Physiological drivers of the live foliar moisture content 'spring dip' in *Pinus resinosa* and *Pinus banksiana* and their relationship to foliar flammability

W. Matt Jolly[a], John Hintz[b], Rachael C. Kropp[c] and Elliot T. Conrad[d]

[a]*US Forest Service, RMRS, Fire Sciences Labortory, 5775 Hwy 10 W, Missoula, MT, USA, 59808, mjolly@fs.fed.us*
[b]*Wisconsin Dept of Natural Resources, 473 Griffith Ave, Wisconsin Rapids, WI, USA, 54494-7859, John.Hintz@wisconsin.gov*
[c]*US Forest Service, RMRS, Fire Sciences Labortory, 5775 Hwy 10 W, Missoula, MT, USA, 59808, rachaelckropp@fs.fed.us*
[a]*US Forest Service, RMRS, Fire Sciences Labortory, 5775 Hwy 10 W, Missoula, MT, USA, 59808, eliotttconrad@fs.fed.us*

Abstract
A phenomenon known as the 'Spring Dip' in conifer live foliar moisture content (LFMC) has been documented and monitored for decades. This period also corresponds with intense crownfire activity in areas dominated by *Pinus resinosa* (Red pine) or *Pinus banksiana* (Jack pine). Despite a long-standing tradition of measuring LFMC during the dip period, the drivers of these variations have been the source of much speculation but little investigation and the actual causes of foliar flammability change have received even less attention. Here we assess the seasonal drivers of LFMC variations and their impact on foliar flammability. Foliar samples were collected for an entire year from both Red pine and Jack pine at a site in Central Wisconsin. New and previous year's foliage were sampled separately when both were present. From these samples, we determined LFMC, foliar chemistry and foliar density. We also ignited samples in an open flame burner to assess seasonal changes in their flammability. We verified that there is indeed a drop in the foliar moisture content during the spring. However, foliar density changes explained 96.7% of the variation in LFMC across both species and both needle age categories. These density changes were driven by an accumulation of starch and sugar in the previous year's foliage, most likely as a result of the onset of photosynthesis in the spring. Foliar starch, sugar and crude fat content explained 86.4% of the variation in foliar density. Foliar flammability followed the same trend as LFMC, reaching its period of highest flammability during the time of the lowest LFMC. However, these changes were strongly related to changes in foliar density, where density explained 51% and 77.4% of the variations in foliar flammability. Our results challenge the assumption that live conifer foliage flammability is limited by its water content and this study has led to a new theory of the factors that dominate live fuel flammability.

Keywords: Live Foliar Moisture Content, Spring Dip, Foliar Density, Flammability

1. Introduction

Jack pine (*Pinus banksiana*) and Red pine (*Pinus resinosa*) are distributed throughout much of the high latitude and temperate North American forests and collectively they cover parts of eleven states and eight Canadian provinces. Wildfires are an integral component of their ecology (Ahlgren and Ahlgren 1960). Fires that occur in these areas can vary from low intensity surface fire to high intensity crown fires. Fire severity significantly affects the ecological succession and subsequent distribution of these trees throughout the boreal region (Arseneault 2001). It is therefore important to develop a complete understanding of the factors that drive fire severity in these forests.

Fire behavior in these forests is a crucial component of the development of management strategies for these species (Johnson and Miyanishi 1995). Successful prediction of fire behavior in these stands has been the source of much investigation (Quintilio et al. 1977, Stocks 1987, 1989, Stocks et al. 2004). Both weather and fuel conditions can significantly influence fire behavior in these stands. Strong winds and dry conditions lead to intense fires that spread rapidly. Fuel factors such as the crown base height, canopy bulk density and foliar moisture content are important determinants of their fire behavior (Van Wagner 1977, 1993). Variations in crown base height and canopy bulk density happen slowly as stands develop over time, while foliar moisture content can vary significantly throughout the season. As such, foliar moisture content has the largest potential to alter the potential fire behavior of Jack pine and Red pine stands throughout the year.

A phenomenon known as the 'spring dip' in foliar moisture content has been extensively documented (Van Wagner 1967, 1974, Chrosciewicz 1986). It describes a seasonal decline in the foliar moisture before new needle flushing and a subsequent increase in moisture content thereafter. This period of low foliar moisture content corresponds with an increase in crown fire likelihood. While the phenomenon itself has been adequately described, the causes of the dip, and subsequently their potential impact on fire behavior, have not been adequately explored. One difficulty with evaluating seasonal changes in foliar moisture content is that they are driven by a combination of both changes in leaf water content and dry mass. Little (1970) suggests that a similar observed dip in foliar moisture of balsam fir (Abies balsamea), was attributed at least in part to a change in foliar carbohydrates. A complete examination of the seasonal dynamics of foliar moisture content and their influence on crown flammability must then examine changes in foliar dry matter composition as well as changes in foliar water content.

Here we present a study aimed at characterizing the seasonal changes in foliar chemistry during a period the 'spring dip'. We sample current and past year's foliage from mature Red pine and Jack pine trees at varying intervals for an entire year. We measure foliar moisture content, foliar density, chemical composition and each sample is also combusted on an open flame burner to measure their seasonal changes in flammability. We use this extensive dataset to explore the inter-relationships between measured foliar moisture content, foliar water content, foliar dry matter variations and their influence on ignitability.

2. Methods

Jack pine and Red pine sampling sites were located ~ 0.6 km apart in northern Adams County in central Wisconsin, USA, approximately 10 miles south of the city of Wisconsin Rapids. The red pine collection site is at N44° 14' 33", W89° 49' 44". The jack pine site is at N44° 14' 4", W89° 48' 54". Elevation at both locations is 873 feet. Topography at both sites is level to gently rolling on well-drained Plainfield Sand soils of glacial outwash origin. The area is part of a broad sand plain bisected by the Wisconsin River as it crosses the central part of the state.

The soils and topography of the area have made it prime landscape for growth of vast commercial plantations of red pine (*Pinus resinosa*), interspersed with natural forest cover of jack pine (*P. banksiana*) and “scrub” oak (*Quercus ellipsoidalis, Q. palustris, Q. alba, Q. velutina*). The lands are also ideal for residential, agricultural and recreational development, with numerous homes and cabins dotting the landscape and the major community of Rome (over 3500 homes) located within three miles to the south and southeast of the sampling site.

The landscape has experienced frequent fires of both natural and human origin throughout its history, including the pre-settlement period. It has also seen some of the largest and most destructive fires in Wisconsin during the post WWII era, the most recent being the 3400-acre Cottonville Fire of 2005. The red pine sample site itself is a plantation re-established after a forest fire that occurred in 1995, while the jack pine samples were taken from volunteers found in a separate, younger red pine plantation established after a commercial harvest of an oak/jack pine stand in 2000.

Needles were collected in both “new” (current year growth) and “old” (previous two growth seasons combined) age classes for both red and jack pine. Jack pine samples were collected in metal sampling tins, while larger plastic containers were used for the longer red pine needles. Containers were kept sealed during transport to a lab at the Wisconsin Department of Natural Resources (WDNR) office in Wisconsin Rapids. In the lab, the samples from each species/age class were divided into three subsets. Two subsets were designated for chemical and flammability analysis and were packaged for overnight shipping to AgriAnalysis for chemical testing and to the US Forest Service Fire Lab in Missoula, Montana. From the third subset, five fascicles of varying size were selected for determination of needle density while the rest of the subset was used for bulk measurement of live foliar moisture content (LFMC). Fresh weights were measured to the nearest milligram for both the fascicles and bulk samples were obtained and the volume of the fascicles was determined using an Ohaus density apparatus. Fascicle and bulk samples were then dried overnight in at 85°C and measured to obtain dry weights, after which all weight measurements were brought together for final calculations of needle density and LFMC. LFMC was converted from a dry weight basis to a wet weight basis to standardize the scales between the foliar chemistry and moisture content measure using the following equation:

$$\mathbf{M_{wb} = (LFMC * 100 / (100 + LFMC))} \qquad \textbf{Equation 1}$$

Samples were ignited using an open-flame burner. The apparatus was built specifically for the rapid heating and ignition of live fuel samples and is composed of a pre-mixed propane, a sample holder and timer (Figure 1). Flow rates were set at 0.48 mol/min for fuel and 6.47 mol/min for air. This yields a rich flame that is partially pre-mixed and partially diffuse, yet creates a flame that is very similar to wildland flames and a convective heating environment that is conducive to very rapid heating. Samples were introduced to the flame by the sample holder where they were immersed in flame and their time-to-ignition was recorded as the point where flames were visibly attached to the surface of the sample.

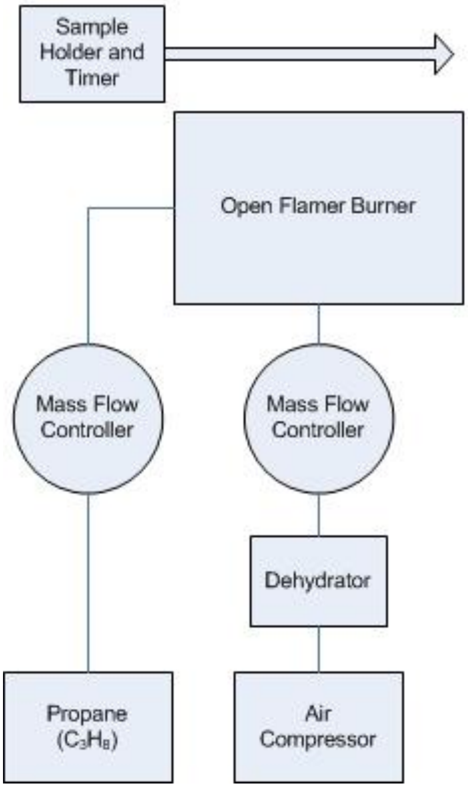

Figure 1 – Flow diagram of the open-flame igniter apparatus.

3. Results

Live foliar moisture content (LFMC) seasonal trends followed patterns similar to those reported by Van Wagner (Van Wagner 1967) (Figure 2). Dormant foliar moisture contents for previous year's needles of red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) were high for both species. Red pine needle moisture was 114.3% on March 29th, 2013 and 120.6% for jack pine but both dropped precipitously starting in about April and recovered completely by August (Figure 2). The lowest recorded LFMC recorded for red pine (82.0%) occurred on June 3rd, 2013 and the lowest LFMC for jack pine (91.5%) occurred on May 13th, 2013, representing a 29% and 26% reduction in LFMC during the 'Spring Dip' for Red pine and Jack pine respectively. LFMC recovery coincided with new needle emergence in mid-June (Figure 2). New needle LFMC was >250% for both species and declined rapidly during needle development (Figure 2).

Foliar chemistry varied substantially between needle age classes but was similar between species (Figure 3). The strongest variations were observed in starch concentrations of old needles in both species, while crude fat and sugar content of new needles continued to rise after emergence signally foliar chemical changes due to needle hardening. Starch concentrations of old needles rose from zero to 14.4% and 11.8% of dry weight for Red pine and Jack pine respectively. Both crude fat and sugar content of new needles more than doubled over the study period.

Foliar density tracked seasonal changes in foliar chemistry. Density of old needles increased during the 'spring dip' period reaching a seasonal maximum value of 0.52 g/cm^3 and 0.497 g/cm^3 for Red pine and Jack pine respectively (Figure 4). Density of old needles for both species increased by more than 20% during the dip period. Starch, sugar and crude fat content of needles explained 86.2% of the variations in foliar density across both species and needle ages (Figure 5). Foliar density exhibited a linear relationship with foliar moisture content and it explained 96.7% of the variation, when foliar moisture content was translated from a dry weight to a wet weight basis (Equation 1).

Foliar density also explained much of the variation in time to ignition of both species. Density was most related to Jack pine flammability where it explained 77.4% of the variation in time to ignition, while density explained 51% of the variation in time to ignition for Red pine across both needle ages.

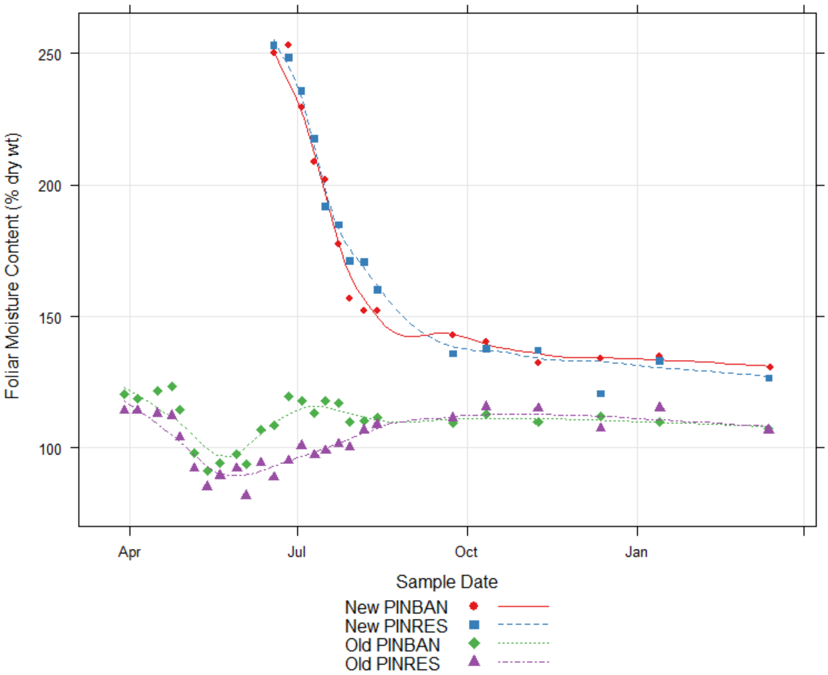

Figure 2 – Seasonal variations in live foliar moisture content for Red pine and Jack pine from April 2013 - April 2014. Seasonal low LFMC values were observed in old needs of both species during the 'spring dip' period and the highest recorded values were observed in new needles. By the end of the study period, old and new needles had similar foliar moisture contents but new needle moisture contents were consistently higher for both species.

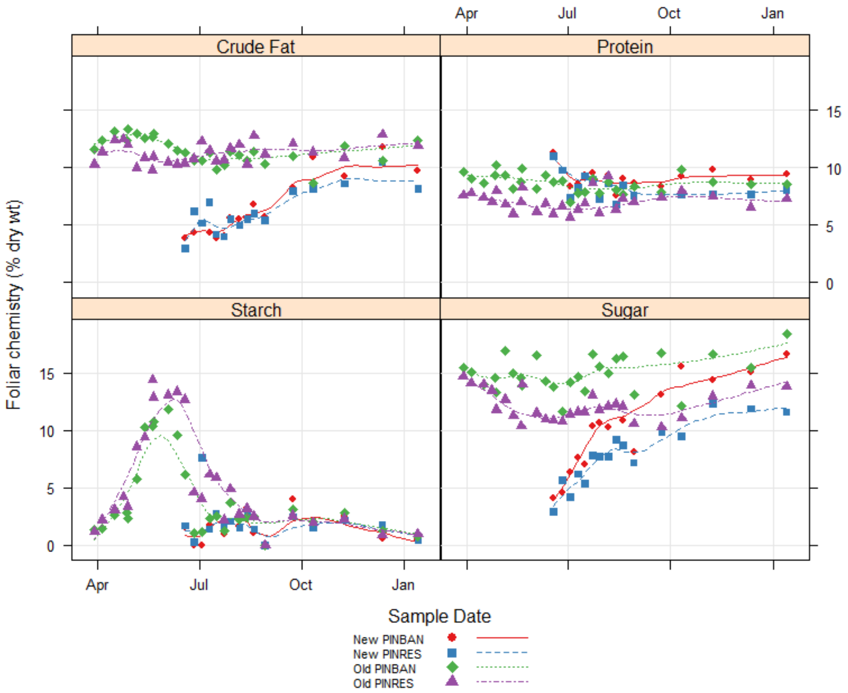

Figure 3 – Seasonal variations in live foliar chemistry for Red pine and Jack pine from April 2013 - April 2014. Crude fat was lowest in new needles of both species and increased during needle development. Needle starch content showed over a ten-fold increase during the spring, increasing from 0% during dormancy to 14.4% and 11.8% for Red pine and Jack pine respectively just prior to new needle emergence. Additionally, sugar content of new needles increased during needle development but protein was similar between needle ages and species.

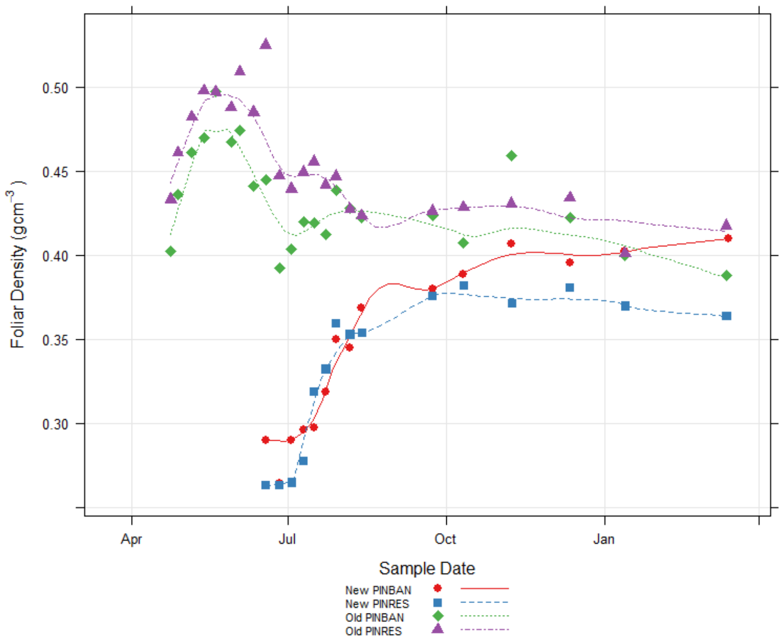

Figure 4 – Seasonal changes in the foliar density of old and new Jack pine and Red pine needles from April 2013 to April 2014. Highest needle densities for old needles of both species occurred during the spring while lowest densities observed for both species occurred just after bud break as new needles emerged. New needle density increased as needles matured, while old needle density decreased over that period.

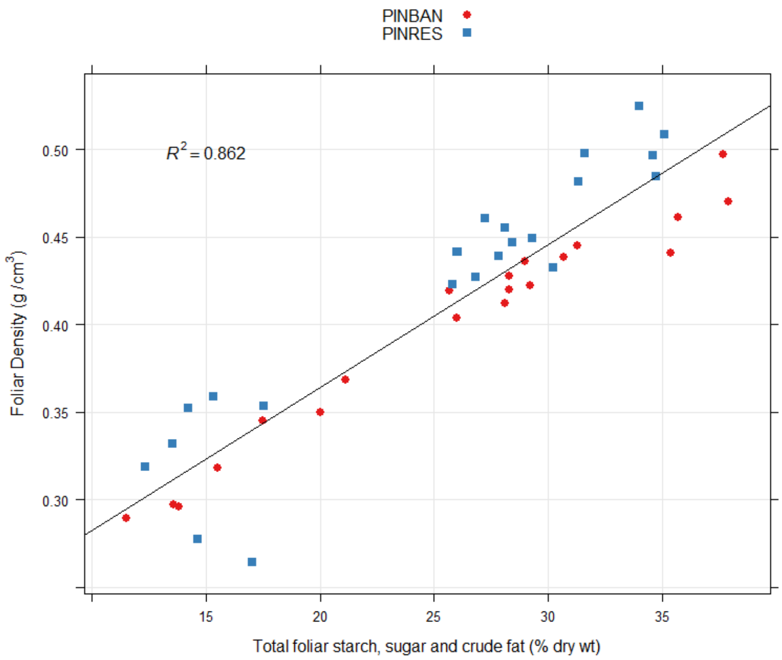

Figure 5 – Relationship between total foliar starch, sugar and crude fat concentrations (as a percentage of total dry matter) and foliar density. These variables explained 86.2% of the variation in foliar density across both species and both age classes suggesting that seasonal variations in foliar density are primarily dependent on carbon dynamics (starch and sugar) and needle development (crude fat).

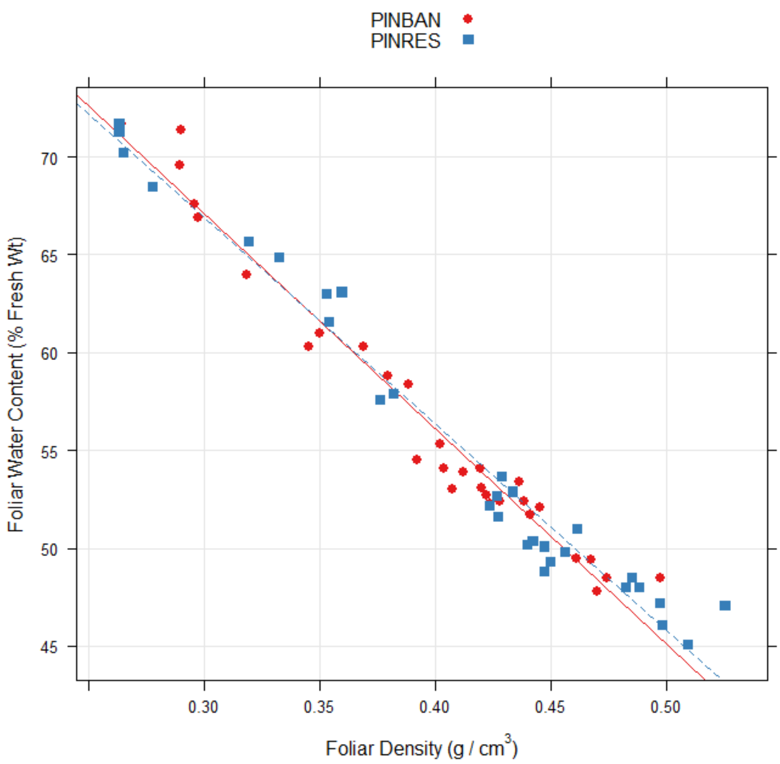

Figure 6 – Relationship between total foliar density and foliar water content (% fresh wt). Foliar density explained 96% of the variation in foliar water content across both species and needle ages.

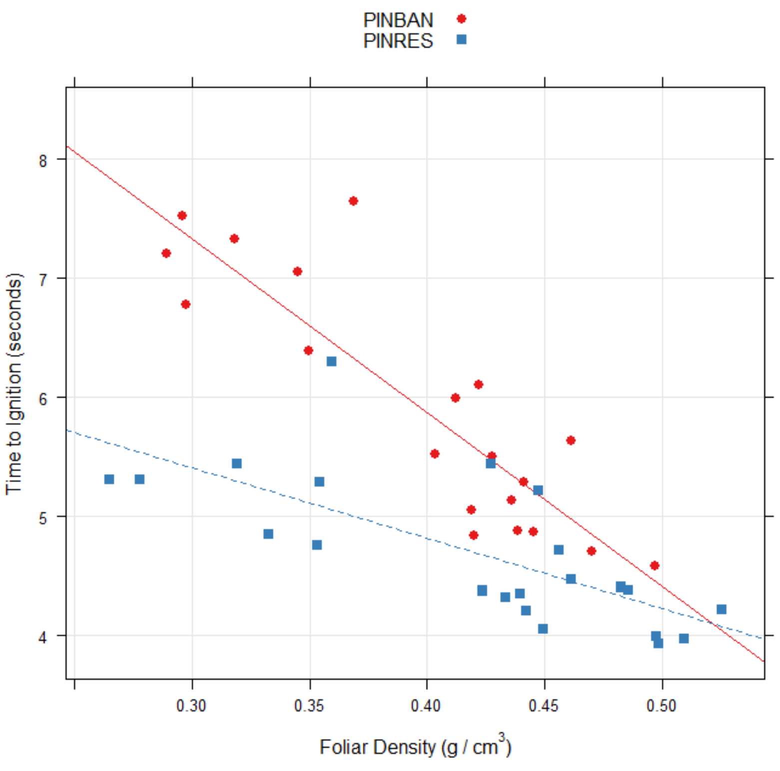

Figure 7 – Relationship between foliar density and time to ignition for Red pine (PINRES) and Jack pine (PINBAN). Foliar density explained 51% of the variations in time to ignition for Red pine and 77.4% of the variation in time to ignition for Jack pine.

4. Discussion

Foliar moisture content has long been assumed to relate to red pine and jack pine flammability but little work has explained the interactive drivers that influence their seasonal changes. Our study has shown that foliar moisture content variations are a direct result of seasonal changes in foliar chemistry, not moisture content variations, which is consistent with previous findings (Little 1970). These chemical changes are reflected in seasonal changes in foliar density and subsequent changes in seasonal foliar flammability.

Foliar moisture content variations coincided with the onset of photosynthesis and the accumulation of carbon compounds prior to the flushing of new needles. During the early season, once trees have broken dormancy, we observed large increases in stored starch prior to the immergence of new foliage (Figure 3). Once new needles emerged, that stored starch was depleted because during needle development, carbon is translocated from old needles to new needles (Gordon and Larson 1968). 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). Ultimately, photosynthesis is the main driver of the spring dip and the plant-level carbon cycle determines the apparent moisture content of the foliage but these changes could be affecting foliar flammability in ways that have not been previously considered.

It is conceivable that while the apparent moisture content of foliage varies substantially throughout the season, the absolute water content of the foliage could stay relatively constant. If this were the case, it would imply that the true seasonal drivers in foliar flammability lie not in changes in the water content of the foliage but in the chemical changes that compose the foliage. These chemical compounds might alter how rapidly needles can ignite. We noted strong seasonal changes in starch content of old foliage during the dip. Starch and sugar compose over 28% of the dry weight of foliage yet they have never been considered as driving components of wildland fires. Generally, time-to-ignition is positively related to density (Incropera and DeWitt 2002). However, we found that these two quantities were negatively related, suggested that the drivers of the density increase, were more easily volatilized and thus lead to faster ignition, despite their contribution to particle density. Sugar, starch and crude fat should be studied further to determine whether or not they appreciably alter foliage ignitability.

This is the first study to combine moisture content, chemistry, density and ignition testing during the “Spring Dip” period. We have revealed some previously undiscovered linkages that could change how we assess live fuel flammability in the future. This new knowledge may lead to better tools to help fire managers assess crown fire potential in these dynamic forests.

5. References

Ahlgren, I. F. and C. E. Ahlgren. 1960. Ecological effects of forest fires. The Botanical Review **26**:483-533.

Arseneault, D. 2001. Impact of fire behavior on postfire forest development in a homogeneous boreal landscape. Canadian Journal of Forest Research **31**:1367-1374.

Chrosciewicz, Z. 1986. Foliar moisture content variations in four coniferous tree species of central Alberta. Canadian Journal of Forest Research **16**:157-162.

Ericsson, A. 1978. Seasonal Changes in Translocation of 14C from Different Age-Classes of Needles on 20-Year-Old Scots Pine Trees (Pinus silvestris). Physiologia Plantarum **43**:351-358.

Gordon, J. C. and P. R. Larson. 1968. Seasonal course of photosynthesis, respiration, and distribution of C14 in young Pinus resinosa trees as related to wood formation. Plant Physiology **43**:1617-1624.

Incropera, F. P. and D. P. DeWitt. 2002. Introduction to Heat Transfer. 4th edition edition. John Wiley and Sons, New York.

Johnson, E. A. and K. Miyanishi. 1995. The Need for Consideration of Fire Behavior and Effects in Prescribed Burning. Restoration Ecology **3**:271-278.

Little, C. H. A. 1970. Seasonal changes in carbohydrate and moisture content in needles of balsam fire (Abies balsamea). Canadian Journal of Botany **48**:2021-2028.

Quintilio, D., G. R. Fahnestock, and D. E. Dubé. 1977. Fire behavior in upland jack pine: the Darwin Lake Project. NOR-X-174, Edmonton, Alberta.

Stocks, B. J. 1987. Fire behavior in immature jack pine. Canadian Journal of Forest Research **17**:80-86.

Stocks, B. J. 1989. Fire behavior in mature jack pine. Canadian Journal of Forest Research **19**:783-790.

Stocks, B. J., M. E. Alexander, B. M. Wotton, C. N. Stefner, M. D. Flannigan, S. W. Taylor, N. Lavoie, J. A. Mason, G. R. Hartley, and M. E. Maffey. 2004. Crown fire behaviour in a northern jack pine black spruce forest. Canadian Journal of Forest Research **34**:1548-1560.

Van Wagner, C. E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires.

Van Wagner, C. E. 1974. A spread index for crown fires in spring. Information Report PS-X-55, Petawaw Forest Experiment Station, Chalk River, Ontario.

Van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research **7**:23-34.

Van Wagner, C. E. 1993. Prediction of crown fire behavior in two stands of jack pine. Canadian Journal of Forest Research **23**:442-449.