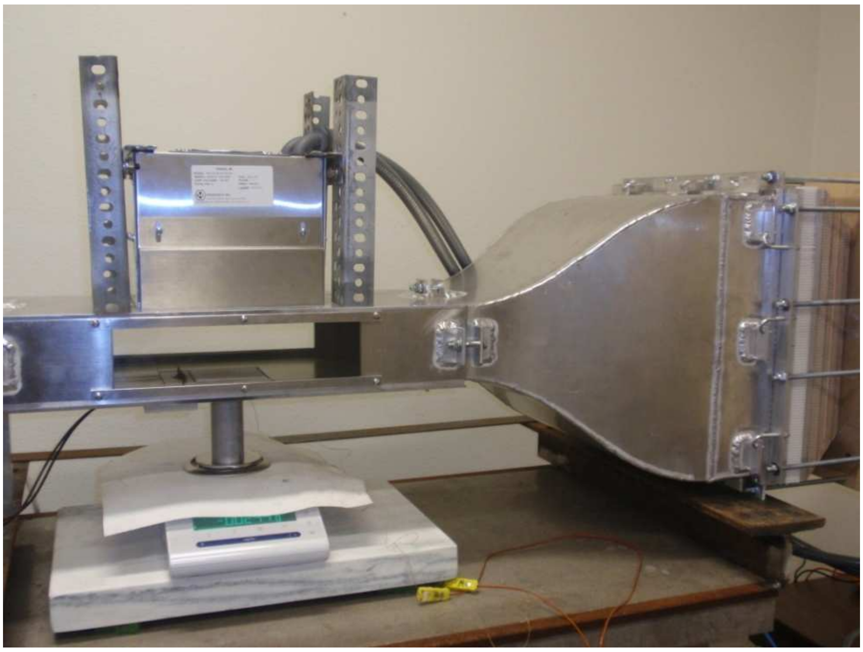

Figure 1 -- Experiment apparatus: small-scale wind tunnel with high precision balance

Figure 2 -- Lodgepole pine (left) and Douglas fir (right) samples

3. Results and Discussion

Table 1 – Mean time to ignition, moisture content, non-fiber carbohydrates and moisture content / non-fiber carohydrate ratio for the two species tested.

Species	Mean Time to Ignition (seconds) (n = 12 for both)	Mean Moisture Content (% dry wt)	Mean Non-fiber carbohydrates (% dry wt)	Mean ratio of moisture content to non-fiber carbohydrates
Lodgepole Pine	46.1	104.53	43	2.43
Douglas Fir	35.86	91.77	58	1.6

A summary of the time to ignition, moisture contents, non-fiber carbohydrates and the MC/NFC ratio is given in

Table 1. The data suggest that on average, Douglas fir ignited faster than lodgepole pine but it also had a lower moisture content and higher non-fiber carbohydrate concentration. On average, Lodgepole pine took longer to ignite than Douglas fir because it had both a higher average moisture content and lower average non-fiber carbohydrate concentration.

Mean ignition times for Douglas fir were 46.1 seconds compared to 35.6 seconds for Lodgepole pine. Time to ignition versus the moisture content of both species are shown in Figure 3. There is a strong relationship between moisture content within species but when species are combined, there are clearly differences in the time to ignition between species that are not explained by moisture content alone. Individually, moisture content explains 72% and 74% of the variation in Lodgepole pine and Douglas fir ignition times respectively but when pooled , it only explains 46% of the variance due to the species effect. In general, as the moisture content increases the time to ignition increases.

Overall, the combined ratio of moisture content and non-fiber carbohydrates explained more of the variability in time to ignition than any either of the two variables individually. This suggests that moisture content and non-fiber carbohydrates work in counterpoint to each other. As the moisture content of the live fuels increases, the time to ignition increases, but as the non-fiber carbohydrate concentrations increase the time to ignition decreases. For example, on 30 March 2010, the fuel moistures for both Lodgepole pine and Douglas fir were nearly the same (130% vs 128%) but Douglas fir ignited 12 seconds faster than Lodgepole pine. When we examine the non-fiber carbohydrates for that sample period, we see that Douglas fir had substantially higher concentrations during that time (58.3% vs 41%). We propose that this represents a balance between the types of carbon compounds available for pyrolysis and the required vaporization energy of the moisture within the leaf. Essentially, higher moisture contents are partially compensated for by the presence of more easily pyrolyzed compounds such that a flammable mixture of gases can still be produced in the presence of high moisture contents. This might explain how igntion and combustion can occur with materials with high water content.

The relationship between non-fiber carbohydrates and time to ignition is shown in Figure 4. The two species appear to ordinate into easily seperable groups. In general, as the non-fiber carbohydrate concentration of a leaf increases, the time to ignition for that leaf decreases.

The average non-fiber carbohydrates of Lodgepole pine and Douglas fir needles was 43% and 58% respectively.

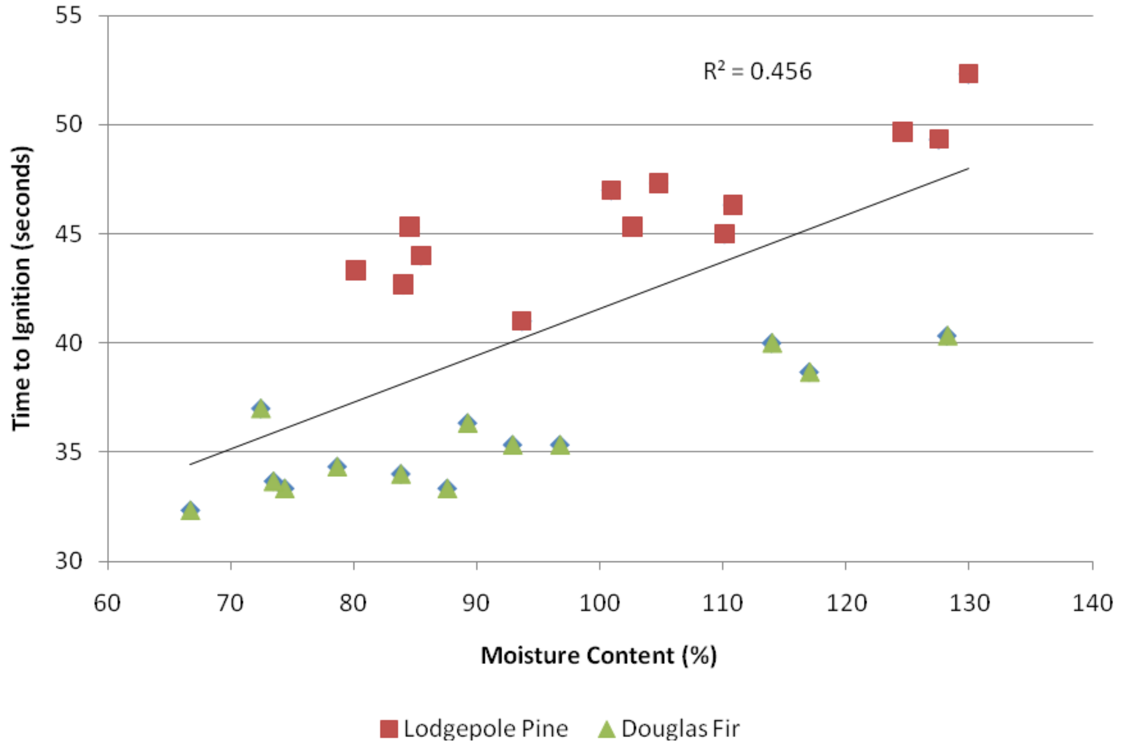

Figure 3 -- Time to ignition versus moisture content for Lodgepole pine and Douglas fir.

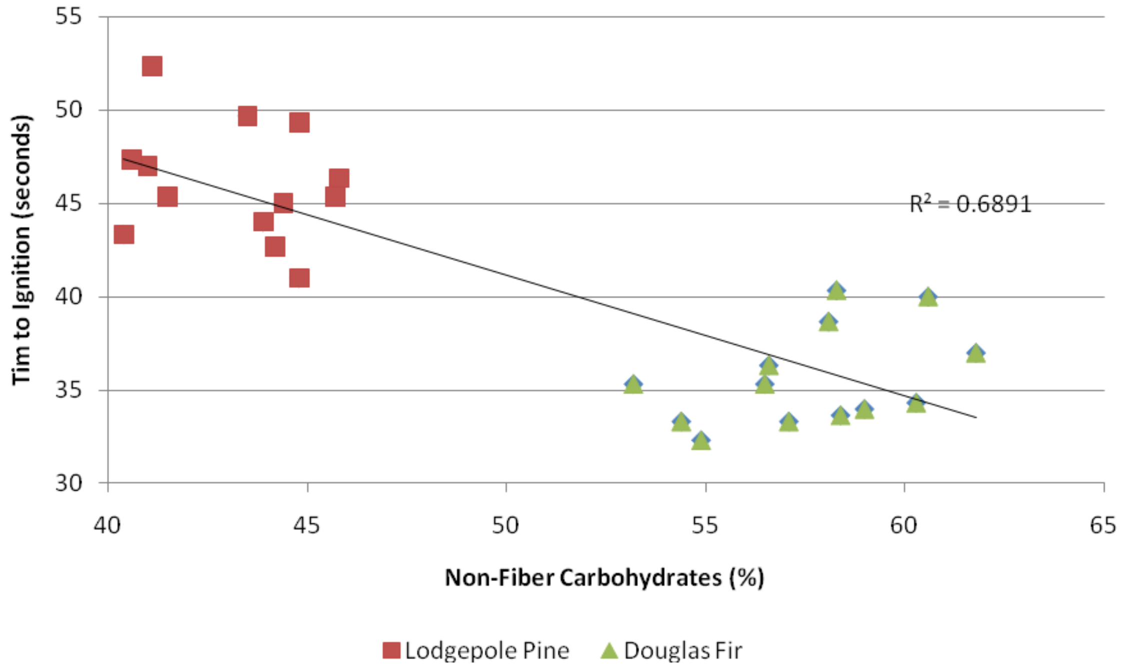

Figure 4 -- Time to ignition versus non-fiber carbohydrates for Lodgepole pine and Douglas fir.

Based on the opposing trends shown in Figure 3 and Figure 4, we plotted the time to ignition against the ratio of moisture content and non-fiber carbohydrates (MC/NFC) and these results are shown in
Figure 5. This ratio explains 85% of the variation in ignition timing for both species using a common linear model.

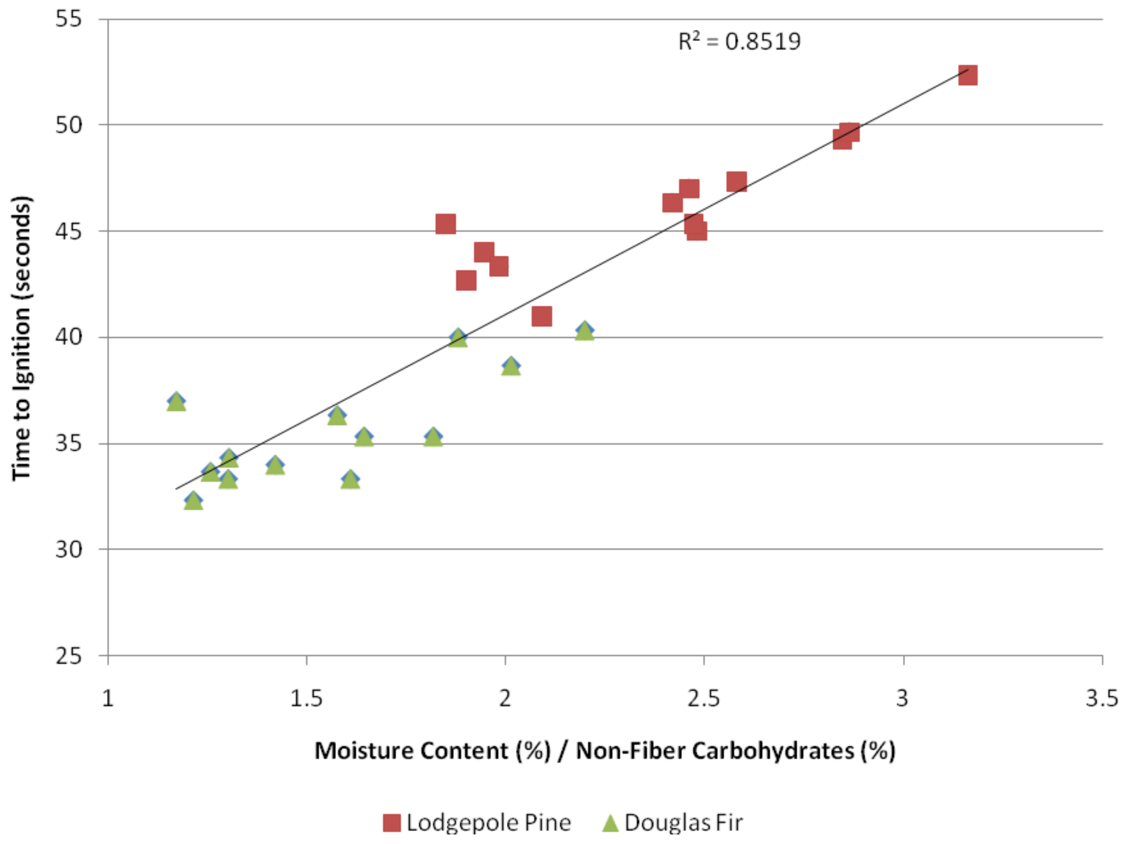

Figure 5 – The ratio of moisture content and non-fiber carbohydrate percentage compared to time to ignition.

Historically, little, if any, attention has been given to the types of carbon compounds that compose a leaf and how differences in these compounds may change their flammability. However, researchers have observed that leaves are more flammable than branches (Dimitrakopoulos and Papaioannou 2001), even though branches may have similar moisture contents. Differences in geometry and thermal properties between leaves and branches could explain part of these differences but chemical differences may also play a role. Wood is mostly composed of structural carbohydrates while leaves generally have more non-structural carbohydrates. Given the same moisture content, our results would suggest that materials with lower non-structural carbohydrates would take longer to ignite and thus may explain these observed flammability differences between leaves and wood.

Traditional (empirical) time to ignition models for wildland fuels were only built with moisture content as a dependent variable (Xanthopoulos and Wakimoto 1992, Dimitrakopoulos and Papaioannou 2001). Separate regression equations for each species were developed in those studies which limits the potential of that approach to provide meaningful assessments across many species. The simple regression model presented here explains much of the variation in ignition times for both species, suggesting that this method may serve to normalize the differences in leaf chemistry between species.

The model presented here is the first step in linking the physiology of living plants with their combustion characteristics. Plants are complex organisms that must balance their need for water with their need to uptake atmospheric carbon for photosynthesis. These two balancing processes are both fundamental to their combustion behavior and thus can both serve limiting roles to the ignition characteristics. The plant water balance determines its required energy for water vaporization because it regulates the plants moisture content during photosynthesis and the allocation of fixed carbon provides the substrates necessary to create the pyrolyzates for flaming combustion. Ultimately, the work presented here encourages us to explore the relationships between plant physiological traits and combustion characteristics.

4. Acknowledgements

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