

# Final Report for JFSP-Funded Project entitled: “Linking Photosynthesis and Combustion Characteristics in Live Fuels: The Role of Soluble Carbohydrates in Fuel Preheating” (JFSP Project ID: 10-1-08-6)

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# Abstract

Operational fire behavior models make several assumptions about the combustion characteristics of fuels that may apply well to dead fuels but might be inappropriate for live fuels. Three of these assumptions are that pure water must be evaporated from the fuels, the chemical make-up of the fuel does not influence its ignition behavior and that all of the water contained in a fuel must be removed before combustion can occur. Plants accumulate carbohydrates in the foliage by photosynthesis and this can raise the temperature required to boil and thus evaporate water from the foliage. However, since the gases that support flames are derived from the dry mass of the fuel, it is also possible that the presence of certain chemical compounds in the foliage could actually enhance its flammability. Furthermore, evidence exists to suggest that significant water remains in the foliage at the time of ignition. These three factors could have profound impacts on the pre-heating and ignition requirements of live fuels that would not be found in comparable dead fuels.

Here we present the results of several nested studies aimed at decoupling foliar chemistry and foliar moisture dynamics in an effort to better understand the linkages between the plant carbon / water cycles and foliar flammability. Contrary to our original hypothesis, we found a strong positive link between plant foliar chemistry and foliar flammability. As foliar compounds such as starch, sugar and crude fat increased, foliage ignited more rapidly. We demonstrate that seasonal changes in foliar carbohydrates and crude fat are the main drivers behind apparent changes in foliar moisture content. In fact, carbohydrate and fat content of foliage explained 91% of the seasonal variation in live foliar moisture content. We also show that foliar flammability could be explained solely as a function of foliar chemistry. Finally, we show that under rapid heating, roughly ~10% of fuel's initial moisture content remains at ignition. Ultimately, our work has led to a more complete definition of the factors that drive seasonal changes in live foliar moisture content and the potential influence of those factors on foliar ignition and it has allowed us to develop a new, holistic way of assessing live fuel flammability. This work benefits a variety of modeling efforts aimed at quantify the factors controlling fire spread through a mixture of live and dead wildland fuels. Additionally, it calls into question the use of live foliar moisture content as a direct indicator of live fuel water stress and subsequent flammability. This study has allowed us to more effectively establish a link between plant eco-physiology and plant combustion and it has helped to develop a new working theory on the factors that truly dictate live fuel flammability. If this theory holds true, it could completely change the way that we assess when and how live fuels might burn.

## Background and purpose

Wildland fires are a common global ecosystem disturbance (Bowman, Balch et al. 2009) and they spread through a combination of living and dead vegetation. Many environmental factors influence how these fires behave but fuel moisture content (FMC) has long been shown to influence how wildland fires ignite and spread (Anderson and Rothermel 1965; Dimitrakopoulos and Papaioannou 2001; Fons 1946; Gisborne 1936; Pellizzaro, Cesaraccio *et al.* 2007; Weise, Zhou *et al.* 2005; Xanthopoulos and Wakimoto 1993). Fuel moisture can affect the preheating of fuels (Byram 1959) and the resulting water vapor can attenuate radiant heat transfer to adjacent fuels (Frankman, Webb *et al.* 2008) causing fires to spread faster through fuels with lower moisture contents (Anderson and Rothermel 1965).

Heat transfer theory and experimental data both indicate that ignition takes longer for live foliage with high moisture contents than dead fine fuels at nominal moisture contents. Empirical studies have been performed that correlated ignition time with moisture content (Dimitrakopoulos and Papaioannou 2001; Xanthopoulos and Wakimoto 1993), but these studies are only applicable to the materials tested and the testing method. Currently no reliable methods exist to predict/describe live fuel ignition. Thus, a fundamental, physical understanding of live fuel ignition processes is needed. Live foliar moisture affects ignition in both the solid and gas phase resulting in increased ignition time (Babrauskas 2003). Water can also change the thermal properties of the fuel such as its density, thermal conductivity and specific heat. Water vapor dilutes flammable pyrolyzates and absorbs energy. Preliminary studies (Cohen and Finney 2010; Finney, Cohen *et al.* 2010; Pickett, Isackson *et al.* 2010; Yedinak, Cohen *et al.* 2010) and observations suggest that fire spread through live canopy fuels does so with significant foliar water remaining. Water vaporization and pyrolysis occur simultaneously and, thus, affects the gas phase by diluting flammable pyrolyzates, absorbing energy and possibly altering combustion reactions resulting in ignition delay (Babrauskas 2006; Janssens 1991).

Furthermore, the non-structural carbohydrates and other compounds in solution change the water colligative properties and potentially leave the foliage with the water solution. The presence of a solute such as sugar can raise the boiling point to nearly 135° (Özdemir and Pehlivan 2008). Pickett, Isackson et al. (2010) conducted foliage ignition experiments using convective heating resulting in measured interior leaf temperatures of 130° C. This suggests very different ignition and combustion processes for live foliage fuels than that of dead fuels. Current literature reflects neither a definitive understanding of live fuel ignition and combustion nor a consensus as to what ignition and combustion processes are important (Finney, Cohen *et al.* 2013).

While both live and dead fuel moisture content are important factors in fire behavior, the mechanisms that drive their spatial and temporal variations are different (Nelson Jr. 2001). Dead fuel moisture contents (DFMC) are generally driven by direct diffusion of water into and out of the fuel (Nelson 2000; Viney 1991). DFMC is driven by the weather conditions around the fuel and only change as a function of changes in the fuel's water weight, because dry matter remains constant. In contrast, live fuel moisture content (LFMC), particularly that of foliage, is driven more by plant physiological process, varying from changes in its water content due to soil water uptake and evapotranspiration, or through possible changes in its dry mass due to phenology and photosynthesis (Kozlowski and Pallardy 1979). Ackley (1954) suggested that changes in Bartlett pear foliar moisture content were more linked to changes in dry matter than to changes in actual

water content. Additionally, Little (1970) demonstrated that seasonal changes in carbohydrates and fats explain some of the observed seasonal changes in moisture content but they suggest that concurrent changes in water content must also be important. Others have suggested that the dynamics of LFMC are a combination of seasonal changes in actual water content and dry matter change (Gary 1971; Kozlowski and Clausen 1965).

Live foliar moisture content is a parameter for many empirical and physical fire behavior models (Linn, Reisner *et al.* 2002; Mell, Jenkins *et al.* 2007; Rothermel 1972; Van Wagner 1977) and there is considerable effort to periodically measure LFMC as an indicator of wildland fire potential (Brenner 2002; Southwest Area 2004). However, relationships between LFMC and fire behavior are still poorly understood. A recent review by Alexander and Cruz (2013) suggests that LFMC may not significantly influence live crown fire spread rates despite the many studies that have demonstrated linkages between LFMC and flammability in both field experiments and laboratory burns (Cruz, Alexander *et al.* 2005; Dimitrakopoulos and Papaioannou 2001; Pellizzaro, Duce *et al.* 2007; Van Wilgen, Le Maitre *et al.* 1985; Weise, Zhou *et al.* 2005; Xanthopoulos and Wakimoto 1993). One reason for these inconsistencies may be that physical descriptions of live fuel dynamics which include both water and dry matter partitioning are lacking. This may be important because both water content and chemical composition are important factors in fuel flammability (Finney, Cohen *et al.* 2013). Ultimately, describing the interactions between seasonal changes in water mass, dry mass and subsequent LFMC may improve our ability to assess how living plants influence wildland fire behavior.

Ultimately, this study's purpose was to quantify the influence of seasonal changes in foliar chemistry on the ignition behavior of live fuels. We sought to elucidate the primary drivers of foliar combustion and to assess and derive suitable metrics that could most effectively determine their flammability.

# Materials and methods

## Sample Sites

For the radiant ignition study in 2010, foliar samples were collected weekly from Evaro Hill (47.0767° Lat, -114.0503° Lon) for *Pinus contorta* (Lodgepole pine) and *Pseudotsuga menziesii* (Douglas fir). For the foliar chemistry and ignition studies, foliar samples were collected in 2010 and 2011 from *Pinus contorta* (lodgepole pine) trees at two proximal sites located on exposed South or Southwest aspects in Western Montana, USA. The first site (Lubrecht) was at 1262 meters (4141 ft) elevation and was located on the Lubrecht Experimental Forest (46.89785° Lat., -113.4395° Long.). The second site (Garnet) was at 1699 meters (5575 ft) elevation and was located on the Garnet Range Road (46.85183° Lat., -113.4036° Long.). In 2012, samples were collected from both *Pinus contorta* (Lodgepole pine) at two locations and *Artemisia tridentata* (Big sagebrush) at two locations. In 2013, *Pinus contorta* samples were collected at three sites. Additionally, in 2013, we were able to collaborate with the Wisconsin Department of Natural Resources to sample both *Pinus resinosa* (Red pine) and *Pinus banksiana* (Jack pine) for the entire growing season.

## Live fuel metrics

The emphasis of this study was to quantify the role of leaf chemistry on ignition behavior. Therefore, the metrics that we used measured on various samples throughout the year were meant to summarize the chemical composition, moisture content, moisture stress and flammability of live conifer foliage.

### *Foliar Moisture Content*

For all samples, we measured the traditional metric of live foliar moisture content (LFMC). This was either done with in a conventional convection oven or using a CompuTrac Max2000XL moisture analyzer. As a side project, we were able to compare the results between oven drying and moisture analyzer-derived foliar moisture content and we found them to be nearly identical (Jolly and Hadlow 2012). Both methods are useful in laboratory analyses of live fuels and we used each method as appropriate for a given task. For LFMC measurements, samples were taken from branches at the lower 1/3 of trees growing in road cuts. Sampling only from exposed crowns helped to control for within-crown foliar moisture content differences that are observed due to shading (Pook and Gill 1993). Foliage from current year's growth was collected separate from foliage from previous year's growth because there are generally large differences between old and new foliar moisture content until the new foliage is fully matured (Chrosciewicz 1986; Keyes 2006). Old growth was sampled irrespective of needle age class but was generally less than six years old.

### *Relative Water Content*

Relative Water Content (RWC) is a standard metric used by physiologists to quantify the water status of plants (Barrs and Weatherley 1962). This value expresses the moisture content of the sample as a fraction of its saturated weight and it is naturally bounded between 0 and 100. RWC samples were collected, weighed fresh, hydrated for 24 hours in a water bath and re-weighed to determine their turgid weight. Finally, samples were oven dried to determine their dry weight and RWC was expressed as a percentage of saturation.

### *Foliar chemistry*

Each week, a twenty gram sub-sample was collected from the same foliar samples used to determine foliar moisture content and relative water content. New and old foliage were separated when both were present. Leaf chemical composition was determined using the wet reference method by an external forage testing laboratory (AgriAnalysis 2012; AOAC 1984; Horwitz and Latimer 2000). The analysis provided measurements of neutral detergent fiber (Fiber carbohydrates) (NDF), Non-fiber carbohydrates (NFC), crude fat (CF), crude protein (CP) and ash content (AC). Additional measurements of total non-structural carbohydrates (NSC) were also made using standard wet chemistry methods (AOAC 1984). Crude protein was determined using a TruSpec combustion analyzer. Crude fat was determined using an ANKOM Fat Analyzer with petroleum ether. NDF was determined using an ANKOM 200 Fiber Analyzer. Non-fiber carbohydrates (NFC) were calculated by the difference method. Neutral detergent fiber quantifies 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. Non-structural carbohydrates are a component of NFC and are composed of starch and simple sugars. Crude protein is generally proportional to the amount of Nitrogen in each sample. Crude fats quantify the amount of isoprenoids, waxes and oils present in the foliage and ash content quantifies the mineral content of the needle (Kozlowski and Pallardy 1979). These tests are simple and cost-effective, yet they have yielded a depth of information regarding the chemical makeup of live fuels that we have never fully considered.

### *Ignition Tests*

For this study, two different test platforms were used to perform ignition tests. The first was an apparatus that 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). This apparatus, based on the Forced Ignition and Flamespread Test (Cordova, Walther *et al.* 2001), consists of a small-scale wind tunnel, infrared heater, coiled wire igniter, and a high precision mass balance. 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<sup>2</sup> over the sample surface. As the sample is heated, pyrolysis begins. The forced flow pushes the pyrolysis gases into the coiled Kanthal 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<sup>2</sup>. All tests are repeated three times to provide an estimate of the experimental variability.

The second ignition testing platform was an open flame burner that was constructed specifically

for this project to rapidly heat fuel samples in a mostly convective environment. The test platform consists of three major components: the sample holder, the open flame burner and the quenching chamber. The sample holder is sliding steel rod that moves the sample over the flame. A switch and timer are connected to the sample holder that records the amount of time that a sample is introduced to the flame. The open flame burner is pre-mixed flame that is regulated by two mass flow controllers. The open flame is adjusted to approximate the conditions of a live fuel sample being introduced to a wildland fire. The air temperature above the open flame burner are between 520°C - 650°C with peak temperatures reaching 780°C. Average heat flux was nearly identical to the FIST apparatus at 50 kW/m<sup>2</sup>. The final component of the test set-up was the quenching chamber. This chamber allows the operator to slide an ignited sample into a 100% N<sub>2</sub> environment, effectively stopping all combustion. The chamber is constructed from polycarbonate with an inlet to feed a constant supply of Nitrogen. A picture of the test apparatus in action is shown in Figure 1.

These two test apparatuses involved different modes of heating. The FIST apparatus is driven completely by radiant heating while the open flame burner is dominated by convective heating.



Figure 1 – Open flame burner with quenching chamber

### *Quenching*

For the quenching study, the open flame burner was used along with the nitrogen quenching chamber. Lodgepole pine samples were collected and a sub-sample was taken to determine their initial moisture content. The remaining samples were then heating just to the point of flaming ignition, quenched in nitrogen and the moisture content of the remaining samples was measured using the CompuTrac Max2000XL. Additionally, samples were allowed to air dry over for up to three days to achieve moisture contents below those typically found for live fuels.



## Key findings

*Finding 1: There is a strong relationship between non-structural carbohydrates, crude fat and foliar moisture content.*

Foliar moisture content has long been used as an indicator of flammability. However, the physical mechanisms that drive seasonal changes in foliar moisture content have never been considered. We found a strong relationship between seasonal changes in foliar chemistry and subsequent changes in foliar density and apparent changes in foliar moisture content. This happens because live foliar moisture content is expressed on a dry-weight basis and anything that alters the dry weight can also alter the calculated moisture content. In fact, foliar moisture content can change even if the total amount of moisture in the fuel stays the same. This is shown graphically in Figure 2. The bottom three panels show the relationship between Non-structural carbohydrates (NSC), crude fat, ash and foliar dry mass. NSC, crude fat and ash explain 86%, 82% and 10% of the variation leaf foliar dry mass, respectively. Additionally, the upper panel shows that relative water content explains 62% of the variation in the water mass of the fuel.

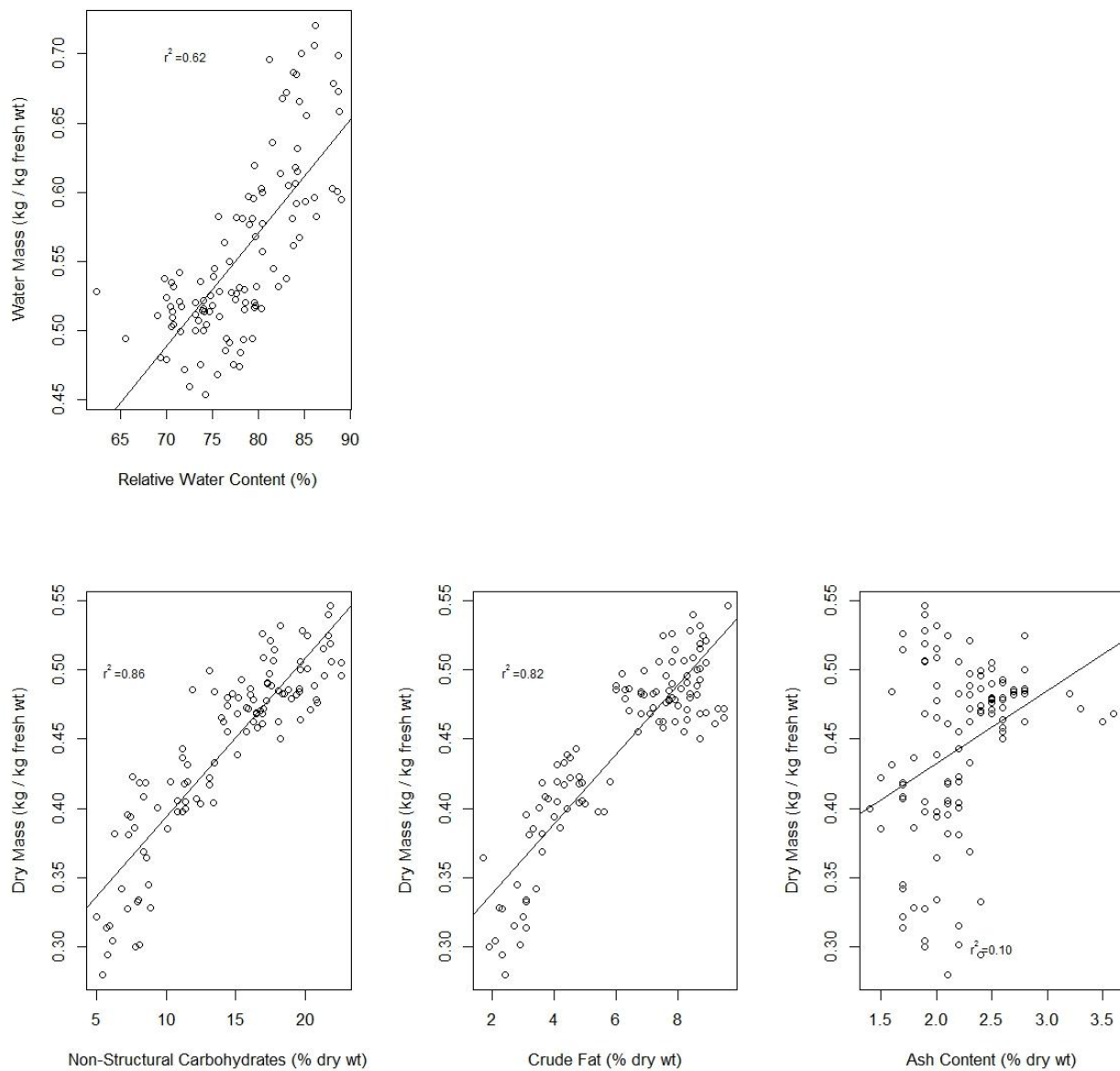
Changes in dry matter are likely a dynamic combination of foliar development, photosynthesis, respiration and carbon allocation. During the early period of development, we saw large declines in old needle foliar moisture content and slight increases in the moisture content of new needles. These changes were observed concurrent with continuous increases in the non-structural carbohydrates and crude fats of new needles and slight declines of those chemical components in new needles. These changes are likely a function of the complex linkages between growth and respiration of new needles. During early needle development, carbon is translocated from old needles to new needles (Gordon and Larson 1968). This causes the dry weight of old needles to decrease (and their apparent foliar moisture content to increase) and the dry weight of the new needles to increase (and their apparent foliar moisture content decreases). New needles also have a high demand for carbohydrates during their early development and they only export carbon to other parts of plant several weeks after they are fully developed (Ericsson 1978). Thus, greater understanding of physiological drivers that control the dry matter changes in live fuels could allow us to better seasonally predict dry matter content.

These relationships bring into question two commonly held beliefs about live fuels. First, it questions whether or not the perceived relationships between foliar moisture content and flammability are actually due to the moisture content of the fuel or are more driven by changes in foliar chemistry that influence the chemical composition of the fuel. While our original hypothesis would have led us to believe that an increase in foliar sugar concentrations may actually increase the time to the ignition of the foliage, what we found was quite the opposite. In fact, it is possible that non-structural carbohydrates, such as starches and sugar, may provide a source of readily pyrolyzed material to support the rapid ignition of fuels.

The second factor that is called into question is whether or not live fuel moisture is actually an indicator of drought. Historically, both managers and scientists have believed that a decrease in live foliar moisture content represented a ‘drying out’ of the vegetation and increased its flammability. We have demonstrated that changes in live fuel moisture can occur without any appreciable change in the actual water content of the fuel. This finding has profound influence on



how live foliar moisture content is interpreted and used as an indicator of drought and it suggests that other metrics of stress, such as water potential or relative water content, may be better indicators to track the seasonal water stress of live vegetation. However, we did find a modest correlation between derived fuel water content and relative water content, indicating that relative water content may be a good indicator of drought stress in wildland fuels.



**Figure 2 – The relationship between leaf water mass and relative water content (Top) and leaf non-structural carbohydrates, crude fat, ash content and dry mass (Bottom).**

*Finding 2: There is an inverse relationship between time to ignition and foliar non-structural carbohydrates under both slow and rapid heating*

The most interesting finding of this study is that foliar ignition delay time, which is used as an indicator of flammability, is inversely related to the non-structural carbohydrate concentration of the foliage. Figure 3 shows that as the dry matter percentage of non-structural carbohydrates increases, the time to ignition decreases (or the foliage becomes more flammable). This is contrary to our original hypothesis but it is very important in several ways. First, nearly every fire behavior model currently in use assumes that live fuels are chemically similar to wood and thus only the combustion and chemical kinetics of wood are used. Our results have shown that live fuels are chemically different than wood and that the sometimes contain as much as 40% non-structural carbohydrates (Figure 3, top panel). This group of compounds has never been considered as a source of flammable gases and it may very well be found that these easily decomposed compounds provide a readily evolved source of flammable gases and subsequently increase flammability of fuels that contain them. However, this relationship does not necessarily hold true for all species. For example, Figure 3 (bottom) shows that the relationship between non-structural carbohydrates and sagebrush is not significant while it is significant for lodgepole pine. Other factors may be influencing the flammability of sagebrush.

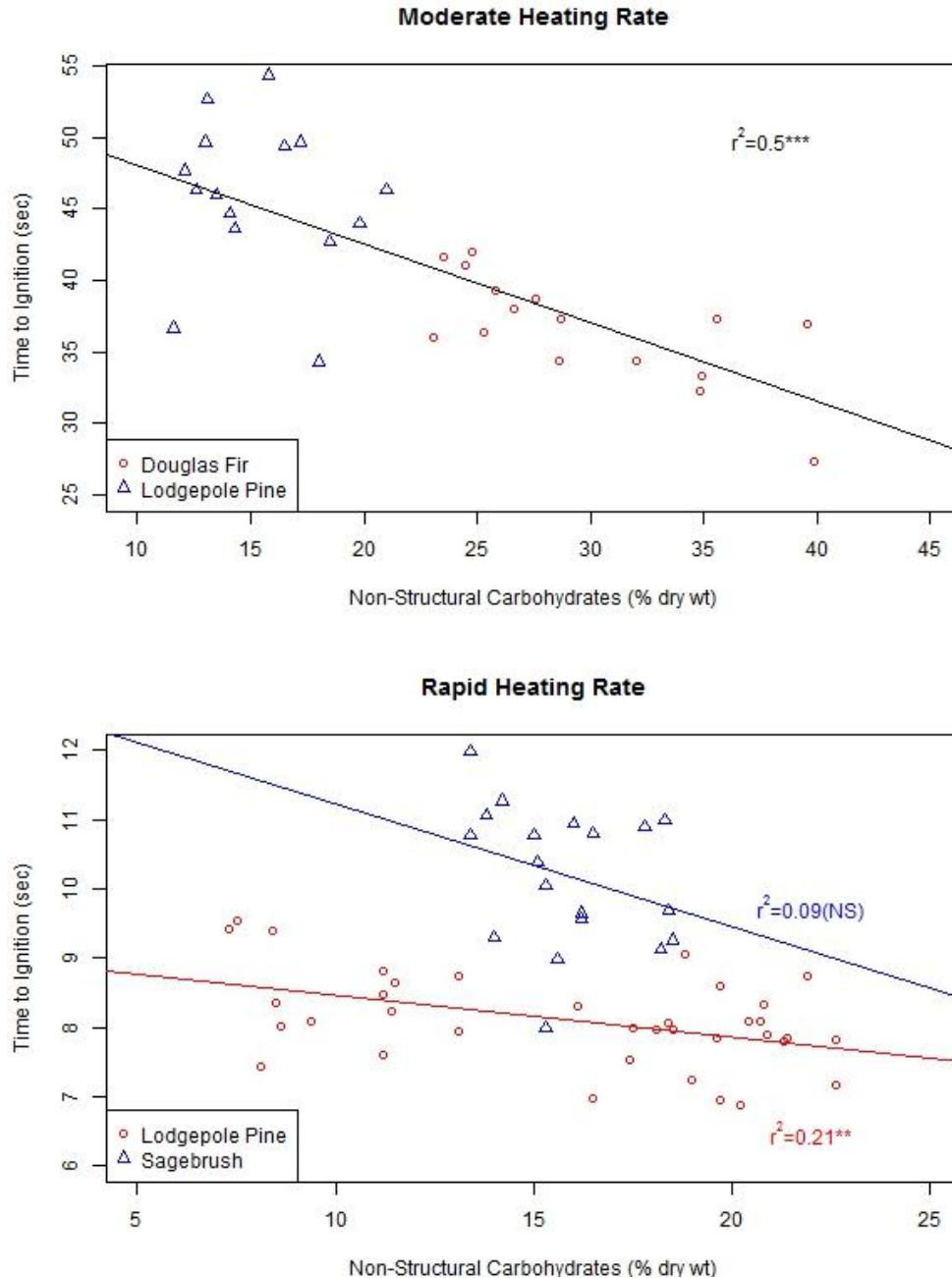
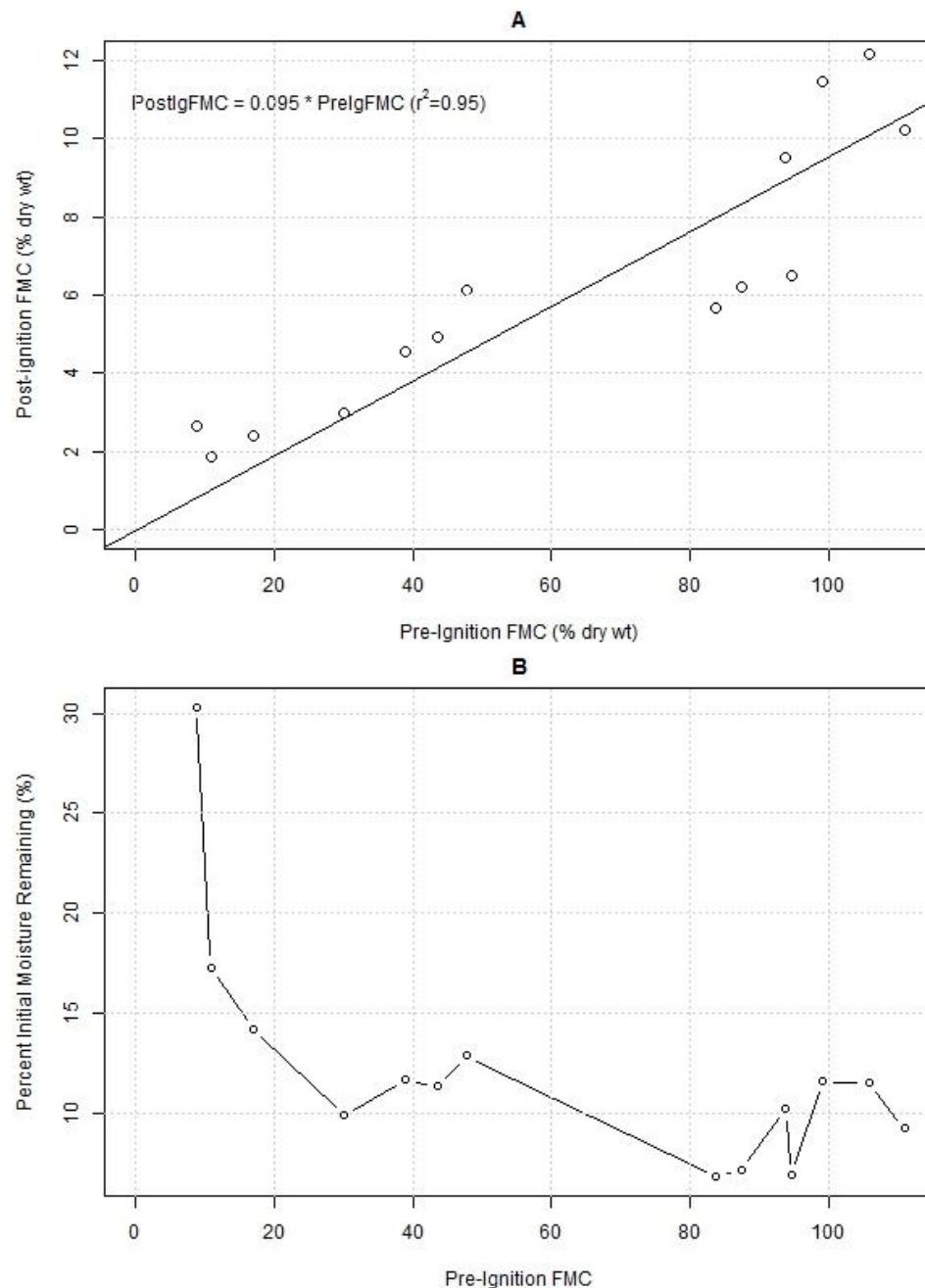


Figure 3 – Relationship between non-structural carbohydrates and time to ignition for one shrub and two tree species under both moderate and rapid heating.

***Finding 3: Moisture loss during rapid heating is conserved and is generally 9.5% of initial moisture content***

Traditional fire behavior models are built on the assumption that ALL moisture in a fuel is first evaporated and then the fuel is raised to ignition temperature. In this study, we found that this assumption is not entirely true. Figure 4 shows the relationship between pre-ignition and post-ignition moisture content for lodgepole pine over a range of initial moisture contents that varies more than ten-fold. What we found was for our given rapid heating rate, about 9.5% of the initial moisture content remains at the point of ignition and this relationship is conserved across a ten-

fold range of initial moisture contents ( $r^2=0.95$ ). Additionally, we found that when we expressed the percent moisture remaining in the fuel relative to its initial moisture content, a higher percentage of moisture remains in fuels with a lower moisture (Figure 4, Panel B), suggesting that this may be more important for dead fuels than live. Both of the findings suggest that fire behavior models should consider how this remaining moisture may impact the heat transfer and kinetics of spreading flames.



**Figure 4 – Relationship between pre-ignition and post-ignition moisture content for lodgepole pine needles subjected to rapid heating. Panel A shows that the moisture loss relationship is conserved across an FMC gradient that varies over ten-fold, indicating that moisture content of fuels at ignition is approximately 9.5% of its initial moisture content. Panel B shows that dead needles, with less than 30% moisture content, have as much as 30% of their initial moisture content remaining at ignition.**

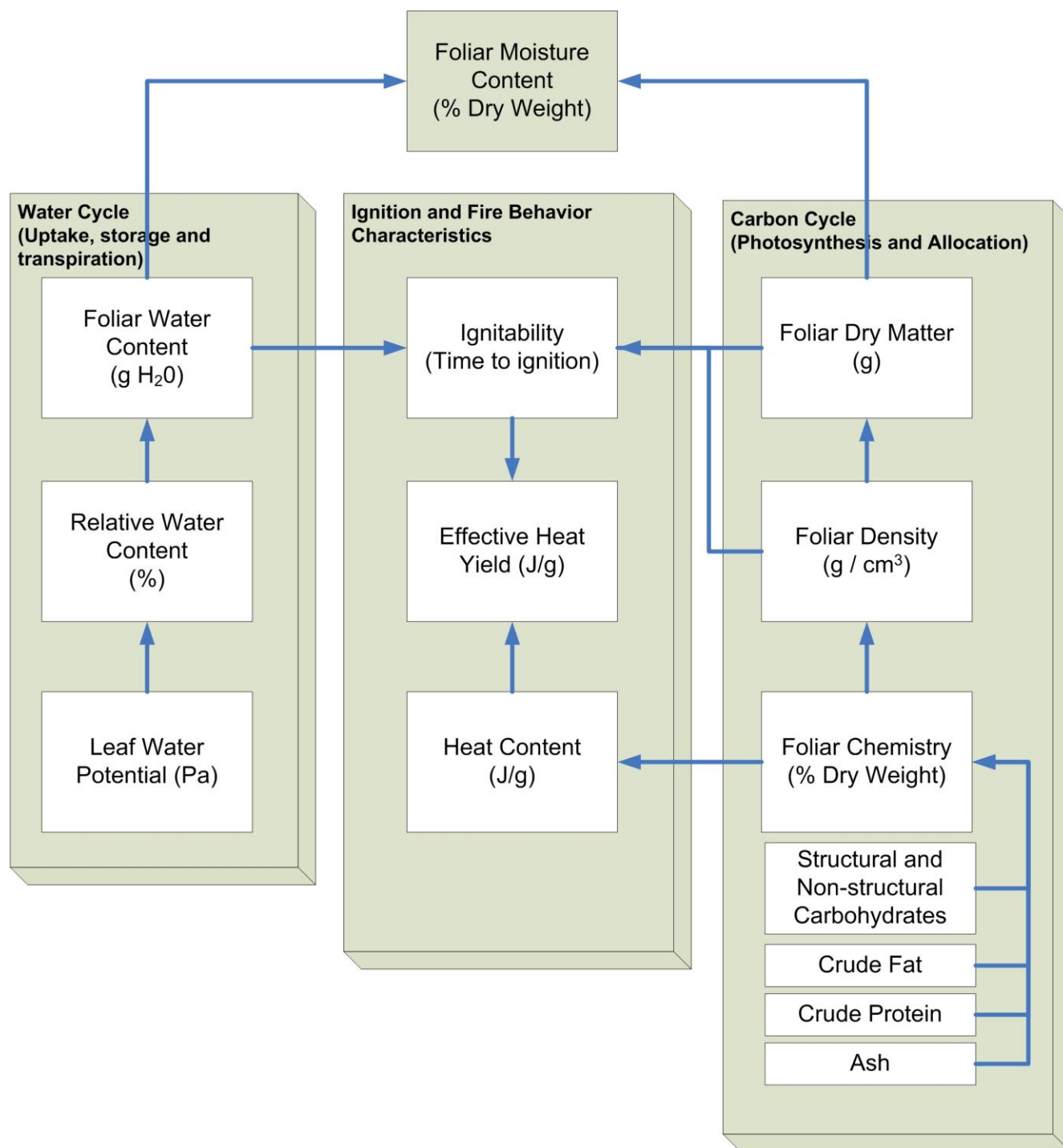


Figure 5 -- New conceptual model of the inter-relationships between foliar moisture, chemistry and flammability of live fuels.

## Management implications

### *Fire behavior models may be missing the actual drivers of live fuel flammability*

Based on our studies, we have found that live fuel chemistry is significantly different from that of wood. As such, fire behavior models that assume all fuels are composed of wood (cellulose, hemi-cellulose and lignin), may not be adequate for simulating the combustion of and fire spreading through live fuels. While these models may be appropriate for fires spreading through dead grasses and tree litter, they may be less appropriate for simulating fires in live fuels. Additionally, we have shown that at least 9.5% of the initial moisture content of the foliage is still present at the time of ignition. This implies that models which assume all the moisture is evaporate prior to ignition are not accurate. More work must be done to assess the potential impacts of this faulty assumption on fire spread model dynamics but until then, models should be used with caution.

Additionally, live fuel moisture content has been shown to be related to live fuel flammability but the underlying drivers of this relationship are called to question by our results. The strong relationship between foliar chemistry and apparent moisture content may suggest that the underlying chemical changes are actually affecting flammability rather than the amount of water in the fuel. This has profound implications for the flammability assessments of live fuels. It is possible that live fuel moisture content could still be used as a surrogate for the actual drivers of live fuel flammability but the interpretation of seasonal LFMC changes must be modified to include both the changes in plant water content AND plant chemical content.

### *New and old foliage should always be sampled separately*

Our results show that the moisture contents and foliar chemistry of new and old needles are significantly different throughout most of the growing season and that they have distinctly different flammability characteristics. However, these two foliar components are often not separated when sampled in the field and they may be combined into a single sample during collection (eg. (Castro, Tudela *et al.* 2003; Pellizzaro, Duce *et al.* 2007)). This sampling strategy would explain why reported seasonal live fuel moisture values typically show a rise to some peak value and an eventual decline. Much of these dynamics can be explained by the mixing of new foliage with high moisture contents, and old foliage with lower moisture contents. Others have demonstrated the large discrepancies in moisture content between new and old foliage (Agee, Wright *et al.* 2002; Chrosciewicz 1986) and have suggested the need to separate the two categories when sampling. Our results extend these studies by showing the large differences in dry matter composition between old and new needles and reinforce the need to separate new and old foliage when examining their seasonal dynamics. Additionally, it emphasizes the need to develop a better understanding of canopy development as suggested by Agee and others (Agee, Wright *et al.* 2002). Understanding the timing and rate needle elongation and needle hardening and the proportions of new and old needles would allow us to better assess canopy-scale foliar moisture content and it would allow us to better assess crown flammability based on the fractional proportions of new and old foliage.

### *Live foliar moisture content may not be an indicator of drought*

Considerable time and effort are expending by fire management agencies to measure and track live foliar moisture content as an indicator of foliar flammability and potential fire behavior. Our results suggest that foliar chemical changes are the actual mechanisms driving seasonal changes in foliar moisture content. This result is important because it suggests that we should be examining other metrics, such as relative water content, as indicators of actual water stress in plants and that measured

live fuel moisture content should not be considered as suitable indicator plant stress. Suitable live fuel metrics are still needed to relate plant water stress to flammability but relative water content is a relatively easy, and physiologically meaningful, metric that could be applied to field sampling in support of fire management decision making.

## **Relationship to other recent findings and ongoing work on this topic**

This study is very unique in that it seeks to examine the interplay between foliar physio-chemical properties and flammability in a way that has been before been attempted. As such, there has been very little work by other parties that follows a similar path. However, after several presentation of our results, other researchers are using what we have learned to better understand linkages between chemistry, moisture and ignition. For example, Paige et. al. (2012) used our laboratory analysis techniques to examine the influence of foliar chemistry on the ignition behavior of lodgepole needles from trees attacked by the ubiquitous Mountain Pine Beetle. Also, as a successful offshoot of our research, we were able to collaborate with Dr. Phil Dennison and PhD student Yi Qi, both from the University of Utah, to examine the spectral signatures of dry matter changes. This work was couple with our data collection during the 2012 field season where we were able to collect foliar moisture, chemistry and spectra throughout the season. This work may lead to a more effective way of mapping spatial and temporal changes in foliar moisture content and live fuel flammability using remote sensing platforms such as the MODIS sensor. A manuscript of this work has been submitted to the journal Remote Sensing of the Environment and is now in review.

Additionally, this work was presented to the Eastern and Alaskan Fire Science Consortiums. That presentation lead to a collaboration with Wisconsin Department of Natural Resources where we continue to explore the relationship between foliar moisture content, foliar chemistry and flammability during the 'spring dip' in foliar moisture content of jack pine and red pine in the lake states. This work has the potential to completely change how live fuel flammability is assessed in these species and it may lead to a more complete understanding of the factors which control a highly confined period of extreme flammability.

Previous work has attempted to link the seasonal dynamics of live foliar moisture content to changes in meteorological conditions, such as those that are depicted by various drought indices (Castro, Tudela *et al.* 2003; Dennison, Roberts *et al.* 2003; Dimitrakopoulos and Bemmerzouk 2003; Pellizzaro, Cesaraccio *et al.* 2007; Viegas, Piñol *et al.* 2001). However, these studies have had limited or mixed success. For example, for some Mediterranean shrub species, Pellizzaro et. al. (2007) found strong correlations between live foliar moisture content and five drought indices during periods of water stress but poor correlations as drought stress was relieved. Also, Dimitrakopoulos and Bemmerzouk (2003) found that while drought indices closely match the moisture content of herbaceous plants, they were poorly correlated with the foliar moisture content of deep-rooted *Pinus brutia* trees. Our work will allow researchers to de-couple the effects of water stress from seasonal dry matter changes and this will likely lead to a better understanding of the interactive factors that influence the fire dynamics of living plants.



Ultimately, the work complete by this project has potentially spawned a new field of fire science that recognizes the need to link the physiological mechanisms that drive seasonal variations in plants with their impact on foliar flammability.

## Future work needed

Many aspects of this study need further exploration to fully develop the linkages and relationships that we have discovered. Foliar chemistry varies strongly both seasonally and within the plant as a function of needle longevity. It also varies strong between plant species. Future work would involve the examination of the influence of various plant compounds, such as sugars, starches, crude fat, and trace elements such as phosphorous, on the rate of flammable pyrolyzate production on plants. As previously stated, all current models of wildland fire behavior assume that all fuel is composed of the same components of woody biomass. Our study clearly shows that foliage is composed of a variety of compounds that don't exist in wood and it only shares approximately 40% of its chemical makeup with the compounds that make up wood. This is a great unknown in the combustion characteristics of these fuels and it deserves intense future study because these linkages have the potential to unravel the 'live fuel mystery'. This would require some degree of inter-disciplinary research that combines a knowledge of plant physiology and chemistry with combustion and fire spread exploration. This information would also inform fire combustion physics that is incorporated into computational fluid dynamics-based fire behavior models such as the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) or FIRETEC (Linn, Reisner *et al.* 2002; Mell, Jenkins *et al.* 2007).

Future work is also needed to examine the relationship between actual metrics of plant water stress, such as relative water content or leaf water potential, and plant flammability. Our study showed that live foliar moisture content may not be an adequate indicator of drought stress on live vegetation. However, metrics that quantify the potential flammability of live vegetation are desirable to fire managers who need to continual assess conditions throughout the season in order to more effectively manage fire across the landscape. More work is needed to develop metrics that can easily be measured in the field and that relate directly to the flammability of live vegetation. We have evaluate some metrics within the context of this study that show promise, but more work must be done to evaluate and test various metrics and to determine the most appropriate methods to use for rating live fuel flammability.

Finally, this work has led to a new working theory about the factors that drive the seasonal flammability of live vegetation Figure 5. This theory involves a set of linkages that drive the seasonal water and carbon cycles of plants. Many of these factors have been shown to impact flammability and heat yield. More work is needed to evaluate this conceptual model and to develop the direct ties between proxy variables, such as relative water content or leaf starch content, and the physiological processes that drive their changes. However, the range of species tested in this study was limited. Future work should involve the testing and evaluation of this theory across a range of plant functional types to determine whether the relationships we have found hold true across a variety of vegetation types. If this conceptual model is found to be true, it will change the way that live fuel flammability is evaluated in the future.

## Deliverables crosswalk table

Below is the table of deliverables from the original proposal and an additional table detail other work that was completed but not promised for this project. All deliverables, except for the publication documenting the moisture loss at ignition have been completed for this project and all data have been collected and analyzed for that component of this study. Additionally, we have produced 5 additional publications, given four additional presentations and presented 1 additional poster for this project.

**Table 1 – Deliverables table from original proposal.**

<b>Deliverable Type</b>	<b>Description</b>	<b>Status</b>
Annual Reports	Annual reports to JFSP	Complete
Publication	Peer-review publication or GTR documenting the relationship between soluble carbohydrates and of time-to-ignition component of the study.	Complete: Paper in Press with International Journal of Wildland Fire entitled: <i>“Decoupling seasonal changes in water content and dry matter to predict live conifer foliar moisture content”</i>
Publication	Peer-reviewed publication or GTR documenting the moisture loss at ignition results of this study.	Partially Complete: Data collected, analysis complete, manuscript in preparation
Presentation	Present the results of the soluble carbohydrates component of the study at an academic conference.	Complete: Presented at the 6 <sup>th</sup> International Conference on Forest Fire Research, Coimbra, Portugal entitled: <i>“Time to ignition is influenced by both moisture content and soluble carbohydrates in live Douglas fir and Lodgepole pine needles”</i>
Presentation	Present the results of the moisture loss at ignition experiments at an academic conference.	Complete: Presented at the 4 <sup>th</sup> Fire Behavior and Fuel Conference, Raleigh, NC entitled: <i>“Decoupling seasonal changes in water content and dry weight to predict live conifer foliar moisture content and its implications for live fuel ignition”</i>
Model	Time-to-ignition and solute concentration model for live fuels.	Complete: We have presented a model that links foliar solute concentrations to live foliar moisture content in the
Final Report	Final report to JFSP	Presented Here

Table 2 – Additional deliverables completed through this project.

Deliverable Type	Description
Publication	W. Matt Jolly, Russell A. Parsons, Ann M. Hadlow, Greg M. Cohn, Sara S. McAllister, John B. Popp, Robert M. Hubbard, Jose F. Negron, Relationships between moisture, chemistry, and ignition of <i>Pinus contorta</i> needles during the early stages of mountain pine beetle attack, Forest Ecology and Management, Volume 269, 1 April 2012, Pages 52-59, ISSN 0378-1127, <a href="http://dx.doi.org/10.1016/j.foreco.2011.12.022">http://dx.doi.org/10.1016/j.foreco.2011.12.022</a> .
Publication	Jolly W. Matt, Hadlow Ann M. (2012) A comparison of two methods for estimating conifer live foliar moisture content. <i>International Journal of Wildland Fire</i> <b>21</b> , 180–185.
Publication	Jolly, McAllister, Finney and Hadlow. “Time to ignition is influenced by both moisture content and soluble carbohydrates in live Douglas fir and Lodgepole pine needles” in Proceedings of the 6 <sup>th</sup> International Conference on Forest Fire Research.
Publication	Finney Mark A., Cohen Jack D., McAllister Sara S., Jolly W. Matt (2013) On the need for a theory of wildland fire spread. <i>International Journal of Wildland Fire</i> <b>22</b> , 25–36.
Publication	S. McAllister, I. Grenfell, A. Hadlow, W.M. Jolly, M. Finney, J. Cohen, Piloted ignition of live forest fuels, Fire Safety Journal, Volume 51, July 2012, Pages 133-142, ISSN 0379-7112, <a href="http://dx.doi.org/10.1016/j.firesaf.2012.04.001">http://dx.doi.org/10.1016/j.firesaf.2012.04.001</a> .
Presentation	Eastern and Alaska Fire Science Consortium talk entitled: “Live Fuel Moisture: A new look at the combustion of living plants”
Presentation	Lake States Forest Fire Compact entitled: “Assessing the drivers of the ‘spring dip’ in foliar moisture content and their potential impact on forest fire behavior”
Presentation	University of Montana Seminar Series entitled: “Seasonal leaf chemistry, foliar moisture content and ignition characteristics of live wildland fuels”
Presentation	Association of Fire Ecology 2011 meeting, Snowbird, UT entitled: “Apparent changes in conifer foliar moisture are driven by seasonal dry weight allocation”
Poster	Association of Fire Ecology 2012 meeting, Portland, OR entitled: “Monitoring Seasonal Variation of Foliar Heat Content in Big Sagebrush”

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