Forest Ecology and Management 373 (2016) 167–178

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Seasonal variations in red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) foliar physio-chemistry and their potential influence on stand-scale wildland fire behavior

W. Matt Jolly [a,*], John Hintz [b], Rodman L. Linn [c], Rachael C. Kropp [a], Elliot T. Conrad [a], Russell A. Parsons [a], Judith Winterkamp [c]

[a] US Forest Service, RMRS, Fire Sciences Laboratory, 5775 Hwy 10 W, Missoula, MT 59808, USA
[b] Wisconsin Dept of Natural Resources, 473 Griffith Ave, Wisconsin Rapids, WI 54494-7859, USA
[c] Los Alamos National Laboratory, P.O Box 1663, Los Alamos, NM 87544, USA

ARTICLE INFO

Article history:
Received 12 October 2015
Received in revised form 29 March 2016
Accepted 3 April 2016
Available online 28 April 2016

Keywords:
Live foliar moisture content
Spring dip
Foliar density
Flammability
Fire behavior
Fire modeling
FIRETEC

ABSTRACT

The 'Spring Dip' in conifer live foliar moisture content (LFMC) has been well documented but the actual drivers of these variations have not been fully investigated. Here we span this knowledge gap by measuring LFMC, foliar chemistry, foliar density and foliar flammability on new and old foliage for an entire year from both *Pinus resinosa* (red pine) and *Pinus banksiana* (jack pine) at a site in Central Wisconsin. We found that needle dry mass increased by up to 70% in just three weeks and these increases were manifested as strong seasonal variations in foliar moisture content and foliar density. These needle dry mass changes were driven by an accumulation of starch in old foliage, likely resulting from springtime photosynthesis onset, and also by accumulations of sugar and crude fat in new needles as they fully matured. Foliar starch, sugar and crude fat content accounted for 84% of the variation in foliar density across both species. Flammability differences were also strongly related to changes in foliar density, where density accounted for 39% and 25% of the variations in foliar time-to-ignition of jack pine and red pine respectively. Finally, we use the computational fluid dynamics-based wildland fire model FIRETEC to examine how these foliar physio-chemical changes may influence wildland fire behavior. Under the lowest canopy density and windspeed, simulated fires in dormant condition stands did not propagate as crown fires while spring dip stands successfully spread as crown fires as a result of the higher potential energy content of the canopy. Simulated wildland fire spread rates increased by as much as 63%, nominal fireline width increased by as much as 89% and active fire area more than doubled relative to dormant season fuel conditions and the most significant changes occurred in areas with low canopy cover and low within-tree bulk density. Our results challenge the assumption that live conifer foliage flammability is limited only by its water content; this study suggests a new theory and an expanded view of the factors that dominate live fuel flammability and that subsequently influence larger scale wildland fire behavior.

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1. Introduction

Jack pine (*Pinus banksiana*) and red pine (*Pinus resinosa*) are distributed throughout much of the high latitude and temperate North American forests; collectively they cover parts of eleven US 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 this fire behavior. Strong winds and dry conditions lead to intense fires that spread rapidly. Fuel factors such as the crown base height, canopy

* Corresponding author.
E-mail addresses: mjolly@fs.fed.us (W.M. Jolly), John.Hintz@wisconsin.gov (J. Hintz), rrl@lanl.gov (R.L. Linn), rachaelckropp@fs.fed.us (R.C. Kropp), eliotttconrad@fs.fed.us (E.T. Conrad), rparsons@fs.fed.us (R.A. Parsons), judyw@lanl.gov (J. Winterkamp).

http://dx.doi.org/10.1016/j.foreco.2016.04.005
0378-1127/Published by Elsevier B.V.

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. These seasonal variations in foliar moisture content have been directly incorporated into the Canadian Forest Fire Danger Rating System to provide decision support tools for wildland fire management (Van Wagner and Pickett, 1985). 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 (Jolly et al., 2014). 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.

It is difficult to assess the impacts of foliar physio-chemical changes on wildland fire behavior because it is nearly impossible to standardize any field experiment during an active wildland fire while controlling for many other potential sources of variation. However, wildland fire models provide an ideal experimental platform to assess these potential impacts. Numerical experiments can be performed which control for potential sources of variation while varying quantities of interest and assessing their impact on fire behavior characteristics such as rate of spread, fire intensity and burned area. Recently, computational fluid dynamics-based simulations of wildland fire are maturing into platforms that can facilitate these types of numerical simulations. Models such as FIRETEC (Linn et al., 2002) and the Wildland Urban Interface Fire Dynamics Simulation (Mell et al., 2007) (WFDS), utilize three dimensional descriptions of fuel, terrain and weather to simulate the coupled fire atmosphere behavior including the impacts of changes in fuel load or spatial distribution in tree canopies. These platforms are ideal tools to examine the impact of physio-chemical fuel changes on wildland fire behavior.

Here, we present a study aimed at characterizing the seasonal changes in foliar physio-chemistry during the spring dip period. 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 time to ignition using a bench-scale open flame burner. We use this extensive dataset to explore the inter-relationships between seasonal fuel physical and chemical properties and their influence on ignitability. Finally, we leverage these data to perform numerical experiments using the computational fluid dynamics (CFD)-based wildland fire model FIRETEC to explore how these physio-chemical fuel changes may impact wildland fire behavior at stand scales.

2. Materials and methods

2.1. Sampling sites

Red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) 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 site was located at N44°14′33″, W89°49′44″ and the jack pine site was located at N44°14′4″, W89°48′54″. Elevation at both locations is 265 m (873 ft). 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 central Wisconsin.

The soils and topography of the area have made it prime landscape for growth of vast commercial plantations of red pine, interspersed with natural forest cover of jack pine and "scrub" oak (*Quercus ellipsoidalis*, *Quercus palustris*, *Quercus alba*, *Quercus velutina*). The landscape has 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 naturally regenerated trees found in a separate, younger red pine plantation established after a commercial harvest of an oak/jack pine stand in 2000.

2.2. Foliar sampling

Needles were collected weekly from April through September 2013 and monthly from October 2013 to March 2014 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. Needles were collected by stripping the fascicles from the sun-exposed branches of 10–12 trees per sampling period. Only the previous year's foliage was sampled until approximately two weeks after budbreak when new foliage was longer than ~1 cm. New foliage sampling began in early July 2013 and new and old foliage was collected separately through the following spring (March 2014).

The samples from each species/age class were divided into three subsets in the laboratory, which were used for different sets of measurements to determine chemical composition, ignitability, and physical properties, respectively.

2.3. Measurement of foliar chemical composition

A subsample of needles from each species and age class was provided to an external forage testing laboratory where leaf chemical composition was determined using the wet reference method (AOAC, 1984; Horwitz and Latimer, 2000; AgriAnalysis, 2015). 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 starch and sugar 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 was calculated as the remainder of dry matter after NDF, CF, CP and AC were determined where NFC = 100 – NDF + CF + CP + AC. 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. 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).

2.4. Measurement of foliar physical properties

From the second subset, fuel physio-chemical measurements were made onsite in Wisconsin. Five fascicles of varying size were selected for determination of foliar density while the rest of the subset was used for bulk measurement of LFMC. Fresh weights were measured to the nearest milligram for both the fascicles and bulk samples and the green volume of the fascicles was determined using an Ohaus Density Determination Kit (P/N 80850045). Fascicle and bulk samples were then dried overnight at 85 °C and measured to obtain dry weights, after which all weight measurements were brought together for final calculations of foliar density and LFMC.

2.5. 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). RWC was measured on five fascicles of needles. First, their fresh weight was recorded. Samples were then soaked for 24 h in distilled water, blotted dry and re-weighed for their turgid weight. Samples were then dried overnight at 85 °C in a convection oven. RWC was then calculated as follows:

$$RWC = ((FW - DW)/(TW - DW)) \times 100 \qquad (1)$$

where RWC is the relative water content (% turgid wt), FW is the sample Fresh Weight (g), DW is the sample dry weight (g) and TW is the samples turgid weight (g) determined after the 24 h rehydration period. 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.

2.6. Measurement of foliar ignitability

The third needle subsets were shipped overnight from Wisconsin Rapids to the USFS Fire Sciences Laboratory where needle ignitability was tested. These ignition tests were performed on samples from April 16, 2013 through August 19, 2013 to capture the full period of the spring dip ($N = 18$ for previous years foliage and $N = 7$ for current year foliage). Samples were ignited using an open-flame burner to test their relative ignitability. The apparatus was built specifically for the rapid heating and ignition of live fuel samples and is composed of a pre-mixed propane open flame burner, a sample holder and timer (Fig. 1). Flow rates were set at 0.48 mol min^{-1} for fuel and 6.47 mol/min for air. Gas temperatures measured using a thermocouple once per second had an inner-quartile range of 553–630 °C with a mean gas temperature of 592 °C and minimum of 388.7 °C and a maximum of 834 °C. This yields a rich flame that is partially pre-mixed and partially diffuse, yet creates a flame that is 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 using an integrated timer as the point where flames were visibly attached to the surface of the sample.

2.7. FIRETEC CFD-based fire behavior simulations

The combination of mass changes and chemical composition changes in the foliage during the spring dip can result in increased energy release rates at the needle level. It is unclear how significant the effects of either one of these factors might be in the context of landscape scale fires and what various landscape-scale environmental conditions might have on the magnitude of these effects. To extend our investigation to larger scales, we carried out a series of simulations using the physics-based fire behavior model HIGRAD/FIRETEC (Linn et al., 2002). Our objective was to explore the potential impacts of the spring dip effect on fire

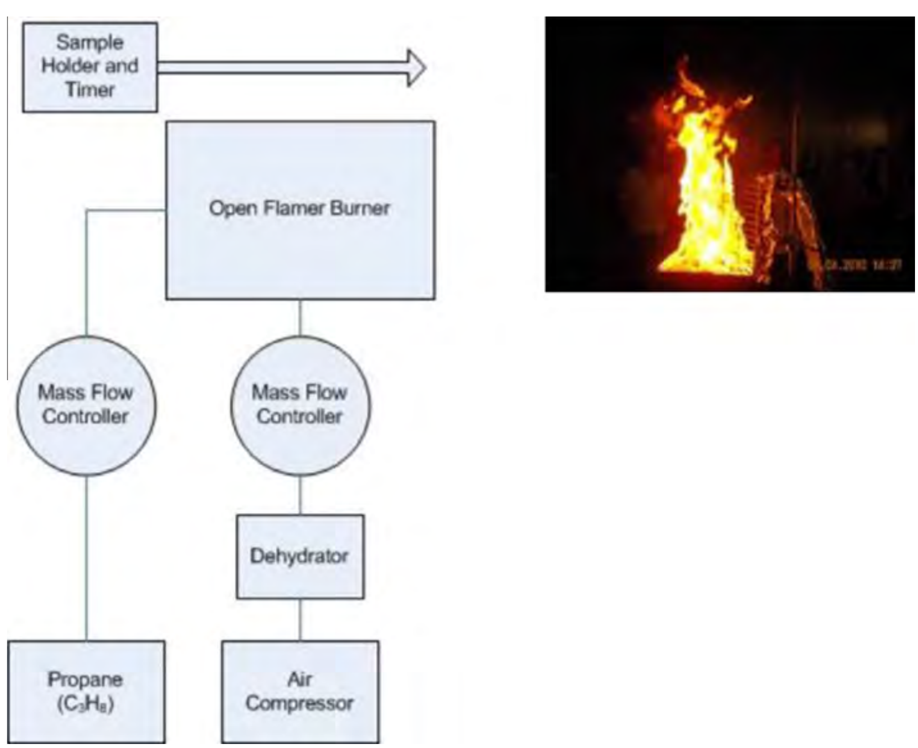

Fig. 1. Flow diagram of the open-flame igniter apparatus.

behavior, and to assess the sensitivity of the spring dip effect to fuel parameters (stand canopy cover and within-tree crown bulk density) as well as environmental conditions (wind speed). We chose to use the changes in foliar mass and resulting dip in moisture fraction as the dominant influence of the spring dip for this initial exploration, but the additional influences of the chemical composition and leaf water content changes on landscape-scale fire behavior will be subsequently explored.

Simulation of stand scale fire behavior with FIRETEC requires a spatially explicit representation of the forest canopy across the simulation domain. Canopies can be represented in many ways and with different levels of detail (Godin, 2000), ranging from homogeneous patches (Keane et al., 2008) to highly resolved architectural models of individual trees (Pradal et al., 2009; Parsons et al., 2011). Our intent was to explore general fire-behavior effects at scales of a few hundred meters rather than more detailed interactions at finer scales, so we used an easily replicable approach in which individual tree crowns, represented as non-overlapping, homogeneous rectangular volumes with a square base 4 m $\times$ 4 m and crown length of 10.2 m, were randomly placed within a flat rectangular domain measuring 480 m (x) by 384 m (y) for a total simulation area of 18.4 ha. The spatial pattern of these simple tree crowns was generated by creating a continuous surface using an Inverse Discrete Fourier Transform (IDFT) to simulate a $1/f$ noise process (Lennon, 2000). A threshold was applied to this continuous surface to retain a proportion of trees to achieve the desired canopy cover. For our set of numerical experiments, we simulated three different canopy covers: 30%, 60% and 80%. This approach enabled us to ensure that all simulated forest canopies with the same canopy cover had identical fuel quantities. Although this process can be used to produce autocorrelated spatial patterns, the surfaces generated here were not autocorrelated and were characterized instead by a purely random pattern for simplicity. Example canopy fuel arrangements can be seen in Fig. 7.

CFD fire models such as FIRETEC explicitly model drag effects of individual tree crowns on the wind flow patterns through the canopy. To ensure realistic wind dynamics in our fire simulations, we induced variability in crown base height. We accomplished this by drawing from a normal distribution characterized with a mean of 14.19 m and a standard deviation of 3.3 m, consistent with the overstory tree data from trees intensively measured and destructively sampled in the field in 2000 and 2001 on a 10-m radius circular plot (0.03 ha) located in the Ninemile area of the Lolo National Forest in western Montana (Reinhardt et al., 2006). The 10.2 m crown length used for our simplified tree crowns corresponds to the average field-measured crown length for overstory trees in that study and are consistent with measured crown lengths for red pine (Larocque and Marshall, 1994).

Surface fuels were modeled as litter fuel beds with a depth of 0.032 m, bulk density of 22.4 kg m^{-3} within the fuel bed, producing a fuel load of 0.7168 kg m^{-2} (Brown, 1981) while surface cells in open areas were specified as grass, with depth of 0.3 m, bulk density of 1.4 kg m^{-3} within the grass bed, and a fuel load of 0.42 kg m^{-2} (Brown, 1981). Surface area to volume for litter was 5760 m^{-1} (Brown, 1970) and 6860 m^{-1} for grass (Brown, 1970). Fuel moistures for both litter and grass were 6%, consistent with conditions commonly associated with active crown fire (Cruz and Alexander, 2010).

These canopy and surface fuel parameters provide a generalized process for representing forest fuels applicable to both open and closed canopy pine stands that allows us to standardize fuel arrangement between simulations to isolate and directly compare the impacts of changes in foliar physio-chemistry between spring dip and dormant fuel conditions on predicted fire behavior across a range canopy fuel configurations and wind speeds.

In order to investigate the spring dip effects on fire behavior under different environmental conditions, a series of wind, canopy cover, and tree crown bulk density scenarios were simulated for both dormancy and spring dip conditions (Table 1). Based on field observations, needle dry mass, and subsequently foliar density, increased during the spring dip period. Needle volume was assumed to remain constant, resulting in an increase in the foliar density during the spring dip period in the FIRETEC simulations. Any needle volume changes during the dip were ignored to ensure canopy drag was the same between simulation pairs to provide the same incoming windfield for both simulations. The apparent decline in foliar moisture contents as described by the ratio of needle water mass to needle dry mass during the spring dip was achieved without changing the total amount of moisture in the needle, but instead increasing the needle dry mass. For all pairs of simulations the absolute water content of the canopy remained constant. Needle dry mass was increased by 22% during the spring

Table 1
Wind speed, canopy fuel and canopy water characteristics used for each FIRETEC simulation.

Wind speed (10 m above canopy) (m s^{-1})	Canopy cover (%)	Within tree canopy bulk density (kg m^{-3})		Fuel moisture fraction (% dry wt)		Bulk average density of water (mass of water per volume of tree crown) (kg m^{-3})	
		Dormant	Spring dip	Dormant	Spring dip	Dormant	Spring dip
4.2	30	0.12	0.158	123.3	96.6	0.153	0.153
		0.22	0.283	123.3	96.6	0.274	0.274
		0.32	0.408	123.3	96.6	0.395	0.395
	60	0.12	0.158	123.3	96.6	0.153	0.153
		0.22	0.283	123.3	96.6	0.274	0.274
		0.32	0.408	123.3	96.6	0.395	0.395
	80	0.12	0.158	123.3	96.6	0.153	0.153
		0.22	0.283	123.3	96.6	0.274	0.274
		0.32	0.408	123.3	96.6	0.395	0.395
6.2	30	0.12	0.158	123.3	96.6	0.153	0.153
		0.22	0.283	123.3	96.6	0.274	0.274
		0.32	0.408	123.3	96.6	0.395	0.395
	60	0.12	0.158	123.3	96.6	0.153	0.153
		0.22	0.283	123.3	96.6	0.274	0.274
		0.32	0.408	123.3	96.6	0.395	0.395
	80	0.12	0.158	123.3	96.6	0.153	0.153
		0.22	0.283	123.3	96.6	0.274	0.274
		0.32	0.408	123.3	96.6	0.395	0.395

dip from the dormancy state mass using dry material densities of 515 kg m^{-3} and 403.5 kg m^{-3} for the spring dip and base states derived from field measured needle densities. By keeping the mass of the water in the needles the same for all simulation pairs, the dry weight-based fuel moisture contents were 96.6 and 123.3 for the spring dip and dormancy cases which fall within our measured spring dip and dormant season measured fuel moistures for red pine. These time periods were chosen because they represent two points in time where canopy chemistry is changing but the physical structure of the canopy remained the same. After new needles emerge, the bulk canopy moisture begins to change as new needle matures and the physical structure of the canopy also changes. Our chosen time periods help ensure that the dynamics that we observe in FIRETEC are based only on foliar chemistry changes and are not also influenced by changes in the fluid dynamics of air flow through the canopies.

Three within-tree canopy bulk density (TBD) conditions were simulated: 0.12 kg m^{-3}, 0.22 kg m^{-3} or 0.32 kg m^{-3}. TBD is defined as the mass of fuel inside the rectangular tree crown envelopes and is thus different from stand scale metrics of bulk density that are calculated using total stand foliage and fine branch biomass and canopy volume. Since the foliar density and surface area per unit volume of the needles are unchanging, these bulk densities can be thought of as being proportional to the number of needles in the tree crown envelope. We assumed that the number of needles remained unchanged between dormant and spring dip conditions, so the bulk densities of the spring dip crowns is 22% larger than the associated dormancy scenario: 0.146 kg m^{-3}, 0.268 kg m^{-3}, and 0.390 kg m^{-3}. We used a surface area to volume of 4419 m^{-1} for red pine foliage based on direct measurements taken from foliage samples collected in 2014.

Two wind speed cases were simulated representing low (4.2 m s^{-1} or 15.12 km h^{-1}) and moderate (6.2 m s^{-1} or 22.32 km h^{-1}) winds with velocities specified for 10 m above the top of the canopy, according to common conventions (Lawson and Armitage, 2008). These mean wind speed cases are consistent with documented active crown fire conditions (Cruz and Alexander, 2010). In order to specify a spatially heterogeneous and time varying wind field with these mean wind speeds, wind fields were developed using the Large Scale Pressure Gradient Force (LSPGF) technique. With this technique, consistent wind fields are developed with the specified mean wind and canopy through simulations with cyclic lateral boundary conditions in the presence of a large-scale pressure gradient force. The large-scale pressure gradient force provides a momentum source counteracting the drag imposed by the vegetation during the cyclic calculation. The result of this technique is a time series of fluctuating winds for all cells around the boundary of the computational domain. For each canopy scenario a separate upstream wind scenario was developed, but because the volume of needles is assumed to remain constant in the change from dormancy to the associated spring dip case, the vegetation drag is also assumed be unchanged. Thus, the same upstream wind fields were used for each pair of dormant and spring dip simulations with a given canopy bulk density and canopy cover. Fires were ignited with a 100 m long fireline located 100 m downwind from the inlet boundary within the 480×384 m domain (Fig. 8). Simulations were allowed to continue until the fire was affected by the outflow boundary.

These simulations are not meant to be an exhaustive set of fuel and weather conditions that cover the full range of variation in nature. Rather, they are meant to capture a range of variations in fuel and weather conditions to allow us to explore the impacts of leaf-scale physio-chemical fuel changes on stand-scale fire behavior. We performed a total of 18 paired simulations, for a total of 36 FIRETEC simulations.

2.8. Data analysis

All data analysis was performed using the R statistical software package, version 3.2.4 (R Core Team, 2016). FIRETEC simulations were analyzed by examining three macroscopic metrics of fire behavior, using the point in time when each fire reached 300 m downwind of the ignition line as a common basis for comparison (Fig. 8). We evaluated the first metric, rate of spread (ROS) as the time it took for the fire to spread from 150 m downwind of the ignition line to 300 m downwind of the ignition line (Fig. 8). The second metric, nominal fireline width (NFW), was calculated by dividing the cumulative area burned (A), defined as those surface fuel cells with >= 20% fuel consumption at the time the fire reached 300 m from the ignition line, by the travel distance, 300 m (Fig. 8). NFW is a simple metric of the shape of the fire and as NFW increases, lateral fire spread, or flanking, increases. The third metric, active fire perimeter (AFP), was calculated as the active fire area, defined as the area of all surface fuel cells with average solid temperatures greater than 600 K, divided by NFW (Fig. 8). A, NFW and AFP can be considered relative measures that facilitate comparison between fires with different geometries and those metrics are better descriptors of the dynamic, two dimensional fire behavior than one dimensional spread rates.

3. Results

3.1. Seasonal foliar physio-chemical variations

Live foliar moisture content (LFMC) seasonal trends followed patterns similar to those reported by Van Wagner (1967) (Fig. 2A). 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 early April and recovered completely by August (Fig. 2A). The lowest recorded LFMC 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 (Fig. 2A). New needle LFMC was >250% for both species and declined rapidly during needle development (Fig. 2A). Foliar water density (mass of water per unit fresh volume of needles) also declined during the spring dip period (Fig. 2B). Foliar density inversely followed LFMC, reaching their highest values during the spring dip for old needles of both red pine and jack pine and increasing in new needles for both species through late summer (Fig. 2C). Relative water content (RWC) was nearly constant for old needles of both species during the spring and early summer and declined in late summer while RWC for new needles declined as needles matured (Fig. 2D).

Mean foliar dry mass increased precipitously during the spring dip period (Fig. 5). Seasonal needle dry mass varied from 0.011 g to 0.0268 g for jack pine and 0.0476 g to 0.105 g for red pine. Old needle mass on 16 April 2013 was 0.018 g for jack pine and 0.0616 g for red pine. Needle mass increased rapidly and peaked on 06 May 2013 where needle mass measured 0.030 g and 0.105 g representing a 68% and 70% increases in jack pine and red pine needle mass respectively over approximately three weeks. These maximum needle dry masses occurred concurrently with the lowest measured LFMC for both species.

Foliar chemistry varied substantially between needle age classes but was similar between species (Fig. 3). The strongest seasonal variations were observed in starch content of old needles in both species, while crude fat and sugar content of new needles

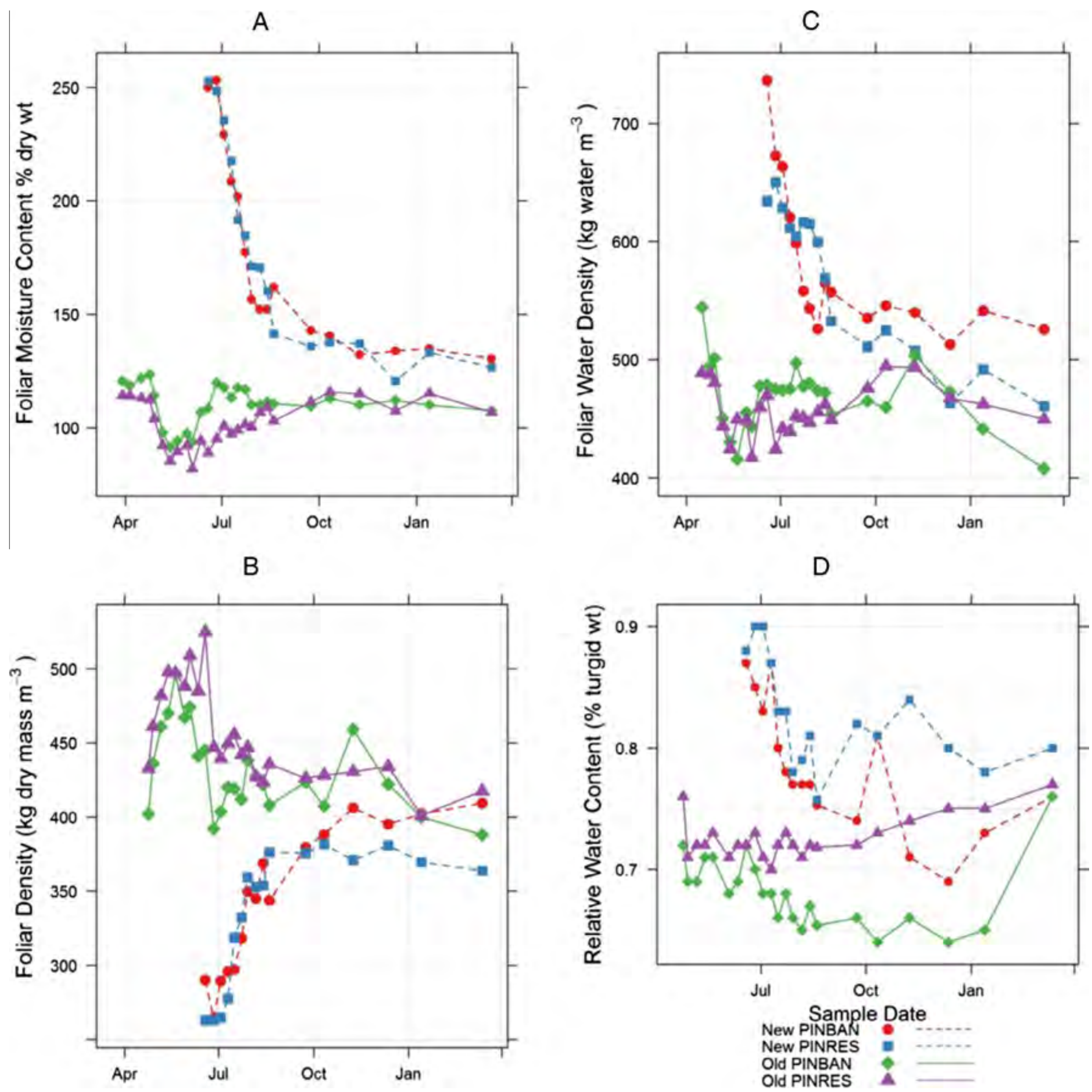

Fig. 2. Seasonal variations in live foliar moisture content, foliar water density, foliar dry matter density and relative water content for Red pine and Jack pine from April 2013 to April 2014. Seasonal low LFMC values were observed in old needless of both species during the spring dip period and the highest recorded values were observed in new needles. 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. Foliar water density decreased during the dip period and recovered concurrent with variations in foliar moisture content. New foliage density increased as needles matured, while old foliage density decreased over that period. Relative water content was very high for new needles and relatively constant for old needles for both species.

continued to rise after needle emergence signaling foliar chemical changes due to needle hardening. Old needle starch concentrations rose from zero during dormancy 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 chemistry changes account for much of the variation in foliar dry mass. Starch, sugar and crude fat percentages accounted for 26.2% and 87.5% of the variation in needle dry mass for jack pine and red pine respectively.

Foliar density tracked seasonal changes in foliar mass and 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 (Fig. 2C). 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 83.7% of the variations in foliar density across both species and needle ages (Fig. 4).

Foliar density also accounted for much of the variation in time to ignition of both species. Density was most related to Jack pine ignitability where it accounted for 39% of the variation in time to ignition, while density explained 25% of the variation in time to ignition for Red pine for old needles (Fig. 6). No clear relationships between new needle density and ignition time were observed for either species (Fig. 6).

Substantial differences in FIRETEC-simulated fire behavior were observed between spring dip and dormant period fuels conditions, with dramatic differences between certain simulation pairs (Table 2). At the lowest wind speed and bulk density, dormant season simulated fires failed to propagate as crown fires, while associated simulations during the spring dip period actively spread as crown fires (Table 2). On average, fires burning under spring dip conditions had ROS ~12 m min^{-1} faster than fires burning under dormant conditions; the magnitude of this effect declined, however, with increasing bulk density and increasing wind speed

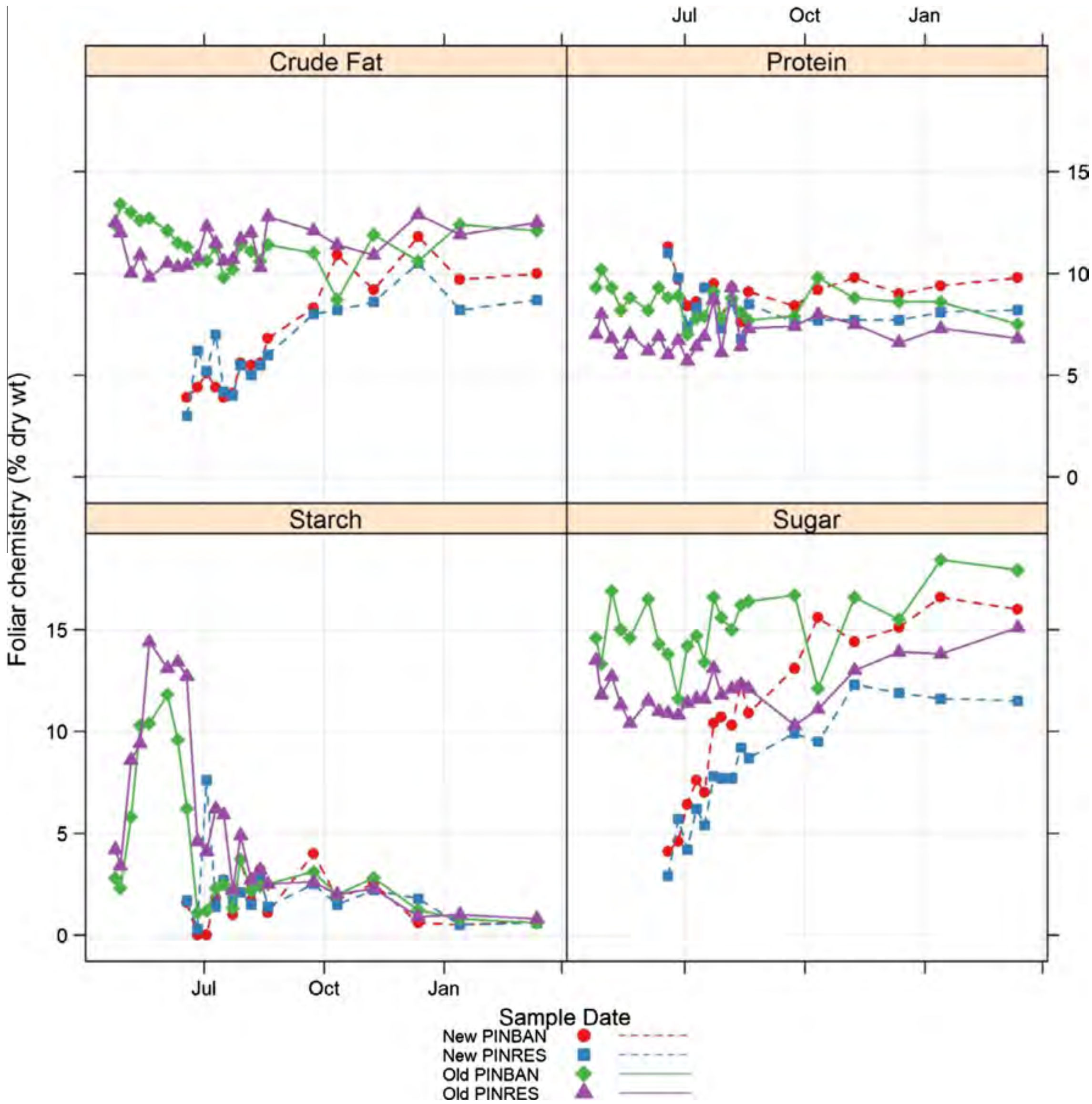

Fig. 3. Seasonal variations in live foliar chemistry for Red pine and Jack pine from April 2013 to April 2014. Crude fat was lowest in new needles of both species and increased during needle development. Needle starch content showed over a ten-fold increase during the spring, increasing from 0% during 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.

(Fig. 9). Area burned was consistently higher during spring dip conditions, even in simulations where rates of spread actually decreased, such as the high TBD and high windspeed cases (Table 2). Nominal fireline widths increased consistently between simulation pairs with increasing canopy cover and bulk density suggesting that spring dip fires exhibit more lateral spread. The largest differences occurred under low bulk densities and moderate wind speeds (ws = 6.2 m s^{-1}, cc = 60%, cbd = 0.22 kg m^{-3}) (Table 2). The active fire perimeter increased consistently between dormant and dip conditions for all simulation pairs. The largest differences were again noted in the lowest density and canopy cover classes.

4. Discussion

Foliar moisture content has long been assumed to relate to red pine and jack pine ignitability 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 which is consistent with previous findings (Little, 1970). These chemical changes are reflected in seasonal changes in foliar dry mass, foliar density and subsequent changes in seasonal foliar ignitability.

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 (Fig. 3). Once new needles emerged, stored starch was depleted because carbon is trans-located from old needles to new needles during needle development (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 the plant several weeks after they are fully developed (Ericsson, 1978). Ultimately, photosynthesis is the main driver of the spring dip; the plant-

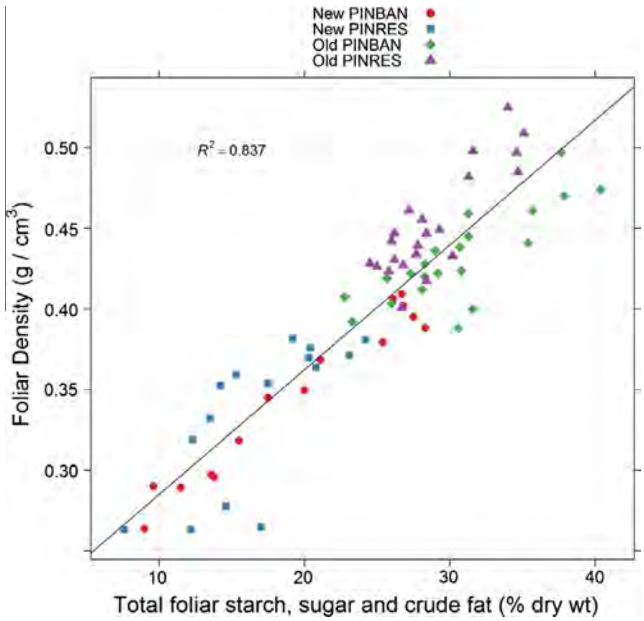

Fig. 4. Relationship between total foliar starch, sugar and crude fat concentrations (as a percentage of total dry matter) and foliar density.

level carbon cycle influences the dry weight of the needles and these changes 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 foliar water content only changes because of an increase in the stored foliar carbon that displaced water out of the needles. This is consistent with our findings that while LFMC dipped during the spring, RWC remained relatively constant throughout the entire period but foliar water density decreased during the dip. 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 seasonal changes in foliar chemistry that drive major changes in dry mass. These mass changes 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 red pine and jack pine foliage, yet they have never been considered as driving components of wildland fires. Generally, time-to-ignition is positively related to density for thermally thin fuels such as leaves and needles (Incropera and DeWitt, 2002). However, we found that these two quantities were negatively related, suggesting that the drivers of the density increase were more easily volatilized and thus lead to faster ignition, despite their contribution to higher particle

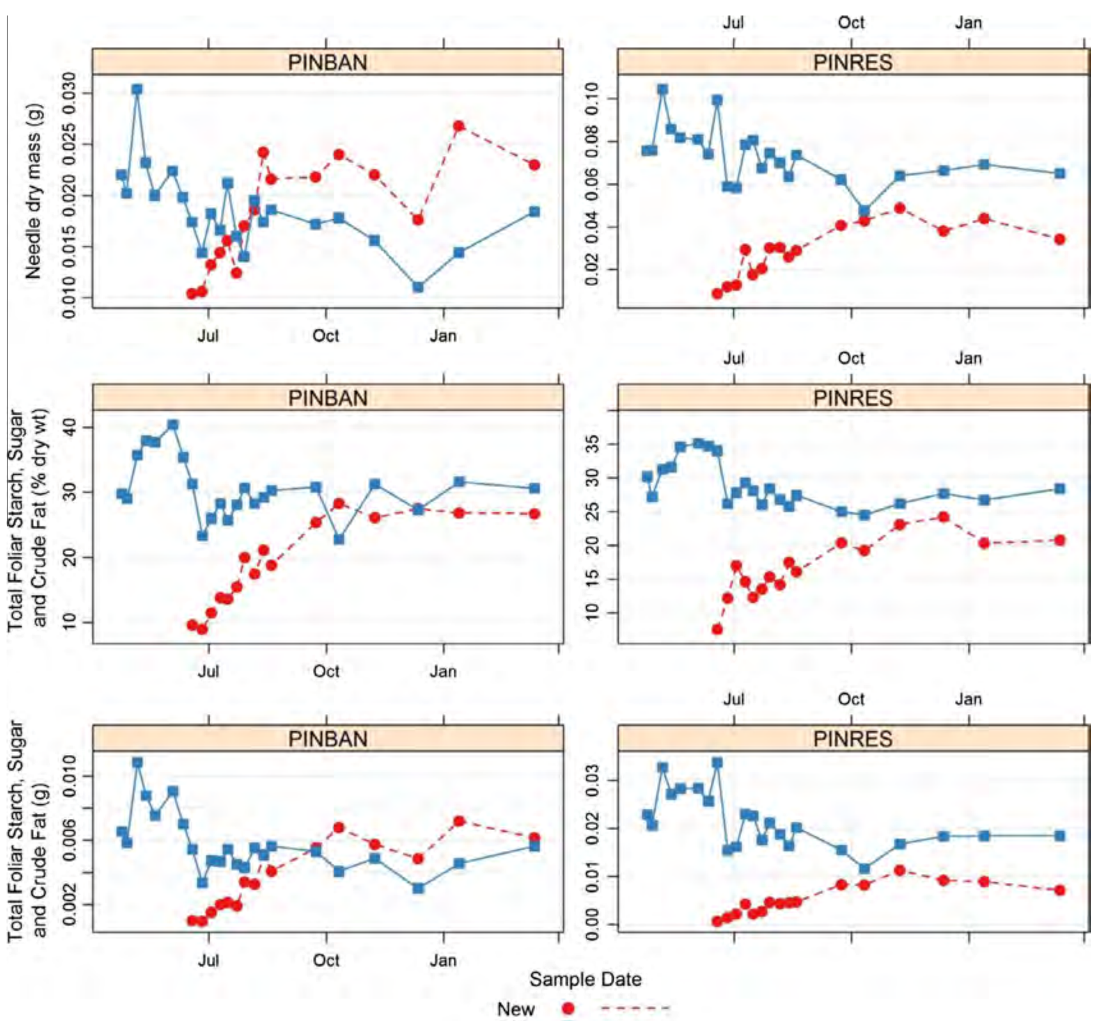

Fig. 5. Seasonal variations in Jack pine (PINBAN) and Red pine (PINRES) needle dry mass (top row) and total foliar starch, sugar and crude fat expressed both as a percentage of dry mass (center row) and as total mass (bottom row) from April 2013 to March 2014.

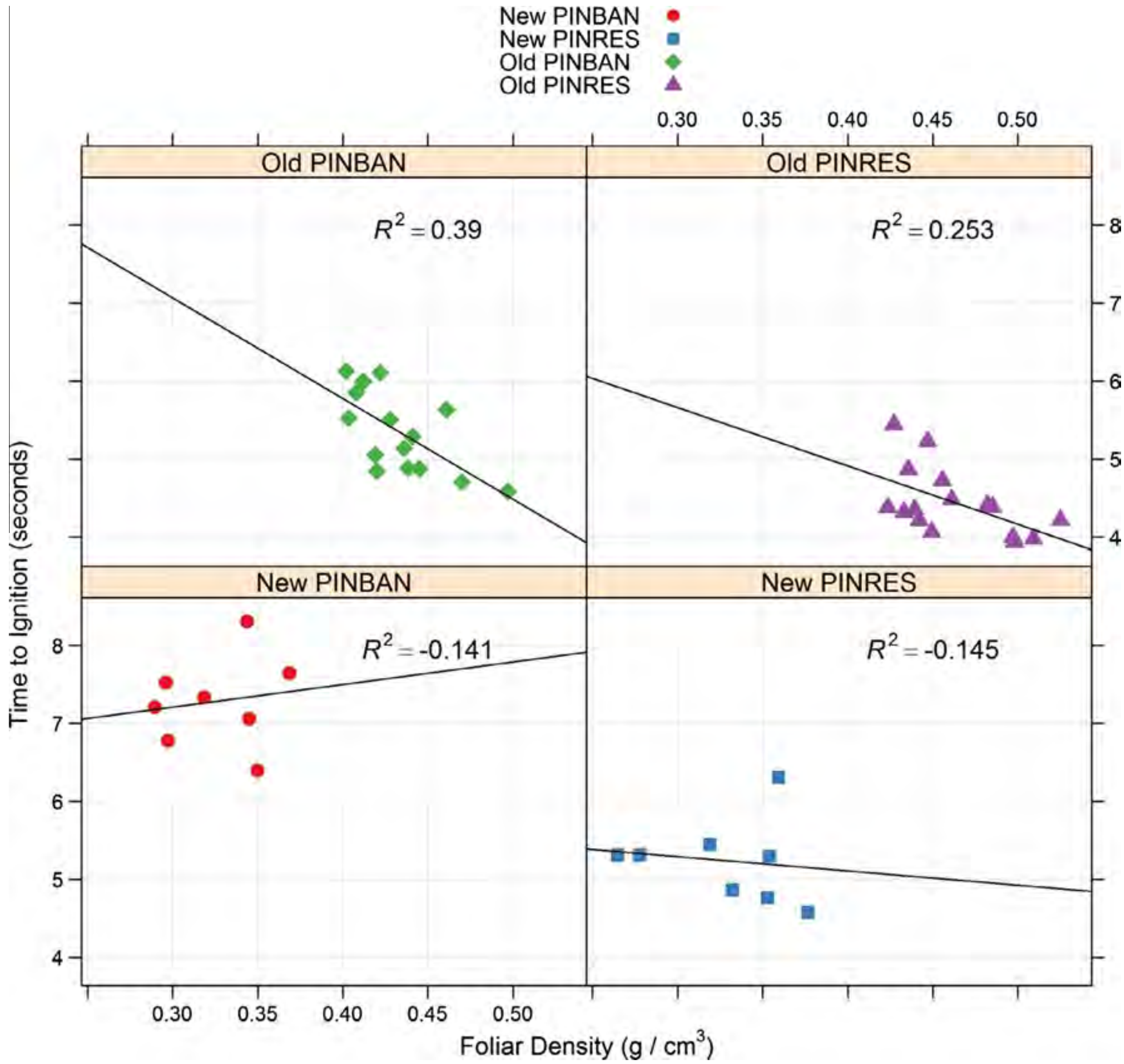

Fig. 6. Relationship between foliar density and time to ignition for new and old foliage of Jack pine (PINBAN) and Red pine (PINRES). Ignition time was most influenced by foliar density in old foliage of both species and was less pronounced in new foliage.

density. Sugar, starch and crude fat should be studied further to determine whether or not they appreciably alter foliage ignitability.

LFMC and green volume-based density are not independent measurements because the density limits the maximum potential moisture content of living plants (Simpson, 1993). Ultimately, LFMC can be expressed as a simple ratio of the volumetric water content in a fuel particle and that particles density as follows:

$$\text{LFMC}\ (\%) = \frac{\rho_{H_2O}}{\rho_{Dry}} \times 100 \tag{2}$$

where ρ_{H_2O} is the mass of water in the fuel particle dividing by the green volume of the fuel particle and ρ_{Dry} is the dry mass of the fuel particle divided by its green volume. More work is needed to understand how chemically-mediated changes in both particle density and apparent moisture content affect the fuels thermal properties and subsequent flammability.

Most of the seasonal changes in live foliar moisture content during the spring coincided with the onset of photosynthesis in the old foliage. As such, it is likely to vary substantially each year as a function of springtime weather. However, Van Wagner contended that the timing of the 'dip' is relatively constant each year and thus is only a function of the lengthening of days with increased latitude. If this phenomenon is driven by phenological changes, the timing of the 'dip' could potentially be subject to even greater variability in the future because climatic changes are promoting earlier springtime budbreak each year (Menzel and Fabian, 1999).

Several notable behaviors were observed in the CFD-based fire simulations from FIRETEC. First, fires under the lowest wind speeds and lowest within-tree bulk densities (0.12 kg m^{-3}) did not spread as crown fires under dormant conditions but actively spread as crown fires under spring dip conditions. The additional foliar mass accumulated during the spring dip period is sufficient to allow the fire to transition past the burn/no-burn threshold and span gaps between trees. These thresholds were achieved without changing the canopy structure or altering the ambient wind's interaction with the canopy. Thus, it is simply a result of larger amounts of mass in the canopy to combust and larger amounts of energy being released causing more effective heating of adjacent trees.

In addition to the emergent spread/no spread threshold behaviors, we also saw significant interactions between bulk density, windspeed and fire behavior metrics, especially in the lowest canopy cover. Spread rates increased by 63% at intermediate within-tree bulk density (0.22 kg m^{-3}) and low windspeeds and

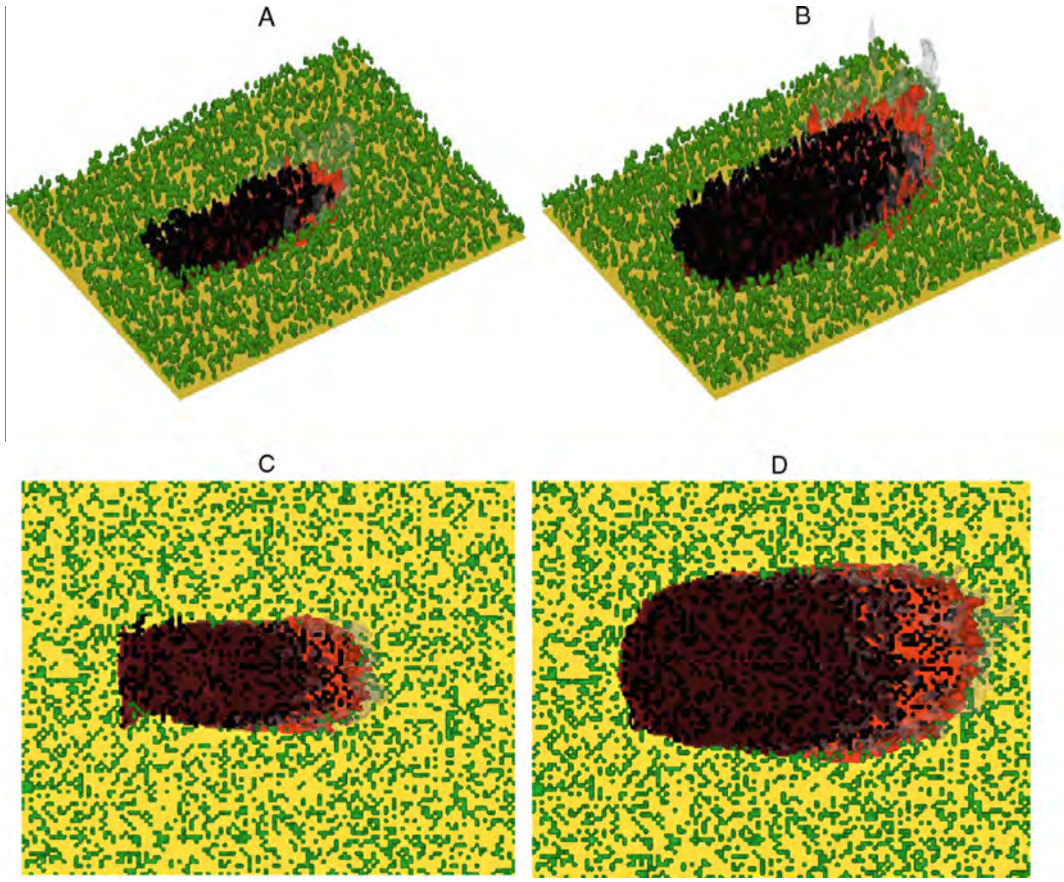

Fig. 7. Comparison of the area burned over the same simulation time (280 s) for the moderate density (0.22 kg m^{-2}), low canopy cover (30%) and low windspeed case (4.2 m s^{-1}) for dormant season conditions (A and C) and spring dip conditions (B and D).

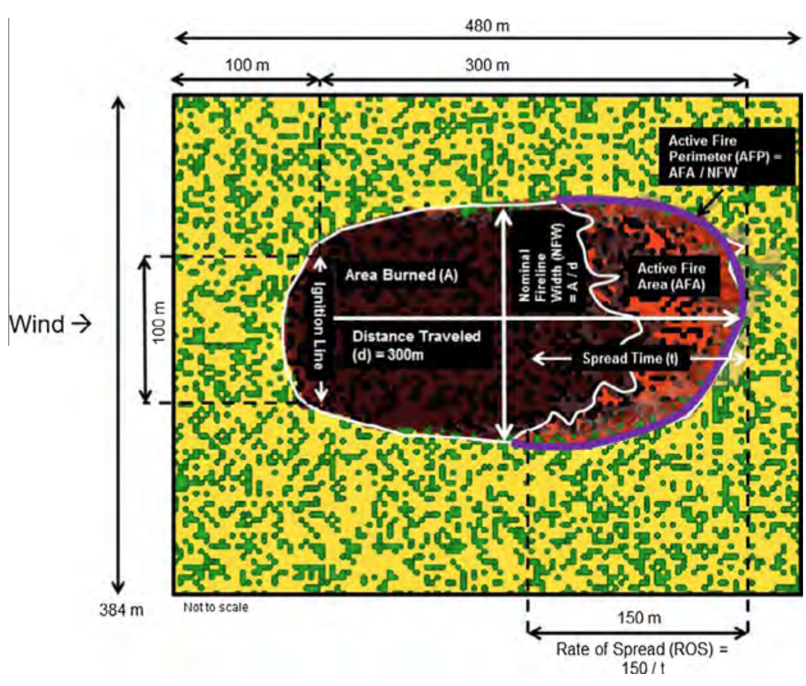

Fig. 8. Schematic summary of FIRETEC simulation analysis metrics. Four metrics were derived from each simulation: area burned, rate of spread, nominal fireline width and active fire perimeter and all metrics were compared between pairs of simulations for dormant and spring dip conditions.

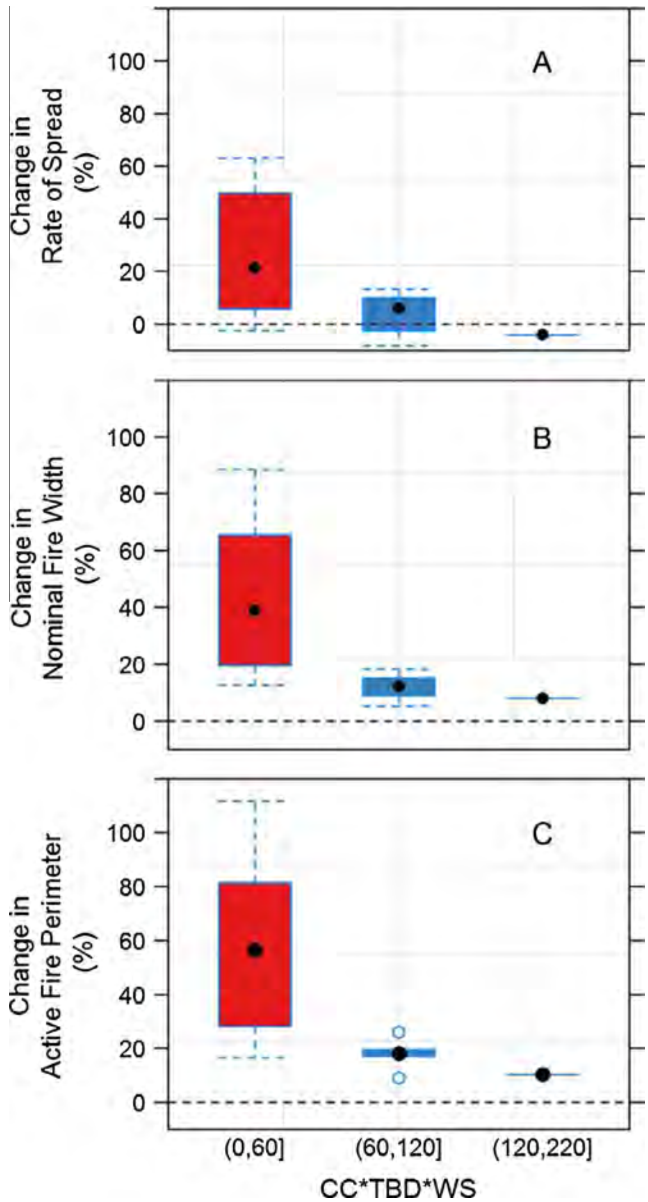

Fig. 9. Summary of changes in FIRETEC-modeled rate of spread (A), nominal fireline width (B) and active fire perimeter (C) between dormant and spring dip conditions plotted against the product of canopy cover (CC), within-tree bulk density (TBD) and wind speed (WS). For all variables as CC, TBD and/or WS increases, the influence of the dip on simulated fire behavior diminishes.

these changes diminished with increasing canopy cover. This suggests that in cases of low fuel density, fire spread could be limited by available fuel mass and subsequent heat release needed to effectively span gaps between trees. However, as fuel density increased beyond optimum, relative fire behavior differences between dormant and dip simulations were less pronounced (Fig. 9) but absolute area burned always increased under spring dip conditions relative (Table 2).

As within-tree bulk density, canopy cover or windspeed increased, fire behavior differences between dormant and spring dip conditions diminished (Fig. 9). This was caused by an increase in the active flanking behavior of simulated fires and it is well captured by our Active Fire Perimeter metric. This metric is an indication of the amount of active fire per projected upstream width, which can be thought of as the amount of active fire that is fed by a fixed amount of upstream wind. The upstream wind blowing through the fire front is largely responsible for the spread of the fire, especially for the headfire. As the amount of active fire that is being fed by a given amount of upstream wind increases, there is effectively less wind to push the fire forward, so the fire's ROS will decrease if all other conditions were held constant. The increase in the amount of active fire per upstream wind or upstream projected area is indicative of fires with both a well-developed head and flanks. Despite the decreased spread rates with higher canopy densities and windspeeds, area burned always increased during spring dip conditions because of the increase in lateral spread of the fire.

Under high canopy mass and high wind speed scenarios, the spring dip effect on ROS was less noticeable. In some of the cases with moderate winds and either higher cover fraction or a dormant crown bulk density of 0.32 kg m^{-3}, the ROS of the spring dip scenario was nearly equal or slightly lower than the ROS of the corresponding dormant case. This is likely associated with two factors: (1) the canopy cover, crown bulk density and winds were already sufficient to carry active crown fire in the dormant case and (2) the added canopy mass in the spring dip scenarios increases headfire intensity and persistence of flanking fires, which ultimately reduces the ROS as the stronger convective updrafts diminish the relative impact of the ambient winds.

Ultimately, two behaviors dominate these simulation results. First, fires with inherently low fuel loads per unit area benefit from the additional available fuel that is present during the spring dip conditions as a result of increases in foliar density. In some cases, this can lead threshold behavior where fires can spread through stands during spring dip conditions that it would be unable to spread through in dormant conditions. When fires did successfully spread through low density fuels, they generally spread as head fires with minimal flanking behavior. However, as fuel loads increase, either through increases in the within-tree bulk density or by increases in canopy cover, fires had both more pronounced lateral spread and well developed flanks yielding fires that spread at the same rate (or even slightly slower), yet still burned more area. This suggests a competitive effect between heat release, air entrainment into the combustion zone and dynamic flame structure that can have a pronounced impact on realized fire behavior.

With this FIRETEC numerical study we only studied the influence of increased mass in the foliage, which is only part of the story since there are also changes in the foliar moisture content and foliar chemistry that are also expected to constructively affect fire behavior during the spring dip. Foliar chemical variations could have substantial impacts on the mass loss and heat release rates of burning foliage and these impacts could further contribute to realized fire behavior differences between dormant and spring dip periods. The potential significance of these added effects of the chemical changes to landscape-scale fire behavior changes will be investigated in follow on research.

This is the first study to combine moisture content, chemistry, density and ignition testing during the spring dip period, and to link these bench-scale measurements to stand scale fire behavior changes through simulation modeling. We have revealed some previously undiscovered linkages that could change how we assess live fuel flammability in the future. Historically, studies have focused exclusively on variations in foliar moisture content but have ignored the influences of variations in foliar dry matter and subsequent changes in available canopy fuel. Our findings suggest a new hypothesis about the key factors that drive seasonal variations in crown fire potential. While we do not doubt that moisture plays a key role in ignition, we have demonstrated that seasonal mass variations can profoundly affect needle ignitability and stand scale fire behavior. This new knowledge may lead to better tools to help fire managers assess seasonal crown fire potential in these dynamic forests.

Table 2
FIRETEC fire behavior simulation results for paired simulations representing dormant and spring dip fuel conditions across a range of canopy bulk densities, wind speeds and canopy covers. NS indicates simulations that did not spread (propogate).

Wind speed 10 m above canopy (m s^{-1})	Within tree canopy bulk density (kg m^{-3})		Canopy cover (%)	Area burned (A) (ha)		Rate of spread (ROS) (m s^{-1})		Nominal fireline width (NFW) (m)		Active fire perimeter (AFP) (m)	
	Dormant	Spring dip		Dormant	Spring dip	Dormant	Spring dip	Dormant	Spring dip	Dormant	Spring dip
4.2	0.12	0.158	30	NS	1.86	NS	0.80	NS	61.9	NS	52.3
			60	NS	4.13	NS	1.34	NS	138.0	NS	96.6
			80	NS	4.31	NS	1.46	NS	144.0	NS	131.0
6.2			30	2.63	3.19	1.34	1.67	87.6	106.0	62.4	121.0
			60	2.37	4.46	1.35	1.95	79.0	149.0	89.4	151.0
			80	2.57	4.28	1.32	2.05	85.6	143.0	98.0	163.0
4.2	0.22	0.283	30	3.01	4.61	1.03	1.68	100.0	154.0	51.5	109.0
			60	4.51	5.08	1.74	1.97	150.0	169.0	112.0	150.0
			80	4.62	5.04	1.61	1.69	154.0	168.0	129.0	151.0
6.2			30	3.02	4.91	1.61	1.90	100.0	164.0	89.4	131.0
			60	4.26	5.03	1.95	1.90	142.0	168.0	129.0	154.0
			80	4.58	4.82	1.76	1.88	153.0	161.0	139.0	164.0
4.2	0.32	0.408	30	4.64	5.50	1.53	1.50	155.0	183.0	90.1	105.0
			60	4.71	5.43	1.50	1.70	157.0	181.0	116.0	146.0
			80	4.62	5.03	1.58	1.74	154.0	168.0	127.0	150.0
6.2			30	4.23	5.22	1.97	1.92	141.0	174.0	107.0	131.0
			60	4.82	5.60	1.97	1.81	157.0	181.0	145.0	158.0
			80	4.83	5.24	1.74	1.67	161.0	174.0	145.0	160.0

Acknowledgements

This work was made possible by funding from the Joint Fire Science Program of the U.S. Department of Agriculture (USDA) and U.S. Department of the Interior (USDI) Projects (12-1-03-30), as well as by the USDA Forest Service's Rocky Mountain Research Station (RMRS). Los Alamos National Laboratory's Institutional Computing Program provided computational resources to perform the FIRETEC simulations for this work.

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