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Bark Beetle-Induced Changes to Crown Fuel Flammability and Crown Fire Potential

Wesley G. Page
Utah State University

BARK BEETLE-INDUCED CHANGES TO CROWN FUEL FLAMMABILITY AND

CROWN FIRE POTENTIAL

by

Wesley G. Page

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Approved:

Michael J. Jenkins Major Professor	Martin E. Alexander Committee Member
Barbara J. Bentz Committee Member	Edward W. Evans Committee Member
Michael R. Kuhns Committee Member	Mark R. McLellan Vice President for Research and Dean of the School of Graduate Studies

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ABSTRACT

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Crown Fire Potential

by

Wesley G. Page, Doctor of Philosophy

Utah State University, 2014

Major Professor: Dr. Michael J. Jenkins
Department: Wildland Resources

Recent outbreaks of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests and spruce beetle (*Dendroctonus rufipennis* Kirby) in Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) forests have affected vast areas across western North America. The high levels of tree mortality associated with these outbreaks have raised concerns amongst fire managers and wildland firefighters about the effects of the tree mortality on fire behavior, particularly crown fire behavior, as crown fires hinder the ability of firefighters to conduct safe and effective fire suppression operations. Current information regarding crown fire dynamics in recently attacked forests is limited to results obtained from simulations employing either inappropriate and/or unvalidated fire behavior models based on inadequate descriptions of crown fuel flammability. The purpose of this research was to measure and characterize the changes in crown fuel flammability caused by recent bark beetle attack and to describe the implications of these changes on crown fire potential in affected forests.

Results indicated that bark beetle attack causes a significant decline in moisture content and change in chemical composition in lodgepole pine and Engelmann spruce tree foliage, which substantially increases foliage flammability. Additionally, it was found that conventional models used to predict the moisture content of fine, dead surface fuels were inappropriate for predicting the moisture content of foliage on mountain pine beetle-attacked lodgepole pine trees during the red stage. Therefore, calibrated operational models and models based on diffusion theory were developed and evaluated that could accurately predict hourly fluctuations in moisture content. The implications of these changes on crown fire potential are dependent upon a host of site specific factors including outbreak duration, severity, and the specific stand characteristics. Based on our results, we believe that current fire behavior models, including popular semi-empirical and physics-based models, are currently inadequate for accurately predicting crown fire potential in forests recently attacked by bark beetles. In order to make significant progress in our understanding of crown fire potential in recently attacked forests, a substantial effort to document wildfire behavior in the field and/or to conduct experimental fires is needed.

(271 pages)

PUBLIC ABSTRACT

Bark Beetle-Induced Changes to Crown Fuel Flammability and

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Recent outbreaks of aggressive tree-killing bark beetles, including mountain pine beetle in lodgepole pine forests and spruce beetle in Engelmann spruce forests, have recently affected vast areas across western North America. The high levels of tree mortality associated with these outbreaks have raised concerns amongst fire managers and wildland firefighters about the possible effects on fire behavior potential, particularly crown fire potential, as crown fires (fires that consume part or all of tree crowns) hinder the ability of firefighters to conduct safe and effective fire suppression operations. The purpose of this research was to measure and characterize the changes in moisture content, chemical composition, and resulting flammability of foliage on bark beetle-attacked trees and to describe the implications of these changes on crown fire potential in affected forests.

Results indicated that bark beetle attack causes a significant decline in moisture content and change in chemical composition in lodgepole pine and Engelmann spruce tree foliage, which substantially increases foliage flammability. The results also suggested that the moisture content of dead foliage on mountain pine beetle-attacked lodgepole pine trees cannot be predicted using conventional models, so data were collected to develop and test new models. The implications of these changes on crown

fire potential are dependent upon site specific factors such as outbreak duration, severity, and the structural characteristics of the forest. Based on our results, we believe that current fire behavior models are inadequate for accurately predicting crown fire potential in bark beetle-affected forests. In order to make significant progress in our understanding of crown fire potential in recently attacked forests, a substantial effort to document wildfire behavior in the field and/or to conduct experimental fires is needed.

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Wesley G. Page

CONTENTS

Page

ABSTRACT ii

PUBLIC ABSTRACT iv

ACKNOWLEDGMENTS vi

LIST OF TABLES x

LIST OF FIGURES xiii

CHAPTER

1. INTRODUCTION 1

    Problem Statement and Research Objective 1
    Research Questions 2
    References 3

2. FUELS AND FIRE BEHAVIOR DYNAMICS IN BARK BEETLE-ATTACKED FORESTS IN WESTERN NORTH AMERICA AND IMPLICATIONS FOR FIRE MANAGEMENT 4

    Abstract 4
    Introduction 5
    Bark Beetle Effects on Forest Structure, Composition and Fuel Bed Characteristics 10
    Crown Fire Initiation and Spread 17
    Challenges in Modeling Crown Fire Behavior in Bark Beetle-Affected Forests 21
    Short- and Long-Term Implications for Fire Suppression 28
    Bark Beetles, Fires, and Forest Health 30
    References 32

3. MOUNTAIN PINE BEETLE ATTACK ALTERS THE CHEMISTRY AND FLAMMABILITY OF LODGEPOLE PINE FOLIAGE 44

    Abstract 44
    Introduction 45
    Methods 48
    Results 58
    Discussion 73

Conclusion 76
References.. 78

4. SPRUCE BEETLE-INDUCED CHANGES TO ENGELMANN SPRUCE FOLIAGE FLAMMABILITY 84

Abstract 84
Introduction.. 85
Methods.. 88
Results.. 96
Discussion 106
Conclusion 113
Literature Cited 113

5. FOLIAR MOISTURE CONTENT VARIATIONS IN LODGEPOLE PINE OVER THE DIURNAL CYCLE DURING THE RED STAGE OF MOUNTAIN PINE BEETLE ATTACK 120

Abstract 120
Introduction.. 121
Material and Methods 122
Results.. 126
Discussion and Conclusions 130
References.. 132

6. MODELS TO PREDICT THE MOISTURE CONTENT OF LODGEPOLE PINE FOLIAGE DURING THE RED STAGE OF MOUNTAIN PINE BEETLE ATTACK 136

Abstract 136
Introduction.. 137
Description of Models.. 139
Methods.. 142
Results.. 146
Discussion and Conclusions 152
Literature Cited 154

7. CROWN FIRE POTENTIAL IN LODGEPOLE PINE FORESTS DURING THE RED STAGE OF MOUNTAIN PINE BEETLE ATTACK 157

Abstract 157
Introduction.. 158
MPB Effects on Surface Fuels.. 161
MPB Effects on Crown and Canopy Fuel Properties 163
Crown Fire Initiation in Recently Attacked Lodgepole Pine

Forests 168
Crown Fire Spread in Recently Attacked Lodgepole Pine
Forests 175
Field Observations of Fire Behavior 182
Conclusion 189
References 191

8. WILDFIRE'S RESISTANCE TO CONTROL IN MOUNTAIN PINE BEETLE-ATTACKED LODGEPOLE PINE FORESTS 200

Abstract 200
Introduction 201
Broadening the Definition of "Resistance to Control" 205
Fire Behavior Characteristics 206
Fire Suppression Operations 213
Firefighter Safety Considerations 216
Implications for Fire Research and Fire Management 219
Conclusions 222
References 222

9. SUMMARY AND CONCLUSIONS 230

Introduction 230
Seasonal Changes in Moisture Content, Chemistry, and Flammability
of Lodgepole Pine and Engelmann Spruce Foliage 232
Diurnal Changes in Lodgepole Pine Foliar Moisture Content 234
Crown Fire Potential in Lodgepole Pine Forests 235
Conclusions 236
References 237

APPENDICES 239

CURRICULUM VITAE 249

LIST OF TABLES

Table Page

3.1 Mean (± standard error (SE)) percentage of oven-dried fuel moisture content, averaged over all sampling periods (July–September), for old foliage and twigs < 0.64 cm in diameter and the minimum mean values (Min.) recorded for each crown condition class (G, green; GI, green-infested; Y, yellow; R, red) 59

3.2 Mean proportion of foliage chemical composition for each sampling period across all crown condition classes (G, green; GI, green-infested; Y, yellow; R, red)......62

3.3 Parameter estimates and goodness-of-fit statistics for the best linear regression model obtained using stepwise selection regressing time to ignition of fresh foliage on the chemical composition variables 66

3.4 Pearson's correlation coefficients (*r*) and associated *P* values among the flammability parameters time to ignition, temperature at ignition, and maximum rate of mass loss with individual terpene compound emission rates ($ng \cdot h^{-1} \cdot g$ fresh $mass^{-1}$) for fresh foliage 66

3.5 Pearson's correlation coefficients (*r*) and associated *P* values for duration of flaming, temperature at ignition, and high heat of combustion with the chemical composition groups for dry foliage...69

3.6 The mean high heats of combustion obtained from the bomb calorimeter testing for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red) for every sampling period 71

4.1 List of abbreviations, sorted alphabetically, used in the manuscript 93

4.2 Total volatile terpene emission rate and within-needle terpene concentration for all sample periods for each of the crown condition classes. Data are means ± SE. Different letters within a column indicate significant differences, $\alpha < 0.10$. E, first 2 weeks of each month; L, last 2 weeks of each month.....................................101

4.3 Results of multiple linear regression of the dependence-free residuals of the old foliage principal component scores on axis 1 and 2 with the fuel moisture and chemistry variables using stepwise selection. Estimates of variable coefficients are given along with the SE, *t* values, and the proportion of variability explained by that variable using type I sums of squares (SS). The goodness-of-fit statistics of root mean square error (RMSE) and the adjusted R^2 are also given. The final models included FMC, ADF, protein, crude fat, and total terpene concentration (TC) ($n = 76$)...105

4.4 Results of multiple linear regression of the dependence-free residuals of high heat of combustion with the chemistry variables using stepwise selection. Estimates of variable coefficients are given along with the SE, *t* values, and the proportion of variability explained by that variable using type I sums of squares (SS). The goodness-of-fit statistics of root mean square error (RMSE) and the adjusted R^2 are also given. The final model included ADF, ash, and total terpene concentration (TC) (n = 79) 107

5.1 Measures of long term dryness for the site for each of the sampling days. All values were calculated based on historical data from the Hewinta RAWS. Measures of dryness included the Energy Release Component (ERC) from the National Fire Danger Rating System, the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index System, and the Keetch-Byram Drought Index (KBDI). The means, standard errors, and 90th percentiles were based on the historical weather for that day from the period 1984 to 2012 127

5.2 Range in observational data obtained from the Hewinta RAWS over the course of two diurnal sampling periods during the 2012 fire season 127

5.3 Summary of statistics associated with the comparison of predicted fine dead fuel moistures versus observed dead foliar moisture contents of red needles on mountain pine beetle attacked lodgepole pine trees. The deviation statistics are root mean square error (RMSE), mean absolute error (MAE), mean absolute percent error (MAPE), and mean bias error (MBE) 129

6.1 The observed and historical (1988-2012) mean and 90th percentile Energy Release Component (ERC), Duff Moisture Code (DMC), Drought Code (DC), and Keetch-Byram Drought Index (KBDI) calculated at the Saw Mill Park RAWS for each of the days when sampling was conducted....................148

6.2 Deviation statistics from the comparison of the observed dead foliar moisture contents with the predicted values from the five proposed models with their mean (± standard error [SE]) and range of observed values across all four sample periods. Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percent mean absolute error (PMAE), and mean bias error (MBE). All units are percent oven-dry weight except for PMAE 150

6.3 Deviation statistics from the comparison of the observed dead foliar moisture contents from Chapter 5 with the predicted values from the five proposed models along with their mean (± standard error [SE]) and range of observed values for both sample periods. Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percent mean absolute error (PMAE), and mean bias error (MBE) 151

6.4 Deviation statistics from the comparison of the observed dead foliar moisture contents from Armitage (2004) with the predicted values from the five proposed models along with their mean (± standard error [SE]) and range of observed values. Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percent mean absolute error (PMAE), and mean bias error (MBE). All units are percent oven-dry weight except for PMAE. 152

7.1 Summary of the weather conditions, fire behavior, and fire danger ratings associated with the experimental fires and wildfires that burned through recently attacked mountain pine beetle (MPB)-infested lodgepole pine stands or simulated cases (i.e. Archer Lake). The observed (Obs.) and 97th percentile Energy Release Component (ERC) of the National Fire Danger Rating System (Deeming *et al.*, 1977) and the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987) are also displayed for each fire according to country of origin, either United States or Canada. The 6.1 m open wind speeds for the Valley Road and Salt wildfires were adjusted to 10-m based on the 1.15 adjustment factor suggested by Lawson and Armitage (2008). Archer Lake plots missing observed rates of spread were omitted for control plots (a) and simulated attack plots (b)................................185

8.1 Summary of the potential effects of mountain pine beetle mortality in lodgepole pine forests on fire behavior, suppression operations, and firefighter safety over the course of severe outbreak by bark beetle attack stage (after Jenkins *et al.* 2008, see Chapter 2, 2014; Hicke *et al.* 2012)..210

LIST OF FIGURES

Figure Page

2.1 View of the convection/smoke column associated with the 1961 Sleeping Child Fire on the Bitterroot National Forest in western Montana that spread through lodgepole pine stands that had previously sustained heavy mortality from a mountain pine beetle outbreak in 1928–1932 (Roe and Amman, 1970). This lightning-ignited fire started on August 4 and in spite of rapid initial attack grew to nearly 60 ha in the first two hours following detection and then to 3640 ha within 24 h (Morrison, 1964). The fire continued to grow until August 13 when it was controlled after having covered more than 11,330 ha of upper montane and subalpine forest. Photo by Ernest Peterson, USDA Forest Service. 11

2.2 (a) An Engelmann spruce stand near Purple Lake on the Fishlake National Forest taken in 1902. (b) Repeat photo from the same location taken in 2002 showing the stand as it regenerated following an extensive spruce beetle outbreak in the 1920's. Photo (b) by Mike Jenkins. 13

2.3 Engelmann spruce beetle condition classes shown during the course of the bark beetle rotation; (a) endemic (EN), (b) epidemic (EP), and (c) post-epidemic (PE). Changes in (I) stand structure, (II) canopy fuel condition, and (III) surface fuel complex are shown (Jorgensen and Jenkins, 2011). Photos by Mike Jenkins...... 14

2.4 Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS) (Reinhardt and Crookston, 2003) was used to simulate changes in large woody fuels greater than 7.62 cm in diameter resulting from low (Case 1) moderate (Case 2) and high (Case 3) fall rates following the spruce beetle outbreak in the 1920's at Purple Lake, Utah. Repeat photos (top to bottom), taken in 1948, 1968, 1988 and 2010 are representative of Case 3 fall rate. Data are from Jorgensen and Jenkins (2011). 1988 photo by Steve Munson and 2010 photo by Jesse Morris. 15

2.5 Aerial view of a surface fire slowly spreading upslope in green white spruce (*Picea glauca* (Moench) Voss) forest (top) and then transitioning to active crowning upon reaching a patch of "red stage" mountain pine beetle-attacked lodgepole pine forest (bottom). This wildfire occurred in the central interior region of British Columbia, Canada, in midafternoon on August 18, 2003. Photos by M. Simpson, British Columbia Wildfire Management Branch. 18

2.6 Graphic illustration of fuel properties affecting crown fire initiation and spread. CBH = crown base height, ICD = intercrown distance, CBDmax and CBDmin = maximum and minimum canopy bulk density, SFI = surface fire intensity and FL = flame length. In the illustration we represent a fire spreading from left to right and depict suggested fire behavior from low intensity surface fire (a), passive crown fire (b), active crown fire (c) and high intensity surface fire (d) for the different fuel properties under constant wind and slope. See text for a discussion of the influence of foliar moisture and chemical composition on crown fire initiation and spread. 19

2.7 Critical surface fire intensity for crown combustion in a conifer forest stand as a function of canopy base height and foliar moisture content (FMC) according to Van Wagner (1977) crown fire initiation model for the mean FMC values associated with tree crown condition classes of mountain pine beetle attack in lodgepole pine (data used with permission from Jolly et al., 2012). 24

3.1 Experimental setup for laboratory flammability testing: (*a*) type K thermocouple probe; (*b*) 500 W silica epiradiator; (*c*) pilot ignition source; (*d*) sample holder; and (*e*) data logger connected to scale and thermocouple 54

3.2 Mean foliar moisture content for new and old foliage and the mean litter moisture content for all sampling periods (July–September (E, early; L, late)), with associated standard error bars, for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red) 59

3.3 Mean twig (<0.64 cm in diameter) moisture content for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red) and the mean litter moisture content for all sampling periods (July–September (E, early; L, late)), with associated standard error bars..........61

3.4 Mean volatile terpene emission rates separated by compounds that were significantly correlated with flammability by crown condition class (G, green; GI, green-infested; Y, yellow; R, red) for all months (July–September), with associated standard error bars; letters on bars indicate significant differences within sampling period. The individual terpene compounds are stacked according to the order in the legend. Comparisons of individual terpenes are for mean emission rates across all sampling periods, and significance is indicated in the legend in parentheses after each compound (condition class in bold followed by corresponding significance letter(s)). The crown condition classes in the legend are arranged from highest to lowest mean values, and bars and terpene names with a different letter have means that are significantly different 63

3.5 Box-and-whisker plots of the flammability test results for fresh foliage, including (A) time to ignition, (B) duration of flaming, (C) temperature at ignition, (D) maximum temperature, (E) maximum (Max.) rate of mass loss, and (F) maximum (Max.) rate of temperature change for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red), averaged over all sampling periods. The diamond represents the mean, the horizontal line is the median, the lower and upper box ends represent the lower and upper quartiles, and the whiskers are the minimum and maximum values, respectively. Bars with a different letter have means that are significantly different at the $\alpha = 0.05$ level. n.s., nonsignificant ...65

3.6 Box-and-whisker plots of the flammability test results for dry foliage, including (A) duration of flaming and (B) temperature at ignition for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red), averaged over all sampling periods. The diamond represents the mean, the horizontal line is the median, the lower and upper box ends represent the lower and upper quartiles, and the whiskers are the minimum and maximum values, respectively. Bars with a different letter have means that are significantly different at the $\alpha = 0.05$ level. ○, outliers 68

3.7 Summary results matrix for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red)........72

4.1 The mean historical (1983–2011) and 2012 precipitation and mean air temperature at the Norway remote automated weather station for the spring and summer months. The station was located approximately 22 km north of the study site at an elevation of 2,524 m above mean sea level. The number of years in the historical database varied by month: April and May, 11 years; June, 12 years; July, 23 years; August, 27 years; September, 26 years; and October, 27 years 97

4.2 The seasonal change in foliar moisture content of Engelmann spruce foliage from new and old foliage on G, GI, and Y. The mean values are representative of the first 2 weeks of each month (E) and the last 2 weeks of each month (L) and are shown along with associated standard error bars (Old: G, $n = 207$; GI, $n = 177$; Y, $n = 69$) (New: G, $n = 53$; GI, $n = 48$)........98

4.3 The seasonal change in chemical composition (June to September) of Engelmann spruce foliage from G and spruce beetle-attacked trees, either recently attacked (GI) or mass attacked the previous year (Y). The chemical composition variables were the proportion of NDF, NFC, protein, and crude fat content. The mean values are those from the first 2 weeks of each month and are shown along with associated SE bars (G, $n = 33$; GI, $n = 31$; Y, $n = 15$)........99

4.4 Correlations of principal component scores of axis 1 (PC1) and axis 2 (PC2) with the eight measures of flammability from fresh foliage: TAI, TTI, DOF, maxTDF, $_{maxrate}$MLR, $_{maxrate}$TDF, $_{prop}$MLDF, and HY. The appropriate Pearson correlation coefficient is shown in each cell. The lines are the ordinary least squares line of best fit. *, Log transformation ($n = 147$ for all correlations)........102

4.5 Plot of principal component scores through time by crown condition class from axis 1 of the principal component analysis of old foliage flammability. Higher scores indicate higher flammability. The mean values are representative of the first 2 weeks of each month (E) and the last 2 weeks of each month (L) and are shown along with associated SE error bars (G, $n = 67$; GI, $n = 58$; Y, $n = 22$)...103

4.6 Box and whisker plots for the measured high heats of combustion of Engelmann spruce foliage during the fire season from G, GI, and Y trees. The values are representative of the first 2 weeks of each month (E) and the last 2 weeks of each month (L). The mean is the asterisk, the median is the horizontal line, the ends of the boxes are the first and third quartiles, and outliers are more than 1.5 times the interquartile range. Different letters within a crown condition class indicate significant differences, $\alpha < 0.10$ (G, $n = 69$; GI, $n = 59$; Y, $n = 23$)....................106

5.1 Diurnal changes in weather conditions and in dead foliar moisture content of red needles on mountain pine beetle attacked lodgepole pine trees during both sampling periods in May and August, 2012. The shaded area signifies the night-time period 128

5.2 Plots of the observed dead foliar moisture contents of red needles on mountain pine beetle attacked lodgepole pine trees during the red stage with the predicted values from the National Fire Danger Rating System (Bradshaw et al., 1984) modified model, the Rothermel (1983) lookup tables, the Sharples et al. (2009) model, and the 10-h timelag fuel moisture indicator stick for both sampling periods. The shaded area signifies the night-time period 129

6.1 Time series of the mean observed dead foliar moisture contents (± standard error) for Period 1 (a), Period 2 (b), Period 3 (c), and Period 4 (d). The measured relative humidity from the Saw Mill Park Remote Automated Weather Station is shown on the secondary axis...147

6.2 Change in relative moisture content for three lodgepole pine foliage samples during the red stage of mountain pine beetle attack under desorption conditions (air temperature ~22.2°C and relative humidity 51.4%). The calculated mean (± standard error [SE]) first period timelag is 3.21 (±0.21) h 148

6.3 Time series of the observed mean dead foliar moisture contents (± standard error [SE]) from Chapter 5 with the predictions made from the five proposed models. The models were derived from the modification of the National Fire Danger Rating System fine fuel moisture equations suggested by Anderson (1985) using both the timelags reported for recently cast lodgepole pine foliage and the mean timelag from the laboratory analysis reported in this study. The corrected models from Rothermel (1983) (eq. 6.10) and the hourly Fine Fuel Moisture Code (FFMC) (Van Wagner 1977) (eq. 6.11) were also used along with the fit obtained from the methods described by Catchpole et al. (2001). The shaded area represents the night time period..151

7.1 Photographs of mountain pine beetle-affected (a) lodgepole pine stand on the Sawtooth National Recreation Area (SNRA), central Idaho, USA, in July 2004 with unattacked (green) tree crowns intermixed with currently attacked trees, trees attacked the previous year (yellow), and trees attacked more than two years previously (red) (photo by M.J. Jenkins); (b) mixed conifer forest near Butte, Montana, USA, with both mountain pine beetle and western spruce budworm (*Choristoneura occidentalis* Freeman) mortality distributed across the hillside (photo by M.J. Jenkins); (c) single tree experimental fires conducted by Rocca (2010) in Rocky Mountain National Park, Colorado, USA (photo by B. Cotton, Colorado State University); (d) Carrott Lake experimental fire in British Columbia, Canada, August 2006 (photo by D. Hicks, British Columbia Wildfire Management Branch); (e) Archer Lake experimental fire (plot 7) in north-eastern Alberta, Canada, May 2009 (photo courtesy of FPInnovations and Alberta Environment and Sustainable Resource Development); (f) Valley Road Fire on the SNRA, September 8, 2005 (photo by A. Norman, USDA Forest Service); and (g) Tatuk Lake Fire in British Columbia, Canada, June 23, 2004 (photo courtesy of British Columbia Forests, Lands and Natural Resources Operations) 159

7.2 Flow diagram illustrating the primary characteristics and inter-relationships among the elements contributing to crown fire potential in mountain pine beetle-affected lodgepole pine forests 162

7.3 Combined seasonal changes in foliar moisture content measured on lodgepole pine: unattacked, green (G old foliage); recently attacked, green-infested (GI old foliage); attacked the previous year, yellow (Y); and attacked two or more years previously, red (R) by the mountain pine beetle. Data are from four study sites: (1) far eastern Idaho, elevation 1768 m (see Chapter 3), (2) Cameron Pass, north-central Colorado, 2658 m (Jolly *et al.*, 2012b), (3) Fraser Experimental Forest, north-central Colorado, 2678 m (Jolly *et al.*, 2012b), and (4) Point 6, western Montana, 2031 m (Jolly *et al.*, 2012b)..165

7.4 Needle retention over time for lodgepole pine and jack pine slash after harvest based on summaries by Salazar and Bevins (1984) and McRae *et al.* (1979).....167

7.5 Summary of red and green foliage fuel loads in recently attacked mountain pine beetle-infested lodgepole pine stands sampled in Utah on the Wasatch-Cache National Forest and on the Sawtooth National Recreation Area in Idaho by Page and Jenkins (2007a) and in Colorado by Schoennagel *et al.* (2012). The proportion of attacked trees within crown bulk density categories sampled by Page and Jenkins (2007a) is also shown for the stands in Utah and Idaho..........169

7.6 Graphical representation of Van Wagner's (1977) crown fire initiation relationship with demarcation of the critical intensities obtained at foliar moisture contents of 10 and 100% and canopy base heights between 0 and 10 m. The foliar moisture content of 100% represents the common value assumed to represent live, healthy conifer stands during the fire season (Keyes, 2006) and the 10% represents a low foliar moisture content expected in recently attacked mountain pine beetle-affected stands with near complete mortality (see Chapter 5). The three designated zones correspond to the range of fireline intensities and canopy base heights where crown fire initiation is expected within both healthy, unattacked stands and recently attacked stands (Crown fire – All), where crown fire initiation may occur in recently attacked stands but not in unattacked stands (Crown fire – Red), and where crown fire initiation is unlikely (Surface fire – All). Fireline intensities were calculated as the product of rate of spread and fuel consumption as per Byram (1959), assuming a net heat of combustion of 18 000 kJ kg^{-1} (Stocks *et al.*, 2004b). The fireline intensity can be obtained by noting the intersection between the appropriate rate of spread and fuel consumption lines and reading the y-axis. **SAMPLE CALCULATION:** Given a fine surface fuel load of 0.6 kg m^{-2}, a rate of spread of 10 m min^{-1}, and a canopy base height of 6 m, the estimated fireline intensity would be noted by reading the y-axis where the appropriate fuel consumption and rate of spread lines meet, which in this case would be approximately 1800 kW m^{-1}. Then to determine the possible influence of recent tree mortality on crown fire initiation, note where the 1800 kW m^{-1} and 6 m canopy base height (located on top of graph) lines intersect. In this case they intersect in the Crown fire – Red zone, which indicates that conditions are such that a transition to crowning caused by the presence of recently killed trees is possible when such a transition would otherwise be unlikely if the stand contained only live and healthy foliage..174

8.1 Photographs of lodgepole pine forests in different mountain pine beetle attack stages, (a) endemic or pre-attack condition, note green and mature overstory and sparse understory (photo by W.G. Page), (b) “red” stage, recently attacked lodgepole pine trees (red) intermixed with new attacks (off-green or yellow) and unattacked trees (green) (photo by M.J. Jenkins), (c) “gray” stage, most or all susceptible lodgepole pine killed and still standing with needles fallen, intermixed with surviving lodgepole pine or non-host species and advanced regeneration in the understory (photo by W.G. Page), and (d) post-epidemic stage, note heavy accumulations of dead and down woody material in “jackstraw” condition intermixed with overstory of mostly non-host species and understory of advanced regeneration (photo by W.G. Page). Wildfires burning through lodgepole pine forests, (e) active crown fire run during the Davis Fire in Montana, August 2010, burning in “red” stage lodgepole pine (photo courtesy of U.S. Forest Service, from Stiger and Infanger 2010) and, (f) high-intensity fire in “gray” stage lodgepole pine in British Columbia, September 2012, Fire R10171 near Entiako Lake (photo by R. Krause, British Columbia Forests, Lands and Natural Resources Operations). 202

8.2 Conceptual diagram of the three primary factors affecting the resistance to control of wildfires in mountain pine beetle-attacked lodgepole pine forests. 206

8.3 A fire behavior characteristics chart (Alexander and Cruz 2012b) showing the general range in rate of spread, fuel consumption and fireline intensity for cured grass, shrubland, conifer forest, and logging slash fuel complexes based on experimental field fires (after Stocks and Kauffman 1997). Numerically, fireline intensity is equal to the product of the net low heat of combustion (18 000 kJ/kg is assumed here), quantity of fuel consumed and the linear rate of spread. Flame size is its main visual manifestation...208

8.4 Summary of the predicted hazard induced by severe tree morality from a mountain pine beetle outbreak in lodgepole pine forests, relative to the case of no tree mortality, for the three main elements of resistance to control, namely, fire behavior characteristics (e.g., in relation to crowning and fireline intensity), firefighter safety considerations (e.g., in relation to snag conditions), and fire suppression operations (e.g., in relation to spotting and rate of fireline construction). Developed based on summaries by Hicke *et al.* (2012) and Jenkins *et al.* (2008, see Chapter 2, 2014). The long-term (50+ years) hazards are currently unknown, as indicated by a question mark..209

8.5 Plots of observed direct line construction rates and lines of best fit based on linear and non-linear least squares regression for: (a) Type 1 hand crew by fire behavior fuel models 1 to 13 (Anderson 1982) and total fine surface fuel load (TSFL), using estimates from National Wildfire Coordinating Group (1998), (b) Type 1 hand crew by fire behavior fuel models 1, 2, 4 to 6, and 8 to 10 and TSFL, based on estimates from Broyles (2011), (c) 20-person hand crew using estimates from Haven *et al.* (1982) for U.S. Forest Service Regions 1, 2, and 4 by fuel resistance class, and (d) Type 1 dozer working uphill (0%–25% slope class) by fire behavior fuel models 1–13 and TSFL, using the midpoint of estimates from National Wildfire Coordinating Group (1998). The appropriate regression model is displayed in each cell along with the unadjusted r^2 (linear model) and pseudo-r^2 (non-linear model) 216

CHAPTER 1

INTRODUCTION

Problem Statement and Research Objective

Recent epidemics of various bark beetles species in the genus *Dendroctonus* have caused widespread tree mortality in their respective conifer hosts across western North America. It has previously been demonstrated that bark beetle-caused tree mortality can cause significant changes to stand structure, woody surface fuel loading, and canopy fuel loading and arrangement (Jenkins et al., 2008; Hicke et al., 2012). The effects of those changes on potential surface fire behavior are generally believed to be dependent upon the time since mortality, the relative concentration of fine fuel accumulation, and micro-climatic changes within affected stands that can cause variations in surface fuel moisture and in-stand wind speed conditions (Jenkins et al., 2008). What remains unclear however, are the possible alterations to crown fire potential as bark beetle-infested trees undergo changes in their physical and chemical characteristics as they proceed from their healthy or unattacked state to their “red” condition.

The objective of this research was to describe and quantify these physical and chemical changes and to assess the effects of those changes on crown fuel flammability and crown fire potential in bark beetle-infested lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) forests.

Research Questions

Chapter 2 represents a comprehensive literature review on the general topic area that the dissertation is directed at, namely the effects of bark beetle attack on fuel characteristics and fire dynamics in lodgepole pine and Engelmann spruce forests, especially as it pertains to crowning phenomena.

The next five chapters are directed at answering the following research questions:

1. How does successful attack by mountain pine beetle in lodgepole pine and spruce beetle in Engelmann spruce trees alter the moisture content, chemistry, and flammability of foliage over time? (Chapters 3 and 4)
2. How does the moisture content of dead foliage on lodgepole pine trees during the red stage of mountain pine beetle attack change diurnally? (Chapter 5)
3. Can models be developed to predict the hourly change in moisture content of foliage on lodgepole pine trees during the red stage? (Chapter 6)
4. What are the consequences of mountain pine beetle-caused changes to crown and canopy fuels on crown fire initiation and spread in lodgepole pine forests? (Chapter 7)

In Chapter 8 we frame the results from the preceding chapters along with additional information about the effects of mountain pine beetle-caused tree mortality over longer time frames (i.e. during the gray and post-epidemic stages) within the context of the concept of resistance to control of a wildfire. The ninth and final chapter constitutes a summary of the seven preceding chapters and the conclusions for the dissertation as a whole.

The dissertation is organized using the multiple paper format, which consists of individual chapters structured to each represent a separate research paper. Accordingly, each chapter is organized and formatted slightly different, based to the style of the journal selected for publication.

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CHAPTER 2

FUELS AND FIRE BEHAVIOR DYNAMICS IN BARK BEETLE-ATTACKED FORESTS IN WESTERN NORTH AMERICA AND IMPLICATIONS FOR FIRE MANAGEMENT[1]

Abstract

Declining forest health attributed to associations between extensive bark beetle-caused tree mortality, accumulations of hazardous fuels, wildfire, and climate change have catalyzed changes in forest health and wildfire protection policies of land management agencies. These changes subsequently prompted research to investigate the extent to which bark beetle-altered fuel complexes affect fire behavior. Although not yet rigorously quantified, the results of the investigations, in addition to a growing body of operational experience, indicate that predictable changes in surface, ladder and canopy fuel characteristics do occur over the course of a bark beetle rotation. Input of these changes in fuel characteristics into conventional fire behavior modeling systems can readily provide predictions of potential fire behavior, including the likelihood of crowning. However, several factors limit the direct application of these modeling systems in their current form and consequently, they may largely under predict fire potential in such stands. This presents a concern where extreme fire behavior involving both crowning and spotting coupled with flammable fuel conditions can pose serious challenges to incident management and threaten the safety of firefighters and the general public alike. In this paper, we review the nature and characteristics of bark beetle-altered

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fuel complexes in the conifer forests of the Interior West and the challenges of understanding the effects on extreme fire behavior, including the initiation and spread of crown fires. We also discuss how emerging fire management plans in the U.S. have begun to integrate wildfire management and other forest health objectives with the specific goal of achieving biodiversity and ecosystem resiliency while simultaneously reducing the existence of hazardous fuel complexes.

Introduction

Agents of disturbance in forested ecosystems include wind, snow, ice, insects, pathogens, fires, avalanches, hurricanes and floods. Many of these disturbances occur in a random, non-cyclic and unpredictable manner while others occur periodically and are largely predictable. The occurrence of disturbance events, their timing, severity, frequency, magnitude, and interactions over time and space characterize a disturbance regime (Pickett and White, 1985). Few forests in western North America are free from the effects of disturbance. To the contrary, biotic and abiotic agents regulate many aspects of forest composition and structure. The interaction of disturbance agents over large spatial and long temporal scales often determines the nature of the forested landscape (Veblen et al., 1994). Among biotic agents of disturbance, bark beetles have the ability to dramatically alter stand composition and structure, fuels quantity and quality, and carbon cycling over very short to long time frames (Hawkes et al., 2004; Jenkins et al., 2008; Kurz et al., 2008).

Bark beetles in the genus *Dendroctonus* (Coleoptera: Curculionidae, Scolytinae) are native insects that play an important role in western North American coniferous forest ecosystems. At low population levels bark beetles typically infest large, old, and weakened trees, whose deaths serve to recycle nutrients and create openings for regeneration. Large-scale outbreaks have been a common feature of coniferous forests at least since the last glacial retreat about 13,000 years ago (Brunelle et al., 2008). Bark beetle outbreaks and the associated loss of mature host trees results in a modification of stand and age-class structure and species composition. During the outbreak phase the bark beetle population and host tree mortality increase by orders of magnitude and may impact forest management activities (Teale and Castello, 2011). Warm, dry weather conditions may trigger outbreaks by stressing otherwise vigorous trees and decreasing bark beetle development time (Raffa et al., 2008). Hebertson and Jenkins (2008) showed that spruce beetle (*Dendroctonus rufipennis* Kirby) outbreaks were associated with prolonged droughts during the past century.

Over the past 25 years a total of 6.6 million hectares of western coniferous forests were infested by bark beetles including 4.3 million hectares by mountain pine beetle, 128,000 hectares by spruce beetle and 185,000 hectares by Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins) (Man, 2010). Mountain pine beetle mortality in the western United States also increased dramatically in high elevation five-needle pines, reaching levels not previously recorded and resulting in the deaths of 6 million five-needle pines on 486,000 hectares (Gibson et al., 2008) and the loss of up to 95% of cone bearing white bark pine (*Pinus albicaulis* Engelm.) trees in some areas. The scale of bark beetle-caused tree mortality, particularly in high elevation species such as whitebark pine, may be unprecedented and influenced by climate warming (Logan et al., 2010). It is equally important to note, however, that the initiation of bark beetle outbreaks and population spread is not possible without susceptible stands which are usually dense and composed of a large percentage (>60%) of mature, large diameter host trees. Changes to fuels complexes and fire behavior due to 20th century fire suppression and exclusion policies, livestock grazing and a more recent decrease in active timber management have created an abundance of large, old conifers in western North America (Samman and Logan, 2000). The rash of large, human-caused wildfires in the late 1800s in subalpine forests may have also contributed to increased landscape homogeneity by initiating stands that, by the 20th century, were susceptible to bark beetle attack in terms of average tree size and age class distribution (Sibold et al., 2006; Baker, 2009). The period of landscape level fires in subalpine forests may have also been associated with major climate drivers and a generally warmer and drier climate (Kitzberger et al., 2007; Schoennagel et al., 2007).

Fire is the most important abiotic disturbance in western forest ecosystems (Wright and Heinselman, 1973). Fires vary in kind, frequency, and magnitude resulting in a broad range of vegetative responses. For example, crown fires regulate the availability of sites for the initiation of new stands by killing the majority of living trees and exposing mineral soil (White, 1979; Oliver, 1981). Surface fires typically result in partial removal of the overstory or the death of individual trees creating canopy gaps and allowing recruitment of subcanopy trees into the overstory (White et al., 1984; Veblen et al., 1994).

The number of large fires, the total annual area burned, and associated suppression costs have also risen dramatically across much of the western United States over the past 25 years (Calkin et al., 2005; Stephens, 2005; GAO, 2007). The reasons for these increases have been linked to a combination of climate change and past land use histories with general agreement that moist, high elevations forests are subject to climate-induced changes while drier, lower elevation forests are subject to combinations of climate and land use changes including grazing and fire exclusion practices (Agee, 1997; McKenzie et al., 2004; Schoennagel et al., 2004; Collins et al., 2006; Westerling et al., 2006; Littell et al., 2009). Dillon et al. (2011) used satellite-derived burn severity data to suggest that topography and climate were the principal influences on fire severity, and that only the southwestern U.S. experienced increases in area burned between 1984 and 2006. From 2000 to 2005, the average annual acreage burned was 70% greater than the acreage burned during the 1990s, with annual fire management and suppression appropriations to federal land management agencies exceeding $3 billion (GAO, 2007). There was an average increase of over 283,000 hectares in annual total area burned on Forest Service administered lands during the period 1987–2002 compared to the period 1970–1986 (Calkin et al., 2005). Westerling et al. (2006) associated the shift in annual area burned and large fire frequency during the mid-1980s with increased spring and summer temperatures and earlier spring snowmelt. Lightning-ignited fires have resulted in significant increases in hectares burned with no change in the number of lightning ignitions in the northern Rocky Mountains, southwest, and northeast (Stephens, 2005).

Although fire and bark beetles are both important drivers of vegetation dynamics in western North American forests, relatively few studies have addressed questions regarding their potential relationships. The earliest research used qualitative assessments of the potential effect of mortality on subsequent fires using basic principles of fire ignition and spread (Brown, 1975; Knight, 1987). Later retrospective studies used combinations of fire history and remote sensing technologies to assess interactions in a more quantitative way (Bebi et al., 2003; Kulakowski et al., 2003; Bigler et al., 2005; Kulakowski and Jarvis, 2011). Only recently have detailed stand level bark beetle effects and fire behavior potential been documented (Schulz, 2003; Romme et al., 2006; Kulakowski and Veblen, 2007; Page and Jenkins, 2007a; Klutsch et al., 2009; Jorgensen and Jenkins, 2011; Simard et al., 2011).

In this paper, we critically review the influence of variably flammable, bark beetle-altered complexes of surface, ladder, and canopy fuels and the challenges of understanding the effects on extreme fire behavior, including the initiation and spread of crown fires in conifer forests in the Interior West. We will draw on examples from previously published work and combine and interpret results from various fire behavior modeling software systems and decision support tools to make general inferences about bark beetle-altered fuel complexes. The theoretical relationships presented are meant to draw the reader's attention to potential bark beetle, fuels and fire interactions, with an emphasis on the general nature of the ecological and physical processes at work. The inherent limitations, knowledge gaps and research needs in predicting and understanding these interactions will be discussed, as well as potential future advances in overcoming these limitations. Our discussion ends with an emphasis on forest health as a measure of resistance and resilience to disturbance and the forest's ability to satisfy management objectives from both a planning and operational perspective. Specifically we will discuss:

→ bark beetle effects on forest structure, composition and fuel bed characteristics,

→ crown fire initiation and spread,

→ challenges in modeling crown fire behavior in bark beetle-affected forests,

→ short-and long-term implications for fire suppression considerations, and

→ bark beetles, fires and forest health.

Bark Beetle Effects on Forest Structure, Composition and Fuel Bed Characteristics

The earliest and best known wildfire incident linked to bark beetle activity was the Sleeping Child Fire that occurred in western Montana in August 1961 (Fig. 2.1). At the time, it was the single largest wildfire in the U.S. northern Rocky Mountain region in more than 20 years and "was treated as an event almost without precedent" (Lyon, 1984). The fuel accumulation resulting from a mountain pine beetle attack some 30 years earlier greatly increased the difficulty of controlling the fire (Roe et al., 1971) as shown in the 1962 USDA Forest Service fire control training film *Fire Weather*.

It's only been relatively recently that research has systematically focused on an understanding of bark beetle, fuel and fire interactions (Jenkins et al., 2008) in whitebark pine (Jenkins, 2011), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Jenkins et al., 2008), lodgepole pine (*Pinus contorta* Dougl) (Page and Jenkins, 2007a; Page and Jenkins, 2007b; Kaufmann et al., 2008; Klutsch et al., 2009; Klutsch et al., 2011; Simard et al., 2011; Schoennagel et al., 2012), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm) (Bebi et al., 2003; Kulakowski et al., 2003; Jorgensen and Jenkins, 2011). Much of this information is provided in an internet-based decision support tool created to assist fire managers and others interested in fuels and fire behavior in relation to bark beetle activity (Jenkins et al., 2011).

The bark beetle rotation begins when a stand becomes susceptible to bark beetle infestation and is capable of supporting an outbreak or epidemic. Prior to the epidemic phase the bark beetle population is considered endemic with only one to several trees

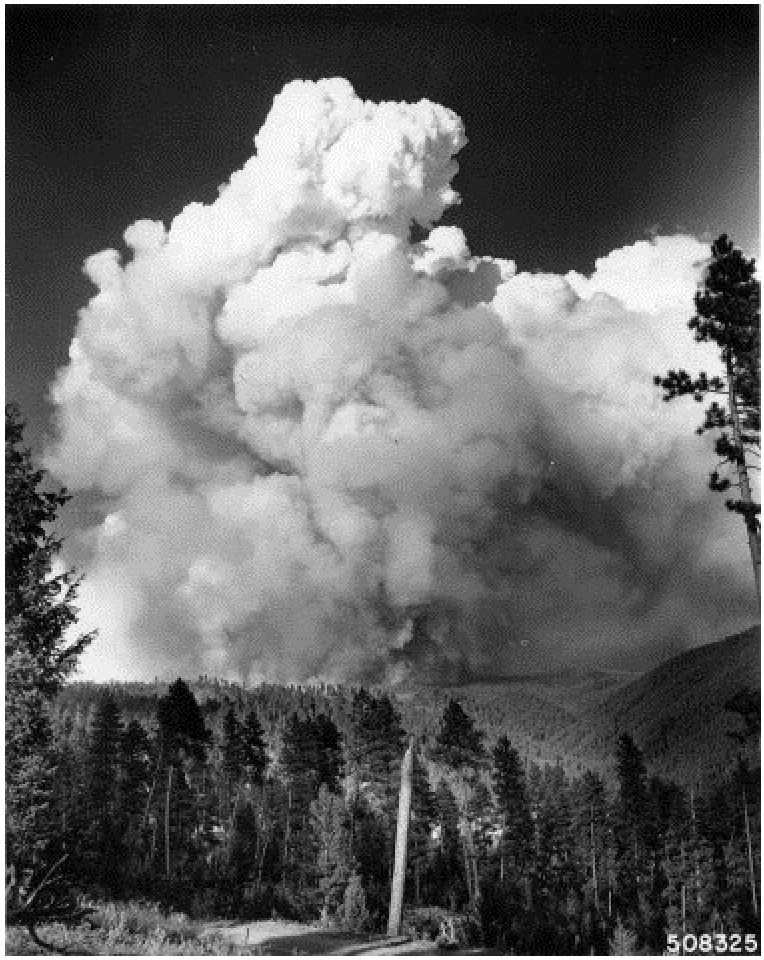

Fig. 2.1. View of the convection/smoke column associated with the 1961 Sleeping Child Fire on the Bitterroot National Forest in western Montana that spread through lodgepole pine stands that had previously sustained heavy mortality from a mountain pine beetle outbreak in 1928–1932 (Roe and Amman, 1970). This lightning-ignited fire started on August 4 and in spite of rapid initial attack grew to nearly 60 ha in the first two hours following detection and then to 3640 ha within 24 h (Morrison, 1964). The fire continued to grow until August 13 when it was controlled after having covered more than 11,330 ha of upper montane and subalpine forest. Photo by Ernest Peterson, USDA Forest Service.

attacked per hectare (Bentz and Munson, 2000). The occurrence of epidemics often coincides with periods of short-term stress, such as drought (Berg et al., 2006; Negrón et al., 2009). Under stressful conditions, aggressive bark beetle species, like mountain pine beetle and spruce beetle, can overcome host tree resistance resulting in rapidly increasing population numbers. During the epidemic phase, 80% or more of susceptible trees are killed. As time progresses, canopy openings result in significant increases in live shrub and herbaceous cover and loading and regeneration (Reid, 1989; Stone and Wolfe, 1996). In epidemic stands, the total amount of available canopy fuel is greatly reduced leading to decreases in canopy sheltering of wind and solar radiation (Brown, 1975; Knight, 1987). The length of the epidemic phase varies with conifer species, but generally lasts 5–10 years, and ends when most large diameter trees have been killed and the bark beetle population returns to endemic levels (Schmid and Amman, 1992). At this time, stands enter the post-epidemic phase which is characterized by the fall of dead trees. This phase lasts for decades to centuries until small surviving or newly regenerated host trees again reach susceptible age and size (Fig. 2.2).

The general changes in fuel bed characteristics over the course of a bark beetle rotation were described by Jenkins et al. (2008). For example, in Fig. 2.3 we illustrate the changes to forest structure, fine surface fuel and the abundance and condition of canopy fuels during the course of a bark beetle rotation in Engelmann spruce in central Utah. In general, there is a reduction in the number of live trees per hectare, average stand diameter, canopy base height, and the quantity, and quality of canopy foliage. During early stages of the outbreak there is an increase in the amount of dead canopy foliage and in turn a transfer of needles and some fine twig material from the conifer canopy to the forest floor such that surface litter amounts increase at the expense of canopy fuels (Page and Jenkins, 2007a; Jorgensen and Jenkins, 2011; Simard et al., 2011). Total surface fuel accumulation amounts to nearly a one-to-one transfer of aerial needles to surface litter, minus whatever decomposition occurs over the period of needle

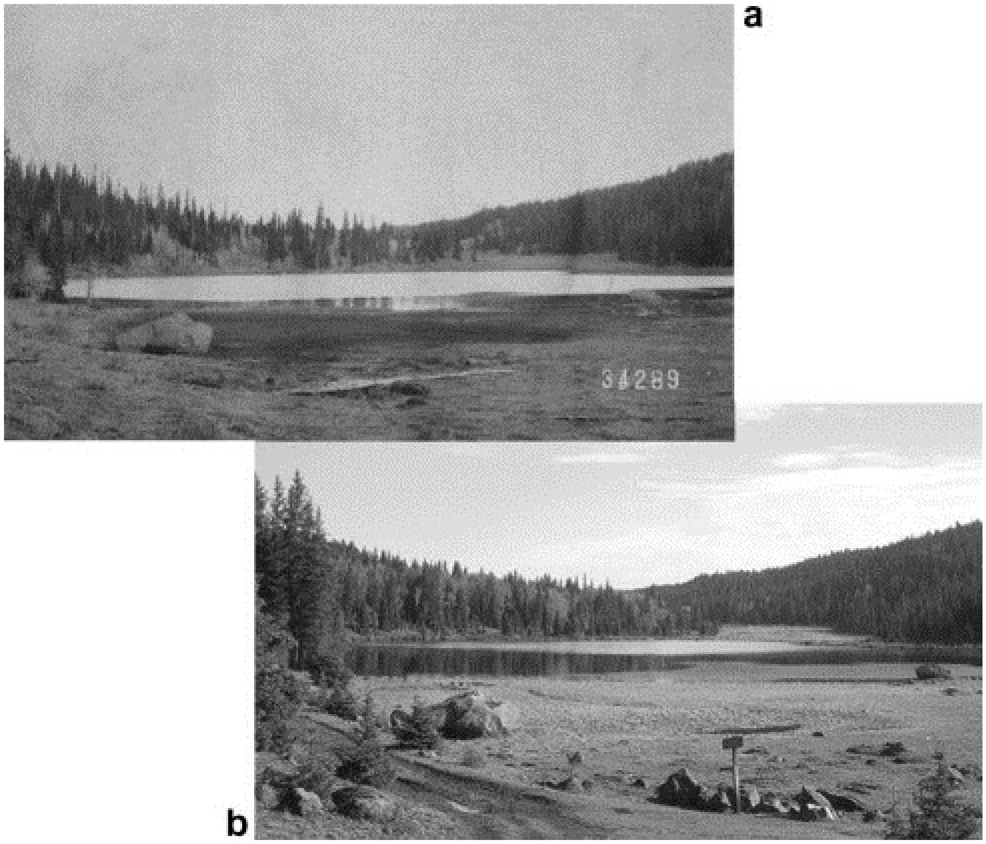

Fig. 2.2. (a) An Engelmann spruce stand near Purple Lake on the Fishlake National Forest taken in 1902. (b) Repeat photo from the same location taken in 2002 showing the stand as it regenerated following an extensive spruce beetle outbreak in the 1920's. Photo (b) by Mike Jenkins.

shed (Bigler and Veblen, 2011). Overstory tree mortality not only results in a pulse of needle litter and small diameter woody fuels to the forest floor during the epidemic phase, but also a release of shrubs and forbs in the early part of the post-epidemic (Reid, 1989; Stone and Wolfe, 1996; Jorgensen and Jenkins, 2011). The accumulation of coarse woody fuels is dependent upon the rate at which dead overstory snags fall to the surface. In Fig. 2.4 the accumulation of coarse woody surface fuels is shown for three different rates of tree fall over the 100 years following spruce beetle outbreak. There is

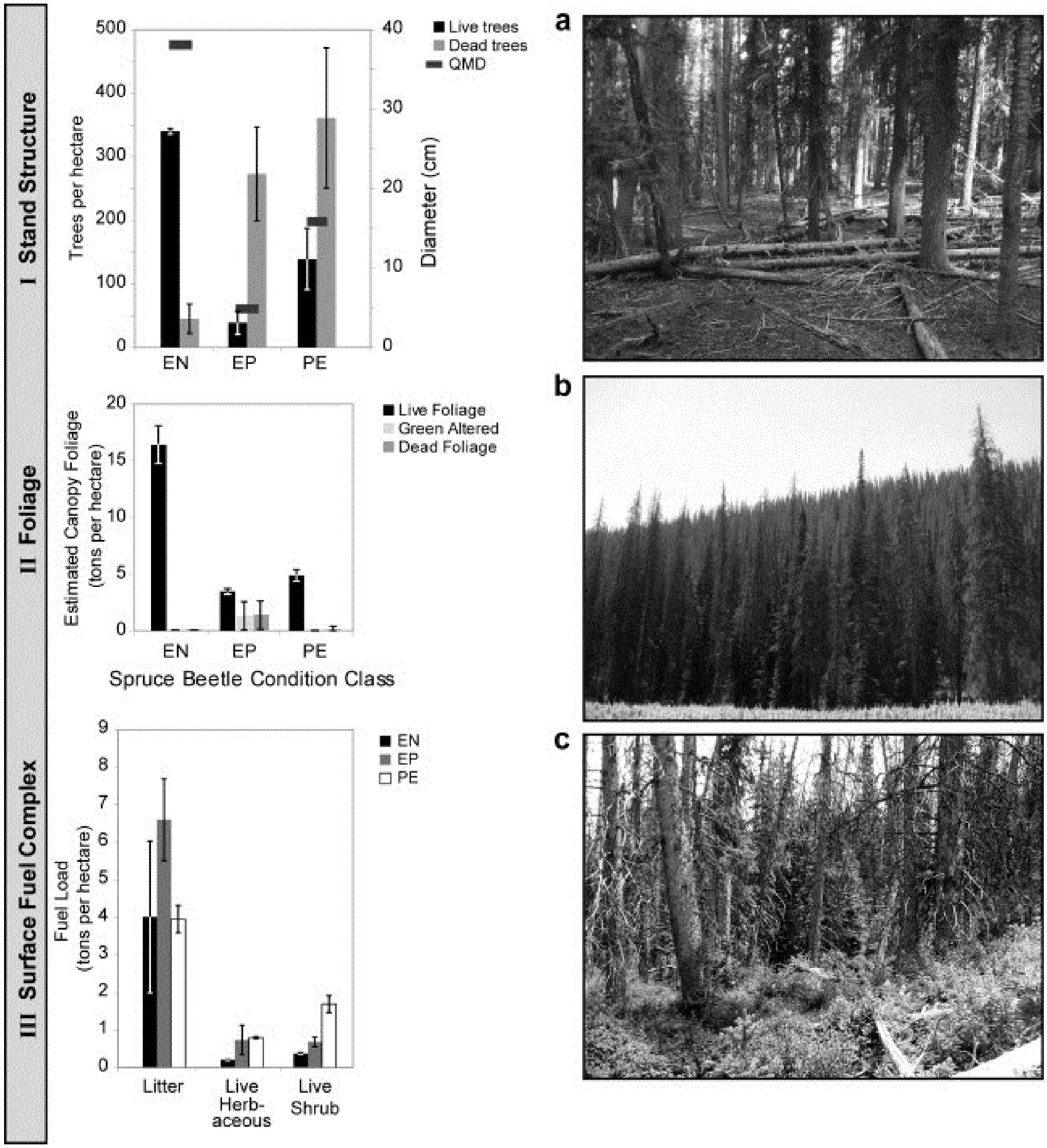

Fig. 2.3. Engelmann spruce beetle condition classes shown during the course of the bark beetle rotation; (a) endemic (EN), (b) epidemic (EP), and (c) post-epidemic (PE). Changes in (I) stand structure, (II) canopy fuel condition, and (III) surface fuel complex are shown (Jorgensen and Jenkins, 2011). Photos by Mike Jenkins.

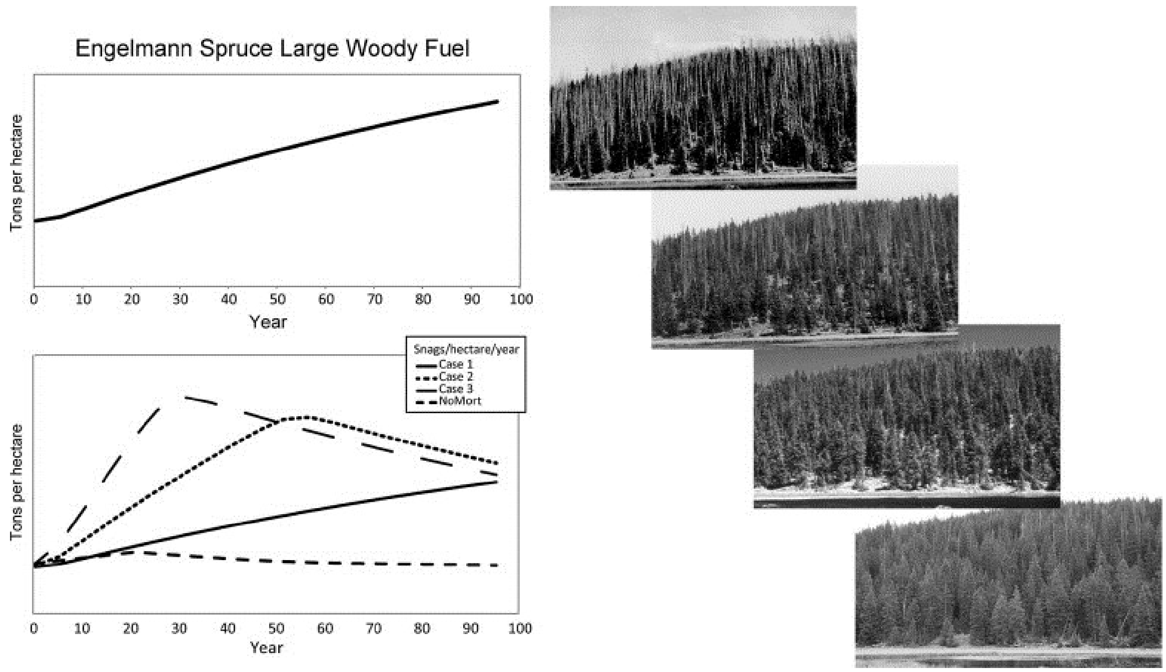

Fig. 2.4. Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS) (Reinhardt and Crookston, 2003) was used to simulate changes in large woody fuels greater than 7.62 cm in diameter resulting from low (Case 1), moderate (Case 2), and high (Case 3) fall rates following the spruce beetle outbreak in the 1920's at Purple Lake, Utah. Repeat photos (top to bottom), taken in 1948, 1968, 1988 and 2010 are representative of Case 3 fall rate. Data are from Jorgensen and Jenkins (2011). 1988 photo by Steve Munson and 2010 photo by Jesse Morris.

considerable variation in coarse woody fuel accumulation depending on stand structure, species composition, site, soils, physiography, and incidence of root disease and when compared to other bark beetle/host ecosystems (Mielke, 1950; Hinds et al., 1965; Schmid and Hinds, 1974).

Jenkins (2011) described the characteristic changes of the crowns of individual attacked whitebark pine trees during the period of *Dendroctonus* bark beetle colonization, brood development and dispersal which is generally similar for other conifer species. In summary, an otherwise healthy, susceptible host tree retains a typical green (G) crown. During the first season of bark beetle infestation adults and early instar larvae are present within the inner bark and blue stain development has likely begun. Blue stain is caused by a complex of fungi that are carried in bark beetle mycangia (specialized mouthpart structures) and inoculated into the sapwood. The fungi spread in the sapwood through living parenchyma cells and the bordered pit pairs of water conducting tracheid elements. The degree of blue stain development is dependent upon degree of host colonization, fungal pathogenicity, host resistance and the ability of the tree to compartmentalize the fungi (Raffa and Berryman, 1983). The amount of sapwood affected thus varies considerably, but in any case, infection reduces water flow to the crown resulting in a net reduction in the moisture content of the needle foliage (Parmeter et al., 1989) and a drop in sapwood moisture (Reid, 1961). At this time, the crown is considered to be green-infested (Gi) (Wulder et al., 2006). Larvae overwinter within the inner bark and at the beginning of the following season resume development. Rates of larval development vary depending on temperature, with pupation occurring within one-to-three years. Following pupation new adults emerge from the brood tree to colonize another susceptible host. In about twelve months after initial attack the tree crown will begin to fade to yellow (Y) (Amman, 1982), a transition largely regulated by blue stain development. In 16 months after attack, Y will have turned red (R). The R crown class can last up to 48 months after attack, but the time period varies with conifer host. Needle-fall accelerates during the R stage until all needles have fallen from the crown to the forest floor and the tree appears largely gray (Gr) (Wulder et al., 2006). Many factors may influence crown change including the variability in bark beetle life histories and attack severity (number of successful beetle attacks per unit of bark surface area), the physical characteristics of host trees, and foliar moisture content and chemistry

(Safranyik, 2003). Stand composition and structure, site and patterns of tree mortality influence the distribution of these classes across the landscape and consequently the spatial distribution and arrangement of surface and canopy fuels.

Crown Fire Initiation and Spread

High intensity, stand-replacing crown fires are a common feature in certain conifer forest types in western North America (Arno, 2000; Baker, 2009), with or without disturbance-altered surface and canopy fuels. In discussing the subject of tree mortality-caused fuel buildup in lodgepole pine forests, Brown (1975: 446) said:

> *The large increase in ground fuel and associated increase in the probability of large, high-intensity fires due to beetle epidemics suggests that the relationship among beetles, fire, and lodgepole pine tends to perpetuate lodgepole pine. The mountain pine beetles' strong preference for large trees gears heavy fuel buildup to a time when stands are mature or overmature. In some areas, this is when climax species are developing prominence in the understory and together with the ground fuels present a high chance of crown fire*.

Crown fires can also readily occur during the R stage of bark-beetle affected forests (Fig. 2.5) as vividly demonstrated recently during a major run of the Salt Fire on the Salmon-Challis National Forest in central Idaho on August 29, 2011 (Church et al., 2011)[2]. Fig. 2.6 illustrates the important fuel complex characteristics affecting crown fire dynamics. The most important parameter to consider in assessing crown fire potential is a surface fire's energy release rate or intensity. Byram (1959) defined fireline intensity

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[2] To view video footage taken by the USDA Forest Service of the Salt Fire taken on August 29, 2011 go to: http://www.youtube.com/watch?v=KKpBqdf16rE

Fig. 2.5. Aerial view of a surface fire slowly spreading upslope in green white spruce (*Picea glauca* (Moench) Voss) forest (top) and then transitioning to active crowning upon reaching a patch of “red stage” mountain pine beetle-attacked lodgepole pine forest (bottom). This wildfire occurred in the central interior region of British Columbia, Canada, in midafternoon on August 18, 2003. Photos by M. Simpson, British Columbia Wildfire Management Branch.

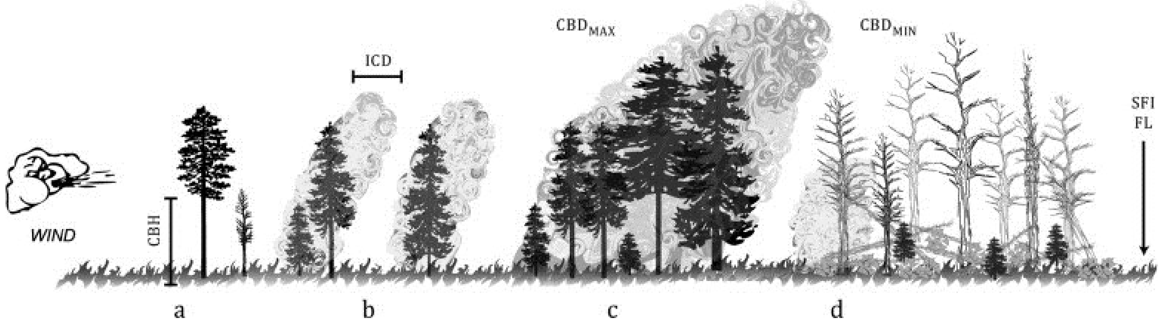

Fig. 2.6. Graphic illustration of fuel properties affecting crown fire initiation and spread. CBH = crown base height, ICD = intercrown distance, CBDmax and CBDmin = maximum and minimum canopy bulk density, SFI = surface fire intensity and FL = flame length. In the illustration we represent a fire spreading from left to right and depict suggested fire behavior from low intensity surface fire (a), passive crown fire (b), active crown fire (c) and high intensity surface fire (d) for the different fuel properties under constant wind and slope. See text for a discussion of the influence of foliar moisture and chemical composition on crown fire initiation and spread.

(I_B, kW m^{-1}) as the rate of heat released from a linear segment of the fire perimeter as calculated by the following equation:

$$I_B = \frac{H \cdot w_a \cdot R}{60} \tag{2.1}$$

where H is the low heat of combustion (kJ kg^{-1}), w_a is the 'available fuel' or fuel consumed in the active flame front (kg m^{-2}), and R is the rate of fire spread (m min^{-1}). Flame length is its main visual manifestation (Alexander and Cruz, 2012).

The pioneering research of Van Wagner (1977) provides the fundamental basis for most current operational systems for predicting crown fire behavior although other models and modeling systems are slowly being produced elsewhere (e.g., Alexander and Cruz, 2011). Van Wagner (1977) models do not provide for the prediction I_B or R, which must be derived by other means, but rather they provide quantitative criteria for determining the onset of crowning and active crown fire propagation.

Van Wagner (1977) developed a simple model for determining crown fire initiation on the basis of two canopy fuel properties:

$$I_o = (C \cdot CBH \cdot h)^{1.5} \tag{2.2}$$

where I_o is the critical surface fire intensity needed for initial crown combustion (kW m^{-1}), C is the criterion for initial crown combustion (kW$^{2/3}$ kJ^{-1} kg m$^{-5/3}$) which he described as "an empirical constant of complex dimensions," CBH is the canopy base height (m), and h is the heat of ignition (kJ kg^{-1}). The heat energy required to raise the crown foliage to its ignition temperature is in turn calculated using the following function (from Van Wagner, 1993):

$$h = 460 + 25.9 * FMC \tag{2.3}$$

where FMC is the foliar moisture content (% oven-dry weight basis). The onset of crowning is thus expected to occur when CBH and FMC are sufficiently low for a surface fire of given intensity to ignite the foliage (i.e., when $I_B \geqslant I_o$). Vertical spread of fire into the crowns is for practical purposes assumed to be independent of the canopy bulk density (CBD, kg m^{-3}) which in turn represents the available canopy fuel load (ACFL, kg m^{-2}) divided by the depth of the canopy fuel layer (i.e., the average stand height less the CBH). Van Wagner (1977) also proposed a simple model for determining the requirement for a fully developed crown fire to occur in relation to the forest stand structure:

$$R_o = \frac{S_o}{CBD} \tag{2.4}$$

where R_o is the critical minimum spread rate for active crown fire (m min^{-1}) and S_o is the critical mass flow rate for solid crown flame (kg m^{-2} min^{-1}). Active crowning thus occurs when $I_B \geqslant I_o$ and the R after the onset of crowning is $\geqslant R_o$. Passive crowning occurs in cases where $I_B \geqslant I_o$ but $R < R_o$ (i.e., crown fuel consumption takes place but crown-to-crown spread is limited).

It is worth noting that in Van Wagner (1977) crown fire theories, both passive and active crown fires are dependent on surface fire for their continued existence. The extent to which the intercrown distance (ICD) directly affects active crown fire propagation is presently unknown as this fuel complex characteristic is embedded in the CBD. However, from observation evidence obtained through experimental burning, it appears that active crown fires are able to breach gaps in the forest canopy of 10–20 m with ease (Alexander et al., 1991).

The value of the Van Wagner (1977) equations is their simplicity, but that is also a major limitation as discussed by Alexander and Cruz (2011). For example, while Van Wagner (1977) two equations are theoretically based, empirically-derived values are needed for the C and S_o quantities (currently given as 0.010 and 3.0 respectively). These values are presently based upon experimental fires in a red pine (*Pinus resinosa* Aiton) plantation in eastern Canada involving live, green needles (Van Wagner, 1968) for a specific set of conditions (i.e., FMC = 100%, CBH = 6 m, and CBD = 0.23 kg m^{-3}) (Cruz and Alexander, 2010).

Challenges in Modeling Crown Fire Behavior in Bark Beetle-Affected Forests

An increasing body of research and field observation is emerging describing the influence of bark beetle mortality on fire behavior. Various fire behavior prediction modeling systems (Cruz and Alexander, 2010) including BehavePlus in lodgepole pine (Page and Jenkins, 2007b; Schoennagel et al., 2012), NEXUS in lodgepole pine (Simard et al., 2011), and the Fuels and Fire Extension (FFE) to the Forest Vegetation Simulator

(FVS) in Engelmann spruce (DeRose and Long, 2009) and lodgepole pine (Klutsch et al., 2011) have been used in assessing potential crown fire behavior in bark beetle-affected fuels. At the heart of all these modeling efforts is the semi-physical surface fire model developed by Rothermel (1972) which is linked directly, or through various reformulations, to Van Wagner (1977) and Van Wagner (1993) crown fire initiation and propagation equations and Rothermel (1991) statistically-derived crown fire rate of spread model. Cruz and Alexander (2010) have described in detail the various limitations and biases inherent in these models both individually and in the techniques employed in linking them together. For example, it is uncertain whether the Rothermel (1972) model can predict the rate of spread, and in turn, the intensity of surface fires that would lead to the onset of crowning without fuel model calibration.

One of the most fundamental assumptions in forecasting or predicting wildland fire behavior is that the fuels are continuous, uniform, and homogeneous (Albini, 1976; Rothermel, 1983). The more the situation departs from this ideal, the more difficult it is to forecast or predict wildland fire behavior. The mixture of physically and chemically altered canopy fuel in bark beetle-affected conifer forests results in rapid and highly unstable spatial and temporal variation (Fig. 2.5) creating difficulties in using the common crown fire behavior models. Existing crown fire initiation, propagation and spread rate models were developed to predict fire behavior where the majority of available fuels are composed of green or otherwise live, healthy foliage. Canopy fuels of trees recently affected by bark beetles undergo very rapid changes in FMC and chemistry that in turn affect forest flammability (Jolly et al., 2012). Significant changes in the moisture content of tanoak (*Lithocarpus densiflorus* Hook. & Arn. Rehder) foliage affected by sudden oak death have been documented suggesting an increased likelihood of crown fire ignition (Kuljian and Varner, 2010). It is presently unknown to what degree existing models are able to account for these factors when bark beetle-altered canopy fuels represent a significant proportion of the canopy.

Onset of Crowning

Subsequent research has shown that the empirical constant *C* contained within Van Wagner (1977) crown fire initiation model to be a variable quantity dependent on certain factors such as ladder fuels and certain surface fire behavior characteristics (Cruz et al., 2006b).

Thus, use of the model is undoubtedly inappropriate in assessing crown fire potential in tanoak forests impacted by sudden oak death due to the abundance of dead, elevated leaf material with very low FMC values (Kuljian and Varner, 2010). Application to mountain pine beetle attacked stands still requires some form of field verification, either through experimental burning and/or wildfire observations. The present indications are that extension of the model to very low FMC values to stands with a distinct gap between the surface fuels and CBH seem hardly realistic when examined in the light of flame length as opposed to I_o (Fig. 2.7).

To properly apply Van Wagner (1977) crown fire initiation model to disturbance-altered canopy fuel one must assume that the burning characteristics (total heat content, rate of energy release, etc.) of live and variously altered (Gi, Y and R) foliage are equivalent. Current evidence suggests that live and dead foliar fuels of the same species have different flammability characteristics, in terms of heat of combustion, ignitability, and sustainability, due to differences in ether extractable content including fats, resins,

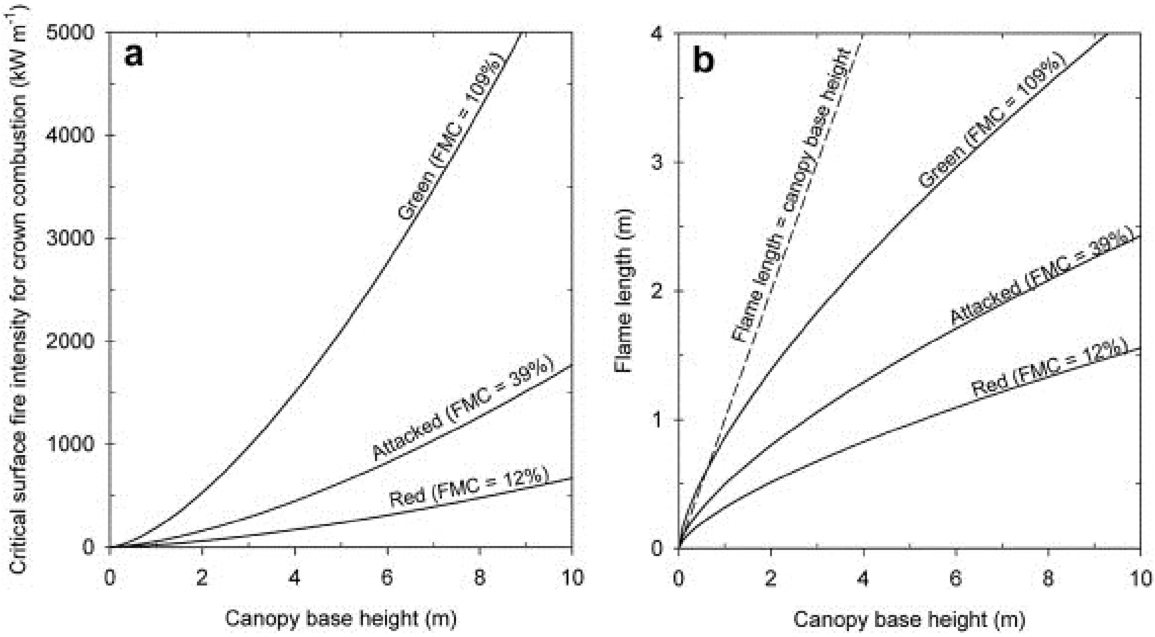

Fig. 2.7. Critical surface fire intensity for crown combustion in a conifer forest stand as a function of canopy base height and foliar moisture content (FMC) according to Van Wagner (1977) crown fire initiation model for the mean FMC values associated with tree crown condition classes of mountain pine beetle attack in lodgepole pine (data used with permission from Jolly et al., 2012).

oils, and terpenes (Hough, 1969; Philpot and Mutch, 1971). However, it is yet to be determined whether the presence of flammable volatile foliage organic compounds (Ormeño et al., 2009) directly influences crown fire initiation.[3]

Once a tree dies many of these organic compounds are likely to decrease and break down due to their inherent volatility (Tingey et al., 1980). Hough (1969) found significant differences in heats of combustion for live versus dead fuels of various herbaceous species and wiregrass. Likewise, Philpot and Mutch (1971) and Susott (1980) emphasized the importance of volatile extractives from live conifer foliage on fuel

[3] This is the subject of a current research project supported by the Joint Fire Science Program (JFSP) entitled "The Influence of Fuel Moisture and Flammable Monoterpenes on the Combustibility of Conifer Fuels" (JFSP 11-1-4-16) under the leadership of the first author.

flammability due to relatively high heats of combustion and low vaporization temperatures. Others have shown increases in heat of combustion of dead material as it decomposes (Golley, 1961; Daubenmire and Prusso, 1963). Edmonds (1980) suggested that the increase was due to higher lignin concentration in dead material. Lignin has higher heat content and decomposes more slowly than other cell wall materials. Thus, the assumption that dead and live crown fuels have equivalent burning characteristics is not currently supported, which suggests that Van Wagner (1977) crown fire initiation model may be inappropriately applied to canopy fuel conditions common in bark beetle-affected stands in the Gi to advanced G_r stages as done, for example, by Simard et al. (2011).

In addition to the complications inherent in Van Wagner (1977) empirical constant, the heat of ignition function included within his crown fire initiation equation may not adequately capture the effects of changes in volatile content in live versus dead foliage on ignition temperatures even though it was applied to FMC values as low as 56% (Van Wagner, 1993). His model assumes the ignition of all fuels occurs at 300°C, which has been shown by Owens et al. (1998) and Ormeño et al. (2009) to vary due to the presence of volatiles such as monoterpenes. They demonstrated the potential contribution of terpene content on foliage and litter flammability by showing decreased time to ignition and increased proportion of burned material where terpene contents were high. Van Wagner (1977) did acknowledge the potential role of a lower ignition temperature in his model and determined that even if the ignition temperature dropped by 100°C it would only lower the calculated ignition energy of fuel at a FMC of 100% by about 6%. However, in the formulation of his heat of ignition function he assumed that all of the moisture in the fuel must be driven off before ignition can occur (Van Wagner, 1968), which has subsequently been shown not to be the case (Pickett et al., 2010).

Crown Fire Rate of Spread

The most commonly used crown fire spread models are empirical in nature and are thus limited in their potential scope of inference to the conditions for which the underlying data were derived. Van Wagner (1977) described the conditions for which active crown fire becomes possible using the CBD based on the available canopy fuel to determine a minimum threshold needed to sustain active crown fire spread. Later he advocated a theoretical foliar moisture effect (FME) function for adjusting crown fire rate of spread (Van Wagner, 1993) that he had devised earlier (Van Wagner, 1974). It is unknown whether this FME term, which has yet to be validated for magnitude of its relative effect (Van Wagner, 1998), can adequately capture the effect of dead foliage with FMCs lower than 30% of oven-dry weight because it was initially developed, although not exclusively, for use in canopy fuels with FMC levels in the range of about 90 to 130% of oven-dry weight (Van Wagner, 1974).

Rothermel's (1991) crown fire rate of spread model is based on a statistical correlation between a limited number of wildfire observations (n = 9) in the northern Rocky Mountains (that presumably did not involve significant amounts of bark beetle-affected crown fuels) with predictions for a standard fuel model based on his surface fire model. A more robust empirically-based model developed by Cruz et al. (2005) has been extensively tested against experimental fires and wildfires (Alexander and Cruz, 2006), although as Alexander et al. (2006) point out, it is not appropriate for use in bark beetle-altered fuel complexes. Thus, it is unlikely that either the Rothermel (1991) or Cruz et al.

(2005) model will be able to sufficiently predict active crown fire spread in forests recently affected by bark beetles (i.e., R stage) as a stand alone method at the present time, although no comparisons against wildfire observations in such fuel complexes have been undertaken to date.

Looking Ahead

The development of empirically-based fire behavior prediction models derived from conducting experimental fires (e.g., Stocks, 1987), such as undertaken for the Canadian Forest Fire Behavior Prediction System (Wotton et al., 2009), is not considered a realistic option at the present time in the western United States. Increasingly, physically-based fire behavior models are being formulated that have their basis in fundamental chemistry and physics of combustion and heat transfer processes (Morvan, 2011). These models hold great promise in being able to advance our theoretical understanding of wildland fire dynamics. The approach has the potential to simulate fire behavior in three-dimensional form (Parsons et al., 2011) based on the unique physical and chemical properties associated with bark beetle-altered fuel complexes (Hoffman, 2011). However, the capacity of these models to adequately describe crown fire behavior is still open to question, given that there has been very limited testing of model performance and more importantly there has been no evaluation against any empirical crown fire dataset undertaken to date (Alexander and Cruz, 2011). On the other hand, a physical-based model for predicting crown fire initiation developed by Cruz et al. (2006b) has in fact been evaluated for its performance, at least in healthy conifer forest stands (Cruz et al., 2006a).

The greatest potential for assessing the immediate impact (i.e. first 5 years) of bark beetles on conifer forest fire behavior will likely involve a combination of simulation or numerical modeling, experienced judgment, and case study knowledge (Williams and Rothermel, 1992; Alexander, 2007) involving both wildfires (historic and present day), operational prescribed fires, and experimental fires (Alexander and Taylor, 2010).

Short- and Long-Term Implications for Fire Suppression

Concerns about the consequences of bark beetle-altered fuel complexes amongst fire managers is not new (Morrison, 1964, 1968; Maupin, 1979). Recent observations by fire managers on fires in western conifer forests confirm the influence of bark beetle-altered surface and canopy fuels on fire behavior and fire suppression operations (Stiger and Infanger, 2011). Firefighters have reported experiencing extreme fire behavior in currently infested stands with prolific spotting occurring in areas with heavy surface fuel buildup (Church et al., 2011). Additionally firefighters have noticed that mountain pine beetle-affected trees tend to break off at mid-tree and uproot more easily than other dead trees. Stiger and Infanger (2011) urge a higher level of vigilance for firefighters exposed to bark beetle-affected forests. The same can certainly be said for members of the general public as well (Alexander et al., 2012).

Safe and effective control of wildfires involves a multitude of issues (Alexander, 2000). Alexander and Stam (2003) have discussed fire suppression considerations beyond crown fire behavior that may be affected in post bark beetle-altered ecosystems and that can still lead to other aspects of extreme fire behavior. For example, trees in various stages of decay will exhibit sloughing bark, loose branch material of various sizes, and persistent cones in the canopy providing abundant material to be lofted into convection columns for short and long range spotting (Rothermel, 1994). Coupled with the readily available firebrand material in bark beetle-affected forests is the receptive fuel beds. In this regard, the following appeared in the administrative fire analysis report on the 1961 Sleeping Child Fire:

> *About 75% of the original timber stand was on the ground. A young stand of lodgepole pine and alpine fir was growing as understory in the remaining live stand. The dead and down timber had decomposed to the point where it would ignite easily and burn intensely during dry weather. Fuels were highly vulnerable to flying sparks and radiant heat.*

Prolific spotting greatly reduces fire suppression effectiveness and puts constructed fuelbreaks at risk of being compromised (Agee et al., 2000).

Increased resistance to control through increases in fireline construction time (Broyles, 2011), time for snag mitigation for crew safety, reduction in areas suitable for fire shelter deployment (Rothermel and Mutch, 1986) and the ability to secure fireline due to the large accumulations of down woody fuels associated with the older Gr stage are also important considerations. These large diameter fuels have significant burn out times which puts constructed firelines at risk of being compromised for long periods of time and heavy coverage levels if fire retardants are to be effective (George and Fuchs, 1991). Additionally, these large diameter fuels can cause significant delays in attaining full control due to the extensive mop-up work required. Large numbers of dead standing trees can cause significant firefighter safety concerns due to the dangers associated with the snags falling on firefighters, especially when weakened by fire, and from the dangers associated with snag mitigation (Leuschen and Frederick, 1999). Heavy accumulations of woody fuels also increase total heat output requiring the construction of larger safety zones (Butler and Cohen, 1998) and creating escape routes (Beighley, 1995), further slowing fire suppression operations.

Bark Beetles, Fires, and Forest Health

A common approach to managing bark beetles in general forest areas involves sanitation and salvage in which susceptible, infested and dead trees are removed to reduce local population levels, decrease residual stand susceptibility, and derive some economic benefit (Jenkins et al., 2008). A more proactive approach is thinning in advance of an outbreak to create stands of young, small diameter trees and microclimatic conditions which are less favorable for bark beetle infestation and population spread (Whitehead et al., 2007). Limitations on the size of thinning treatments, however, often reduce their potential for success. Post-disturbance salvage logging may be socially, politically and economically justifiable when a harvesting infrastructure, including roads, mills and markets exists, and when the value of standing trees is sufficient to cover harvesting costs. Otherwise, bark beetle management activities may not be justified if they are not compatible with forest sustainability and inhibit the natural role of the insect in promoting ecosystem health and biodiversity (Lindenmayer and Noss, 2006; Schmiegelow et al., 2006).

In 2003, the U.S. Congress passed the Healthy Forest Restoration Act (HFRA) after an especially costly fire year in 2002. HFRA is designed to reduce fire risk while improving commercial value for forest biomass in ways that contribute to forest health by managing insect outbreaks and fire. The legislation supports ecosystem enhancement, sensitive species, biodiversity and carbon sequestration. Management practices implemented under HFRA generally have a hazardous fuels reduction objective.

Two more recent pieces of legislation have the potential to fundamentally alter the way in which wildfires are managed on public lands. The Federal Land Assistance, Management and Enhancement (FLAME) Act of 2009 established an account to pay for fighting large, complex wildland fires. The legislation will provide a separate budget for fighting the largest fires, so that adequate funding is available and agencies' land management functions are not shorted during costly fire years by "borrowing" from other resource programs to cover fire suppression costs. The FLAME Act required the Secretaries of Agriculture and Interior to develop a Cohesive Wildland Fire Management Strategy (CWFMS) and initiate a collaborative process between government and non-government agencies and devise solutions to wildland fire management issues. CWFMS is being implemented in phases and addresses the associations between wildfire, insects and climate change and recognizes that declining vegetative health across landscapes is significantly responsible for increased costs and losses associated with catastrophic wildfires (USDA and USDI, 2011).

In order to achieve the biodiversity and ecosystem resiliency goals outlined within the CWFMS, fire management activities will need to incorporate multiple objectives that preserve important ecological processes and recognize the inherent variability in forested ecosystems. To be effective, hazardous fuel treatments will need to incorporate fine scale ecological principles implemented at the landscape scale (Dellasala et al., 2004). In those forested ecosystems that are affected by severe bark beetle activity, hazardous fuel treatments should place potential treatment gains in context with the ecosystems in which they are planned. In ecosystems where high intensity, stand-replacing crown fires are a part of the natural fire regime, such as lodgepole pine forests, fuel treatments may have little impact or be ecologically undesirable (Turner et al., 2003; Schoennagel et al., 2004). In these forests the most successful treatment strategies will focus on removing those trees deemed most hazardous to the public or other values in the wildland–urban interface and to provide access to firefighting personnel. Additional treatments along potential future fire control points (e.g., major road networks and useful topographic features) will aid future fire suppression operations by increasing firefighter safety and decreasing resistance to control.

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CHAPTER 3

MOUNTAIN PINE BEETLE ATTACK ALTERS THE CHEMISTRY AND FLAMMABILITY OF LODGEPOLE PINE FOLIAGE[4]

Abstract

During periods with epidemic mountain pine beetle (*Dendroctonus ponderosae* Hopkins) populations in lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests, large amounts of tree foliage are thought to undergo changes in moisture content and chemistry brought about by tree decline and death. However, many of the presumed changes have yet to be quantified. In this study, we quantified and compared fuel moisture, chemistry, and resulting flammability of bark beetle-affected foliage in terms of ignitability, combustibility, consumability, and sustainability at a site in far eastern Idaho, USA. Results revealed substantial decreases in moisture content, the proportion of starches and sugars, and crude fat and increases in the proportions of lignin, cellulose, and hemicellulose in foliage of trees attacked in the previous year (yellow foliage) or more than two years previously (red foliage). Increases in emission rates of several terpenes that were correlated with flammability were also detected in yellow foliage. The flammability of fresh yellow and red foliage increased with regard to ignitability and sustainability, with shorter times to ignition, lower temperatures at ignition, and higher heat yields when compared with unattacked green foliage. Our results confirm the overwhelming importance of fuel moisture on flammability and

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suggest that fuel chemical composition also has significant effects on lodgepole pine foliage flammability.

Introduction

Lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests in North America have experienced widespread mountain pine beetle (MPB; Coleoptera: Curculionidae; *Dendroctonus ponderosae* Hopkins) mortality since the 1990s. Dramatic increases in total area affected by the MPB have been observed in the western United States since 2000, with over 3.5 million hectares of mortality in 2009 alone (Man 2010). Although the scale of the recent mortality is unparalleled during the last 100 years, the last two decades have been characterized by a combination of conditions favorable for an outbreak, including warming, drought, and contiguous areas stocked with susceptible trees (Bentz et al. 2010). The severity and scale of the outbreak have caused concern among forest managers, politicians, and the public about the potential impact of the mortality on fire occurrence, severity, and behavior (Rocky Mountain Research Station 2011). Jenkins et al. (2008) reviewed literature on the influence of bark beetles on fuels and fire behavior in three conifer–host systems. Other recent studies have quantified MPB-induced changes to fuels and potential fire behavior in affected forests in Colorado (Klutsch et al. 2009, 2011), Idaho and Utah (Page and Jenkins 2007*a*, 2007*b*), and Wyoming (Simard et al. 2011). However, significant uncertainty still remains as to the applicability of the fire modeling systems used in these studies to assess fire behavior potential, particularly crown fire potential, due to unknown changes in the moisture content and chemistry of the foliage brought about by tree decline and death.

Conifer forest fuels are composed of varying proportions of lignin, cellulose, hemicellulose, extractives, and minerals (Browning 1963). The proportions can differ by tree species and tissue, with the woody constituents containing high proportions of lignin, cellulose, and hemicellulose and the foliage having more extractive content (Kramer and Kozlowski 1960). The relative amounts of these compounds in forest fuels are known to affect flammability (Shafizadeh et al. 1977; Rundel 1981). Lignin is the primary polymer providing structure to woody fuels. Its high relative molecular mass requires relatively high temperatures for volatilization, producing much of the char residue left after combustion (Shafizadeh 1971). The celluloses and hemicelluloses, found in the cell walls of plants, are the primary source of volatiles in flaming combustion (Shafizadeh 1968). Mineral ash is composed of silica, calcium, magnesium, and potassium and represents the noncombustible portion of plant material. The minerals are usually present in low amounts, though they can influence flammability (Philpot 1970). Extractives are the high energy resins, waxes, oils, and other fatty acids involved in the early phases of combustion due to their low relative molecular masses and ability to volatilize at low temperatures (Philpot and Mutch 1971; Rundel 1981). Terpenes are the main constituents of plant essential oils and resins and include all chemically modified forms such as terpenoids, also known as isoprenoids. They make up the majority of what are known as volatile organic compounds and are classified based on the number of isoprene units in their chemical structure, with monoterpenes having two isoprene units (Goldstein and Galbally 2007). Terpenes have a wide array of uses both ecologically and commercially and are known to play important roles in plant defenses against insect herbivores (Gershenzon and Dudareva 2007). They are also highly flammable both in their pure form and within wildland fuels (Ormeño et al. 2009).

The term flammability has been variously defined, interpreted, and measured using an array of equipment and methodologies (White and Zipperer 2010). Anderson (1970) quantified flammability in terms of three basic components of fire ignition and combustion: ignitability, sustainability, and combustibility. Martin et al. (1994) added the term, consumability, to describe a fourth basic component, the amount of fuel consumed during combustion. There is currently no standard methodology for determining flammability, but several researchers have used these four components to test and classify plants and their parts (Alessio et al. 2008; Ormeño et al. 2009; White and Zipperer 2010). The characteristics that affect plant flammability are relatively well known and can be divided into physical or structural elements and physiological or cellular elements (Rundel 1981). The physiological elements that affect plant flammability are moisture content (Gill et al. 1978), silica-free mineral content (Mutch and Philpot 1970), volatile compounds and ether extractive content (Philpot and Mutch 1971; Susott 1982; Ormeño et al. 2009), cellulose content (Rundel 1981), and phosphorous content (Philpot 1970).

Although substantial progress has been made in recent years in understanding the interactions between bark beetle-caused tree morality and subsequent changes in fire behavior, numerous challenges remain. The applicability and accuracy of crown fire behavior models to disturbance-altered fuel complexes remain in question because many were developed based on live healthy crown fuel and do not have the ability to incorporate changes in the physical and chemical properties of altered crown fuel (see

Chapter 2). For example, one of the most widely used crown fire initiation relationships described by Van Wagner (1977) may be affected by changes in the flammability characteristics of foliage because the relationship was based in part on an experimental fire in a live red pine (*Pinus resinosa* Aiton) plantation in eastern Canada. In a recent critique of the use of crown fire behavior models in simulation studies, Cruz and Alexander (2010) questioned the validity of using Van Wagner's (1977) crown fire initiation model in insect-damaged stands without verifying the need for appropriate adjustments.

The work presented here describes changes to the chemistry and flammability of lodgepole pine foliage when trees have been attacked by the MPB. The specific objectives of the study were (*i*) to compare the changes in fuel moisture, chemical composition, and flammability of foliage from lodgepole pine trees currently infested by MPB (green-infested, GI), infested one year earlier (yellow, Y), and infested more than two years earlier (red, R) with uninfested (green, G) trees, and (*ii*) to determine the relative importance of fuel moisture and chemical composition, including terpene emissions, on foliage flammability using correlation and regression based analyses.

Methods

USDA Forest Service Forest Health Monitoring insect and disease aerial detection maps and ground reconnaissance were used to identify potential study areas within the Intermountain Region of the western United States. We selected a study area located near our laboratory in Logan, Utah, that had adequate numbers of uninfested and recently infested lodgepole pine trees. The area chosen was located approximately 5 km west of Alpine Junction, Wyoming, on the Palisades Ranger District of the Caribou–Targhee

National Forest (43°8′14″N, 111°3′44″W). Within the study area, we selected a sampling site of approximately 1 km^2 in size at an elevation of 1768 m above mean sea level. The site had an average slope of 2% and was dominated by a mixture of lodgepole pine, Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), and subalpine fir (*Abies lasiocarpa* Nutt.), with an average tree density between 3000 and 5000 stems per hectare and a stand basal area of 10 to 20 $m^2 \cdot ha^{-1}$. The habitat type was classified as subalpine fir – common snowberry, and the age of the stand was approximately 100 years. The site has been subject to MPB-caused tree mortality since 2004 (Robertson 2011).

The general study design consisted of the repeated sampling of individual trees over the summer of 2011 during the historically significant portion of the fire season, from July through September. We categorized potential sample trees according to four crown condition classes based on Jenkins (2011): G, green, unattacked but susceptible to attack (i.e., ≥20 cm diameter at breast height, dbh); GI, green, currently infested; Y, yellow, attacked the previous summer; and R, red, more than two years after infestation. We used a combination of physical inspection of the tree bole (e.g., pitch tubes, frass) and needle color, similar to Klutsch et al. (2009), to identify time since attack. Specific trees were selected, in order of importance, (*i*) based on their suitability for repeated field sampling (i.e., presence of branches within reach of equipment), (*ii*) to minimize between-tree variation (i.e., sample trees had similar diameters and heights), and (*iii*) to facilitate the logistical needs of sampling (e.g., distance to road or trail).

Field Sampling

Field sampling occurred each week from the beginning of July to the end of September. In total, we sampled 30 trees, 12 G trees, six GI trees, six Y trees, and six R trees; however, only 24 trees were sampled throughout the entire study period. An additional six G trees were sampled only during the month of July as the GI trees were not yet available; these extra G trees were dropped from sampling starting the first week in August. The mean dbh (standard error) of selected G, GI, Y, and R trees were 29.1 (2.15), 30.7 (2.44), 33.8 (4.04), and 32.2 cm (1.67 cm), respectively. Due to logistical and time constraints, we sampled 12 trees each week, three trees in each of the four crown condition classes, except during the month of July when the additional G trees were sampled. The remaining 12 trees were sampled the following week. This process was repeated throughout the field season, with each tree (minus the extra six G trees) sampled a total of six times. Sampling occurred on the Monday of each week from the hours of 1000 to 1600 local time. Air temperature and relative humidity were measured with a sling psychrometer before each sampling period. Temperatures ranged from 12.2 to 23.3 °C and relative humidities ranged from 46% to 90%. Individual tree sampling consisted of the removal of three subsamples of approximately the 30 cm apical part of lower branch and foliage material from the lower one-third of each crown, and the collection of about 100 g of litter beneath each tree. Although changes in moisture content and foliage chemical composition are expected at different crown locations within live conifers (White 1954; Hinckley et al. 1978), these changes are relatively minor compared with expected differences among crown condition classes, and crown locations outside of the crown base are not as important in terms of crown fire initiation. Collected samples were placed in separate plastic bags and labeled for transport back to the laboratory. All sampling was completed by 1600 h, after which samples were returned to the laboratory for further processing and analyses.

Volatiles were collected once each month (during the first two weeks) on each sample tree using portable volatile collection systems comprised of automated vacuum pumps enclosed in a waterproof case (Volatile Assay Systems, Rensselaer, New York). For each tree, approximately 70 cm of the apical part of a lower branch was enclosed in a clear Teflon bag (50 cm wide × 75 cm deep; American Durafilm Co., Holliston, Massachusetts) and the air was pulled out through a side port ($0.5\ L \cdot min^{-1}$) through volatile traps containing 30 mg of the adsorbent HayeSep-Q (Restek, Bellefonte, Pennsylvania). Volatile emissions were collected for 30 min from each tree. Once collections were completed, the enclosed portion of branch and foliage was clipped and placed into a plastic bag for transport back to the laboratory to obtain the fresh mass.

Laboratory Analyses

Once the bagged samples reached the laboratory, they were processed for further analyses. The needles were separated from the branches, and the branches were trimmed to retain material less than 0.64 cm in diameter because these fuels can contribute to crown fire activity (Call and Albini 1997). The needles were then subdivided by separating current year's needle growth from older needles using visual indicators of color, texture, and location of the previous year's terminal bud. Fuel moisture was the only measured variable on current year's needles, whereas the older needles were used for all other analyses, as they usually make up the majority of tree foliage. To determine fuel moisture content, 15 to 40 g of each sample were weighed and placed in a forced-air drying oven set at 60°C rather than 105°C, as recommend by Matthews (2010), to dry for 24 h to minimize the loss of volatiles (Englund and Nussbaum 2000).

During the first two weeks of each month, an additional ~70 g of the fresh foliage and the volatile traps were shipped to external laboratories for chemical analyses. The foliage samples were shipped to a forage testing laboratory where they were analyzed to determine the chemical composition using the wet chemistry method for the fiber and non-fiber determinations (Agrianalysis 2012). Acid detergent fiber (ADF) was measured following AOAC (Association of Official Analytical Chemists) standard 973.18 in which the samples were extracted using a quaternary detergent solution (AOAC 1990). Neutral detergent fiber (NDF) was measured using a combination of the ANKOM filter-bag technique (ANKOM Technology 2012) and the amylase procedure (Undersander et al. 2011). Crude fat content was determined using an ANIKOM fat extractor, and ash content was measured following AOAC standard 942.05 by subjecting samples to 600 °C for 2 h in a furnace (AOAC 1990; Agrianalysis 2012). The non-fiber carbohydrates (NFC) represented the remaining fraction of dry matter after subtracting NDF, crude fat, protein, and ash content. NDF includes the hemicelluloses, cellulose, and lignin portions of the foliage. ADF is a subset of NDF and includes the lignin and cellulose portions of the foliage. NFC represents primarily the starches and sugar portion of the foliage. The crude fat characterizes the ether extractable portion of the foliage, which includes compounds such as triglycerides, alcohols, waxes, terpenes, and resins (Barnes et al. 2007).

The volatile collection traps were shipped to the Rocky Mountain Research Station laboratory in Bozeman, Montana, for analysis of volatile emissions, based on methods adapted from Runyon et al. (2008). Volatiles were eluded from traps with 200 µL of dichloromethane using 500 ng of *n*-octane and 1000 ng of *n*-nonyl-acetate as internal standards. Samples were analyzed using an Agilent 7890A gas chromatograph (GC) coupled with a 5975C mass spectrometer and separated on a HP-1ms (30 m × 0.25 mm inside diameter, 0.25 μm film thickness) column; hydrogen was used as the carrier gas. The GC oven was maintained at 35°C for 3 min and then increased by 5°C·min^{-1} to 125 °C, then 25°C·min^{-1} to 250°C. Quantifications were made relative to internal standards using ChemStation software (Agilent Technologies, Wilmington, Delaware), and identifications of compounds were confirmed by comparing retention times and mass spectra with commercial standards. We lacked internal standards for identification of some compounds, which we labeled as unknown terpenes 1 through 6. All measurements of volatile emissions (ng·h^{-1}·g^{-1}) were on a fresh mass basis.

Flammability Testing

Flammability testing was accomplished in the laboratory using an epiradiator, adapted to work with a scale, and a bomb calorimeter. The laboratory setup was comprised of a heat source, type K thermocouple, and pilot ignition source, set over a scale to measure the rate of mass loss (Fig. 3.1). Mass loss information, as well as temperature, were recorded using a Campbell Scientific CR800 data logger. The heat source consisted of a 500 W silica epiradiator with a 100 mm diameter disk producing approximately 6 W·cm^{-2} of radiation at the surface. The sample was placed 4 cm below the epiradiator on top of a stand to protect the scale from excessive heat. A type K thermocouple probe was set approximately 1.5 cm above the middle of the sample to record temperature. The pilot ignition source was provided by a Bunsen burner, the center of which was placed 3 cm above and at the edge of the sample. The pilot flame was 2.5 cm long with a 1.5 cm long inner flame core (cf. Dimitrakopoulos and

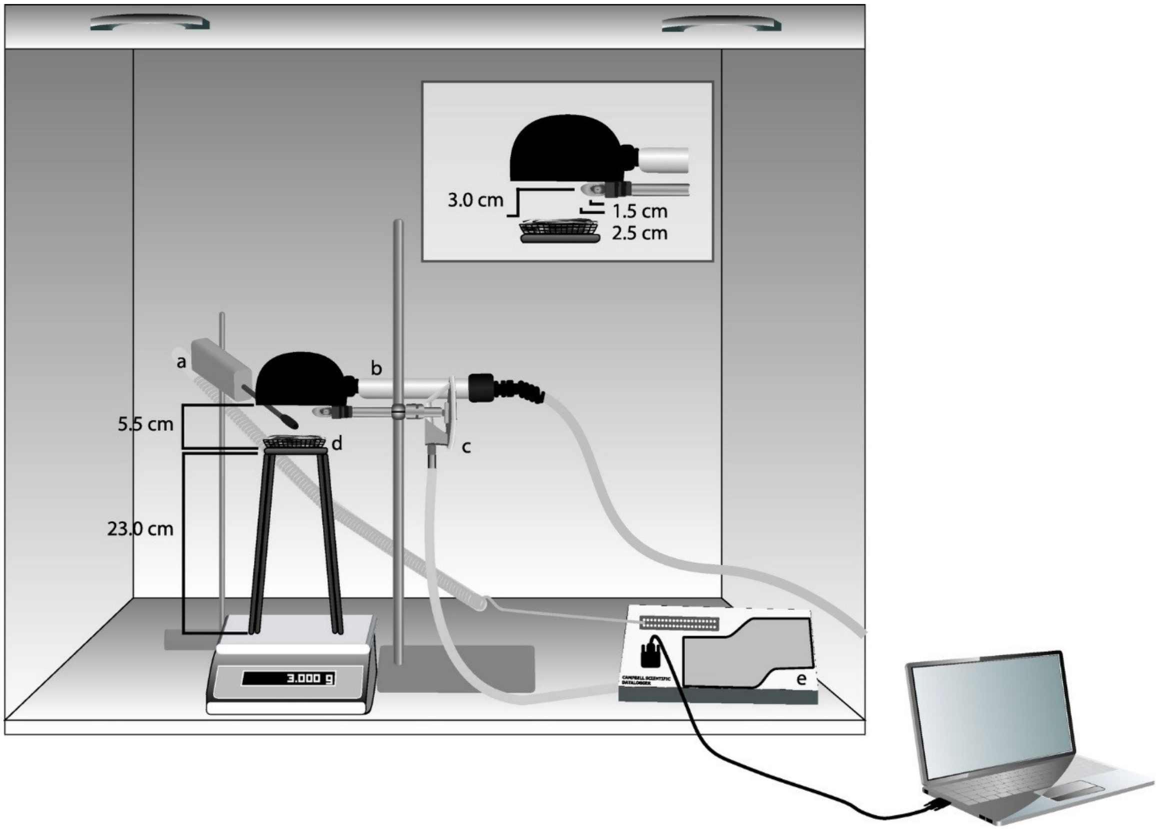

Fig. 3.1. Experimental setup for laboratory flammability testing: (*a*) type K thermocouple probe; (*b*) 500 W silica epiradiator; (*c*) pilot ignition source; (*d*) sample holder; and (*e*) data logger connected to scale and thermocouple.

Papaioannou 2001). The individual samples were placed under the middle of the epiradiator in a 7 × 8 cm wire mesh holder. The experimental setup was similar to those of other studies that have used an epiradiator for flammability testing of wildland fuels (e.g., Alessio et al. 2008; Ormeño et al. 2009). It is recognized that the heating regime produced by the epiradiator in this study does not replicate the potential heat flux observed in crown fires and that the level of heat flux can affect the influence of fuel properties on flammability, especially moisture content (Fletcher et al. 2007; Fernandes and Cruz 2012). However, the relatively low heat flux levels used in this study are important for determining the influence of fuel properties during the transition from a surface fire to a crown fire. At heat flux levels near this critical transition threshold, differences in the intrinsic fuel properties could potentially have important implications on the likelihood for the onset of crowning. A bomb calorimeter was used to measure the high heat of combustion of oven-dried foliage samples. All calorimeter samples were tested following ASTM D standard 1989-96, with corrections for the fuse wire, aqueous sulfuric acid, and nitric acid formed during the bomb reaction.

Flammability testing with the bomb calorimeter started during the first week in July, whereas the epiradiator-based testing began during the first week in August. One sample from each tree was tested with the bomb calorimeter each week, whereas two samples per tree, fresh and oven-dried, were tested with the epiradiator each week. Fresh foliage samples were tested first during each sampling period followed by oven-dried foliage. The epiradiator samples were prepared for testing by placing the needles evenly across the entire holder surface to a depth of approximately 1.5 cm. Due to the significant variation in foliage moisture content, the fresh samples had different initial masses; however, the dry foliage samples were all tested at a mass of 3.0 g ± 0.1 g. Once a sample was prepared, it was placed on top of the stand and the epiradiator was lowered into position. The data logger was set to collect mass and temperature continuously throughout the experiment every 0.1 s, with a date and time stamp for each recorded observation. The time of initiation of flaming and the end of flaming were recorded to the nearest second. Samples were allowed to smolder until the rate of mass loss was negligible. This process was repeated for each sample until all tests were completed.

Measures of Flammability

Ignitability, the amount of time that it takes a material to ignite given an external heat source and (or) the minimum temperature or heat flux required for ignition, was assessed using time to ignition and temperature at ignition (Anderson 1970). Time to ignition was measured from when the temperature of the thermocouple reached 60°C until the first appearance of flame, rounded to the nearest second. The temperature at ignition was recorded at the initiation of flaming. Temperatures at ignition reported here do not represent the actual fuel temperature obtained at ignition because the thermocouple was 1.5 cm above the material. Combustibility, which is a measure of how rapid or intensely a fire burns, was the maximum temperature obtained during each test and the maximum rate of temperature increase during flaming combustion ($°C \cdot s^{-1}$) (Anderson 1970; White and Zipperer 2010). Consumability, or the quantity and completeness of combustion, was judged using time profiles of mass loss, as well as the maximum rate of mass loss ($g \cdot s^{-1}$) (Martin et al. 1994; White and Zipperer 2010). To smooth the mass loss rate profiles, the 5 s running mean was calculated and used to determine the maximum mass loss rate. Sustainability, the amount of time that materials will combust with or without a heat source, was recorded as the duration of flaming (s) and the high heat of combustion ($kJ \cdot kg^{-1}$). The high heat of combustion is the total amount of heat released by a fuel when it is completely consumed to water and carbon dioxide without reductions for moisture, radiation, or incomplete combustion. A low heat of combustion or net heat of combustion, which incorporates a reduction based on the latent heat absorbed when the water of reaction is vaporized, is usually used in fire behavior applications (Byram 1959; Alexander 1982). However, when comparing the potential heat available under field conditions, a further correction is used to account for the heat required to evaporate the moisture in the fuel, termed heat yield (Van Wagner 1972). In this study, we report the high heat of combustion, but we refer to heat yield when discussing potential energy release among crown condition classes.

Statistical Analysis

Repeated measures analysis of variance was used to compare mean responses between crown condition classes for each of the response variables. The fuel moisture and flammability data were grouped by the two-week intervals for which we had data for each of the trees measured. This grouping resulted in comparisons of six different two-week time periods for the fuel moisture and bomb calorimeter data and four two-week periods for the epiradiator-based flammability testing. The chemical analysis data, both volatile emissions and foliage chemistry, were grouped by the month in which they were collected, for a total of three unique time periods. The three subsamples of fuel moisture collected from each tree were averaged by tree for analysis. Square-root and natural logarithm transformations were used where needed to meet assumptions of normality and equal variances. Post hoc means comparisons using the Tukey–Kramer method to control the experiment-wise error rate were used when a significant difference among crown conditions classes was identified (Zar 1999). When the assumptions of normality and equal variance were not satisfied with transformations, the nonparametric Kruskal–Wallis test (Zar 1999) was used to compare ranks followed by multiple comparison tests among crown condition classes using the technique described by Elliott and Hynan (2011). Pearson's correlation coefficients (r) were used to identify linear relationships between the flammability parameters and the various chemical attributes. Multiple linear regression analysis with stepwise selection was also used to evaluate linear relationships between time to ignition and the chemical attributes for fresh foliage to account for the influence of fuel moisture. SAS software (version 9.3, SAS Institute, Inc. 2010) was used for all statistical analysis. Significance for all tests was identified using $\alpha = 0.05$.

Results

Fuel Moisture

Foliar moisture content varied substantially by crown condition class (Fig. 3.2). The moisture content of new foliage for G trees was well above 200% of oven-dried mass during the early part of July and dropped to near 150% by the end of September; new foliage moisture content of GI trees followed a similar trend. Older foliage moisture content was the same for G and GI trees ($P = 0.2970$) when averaged over all sampling periods, with means of 113% and 115%, respectively (Table 3.1). The moisture content of G foliage was nearly constant over time, with a peak during early August of 125%. During early July, the foliage from Y trees had a mean moisture content of 43%, which was less than the G mean of 99% ($P < 0.0001$) and greater than the R mean of 10% ($P = 0.0019$). However, by the end of July, the moisture content of Y and R foliage did not differ ($P = 0.3533$) and stayed the same throughout the remaining sampling periods. The mean foliar moisture content of 113% for the G trees, averaged over all sampling periods, was greater than the mean foliar moisture content of both the Y (24%; approximately five times greater) and R (13%; approximately nine times greater) trees ($P < 0.0001$) (Table 3.1). Moisture content of litter and R foliage was the same throughout all sampling periods ($P = 0.6531$). The moisture content of twig fuel was similar to that of

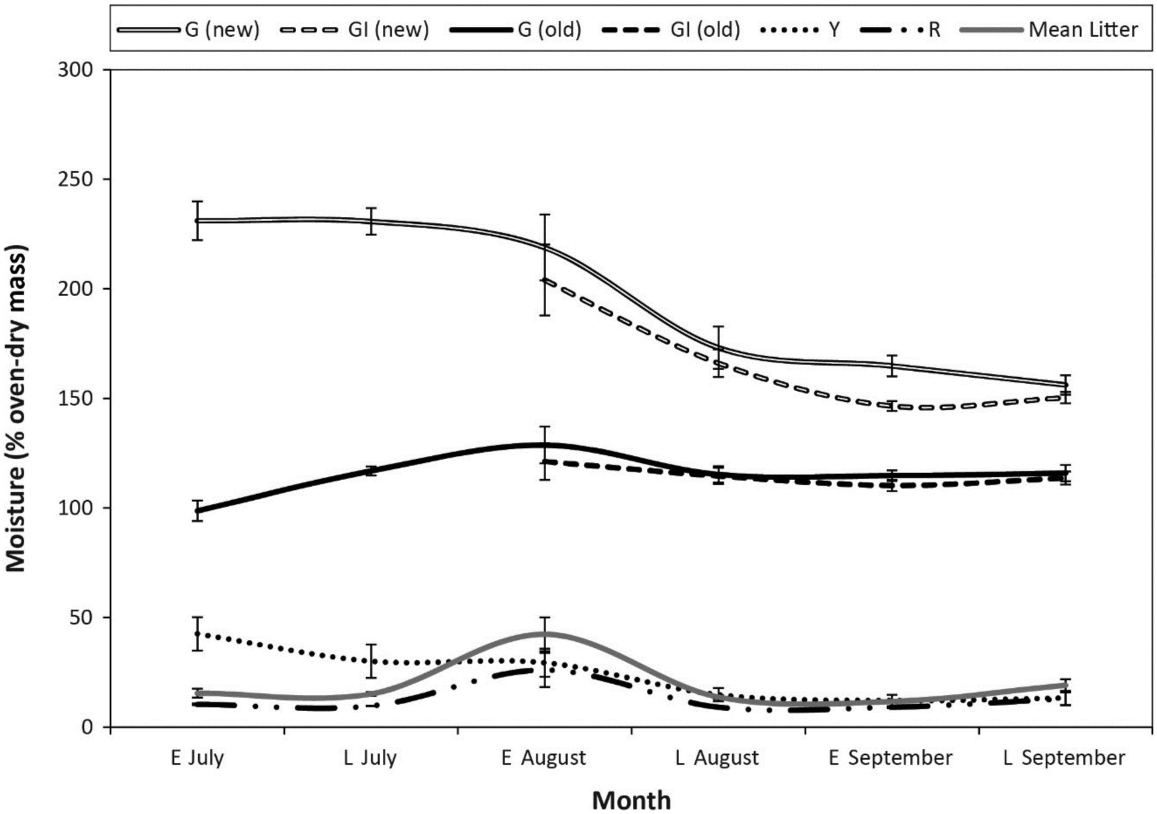

Fig. 3.2. Mean foliar moisture content for new and old foliage and the mean litter moisture content for all sampling periods (July–September (E, early; L, late)), with associated standard error bars, for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red).

Table 3.1. Mean (± standard error (SE)) percentage of oven-dried fuel moisture content, averaged over all sampling periods (July–September), for old foliage and twigs < 0.64 cm in diameter and the minimum mean values (Min.) recorded for each crown condition class (G, green; GI, green-infested; Y, yellow; R, red).

	Crown condition							
	G		GI		Y		R	
Type	Mean ± SE	Min.	Mean ± SE	Min.	Mean ± SE	Min.	Mean ± SE	Min.
Old foliage (%)	113±2a	99	115±2a	110	24±3b	12	13±2b	9
Twig < 0.64 cm (%)	107±3a	99	100±5a	91	19±3b	9	15±3b	9

Note: Means followed by a different letter within a row are significantly different (α = 0.05).

the foliage (Fig. 3.3). The G and GI twig moisture contents did not differ ($P = 0.8749$) and were greater than the Y and R twig moisture contents ($P < 0.0001$). Mean litter and R twig moisture contents were the same for all sampling periods ($P = 0.8890$). The peak in moisture content of mean litter, R foliage, and twigs during early August is attributed to a high relative humidity (90%) during sampling. The minimum mean foliar moisture content recorded for G trees was 99%, which occurred during early July (Table 3.1). The minimum moisture contents for Y and R foliage, which both occurred in September, were 12% and 9%, respectively.

Chemical Analyses

Chemical analysis of the foliage in each of the four crown condition classes revealed significant differences in NDF, ADF, NFC, crude fat, and mineral content (Table 3.2). For all compounds, comparison of the mean levels of G and GI foliage and of Y and R foliage were the same ($P > 0.05$). The mean level of NDF for G foliage across all three months, 43%, was less than the mean level of both Y foliage, 67% ($P < 0.0001$), and R foliage, 69% ($P < 0.0001$). Mean ADF levels for Y and R foliage were also greater than G foliage over all sampling periods. The mean proportion of NFC in G foliage was 38%, which was greater than the mean levels for Y foliage, 18% ($P < 0.0001$), and R foliage, 14% ($P < 0.0001$). The proportion of phosphorus in R foliage was higher than in G foliage when averaged over all sampling periods ($P = 0.0441$) and during the month of July ($P = 0.0335$). Levels of magnesium were also different, with higher proportions in GI foliage than in Y foliage ($P = 0.0371$) when averaged over all sampling periods. The proportion of crude fat was significantly greater in G foliage than

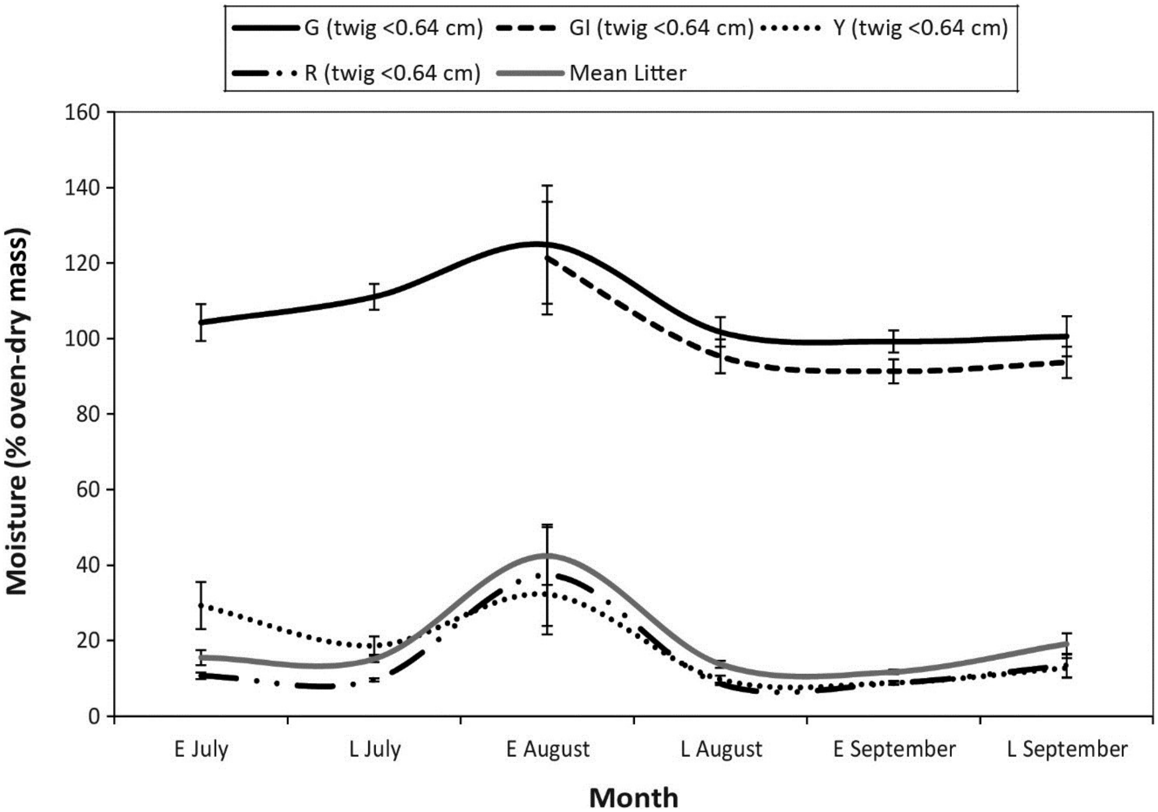

Fig. 3.3. Mean twig (<0.64 cm in diameter) moisture content for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red) and the mean litter moisture content for all sampling periods (July–September (E, early; L, late)), with associated standard error bars.

in Y foliage (*P* = 0.0008) and R foliage (*P* = 0.0098),with mean levels of 8.7%, 5.9%, and 6.5%, respectively. The most significant changes over time occurred in the chemical makeup of Y foliage. The mean proportion of ADF increased in Y foliage each month of sampling but was only significant when comparing July with September (*P* = 0.0003). The proportion of crude fat also decreased in Y foliage from July to September (*P* = 0.0481).

Analysis of volatile emissions revealed large variation in emission rates within crown classes and significant differences both in mean total and individual emission rates

Table 3.2. Mean proportion of foliage chemical composition for each sampling period across all crown condition classes (G, green; GI, green-infested; Y, yellow; R, red).

	Crown condition	July	August	September	Overall
Protein (%)	G	7.8±0.33a	7.8±0.32a	8.1±0.48a	7.9±0.21a
	GI	n/a	7±0.34a	7.5±0.37a	7.2±0.25a
	Y	6.9±0.22a	6.9±0.34a	7±0.15a	6.9±0.13a
	R	8.1±0.37a	7.8±0.52a	7.9±0.41a	7.9±0.24a
Acid detergent fiber (%)	G	35.8±0.46a	35.5±0.57a	34.7±0.91a	35.4±0.35a
	GI	n/a	37.6±1.45a	36.3±0.92a	36.9±0.84a
	Y	48±1.8b	51.7±1.98b	54.7±1.41b	51.5±4.91b
	R	52.4±1.48b	52.5±1.19b	54.1±1.1b	53.0±3.02b
Neutral detergent fiber (%)	G	44.2±1.53a	42±0.59a	41.7±1.1a	43±0.84a
	GI	n/a	47±3.47a	42.3±1.58a	44.6±1.95a
	Y	62.8±4.16b	70.7±1.08b	66.5±1.25b	66.7±1.6b
	R	70.7±0.91b	69.6±1.42b	67.2±1.34b	69.2±0.76b
Nonfiber carbohydrates (%)	G	36.2±1.25a	40±0.66a	40.3±0.75a	38.2±0.77a
	GI	n/a	34.1±3.32a	39.2±1.24a	36.6±1.86a
	Y	21.1±4.21b	14.4±0.62b	19.1±1.37b	18.2±1.56b
	R	12.4±0.76b	13.1±1.61b	15.8±1.46b	13.8±0.8b
Calcium (%)	G	0.43±0.04a	0.39±0.05a	0.34±0.02a	0.4±0.02a
	GI	n/a	0.58±0.11a	0.44±0.05a	0.51±0.06a
	Y	0.43±0.05a	0.31±0.04a	0.36±0.04a	0.37±0.03a
	R	0.34±0.03a	0.38±0.05a	0.4±0.03a	0.37±0.02a
Phosphorus (%)	G	0.1±0.01a	0.08±0.01a	0.1±0.01a	0.1±0.005a
	GI	n/a	0.09±0.01a	0.1±01a	0.1±0.005ab
	Y	0.12±0.01ab	0.11±0.02a	0.1±0.01a	0.11±0.01ab
	R	0.14±0.01b	0.1±0.01a	0.11±0.01a	0.12±0.01b
Potassium (%)	G	0.44±0.03a	0.46±0.07a	0.38±0.05a	0.43±0.03a
	GI	n/a	0.46±0.12a	0.45±0.11a	0.46±0.08a
	Y	0.49±0.07a	0.45±0.06a	0.32±0.03a	0.42±0.04a
	R	0.49±0.05a	0.5±0.06a	0.36±0.03a	0.45±0.03a
Magnesium (%)	G	0.15±0.01a	0.15±0.01ab	0.13±0.01a	0.14±0.01ab
	GI	n/a	0.2±0.02a	0.15±0.02a	0.18±0.02a
	Y	0.15±0.01a	0.12±0.01b	0.12±0.01a	0.13±0.01b
	R	0.14±0.01a	0.16±0.02ab	0.14±0.004a	0.15±0.01ab
Crude fat (%)	G	9.5±0.42a	8±0.51ab	7.8±0.46a	8.7±0.31a
	GI	n/a	9.1±0.65a	8.6±0.2a	8.8±0.33a
	Y	6.6±0.74b	5.8±0.71b	5.2±0.63b	5.9±0.4b
	R	6.4±0.27b	6.6±0.28ab	6.5±0.28ab	6.5±0.15b
Total ash (%)	G	2.3±0.11a	2.2±0.13a	2.2±0.06a	2.2±0.06a
	GI	n/a	2.9±0.26a	2.5±0.12a	2.7±0.15a
	Y	2.5±0.21a	2.1±0.14a	2.2±0.11a	2.2±0.1a
	R	2.4±0.27a	2.9±0.48a	2.6±0.19a	2.6±0.19a

Note: Values are mean ± standard error. All values are percent dry mass. Means followed by a different letter within a column are significantly different ($\alpha = 0.05$).

(Fig. 3.4). In total, 16 different terpenes were identified, with nine of the compounds significantly correlated with flammability (see results below). The mean total volatile emissions averaged over all sampling periods for Y foliage was greater than the mean emission rates for R foliage ($P = 0.0079$). No other significant differences were detected. However, several of the individual terpene emissions were greater in Y foliage than in the

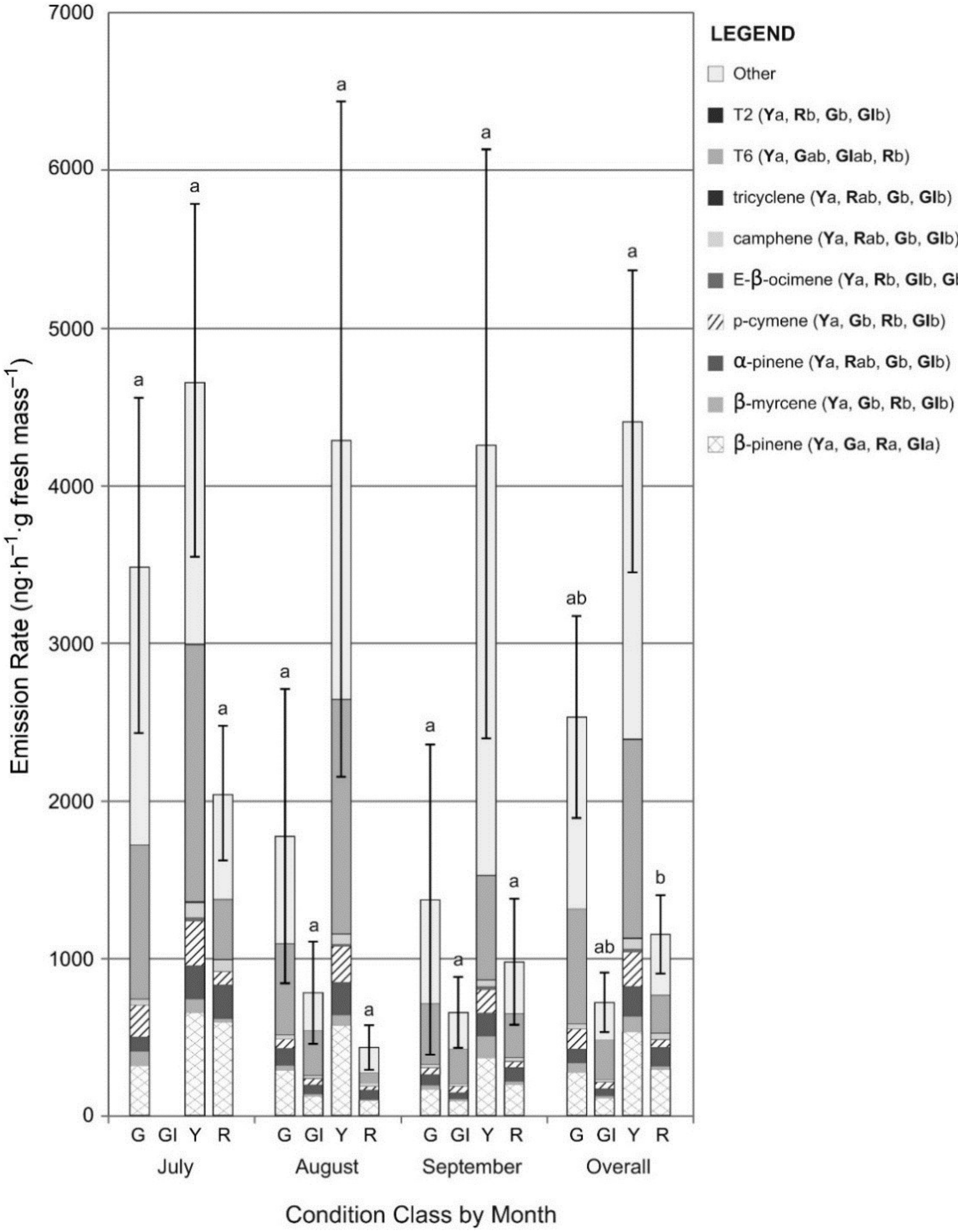

Fig. 3.4. Mean volatile terpene emission rates separated by compounds that were significantly correlated with flammability by crown condition class (G, green; GI, green-infested; Y, yellow; R, red) for all months (July–September), with associated standard error bars; letters on bars indicate significant differences within sampling period. The individual terpene compounds are stacked according to the order in the legend. Comparisons of individual terpenes are for mean emission rates across all sampling periods, and significance is indicated in the legend in parentheses after each compound (condition class in bold followed by corresponding significance letter(s)). The crown condition classes in the legend are arranged from highest to lowest mean values, and bars and terpene names with a different letter have means that are significantly different at the $\alpha = 0.05$ level.

other crown condition classes when averaged over all sampling periods (Fig. 3.4). Unknown terpenes 2 and 6, *p*-cymene, *E*-β-ocimene, and β-myrcene had higher emission rates in Y foliage than in R foliage. The emission rates of unknown terpene 2, *E*-β-ocimene, β-myrcene, α-pinene, *p*-cymene, tricyclene, and camphene were higher in Y foliage than in G foliage.

Ignitability

Time to ignition for fresh foliage differed among crown condition classes (Fig. 3.5A). Mean time to ignition for G and GI foliage was 216 and 232 s, respectively, which was longer than the mean times for Y and R foliage, 79 and 66 s, respectively ($P < 0.0001$). Mean time to ignition for dry foliage among G (28 s), Y (34 s), and R foliage (32 s) ($P = 0.6733$) was not significantly different. Multiple linear regression analysis indicated that fuel moisture and collection date were the most significant predictors of time to ignition for fresh foliage, which together explained 77% of the total variation. Fuel moisture alone accounted for 65% of the total variation in time to ignition of fresh foliage. After accounting for the effects of fuel moisture, the proportion of protein ($P = 0.009$) and potassium ($P = 0.0157$) had significant negative relationships with time to ignition, which increased the proportion of total variation explained to 82% (Table 3.3). Individual correlation analysis of the volatile terpene compounds with time to ignition for fresh foliage indicated that two compounds had significant negative correlations (Table 3.4): *E*-β-ocimene and tricyclene. The strongest relationship was with *E*-β-ocimene, with an r of –0.366.

The differences between temperatures recorded at ignition for fresh foliage were similar to the results for time to ignition (Fig. 3.5C). The temperatures between G and

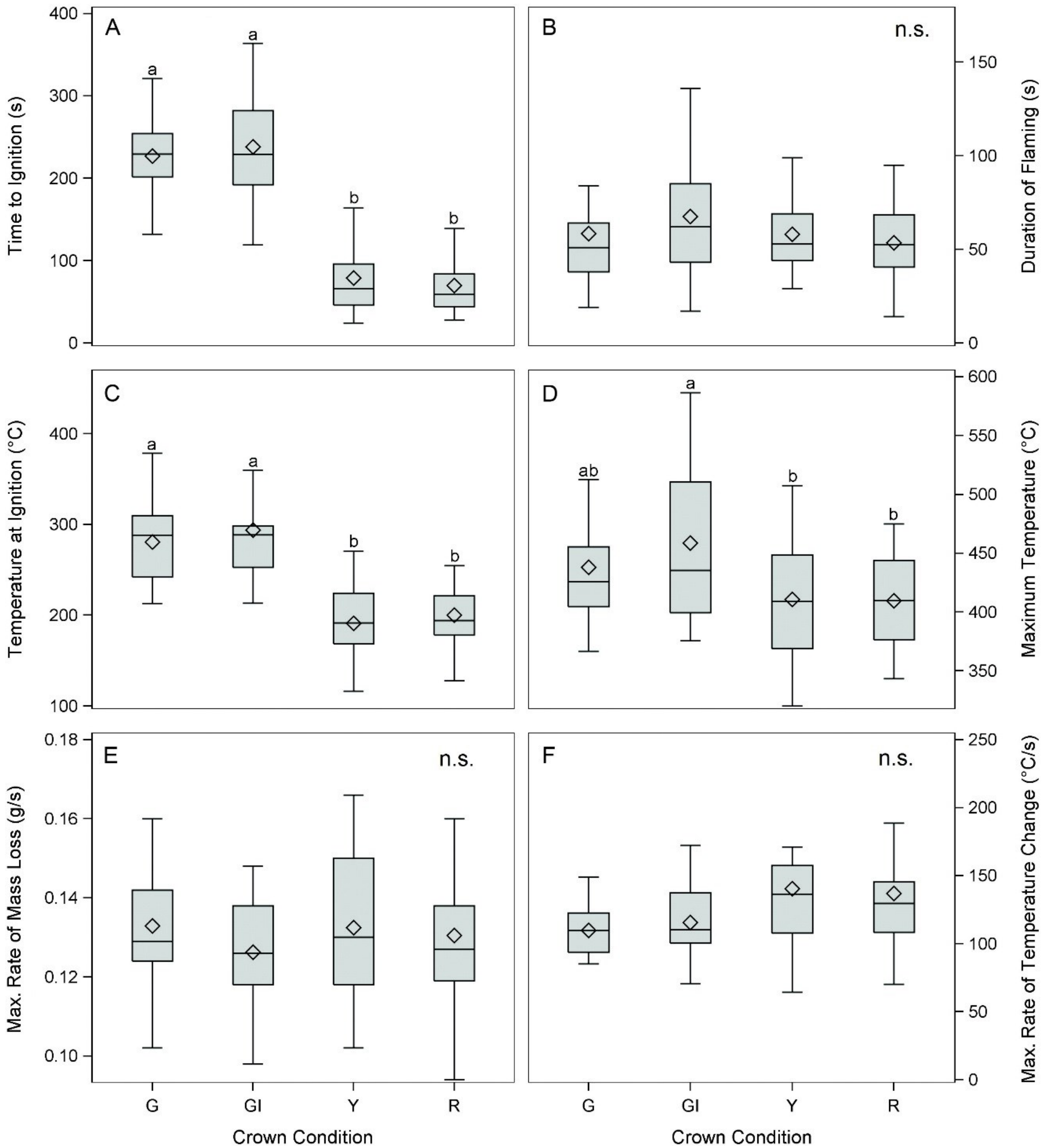

Fig. 3.5. Box-and-whisker plots of the flammability test results for fresh foliage, including (A) time to ignition, (B) duration of flaming, (C) temperature at ignition, (D) maximum temperature, (E) maximum (Max.) rate of mass loss, and (F) maximum (Max.) rate of temperature change for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red), averaged over all sampling periods. The diamond represents the mean, the horizontal line is the median, the lower and upper box ends represent the lower and upper quartiles, and the whiskers are the minimum and maximum values, respectively. Bars with a different letter have means that are significantly different at the $\alpha = 0.05$ level. n.s., nonsignificant.

Table 3.3. Parameter estimates and goodness-of-fit statistics for the best linear regression model obtained using stepwise selection regressing time to ignition of fresh foliage on the chemical composition variables.

Variable	Coefficient	Standard error	*P* value
Intercept	9.24	2.42	0.0001
Collection date	0.64	0.13	<0.0001
Moisture content	7.01	0.51	<0.0001
Protein (%)	−0.74	0.272	0.009
Potassium (%)	−3.99	1.59	0.0157
R^2	0.823		
Adjusted R^2	0.806		
Mean square error	3.1		

Note: The response variable is the square root of the time to ignition, $n = 48$.

Table 3.4. Pearson's correlation coefficients (r) and associated P values among the flammability parameters time to ignition, temperature at ignition, and maximum rate of mass loss with individual terpene compound emission rates ($ng \cdot h^{-1} \cdot g$ fresh $mass^{-1}$) for fresh foliage.

	Time to ignition*		Temperature at ignition*		Maximum rate of mass loss†	
	r	*P* value	r	*P* value	r	*P* value
α-Pinene†	−0.227	0.1215	−0.148	0.3157	**0.325**	0.0257
β-Pinene†	−0.104	0.4815	−0.047	0.7515	**0.305**	0.0371
β-Myrcene†	−0.110	0.4554	−0.114	0.4403	**0.301**	0.0398
E-β-Ocimene†	**−0.366**	0.0106	**−0.304**	0.0354	**0.302**	0.0391
p-cymene†	−0.177	0.2296	−0.158	0.2840	**0.295**	0.0443
Camphene†	−0.275	0.0590	−0.181	0.2171	**0.311**	0.0331
Tricyclene†	**−0.285**	0.0500	−0.192	0.1914	**0.319**	0.0289
Unknown T2†	−0.222	0.1286	−0.199	0.1760	**0.357**	0.0138
Unknown T6†	−0.049	0.7440	−0.028	0.8517	**0.345**	0.0187
Total†	−0.163	0.2697	−0.139	0.3473	**0.309**	0.0345

Note: Significant correlations are presented in bold.
*Variables transformed using the square-root function.
†Variables transformed using natural logarithm. $n = 48$ for all correlations except $n = 47$ for maximum rate of mass loss correlations.

GI foliage ($P = 0.3519$) and between Y and R foliage ($P = 0.9936$) were not different. The mean temperature at ignition for G foliage of 279°C was higher than the mean temperatures for Y of 195°C ($P < 0.0001$) and for R of 198°C ($P = 0.0001$) fresh foliage. Mean temperature at ignition of dry foliage for G trees of 131°C was lower than the mean temperatures for Y of 159°C ($P = 0.0024$) and for R foliage of 150°C ($P = 0.0228$)

(Fig. 3.6B). Correlations of individual terpene compounds with temperature at ignition for fresh foliage indicated that *E*-β-ocimene had a negative relationship, with an *r* of –0.304 (Table 3.4). Correlations of dry foliage with the chemical compounds indicated that NDF, ADF, NFC, and crude fat had significant linear relationships with temperature at ignition (Table 3.5). NDF and ADF had positive relationships, whereas NFC and crude fat content had negative relationships with temperature at ignition.

Combustibility

The mean maximum temperature obtained during the flammability testing of fresh foliage was highest for GI foliage (460°C), which was greater than Y (413°C) (P = 0.0201) and R (410°C) (P = 0.0122) foliage (Fig. 3.5D). Mean maximum temperatures among G, Y, and R fresh foliage were not different (P = 0.2292). Mean maximum temperatures of dry foliage were not significantly different among crown condition classes. Comparisons of the maximum rate of temperature increase among crown condition classes indicated no significant differences for fresh or dry foliage (Fig. 3.5F).

Consumability

Comparisons of the time series of mass loss rates of dry foliage for each of the crown condition classes suggested similarity both when the mass loss rates were averaged over all sample periods and during individual sampling periods. The mean level of mass loss for dry G foliage was higher than those for the other crown condition classes, but when the 95% confidence intervals were included, the mass loss rates overlapped substantially among all crown classes.

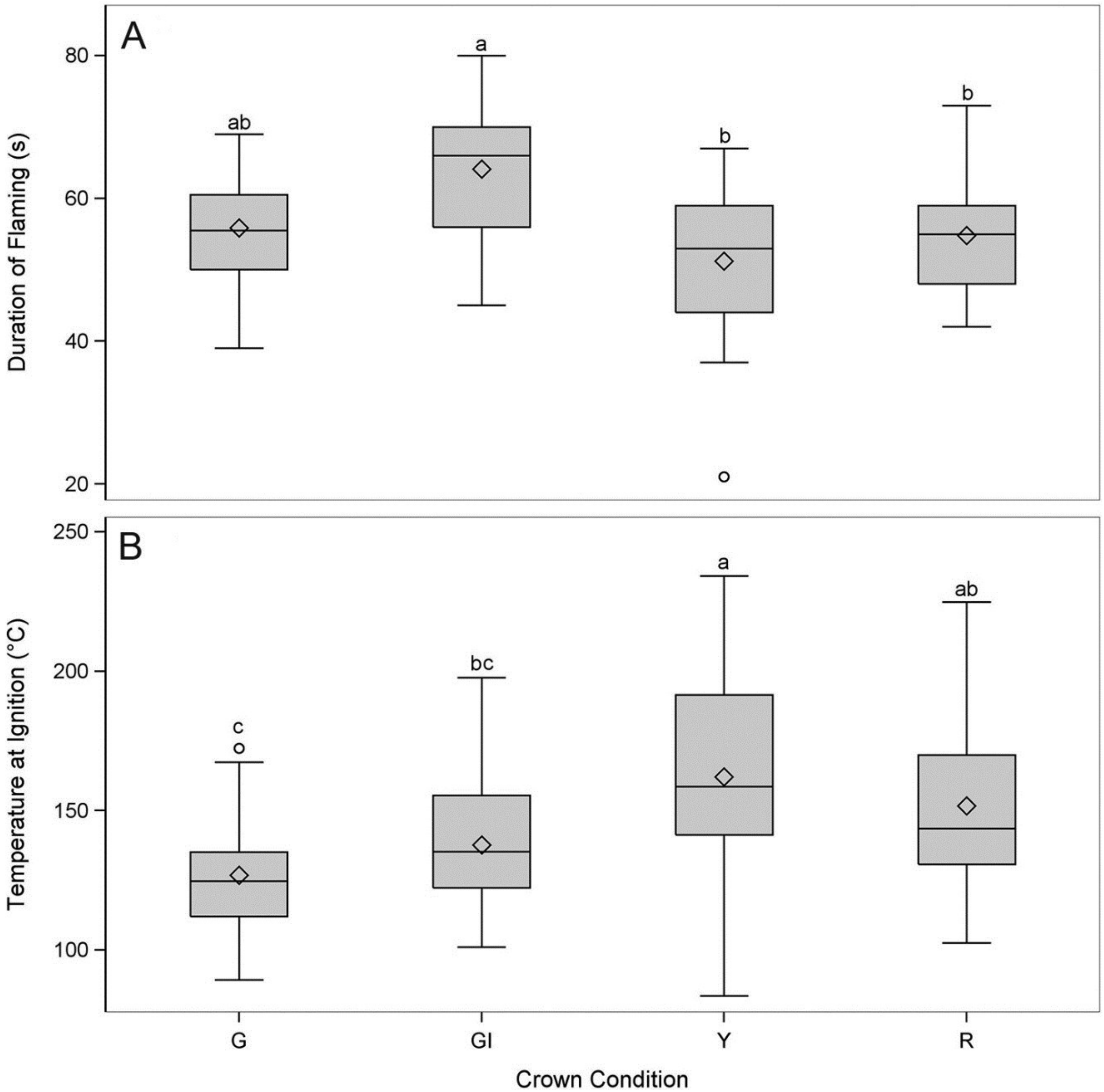

Fig. 3.6. Box-and-whisker plots of the flammability test results for dry foliage, including (A) duration of flaming and (B) temperature at ignition for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red), averaged over all sampling periods. The diamond represents the mean, the horizontal line is the median, the lower and upper box ends represent the lower and upper quartiles, and the whiskers are the minimum and maximum values, respectively. Bars with a different letter have means that are significantly different at the $\alpha = 0.05$ level. ○, outliers.

Table 3.5. Pearson's correlation coefficients (r) and associated P values for duration of flaming, temperature at ignition, and high heat of combustion with the chemical composition groups for dry foliage.

	Duration of flaming		Temperature at ignition		High heat of combustion	
	r	P value	r	P value	r	P value
Protein	0.098	0.5381	–0.216	0.1694	**0.270**	**0.023**
Acid detergent fiber	**–0.471**	**0.0016**	**0.488**	**0.001**	**–0.451**	**<0.0001**
Neutral detergent fiber	**–0.344**	**0.0258**	**0.507**	**0.0006**	**–0.459**	**<0.0001**
Nonfiber carbohydrates	0.300	0.0536	**–0.485**	**0.0011**	**0.413**	**0.0003**
Ca	**0.311**	**0.0451**	–0.119	0.4513	–0.034	0.7765
P	–0.141	0.3714	0.293	0.0596	0.001	0.9962
Mg	**0.430**	**0.0045**	–0.081	0.6117	0.019	0.873
Crude fat	**0.536**	**0.0003**	**–0.317**	**0.0405**	**0.520**	**<0.0001**

Note: Significant correlations are presented in bold; n = 48.

The mean maximum rates of mass loss obtained from the flammability testing with fresh foliage did not differ among crown condition classes (Fig. 3.5E). Correlations of emission rates of total and individual terpene compounds with maximum rate of mass loss for fresh foliage indicated that there were significant positive linear relationships (Table 3.4). The compounds α-pinene, β-pinene, β-myrcene, *E*-β-ocimene, *p*-cymene, camphene, unknown terpenes 1, 2, and 6, and total emissions had significant positive relationships with maximum rate of mass loss. The strongest relationship was with unknown terpene 2, with an r of 0.357. Maximum rates of mass loss among crown condition classes with dry foliage were not significantly different.

Sustainability

Measurements of the duration of flaming for fresh foliage indicated that there were no significant differences among crown condition classes (Fig. 3.5B). For dry foliage, the mean duration of flaming for GI foliage of 64 s was longer than the means for Y foliage of 49 s (P = 0.0010) and for R foliage of 55 s (P = 0.0352) (Fig. 3.6A). The mean duration of flaming for G foliage of 56 s was not different from those for GI (P =

0.1353), Y (*P* = 0.2007), or R (*P* = 0.9809) foliage. Correlations of duration of flaming with the chemical attributes for dry foliage indicated that several of the chemicals had significant linear relationships (Table 3.5). NDF and ADF had negative *r* values, –0.344 and –0.471, respectively, with duration of flaming. Calcium, magnesium, and crude fat had significant positive linear relationships with the duration of flaming, with *r* values of 0.311, 0.430, and 0.536, respectively.

Differences in high heat of combustion among crown condition classes were found (Table 3.6). G foliage had higher heat of combustion than Y (*P* = 0.0091) and R (*P* = 0.0136) foliage averaged over all sampling periods. High heats of combustion between G and GI foliage (*P* = 0.7814) and R and Y foliage (*P* = 0.9881) were not different. Measured heats of combustion did not change over time for GI, Y, or R foliage. However, the heat of combustion for G foliage dropped from early July to late August (*P* = 0.0277) but increased to early July levels by late September (*P* = 0.9763). When the overall mean high heats of combustion were adjusted for the latent heat of water during combustion and for moisture content, the mean heat yield of Y foliage (18610 $KJ \cdot kg^{-1}$) and R foliage (18900 $KJ \cdot kg^{-1}$) was higher than the heat yield of G foliage (17070 $KJ \cdot kg^{-1}$). There were several significant correlations of high heat of combustion with the chemical attributes (Table 3.6). NDF and ADF had negative relationships with heat of combustion, with *r* values of –0.459 and –0.451, respectively. Proportions of protein, NFC, and crude fat had significant positive relationships with the high heats of combustion. The strongest relationship was with the proportion of crude fat, with an *r* of 0.520. A summary of all results is presented in Fig. 3.7.

Table 3.6. The mean high heats of combustion obtained from the bomb calorimeter testing for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red) for every sampling period.

Crown condition	Early July	Late July	Early August	Late August	Early September	Late September	Overall
G	21 210±91a	21 020±114a	21 033±170a	20 810±157a	21 003±122a	21 058±125a	21 045±52a
GI	n/a	n/a	20 952±197a	21 092±111a	20 969±152a	20 760±130a	20 943±71ab
Y	20 530±232a	20 448±240a	20 576±74a	20 364±170a	20 394±142a	20 395±139b	20 451±68b
R	20 677±171a	20 475±198a	20 564±184a	20 297±130a	20 489±99a	20 369±168b	20 479±65b

Note: Values are mean ± standard error. All values are expressed in $KJ \cdot kg^{-1}$. Means followed by a different letter within a column are significantly different ($\alpha = 0.05$).

↑ higher ↓ lower ← shorter → longer	Fuel Moisture / Chemistry	Ignitibility		Combustibility		Consumability		Sustainability	
		Fresh	Dry	Fresh	Dry	Fresh	Dry	Fresh	Dry
G 	• ↑ proportions of NFC and crude fat than Y and R	• ↑ TTI and TAI than Y and R	• TTI and TAI similar to GI, Y, and R	• MT and MRT similar to GI, Y, and R	• MT and MRT similar to GI, Y, and R	• MLR and MMLR similar to GI, Y, and R	• MLR and MMLR similar to GI, Y, and R	• Similar duration of flaming to GI, Y, and R	• Similar duration of flaming to GI, Y, and R • Lowest heat yields
GI 	• Fuel moisture and chemistry unchanged from G	• TTI and TAI equivalent to G	• TTI and TAI equivalent to G	• MT and MRT equivalent to G	• MT and MRT equivalent to G	• MLR and MMLR equivalent to G	• MLR and MMLR equivalent to G	• Duration of flaming equivalent to G	• Duration of flaming → than Y and R • Heat yield equivalent to G
Y 	• Foliage fuel moisture equivalent to R from late July onward • NDF and ADF↑, NFC and crude fat ↓ than G • ↑ emission rates of several terpenes than G and R	• ← TTI than G • ↓TAI than G • Several terpenes emitted at ↑ levels than G negatively correlated with TTI and TAI	• ↑TAI than G	• MT and MRT equivalent to G • ↑ emissions of two terpenes positively correlated with maximum rate of temperature change	• MT and MRT equivalent to G	• MLR and MMLR equivalent to G • ↑ emissions of several terpenes positively correlated with maximum rate of mass loss than G	• MLR and MMLR equivalent to G	• Duration of flaming equivalent to G	• ← duration of flaming than GI • Heat yield ↑ than G • Duration of flaming and heat yield positively correlated with NFC and crude fat, negatively correlated with NDF and ADF
R 	• Moistures similar to Y and litter • NDF and ADF ↑, NFC and crude fat ↓ than G	• ← TTI and ↓ TAI than G	• ↑ TAI than G	• MT and MRT equivalent to G	• MT and MRT equivalent to G	• MLR and MMLR equivalent to G	• MLR and MMLR equivalent to G	• Duration of flaming equivalent to G	• ← duration of flaming than GI • Heat yield ↑ than G • Duration of flaming and heat yield positively correlated with NFC and crude fat, negatively correlated with NDF and ADF

TTI = Time to Ignition
TAI = Temperature at Ignition
MT = Maximum temperature
MRT = Maximum rate of temperature increase
MLR = Mass loss rate
MMLR = Maximum mass loss rate

Fig. 3.7. Summary results matrix for each of the crown condition classes (G, green; GI, green-infested; Y, yellow; R, red).

Discussion

Our results indicated that MPB attack significantly alters the chemistry and flammability of lodgepole pine foliage. The moisture content and chemical makeup of foliage from the most recently attacked trees (GI) did not substantially differ from G foliage. It has been suggested by Jolly et al. (2012) that the foliar moisture content of recently attacked trees may decrease during the summer of attack. Beetle flight on our site began during the last week in June and was not complete until mid- to late July. Other sites at lower latitudes and elevations may experience beetle flight sooner, possibly affecting the potential for significant decreases in moisture content during the summer of attack. As a result of the similarities between G and GI foliage, the measured flammability parameters for ignitability, combustibility, consumability, and sustainability were equivalent.

The substantial differences in moisture content detected among G, Y, and R foliage had clear implications on flammability. The bulk of moisture loss in the transition from the GI to Y crown condition class occurred during the winter and spring months, outside the main fire season when we sampled. This is similar to the results of Gibson and Negrón (2009), who reported substantial decreases in foliar moisture during the early spring and summer following the summer of attack. This decrease in moisture content substantially altered the ignitability and sustainability flammability parameters of foliage. Mean times to ignition of fresh Y and R foliage were more than 2.5 times shorter than for G foliage. Likewise, the mean temperature at ignition for Y and R foliage was almost 1.5 times lower than G foliage. The shorter times to ignition suggest that stands composed of significant proportions of Y and R foliage may have lower transition thresholds for crown fire development, as proposed by Knight (1987) and Jenkins et al. (2008), both diurnally and seasonally compared with healthy stands. The measured high heats of combustion for G and GI foliage were within the range reported by others for live foliage (Hough 1969; Williamson and Agee 2002). However, by adjusting the high heat of combustion to heat yield, we found that the heat yields of Y and R foliage were higher than the heat yield of G foliage, suggesting that once crown fire activity begins, there may be higher fire intensities in stands with Y and R trees than similar healthy stands.

The increase in the structural compounds of foliage (NDF and ADF) and the decrease in the starches and sugars (NFC) and crude fat in Y and R foliage had significant influences on flammability, particularly ignitability and sustainability. The increase in temperature at ignition of dry Y and R foliage compared with G foliage may be the result of increasing portions of lignin, cellulose, and hemicellulose and decreasing proportion of crude fat content. Lignin, which has a relatively high relative molecular mass, is known to be more thermally stable and therefore less volatile than cellulose or carbohydrates (Kitao and Watanabe 1967; Shafizadeh 1971). In contrast, carbohydrates, and especially ether extractable compounds (crude fat), have low relative molecular mass and are known to be relatively more volatile and flammable (Shafizadeh et al. 1977; Susott 1980). These changes in foliar chemistry indicate that the inherent ignitability of Y and R foliage is lower than that of G foliage, but our results confirm that the effect of fuel moisture overwhelmed these apparent decreases in ignitability.

The duration of flaming of dry foliage for all crown condition classes was negatively related to the proportions of lignin, cellulose, and hemicellulose but positively related to the proportions of calcium, magnesium, and crude fat. Again, it appears that the high relative molecular mass of the structural compounds of lignin and cellulose reduced the ability of the fuel to sustain flaming combustion, whereas the low relative molecular mass and high energy compounds in crude fat extended the period of flaming. The high heats of combustion also had positive linear relationships with crude fat content and the proportion of starches and sugars and negative relationships with the proportions of lignin, cellulose, and hemicellulose. The importance of crude fat content on heat of combustion has been demonstrated by others (Philpot 1969; Philpot and Mutch 1971). However, the negative relationship between the proportion of lignin and cellulose with high heat of combustion appears contrary to the results of White (1987), who found increasing high heats of combustion with increasing lignin content. Determining the nature of the discrepancy is difficult because our measure of lignin (ADF) is confounded with cellulose; thus we were unable to make a direct comparison between high heat of combustion and lignin content to ascertain the reason for the observed drop in heat of combustion.

The results from the volatile terpene measurements indicated significant changes in both total and individual terpene emission rates among Y, R, and G foliage. The mean total emission rate of volatiles in Y foliage was consistently higher during each month of sampling, but due to high variability, the only significant increase detected was between the mean emission rate for Y foliage and the mean rate for R foliage. However, several of the individual terpenes related to flammability had higher emission rates in Y foliage compared with G foliage. Both of the terpenes identified as negatively correlated with time to ignition and temperature at ignition were emitted at higher rates in Y foliage than in G foliage. Likewise, all but two of the nine compounds positively correlated with the maximum rate of mass loss were emitted at higher levels in Y foliage than in G foliage. Terpenes have previously been shown to be an important predictor of flammability for some wildland fuels (Owens et al. 1998; Ormeño et al. 2009) but not for others (Bunting et al. 1983; Alessio et al. 2008). Our results imply that the higher emission rates of some of the terpenes in Y foliage may have contributed to the increased ignitability observed in Y versus G foliage, although the strongest relationship observed was still relatively weak ($r = -0.366$) compared with the effect of fuel moisture. The cause for the increase in volatile emissions in Y foliage may be related to the decomposition, breakdown, and drying of plant material. The mobilization of water through drying likely supported terpene transport from within the needle to the surface, which, when followed by evaporation, may have produced increased emission rates (Banerjee 2001).

Conclusion

The foliage of lodgepole pine trees recently affected by MPB undergoes significant changes in moisture status and chemical composition over the course of tree decline and death. Beginning during the first summer following attack, the flammability of infested tree foliage significantly increases and remains high throughout the red crown condition class stage. The most prominent flammability characteristics enhanced in recently infested foliage are ignitability and sustainability, with beetle-affected foliage igniting more readily than healthy foliage and having more potential net energy under field conditions to sustain and promote fireline intensity. The primary factor increasing flammability is decreased moisture content, which overwhelms the inherent decreases in flammability of recently affected foliage caused by decreases in starches, sugars, and crude fat and increases in lignin, cellulose, and hemicellulose. Considerable quantities of volatile terpenes are present in dead and dying foliage, with trees attacked one year prior (Y) having higher emission rates of those terpenes that promote increased flammability. Although not described here, physical changes in foliage at the individual needle scale were observed that could influence flammability. Observations of Y and R needle foliage compared with G foliage clearly suggest structural differences in the surface area to volume ratio of the needles. Cross sections of individual G needles of lodgepole pine are best described as cylinders, whereas R foliage has a flattened, concave structure resembling a blade of grass. The work of Lopushinsky (1970) and Brown (1970) showed differences in the surface area to volume ratio between fully turgid lodgepole pine needles ($46.1 \cdot cm^{-1}$; Lopushinsky 1970) and air-dried lodgepole pine needles ($64.7 \cdot cm^{-1}$; Brown 1970), suggesting enhanced heat transfer to dried-out needles.

Although the period of increased flammability may be relatively short for individual trees (i.e., less than five years), mortality generally occurs over a period of several years within an individual stand, and therefore all stages (G, Y, and R) may occur together for long periods of time. During this window of time, fire managers and firefighters should be aware of the possibility of increased potential for crown fire initiation in affected stands and the prospect for rapid changes in fire behavior as fires move in and out of beetle-affected areas. Future research should focus on documenting wildfire behavior in beetle-affected stands to verify the enhanced flammability predicted here and to gain a better understanding of applicability of current empirical and physics-based models of fire behavior.

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CHAPTER 4

SPRUCE BEETLE-INDUCED CHANGES TO ENGELMANN SPRUCE FOLIAGE FLAMMABILITY[5]

Abstract

Intermountain Engelmann spruce (*Picea engelmannii* Parry ex Engelm) stands affected by the spruce beetle (*Dendroctonus rufipennis* Kirby) represent a unique and growing fuel complex. In this study, we quantified and compared the changes in moisture content, chemistry, and flammability of foliage from trees in three crown condition classes: unattacked (green [G]), currently mass attacked (green-infested [GI]), and mass attacked the previous year (yellow [Y]) over the course of a fire season. GI trees displayed highly variable decreases in moisture content both between trees and within individual tree crowns that produced variable increases in flammability. The foliage on Y trees had significantly lower moisture contents, higher proportions of lignin and cellulose, and lower proportions of carbohydrate-based compounds than G foliage, which resulted in increased flammability. This increase in crown flammability was short-lived because the foliage on Y trees dropped abruptly approximately 14 months after mass attack (by late July). Given the observed changes in flammability, increased crown fire potential may occur in spruce beetle-infested forests during the spring when G and Y foliage flammability is highest, provided sufficiently dry conditions, and in late summer when the combination of peak GI foliage flammability coincides with the peak in seasonal drying.

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Introduction

Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* var. *latifolia* Nutt.) forests occur throughout the Intermountain region of the United States, generally above 2,400 m in elevation (Long 1994). Dense, pure stands of Engelmann spruce grow on moist, cool, high elevation sites but are often codominant with subalpine fir on drier sites at lower elevations (Alexander 1987). The primary agents of disturbance in spruce-fir forests are fire and the spruce beetle (*Dendroctonus rufipennis* Kirby [Coleoptera: Curculionidae]). Large fires are relatively rare in spruce-fir forests because of short snow-free periods and long episodes of unfavorable fire weather conditions with fire return intervals often exceeding 150 years (Arno 1980, Jenkins et al. 1998). Outbreaks of the spruce beetle occur between stand-replacing fire events as post-fire stands mature (Baker and Veblen 1990), being triggered by a combination of the availability of suitable down host material (Schmid 1981) and favorable climatic conditions (Schmid and Frye 1977, DeRose and Long 2012). Outbreaks have been documented in the western United States since the mid-1880s, but mortality levels have risen sharply in recent decades (Berg et al. 2006, Hebertson and Jenkins 2008). Since 2001, spruce beetle has affected >180,000 ha of Engelmann spruce forests in the Intermountain region (Man 2010), which has caused widespread concern among land managers about the accumulation of dead forest fuels and the effects on potential fire behavior (Jenkins et al. 2008).

Recent research has quantified the influence of bark beetle-induced tree mortality on fuel complexes in several forest types common in the Intermountain West, including spruce beetle in spruce-fir forests (DeRose and Long 2009, Jorgensen and Jenkins 2011).

However, it has been difficult to correlate mortality with increases in the number of ignitions, fire risk, or changes in fire behavior (Bebi et al. 2003, Kulakowski et al. 2003). Real-time fire weather, drought, and the point of ignition have all been shown to exercise greater influence on fire occurrence and extent than the pre-fire fuel conditions caused by spruce beetle outbreaks (Kulakowski and Veblen 2007). Current debates about the need for and appropriateness of mechanical treatments to reduce perceived fire risk in high elevation, bark beetle-attacked forests are ongoing (Black et al. 2013) and hindered by a lack of detailed information about the changes in crown fuel characteristics that influence crown fire initiation and spread (Hicke et al. 2012) and the inadequacy of current fire behavior models (see Chapter 2).

Although several studies have demonstrated the relatively minor influence of spruce beetle outbreaks on long-term fire risk, other work has shown that short-term changes in foliar moisture content (FMC) and chemistry in mountain pine beetle (*Dendroctonus ponderosae* Hopkins)-attacked lodgepole pine (*Pinus contorta* Dougl. Ex Loud. var. *latifolia* Engelm.) tree crowns have the potential to alter crown fire initiation and spread (Jolly et al. 2012, see Chapter 3). Jolly et al. (2012) in Colorado and Montana and Page et al. (see Chapter 3) in Idaho demonstrated that as attacked trees die and senesce, their foliage undergoes substantial decreases in moisture content and changes in chemistry, which substantially increases foliage ignitability, mostly as a result of decreases in moisture content. Other research has also demonstrated the importance of moisture content on flammability (Van Wagner 1967a, Dimitrakopoulos and Papaioannou 2001), although the effect can decrease as the magnitude of the heat flux used in testing increases (White and Zipperer 2010). For example, using heat fluxes between 80 and 140 kW m^{-2}, Fletcher et al. (2007) found that the mass of moisture in individual leaf samples had little effect on time to ignition and ignition temperature. Fernandes and Cruz (2012) noted that peak heat fluxes in shrubland fires and crown fires in conifer forests can approach those used by Fletcher et al. (2007) and are more representative of the influence of moisture content during high-intensity fires. However, low heat flux levels representative of lower intensity surface fires and the resulting influence of moisture content may be more important when considering the transition from surface to crown fire (Van Wagner 1977, Xanthopoulos and Wakimoto 1993).

To our knowledge, no research has been published that quantifies the changes in FMC, chemistry, and flammability of Engelmann spruce affected by spruce beetle. This information is needed to improve our understanding of the effects of recent bark beetle mortality on crown fire potential (Hicke et al. 2012) and as a part of the basic fundamental research necessary to enhance current and future operational product development (Cohen 1990). As fire behavior models continue to improve by resolving more of the underlying physical processes and incorporating the spatial heterogeneity of natural fuel complexes, detailed descriptions of each of the fuel elements will be needed (Mell et al. 2009, 2010). To fill this knowledge gap and provide a better understanding of the effects of recent spruce beetle mortality on crown fuel and flammability dynamics, we quantified and compared the changes to FMC, chemistry, and flammability of foliage on Engelmann spruce trees unattacked but susceptible to attack (green [G]), currently infested (green-infested [GI]), and mass-attacked the previous year (yellow [Y]) over the course of a fire season. Based on previous research conducted in lodgepole pine forests affected by the mountain pine beetle (i.e., Jolly et al. 2012, see Chapter 3), we hypothesized that there would be significant changes in FMC, chemistry, and flammability in both unattacked and recently attacked foliage. Specifically, as the time since attack increases, we expect FMC and soluble carbohydrates to decrease, and structural lignin and cellulose to increase in relative proportion, resulting in increased foliage flammability due primarily to decreases in FMC. In addition, we expect unattacked tree foliage to display significant changes in FMC and chemistry in response to translocation of soluble carbohydrates from old to new foliage and for GI foliage to show increases in within-needle terpene concentration and volatile emission rates due to the production of plant defensive compounds.

Methods

Study Area

U.S. Department of Agriculture Forest Service Forest Health Monitoring aerial detection survey maps, consultation with local land managers, and ground reconnaissance were used to identify sites with significant levels of recent spruce beetle-caused tree mortality. The specific study site chosen was located in the western Uinta Mountains in northern Utah on the Uinta-Wasatch-Cache National Forest (40°27′47′′ N, 111°7′54′′ W) at an elevation of 2,987 m above mean sea level. The study site was approximately 2 ha in size with a northwest aspect and slope of 5%. Soils at the site were classified as sandy loams to loamy sands, quartzite derived, and probably nutrient poor (Briggs and MacMahon 1982). The site supported a relatively open, mixed-aged stand of Engelmann spruce and subalpine fir that was selectively harvested in the 1980s. Stand density ranged between 500 and 1,500 stems ha^{-1}, and the mean basal area was 10 to 15 m^2 ha^{-1}. The stand experienced significant spruce beetle-caused tree mortality over the previous 2-

3 years (>75% of mature spruce killed) with a large increase in mortality during the summer of 2011.

Tree Selection

The foliage of eight trees in each of three crown condition classes (G, GI, and Y) for a total of 24 trees was selected for repeated sampling based on the following selection criteria: (1) similar tree characteristics in terms of size and height, (2) free from secondary disturbances, (3) adequacy of lower crown to facilitate the needs of repeated sampling, and (4) accessibility for equipment. The mean (±SE) dbh (cm), canopy base height (m), and tree height (m) of the selected trees were 26.4±1.93, 0.8±0.08, 11.7±0.51 for G, 25.5±1.3, 1.0±0.11, 13.6±0.73 for GI, and 38.5±2.48, 1.1±0.06, 17.1±0.94 for Y, respectively. All sample trees within a crown condition class had similar sizes, but the Y trees were larger than the G or GI trees because of a host size preference during the early stages of an outbreak (Schmid and Frye 1977). Older spruce beetle-attacked trees within the study site had dropped their foliage by the time of sampling; thus, the red stage typical in other conifers attacked by bark beetles was not present. All sampling was conducted during the primary fire season in the western Uinta Mountains (June to September). In late July, the Y trees dropped all of their needles within a 2- to 3-week period. Therefore, from late July to late September only the 8 G and 8 GI trees were sampled.

Fuel Moisture and Chemistry Sampling

Fuel moisture, within-needle terpene concentration, and terpene volatile emissions were sampled from each tree twice per month. Field sampling consisted of removing approximately three 100-g samples of foliage from the lower crown of each sample tree between 1100 and 1400 hours local time at the beginning of each week. The foliar samples were returned to the laboratory where new and old needles were separated and removed from the twig material. The growth of new needles had begun by late June and made up only a small fraction of the total needles on each branch. Old foliage was considered to be all foliage attached to the twig excluding the present year's growth. About 20 to 30 g of foliage from each sample was weighed to the nearest 0.01 g to obtain a fresh weight and then oven-dried at 60°C for 24 hours and reweighed to obtain a dry weight. The FMC for old and new foliage was computed as the percentage of the oven-dry weight.

Field sampling of volatile terpene emissions was conducted following the procedures from Chapter 3 by enclosing the outer 70 cm of one branch on each tree in a clear Teflon bag and using portable automated vacuum pumps to pull air at a rate of 0.5 L min^{-1} through volatile traps containing 30 mg of the absorbent HayeSep-Q (Restek, Bellefonte, Pennsylvania). Volatile terpene emissions were collected for 30 min and then the enclosed portion of branch was clipped and later weighed to obtain a fresh weight. Approximately 20 to 30 g of fresh foliage from each tree along with the volatile traps were immediately shipped to the Rocky Mountain Research Station in Bozeman, Montana and stored at -80°C until processed. Within-needle terpenes were extracted from the foliage samples following the procedures used by Ormeño et al. (2009) with some modifications. Five grams of each foliage sample was ground to a fine powder in liquid nitrogen using a mortar and pestle. Approximately 0.1 g of powdered needles were transferred into 2 ml FastPrep tubes (MP Biomedical, Solon, Ohio) and 1.5 ml of cyclohexane was added and sonicated at room temperature for 20 minutes. Tubes were then centrifuged at 13,000 *g* for one minute and 200 μl of cyclohexane (top layer) was transferred to a gas chromatograph (GC) vial for analysis. Terpene concentration and volatile emission rate were measured using an Agilent 7890A GC coupled with a 5975C mass spectrometer; helium was used as the carrier gas. Individual compounds were identified by comparing retention times and mass spectra to appropriate internal standards. Total terpene concentration and volatile emission rate were reported on a fresh weight basis.

During the first two weeks of each month approximately 60 to 80 g of fresh foliage from each tree was also shipped to a forage testing laboratory for chemical analysis (Agrianalysis 2013). The chemical measures included the proportion of the sample that was lignin, cellulose, and hemicellulose, called neutral detergent fiber (NDF); the proportion composed of just lignin and cellulose (a subset of NDF), called acid detergent fiber (ADF); the proportion composed of crude fat, ash, and protein; and the remaining portion that were the starches and sugars referred to as the non-fiber carbohydrates (NFC). A detailed listing of the procedures used to determine ADF, NDF, crude fat, and ash using the ANKOM filter bag technique, fat extractor, and ashing are detailed elsewhere (see ANKOM Technology 2013).

Flammability Testing

Each week, the old foliage collected from all trees in each condition class was subjected to flammability testing using the same setup as Page et al. (see Chapter 3). In brief, a 500-W silica epiradiator was used as the heat source in conjunction with a scale, pilot flame, metal stand, and a type K thermocouple probe located approximately 1.5 cm above the sample. The thermocouple and scale were connected to a data logger that recorded the temperature and mass of the sample every 0.1 s. The sample holder was composed of a wire mesh (8 x 8 cm) placed 3 cm below the epiradiator on top of the stand. The pilot flame was located 2 cm above the top of the sample at the edge of the sample holder. Foliage was placed evenly across the holder to a depth of approximately 0.5 cm. The initial mass of the fresh samples varied from 6.3 to 10.6 g as a result of moisture differences. During each test, the sample was placed on top of the stand and the epiradiator was lowered into position. Then the time when ignition started and time that flaming ceased were recorded. The high heat of combustion was also measured for one oven-dry foliage sample taken from each tree during each week using an oxygen bomb calorimeter following ASTM D standard 1989-96 with corrections for the fuse wire, nitric acid, and aqueous sulfuric acid formed during the reaction.

Assessment of Flammability

The flammability of old foliage samples was assessed using eight different measures, two measures each of ignitability, combustibility, consumability, and sustainability (Anderson 1970, White and Zipperer 2010). Ignitability was considered to be the time to ignition (TTI) and the temperature at ignition (TAI). TTI was recorded as the time in seconds from when the thermocouple reached 60°C until flaming began (Alessio et al. 2008). TAI was the temperature of the thermocouple at ignition. Note that the thermocouple was not in contact with the sample but was 1.5 cm above it to avoid affecting the mass measurements. Combustibility was measured as the maximum temperature recorded during flaming ($_{max}$TDF) (°C) and the maximum rate of temperature increase during flaming ($_{maxrate}$TDF) (°C s^{-1}). Consumability was represented as the maximum rate of mass loss during flaming ($_{maxrate}$MLR) (g s^{-1}), using the 5 s running mean of mass loss rate to smooth the response, and the proportion of total mass lost during flaming ($_{prop}$MLDF). Sustainability was considered to be the duration of flaming (DOF) (s) and the heat yield (kJ kg^{-1}) to account for the moisture content of the fuel. Heat yield estimates were obtained by reducing the high heat of combustion values for the latent heat absorbed when the water of reaction is vaporized and to account for the energy required to evaporate the moisture in the fuel following Van Wagner (1972) and Alexander (1982). See Table 4.1 for a complete listing of all abbreviations used in this paper.

Table 4.1. List of abbreviations, sorted alphabetically, and their units used in the manuscript.

Abbreviation	**Full name**	**Units**
ADF	Acid detergent fiber	% of dry weight
DOF	Duration of flaming	seconds (s)
FMC	Foliar moisture content	% of oven-dry weight
G	Green foliage	-
GI	Green-infested foliage	-
HC	High heat of combustion	kJ kg^{-1}
HY	Heat yield	kJ kg^{-1}
$_{max}$TDF	Maximum temperature during flaming	°C
$_{maxrate}$MLR	Maximum rate of mass loss during flaming	g s^{-1}
$_{maxrate}$TDF	Maximum rate of temperature increase during flaming	°C s^{-1}
NDF	Neutral detergent fiber	% of dry weight
NFC	Non-fiber carbohydrates	% of dry weight
$_{prop}$MLDF	Proportion of mass lost during flaming	dimensionless
TAI	Temperature at ignition	°C
TTI	Time to ignition	seconds (s)
Y	Yellow foliage	-

Historic Weather Data

Historic weather data from the Norway remote automated weather station for the period 1983-2011 were compared with the observed 2012 weather. Mean precipitation and air temperature for the spring and summer months were evaluated to compare the level of dryness during sampling with the historical average. The station was located approximately 22 km north of the study site at an elevation of 2,524 m above mean sea level. The number of years in the historical database varied for each of the months evaluated. April and May had 11 years of data, June had 12 years of data, July had 23 years of data, September had 26 years of data, and August and October had 27 years of data.

Data Analysis

Repeated-measures analysis of variance with the mixed procedure in SAS (version 9.3; SAS Institute, Inc. 2010) was used to assess differences in the mean responses of fuel moisture, chemistry, and flammability among crown condition classes and through time with crown condition class and sampling date as fixed effects. The three subsamples of old FMC from each tree were averaged to produce one value for each tree for each sampling period. The FMC, flammability, terpene concentration, and emission data were then grouped by 2-week intervals (early month and late month) for comparison. The chemistry variables (e.g., ADF and NDF) obtained from the forage testing analyses were grouped by the month in which they were sampled. Thus, for the FMC, flammability, terpene concentration, and emission data, there were eight time periods whereas the chemistry data had four time periods for comparison. Appropriate transformations were applied when necessary to meet the assumptions of normality and homogeneity of variance. The model that minimized Akaike's information criterion was used to select the proper covariance structure, which was either compound symmetry, autoregressive, or unstructured. If significant differences among the crown condition classes were found, the post hoc means comparison experiment-wise error rate was controlled using the Tukey-Kramer method.

Additional analyses using the ungrouped data were performed to evaluate the relative importance of FMC and chemistry on flammability. Specifically, because many of the flammability measures shared much of the same information, principal component analysis was used to reduce the dimensionality of the responses based on the correlation matrix. The resulting eigen values and vectors for each axis were assessed in terms of their direction, magnitude, and variability explained to determine how many dimensions to keep in the analysis. The assumption of multivariate normality was assessed by examining plots of the individual responses and applying appropriate transformations when needed. Pearson's correlation coefficients (r) were used to identify significant linear relationships between the resulting principal component scores and the original flammability responses to ascertain the principal component loadings and to interpret the importance of the individual axes. Some of the flammability observations were removed from the analysis because of incorrect readings from the data logger. The sample size for each analysis is reported in the appropriate figure or table.

To identify and correct dependence structures (serial autocorrelation) in the principal component scores and the high heat of combustion values, time series analysis using Box-Jenkins methodology (Box and Jenkins 1976) with unconditional least squares was used. Once the serial autocorrelation was accounted for, the dependence free residuals from the appropriate autoregressive integrated moving average model were then used with multiple linear regression to identify significant linear relationships with the fuel moisture and chemistry variables, a form of two-stage regression (Durbin 1960, Tsay 1984). Stepwise selection with $\alpha = 0.15$ for entry and exit was used to select the most appropriate variables in the multiple linear regression models. We considered $\alpha = 0.05$ to indicate statistical significance but due to low sample sizes we also considered $\alpha = 0.10$ to indicate moderate evidence of significance. As high heat of combustion is a useful parameter for fire behavior modelling its results are also presented separately.

Results

Foliar Moisture and Chemistry

The weather near the study site during the spring and summer of 2012 was substantially drier and slightly warmer than the historical average (Figure 4.1). May and June were particularly dry with precipitation between 0 and 4% of normal. Precipitation during the summer was also below average.

Beetle flight at the study site had begun by early June; thus, all three crown condition classes were available for sampling through all time periods. The observed FMCs displayed a typical seasonal pattern for new and old foliage (Figure 4.2). New G and GI foliage had FMCs exceeding 300% during green-up in late June followed by a gradual decrease through the end of September. The mean FMC of new G and GI foliage remained similar until September when the mean value for new GI foliage began to dip below that of G foliage, but the difference was not significant ($P = 0.4165$). The mean FMC of both old G and GI foliage was at a low of 76% in early June. The mean FMC of old G foliage reached a maximum of 107% by early September, whereas the mean FMC

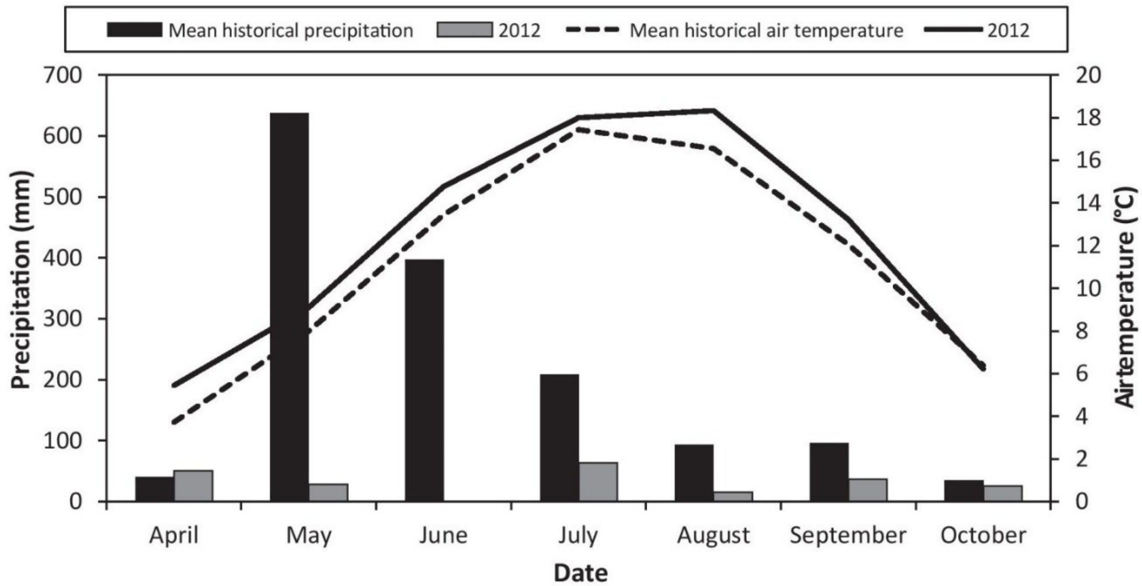

Figure 4.1. The mean historical (1983–2011) and 2012 precipitation and mean air temperature at the Norway remote automated weather station for the spring and summer months. The station was located approximately 22 km north of the study site at an elevation of 2,524 m above mean sea level. The number of years in the historical database varied by month: April and May, 11 years; June, 12 years; July, 23 years; August, 27 years; September, 26 years; and October, 27 years.

of GI foliage reached a high of 83% in late July and then decreased to its low of 76% again by late September. There was moderate statistical evidence suggesting that the FMC of old GI foliage was lower than that of G foliage ($P = 0.0776$) when all sampling periods were compared; however, all of the individual sampling period comparisons were not significant ($P > 0.10$). The mean FMC of Y foliage was significantly lower than that of both G and GI foliage ($P < 0.0001$) from early June to early July, reaching a minimum of 24% in early July before the needles dropped to the ground.

The chemistry of Engelmann spruce foliage displayed significant changes both among crown condition classes and seasonally (Figure 4.3). The proportion of NDF increased in both G and GI foliage from a low of 37 and 39% in June to a high of 42 and

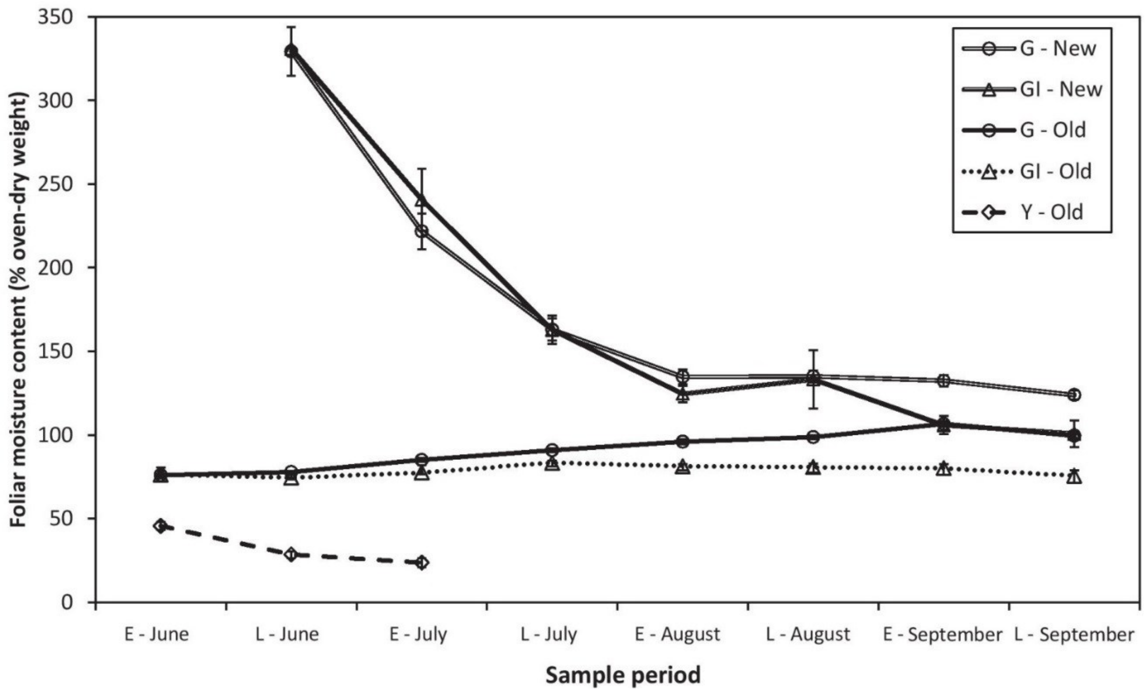

Figure 4.2. The seasonal change in foliar moisture content of Engelmann spruce foliage from new and old foliage on G, GI, and Y. The mean values are representative of the first 2 weeks of each month (E) and the last 2 weeks of each month (L) and are shown along with associated standard error bars (Old: G, *n* = 207; GI, *n* = 177; Y, *n* = 69) (New: G, *n* = 53; GI, *n* = 48).

43% in September (*P* = 0.036 and *P* = 0.181), respectively. Likewise, the proportion of ADF increased from 29 and 30% in June to 33 and 34% by September for G and GI foliage (*P* = 0.0007 and *P* = 0.0454), respectively. Y foliage NDF was greater than G foliage with a mean of 42% in June (*P* = 0.0045) and 44% in July (*P* = 0.0394) but was not significantly different from that of GI foliage. The proportion of ADF in Y foliage was also greater than those of G and GI foliage with mean values of 33 and 34% in June and July (*P* = 0.001 and *P* = 0.0003), respectively. The proportion of protein among the crown condition classes was equivalent, but G and GI foliage displayed a significant seasonal increase from 6 and 5% in June to 7 and 6% by September (*P* = 0.0014 and *P* =

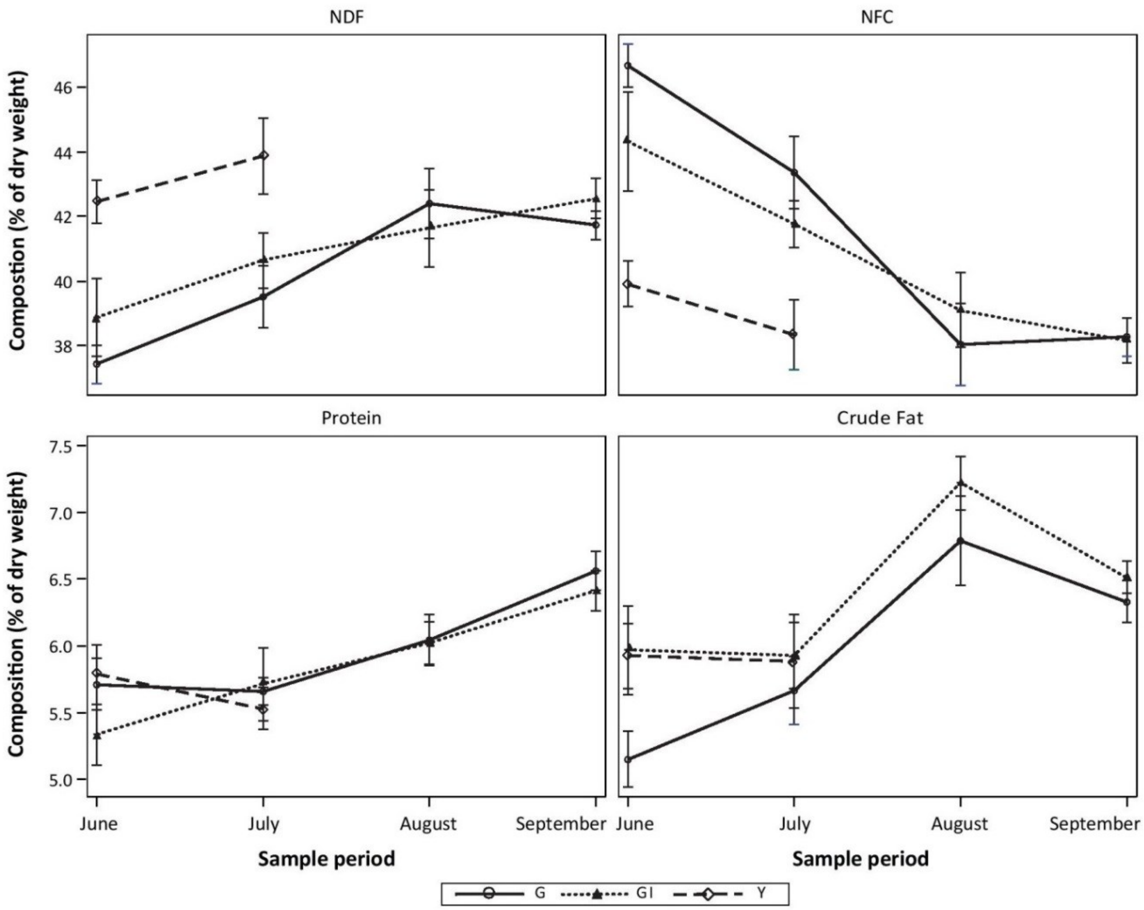

Figure 4.3. The seasonal change in chemical composition (June to September) of Engelmann spruce foliage from G and spruce beetle-attacked trees, either recently attacked (GI) or mass attacked the previous year (Y). The chemical composition variables were the proportion of NDF, NFC, protein, and crude fat content. The mean values are those from the first 2 weeks of each month and are shown along with associated SE bars (G, *n* = 33; GI, *n* = 31; Y, *n* = 15).

0.0004), respectively. The proportion of crude fat also increased for both G and GI foliage from 5 and 6% in June to 6 and 7% by September, but remained equivalent between each other and with Y foliage ($P > 0.10$). The proportion of ash remained equivalent among the crown condition classes and seasonally except for G foliage, which displayed a significant increase from June (5%) to September (7%) ($P < 0.0001$).

The only chemical constituent to decrease through all sampling periods was NFC. The proportion of NFC for G and GI foliage decreased from highs of 47 and 44%, respectively, in June to a low of 38% by September ($P < 0.0001$, $P = 0.0029$). The mean level of NFC between G and GI foliage remained equivalent ($P > 0.10$) for all sampling periods. The proportions of NFC in Y foliage, 40 and 38% for June and July, were significantly lower than the mean proportions for G ($P < 0.0001$) and GI foliage ($P = 0.0047$).

The total within-needle terpene concentrations were highly variable and not significantly different among crown condition classes (Table 4.2). Mean total terpene concentrations for G foliage did display a tendency to increase seasonally with means of 2798 and 4635 ug g^{-1} fresh weight in early July and late September, respectively, but due to the high variability the change was not significant ($P = 0.9702$). The emission rates of volatile terpenes for both G and GI foliage did show a stronger seasonal increase but no difference between crown condition classes (Table 4.2). Total emission rates were at a low in early June for G and GI foliage with mean values of 247 and 274 ng h^{-1} g^{-1} fresh weight but increased to highs of 1289 and 1300 ng h^{-1} g^{-1} fresh weight by late September ($P = 0.1847$, $P = 0.08$). Y foliage volatile terpene emission rates peaked in late June at 1165 ng h^{-1} g^{-1} fresh weight but were not different from G ($P = 0.9236$) or GI ($P = 0.9922$) foliage.

Flammability

There were strong linear associations among the flammability measures. The majority of the variability was accounted for by two principal component axes, cumulatively explaining approximately 66% of the total variability (46% axis 1 and 20%

Table 4.2. Total volatile terpene emission rate and within-needle terpene concentration for all sample periods for each of the crown condition classes. Data are means ± SE. Different letters within a column indicate significant differences, $\alpha < 0.10$. E, first 2 weeks of each month; L, last 2 weeks of each month.

	G		GI		Y	
Date	**Volatiles**	**Within-needle**	**Volatiles**	**Within-needle**	**Volatiles**	**Within-needle**
E-June	247±31.7a	3568±1057.5a	274±31.6a	5668±1326.9a	308±48.1a	2825±1468.6a
L-June	261±66.9ab	3780±1040.9a	523±183.4ab	2389±772.4a	1165±592.1a	3213±1448.0a
E-July	492±108.9ab	2798±959.3a	352±74.4a	4712±1060.5a	576±127.1a	4141±1491.0a
L-July	424±95.7ab	5008±1637.0a	337±148.9ab	2765±770.0a		
E-Aug.	603±251.9ab	3987±1092.4a	492±181.4ab	4674±1239.4a		
L-Aug.	742±104.1b	4423±1289.9a	607±139.5ab	4525±1134.9a		
E-Sep.	609±148.1ab	4104±1260.2a	675±131.5b	3325±899.2a		
L-Sep.	1289±535.1ab	4635±1506.5a	1300±245.5b	3992±1160.8a		

axis 2). Correlations of the first two principal component axis scores with the original flammability variables indicated that axis 1 was strongly related to all flammability measures with higher scores indicating increased flammability, i.e. lower TAI and TTI, and high DOF, $_{max}$TDF, $_{maxrate}$MLR, $_{maxrate}$TDF, $_{prop}$MLDF, and heat yield (Figure 4.4). Axis 2 was not as strongly correlated with the flammability measures and the resulting directions of the correlations were difficult to interpret. High principal component scores on axis 2 indicated high values of TAI, TTI, DOF, $_{max}$TDF, $_{maxrate}$TDF, $_{prop}$MLDF and low values of the $_{maxrate}$MLR and heat yield.

A plot of the principal component scores for axis 1 through time by crown condition class revealed significant seasonal changes as well as differences among crown condition classes (Figure 4.5). On this scale, Y foliage was more flammable than both G

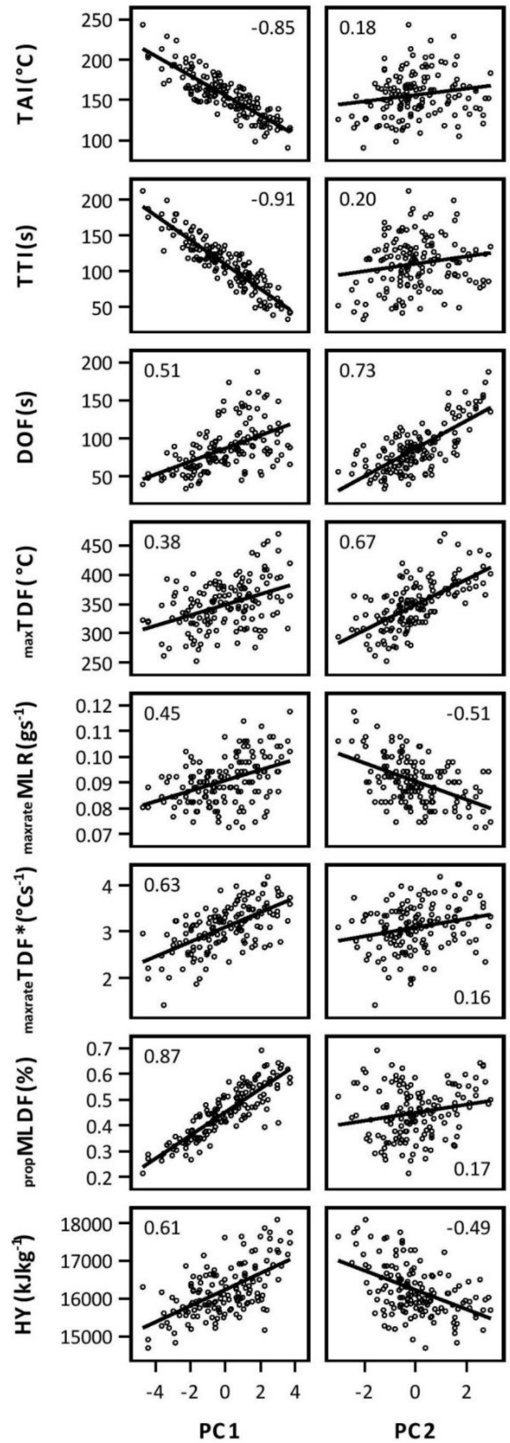

Figure 4.4. Correlations of principal component scores of axis 1 (PC1) and axis 2 (PC2) with the eight measures of flammability from fresh foliage: TAI, TTI, DOF, maxTDF, $_{\text{maxrate}}$MLR, $_{\text{maxrate}}$TDF, $_{\text{prop}}$MLDF, and HY. The appropriate Pearson correlation coefficient is shown in each cell. The lines are the ordinary least squares line of best fit. *, Log transformation (n = 147 for all correlations).

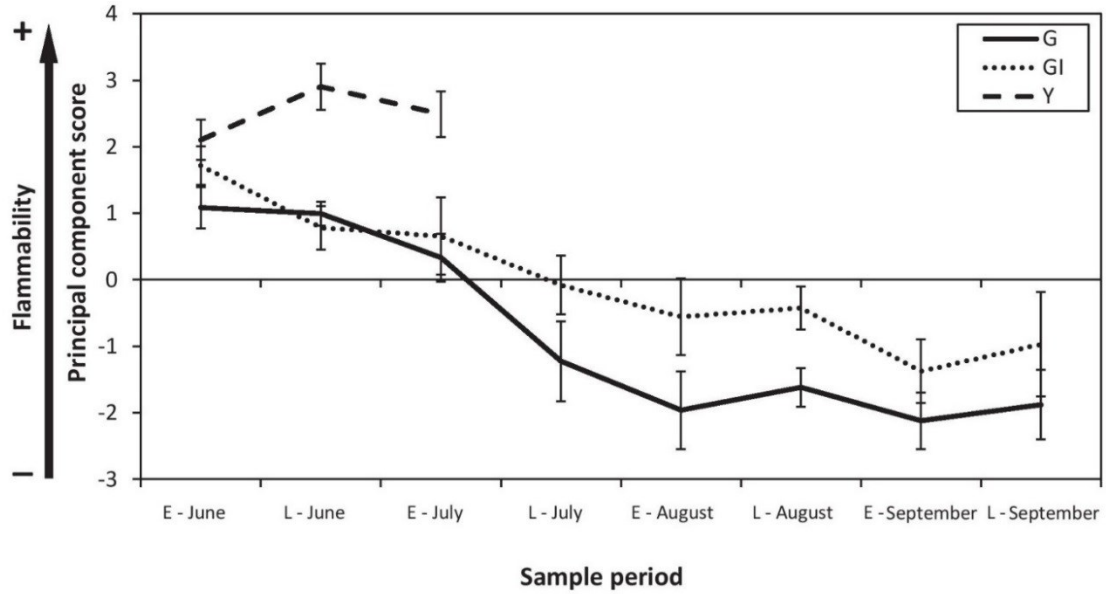

Figure 4.5. Plot of principal component scores through time by crown condition class from axis 1 of the principal component analysis of old foliage flammability. Higher scores indicate higher flammability. The mean values are representative of the first 2 weeks of each month (E) and the last 2 weeks of each month (L) and are shown along with associated SE error bars (G, n = 67; GI, n = 58; Y, n = 22).

($P < 0.0001$) and GI ($P = 0.0013$) foliage with higher scores from late June to early July. The high values were primarily attributed to increases in ignitability as Y foliage displayed significantly lower mean TTI and TAI than G ($P < 0.0001$) or GI ($P = 0.0023$) foliage. The mean TTI for G and GI foliage was 122 s and 105 s respectively, compared to 57 s for Y foliage while the mean TAI for G and GI was 162°C and 151°C, respectively, compared to 123°C for Y. Additionally, Y foliage had significantly higher $_{maxrate}$MLR than G ($P = 0.0039$) and GI ($P = 0.039$) foliage with a mean of 0.10 g s^{-1} compared to a mean of 0.09 g s^{-1} for G and GI foliage.

Green foliage flammability was highest in early June and subsequently decreased reaching a low by early September ($P < 0.0001$). This trend followed observed increases in TTI ($P = 0.0001$) and TAI ($P < 0.0001$), when comparing early June to late September.

The mean TTI of G foliage increased from 88 s in early June to 149 s by late September, likewise, TAI increased from 132°C to 179°C from early June to late September. Significant decreases in the other flammability measures for G foliage were also observed when comparing mean values from early June to late September for DOF, 116 s to 73 s (P = 0.0232), $_{prop}$MLDF, 49 to 34% (P = 0.0066), and $_{maxrate}$TDF, 36.9 °C s^{-1} to 21.3 °C s^{-1} (P = 0.0611). The mean level of flammability for GI foliage was slightly higher than G foliage through the summer but the difference was not significant (P > 0.10). GI foliage followed the same seasonal pattern of decreasing flammability as G foliage when comparing early June to late September due to increases in TTI, 85 s to 139 s (P = 0.0313) and TAI, 124 °C to 181 °C (P = 0.0004) and decreases in $_{prop}$MLDF, 54 to 38% (P = 0.0327) and $_{maxrate}$TDF, 40.5 °C s^{-1} to 20.5 °C s^{-1} (P = 0.0267).

The dependence free residuals from the principal component scores of axis 1 and 2 were significantly related to several variables (Table 4.3). The main flammability axis had a strong negative relationship with FMC, which accounted for the majority of the variability in the final model (74%). Total terpene concentration and the proportion of protein had significant positive relationships with the scores on axis 1, each explaining approximately 12% of the variability in the model. The dependence free residuals of the scores from principal component axis 2 were significantly related to ADF, FMC, crude fat, and total terpene concentration, in descending order of variability explained in the model.

The high heat of combustion values from the bomb calorimeter testing are shown in Figure 4.6. Mean differences among G, GI, and Y foliage were not significant but values for both G and GI foliage displayed significant seasonal increases. For G foliage

Table 4.3. Results of multiple linear regression of the dependence-free residuals of the old foliage principal component scores on axis 1 and 2 with the fuel moisture and chemistry variables using stepwise selection. Estimates of variable coefficients are given along with the SE, *t* values, and the proportion of variability explained by that variable using type I sums of squares (SS). The goodness-of-fit statistics of root mean square error (RMSE) and the adjusted R^2 are also given. The final models included FMC, ADF, protein, crude fat, and total terpene concentration (TC) (n = 76).

Variable	**Estimate**	**S.E.**	**t-value**	**P > t**	**SS (% of total)**	**RMSE**	**Adjusted R^2**
Principal component axis 1 scores						1.04	0.44
Intercept	-0.2	1.2	-0.16	0.8727	1.7		
FMC (% oven-dry weight)	-0.04	0.005	-7.46	<.0001	74.4		
Protein (% of dry weight)	0.5	0.2	2.2	0.0307	11.7		
TC (ng g^{-1} fresh weight)	1.1E-07	3.9E-08	2.77	0.0071	12.3		
Principal component axis 2 scores						1.03	0.22
Intercept	3.9	1.6	2.54	0.0134	0.3		
FMC (% of dry weight)	0.02	0.005	3.17	0.0022	30.9		
ADF (% of dry weight)	-0.1	0.05	-2.09	0.0399	40.7		
Fat (% oven-dry weight)	-0.3	0.2	-2.28	0.0256	16.5		
TC (ng g^{-1} fresh weight)	6.6E-08	3.9E-08	1.71	0.0918	11.5		

the lowest mean value of 19000 kJ kg^{-1} was recorded in early July which subsequently increased to a high of 19620 kJ kg^{-1} by late September (P = 0.0072). The lowest mean heat of combustion for GI foliage was recorded in early June (19062 kJ kg^{-1}) and a high of 19990 kJ kg^{-1} by late September (P = 0.0002). The mean heat of combustion for Y foliage reached a high of 19548 kJ kg^{-1} in late June which was slightly higher than the mean values for G or GI foliage, but the difference was not significant.

Multiple linear regression of the dependence free residuals of high heat of combustion with the chemistry variables indicated that the proportion of ADF, ash, and total terpene concentration were significantly related to the high heat of combustion

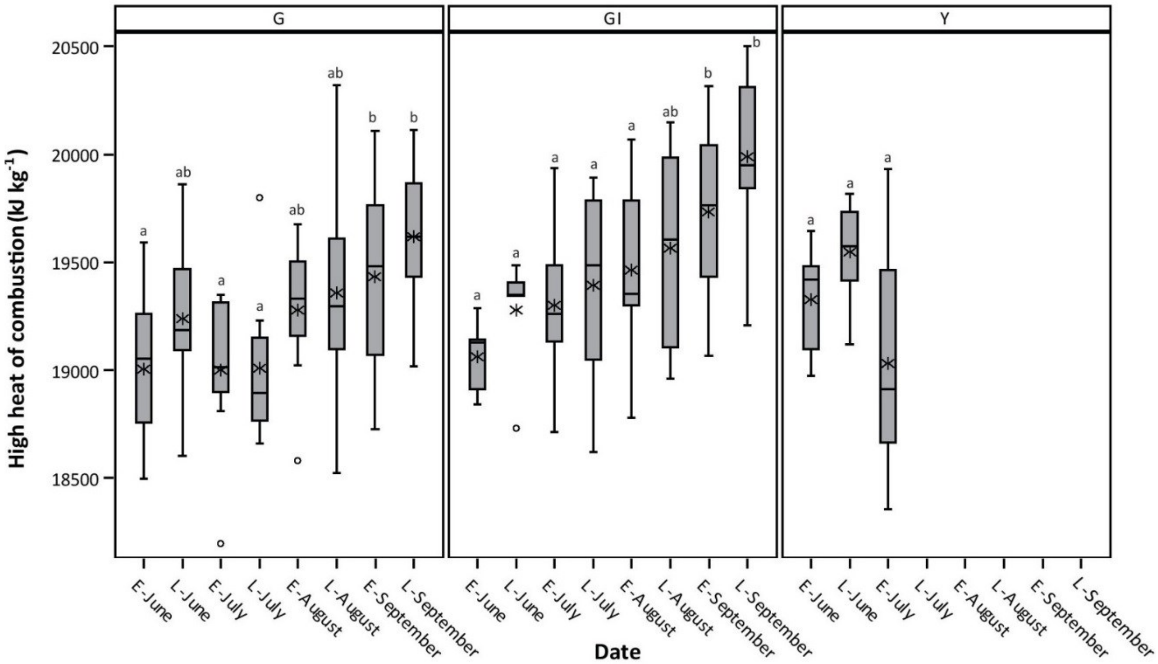

Figure 4.6. Box and whisker plots for the measured high heats of combustion of Engelmann spruce foliage during the fire season from G, GI, and Y trees. The values are representative of the first 2 weeks of each month (E) and the last 2 weeks of each month (L). The mean is the asterisk, the median is the horizontal line, the ends of the boxes are the first and third quartiles, and outliers are more than 1.5 times the interquartile range. Different letters within a crown condition class indicate significant differences, $\alpha < 0.10$ (G, $n = 69$; GI, $n = 59$; Y, $n = 23$).

(Table 4.4). Ash and total terpene concentration explained the highest proportion of variability in the model, 52 and 35%, respectively, while ADF explained the least (9%). Both ADF and total terpene concentration were positively related to high heat of combustion while the proportion of ash had a negative association with high heat of combustion.

Table 4.4. Results of multiple linear regression of the dependence-free residuals of high heat of combustion with the chemistry variables using stepwise selection. Estimates of variable coefficients are given along with the SE, *t* values, and the proportion of variability explained by that variable using type I sums of squares (SS). The goodness-of-fit statistics of root mean square error (RMSE) and the adjusted R^2 are also given. The final model included ADF, ash, and total terpene concentration (TC) (n = 79).

Variable	Estimate	S.E.	t-value	P > t	SS (% of total)	RMSE	Adjusted R^2
Intercept	-513.1	487.4	-1.05	0.2959	3.6	323.2	0.32
ADF (% of dry weight)	34.6	14.6	2.37	0.0202	8.7		
Ash (% of dry weight)	-133.5	34.5	-3.87	0.0002	52.3		
TC (ng g^{-1} fresh weight)	0.00004	0.00001	3.81	0.0003	35.4		

Discussion

Spruce Beetle-Induced Changes to Foliar Moisture and Chemistry

Engelmann spruce trees mass attacked by spruce beetle displayed substantial decreases in FMC with the magnitude of the decrease being dependent on the time since attack. In absolute terms, the FMC of Y foliage was 59% lower than that of G foliage, reaching a low mean value of 24% by early July, which was also the time when the lowest FMC on an individual tree was observed at 7%. This finding is similar to that for Y foliage on lodgepole pine attacked by the mountain pine beetle in Idaho, which had a mean FMC of 24% for the period July through September (see Chapter 3). The changes in FMC in old GI foliage were not as substantial, with the greatest mean absolute difference of 27% observed during early September. This finding contrasts with similar work completed by Jolly et al. (2012), who observed decreases in FMC of old GI foliage from lodgepole pine that had been mass attacked by mountain pine beetle, but is consistent with the work of Page et al. (see Chapter 3), who failed to find a significant drop in FMC of old GI foliage on lodgepole pine. Although the mean FMC of old GI foliage in our study did not substantially decrease, the observed values were highly variable among trees and among samples collected from individual trees. At different periods over the course of the fire season, the FMC collected from various portions of GI tree crowns differed, in absolute terms, by as much as 43%. The extent of larval feeding as influenced by the rate of maturation (Wermelinger and Seifert 1998) and/or the rate of blue stain (*Ophiostoma* spp.) (Krokene and Solheim 1998) development might have accounted for the variability observed as well as microsite factors such as water uptake, competition, and genetic variability. Schmid (1976) observed similar variations in individual tree crowns of recently attacked Engelmann spruce, noting that in otherwise green crowns, clusters of needles died and turned yellowish-green (presuming a decrease in FMC) before dropping to the ground.

The differences in the chemistry of Y foliage followed the expected pattern of lower starches and sugars and higher proportions of lignin, cellulose, and hemicellulose compared with those of unattacked foliage. Both Jolly et al. (2012) and Page et al. (see Chapter 3) observed analogous chemical changes in mountain pine beetle-attacked lodgepole pine foliage, reflecting a shift in composition from the soluble carbohydrate compounds to the structural components of lignin and cellulose. Other work studying the rate of litter decomposition has also shown increased concentrations of lignin as decomposition progresses (Edmonds 1980), which is attributed to the breakdown of the soluble carbohydrates and a decrease in volatile compounds as needles age.

Contrary to our initial expectations, we did not find differences in terpene concentration and emission rate between G and GI foliage. Terpenes are known to have inhibitory effects on bark beetle and blue stain development (Raffa and Smalley 1995, Zhao et al. 2011), indicating that trees use these chemicals as a defense against bark beetle attack (Franceschi et al. 2005). Although other research has documented increases in terpenes in spruce boles after inoculation with blue stain (Zhao et al. 2011), we only found seasonal increases in terpene emission rate and concentration in both G and GI foliage. This finding suggests that increases in terpenes in tree boles caused by bark beetle attack may not manifest into increases in tree foliage.

The rapid loss of foliage on Y trees was initially unexpected. Schmid (1976) reported that the needles of Engelmann spruce in Wyoming remained attached for up to 3 years after attack and displayed a gradual loss over that time period. In this study, the vast majority of needles on Y trees (> 75%) dropped over a 2- to 3-week period about 14 months after the attack, which did not appear to be associated with any single weather event. Massey and Wygant (1954) also reported that the needles of infested Engelmann spruce in Colorado fell after approximately 1 year. In addition, research summarizing needle retention after harvest on spruce slash also suggested that needle longevity on branches was near 1 year (Salazar and Bevins 1984).

Seasonal Changes in Foliar Moisture and Chemistry

The observed seasonal change in FMC of old G foliage corresponded to changes observed in other conifers in North America (Keyes 2006) and Engelmann spruce in New Mexico (Gary 1971). Gary (1971) recorded the lowest FMC in 1-year-old Engelmann spruce foliage in June after bud burst with values ranging between 80 and 90% and the highest value of 130% in September. In this study the lowest and highest mean FMCs were also recorded in early June and early September (76 and 107%, respectively);

however, mean FMCs were generally lower than those reported in Gary (1971). The atypically dry spring and summer conditions that prevailed in the western Uintas at the time of sampling may explain this difference. Combining all of the non-new foliage ages into one class may provide another explanation because older foliage generally has lower FMCs (Hatcher 1990).

As expected, there was a seasonal decrease in the proportion of old G foliage composed of carbohydrates. According to Gary (1971), who observed a decrease in the dry weight of 1-year-old foliage, carbohydrate translocation from reserves in old foliage to new foliage may be the primary cause. Other work has also noted a seasonal change of dry weight in various tree species including balsam fir (*Abies balsamea* L. Mill.) (Little 1970) and other gymnosperms (Kozlowski and Clausen 1965) with most suggesting that the mechanism is the reallocation of carbohydrates during the growing season.

Changes in Flammability

Spruce beetle-affected trees displayed substantial increases in flammability compared with unattacked trees. Old Y foliage was more flammable than either old G or GI foliage, exhibiting increases in foliage ignitability and consumability, due primarily to decreases in FMC. In addition, old GI foliage was slightly more flammable than G foliage, being dependent on the highly variable changes in FMC within individual tree crowns. Besides the anticipated importance of FMC on flammability, we also found that foliar chemistry, particularly the proportions of lignin, cellulose, and extractives (crude fat and terpene concentration) were important predictors of flammability. Carbohydrates and compounds such as crude fat, resins, and waxes are known to play an important role in plant flammability because they are less thermally stable and more volatile and have lower boiling points than the structural compounds of lignin and cellulose (Richards 1940, Philpot and Mutch 1971, Shafizadeh 1971). Plant terpenes have also been suggested to have a significant role in both litter flammability (Ormeño et al. 2009) and at larger scales where they may enhance the potential for explosive fire behavior (Chetehouna et al. 2009). The structural compounds of lignin and cellulose were also found to be more strongly related to high heat of combustion. Rothermel (1976) proposed a model for predicting heat of combustion of forest fuels based on the amount of lignin, cellulose, ether extractives, and ash, which is nearly identical to that for the compounds we identified as significantly related to our heat of combustion values.

Implications for Crown Fire Potential

The interpretation of the changes in FMC, chemistry, and resulting flammability described above suggest periods of increased crown fire potential in recently attacked stands. However, as with any fire behavior assessment, site-specific fuel and weather information is needed to make an accurate fire behavior forecast (Rothermel 1983). Assuming all else equal, there exists the potential that stands containing high proportions of the spruce beetle-altered foliage would be vulnerable to changes in crown fire initiation due to the relatively high ignitability of foliage, particularly during periods when surface fire behavior and/or canopy base height would otherwise limit crown fire development, such as under moderate fire weather or at the beginning or end of the burn period. This increase in crown fire potential, relative to that of stands containing no mortality, may be short-lived and dependent on the relative proportion of trees in each crown condition class. If the majority of attacked trees are in the Y class and mixed with G trees, there would be a substantial but relatively small window of increased crown fire potential during the spring coinciding with minimums of FMC in Y and G foliage. This peak in crown fire potential in the spring has been suggested by others (Van Wagner 1967b) and has been linked to the observed dip in FMC that occurs during this period. The period of increased crown fire potential would last until late July by which time most of the Y foliage would have fallen to the ground, resulting in decreased canopy fuel density and continuity. However, as noted by Schmid (1976), there may be cases when the needles are retained for longer periods of time, which may extend the period of increased crown fire potential. Once the needles do fall, subsequent increases in shrubs and forbs in the understory over the next few years may further decrease crown fire potential (Kulakowski et al. 2003, Jorgensen and Jenkins 2011). Where there are substantial proportions of GI trees or stands with mixtures of crown condition classes, another peak in crown fire potential is likely to occur by September due to decreases in FMC on GI trees coupled with normal seasonal drying of the surface fuels.

The proposed changes in crown fire potential should be considered in the context of where these forests occur. It is well accepted that the intervals between large fires in these forests are long and that extended dry periods are needed for large fires (Arno 1980, Williams and Rothermel 1992). In addition, most research to date has suggested that the long-term impact of spruce beetle-caused tree mortality on fire risk in spruce-fir forests may largely be overestimated (Schmid and Frye 1977, Bebi et al. 2003). In light of this fact, the influence of spruce beetle outbreaks on crown fire potential may not be of great or frequent ecological significance but is important to wildland firefighters in an operational setting. When conditions are suitable for fire spread in these forests, firefighters may be faced with situations in stands with high levels of recent mortality where unexpected transitions to crown fire could occur under more moderate fire weather and into the evening or early morning hours. Rapid and/or unexpected shifts from a surface fire to a crown fire pose potential safety risks to firefighters due to increases in fireline intensity that can, in turn, affect spotting potential and safety zone size (Butler and Cohen 1998, see Chapter 2). The changes might also become more important as large fire frequency increases because of projected increases in temperature and drought in the western United States (Westerling et al. 2006, Intergovernmental Panel on Climate Change 2007, Seager et al. 2007).

Conclusion

Although previous research has demonstrated the importance of FMC, chemistry, and resulting flammability on estimating crown fire potential (e.g., Van Wagner 1977), only recently have attempts have been made to measure these variables in stands recently attacked by bark beetles (Jolly et al. 2012, see Chapter 3). Both Cruz and Alexander (2010) and Jenkins et al. (see Chapter 2) noted the substantial limitations of current models used to predict crown fire initiation in bark beetle-attacked stands and the need for quantifying these changes to make accurate assessments of crown fire potential. Computationally intensive physics-based models that can incorporate spatially explicit heterogeneity in crown fuels will need this information as they become more reliable with continued validation and evaluation (Mell et al. 2009, Alexander and Cruz 2013). The work presented here is an important step to fully understanding the range of potential interactions between bark beetle-caused mortality and subsequent fire behavior. As Hicke et al. (2012) noted, there is currently a gap in our understanding of bark beetle-fire interactions during the early stages of attack. The results provided here will help close that gap and provide important information to fire managers and fire behavior modelers.

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CHAPTER 5

FOLIAR MOISTURE CONTENT VARIATIONS IN LODGEPOLE PINE OVER THE DIURNAL CYCLE DURING THE RED STAGE OF MOUNTAIN PINE BEETLE ATTACK[6]

Abstract

Widespread outbreaks of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in the lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests of North America have produced stands with significant levels of recent tree mortality. The needle foliage from recently attacked trees typically turns red within one to two years of attack indicating successful colonization by the beetle and tree death. Attempts to model crown fire potential in these stands have assumed that the moisture content of dead foliage responds similarly to changes in air temperature and relative humidity as other fine, dead surface fuels. However, this assumption has not been verified. In this exploratory study we sampled the moisture content of dead foliage on an hourly basis through two different diurnal cycles during the fire season and compared the results to measurements of 10-h fuel moisture indicator sticks and predictions made from models used to estimate dead fuel moisture in the USA, Canada, and Australia. The observed degree of variation in dead foliar moisture content was small (6.9–14.5%) with a mean value of ~10%. All existing models performed poorly, but measurements of 10-h fuel moisture and a modified version of an existing model where timelags were extended to ~20-h had the best fit to the data. The results from our study suggest that the dead

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foliage on attacked trees does not respond similarly to changing environmental conditions as other fine, dead surface fuels as has been assumed. This in turn has important implications for wildland fire suppression operations, including firefighter safety, and in modeling fire behavior, and solicits the need for further research.

Introduction

Recent and dramatic increases in the total area and severity of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) caused outbreaks in stands of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) have occurred throughout western North America (Bentz et al., 2010), sometimes producing a sea of "red and dead" trees. Once attacked, individual trees undergo substantial changes in foliar moisture content (FMC), chemistry, and resulting flammability as they progress from green-infested (attacked during the current summer), to yellow (attacked the previous summer), and to red (attacked two or more years previously) (Jolly et al., 2012; see Chapter 3). During this dry down process, both Jolly et al. (2012), in north-central Colorado and western Montana, and Page et al. (see Chapter 3), in far eastern Idaho, showed that successfully attacked trees experience a nearly 10-fold decrease in FMC. This process is similar to the decline in moisture content observed in logging slash following tree harvesting (Kiil, 1968) and to the seasonal changes that occur in grass fuels undergoing a transition from green to fully cured (Mutch, 1967). Once in the red stage, infested tree FMC was found to range from 6 to 32% with a mean of 12% by Jolly et al. (2012) and 9 to 41% with a mean of 13% by Page et al. (see Chapter 3).

Concerns about increases in crown fire potential in recently attacked stands have been raised as a result of the observed increases in flammability caused by the reduction in FMC of infested tree foliage (see Chapter 2). Attempts to assess crown fire potential in MPB-affected lodgepole pine stands (Simard et al., 2011; Hoffman et al., 2012; Schoennagel et al., 2012) through the use of fire behavior modeling systems and simulators have assumed that the dead FMC of recently attacked trees respond similarly to changes in air temperature and relative humidity as other fine, dead surface fuels (Hartford and Rothermel, 1991). However, this assumption has yet to be verified.

The focus of this exploratory study was to examine the variations in dead FMC over the course of the diurnal cycle following the "bottoming out" of dead FMC during the red stage of MPB attack during rainless periods in the Intermountain Region of the western United States. Sample data were collected during the course of two distinctly different diurnal cycles during the early (May) and later portions of the fire season (August) in order to first examine the variations in dead FMC and then use that data to compare to measurements of 10-h fuel moisture indicator sticks and to evaluate models of dead fuel moisture considered suitable for estimating dead FMC.

Material and Methods

Study Area

Sampling was conducted on the Evanston-Mountain View Ranger District of the Uinta-Wasatch-Cache National Forest in north-eastern Utah (40° 57′ 3.7″ N, 110° 29′ 6.4″ W), immediately adjacent to the Hewinta remote automated weather station (RAWS) (Weather Information Management System ID 420705) (Zachariassen et al., 2003). The site is flat (<5% slope) and at an elevation of 2800 m above mean sea level on the north slope of the Uinta Mountains. Vegetation is dominated by extensive stands of mature lodgepole pine which have experienced widespread MPB-caused mortality since the mid-2000s.

The Hewinta RAWS is maintained by the U.S. Forest Service and currently meets the criteria for designation as a year round data collection station with hourly transmissions of precipitation duration and amount, a 10-min average measurement of relative humidity, wind direction and speed (6.1-m height), a 60-min average of solar radiation, and an instantaneous air temperature (National Wildfire Coordinating Group, 2012). The instantaneous and 10-min average readings are taken within 5 and 15 min of the transmission time, respectively. The temperature and moisture of a ponderosa pine (*Pinus ponderosa* Laws.) dowel mounted to the station located approximately 25–30 cm above a representative surface fuelbed are also transmitted instantaneously (National Wildfire Coordinating Group, 2012).

Field Procedures

Hourly collections of dead FMC from red needles of six MPB-attacked lodgepole pine trees were made in 2012 during a 28-h period from May 29 to 30 (period 1) and a 27-h period from August 3 to 4 (period 2). Previous seasonal sampling of dead FMC in red needles of lodgepole pine by Page et al. (see Chapter 3) indicated relatively small variation in moisture content from tree to tree, thus using three different trees each sampling period was deemed adequate for this study.

Weather data from the RAWS station for the years 1984–2012 were used to compare the current level of dryness with historic levels for each sampling period based on four fire danger indexes. These indexes included the Energy Release Component (ERC) from the U.S. National Fire Danger Rating System (NFDRS) (Deeming et al., 1977), the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index System (Van Wagner, 1987), and the Keetch–Byram Drought Index (KBDI) (Keetch and Byram, 1968).

During each sampling period, the three most suitable red trees were selected for sampling based upon (*i*) minimizing the distance from the RAWS Station, and (*ii*) similarity in terms of diameter at breast height (DBH), total tree height, crown base height, and estimated year of attack. All sample trees were located within 200 m of the RAWS and had DBHs of 24.4, 23.4, 41.9, 22.1, 18.5 and 22.4 cm and total tree heights of 15, 13, 15, 16, 12, and 13 m. All trees were judged to have been attacked in 2009 based on characteristics of MPB-attacked trees as described by Safranyik and Carroll (2006). The stand adjacent to the station where sampling took place was open with an estimated basal area of 18–23 m^2 ha^{-1} and 500–800 stems ha^{-1}.

The sampling procedure consisted of the removal of approximately 15–30 g of foliage from the lower third of the crown taken at 10 min past the hour on each tree, every hour, corresponding to the transmission time of the RAWS. It is recognized that the moisture content of the lower crown may not be representative of the entire tree, however, the lower crown FMC is the most important in terms of crown fire initiation and thus the focus of our sampling. Each sample was immediately weighed to the nearest 0.01 g in the field to obtain a fresh or wet weight and placed in a bag and labeled for transport back to the laboratory.

In total 84 samples were collected during sampling period 1 and 81 samples during period 2. Five samples were excluded due to illegible wet weight observations recorded in the field. In the laboratory, samples were placed in a forced air-drying oven for 24 h at a temperature of 105 °C (Matthews, 2010). The samples were then removed from the oven and reweighed to obtain the dry weight which was used to compute dead FMC as a percentage of the oven-dry weight.

Performance of Dead Fuel Moisture Models

The sampled dead FMCs were compared to predicted values of dead fuel moisture using the following mathematical models: (*i*) the 1-h and 10-h timelag[7] fuel moisture of the NFDRS (Deeming et al., 1977; Bradshaw et al., 1984); (*ii*) the NFDRS adapted Nelson (2000) model for 1-h and 10-h timelag fuel moisture; (*iii*) the hourly Fine Fuel Moisture Code (FFMC) model (Van Wagner, 1977a) of the Accessory Fuel Moisture System of the Canadian Forest Fire Danger Rating System (Stocks et al., 1989); (*iv*) the fine dead fuel moisture look-up table procedures presented by Rothermel (1983); (*v*) the AERIAL model of Pook (1993) for suspended dead needles of radiata pine (*Pinus radiata* D. Don) in Australia; and (*vi*) a simple index of fine fuel moisture content devised by Sharples et al. (2009) using a scaling factor of $\alpha = 0.5312$ taken from Sharples and McRae (2011).

A modified NFDRS model was also evaluated using the adsorption and desorption timelag values for recently cast lodgepole pine needles, 34.43 h and 20.75 h respectively, from Anderson (1985), which were used to modify the NFDRS fine fuel moisture content equations provided by Bradshaw et al. (1984). Additionally, the equilibrium moisture content (EMC) regression equations provided by Anderson (1990a)

[7] The concept of timelag is defined to be the amount of time required for a fuel particle to lose approximately two-thirds of its initial moisture content. Whereas the equilibrium moisture content (EMC) is the moisture content a dead fuel particle would obtain in constant environmental conditions when there is no longer a net moisture exchange (Bradshaw et al., 1984).

for recently cast ponderosa pine needles were substituted for the original EMC equations used by Bradshaw et al. (1984). Weather observations from the five days prior to each sampling period were used to initialize the modified model with a starting fuel moisture of 10%.

To evaluate model performance, four deviation statistics were calculated based on recommendations of Fox (1981) and Willmott (1982). These were the root mean square error (RMSE), mean absolute error (MAE), mean absolute percent error (MAPE), and mean bias error (MBE). RMSE and MAE describe the average error and are often considered better measures of model performance because RMSE is in the same units as the original data and MAE is less sensitive to extreme values. MAPE calculates overall fit using the average of the sum of the absolute values expressed as a percentage while MBE is the average sum of the difference between the predicted and observed values which allows interpretation of the direction of average bias. The R software package was used for all statistical analysis (R Development Core Team, 2011).

Results

Observed Dead Foliar Moisture Contents

The weather conditions at the site during both sampling periods were fair and dry compared to historical averages (Table 5.1). Both sampling periods had been rain-free for two days prior to sampling with the last recorded 24-h rainfall of 0.5 mm and 2.0 mm for sampling period 1 and 2, respectively. Sampling periods 1 and 2 had ERCs and KBDIs that were above the historical average with the ERC on August 4 at the 90th percentile for that date. The ranges in hourly weather observations were typical for the high elevation site during the early and middle portions of the fire season (Table 5.2).

Table 5.1. Measures of long term dryness for the site for each of the sampling days. All values were calculated based on historical data from the Hewinta RAWS. Measures of dryness included the Energy Release Component (ERC) from the National Fire Danger Rating System, the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index System, and the Keetch-Byram Drought Index (KBDI). The means, standard errors, and 90th percentiles were based on the historical weather for that day from the period 1984 to 2012. Not all days had the same number of observations; May 29 (20 years of data), May 30 (19 years of data), August 3 and 4 (26 years of data).

Date (2012)	ERC Obs	ERC Mean ±S.E.	ERC 90th	DMC Obs	DMC Mean ±S.E.	DMC 90th	DC Obs	DC Mean± S.E.	DC 90th	KBDI Obs	KBDI Mean ±S.E.	KBDI 90th
May 29	49	40±2.4	54	55	30±4	57	215	338±38	573	87	14±3	38
May 30	51	40±2.6	55	58	29±4	59	220	327±39	579	88	14±3	43
August 3	54	40±2.8	60	44	41±5	81	474	389±45	734	87	62±10	129
August 4	56	40±2.7	56	48	38±5	69	481	389±45	736	90	59±10	128

Note: Obs, observed value; S.E., standard error; 90th, 90th percentile.

Table 5.2. Range in observational data obtained from the Hewinta RAWS over the course of two diurnal sampling periods during the 2012 fire season.

Measure	Units	May 29-30	August 3-4
Air temperature	°C	-1.7 – 15.6	1.1 – 23.3
Relative humidity	%	18 – 74	10 – 71
Solar radiation	W m^{-2}	0 – 1170	0 – 1194
10-h timelag fuel temperature	°C	-3.3 – 26.1	-1.1 – 34.4
Dew point temperature	°C	-9.6 – -1.5	-13.9 – 1.1

Sampling period 1 had lower air temperatures and higher relative humidities compared to period 2, while period 2 had the lowest observed relative humidity of 10% on August 3.

The hourly data for dead FMC of red needles and the corresponding observations of air temperature, relative humidity, and solar radiation for both sample periods are shown in Fig. 5.1. The dead FMC displayed little variability in response to changes in

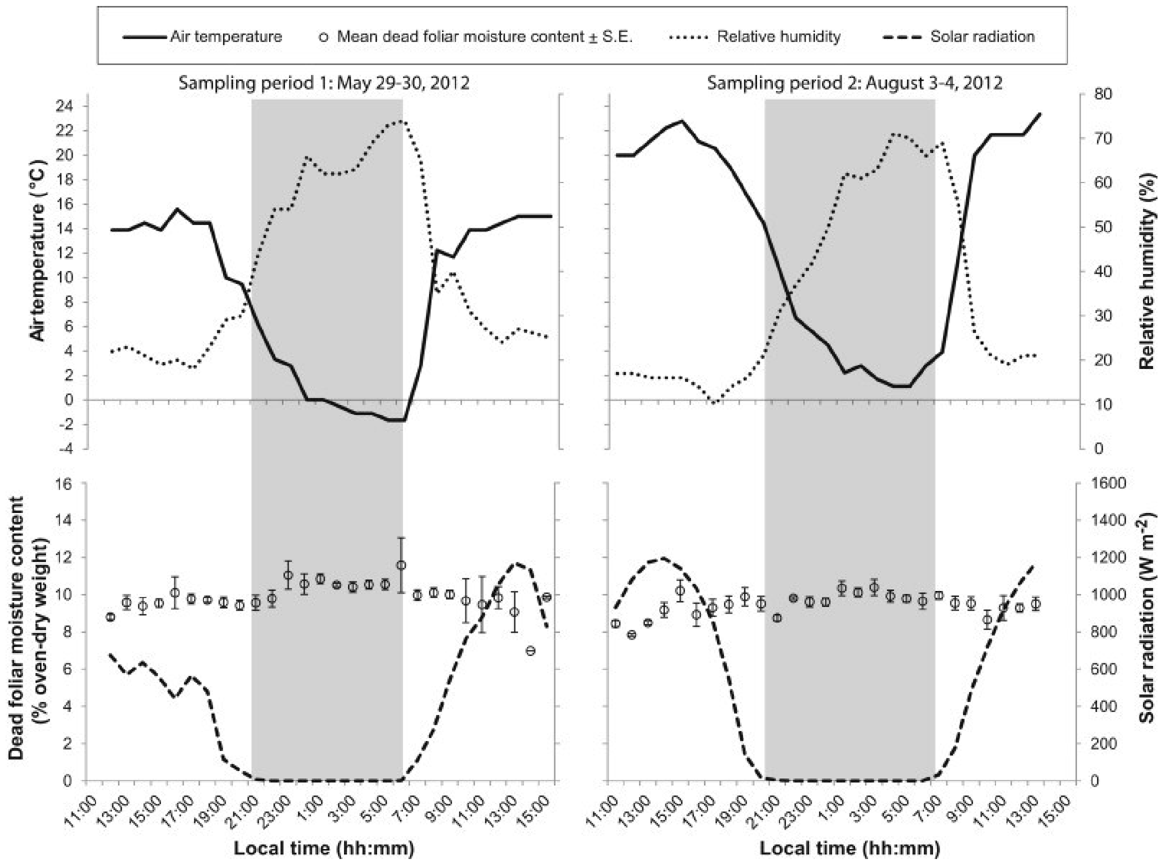

Fig. 5.1. Diurnal changes in weather conditions and in dead foliar moisture content of red needles on mountain pine beetle attacked lodgepole pine trees during both sampling periods in May and August, 2012. The shaded area signifies the night-time period.

relative humidity with observed dead FMCs ranging from 6.9 to 14.5% with the majority of observations occurring near the mean dead FMC of 9.7% (standard error 0.08%).

Evaluation of Dead Fuel Moisture Models

All existing models generally did a poor job of predicting the dead FMC of red needles throughout the diurnal cycle for both sampling periods (Table 5.3). The dead fuel moisture models under predicted dead FMC during the day and over predicted at night (Fig. 5.2). The modified NFDRS model had the best fit of the data in terms of

Table 5.3. Summary of statistics associated with the comparison of predicted fine dead fuel moistures versus observed dead foliar moisture contents of red needles on mountain pine beetle attacked lodgepole pine trees. The deviation statistics are root mean square error (RMSE), mean absolute error (MAE), mean absolute percent error (MAPE), and mean bias error (MBE).

Model	Mean	Range	RMSE	MAE	MAPE (%)	MBE
NFDRS, 1-h timelag	5.8	2.0-11.0	4.61	4.0	41.6	-3.88
Nelson (2000), 1-h timelag	10.2	3.9-17.7	4.15	3.6	37.1	0.46
Van Wagner (1977*a*)	11.2	4.7-19.8	4.64	3.7	37.7	1.53
Rothermel (1983)	8.5	3.0-15.0	3.45	3.0	31.1	-1.25
Pook (1993)	13.5	7.0-22.0	6.01	4.5	45.3	3.76
Sharples et al. (2009)	8.9	3.9-15.4	3.47	3.1	32.4	-0.77
NFDRS modified	10.0	7.8-11.7	1.34	1.8	11.4	0.31
RAWS, 10-h timelag fuel moisture indicator stick	10.0	7.0-13.0	1.58	1.3	28.4	0.02
NFDRS, 10-h timelag	6.2	2.0-10.0	4.09	3.6	76.5	-7.53
Nelson (2000), 10-h timelag	7.0	4.4-9.3	3.04	2.7	58.0	-5.80

Note: All units except MAPE are percent of oven-dry weight.

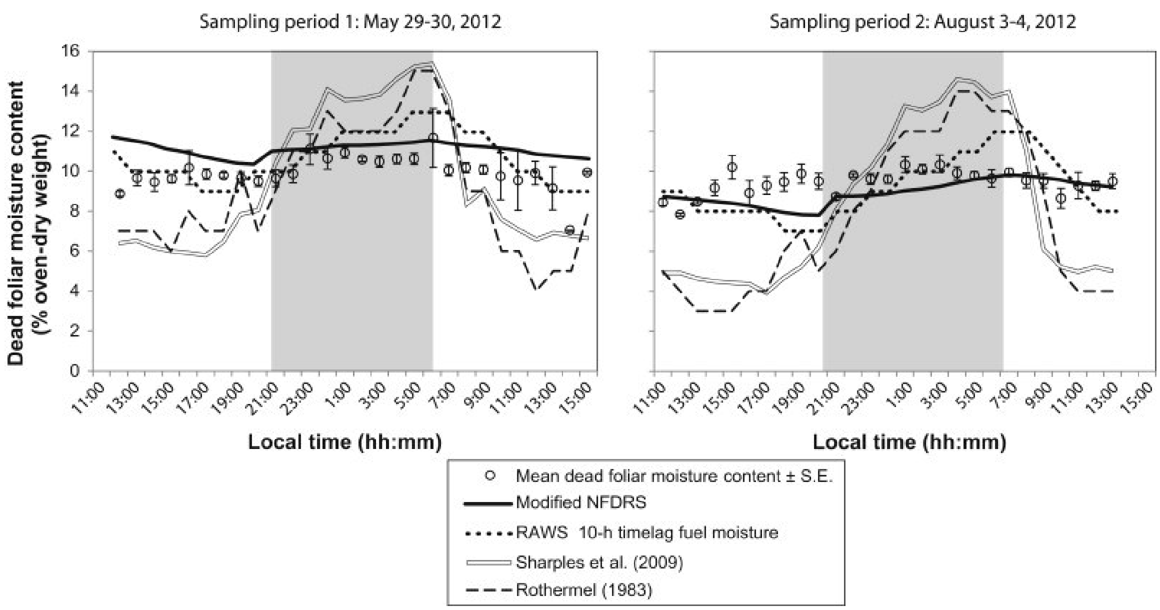

Fig. 5.2. Plots of the observed dead foliar moisture contents of red needles on mountain pine beetle attacked lodgepole pine trees during the red stage with the predicted values from the National Fire Danger Rating System (Bradshaw et al., 1984) modified model, the Rothermel (1983) lookup tables, the Sharples et al. (2009) model, and the 10-h timelag fuel moisture indicator stick for both sampling periods. The shaded area signifies the night-time period.

MAE and MAPE with an overall over prediction bias while the measured 10-h timelag fuel moisture values were the best fit in terms of RMSE, also having a slight over prediction bias (Table 5.3). The modified NFDRS model had an over prediction bias during period 1 and under prediction bias during period 2 (Fig. 5.2).

Discussion and Conclusions

The small degree of variation observed in dead FMC over relatively wide ranges in air temperature and relative humidity was unexpected. Based on logical reasoning, previous attempts to model crown fire potential in recently attacked stands assumed that the FMC of red needles on attacked trees would be similar to the moisture content of other fine, dead surface fuels. However, it is now clear from the data reported here that this assumption is not valid. Due to the lack of variation observed, the dead fuel moisture models evaluated in this study did a poor job of predicting dead FMC because they were built on the assumption of timelags close to one hour. Inspection of the existing literature revealed that timelags of needles from many of the conifers found in the western United States can vary substantially from one hour and can be in excess of 20 h when recently cast (Anderson, 1985) due to their low moisture diffusivities (Anderson, 1990b).

The modification of an existing NFDRS fine fuel moisture model, as recommended by Anderson (1985), improved model accuracy, which suggests that the timelags associated with drying of red stage needles may be quite long, assuming that the needles follow an exponential drying function. Measurements of the 10-h timelag fuel moisture indicator stick also showed promise for being able to estimate dead FMC, but this requires measurements from a RAWS station or the placement of temporary fuel moisture indicator sticks in the field that then must be manually weighed, which may not always be possible.

An understanding of the daily, diurnal FMC pattern found in red needles of MPB-attacked trees is necessary to insure safe and effective fire suppression operations. Although existing models of crown fire initiation or rate of spread (e.g. Van Wagner, 1977b) may not be sensitive enough to distinguish significant changes in fire behavior in relation to the diurnal changes in dead FMC found in this study it is important that wildland firefighters and fire behavior modelers are aware of this lack of variation. Fire suppression operations personnel should not expect to see large increases in dead FMC during typical night-time recovery in relative humidity (Countryman, 1971). The low dead FMCs observed throughout the day and night and their influence on ignitability (Jolly et al., 2012; see Chapter 3) would suggest that wider windows of potential torching and crowning activity are possible than would otherwise be expected.

Spotting potential into red tree crowns, which has been noted as a significant issue during fire suppression operations (Stiger and Infanger, 2011), is also affected by the lack of variability in dead FMC. To aid in estimating the potential of spotting into red tree crowns a probability of ignition (POI) table was released in late July 2012 (Hoyt and Jolly, 2012) for use with the National Wildfire Coordinating Group (2010) incident pocket response guide (IRPG). The POI table indicates that the FMC of green-attacked and red needle foliage can be estimated using the fine dead fuel moisture tables given in Rothermel (1983). The results of the present study suggest that the dead FMC of lodgepole pine in the red stage of MPB attack cannot be reliably estimated by this means, thus making the use of the POI table questionable.

Further field sampling of dead FMC over the course of other diurnal cycles is needed in order to further test the existing fuel moisture models for their applicability and with a view to developing a more robust model. This would include sampling under moister conditions (i.e. relative humidities closer to 100% for extended periods of time) and during warmer and drier atmospheric conditions than captured to date.

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CHAPTER 6

MODELS TO PREDICT THE MOISTURE CONTENT OF LODGEPOLE PINE FOLIAGE DURING THE RED STAGE OF MOUNTAIN PINE BEETLE ATTACK[8]

Abstract

Models were developed and evaluated to predict the moisture content of dead needle foliage of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) trees during the red stage of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) attack. Data for model development was obtained from hourly measurements of moisture content during four 25-h periods spread across the 2013 fire season at a site in southeastern Wyoming, USA. Calibrated models for two popular operational fine fuel moisture models are presented as well as more complicated bookkeeping-system type models derived from diffusion theory. The models were evaluated against two data sets; one from measurements made in northeastern Utah, USA, and another in British Columbia, Canada. All models generally performed well when compared to the data from northeastern Utah, but did not perform as well when compared to the dataset from British Columbia. The calibrated operational fine fuel moisture models appear to be nearly as accurate or more accurate than the more complicated bookkeeping-system type models and are recommended for field use.

[8] This chapter is co-authored with M.J. Jenkins and M.E. Alexander.

Introduction

Extensive tree mortality caused by recent attacks of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) in lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) forests has prompted debate within the research community as to the importance of dead foliage and its low moisture content on crown fire potential (Simard et al. 2011, Jolly et al. 2012a, Moran and Cochrane 2012). Based on the data collected by Simard et al. (2011), Moran and Cochrane (2012) proposed that the low moisture contents in the crowns of dead trees could have considerable impact on crown fire rate of spread through a foliar moisture effect, as originally proposed by Van Wagner (1989). Additionally, both Jolly et al. (2012b) and Page et al. (see Chapter 3) suggested that the low moisture contents in dead crowns could be important in prompting crown fire initiation due to its effect on foliage ignitibility. The magnitude of the effects, if any, could be highly dependent upon the moisture content of the dead foliage and the spatial arrangement of mortality, with the effects possibly strong enough to overwhelm losses in canopy fuel load and continuity (Moran and Cochrane 2012).

Alexander and Cruz (2013) recently reviewed the literature on the effect of foliar moisture content on the rate of spread of crown fires and concluded that the model function proposed by Van Wagner (1989) would overestimate rate of spread at the low moisture contents observed in MPB attacked trees during the red stage, but that an increase in rate of spread on the order of two to three times the no morality case was still possible. While seasonal estimates of the changes in the moisture content of the foliage on recently attacked trees are available (Jolly et al. 2012b, see Chapter 3), a model for predicting the short-term (i.e. hourly) changes in moisture content of the tree foliage during the red stage of MPB attack is lacking. Thus, in order to improve the validity of crown fire potential assessments in lodgepole pine forests recently attacked by the MPB, a model capable of predicting dead foliar moisture content is needed.

Previous work has shown that the moisture content of dead lodgepole pine foliage during the red stage of MPB attack does not follow the typical diurnal variation found in similar fine dead forest fuels (< 0.64 cm in diameter) and that common models of fine fuel moisture do not give accurate predictions (see Chapter 5). Page et al. (see Chapter 5) suggested that the dead foliage may have long timelags which would account for the lack of diurnal variation, as suggested by Anderson (1985). However, the data presented by Page et al. (see Chapter 5) were limited to only dry periods over two diurnal cycles and did not verify that during drying under laboratory conditions the change in moisture content follows the typical exponential decrease seen in other fine forest fuels. Diurnal variation in moisture content has also been investigated in live fuels of ponderosa pine (*P. ponderosa* C. Lawson) in central California (Philpot 1965), pinyon pine (*P. edulis* Engelm.) and various junipers (*Juniperus* spp.) in central Arizona (Jameson 1966), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) in northern New Mexico (Gary 1971). The change in moisture content in these conifers from the peak in the morning to the low point during the afternoon was generally less than 10% of the total needle moisture content and most likely related to physiological changes in the plant during periods of water uptake and loss (Jameson 1966). In fact, in some studies, live fuel moisture contents were seen to increase during the afternoon hours (e.g. Jameson 1966).

In order to provide fire managers a way to reliably and accurately predict the moisture content of the dead needle foliage on lodgepole pine trees this study was undertaken, which expands upon the work of Page et al. (see Chapter 5). Specifically, the primary objectives of this study were to (1) develop and test models capable of predicting the moisture content of dead needle foliage on lodgepole pine trees during the red stage of MPB attack and (2) verify that the dead needle foliage on lodgepole pine follows an exponential decrease during moisture loss under laboratory conditions to confirm the adequacy of models that utilize diffusion theory (Byram 1963).

Description of Models

Two models often used to predict the moisture content of fine, dead fuels by fire managers include the tables produced by Rothermel (1983) and the Fine Fuel Moisture Code (FFMC) component of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). The tables presented by Rothermel (1983) incorporate the effect of time of year, slope, aspect, and shading on the moisture content of fine fuels using mostly unpublished work by U.S. Forest Service fire research (Viney 1991). The FFMC was developed based on empirical correlations obtained from experimental data from lodgepole and jack (*P. banksiana* Lamb.) pine litter for mid-afternoon conditions using air temperature, relative humidity, wind speed, rainfall, and the previous day's observation (Van Wagner 1987). The FFMC has also been adapted to give hourly predictions (Van Wagner 1977). Previous work has shown that these two models fail to accurately predict the moisture content of lodgepole pine foliage during the red stage of MPB attack, with over- and under- prediction biases during periods of high and low atmospheric moisture, respectively (see Chapter 5). However, calibrated operational models using regression techniques, such as done by Wotton and Beverly (2007), have shown promise in their ability to provide useful and accurate predictions for unique fuel conditions.

Anderson (1985) described changes in the moisture content of fine dead fuels during desorption and adsorption conditions obtained from laboratory testing and in turn reported the resulting timelags (i.e. the time required for a fuel particle to lose 63.2% of its evaporable water content). He found that desorption and adsorption timelag values for recently cast lodgepole pine litter ranged, respectively, from 20.28 to 24.22 h and 25.28 to 37.13 h. Anderson (1985) also speculated on the resulting effect of the long timelags on the diurnal changes in moisture content using a modification of the National Fire Danger Rating System (NFDRS) fine fuel moisture content equation as given by Bradshaw et al. (1984):

$$m_t = m_{t-1} + (EMC - m_{t-1})\left(1 - \delta\left(\exp\left(-\frac{t}{\tau}\right)\right)\right), \tag{6.1}$$

where m_t is the moisture content (% oven-dry weight) at time t, EMC is the equilibrium moisture content (% oven-dry weight), δ is a dimensionless similarity coefficient assumed to equal 1, t is the time interval (h), and τ is the timelag (h). Page et al. (see Chapter 5) found that the predictions made using eq. 6.1 with modifications to the EMC based on the equations developed by Anderson (1990), fit the observed dead foliar moisture contents found on lodgepole pine trees quite well. According to Anderson (1990), EMC can be calculated as follows:

$$EMC = MC_v\left(1 - \frac{\ln(\Delta G)}{\ln(\Delta G_0)}\right)100, \tag{6.2}$$

where, EMC is the equilibrium moisture content (% oven-dry weight), $MC_v = -\frac{A}{B}$, $\Delta G = -\left(\frac{RT}{M}\right)\ln\left(\frac{H}{100}\right)$, $\Delta G_0 = A$, T is air temperature (K), H is relative humidity (%), R

is the universal gas constant (1.987 cal mol^{-1} K^{-1}), and M is the molecular weight of water (18.015 g mol^{-1}). The following regression estimates were obtained for recently cast ponderosa pine (*P. ponderosa* Lawson & C. Lawson) needles (from Anderson 1990):

$$A(\text{adsorption}) = 26.3 - 0.15758(T) + 0.0002883(T^2), \tag{6.3}$$

$$B(\text{adsorption}) = -1081.46 + 7.43318(T) - 0.0129658(T^2), \tag{6.4}$$

$$A(\text{desorption}) = 51.842 - 0.30298(T) + 0.0004933(T^2), \tag{6.5}$$

$$B(\text{desorption}) = -1000.25 + 6.7543(T) - 0.0116198(T^2), \tag{6.6}$$

Catchpole et al. (2001) used a different methodology to estimate EMC and timelag from field data based upon the governing differential equation for the diffusion of water vapor from the fuel and the semi-physical formulation of EMC by Nelson (1984). Using a centered piecewise approximation of the differential equation of the diffusion equation, Catchpole et al. (2001) suggested the following can be used to estimate moisture content:

$$m_t = \left(\exp\frac{-\delta t}{2\tau}\right)^2 m_{t-1} + \left(\exp\frac{-\delta t}{2\tau}\right)\left(1 - \left(\exp\frac{-\delta t}{2\tau}\right)\right) q_{t-1} + (1 - \left(\exp\frac{-\delta t}{2\tau}\right) q_t, \tag{6.7}$$

where m_t is the moisture content (% oven-dry weight) and time t, $\delta t = t_i - t_{i-1}$ (sampling interval), τ is the timelag (h), and q_t is the EMC at time t. Nelson's (1984) model of EMC is:

$$q = a + b \ln\left\{-\frac{RT}{M}\ln\left(\frac{H}{100}\right)\right\}, \tag{6.8}$$

where q is the EMC (% oven-dry weight), R is the universal gas constant (1.987 cal mol^{-1} K^{-1}), T is air temperature (K), M is the molecular weight of water (18.015 g mol^{-1}), H is the relative humidity (%), and a and b are constants. The model does not distinguish between desorption and adsorption conditions and it is assumed that the air temperature is equivalent to the fuel temperature, which has been assumed in the modelling of moisture content in other elevated fuels (e.g. Matthews and McCaw 2006). Catchpole et al. (2001) used non-linear regression techniques to estimate values for τ, a, and b based on field data collected from mallee shrubland and buttongrass moorland in Australia and found that the fitted values corresponded well to estimates obtained in the laboratory.

Methods

Study Site

Field sampling of lodgepole pine foliage during the red stage of MPB attack was conducted on the Laramie Ranger District of the Medicine Bow-Routt National Forest in southeastern Wyoming (41° 4' 26" N, 106° 7' 54" W) during the summer of 2013. The study site was located adjacent to the Saw Mill Park Remote Automated Weather Station (RAWS) (Weather Information Management System ID 482105) in the Snowy Mountains at an elevation of 2767 m. The site was comprised of a stand dominated by mature lodgepole pine recently affected by MPB with a basal area and stand density ranging between 20 to 30 m^2 ha^{-1} and 600 to 800 trees ha^{-1}, respectively.

The Saw Mill Park RAWS is designated a year-round NFDRS data collection station with hourly transmissions (52 minutes past the hour) of precipitation duration and amount, a 10-min average measurement of relative humidity, wind direction and speed (at a 6.1-m open height), a 60-min average of solar radiation, and an instantaneous air temperature (National Wildfire Coordinating Group 2012).

Field Procedures

In total, 12 MPB-attacked lodgepole pine trees, 3 trees each period, were sampled hourly over the course of the summer during four different 25-h periods. Sampling periods were spread throughout the main portion of the fire season as follows: June 3-4 (Period 1), July 1-2 (Period 2), August 5-6 (Period 3), and August 31-September 1 (Period 4). Sample trees were selected based on (1) minimizing the distance from the RAWS, (2) adequacy of lower crown to facilitate repeated sampling, and (3) similarity of size and estimated year of attack. All sample trees were estimated to have been attacked in 2011 with a mean (± standard error [SE]) diameter at breast height of 25.4 (±2.8) cm and tree height of 10.8 (±1.0) m and were located within 305 m of the RAWS.

Every hour at the RAWS transmission time, approximately 5 to 20 g of dead needle foliage was removed from the lower third of the crown (1-2 m height) on each sample tree, immediately weighed to the nearest 0.01 g, and placed in a bag for transport back to the laboratory. Needle foliage samples were then dried in a forced air-drying oven for 24-h at a temperature of 105°C and reweighed to obtain a dry weight. Dead foliar moisture content was calculated as a percentage of the oven-dry weight. These sampling procedures were followed during all four periods with the following exceptions. During Period 3, nine samples were discarded as a result of the rainfall that occurred during the time of sampling. During Period 1, the moisture content of dead foliage was also sampled at a height of 5 m on each sample tree every 2 h during the daylight hours to evaluate differences in moisture content between the two heights. Repeated measures analysis of variance with a compound symmetry covariance structure and time and sample type as fixed effects were used to assess differences between the mean moisture contents of dead needle foliage at the two heights (i.e. 1-2 and 5 m).

Laboratory Timelag

Assessment of the desorption timelags of three needle foliage samples collected during Period 4 began with oven-drying the samples for 24-h at 105°C to obtain oven-dry weights and subsequently submerging the samples in water for 24-h. The wetted samples were then drained and placed in 8.5 cm diameter tins located in a temperature and humidity controlled room with a mean temperature of 22.2°C and relative humidity of 51.4%. The mean initial moisture content and EMC were 103.6% and 12.2% respectively. The samples were periodically weighed until moisture loss no longer occurred, which took approximately 25-h. First period timelag (63.2% loss in moisture) was taken to be the inverse of the decay coefficient in the equation:

$$\gamma = \gamma_0 e^{-\lambda t}, \tag{6.9}$$

where γ is relative moisture content, γ_0 is the initial relative moisture content, λ is the decay coefficient, and t is the drying time (Fosberg 1970). The NLIN procedure in SAS (SAS Institute, Inc. 2010) was used to estimate λ based on the collected data. Approximately 1.9 g of oven-dry material was used in each sample equating to a mean loading of 0.33 kg m^{-2} and a fuel-load parameter of 3.8, which is assumed to more closely represent a drying rate controlled by individual particles rather than fuelbed structure -- i.e. the fuel-load parameter was < 4 (Nelson and Hiers 2008).

Model Building

Linear regression was used to fit models capable of predicting dead foliar moisture content using the collected data. Specifically, fine dead fuel moisture values obtained from Rothermel's (1983) tables and the hourly FFMC (Van Wagner 1977) were regressed against the observed dead foliar moisture contents (dependent variable) to obtain calibrated or corrected models predicting dead foliar moisture content using the REG procedure in SAS.

In addition to the calibrated operational models, three bookkeeping-system type models were used to predict dead foliar moisture content. The modification of the NFDRS fine fuel moisture and EMC equations as recommended by Anderson (1985, 1990) were used with both the recently cast lodgepole pine litter desorption and adsorption mean timelags of 20.75 and 34.43 h, respectively, and the mean timelag from the laboratory timelag study. Additionally, the methods proposed by Catchpole et al. (2001) were used to estimate the *a* and *b* constants in eq. 6.8 using the MODEL procedure in SAS with the timelag set to the mean timelag obtained in the laboratory timelag analysis.

Model Evaluation

Evaluation of the five proposed models was undertaken using the data collected in this study and two datasets described by Armitage (2004) and Page et al. (see Chapter 5). Specifically, the hourly measurements from Page et al. (see Chapter 5) (n = 160) from a site in northeastern Utah and hourly measurements from a site in central British Columbia reported by Armitage (2004) (n = 17) were compared to predictions made using each of the proposed models. For each of the three bookkeeping-system type models, the previous five days of air temperature and relative humidity observations were used to initialize the model. Four deviation statistics were calculated for all comparisons with observed data, root mean square error (RMSE), mean absolute error (MAE), percent mean absolute error (PMAE), and mean bias error (MBE) (Fox 1981, Willmott 1982).

Results

Observed Dead Foliar Moisture Contents

Observed dead foliar moisture contents across all four periods ranged from 8.4 to 32% with a mean (±SE) of 13.0% (±0.19) (Figure 6.1). Mean moisture contents increased through the summer, starting from 10.4% (Period 1), 11.7% (Period 2), 15.0% (Period 3), and 15.2% (Period 4). Measures of long term dryness and fire danger tended to decrease through the summer (Table 6.1). The observed Energy Release Component (ERC) of the NFDRS (Deeming et al. 1977), the Duff Moisture Code (DMC) component of the FWI system (Van Wagner 1987), and the Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968) decreased, most likely as a result of increasing amounts of rainfall recorded at the study site (160 mm from June 1 to September 1) generally concentrated in the months of July and August. Compared to historical data (1988-2012) for the study site, the observed 2013 measures of long term dryness and fire danger started either near or above mean levels (drier than average) but dropped to well below average by sampling Periods 3 and 4.

Comparisons of the mean dead foliar moisture contents at 1-2 and 5 m heights on the sample trees indicated no significant differences (F = 2.37, P = 0.1982). The mean (±SE) moisture contents across all sample times were 10.1% (±0.21) at the lower crown and 9.7% (±0.20) at 5 m height.

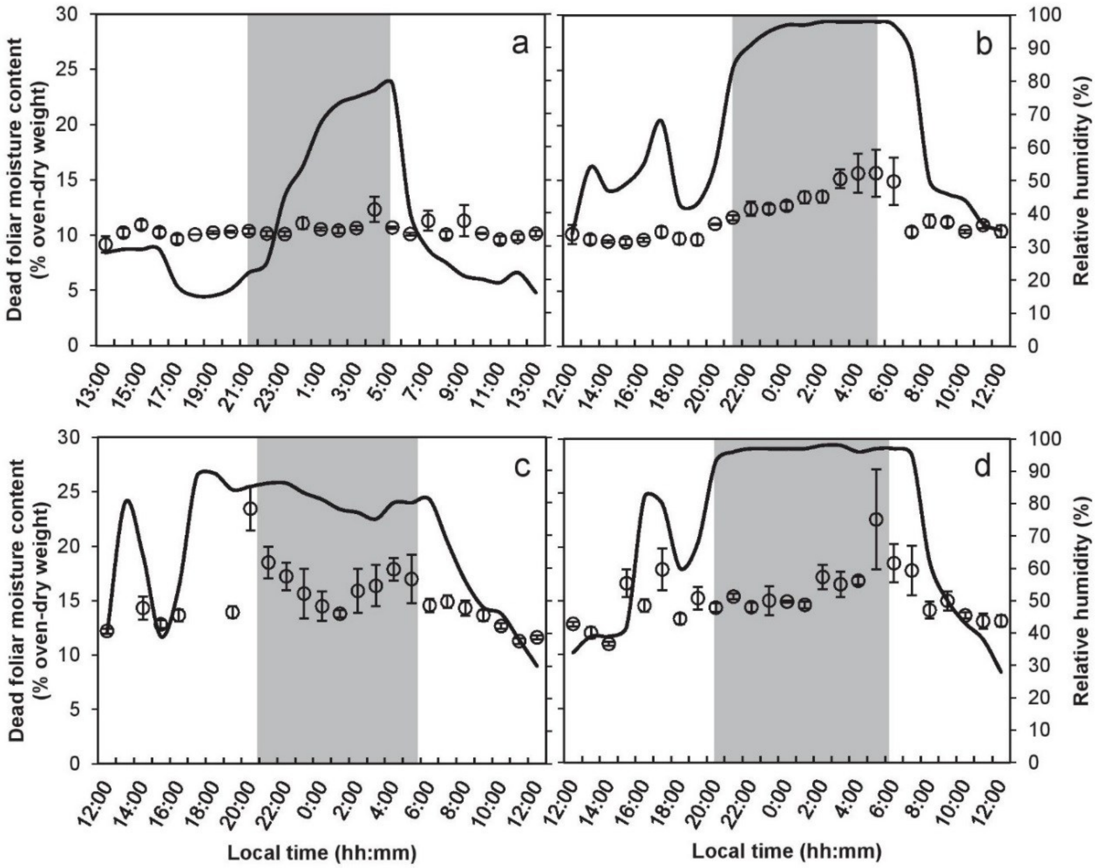

Figure 6.1. Time series of the mean observed dead foliar moisture contents (± standard error) for Period 1 (a), Period 2 (b), Period 3 (c), and Period 4 (d). The measured relative humidity from the Saw Mill Park Remote Automated Weather Station is shown on the secondary axis. The shaded area represents the night time period.

Laboratory Timelag

The moisture loss of all three needle foliage samples displayed a typical pattern of exponential decay over time (Figure 6.2). All samples reached equilibrium within ~25 h and had timelags that ranged between 2.83 and 3.56 h with a mean (±SE) of 3.21 (±0.21) h.

Table 6.1. The observed and historical (1988-2012) mean and 90th percentile Energy Release Component (ERC), Duff Moisture Code (DMC), Drought Code (DC), and Keetch-Byram Drought Index (KBDI) calculated at the Saw Mill Park Remote Automated Weather Station for each of the days when sampling was conducted.

	ERC			DMC			DC			KBDI		
Date (2013)	**Obs**	**Mean ±S.D.**	**90th**	**Obs**	**Mean ±S.D.**	**90th**	**Obs**	**Mean ±S.D.**	**90th**	**Obs**	**Mean ±S.D.**	**90th**
3-Jun	43	35± 11.9	49	42	39± 25.5	67	149	517± 196	702	40	67± 100	196
4-Jun	45	34± 10.4	46	46	41± 23.4	68	155	522± 199	708	42	74± 105	209
1-Jul	46	45± 11.3	59	81	71± 40	119	329	557± 230	799	141	124± 112	268
2-Jul	47	45± 12.3	58	85	71± 42.3	122	337	557± 229	806	140	114± 112	258
5-Aug	31	40± 8.3	52	13	51± 32.1	98	379	601± 188	901	100	143± 105	278
6-Aug	34	39± 9.3	50	11	50± 31.6	91	376	599± 181	909	88	147± 105	281
31-Aug	32	41± 6.3	51	11	54± 25.5	86	333	625± 183	791	7	179± 117	329
1-Sep	31	40± 6.6	51	10	53± 26.6	89	331	619± 184	796	4	167± 119	319

Note: Obs, observed value; S.D., standard deviation; 90th, 90th percentile.

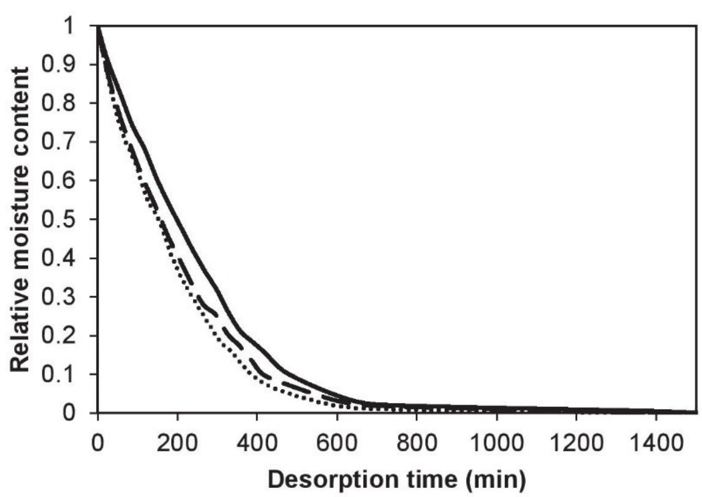

Figure 6.2. Change in relative moisture content for three lodgepole pine foliage samples during the red stage of mountain pine beetle attack under desorption conditions (air temperature ~22.2°C and relative humidity 51.4%). The calculated mean (± standard error [SE]) first period timelag is 3.21 (±0.21) h.

Model Performance

The parameter estimates (±SE) and r-square for each of the corrected operational models are shown below. Linear regression of the observed moisture contents with the estimated values from Rothermel's (1983) tables of fine dead fuel moisture produced the following corrected model of dead foliar moisture content with an r-square of 0.36:

$$m = 9.24(\pm 0.33) + 0.27(\pm 0.02)R, \tag{6.10}$$

where *m* is the predicted dead foliar moisture content (% oven-dry weight) and *R* is the estimated fine dead fuel moisture (% oven-dry weight) from Rothermel (1983). Linear regression with the hourly FFMC (Van Wagner 1987) values produced the following corrected model with an r-square of 0.53:

$$m = 17.85(\pm 0.30) - 0.08(\pm 0.004)FFMC, \tag{6.11}$$

where *m* is the predicted dead foliar moisture content (% oven-dry weight).

The best fitting model based on Catchpole et al. (2001) as represented by eqs. 6.7 and 6.8 with the timelag set to 3.21 h, had parameters *a* and *b* estimated (±SE) to be 0.1634 (±0.010) and -0.0143 (±0.004), respectively.

Comparisons of the predictions with the observed values for each of the proposed models are shown in Table 6.2. The best fitting models were those developed based on the collected data, specifically, the corrected models of Rothermel (1983) and Van Wagner's (1977) hourly FFMC, and the equations from Catchpole et al. (2001). The bookkeeping-system type models of Anderson (1985) using both sets of timelags performed similarly with a slight improvement in fit obtained from using the longer adsorption and desorption timelag values reported by Anderson (1985).

Table 6.2. Deviation statistics from the comparison of the observed dead foliar moisture contents with the predicted values from the five proposed models with their mean (± standard error [SE]) and range of observed values across all four sample periods. Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percent mean absolute error (PMAE), and mean bias error (MBE). All units are percent oven-dry weight except for PMAE.

Model	**Mean (±SE)**	**Range**	**RMSE**	**MAE**	**PMAE (%)**	**MBE**
Anderson (1985)	14.7 (±0.20)	8.9 - 20.2	4.35	3.18	26.0	1.77
Anderson (1985) lab timelag	15.8 (±0.35)	6.6 - 28.1	5.61	4.20	32.0	2.83
Rothermel (1983)-corrected	13.0 (±0.11)	10.1 - 16.1	2.61	1.90	14.0	0.00001
Van Wagner (1977) hourly FFMC-corrected	13.1 (±0.14)	10.3 - 17.8	2.23	1.48	10.6	0.0002
Catchpole et al. (2001)	12.9 (±0.10)	9.7 - 16.5	2.63	1.78	13.0	-0.06

Model Evaluation

The evaluation of the models with the data from Page et al. (see Chapter 5) indicated that most models generally performed well (Table 6.3). The best performing models were those of Anderson (1985), based on the modification of the NFDRS fine fuel moisture equations with long timelags, and Van Wagner's (1977) corrected hourly FFMC. The two other bookkeeping-system type models using the short timelags had similar but slightly worse performance in terms of overall model fit due to more variation in the change in moisture content between day and night than measured in the field (Figure 6.3). The poorest fits were obtained from the corrected Rothermel (1983) and modified Catchpole et al. (2001) models.

Evaluation of the models with the data collected by Armitage (2004) indicated that most of the models produced a moderate to poor fit (Table 6.4). All models over predicted dead foliar moisture content with the best fits obtained from the Van Wagner (1977) hourly FFMC and Rothermel (1983) fine dead fuel moisture corrected models.

Table 6.3. Deviation statistics from the comparison of the observed dead foliar moisture contents from Page et al. (see Chapter 5) with the predicted values from the five proposed models along with their mean (± standard error [SE]) and range of observed values for both sample periods. Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percent mean absolute error (PMAE), and mean bias error (MBE). All units are percent oven-dry weight except for PMAE.

Model	**Mean (±SE)**	**Range**	**RMSE**	**MAE**	**PMAE (%)**	**MBE**
Anderson (1985)	10.0 (±0.09)	7.8 - 11.7	1.34	1.07	11.4	0.31
Anderson (1985) lab timelag	9.5 (±0.18)	5.7 - 13.5	2.14	1.82	18.6	-0.17
Rothermel (1983)-corrected	11.6 (±0.08)	10.1 - 13.4	2.10	1.90	20.2	1.85
Van Wagner (1977) hourly FFMC-corrected	10.6 (±0.03)	10.1 - 11.2	1.26	1.05	11.5	0.90
Catchpole et al. (2001)	11.5 (±0.06)	10.4 - 12.8	2.02	1.84	19.7	1.79

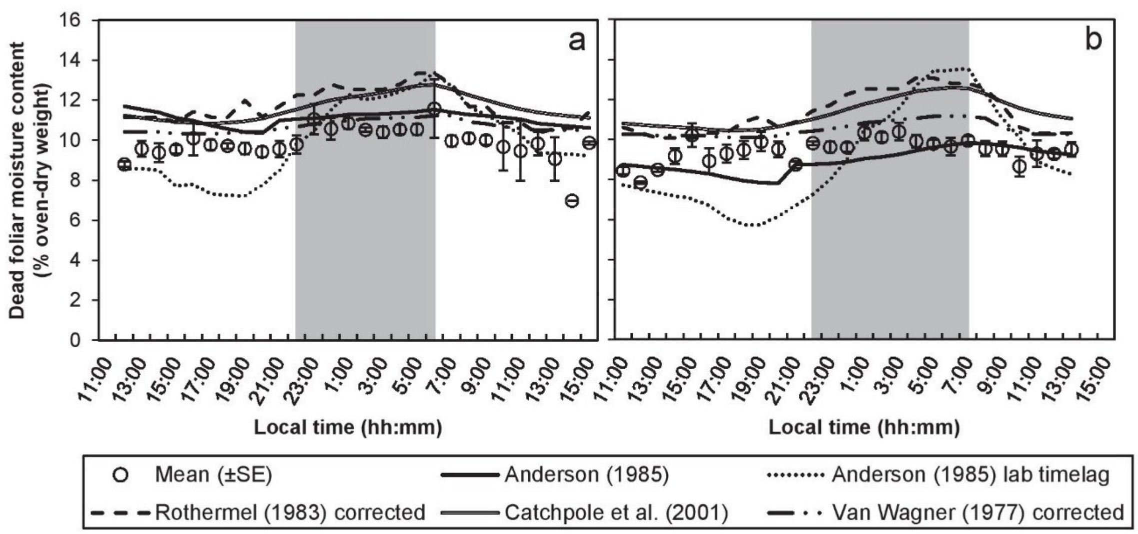

Figure 6.3. Time series of the observed mean dead foliar moisture contents (± standard error [SE]) from Page et al. (see Chapter 5) with the predictions made from the five proposed models. The models were derived from the modification of the National Fire Danger Rating System fine fuel moisture equations suggested by Anderson (1985) using both the timelags reported for recently cast lodgepole pine foliage and the mean timelag from the laboratory analysis reported in this study. The corrected models from Rothermel (1983) (eq. 6.10) and the hourly Fine Fuel Moisture Code (FFMC) (Van Wagner 1977) (eq. 6.11) were also used along with the fit obtained from the methods described by Catchpole et al. (2001). The shaded area represents the night time period.

Table 6.4. Deviation statistics from the comparison of the observed dead foliar moisture contents from Armitage (2004) with the predicted values from the five proposed models along with their mean (± standard error [SE]) and range of observed values. Deviation statistics are root mean square error (RMSE), mean absolute error (MAE), percent mean absolute error (PMAE), and mean bias error (MBE). All units are percent oven-dry weight except for PMAE.

Model	Mean (±SE)	Range	RMSE	MAE	PMAE (%)	MBE
Anderson (1985)	15.6 (±0.32)	14.1 - 17.9	8.22	7.90	110.9	7.90
Anderson (1985) lab timelag	12.1 (±0.62)	9.7 - 18.3	5.24	4.85	65.3	4.39
Rothermel (1983)-corrected	11.7 (±0.13)	10.6 - 12.5	4.37	4.22	59.7	4.00
Van Wagner (1977) hourly FFMC-corrected	10.7 (±0.04)	10.6 - 11.1	3.54	3.38	47.8	3.02
Catchpole et al. (2001)	12.2 (±0.17)	11.6 - 13.9	4.83	4.69	65.9	4.46

Discussion and Conclusions

Based on the evaluation of the models described in this study, it appears that they are all capable of predicting the moisture content of dead lodgepole pine foliage during the red stage of MPB attack with reasonable accuracy. Comparisons of the predictions with the data collected by Armitage (2004) suggest that the models may not be applicable to lodgepole pine forests at higher latitudes, except for perhaps the FFMC-corrected model. However, the dataset provided by Armitage (2004) is limited (n = 17) and does not provide a measure of variability at each sample time, thus it is difficult to make a definite conclusion about geographic applicability beyond the Intermountain Region of the western U.S. Additionally, the results indicate that there appears to be little benefit gained by using the more complicated bookkeeping-system type models based on diffusion theory. The corrected Rothermel (1983) and Van Wagner (1977) hourly FFMC models were reasonably accurate and therefore should be adequate for most applications, particularly for fire managers who already frequently use these models for other purposes.

The relatively short timelags observed in the laboratory study were initially unexpected given the previous work of Anderson (1985). Comparison of the laboratory testing methodology with Anderson (1985) indicated that there may be several reasons for the discrepancy, including, the testing of samples under a narrower range of temperature and relative humidity, the use of a higher equilibrium moisture content, the effects of increasing moisture diffusivity at higher moisture contents (e.g. Simpson and Liu 1991), and the influence of fuel load (Nelson and Hiers 2008). Despite these differences in methodology we have confirmed that the moisture loss of dead lodgepole pine foliage on MPB-attacked trees does follow the typical exponential decay seen in other fine dead fuels and that models based on diffusion theory are capable of making accurate predictions.

Given the similar results between the bookkeeping-system type models with long and short timelags it is difficult to recommend one over the other. Visual inspection of the time series of observed and predicted moisture contents (Figure 6.3) suggest that the observed data do not follow the highs and lows from the night and day time periods associated with the short timelags as well as for the long timelags offered by Anderson (1985). Thus, if a bookkeeping-system type model is desired, until further research can be done to better evaluate red needle timelag it is recommended that the long timelags reported by Anderson (1985) be used.

Using the corrected models based on Rothermel's (1983) fine dead fuel moisture tables and Van Wagner's (1977) hourly FFMC appears to be the simplest way for fire managers and fire behavior specialists to quickly and accurately predict the moisture content of dead lodgepole pine foliage associated with the red stage of MPB attack. These models will be useful to those interested in making assessments of crown fire potential in lodgepole pine forests recently attacked by the MPB. A more detailed timelag analysis of dead foliage on lodgepole pine recently attacked by the MPB is needed to better understand geographic variability and the difference between drying rates controlled by individual particle properties versus fuelbed properties.

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CHAPTER 7

CROWN FIRE POTENTIAL IN LODGEPOLE PINE FORESTS DURING THE RED STAGE OF MOUNTAIN PINE BEETLE ATTACK[9]

Abstract

Mountain pine beetle outbreaks within the previous 10 to 15 years have affected millions of hectares of lodgepole pine forests in western North America. Concerns about the influence of recent tree mortality on changes in fire behavior amongst firefighters and fire managers have led researchers to attempt to quantify the effects on crown fire potential. In this paper we provide an up-to-date review and critique of research that has endeavoured to quantify the effect of recent mountain pine beetle-caused tree mortality, during the red stage, on crown fire potential based upon quantitative descriptions of important crown and canopy fuel characteristics and simulation-based assessments of crown fire initiation and spread using operational and physics-based models. While significant progress has been made in characterizing the important variables affecting crown fire potential in recently attacked forests, we suggest that many of the conclusions drawn from simulation-based studies conducted to-date are suspect given the use of inappropriate and/or un-validated models. A systematic program of experimental burning, the monitoring and documentation of wildfires and prescribed fires, and better models of fuel moisture and fuel structure are urgently needed in order to properly assess crown fire potential in lodgepole pine forests recently attacked by the mountain pine beetle.

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Introduction

Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests in western North America have recently experienced widespread and severe tree mortality caused by mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins). High levels of tree mortality in susceptible stands occurred in British Columbia, Canada, during the early 2000s and more recently in the western United States, affecting more than 7 million hectares (Meddens *et al.*, 2012). The warming observed during the last few decades has led some to suggest that climate change may be contributing to the current severity of MPB outbreaks and on-going range expansion to northern British Columbia and east into Alberta (Bentz *et al.*, 2010; Safranyik *et al.*, 2010). While the majority of the tree mortality has passed its peak levels in western North America, there are concerns that the outbreak will continue to extend east across Canada and involve jack pine (*P. banksiana* Lamb.) forests (Cullingham *et al.*, 2011).

Given the current and potential future impacts of MPB-caused tree mortality on lodgepole pine forests, several studies have been undertaken to describe the changes in fuels and potential fire behavior (e.g. Klutsch *et al.*, 2009, 2011; Page and Jenkins, 2007a, b; Schoennagel *et al.*, 2012; Simard *et al.*, 2011). Reviews by Jenkins *et al.* (2008, see Chapter 2, 2014) and Hicke *et al.* (2012) have provided summaries of the applicable work related to MPB-caused mortality and its effect on fuels and potential fire behavior through 30 to 40 years post-outbreak. Among these review papers was a general view that a period of enhanced crown fire potential exists during the red stage while the dead or 'red' needles are retained within the canopy (Figures 7.1a and 7.1b),

Figure 7.1. Photographs of mountain pine beetle-affected (a) lodgepole pine stand on the Sawtooth National Recreation Area (SNRA), central Idaho, USA, in July 2004 with unattacked (green) tree crowns intermixed with currently attacked trees, trees attacked the previous year (yellow), and trees attacked more than two years previously (red) (photo by M.J. Jenkins); (b) mixed conifer forest near Butte, Montana, USA, with both mountain pine beetle and western spruce budworm (*Choristoneura occidentalis* Freeman) mortality distributed across the hillside (photo by M.J. Jenkins); (c) single tree experimental fires conducted by Rocca (2010) in Rocky Mountain National Park, Colorado, USA (photo by B. Cotton, Colorado State University); (d) Carrott Lake experimental fire in British Columbia, Canada, August 2006 (photo by D. Hicks, British Columbia Wildfire Management Branch); (e) Archer Lake experimental fire (plot 7) in north-eastern Alberta, Canada, May 2009 (photo courtesy of FPInnovations and Alberta Environment and

Sustainable Resource Development); (f) Valley Road Fire on the SNRA, September 8, 2005 (photo by A. Norman, USDA Forest Service); and (g) Tatuk Lake Fire in British Columbia, Canada, June 23, 2004 (photo courtesy of British Columbia Forests, Lands and Natural Resources Operations).

generally considered to be a period of less than 5 to 10 years after the first successful attacks, but that current gaps in our understanding exist due to unknowns associated with red needle flammability and its effect on crown fire initiation and spread (Hicke *et al.,* 2012; Jenkins *et al.*, 2008).

The above noted unknowns and confusion over terminology (i.e. risk vs. hazard), coupled with the misapplication of operational fire behavior models have led some (e.g. Black *et al.*, 2013; Simard *et al.*, 2011) to draw inappropriate conclusions (see Chapter 2; Jolly *et al.,* 2012a). For example, Simard *et al.* (2011) and in turn Black *et al.* (2013) suggested on the basis of the results from their simulation modelling that there is not an increase in crown fire potential in recently attacked stands and therefore there is no need for management action to mitigate any potential dangers associated with wildfire. However, most observational evidence to-date does not support this assertion (e.g. Stiger and Infanger, 2011; see Chapter 8). Additionally, there are other important implications of MPB-induced tree mortality on firefighter safety and suppression tactics, including, safety zone size, escape route designation and escape time, and overall suppression strategy that have significant consequences for wildland fire personnel (see Chapter 8). Fortunately, fire management organizations in British Columbia and the western United States have recognized the safety implications of recent MPB-related tree mortality on fire behavior and have circulated safety bulletins to address potential concerns (e.g. National Interagency Fire Center, 2011). Given the importance and timeliness of this topic, it is imperative that additional clarity be brought to bear on the subject based on new research and the reinterpretation of important concepts and assumptions regarding wildland fire behavior modelling.

This paper constitutes a digest and critical analysis of the pertinent literature dealing with crown fire potential in lodgepole pine stands recently attacked by the MPB. A discussion of the important surface, crown, and canopy fuel characteristics altered by MPB attack that may affect crown fire potential during the red stage are presented (Figure 7.2) along with the results of fire behavior simulation studies focusing on crown fire initiation and spread conducted using both operational and physics-based fire behavior models. The limitations of simulation-based studies are described in detail and the complications associated with variable tree mortality through time are characterized in terms of predicted fire behavior. In addition, results from experimental fires conducted at the single tree and stand levels are reviewed as well as wildfire behavior observations made by firefighters and fire managers in recently attacked stands. We conclude with a discussion of future research needed to improve the robustness of crown fire assessments in lodgepole pine forests recently attacked by the MPB.

Mountain Pine Beetle Effects on Surface Fuels

The amount and distribution of surface fuel and its effect on fireline intensity has important implications on the development and spread of crown fires (Van Wagner, 1977). Therefore, it is important that we highlight the relevant information concerning the changes to surface fuels in recently attacked lodgepole pine forests. Other more detailed discussions of the changes to surface fuels caused by MPB attack are presented elsewhere (see Jenkins *et al.*, 2008, 2014).

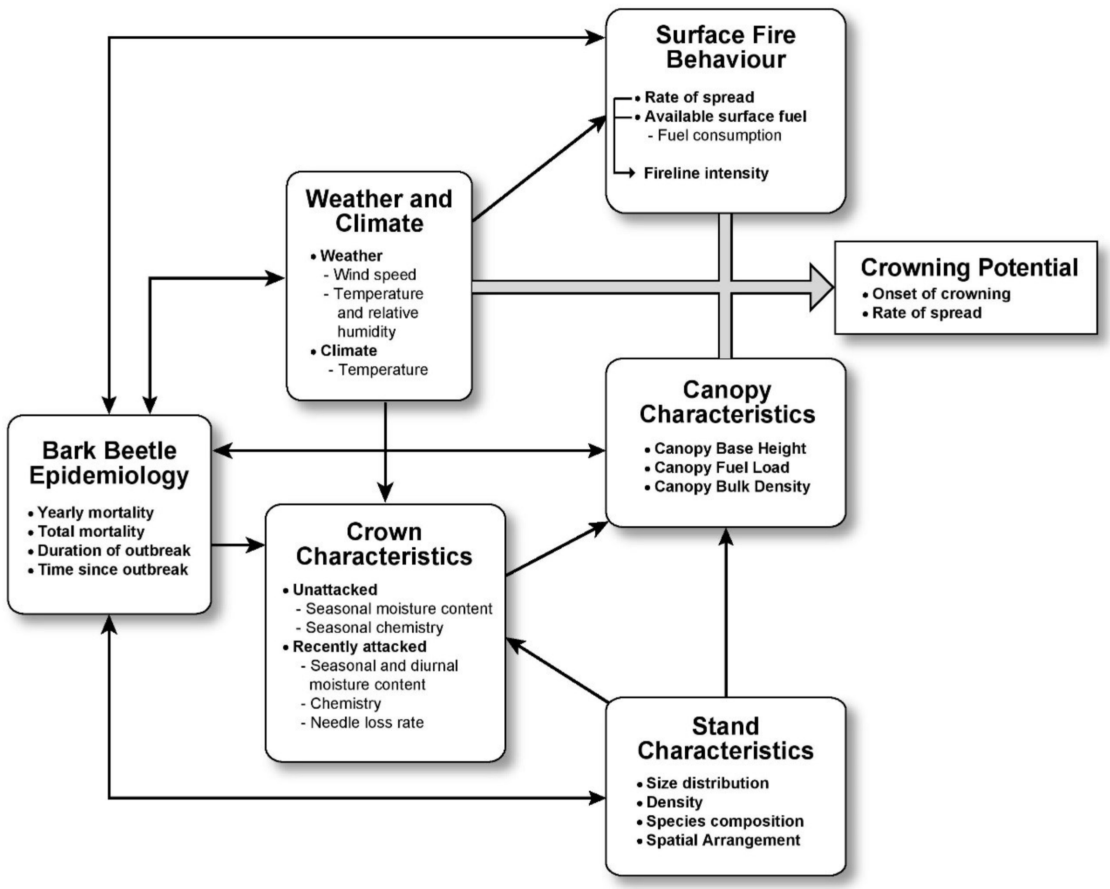

Figure 7.2. Flow diagram illustrating the primary characteristics and inter-relationships among the elements contributing to crown fire potential in mountain pine beetle-affected lodgepole pine forests.

Unattacked lodgepole pine stands generally have sparse surface fuels, but loadings can be highly variable with mean fine fuel loads (i.e. litter and dead wood < 0.64 cm in diameter) reported to be between 0.09 and 0.27 kg m^{-2} in the northern Rockies (Brown and Bevins, 1986) and 0.03 to 0.15 kg m^{-2} along the Colorado Front Range (Alexander, 1979). In recently attacked, MPB-affected lodgepole pine stands, mean fine surface fuel loads, assuming a litter bulk density of 10 kg m^{-3} (Brown, 1981), have been observed to range from 0.17 kg m^{-2} in Colorado (Klutsch *et al*., 2009), 0.4 kg m^{-2} in Wyoming (Simard *et al*., 2011), 0.46 kg m^{-2} in Colorado and southern Wyoming (Schoennagel *et al*., 2012), 0.63 kg m^{-2} in Utah, and 0.8 kg m^{-2} in Idaho (Page and Jenkins, 2007a). Compared to similar unattacked stands, a significant increase in litter depth was observed in the recently attacked stands in each of the studies noted above as well as an increase in dead woody fuel < 0.64 cm in diameter by Page and Jenkins (2007a). The increase in fine woody fuel is related to the decay and deterioration of attacked trees and the resulting transfer of crown foliage and small branch material to the surface. However, depending upon decay rate, fine fuel accumulation may be limited to a relatively small window within a few years of mortality (Simard *et al*., 2012).

Overstory tree mortality not only results in a pulse of needle litter and small diameter woody fuels to the forest floor during the red stage of MPB attack, but there is also the potential for a release of shrubs and herbaceous material due to an increase in available resources caused by tree death. Most research suggests that the release of shrubs and herbs in MPB-attacked forests does not occur until the gray or post-epidemic stages of attack (Page and Jenkins, 2007a; Simard *et al*., 2011), but depending upon the length of the outbreak, an increase in the abundance of grasses is possible and has been noted by fire managers in MPB-attacked forests in Colorado, USA (see Chapter 8).

Mountain Pine Beetle Effects on Crown and Canopy Fuel Properties

Jenkins *et al*. (2008, see Chapter 2, 2014) and Hicke *et al.* (2012) have provided comprehensive summaries of some of the important canopy fuel properties altered by MPB-induced tree mortality. Additional research has been conducted since those reviews that directly addresses some of the gaps in knowledge noted by Hicke *et al.* (2012) that relates to the characteristics of foliage on MPB-attacked trees that have important implications on crown fire development and spread.

Seasonal Changes in Foliar Moisture Content and Chemical Composition

Quantitative descriptions of the seasonal changes in foliar moisture content (FMC), chemistry, and resulting flammability have been undertaken for MPB-affected tree foliage by Jolly *et al.* (2012b) in Colorado and Montana and Page *et al.* (see Chapter 3) in Idaho. It was found that after 12 to 15 months following attack, green unattacked foliage transitioned to red with a nearly 10-fold decrease in moisture content (Figure 7.3). Simultaneously, the chemistry of attacked tree foliage underwent substantial changes with decreases in the proportion of soluble carbohydrates and crude fat and increases in the proportion of structural compounds such as lignin and cellulose (Jolly *et al.*, 2012b; see Chapter 3). Terpenoids, which are highly flammable compounds and include isoprenes, monoterpenes and sesquiterpenes, were also found to be emitted at higher rates in recently attacked foliage, still present in red foliage, and correlated with needle flammability (Amin *et al.*, 2012; see Chapter 3). The net result of the observed changes in moisture content and chemistry was a substantial increase in flammability, specifically ignitability, due primarily to the decrease in moisture content.

Diurnal Changes in Foliar Moisture Content

In addition to the seasonal variation in moisture content of MPB-attacked tree foliage, short-term (i.e. hourly) fluctuations caused by changes in weather have recently been studied. Page *et al.* (see Chapter 5) demonstrated that the average moisture content

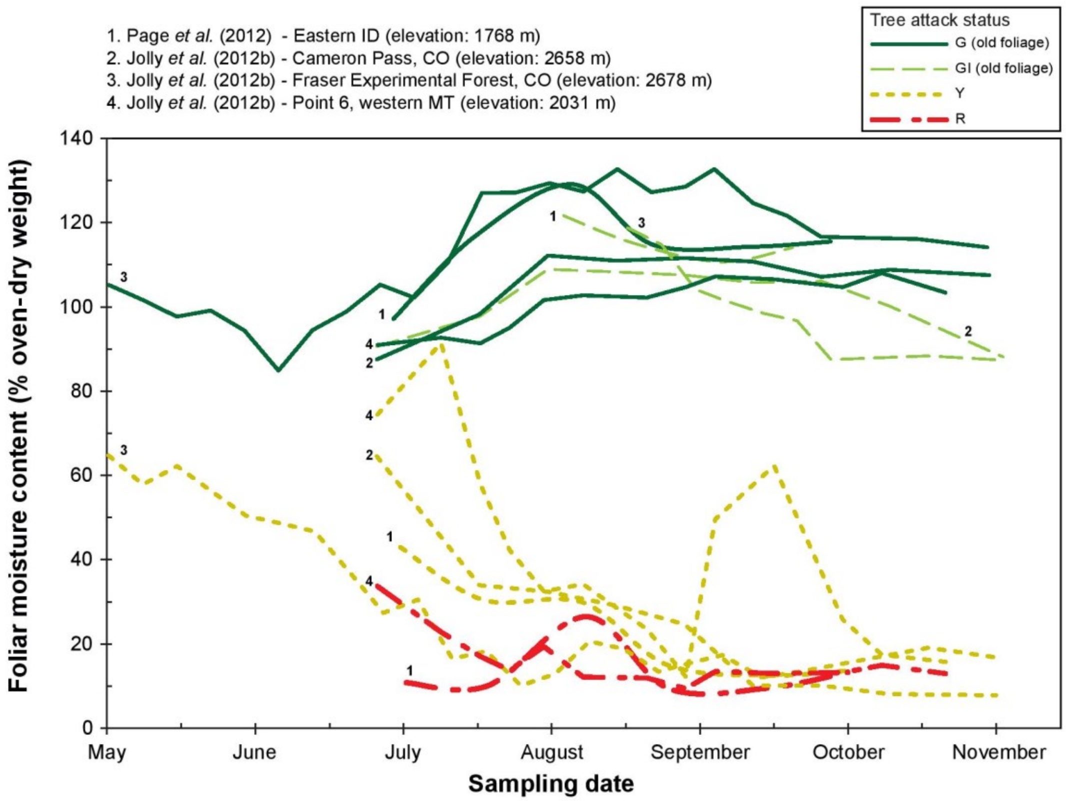

Figure 7.3. Combined seasonal changes in foliar moisture content measured on lodgepole pine: unattacked, green (G old foliage); recently attacked, green-infested (GI old foliage); attacked the previous year, yellow (Y); and attacked two or more years previously, red (R) by the mountain pine beetle. Data are from four study sites: (1) far eastern Idaho, elevation 1768 m (see Chapter 3), (2) Cameron Pass, north-central Colorado, 2658 m (Jolly *et al.*, 2012b), (3) Fraser Experimental Forest, north-central Colorado, 2678 m (Jolly *et al.*, 2012b), and (4) Point 6, western Montana, 2031 m (Jolly *et al.*, 2012b).

of needles on lodgepole pine during the red stage of MPB attack was close to 10% and displayed little variability across ranges in air temperature and relative humidity common during dry, summertime conditions. Previous research has assumed that red needle FMC responded to changes in air temperature and relative humidity similarly to other fine dead surface fuels with a strong diurnal response (i.e. Hoffman *et al.*, 2012; Schoennagel *et al.*, 2012; Simard *et al.*, 2011). Based on the results of a bookkeeping-system type model with fuel moisture time-lags exceeding 20 h during both adsorption and desorption phases it was suggested that longer-term (days to weeks) weather conditions have more of an effect on red needle FMC rather than short-term fluctuations in air temperature and relative humidity (see Chapter 5).

Canopy Needle Retention

To our knowledge there have been no published studies which have quantified the rate of needle drop in MPB-affected lodgepole pine tree crowns even though needle retention is key to understanding the duration and severity of impact on crown fire behavior (Simard *et al.*, 2012). Based on field guides using rough approximations, needles are thought to be retained in crowns for up to three years after attack (British Columbia Ministry of Forests, 1995). While published studies of needle drop rates for MPB-attacked stands are non-existent, there have been several needle retention studies undertaken in short-needled pine logging slash. Salazar and Bevins (1984) presented species specific equations used to predict needle retention over time based on summaries of previous work. In addition, McRae *et al.* (1979) provided estimates of needle retention for jack pine logging slash (Figure 7.4), which is physiologically similar to lodgepole pine (Farrar, 1995). These estimates are likely on the high end of what would be expected in MPB-affected tree crowns due to the crowns constant exposure to wind but do confirm that the majority of the needles are retained for a 3 to 4 year period.

Changes to Canopy Fuel Stratum Characteristics

MPB-caused tree mortality usually occurs over the course of several years, which leads to heterogeneous stand canopies with individual tree crowns (Figures 7.1a and 7.1b) in a variety of physical and chemical conditions (Jenkins *et al.*, 2008; Jolly *et al.*, 2012b;

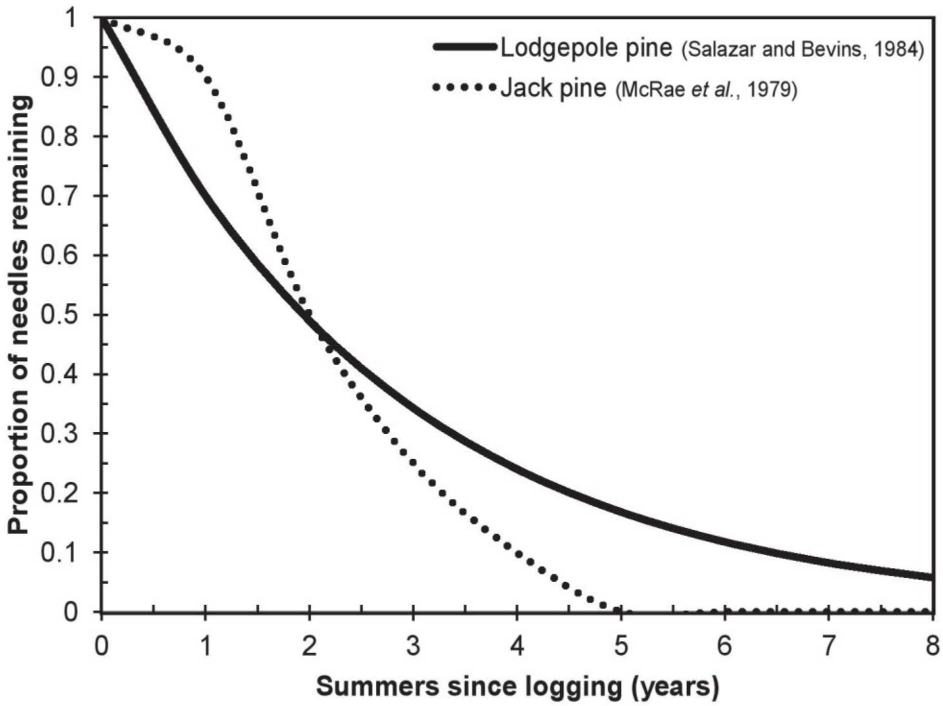

Figure 7.4. Needle retention over time for lodgepole pine and jack pine slash after harvest based on summaries by Salazar and Bevins (1984) and McRae *et al.* (1979).

see Chapter 3). Trees attacked in the previous year (yellow) or two or more years previously (red) occur with unattacked green tree crowns in relative proportions dependent upon the yearly and total amount of mortality, the duration of the outbreak, and the individual stand characteristics.

Most of the quantitative based studies of MPB related tree mortality on canopy fuel characteristics have found that the canopy bulk densities (CBD, kg m^{-3}) in recently attacked stands are lower compared to similar, unattacked stands (Klutsch *et al.,* 2011; Schoennagel *et al.,* 2012; Simard *et al.,* 2011). Even with the effects of needle drop in recently attacked red stage stands, the proportion of red foliage in the canopy can still be significant and can occur with a high proportion of attacked-trees containing the majority of needles within their crowns (Figure 7.5). For example, during the 2004 fire season, Page and Jenkins (2007a) found that in recently attacked stands on the Sawtooth National Recreation Area (SNRA) in central Idaho, USA, 30% of the total foliage in sampled stands was red and that more than 35% of those attacked trees had greater than 50% of their needles present. MPB populations in the lodgepole pine stands on the SNRA were declining during the period of sampling, suggesting that a high level of needle retention is possible even at the end of an outbreak.

In addition to the changes to foliage, it has been noted that the small diameter dead twig material within the crowns of red trees also has low moisture contents, with a seasonal mean of 15%, which was only slightly higher than the mean reported for red foliage of 13% (see Chapter 3). Typically, much of this twig material is not consumed during crown fires in healthy forests, but the dramatic decrease in moisture content could potentially make more of the twig material available for combustion during the active flaming phase of a crown fire, thereby adding mass to the available canopy fuel load. Therefore, the loading of canopy fuel available to crowning within red stage lodgepole pine forests is a function of both the mass of foliage within the canopy and the mass of small diameter twig material that can be consumed during crowning, which has not adequately been incorporated into any previous canopy fuel descriptions.

Crown Fire Initiation in Recently Attacked Lodgepole Pine Forests

Most of the current published research on fire behavior potential in recently attacked, MPB-infested lodgepole pine forests has been carried out using fire behavior modelling systems developed in the U.S., thus the focus of the discussion will be within the context of these systems and their underlying models.

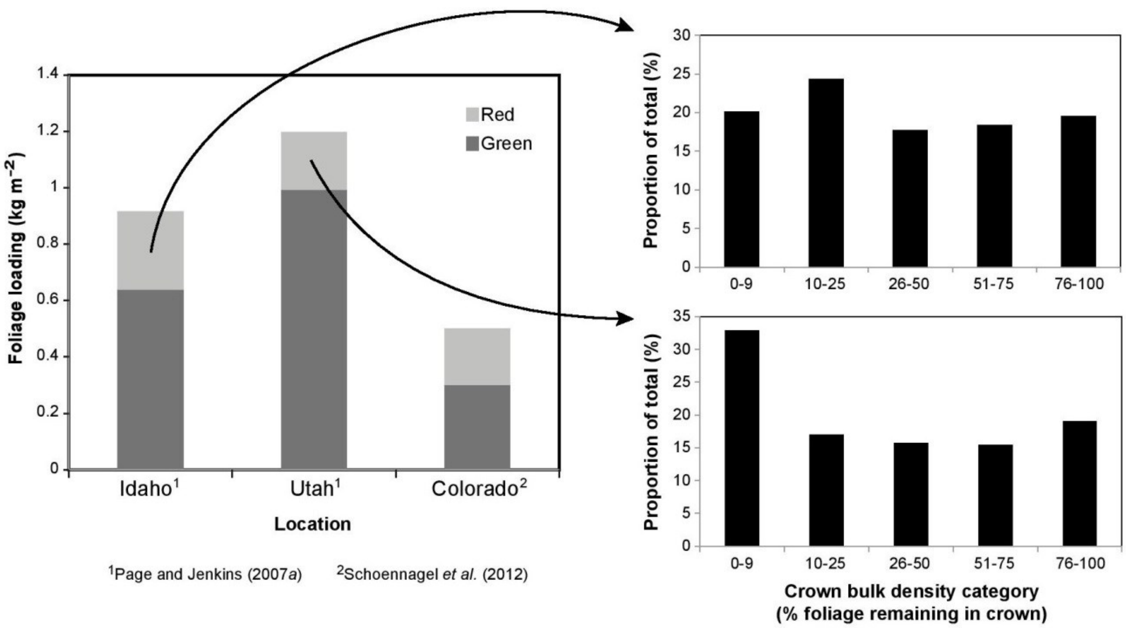

Figure 7.5. Summary of red and green foliage fuel loads in recently attacked mountain pine beetle-infested lodgepole pine stands sampled in Utah on the Wasatch-Cache National Forest and on the Sawtooth National Recreation Area in Idaho by Page and Jenkins (2007a) and in Colorado by Schoennagel *et al.* (2012). The proportion of attacked trees within crown bulk density categories sampled by Page and Jenkins (2007a) is also shown for the stands in Utah and Idaho.

Current Fire Behavior Predictive Models and Known Limitations

Crown fire initiation in conifer forests is dependent upon several characteristics of the canopy fuel layer and surface fire behavior. The surface fire characteristic deemed most important to crown fire initiation is Byram's (1959) fireline intensity, defined as the rate of heat released from a linear segment of the fire perimeter (kW m^{-1}), calculated as the product of the low heat of combustion (kJ kg^{-1}), the fuel consumed in the active flame front (kg m^{-2}), and the linear rate of fire spread (m s^{-1}) (Alexander, 1982). Fireline intensity takes into account the combined physical characteristics of the fuel complex and the effects of long- and short-term weather on fuel dryness, wind speed, and slope steepness on surface fire behavior (Alexander and Cruz, 2012). All of the fire behavior modelling systems developed in the U.S. use Rothermel's (1972) surface fire spread model to estimate fireline intensity, which has been shown to under predict the fire spread rate and fireline intensity in surface fuel beds composed of needle litter (Cruz and Alexander, 2010). The under prediction bias is related to the under-estimation of flame front residence time using Anderson's (1969) model combined with Rothermel's (1972) reaction intensity and the general under prediction of rate of fire spread in timber dominated fuel types, including lodgepole pine (Lawson, 1972), which is thought to be due to the model's sensitivity to the compactness of horizontally oriented fuel beds (Cruz and Alexander, 2010; Cruz and Fernandes, 2008).

Van Wagner (1977) developed a simple model to determine the critical fireline intensity value needed to initiate crowning in a conifer forest based on two canopy fuel properties, namely canopy base height (CBH) and FMC. Embedded within Van Wagner's (1977) simple model is an empirical constant of "complex dimensions" as determined by a single experimental fire conducted in a red pine (*P. resinosa* Aiton) plantation with a FMC of 100% and a CBH of 6.0 m (Alexander and Cruz, 2011). When the relationship is linked with Rothermel's (1972) surface fire spread model in the context of the U.S. fire behavior modelling systems, an under prediction bias in the onset of crowning has been identified (Cruz and Alexander, 2010).

Interpretation and Limitations of Current Research

Due to the limitations associated with the current U.S. fire behavior modelling systems, in terms of accurately quantifying crown fire initiation, some researchers have relied upon qualitative assessments based on logical reasoning and the observed and predicted changes to important surface, crown, and canopy fuels measured in the field as described in the previous sections. For example, the well-established relationship between moisture content and leaf flammability (e.g. Dimitrakopoulos and Papaioannou, 2001; Pompe and Vines, 1966) has been used to suggest that the presence of 'dead and red' trees might more easily facilitate the transition of a surface fire to a crown fire, especially where the combination of CBH and/or surface fireline intensity would otherwise limit crown fire initiation (Jenkins *et al.*, 2008; Page and Jenkins, 2007b; Schmid and Amman, 1992). These predictions were based on assumed decreases in moisture content during the red stage of MPB attack, the significant proportion of canopy fuel composed of the dead or 'red' foliage, and the increase in surface fire behavior predicted to occur from higher fine fuel loads and increases in within-stand wind speeds (Jolly *et al.*, 2012b; Page and Jenkins, 2007b; see Chpater 3).

Even with the known limitations of current fire behavior models, some researchers have still attempted to quantify crown fire initiation in recently attacked stands (e.g. Schoennagel *et al.*, 2012; Simard *et al.*, 2011). Using the NEXUS fire behavior modelling system (Scott and Reinhardt, 2001), it was suggested that that Torching Index (6.1-m open wind speed required to initiate crowning) exceeded 500 km h^{-1} in both unattacked and recently attacked lodgepole pine stands in Wyoming, USA, with a mean canopy base height of 3.1 m (Simard *et al.*, 2011). Clearly those values are unrealistic as crown fires are regularly known to occur in similar forests under much lower wind speeds (e.g. Renkin and Despain, 1992; Thomas, 1991) and reflect the problems associated with current operational fire behavior models. Using the BehavePlus fire behavior modelling system (Andrews *et al.*, 2008) another attempt at simulating crown fire initiation in recently attacked stands (Schoennagel *et al.*, 2012) found that the critical surface fireline intensity needed to initiate crowning was significantly lower in red stage stands than green or unattacked stands, however evidence of an under prediction bias was still evident with 6.1-m open wind speeds in excess of 50 km h^{-1} needed to initiate crowning under very dry fuel conditions and with a mean canopy base height of approximately 4 m.

Despite the widespread use of Van Wagner's (1977) relationship for the onset of crowning, its empirical proportionality constant is in fact specific to the set of fire environment conditions associated with an experimental fire in a red pine plantation from which it was derived (Alexander and Cruz, 2011; see Chapter 2). Thus, when applying the relationship to MPB-attacked lodgepole pine stands the empirical constant undoubtedly needs to be readjusted using experimental fire observations if, for example, it deviates widely from the original derivation (Cruz and Alexander, 2010). Such observations are difficult to come by as most have been qualitative in nature or were not set up to quantify the critical point of transition. For example, in MPB-attacked lodgepole pine forests in Idaho, Montana, and Oregon, wildland fire personnel have observed, but not quantitatively documented, more prolific spotting, an increased tendency for surface fires to transition to crown fires, and increases in resistance to control (Church *et al.*, 2011; Stiger and Infanger, 2011).

However, in more quantitatively-based field observations related to the potential for crown fire initiation, Rocca (2010) reported on individual tree torching tests involving 17 unattacked and recently attacked trees in Rocky Mountain National Park in north-central Colorado using a propane torch applied to the base of tree crowns (Figure 7.1c).

The red trees were tested with four categories: mixed with green needles (100% needles remaining) and 40-59, 60-79, and 80-100% needles remaining. They found that crown flammability was higher in red trees with successful crown ignition in trees having greater than 60% of their needles remaining and that there was no ignition in green tree crowns or red crowns having less than 60% of their needles remaining. They concluded that there was an increase in fire risk immediately following an outbreak but that it may be short-lived due to needle drop.

Given the current limitations of operational fire behavior models and limited observations in the field, it is critical that more quantitative field-based assessments of crown fire initiation be attempted. The evidence to-date still clearly suggests that crown fires are more likely to initiate in recently attacked lodgepole pine forests during the red stage compared to unattacked forests but we will be unable to accurately define the point of transition until either new models are developed or a proportionality constant applicable to dead canopy fuels is defined for Van Wagner's (1977) model for crown fire initiation. The observations should focus on the range of CBHs and surface fire intensities where an effect is most likely to be detected. When Van Wagner's (1977) model for crown fire initiation is applied to normal and worst-case scenarios of FMC, the range of fireline intensities and CBHs where MPB mortality may have the most effect on crown fire initiation can be displayed graphically (Figure 7.6). According to the predictions from Van Wagner's (1977) model, stands with low CBHs (especially < 2.0 m) are susceptible to the onset of crowning regardless of the level of MPB-related tree mortality, while stands with relatively high CBHs are more vulnerable to changes in crown fire initiation due to the presence of recent MPB-related tree mortality. Thus,

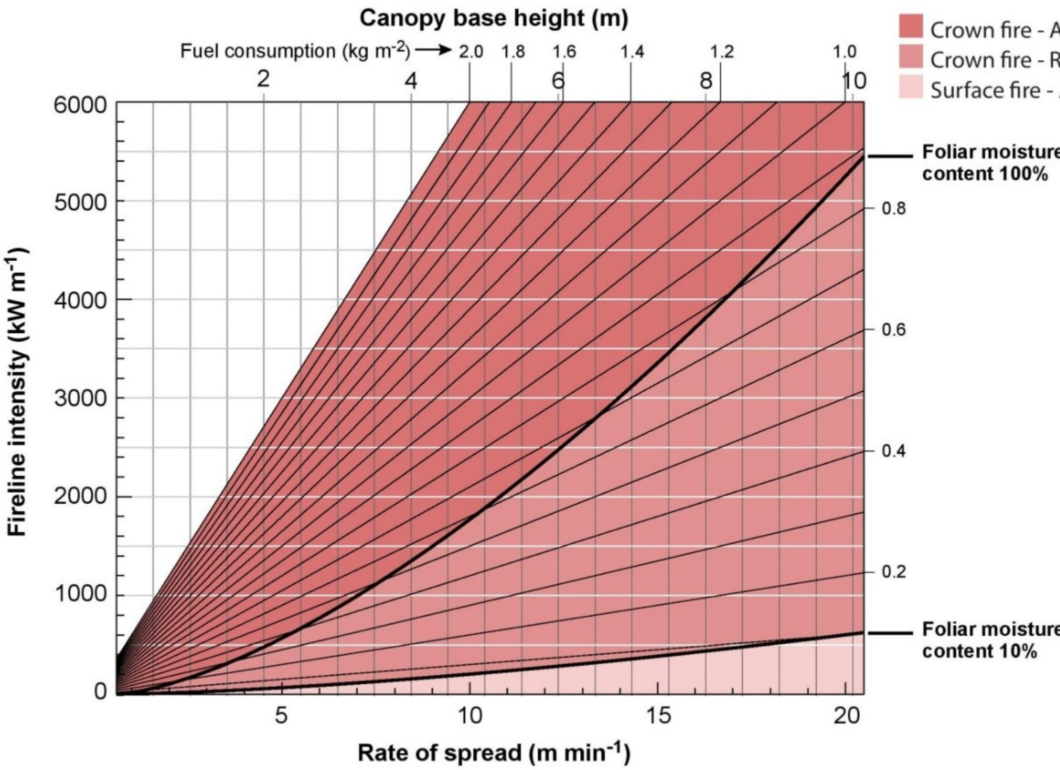

Figure 7.6. Graphical representation of Van Wagner's (1977) crown fire initiation relationship with demarcation of the critical intensities obtained at foliar moisture contents of 10 and 100% and canopy base heights between 0 and 10 m. The foliar moisture content of 100% represents the common value assumed to represent live, healthy conifer stands during the fire season (Keyes, 2006) and the 10% represents a low foliar moisture content expected in recently attacked mountain pine beetle-affected stands with near complete mortality (see Chapter 5). The three designated zones correspond to the range of fireline intensities and canopy base heights where crown fire initiation is expected within both healthy, unattacked stands and recently attacked stands (Crown fire – All), where crown fire initiation may occur in recently attacked stands but not in unattacked stands (Crown fire – Red), and where crown fire initiation is unlikely (Surface fire – All). Fireline intensities were calculated as the product of rate of spread and fuel consumption as per Byram (1959), assuming a net heat of combustion of 18 000 kJ kg^{-1} (Stocks *et al.*, 2004b). The fireline intensity can be obtained by noting the intersection between the appropriate rate of spread and fuel consumption lines and reading the y-axis. **SAMPLE CALCULATION:** Given a fine surface fuel load of 0.6 kg m^{-2}, a rate of spread of 10 m min^{-1}, and a canopy base height of 6 m, the estimated fireline intensity would be noted by reading the y-axis where the appropriate fuel consumption and rate of spread lines meet, which in this case would be approximately 1800 kW m^{-1}. Then to determine the possible influence of recent tree mortality on crown fire initiation, note where the 1800 kW m^{-1} and 6 m canopy base height (located on top of graph) lines intersect. In this case they intersect in the Crown fire – Red zone, which indicates that

conditions are such that a transition to crowning caused by the presence of recently killed trees is possible when such a transition would otherwise be unlikely if the stand contained only live and healthy foliage.

future experimental fires and/or wildfire observations looking to detect an effect of recent mortality on crown fire initiation should focus on stands with relatively high canopy base heights (i.e. >4 to 6 m) and weather conditions that produce surface fireline intensities less than 5000 kW m^{-1} for a given set of surface fuel conditions.

Crown Fire Spread in Recently Attacked Lodgepole Pine Forests

Models that have been used to-date for simulating crown fire spread rate, fuel consumption, and intensity in lodgepole pine forests recently attacked by the MPB can be considered as reflecting the "two solitudes" to forest fire behavior research as described by Van Wagner (1971). The empirical or semi-empirical approach is based on the analysis of observational data gathered from the laboratory or the field (i.e. experimental and/or wildfires) to produce either statistical models incorporating the significant drivers of fire propagation, supplemented by simple theory (e.g. Forestry Canada Fire Danger Group, 1992), or fit into a framework based on physical theory (e.g. Rothermel, 1972). The physics-based approach to fire behavior model development makes use of advances in computational power to solve the fundamental equations of mass, momentum, and energy for spreading wildland fires (Sullivan, 2009).

Current Fire Behavior Models and Known Limitations

The empirically-based models used in the U.S. that have been most often used to quantify crown fire rate of spread in MPB-attacked forests are based on the active crown fire propagation threshold described by Van Wagner (1977) and the active crown fire rate of spread model as described by Rothermel (1991). Crown fire propagation is normally classified on the basis of the dependence upon the surface fire i.e., either passive or active (Van Wagner, 1977). A passive crown fire is expected to occur when CBH and FMC are sufficiently low for a surface fire of given intensity to ignite the foliage but the final spread rate is below the minimum threshold needed to sustain active crowning for a given amount of fuel in the canopy layer. Van Wagner (1977) proposed a simple model for determining this minimum threshold for active crowning based upon the amount of available canopy fuel divided by the depth of the canopy layer (i.e. the CBD), and the minimum mass flow rate needed to sustain active crowning. Van Wagner (1977) assumed a minimum mass flow rate of 0.05 kg m^{-2} s^{-1} based on fire behavior observations in red pine plantations with FMC values between 95 and 135%. An active crown fire is expected to occur when both the surface fireline intensity is above the critical threshold needed to initiate crowning and CBD is high enough to sustain crowning for a given rate of fire spread. In live and healthy conifer stands, a CBD above 0.1 kg m^{-3} is generally considered the minimum for active crown fire spread (Agee, 1996; Alexander and Cruz, 2011; Cruz *et al.*, 2005).

In U.S. fire behavior modelling systems, once the critical intensity needed for crown fire initiation has been met, Van Wagner's (1977) active crown fire propagation threshold is evaluated to determine the type of crown fire, (i.e. either passive or active). If the minimum conditions of rate of spread and CBD have been met then Rothermel's (1991) model is used to predict the active crown fire rate of spread. A significant under prediction bias has been detected on the basis of comparing model predictions to observations of experimental and wildfires in conifer forests (Alexander and Cruz, 2006;

Cruz and Alexander, 2010; Cruz *et al.*, 2005). Possible reasons for the bias include the dependence of the model on the fire behavior fuel model 10 (Anderson 1982), the use of only seven fires to develop the statistical correlation, and the model's low sensitivity to changes in wind speed (Cruz and Alexander, 2010).

The primary physics-based fire behavior model that has been applied in MPB-attacked forests is the Wildland-urban interface Fire Dynamics Simulator (WFDS) (Mell *et al.*, 2007). Additionally, FIRETEC (Linn *et al.*, 2002), another physics-based fire behavior model, has been used to simulate fire spread in pinyon-juniper (*Pinus edulis*-*Juniperus* spp.) woodlands affected by the pinyon ips (*Ips confuses* LeConte) (Linn *et al.*, 2013). Both models attempt to simulate interactions between the atmosphere, fuel, and fire using three-dimensional, time dependent grids where the physical mechanisms of heat and mass transfer are solved. The popularity of the models among fire researchers appears to be increasing because of their perceived ability to simulate fire spread through non-homogenous fuel complexes. This is despite the fact that very little has been done to validate the outputs, particularly in conifer forest stands where surface fuels are dominated by litter and dead woody material, and where a distinct gap exists between surface and canopy fuels. This lack of evaluation with respect to model performance in conifer forests brings into question the accuracy of the outputs obtained and the robustness of the resulting conclusions (Alexander and Cruz, 2013a).

Interpretation and Limitations of Current Research

There is currently widespread agreement among researchers that once the majority of the needles have dropped from the crowns and the stand has entered the gray stage of MPB attack, active crown fire potential substantially decreases (Hicke *et al.*, 2012; Jenkins *et al.*, 2008), although not necessarily fire behavior potential in general (see Chapter 2), based on observations of several well-documented wildfires (Stiger and Infanger, 2011; D.T. Hicks, British Columbia Forests, Lands and Natural Resources Operations, pers. comm., 2013). There is, however, disagreement regarding the assessment of active crown fire spread during the red stage, as both highly flammable foliage is present but is also being lost from the canopy fuel layer as the time since the outbreak began increases. Nevertheless, this disagreement should not underestimate the importance and likelihood of high-intensity, passive crown fires and profuse, short- and medium-range spotting throughout the period of needle fall in red stage forests (see Chapters 2 and 8).

The mixture of crowns in various conditions or attack stages, the gradual loss of foliage, and the site specific characteristics of both the affected stand and adjacent stands results in highly complex spatial arrangements that may have important but as yet unknown implications on crown fire spread. For example, the high ignitability of red trees increases the likelihood of torching, which when considered with their spatial relationship to other trees may facilitate the ignition of adjacent tree crowns. Bark beetle-caused tree mortality has been shown to display clustering (e.g. Rossi *et al.*, 2009), especially during the early stages of an outbreak when large trees are preferentially attacked (Cole and Amman, 1969). The transitions from unattacked to red attack patches or stands, depending upon the scale of interest, are especially important as a shift to crowning can, at the very minimum, double the rate of fire spread and fireline intensity (Alexander and Cruz, 2011). The often dramatic and unanticipated changes in fire behavior that occur as a fire burns from one fuel type to another has been recognized as a key element affecting firefighter safety (Bachop, 1998; Bishop, 2007). Thus, complex interactions among beetle epidemiology such as the yearly, total amount, and distribution of mortality and foliage flammability exist.

The two primary studies that have attempted to quantify crown fire spread in recently attacked, MPB-infested lodgepole pine stands using U.S. fire behavior modelling systems came to opposite conclusions. In red stage stands in north-western Wyoming, USA, there was a predicted decrease in active crown fire potential due to the loss of canopy fuel (Simard *et al.*, 2011) while in similar stands in Colorado, USA, there was an increase in active crown fire potential (Schoennagel *et al.*, 2012). Both conclusions are suspect given the limitations of the underlying operational fire behavior models used in these studies. It is unknown whether Van Wagner's (1977) criteria for active crowning and its assumed minimum mass flow rate of 0.05 kg m^{-2} s^{-1} based on fire behavior observations in red pine plantations containing live foliage is pertinent to stands where the canopy contains significant amounts of dead foliage. Van Wagner's (1977) criterion was shown to be reliable in defining the transition from passive to active crowning in live conifer stands (Cruz and Alexander, 2010; Cruz *et al.*, 2005), but it has yet to be evaluated in stands containing significant amounts of dead foliage.

In an attempt to incorporate the potentially important contribution of the dead foliage on recently attacked trees to crown fire rate of spread, Moran and Cochrane (2012) suggested the use of Van Wagner's (1989) foliar moisture effect (FME) function. Van Wagner (1989) proposed that crown fire rate of spread in live and healthy conifer forest stands is affected by FMC and in turn derived a theoretical function for adjusting the crown fire spread rate based on the average FMC of 97% for the experimental crown fires and crowning wildfires used in the development of the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992; Taylor *et al.*, 1997). Based on the Simard *et al.* (2011) data, Moran and Cochrane (2012) used the function to demonstrate an under prediction bias in active crown fire spread rate by a factor of approximately two, assuming a FMC of 63%. Alexander and Cruz (2013b) discussed in considerable depth the derivation and application of Van Wagner's (1989) FME function for adjusting crown fire rate of spread. They demonstrated that the function is unrealistically strong at the low FMCs found in the red stage of MPB-attack, showing that there would be a 10-fold increase in the predicted crown fire spread rate at a FMC of 5%. It is worth noting that Moran and Cochrane's (2012) use of the FME suggests that a drop in CBD and subsequent rise in the critical rate of spread needed for active crowning can be offset by a corresponding increase in the crown fire rate of spread. This however does not imply that the critical mass flow rate is less in stands with low FMC values as the flow rate is in fact independent of moisture content (Thomas, 1967; Van Wagner, 1977). Rather, the net effect of a low FMC would be either no change or an increase in the fire's final rate of spread once the transition to crowning occurs. Indeed, if a FME does exist it could be on the order of two to three times greater than the no-tree mortality case (Alexander and Cruz, 2013b).

The results of crown fire spread assessments using WFDS in MPB-attacked lodgepole pine stands during the red stage have been closer to expectations but the reliability of the results are still unknown. WFDS was used to examine the influence of recent MPB mortality on simulated fire behavior in lodgepole pine stands using tree data collected from field sites in Oregon and Idaho, USA (Hoffman *et al.*, 2012, 2013).

Hoffman *et al.* (2012) simulated surface fireline intensity using a constant rate of spread of 6.0 m min^{-1}, with a flame front residence time of 25 s, a 6.1-m open wind speed of 7.2 km h^{-1}, and a surface fireline intensity of 625 kW m^{-1}. They found that as tree mortality increased there were increases in crown fuel consumption, fireline intensity, and that pre-outbreak stand structure was an important variable affecting the fireline intensity of crown fires. However, no evaluation was offered of the ability for WFDS to accurately predict either crown fuel consumption or fireline intensity of crown fires in conifer forest stands. Furthermore, the setting of all the relevant surface fire behavior characteristics as constants severely limited the usefulness of the stated purpose of a physics-based model like WFDS, which should be able to predict the full range of fire behavior.

Hoffman *et al.* (2013) also used WFDS to assess crown fuel consumption and a crown fire's fireline intensity in recently attacked MPB-infested stands across three different surface fireline intensity levels. The simulated fireline intensities ranged from 313 to 1250 kW m^{-1}, but the flame front residence time, rate of fire spread, and 6.1-m open wind speed were held constant. The results suggested that higher levels of tree mortality increased crown fuel consumption and the fireline intensity of crown fires, and that the increase was greatest under moderate surface fireline intensity values. Again, no empirical evidence of WFDS's ability to predict crown fuel consumption or intensity of crown fires in conifer forest stands in general was offered. While these results fit with expectations described by previous researchers (e.g. Jenkins *et al.*, 2008), there are underlying concerns as to the reliability of the projections due to the use of an un-validated model and the assumption that the MPB-killed red trees retained all of their foliage at the time of the fire, when in fact, such a situation may be relatively rare (Simard *et al.*, 2012).

In spite of concerns about lack of evaluation of physics-based models and their use to simulate fire spread in complex fuel conditions affected by bark beetle outbreaks (Alexander and Cruz, 2013a), they continue to be applied in similar situations. Linn *et al.* (2013), for example, used FIRETEC to compare fire spread rates in pinyon-juniper woodlands following attack by the pinyon ips by simulating fire spread in unattacked, green or living stands, stands in which the moisture content of pinyon needles were lowered to 15%, and stands where the needles on the attacked pinyon trees were transferred to the ground. It was found that fire spread was approximately two times faster in the simulation containing tree crowns with low moisture contents compared to the green stands and that fire propagation was also enhanced where the needles were transferred to the ground due to increased wind penetration. Although no formal evaluation of the outputs was given, observations and data do exist for green stands (Bruner and Klebenow, 1979; Hester, 1952) to evaluate the model's performance in a semi-quantitative sense (e.g. wind speed threshold in a discontinuous fuel type).

Field Observations of Fire Behavior

As a result of the controversial nature of some of the conclusions drawn from the simulation based assessments of crown fire potential in MPB-attacked forests, it is important to consider the fire behavior observations and measurements made by wildland fire research and fire operations personnel in the field. Comparisons of the observed rates of spread with predictions made using the appropriate operational fire behavior model, either the FBP System for Canadian wildland fires or the U.S. fire behavior modelling systems, are also mentioned where appropriate.

Experimental Fires

The experimental fires conducted in spruce budworm-killed (*Choristoneura fumiferana* Clemens) balsam fir (*Abies balsamea* (L.) Mill.) forests in north-central Ontario, Canada, by Stocks (1987) constitute the only published field study of fire behavior in a standing, dead conifer forest fuel complex. The results, which formed the basis, in part, for the M-3 (dead balsam fir mixedwood – leafless) and M-4 (dead balsam fir mixedwood – green) FBP System fuel types, provide a useful comparison of fire behavior potential in insect-affected stands and may provide additional insights into potential fire behavior in MPB-affected stands. The experimental fires conducted in the spring, soon after nearly complete tree mortality, displayed extensive crowning, high spread rates, and prolific, short-range spotting, even under relatively mild burning conditions. As a wildland fire behavior phenomena, spotting is a process not presently accounted in either WFDS or FIRETEC but is indirectly incorporated into Rothermel's (1991) active crown fire rate of spread model.

Stocks (1987) showed that fire behavior potential in the affected balsam fir stands peaked 5 to 8 years after mortality due to a combination of crown breakage and windthrow, and gradually decreased as surface fuels decomposed and understory shrub cover increased. Using fuel type M-3 as a surrogate for recently attacked-MPB stands and the FBP System fuel type C-3 (mature jack or lodgepole pine) to represent the live and healthy forest stand, Alexander and Cruz (2013b) computed the continuous ratio in the predicted spread rates between the two, finding that the former fuel type would have a rate of fire spread 2.5 to 3.6 times greater.

In August 2006, two experimental fires were conducted at the Carrott Lake experimental burn study area in north-central British Columbia, Canada (Table 7.1), in a mature lodgepole pine stand attacked by the MPB mostly during the period from 2002 to 2004 (Figure 7.1d). The goal of the project was to quantitatively assess the impact of MPB-related tree mortality on fire behavior (Lavoie and Taylor, 2007). The two plots burned were entering the gray stage of MPB attack with most of the successfully attacked lodgepole having lost the majority of their needles (Table 7.1). Observed fire behavior within the plots was primarily a surface fire with observed head fire spread rates similar to predictions made using the FBP System C-3 fuel type, which were ~1.2 m min^{-1} for plot 1 and ~2.4 m min^{-1} for plot 3 (Table 7.1). Due to the rapidly changing nature of the fuel complex and the difficulty of trying to burn during prescribed fire weather conditions, no further burning was done in any plots while they were in the red stage.

In an attempt to better understand the impacts of recent MPB-related tree mortality on fire behavior, a series of experimental fires were conducted near Archer Lake in northeast Alberta, Canada, in July 2008 and July 2009 (Schroeder and Mooney, 2009, 2012). MPB attack was simulated by girdling 90% of the overstory jack pine trees in 2007 on plots 0.12 to 4 ha in size. Fires were simultaneously ignited in simulated green-attack and red stage stands (Figure 7.1e). The results of the green-attack experimental fires in 2008 were inconclusive due to the ignition techniques used and the observation of rapid crown fire development in both the control and girdled plots. The results of the 2009 fires indicated little to no difference in spread rates between the

Table 7.1. Summary of the weather conditions, fire behavior, and fire danger ratings associated with the experimental fires and wildfires that burned through recently attacked mountain pine beetle (MPB)-infested lodgepole pine stands or simulated cases (i.e. Archer Lake). The observed (Obs.) and 97th percentile Energy Release Component (ERC) of the National Fire Danger Rating System (Deeming *et al.*, 1977) and the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987) are also displayed for each fire according to country of origin, either United States or Canada. The 6.1 m open wind speeds for the Valley Road and Salt wildfires were adjusted to 10-m based on the 1.15 adjustment factor suggested by Lawson and Armitage (2008). Archer Lake plots missing observed rates of spread were omitted for control plots (a) and simulated attack plots (b).

Type of observed or measured fire --- Name of fire	**Total mortality (%)**[a]	**Type of fire**[b]	**Head fire spread rate (m min^{-1})**	**Air temperature (°C)**	**Relative humidity (%)**	**10-m open wind speed (km h^{-1})**	**NFDRS ERC**		**FWI System**	
							Obs.	**97th**	**DMC**	**DC**
Experimental fires										
Carrott Lake, BC – Plot 1	86	Surface	~1-3	20	39	10	-	-	43	472
Carrott Lake, BC – Plot 3	84	Surface	~2-6	21	34	9	-	-	74	549
Archer Lake, AB – Burn 1a	0	Surface	3.0	22	45	8	-	-	36	317
Archer Lake, AB – Burn 1b	90	Surface	3.0	22	45	8	-	-	36	317
Archer Lake, AB – Burn 3a	0	Intermittent crown	4.0	24	35	12	-	-	36	317
Archer Lake, AB – Burn 3b	90	Intermittent crown	4.0	24	35	12	-	-	36	317
Archer Lake, AB – Burn 4a	0	Surface	3.0	22	35	6	-	-	40	324
Archer Lake, AB – Burn 4b	90	Surface	3.0	22	35	6	-	-	40	324
Archer Lake, AB – Burn 5a	0	Surface	3.1	23	31	5	-	-	40	324
Archer Lake, AB – Burn 5b	90	Surface	2.6	23	31	5	-	-	40	324
Archer Lake, AB – Burn 6a	0	Intermittent crown	8.8	21	37	10	-	-	43	332
Archer Lake, AB – Burn 6b	90	Intermittent crown	6.5	21	37	10	-	-	43	332
Archer Lake, AB – Burn 7a	0	Intermittent crown	3.2	22	37	10	-	-	43	332
Archer Lake, AB – Burn 7b	90	Continuous crown	7.6	22	37	10	-	-	43	332
Wildfires										
Kenney Dam, BC (June 26, 2004)	nr	Continuous crown	nr	28	30	10	-	-	58	348
Tatuk Lake, BC (June 23, 2004)	nr	Continuous crown	nr	20	64	6	-	-	45	324
Hay Lake, BC (August 18, 2004)	nr	Continuous crown	nr	28	37	6-7	-	-	-	-
Valley Road, ID (Sep. 4, 2005)	>50	Active crown	>20	28	<15	>46	97	88	-	-
Salt, ID (Aug. 29, 2011)	30-70	Active crown	23-27	17-18	25-28	33-36[c]	80	84	-	-

[a] Reported total stand mortality; Carrott Lake plots 1 and 3 had approximately 1 and 7%, respectively, of the dead trees with more than 50% of their needles remaining within the crown at the time of burning. The Archer Lake plots were noted to have dropped at least 25% of their needles at the time of burning; nr is not reported.

[b] Intermittent crown fire is synonymous with passive crown fire and continuous crown fire is synonymous with active crown fire.

[c] Reported from a portable weather station ~9 km northeast and 162 m higher in elevation than the fire.

control and girdled plots, greater crown involvement in the girdled stands during the passive crown fire phase due to the low FMCs, and no difference in the fire danger rating threshold for crown involvement (Table 7.1). Comparisons of the spread rates with the predictions from the FBP System indicated that spread rates were higher than predicted using the C-3 FBP System fuel type, but under the less severe fire weather conditions, the C-4 (immature jack or lodgepole pine) fuel type more closely matched observations for both the control and girdled plots (see Schroeder and Mooney, 2012).

Schroeder and Mooney (2012) suggested that the low crown bulk density of the red simulated attack trees decreased their effect on crown fire development in the attacked stands. The implications of these results on potential fire behavior in MPB-attacked lodgepole pine stands are difficult to interpret due to limitations of the experimental fire design. Rarely in naturally attacked lodgepole pine stands would 90% of the tree mortality occur all within one year. It is also unknown how the rate of needle moisture loss and needle drop in girdled trees compares to MPB-attacked trees. In naturally attacked stands, tree mortality occurs over a period of several years producing stands with heterogeneous crown conditions resulting in more available crown fuel over a longer period of time than if all the tree mortality occurred during one year.

Wildfires

Armitage (2004) reported on fire behavior observations obtained from wildfires that burned through recently attacked lodgepole pine stands during the summer of 2004 in British Columbia (Figure 7.1g and Table 7.1). He noted that fire behavior was more extreme in recently attacked stands compared to unattacked stands, with increased probabilities of ignition, a lower surface fire intensity threshold to initiate crowning, and greater crown fuel consumption. Long distance spotting was also observed in affected stands under low wind conditions and red tree crowns proved to be receptive to spot fire development, which hampered fire suppression operations. Recommendations were that firefighter training should note the possibility of extreme fire behavior and increased suppression difficulties in recently attacked stands even under less than extreme weather conditions and that bull-dozer line width should be increased in order to prevent radiant heat from igniting red crowns on the opposite side of the fireline.

The 2005 Valley Road Fire in the SNRA in central Idaho, USA (Table 7.1), burned through MPB-attacked lodgepole pine stands that contained significant amounts of red foliage, but were entering the gray stage of MPB attack (Figure 7.1f). The fire started on September 3rd and made major runs in MPB-attacked lodgepole pine stands on the 4th with reported 6.1 m-open wind speeds in excess of 40 km h^{-1} and near record dryness with 1000-h timelag fuel moistures (Deeming *et al.*, 1977) of 7% (Table 7.1). Intense crown fire behavior coupled with long range spotting was observed in all lodgepole pine stands regardless of the level of tree mortality during the peak burning period in mid-to-late-afternoon. Due to the critical fire weather conditions at the time, differences in fire behavior caused by the MPB-related tree mortality were difficult to detect (A. Norman, USDA Forest Service, pers. comm., 2012). Comparison of the observed spread rate during the major runs of the Valley Road Fire with the predictions made by Simard *et al.* (2011) under their 'very dry' fuel moisture scenario, assuming a 6.1-m open wind speed of 40 km h^{-1}, indicates an under prediction, with a predicted head fire spread rate of < 1.5 m min^{-1} compared to observed fire spread rates in excess of 20 m min^{-1}.

Wildfires on the Salmon-Challis National Forest in central Idaho, USA, during the 2011 fire season that were a part of the Saddle Complex, burned through recently attacked lodgepole pine stands in both the red and gray stages. In particular, the Salt Fire burned through recently attacked MPB-affected stands with between 30 and 70% tree mortality. On August 29, extreme fire behavior was observed as an active crown fire entrapped a dozer operator and transport driver (Church *et al.*, 2011) with an observed head fire spread rate estimated at 23 to 27 m min^{-1} (Table 7.1). Church *et al.* (2011) reported in the fire behavior forecast for the day, that the maximum predicted spread rate was ~7 m min^{-1} based on the TU4 (dwarf conifer with understory) surface fuel model of Scott and Burgan (2005) utilized by the fire behavior analyst assigned to the incident. The maximum observed spread rate was about 3.3 times higher than the predicted maximum spread rate for the day. Comparison of the maximum observed head fire spread rate with predictions made using the Rothermel (1991) active crown fire spread rate model indicates slight under prediction with a predicted spread rate of 17 m min^{-1} assuming a fine fuel moisture of 7% and a slope of 23%. The Cruz *et al.* (2005) active crown fire spread model predicts an active crown fire spread rate between 53 to 58 m min^{-1}, assuming a CBD of between 0.1 and 0.16 kg m^{-3}, which roughly corresponds to similar lodgepole pine stands in Idaho, USA, with tree heights of ~15 m (Page and Jenkins, 2007a).

A quantitative-based assessment of fire behavior in MPB-affected lodgepole pine forests in British Columbia has recently been undertaken by Perrakis *et al.* (2012). Using photographs obtained from the provincial air attack program for free-burning wildfires during the years 2006 to 2010, an analysis of head fire rates of spread was attempted based on visual interpretation of the photographs taken by air attack officers and weather data gathered from the nearest weather station. This dataset was supplemented with observations from experimental fires (Lavoie and Taylor, 2007) and operational prescribed fires (Kubian, 2013). At this time, their analysis has incorporated 14 observations of fire spread rates ranging from approximately 1 to near 70 m min^{-1} and Initial Spread Index component values (Van Wagner, 1987) ranging from approximately 5 to 23. Preliminary results of the analysis suggests that there is a 2.7 times increase in rate of spread in lodgepole pine stands 1 to 6 years after attack when compared to predictions based on FBP System fuel type C-3.

Conclusion

True insight into understanding and predicting the possible effects of recent MPB-caused tree mortality on surface and crown fire potential in lodgepole pine forests has so far proven to be largely an intractable problem. While significant progress has been made in recent years documenting the effects of MPB-related tree mortality on fuel complex structure as well as seasonal and diurnal fuel moistures, trying to accurately assess potential fire behavior using either operational or physics-based fire behavior models has proven problematic. Except for the recent development in British Columbia, Canada, with respect to a statistical model (Perrakis *et al.*, 2012), existing models tend to be either inappropriate and/or un-validated for use in MPB-attacked forests. Current operational fire behavior models used in the U.S. are not capable of addressing the complex spatial arrangements of crown fuels that occur in recently attacked stands. Physics-based models such as WFDS may in time serve to be useful research tools and aid in understanding the dynamic nature of fire behavior, but until the limitations and sources of error are better understood, interpretations of the resulting simulations must be viewed with scepticism (Alexander and Cruz, 2013a).

Observations from experimental fires and wildfires indicate that a real and considerable increase in crown fire potential exists in recently attacked stands with an increase in rate of spread on the order of 2 to 3 times the no-tree mortality predictions. However, the amount of red foliage within the canopy has important implications on the duration of the increased crown fire hazard. Site-specific factors such as the total and yearly amount of tree mortality, the length of the outbreak, and the pre-existing stand conditions could all be important factors that could affect the severity and duration of the crown fire hazard. Additional factors such as the juxtaposition of red and green crowns and the relative importance of needle drop and subsequent decreases in CBD versus the increased flammability of red foliage may be important to evaluating crown fire hazard but as yet are not fully understood.

Limitations in the ability to accurately assess crown fire potential in MPB-affected stands are likely to persist until accurate wildfire observations and/or experimental fires can be used to either validate current fire behavior models or derive the needed empirical proportionality constants in Van Wagner's (1977) crown fire initiation and propagation models applicable to MPB attacked stands. A program of experimental fires (Alexander and Quintilio, 1990; Stocks *et al.*, 2004a) coupled with more systematic monitoring and documentation of wildfires (Alexander and Taylor, 2010) is needed in order to address these current shortcomings and gain insight into the underlying processes controlling fire behavior in MPB fuel complexes. It is a shocking admission that the only empirical investigation of fire behavior in live, lodgepole pine stands is limited to a single study, involving surface fires, carried out in British Columbia, Canada, 45 years ago (Lawson, 1972, 1973). Additional information on the physical processes of foliage ignition and the relative effect of moisture content under varying heat fluxes will also aid in the development and modification of physics-based models that would greatly enhance our understanding of fire behavior in these forest ecosystems (Mäkelä *et al.*, 2000).

As the number and size of MPB outbreaks in western North America declines, opportunities to conduct experimental fires and observe fire behavior in recently attacked stands will decrease. Simulating MPB-attack, similar to Schroeder and Mooney (2009, 2012), by girdling trees provides a potential way to extend the window of opportunity for experimental fires and to control for confounding factors. Investments in gathering and compiling fire behavior data by fire management and fire research organizations will help provide a means to objectively assess fire behavior potential in this unique fuel complex, which will increase the margin of safety for future wildland firefighters and aid in operational planning for fire managers. Meanwhile, wildland firefighters should continue to be vigilant in recently attacked MPB-affected lodgepole pine forests and follow the guidelines outlined in the fire environment factors listed in the "Look Up, Down and Around" table for insect-killed forests found in the Incident Response Pocket Guide (National Wildfire Coordinating Group, 2010).

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CHAPTER 8

WILDFIRE'S RESISTANCE TO CONTROL IN MOUNTAIN PINE BEETLE-ATTACKED LODGEPOLE PINE FORESTS[10]

Abstract

Concerns about the impacts of mountain pine beetle (*Dendroctonus ponderosae* Hopkins)-caused tree mortality on wildfire potential in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests have to date largely focused on the potential for extreme fire behavior, including the development and spread of crown fires. Given that the wildland fire environment in which fire managers and firefighters work is composed of many interacting physical and human factors, viewing crown fire behavior as the only or even the most important outcome of the tree mortality associated with a mountain pine beetle outbreak is questionable. Proper assessment of wildfire potential entails a broader approach, which requires expanding the concept of wildfire resistance to control to include an analysis of all relevant factors and their interactions. In this paper we describe a holistic concept of analyzing the impacts of mountain pine beetle-caused tree mortality on wildfire potential in lodgepole pine forests on the basis of fire behavior characteristics, fire suppression operations, and firefighter safety considerations within the framework of three recognizable stages of the approximate time since the initiation of an outbreak (i.e., "red" ~1 to 5 years, "gray" ~5 to 15 years, and post-epidemic ~15+ years).

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Introduction

The most recent outbreaks of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests of western North America began slightly more than a decade ago and have affected more than 7 million hectares (Meddens *et al.* 2012). Some of the highest levels of mortality have occurred in the lodgepole pine forests of central and southern British Columbia and the Rocky Mountains of the western U.S. with mortality frequently reported to exceed 70% of the total stand basal area (Brown *et al.* 2010, Collins *et al.* 2012). Current projected changes in climate have also led to fears that the outbreak may expand beyond the species' historic range (Safranyik *et al.* 2010, Hyenegaard 2012). Naturally, the tree mortality associated with such outbreaks, and the vast areas affected or at risk, has raised concerns about the potential for increased levels in fire behavior characteristics in affected stands (Jenkins *et al.* 2008), which has prompted land managers to assess the need for fuel treatments to mitigate potential dangers (USDA Forest Service 2011).

Simard *et al.* (2011), and in turn Black *et al.* (2013), for example, have suggested on the basis of fire behavior simulations, that an increase in the probability of active crown fire is unlikely in affected stands and that treatments to mitigate the impacts of mortality are therefore unwarranted. This conclusion may have been based on the premise that crown fires are beyond the limits of control by conventional means of fire suppression (Alexander and Cruz 2013). Indeed, the increase in the likelihood of active crowning compared to the endemic or pre-attack condition (Fig. 8.1a) may be limited

Fig. 8.1. Photographs of lodgepole pine forests in different mountain pine beetle attack stages, (a) endemic or pre-attack condition, note green and mature overstory and sparse understory (photo by W.G. Page), (b) "red" stage, recently attacked lodgepole pine trees (red) intermixed with new attacks (off-green or yellow) and unattacked trees (green) (photo by M.J. Jenkins), (c) "gray" stage, most or all susceptible lodgepole pine killed and still standing with needles fallen, intermixed with surviving lodgepole pine or non-host species and advanced regeneration in the understory (photo by W.G. Page), and (d) post-epidemic stage, note heavy accumulations of dead and down woody material in

"jackstraw" condition intermixed with overstory of mostly non-host species and understory of advanced regeneration (photo by W.G. Page). Wildfires burning through lodgepole pine forests, (e) active crown fire run during the Davis Fire in Montana, August 2010, burning in "red" stage lodgepole pine (photo courtesy of U.S. Forest Service, from Stiger and Infanger 2010) and, (f) high-intensity fire in "gray" stage lodgepole pine in British Columbia, September 2012, Fire R10171 near Entiako Lake (photo by R. Krause, British Columbia Forests, Lands and Natural Resources Operations).

to a two or three year period immediately following MPB attack (Jenkins *et al.* 2008, Hicke *et al.* 2012). However, this does not negate the possibility of other issues to be considered in terms of wildfire potential, including, wildfire occurrence, other aspects of fire behavior such as spotting, and the ability to conduct safe and effective fire suppression operations. For example, a broader view than just the consideration of increased active crowning is the recognition that people (i.e., firefighters and also members of the general public) are part of the wildland fire environment in these affected forests (Barrows 1974, Stiger 2012).

The purpose of this paper is to present and discuss a comprehensive approach to assessing the impacts of MPB-related tree mortality on wildfire potential by broadening the scope of the traditional concept of wildfire's "resistance to control" (Alexander 2000). Resistance to control provides an ideal framework to address the impacts associated with MPB-induced tree mortality in that it incorporates many of the aspects that the wildland fire management community is directly concerned with or responsible for through their stewardship of forested lands. Others have clearly discussed the important ecological role that the MPB plays in lodgepole pine forests (e.g., Brown 1975), however, as these forests do not exist in a vacuum, the impacts of MPB mortality can only truly be assessed within the context of the human environment, which includes the priorities and responsibilities of forest management. As many of the specific details associated with MPB-induced tree mortality have yet to be studied, some implications are based on comparable work conducted in different contexts or based on the personal observations of fire managers and firefighters (Stiger and Infanger 2011, Box 8.1).

Box 8.1. Firefighters and fire managers have made several observations in mountain pine beetle affected lodgepole pine forests in recent years (as quoted in Stiger and Infanger 2010 based on their own observations and conversations with other fire managers).

Crowning

Bill Cyr, (Lincoln, Montana Fire Chief and Department of Natural Resources and Conservation Fire Forester, Montana, USA).

> "In red/dead lodgepole pine the pitch tubes seem to be acting as ladder fuels providing a means for fire to move up the trunk of the tree and into the crowns."

Bob Drake, (Tri-Lakes Fire Chief, Helena, Montana, USA).

> "It appears that the red/dead provides the ignition source to start a crown fire that is then carried by the volatiles in the green trees."

Greg Archie, (Department of Natural Resources and Conservation, Central Land Office, Fire Program Manager, Helena, Montana, USA).

> "[based on observations of the Davis wildfire, Fig. 8.1e, with 50 to 75% red/dead component] …it was astounding how fast the crown fire gained momentum and spread as a crown fire from an initiating small spot fire. This occurred under rather mundane weather conditions with air temperatures in the 70°F's and relative humidity near 20% with relatively light winds."

Spotting

Jay Lindgren, (U.S. Forest Service, Helena National Forest, Lincoln District Fire Management Officer, Lincoln, Montana, USA).

> "[description based on the smoke from crowning lodgepole pine with more than 50% red/dead component]…, the blackest smoke he had ever witnessed. This event produced profuse spotting. Such unusual black smoke may be the result of enormous amounts [of] aerodynamic bark and red needles exhibiting incomplete combustion."

E.M. Stiger, (Retired U.S. Forest Service Zone Fuel Management Specialist, currently Fire Behavior Analyst for Tri-County area, Helena, Montana, USA).

> "The Probability of Ignition (POI) may play a more important role in anticipating unusual fire behavior in red/dead pines than previously thought. During the North Fork (of Stickney Creek) fire in July, the POI was estimated at 74 to 86. This fire exhibited mass spotting that spread rapidly in the surface fuels."

Broadening the Definition of "Resistance to Control"

Resistance to control has been defined as "the relative difficulty of constructing and holding a control line as affected by resistance to line construction and by fire behavior" (Merrill and Alexander 1987, National Wildfire Coordinating Group 2012). This may also involve the difficulty of mop-up as dictated by a fire's persistence (British Columbia Ministry of Forests 1983). Firefighter safety has not directly been included in this conventional definition. Nevertheless, it is implicit, as constructing and holding a control line is not possible if firefighter safety measures such as lookouts, anchor points, communications, escape routes, and safety zones are not established due to the overriding priority of human life on all wildland fires (Gleason 1991, Alexander 2013).

In this paper we include firefighter safety considerations as a distinct component of resistance to control along with fire behavior characteristics and fire suppression operations, including the rate of fireline construction (Fig. 8.2). In forests with extensive MPB-caused tree mortality, explicitly including firefighter safety considerations is necessary as it can become decoupled from the resultant fire behavior situation, as for example, when extremely dangerous stand conditions in the form of high snag densities exist, yet the ensuing fire behavior may otherwise be mild. Such conditions have been noted in other forests containing high snag densities, for example, in California hardwood forests that have experienced sudden oak death (SOD) due to the pathogen *Phytophthora ramorum* S. Werres & AWAM de Cock (Lee *et al.* 2010). In fact, conditions may exist such that direct suppression by firefighters on the ground may not be possible entirely because of safety concerns as opposed to fire behavior.

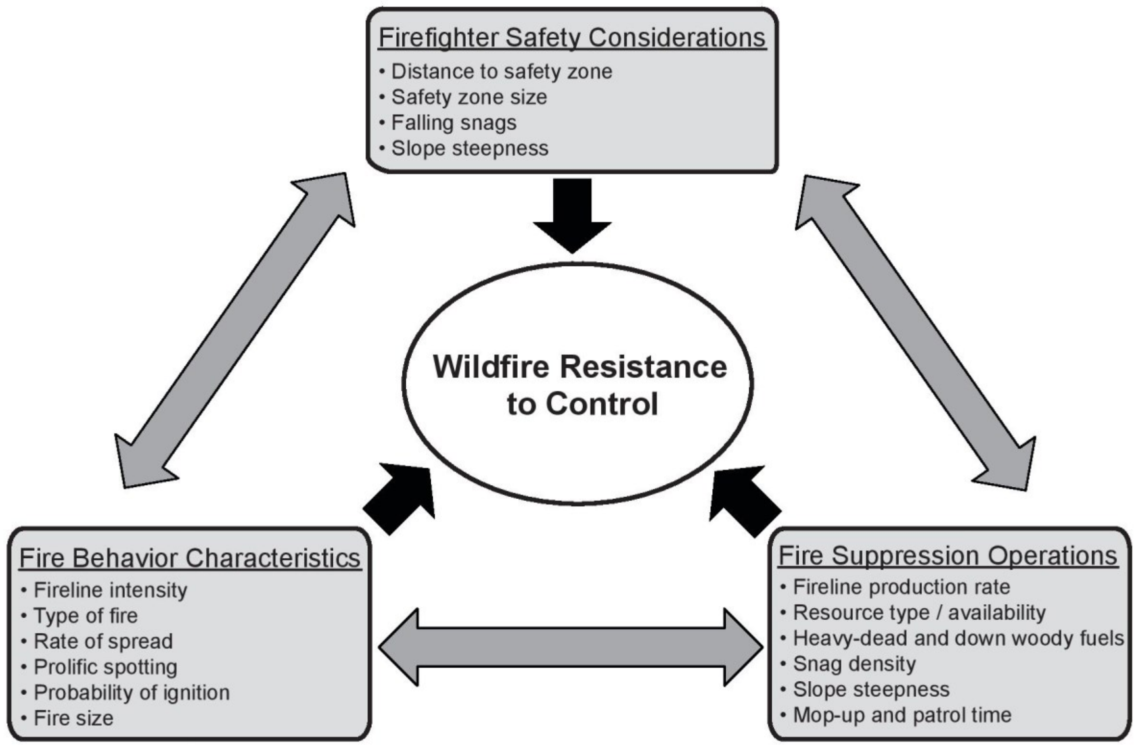

Fig. 8.2. Conceptual diagram of the three primary factors affecting the resistance to control of wildfires in mountain pine beetle-attacked lodgepole pine forests.

Fire Behavior Characteristics

The characteristics of the behavior of free-burning wildland fires generally includes the ignition probability, spread rate, fuel consumed, shape of the fire perimeter, fireline intensity (i.e., rate of energy release at any point about the fire perimeter), flame front dimensions, type of fire (i.e., surface, passive crown, active crown), fire size (area burned and perimeter length), flame residence and burn-out times, and related phenomena such as spotting and fire whirls (Byram 1959, Alexander 2000, Alexander and Cruz 2013). Fires in heavy fuelbeds such as logging slash and blowdown generally exhibit slow spread rates and long flame front residence times whereas fires in light fuel situations like cured grass spread much faster and have very short residence times; fires in conifer forests and shrublands tend to be intermediary (Fig. 8.3). Fireline intensities can be similar under different fuel and weather conditions because of varying rates and amounts of fuel consumption (Alexander and Cruz 2012a).

The changes in the characteristics of fire behavior in MPB-attacked lodgepole pine stands over the course of an outbreak have previously been discussed in detail by Jenkins *et al.* (2008, see Chapter 2, 2014) and Hicke *et al.* (2012). Based on their conclusions, in addition to the endemic or pre-attack condition (Fig. 8.1a), there are at least three distinct periods or stages of stand mortality and structure change following severe MPB attack in lodgepole pine forests that can be described in terms of fire behavior potential in relation to resistance to control: “red”, “gray”, and post-epidemic (Fig. 8.1b-d).

During the “red” stage -- i.e. ~1 to 5 years after outbreak initiation (Fig. 8.1b), characterized by retention of dead needles, a peak in potential fire behavior is present (Fig. 8.4), compared to the pre-attack condition, due largely to the effects of low foliar moisture content and high flammability on crown ignition (Fig. 8.1e) (Jolly *et al.* 2012, see Chapters 3 and 5). The likelihood of such a crown fire event increases with slope steepness (Van Wagner 1977). Hazards associated with short-range spotting, including directly into the red tree crowns themselves, combined with the potential for long-distance spotting due to strong convection column development associated with the crowning (Box 8.1), can also substantially increase potential fire behavior (see Chapter 2) (Table 8.1).

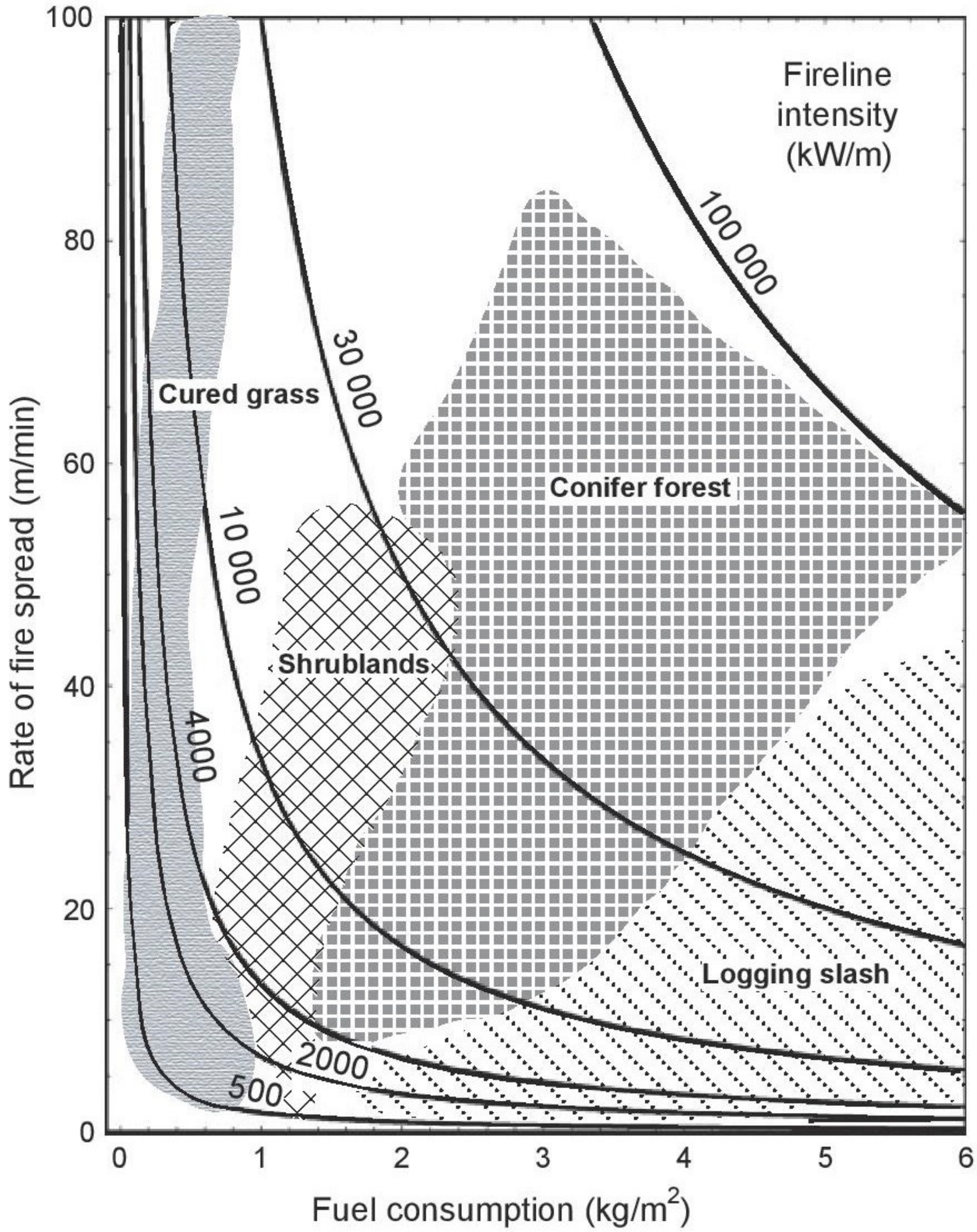

Fig. 8.3. A fire behavior characteristics chart (Alexander and Cruz 2012b) showing the general range in rate of spread, fuel consumption and fireline intensity for cured grass, shrubland, conifer forest, and logging slash fuel complexes based on experimental field fires (after Stocks and Kauffman 1997). Numerically, fireline intensity is equal to the product of the net low heat of combustion (18 000 kJ/kg is assumed here), quantity of fuel consumed and the linear rate of spread. Flame size is its main visual manifestation.

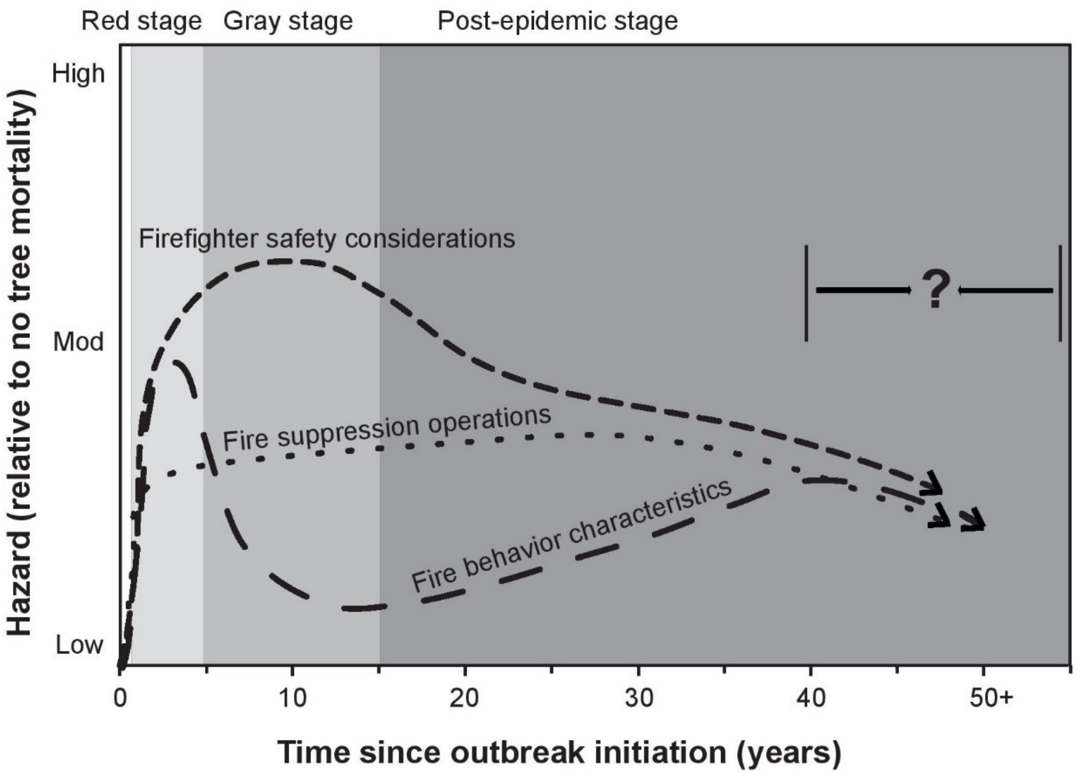

Fig. 8.4. Summary of the predicted hazard induced by severe tree morality from a mountain pine beetle outbreak in lodgepole pine forests, relative to the case of no tree mortality, for the three main elements of resistance to control, namely, fire behavior characteristics (e.g., in relation to crowning and fireline intensity), firefighter safety considerations (e.g., in relation to snag conditions), and fire suppression operations (e.g., in relation to spotting and rate of fireline construction). Developed based on summaries by Hicke *et al.* (2012) and Jenkins *et al.* (2008, see Chapter 2, 2014). The long-term (50+ years) hazards are currently unknown, as indicated by a question mark.

During the “gray” stage -- i.e. ~5 to 15 years after outbreak initiation (Fig. 8.1c) -- when the dead trees lose their needles but remain standing as snags, there is generally considered to be a decrease in crowning potential as the possibility of an active crown fire occurring declines due to the loss of canopy foliage at both the individual tree and stand levels (Fig. 8.4) (Hicke *et al.* 2012). However, this does not preclude other aspects of extreme fire behavior, such as large increases in fireline intensity (Fig. 8.1f).

Table 8.1. Summary of the potential effects of mountain pine beetle mortality in lodgepole pine forests on fire behavior, suppression operations, and firefighter safety over the course of severe outbreak by bark beetle attack stage (after Jenkins *et al.* 2008, see Chapter 2, 2014; Hicke *et al.* 2012).

Impact of concern	Fire behavior characteristics	Fire suppression operations	Firefighter safety considerations
	"Red"-stage (~1-5 years after initial attack)		
High density of 'red' trees	•Lower foliar moisture contents of attacked trees may lead to lower fireline intensity threshold for crowning to develop.	•Higher fireline intensities during crowning or when red trees torch decrease direct suppression effectiveness.	•Higher rates of spread decrease escape times to safety zones. •Higher intensity crown fires require greater safety zone sizes.
Long and short distance spotting	•Stronger convection columns during high intensity fires aid in long distance spotting. •Lower foliar moisture contents in red tree crowns increase ignitability, providing a receptive fuel for spotting.	•Fire suppression becomes increasingly difficult as suppression operations become ineffective with long distance spotting. •Short distance spotting into red crowns hampers control operations and requires wider firebreaks.	•Escape routes can become compromised as spot fires cutoff firefighters from safety zones.
Hazard trees (Snags)	•Weakened trees with loose foliage, bark, and branches provide ample firebrand sources for spotting.	•Fireline construction rate is lower due to extra time for snag mitigation.	•Red trees are weak and susceptible to falling, particularly after fire front passage.
	"Gray"-stage (~5-15 years after initial attack)		
Hazard trees (Snags)	•Standing gray snags have weak and decayed braches and bark providing an ample source for large firebrands with long burn out times.	•Extensive time for snag mitigation is necessary prior to and during fire suppression operations. •Alternative mechanical equipment (i.e., bulldozer) may be necessary for suppression operations.	•Snag mitigation is dangerous and time consuming. •Extremely dangerous post-fire conditions as fire weakened snags fall.
	Post-epidemic (~15+ years after initial attack)		
Hazard trees (Snags)	•Remaining snags are old, decayed, and easily weakened by fire passage.	•Total snag density is lower than gray-stage but remaining snags are rotten and are more difficult and require more time to fall.	•Weak and decayed snags are dangerous to fallers during hazard tree mitigation operations.
Jack straw (dead and down)	• Intense fire behavior possible with heavy accumulations of dead wood, although may not be classified as crown fires. •Decayed wood provides a receptive fuel bed for spotting.	•Reaching fires in remote locations is difficult and time consuming. •Heavy dead and down make constructing and holding fireline difficult.	•More time required for preparing and using escape routes. •Larger safety zone sizes may be needed due to high intensity fires burning in heavy dead and down woody fuel accumulations.

The significant loss of overstory foliage and the resultant exposure of surface fuels to increased solar radiation and wind speed during the "gray"-stage can also enhance fire spread at the ground surface, resulting in more intense fires than would otherwise occur without tree mortality (Jenkins *et al.* 2008, Gray 2013). Furthermore, the dead, weakened and decayed trees that were attacked by MPB can provide an ample source of large firebrands (i.e., bark flakes, twigs, etc.) with long burn-out times that can aid in an increase in spotting density (Hyenegaard 2012) and maximum distance (Albini *et al.* 2012) (Table 8.1). Some fire managers have also noted a significant increase in grass cover and loading at some sites, raising concerns about fast burning, high intensity fires when grasses are cured in the spring and fall (R.D. Wilmore, USDA Forest Service, Eagle, CO, 2013, personal communication).

Following the “gray”-stage comes the post-epidemic condition or stage -- i.e. ~15+ years after outbreak initiation (Fig. 8.1d). This stage is characterized by large accumulations of dead and down woody fuel produced by snag fall and the presence of an understory of advanced spruce (*Picea* spp.) or fir (*Abies* spp.) tree reproduction in seral lodgepole pine forests (Pfister and Daubenmire 1975). These conditions can lead to another peak in fire hazard wherein very intense surface fires (Fig. 8.1f) and passive crown fires (depending on the understory tree structure) are possible (Fig. 8.4). Note that the timing of the second peak in fire hazard can vary by a host of site specific factors, including snag fall and decomposition rates and the characteristics of the understory, such as the existence of advanced regeneration (present before attack) or new regeneration (Pelz and Smith 2013). The presence of large amounts of decayed roundwood on the ground (Brown and See 1981) may also provide a receptive fuelbed for hold-over spot fires (Burgan 1966, Stockstad 1979), which can in turn hamper fire suppression operations.

During the early phases of the post-epidemic stage, fires resemble to a certain extent the behavior of those burning in heavy logging slash or blowdown where large diameter, downed dead woody fuels produce high fireline intensities but relatively slow to moderate rates of spread (Quintilio 1972, Johnston 2012). The Sleeping Child Fire that occurred in western Montana during August 1961 is an example of such a fire in a post-gray stage stand (29-32 years after MPB attack) that proved difficult to control (Lotan 1976, see Chapter 2). Where grass invasion is widespread, a much more volatile situation is possible when the potential exists for both high rates of spread and high fireline intensities due to the combination of abundant fine fuels and heavy loads of coarse woody fuels. This situation was observed on the 2005 Ophir Mt. Fire in Summit County, Colorado (R.D. Wilmore, USDA Forest Service, Eagle, CO, 2013, personal communication) and has also been observed in post-fire lodgepole pine stands where grasses intermixed with heavy loads of coarse woody fuels such as on the Minto Lake Fire in the Yukon Territory, in 2010, approximately 10-15 years post-fire (D.G. Finn, Alberta Environment and Sustainable Resource Development, Rocky Mountain House, AB, 2013, personal communication).

After this second peak in fire behavior potential, there is presently an uncertainty. There may be a gradual decrease in both surface and crown fire behavior potential with time, compared to the no-tree mortality case, as woody fuel decomposition and the maturation of the intermediate and understory tree crop returns the affected forest structure closer to pre-outbreak conditions (Fig. 8.4). The uncertainty arises from our current state of knowledge about late post-epidemic (i.e., 40-80 years) fuel characteristics, which is currently limited to model simulations (e.g., Collins *et al.* 2012, Donato *et al.* 2013) and not empirical measurements (Box 8.2).

Box 8.2. Research needs and knowledge gaps associated with wildfire resistance to control in mountain beetle-attacked lodgepole pine forests.

Fire behavior characteristics

- Models of surface fire spread and crown fire potential (initiation and spread) in “red” and “gray”-stage stands.
- Snag fall rates in MPB-killed stands.
- Spotting dynamics, including probability of ignition, in MPB-affected fuelbeds.
- Long-term (+40 years) impacts of mortality on stand/fuel conditions and potential fire behavior, including decomposition rates of downed logs.

Fire suppression operations

- Fireline construction rates by hand and machine in “red”, “gray”, and post-epidemic stands, including hazard tree mitigation time.
- Effectiveness of indirect suppression strategies.
- Effects of tree mortality on fire cost and duration.

Firefighter safety considerations

- Effectiveness of point or zone protection strategies on decreasing exposure time of firefighters to hazardous conditions.
- Rates of deterioration in standing MPB-killed snags and implications for falling operations.

Fire Suppression Operations

Wildland fire suppression involves all the activities associated with the control and extinguishment of a wildfire following its detection (Brown and Davis 1973, Goodson and Adams 1998). In practical terms, this first means creating a physical barrier (i.e., a fireline) around the fire by one of the following means: (i) removing the fuels or cooling/smothering the flames with water or (ii) covering the fuels with mineral soil, suppressants or chemical fire retardants from either the ground and/or the air. The constructed fireline must then be secured or “held” using effective mop-up. Mop-up requirements can vary substantially by fuel type and site specific characteristics but usually involves frequent patrolling to ensure that old or new spot fires do not go undetected, removing and/or securing snags or logs that might cross the fireline, and extinguishing any remaining burning material that might be the source for new fire starts (González-Cabán 1984).

During the "red"-stage, direct suppression operations may be limited where extensive tree torching and prolific short- and long-range spotting makes holding constructed fireline difficult (Table 8.1). Indirect methods of fire suppression, such as suppression firing (Cooper 1969), may be needed to effectively deal with the high ignitability of red tree crowns, which can add complexity and additional safety concerns to the fire operations (e.g., unburned fuel between firefighters and the fire). For example, Armitage (2004) recommended the use of mechanical equipment (e.g., bulldozers) to widen firelines in order to effectively deal with the high ignitability of red tree crowns. Normal post-fire patrol and mop-up may also be difficult due to the high densities of MPB-affected trees, which may fall following the initial fire front passage thereby potentially crossing the previously constructed fireline (Table 8.1).

During the "gray"-stage, extensive snag felling by hand or machinery will be necessary both prior to and after passage of the fire front in order to mitigate dangers to firefighters and to maintain the integrity of the fireline. Additionally, snags that catch on fire and remain standing will be exposed to higher wind speeds, increasing the possibility of spotting well after the initial fire front has passed. Depending upon the level of tree mortality, the process of mitigating the problems posed by high snag densities may consume significant periods of time and substantially slow fire suppression operations.

Other things being equal, this will lead to an increase in fire size and perimeter length, further increasing the time and effort required for control and extinguishment.

During the post-epidemic phase, heavy accumulations of dead and down woody fuel will substantially slow both the rate of line construction and the process of holding the constructed fireline (Quintilio *et al.* 1990). Analysis of previous (National Wildfire Coordinating Group 1998) and new (Broyles 2011) estimates of direct line construction rates suggest that line construction rate decreases as total fine surface fuel load or fuel resistance increases (Fig. 8.5). Quantifying the effects of fuel characteristics on line construction rates have met with varying levels of success as the process of constructing and holding fireline can be difficult to measure (Barney 1983, Hirsch and Martell 1996). However, most research has clearly identified a decrease in line construction rate as the number of large dead woody fuel particles increase, either through direct measurement (Murphy and Quintilio 1978, Murphy *et al.* 1989) or by summarizing U.S. Forest Service regional estimates using fuel resistance classes (Haven *et al.* 1982).

In addition to the direct effect of increased fuel loading on line construction rate, increases in fireline intensity and flame length have also been shown to have a negative relationship with fireline production rates (Quintilio *et al.* 1988, Murphy *et al.* 1991, Alexander 2000). Thus, the predicted high intensity fires in post-epidemic stands could further decrease line construction rate. Furthermore, holding the constructed fireline may prove difficult as the long burn-out times (Beaufait 1961) and high intensities of fires in heavy dead and down woody fuels subject the constructed fireline and the adjacent unburned fuels to prolonged periods of high heat exposure, likely increasing the chances for short-range spotting.

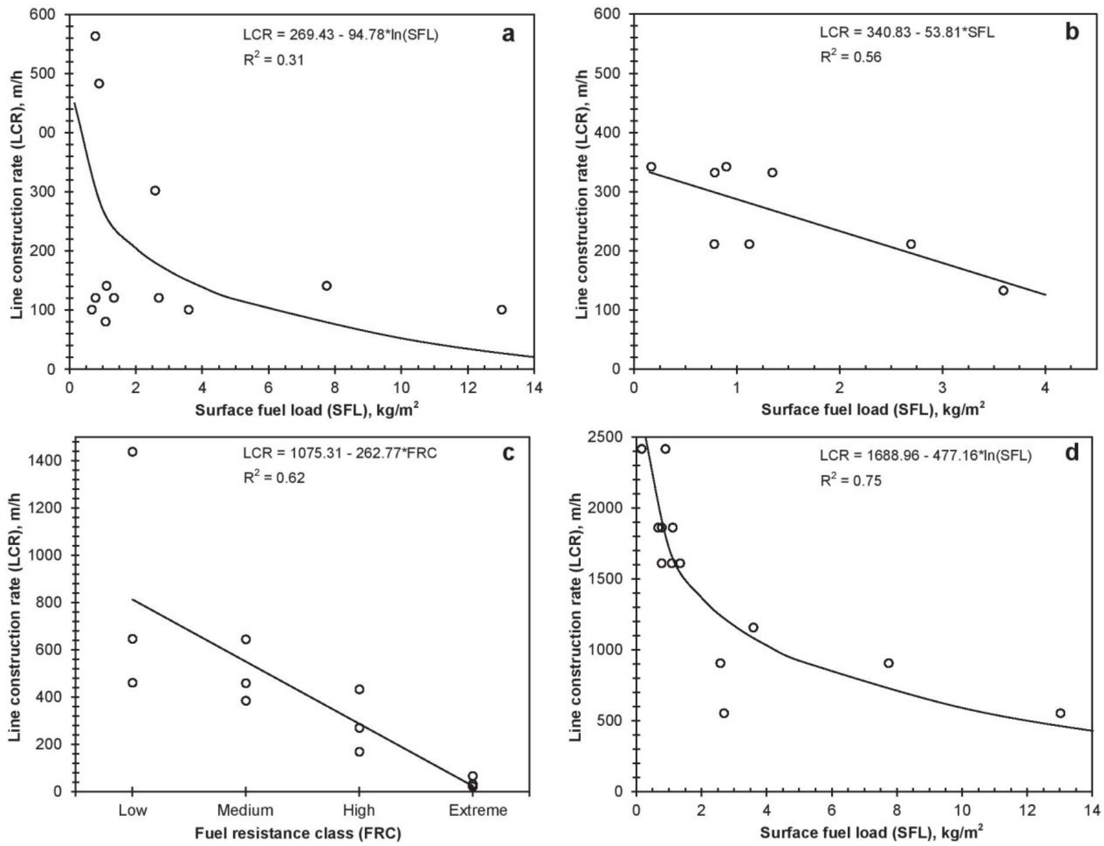

Fig. 8.5. Plots of observed direct line construction rates and lines of best fit based on linear and non-linear least squares regression for: (a) Type 1 hand crew by fire behavior fuel models 1 to 13 (Anderson 1982) and total fine surface fuel load (TSFL), using estimates from National Wildfire Coordinating Group (1998), (b) Type 1 hand crew by fire behavior fuel models 1, 2, 4 to 6, and 8 to 10 and TSFL, based on estimates from Broyles (2011), (c) 20-person hand crew using estimates from Haven *et al.* (1982) for U.S. Forest Service Regions 1, 2, and 4 by fuel resistance class, and (d) Type 1 dozer working uphill (0%–25% slope class) by fire behavior fuel models 1–13 and TSFL, using the midpoint of estimates from National Wildfire Coordinating Group (1998). The appropriate regression model is displayed in each cell along with the unadjusted r^2 (linear model) and pseudo-r^2 (non-linear model).

Firefighter Safety Considerations

Firefighter safety has long been recognized as the most important priority on any wildland fire (Jackson 1948). Thus, the concerns associated with firefighter safety have and should take priority over all other actions. In the wildland fire environment, firefighters are confronted with four basic natural safety hazards (Alexander *et al.* 2012):

- Burn-overs or entrapments by fast-spreading fires
- Snags and fire-weakened timber
- Rolling rocks and logs on steep slopes
- Lightning

To our knowledge there has yet to be a firefighter or civilian fatality associated with a wildfire burning in MPB-attacked lodgepole pine forests, but there have been some close calls. For example, a bulldozer operator and transport driver were burned-over during the Salt Fire in central Idaho during August 2011 (Church *et al.* 2011). Fortunately, neither was injured.

It is worth noting that firefighter injuries and deaths can also occur directly as part of the fire suppression operations itself (Britton *et al.* 2013a, 2013b, Cook 2013), irrespective of whether MPB induced tree mortality is involved. This can result from aircraft (i.e., mechanical failure, rotor downwash and wing-tip vortices), ground-based vehicles (e.g., bulldozer, fire engine, and tractor/plow unit), and hand tools or chainsaws that are involved in containing and/or extinguishing the fire (Teie 2005).

During the “red”-stage conditions of MPB attack, firefighter safety concerns generally coincide with the increased potential for high-intensity crown fire behavior and spotting potential. When fires spreading in surface fuels of conifer forests transition to crowning, at the very minimum they double their spread rate and intensity (Alexander and Cruz 2013). This rapid and dramatic change in the state of fire behavior will reduce the amount of time available for firefighters to reach safety zones (Alexander *et al.* 2013, Fryer *et al.* 2013). Furthermore, it can increase the size of safety zones needed to adequately protect firefighters (Butler and Cohen 1998, Butler and Putnam 2001). Prolific short- and long-range spotting caused by low ignition thresholds in affected crowns and ample firebrand material on decaying trees can also cut off firefighters from using their escape routes to reach their safety zones. These hazards combine to increase the potential safety issues that wildland firefighters are exposed to and require additional mitigation measures (Fig. 8.4).

During the "gray"-stage, as successfully attacked trees become weakened by decay, the safety hazards associated with wildland firefighting reach peak levels as snag densities can exceed 750 stems/ha (Page and Jenkins 2007). Snags are among the most dangerous threats that firefighters face due to their weakened state and subsequent unpredictability during both normal firefighting and tree felling operations (i.e., the cutting of trees and/or snags down) (Mangan 2007). Recent fatalities associated with falling snags (hitting firefighters), such as on the Steep Corner Fire in central Idaho in 2012 (Foster *et al.* 2013), and with tree/snag felling operations such as on the Eagle Fire in northern California in 2008 (Terrell *et al.* 2013), clearly demonstrate the potential dangers of working in an environment with high snag densities and/or where extensive falling operations are needed.

Beyond the initial hazards posed by snags during burning of "gray"-stage forests, there are even greater dangers after the fire front passes. The snags that remain standing are further weakened leading to widespread snag fall for several days, making normal post-fire patrol and mop-up operations especially dangerous, as has been noted following the Basin Complex fires in 2008 in SOD-killed forests in central California (Lee *et al.*

2010). Given the level or risk that firefighters are exposed to in “gray”-stage stands it is probable that direct action by personnel on the ground may not be possible and only equipment with reinforced steel cages may be safely operated.

As affected stands enter the post-epidemic phase and the snags continue to deteriorate and fall, the density of snags decreases but those that remain are weak and likely rotten. While mitigation measures such as hazard-tree falling may continue to be possible (Manning *et al.* 2000), the decayed trees are difficult and dangerous to fall due to a lack of adequate holding wood and the presence of “widow-makers” (i.e., trees or snags that have detached or broken limbs or tops) (Peters 1991, Myers and Fosbroke 1994, National Institute of Occupational Safety and Health 1995).

The transfer of snags to the surface also creates what is commonly referred to as “jack straw” or “jackpot” conditions (Hirsch *et al.* 1979), where large amounts of dead and downed woody fuel stack on top of each other. These conditions hamper access into and out of the fire area. Travel times by foot to remote fires can become long as firefighters must maneuver over and through the heavy, dead and down woody fuel accumulations, which raises concerns about the ability of firefighters to quickly leave the fire area. Escape times to safety zones may increase because of reduced rates of movement (Alexander *et al.* 2013) or because longer routes are required.

Implications for Fire Research and Fire Management

To predict the full consequences of large-scale MPB mortality on wildfire potential, we suggest that it is necessary to broaden the definition of resistance to control as follows: “the relative difficulty of constructing and holding a control line as determined by the fire suppression operations, fire behavior characteristics, and firefighter safety considerations" (Fig. 8.2). That is, the effects of MPB-induced tree mortality on crew safety and the management responses to these changes, must be considered. Fire suppression personnel who have been involved in the control and extinguishment of wildfires in MPB-attacked lodgepole pine forests will have undoubtedly found the idea of a more expanded concept of resistance to control a logical approach (E.M. "Sonny" Stiger, FireSafe Montana, Helena, MT, 2013, personal communication). Researchers who lack this kind of practical field experience may find the suggested approach frustrating at first, as certain models and data are not readily available to enable them to easily conduct simulations and thereby quickly publish their results.

As many of these proposed effects of MPB on resistance to control are based mostly on personal *ad hoc* personal observations, there exists a need for formal documentation of these impacts in the form of wildfire case studies (e.g., Cruz and Plucinski 2007). The analyses undertaken of the effects of SOD-caused changes in fuel structure on potential surface fire behavior in relation to the capability and productivity of fire suppression resources undertaken by Valachovic *et al.* (2011) represents an excellent example of one type of analysis that needs to be undertaken for MPB-attacked lodgepole pine forests. Hopefully, fire researchers and fire managers alike will be attracted to the field to collect the kind of information that is required in order to ultimately develop the fire modelling systems and related facts needed for properly assessing the impacts of MPB-caused tree mortality on wildfire potential in lodgepole pine forest communities in western North America (Box 8.2).

Fire management organizations dealing with widespread tree mortality resulting from a MPB outbreak may be faced with a multitude of potential consequences. Given the likely impacts presented here, it is reasonable to predict detectable increases in common attributes of wildland fires, such as time to containment, cost, and the number of injuries, especially on large fires where MPB-related hazards accumulate over time and space. For example, lower fireline production capability may lead to greater resource needs and types (e.g., bulldozers) in order to maintain an equivalent level of fireline production, which may also lead to higher suppression costs or longer duration fires if resource needs cannot be met. Additionally, higher numbers of firefighters and longer duration fires may lead to increases in the likelihood and number of injuries. Britton *et al.* (2013b), for example, found that on large wildfires in the U.S. that the number of person-days of exposure was the best predictor of the occurrence of injuries.

In recognition of the many dangers faced by wildland firefighters in these forests, incident management personnel have already begun to adjust their strategies and tactics to mitigate potential impacts. Point or zone protection strategies as opposed to full perimeter containment are now frequently implemented where values-at-risk are considered low or where the dangers associated with full suppression are considered too great. Recent examples include the High Park and West Fork Fires in Colorado during the 2012 and 2013 fire seasons, respectively (R.D. Wilmore, USDA Forest Service, Eagle, CO, 2013, personal communication). Although the true impacts of these changing management strategies are as yet unknown, within the wildland fire management community it is believed that fire sizes, and accordingly fire suppression costs, will increase but the frequency of firefighter injuries will decrease.

Fire management agencies should also consider supplementing their conventional fire training with operational prescribed fires in MPB fuel complexes (Cheney 1994). This kind of live fire training would provide the opportunity for those firefighters who have limited exposure to such situations to according gain experience.

Conclusions

The impacts of MPB-induced tree mortality in lodgepole pine forests clearly involve much more than just the effects on selected characteristics of fire behavior. We have argued here that there are three main factors that should be considered in assessing the potential effects of MPB-related tree mortality on a wildfire's resistance to control, namely, fire behavior characteristics, fire suppression operations, and firefighter safety considerations. An emphasis on extreme fire behavior potential in most of the research to date has led to an inadequate accounting of the implications for fire suppression and human safety, which has perhaps caused some confusion as to the potential effects of MPB-induced tree mortality on wildfire potential (Gabbert 2010). High intensity fires, extensive MPB-caused mortality, and their interaction are widely recognized as playing a fundamental role in the ecology of lodgepole pine forests (Brown 1975). However, as long as firefighters are placed in situations where extensive MPB-caused mortality exists, it is vital that proper recognition be given to all the factors that might influence wildfire potential.

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CHAPTER 9

SUMMARY AND CONCLUSIONS

Introduction

Bark beetle-caused tree mortality and its effects on both the fuels complex and potential fire behavior in affected forests, particularly lodgepole pine forests, has been a topic of much debate in recent years (Hicke et al. 2012; see Chapter 2, 2014; Black et al. 2013). Early research on the subject seemed to suggest a straightforward relationship where it was expected that the tree mortality and its resulting direct and indirect effects on forest structure and fuel loading would increase potential fire behavior both in the short- and long-term (Brown 1975; Lotan et al. 1985; Schmid and Amman 1992). However, recent work has suggested a much more complicated relationship than previously thought that is dependent upon a host of site specific factors and the particular bark beetle-host system (Hicke et al. 2012; Donato et al. 2013). Of particular concern and the subject of most debate has been the influence of recent tree mortality on crown fire potential, including crown fire initiation and spread, in lodgepole pine forests. The work presented here represented an attempt to quantify and clarify some of the important changes to crown fuel flammability and crown fire potential caused by bark beetle attack so that more accurate assessments of crown fire potential can be made in the future.

Within this dissertation we answered four primary research questions based on the results from extensive field and lab work conducted in both lodgepole pine and Engelmann spruce dominated forests (Box 9.1). In this chapter we provide a summary of the results from our anlaysis organized by three primary topics, namely, the seasonal

Box 9.1. Summary of the conclusions and implications of the dissertation's four primary research questions.

1. ***How does successful attack by mountain pine beetle in lodgepole pine and spruce beetle in Engelmann spruce trees alter the moisture content, chemistry, and flammability of foliage over time?*** **Conclusions:**
   - There are significant declines in the moisture content of foliage for both species with most of the decline occurring within 12 to 14 months after initial attack.
   - A shift in foliar chemistry occurs for both species with higher proportions of carbohydrates and crude fat in unattacked foliage and lower proportions of those compounds in foliage on attacked trees.
   - There is a significant increase in foliar flammability, particularly igntiability, due primarily to the decrease in moisture content.

   Implications: The high igntiablity of foliage on attacked trees could lead to a decrease in the canopy ignition threshold in stands containing high proportions of bark beetle-altered foliage, and therefore an increase in the potential for crown fire initiation.

2. ***How does the moisture content of dead foliage on lodgepole pine trees during the red stage of mountain pine beetle attack change diurnally?*** **Conclusions:**
   - Contrary to other fine dead surface fuels, the red foliage on mountain pine beetle-killed lodgepole pine trees does not have significant diurnal variation.
   - Existing models used to predict the hourly changes in moisture content of other fine dead fuels are inadequate.

   Implications: The high igntiability of the red foliage could extend into the overnight or early morning hours, thereby potentially lengthening the window of crown fire activity.

3. ***Can models be developed to predict the hourly change in moisture content of foliage on lodgepole pine trees during the red stage?*** **Conclusions:**
   - The red foliage does dry following a typical exponential decline thereby allowing for the development of diffusion-based bookkeeping-type system models.
   - Calibrated operational fine fuel moisture models performed as well or better than the more complicated bookkeeping-type system models.
   - Model evaluation indicated that the proposed models may be limited in geographic applicability to the Intermountain region of the western United States.

   Implication: We recommend that the calibrated operational fine fuel moisture models be used by field personnel.

4. ***What are the consequences of mountain pine beetle-caused changes to crown and canopy fuels on crown fire initiation and spread in lodgepole pine forests?*** **Conclusions:**
   - Bark beetle attack produces stands with highly hetergenous and complex canopy fuel conditions.
   - Existing empirically-based fire behavior models are inadequate for accurately assessing crown fire potential in recently attacked lodgepole pine forests.
   - Results from physics-based models should be interpreted with caution as these models have yet to be evaluated in conifer forests containing either live or dead canopy fuel.

   Implications: Our understanding of crown fire dynamics in recently attacked lodgepole pine forests will not substantially improve until a significant effort is made to collect field-based observations of fire behavior to either validate existing models or develop new ones.

changes in moisture, chemistry, and flammability of bark beetle attacked foliage on lodgepole pine and Engelmann spruce trees, the diurnal changes in moisture content of lodgepole pine foliage during the red stage of mountain pine beetle attack, and the implications of those changes on crown fire initiation and spread in lodgepole pine forests.

Seasonal Changes in Moisture Content, Chemistry, and Flammability of Lodgepole Pine and Engelmann Spruce Foliage

In Chapters 3 and 4 the detailed results pertaining to the seasonal change in moisture content, chemistry, and flammability of foliage on bark beetle-attacked lodgepole pine and Engelmann spruce were presented. Several similarities between tree species were found as well as some important differences that have implications on crown fire potential. Recently attacked lodgepole pine and Engelmann spruce foliage displayed substantial decreases in moisture content compared to unattacked tree foliage, decreasing by a factor of 9 in lodgepole pine and 4 in Engelmann spruce foliage approximately 12 to 14 months following initial attack. Within the crowns of individual trees, lodgepole pine foliage required a longer time period to express significant decreases in moisture content compared to Engelmann spruce foliage. By the end of the first fire season (October) in which the trees were initially attacked, lodgepole pine moisture content was still equivalent to the unattacked foliage moisture content, however, the recently attacked Engelmann spruce foliage displayed patchy but significant declines in moisture content compared to unattacked foliage. It was not until the early portion of the next fire season (i.e. spring) following the summer of initial attack that lodgepole pine foliage displayed significant declines in moisture content.

Bark beetle-induced changes to foliar chemistry for both tree species closely followed observed changes in moisture content. During the process of dry-down the proportion of soluble carbohydrates and crude fat within the foliage decreased while the proportion composed of the structural compounds of lignin and cellulose increased. These results were similar to those reported in litter decomposition studies where the proportion of dry matter composed of lignin was found to increase with time (e.g. Edmonds 1980). Additionally, terpenes including monoterpenes and sesquiterpenes, were found to be emitted at higher rates in recently attacked foliage on lodgepole pine but not on Engelmann spruce and correlated to needle flammability for both species.

The combined effects of the changes in moisture content and chemistry resulted in substantial increases in foliage flammability, particularly ignitability, in both tree species. Moisture content was found to be the most important variable affecting foliage flammability followed by the changes in foliar chemistry. Based on the reported results we suggested that there may be periods of enhanced potential for surface fires to transition to crown fires in stands containing significant amounts of bark beetle-altered foliage due to a lower canopy ignition threshold compared to unattacked stands. This enhanced potential would be most acute under more moderate fire weather and stand conditions where surface fire intensity and/or canopy base height would normally limit crown fire initiation. However, this period of enhanced crown fire initiation is dependent upon both the time since attack and the particular trees species as it was found that the foliage on recently attacked Engelmann spruce only remained attached for a period of 12 to 14 months following initial colonization by the beetle, suggesting that once the needles drop to the forest floor, crown fire potential significantly decreases due to a decrease in aerial fuel continuity.

Diurnal Changes in Lodgepole Pine Foliar Moisture Content

Given the importance of fuel moisture on the ignitibility of lodgepole pine foliage as demonstrated in Chapter 3, it was important that methods be developed to predict short-term (i.e. hourly) changes in moisture content that can be used to more accurately assess crown fire potential at operational time scales. Previous research has assumed that the moisture content of mountain pine beetle-attacked lodgepole pine tree foliage during the red stage is equivalent to the moisture content of other fine dead surface fuels (e.g. Hoffman et al. 2012; Schoennagel et al. 2012). Most fine dead surface fuels show strong diurnal trends in moisture content as they respond to increasing atmospheric moisture during the night and lower moisture during the day (Hartford and Rothermel 1991). This daily trend in moisture content usually corresponds to periods of decreased fire behavior at night and peaks in fire behavior during the afternoon. The results from Chapter 5 showed that many of the models used to estimate fine dead fuel moisture in Australia, Canada, and the USA are inadequate for predicting the moisture content of dead lodgepole pine foliage due to the lack of diurnal variation, with significant under- and over prediction biases during periods of low and high atmospheric moisture, respectively.

Due to the poor predictions obtained from existing fine fuel moisture models it was necessary to develop and test new models or calibrate existing models. Additional field sampling was carried out to capture a wider range of air temperature and relative humidity than observed in Chapter 5 to develop more robust models (see Chapter 6). Five models in total were developed and evaluated including three bookkeeping-type system models based on diffusion theory that used previously identified model forms (e.g. Catchpole et al. 2001) and two calibrated operational models commonly used in the USA and Canada. All models performed well compared to the test dataset with the calibrated operational models performing as well or better than the more complicated bookkeeping-type system models. Based on these results we recommended that fire managers use the calibrated operational models to predict the moisture content of red and dead foliage on mountain pine beetle-attacked lodgepole pine due to their high accuracy and ease of use.

Crown Fire Potential in Lodgepole Pine Forests

Chapter 7 represents a critical review and digest of the literature on the subject of crown fire potential in recently attacked, mountain pine beetle-infested lodgepole pine forests during the red stage using the results from Chapters 3 to 6 as well as other pertinent research. We found inconsistent results in the literature due to the use of inappropriate and/or un-validated fire behavior models that employed inadequate descriptions of the mountain pine beetle-affected crown and canopy fuels. We suggested that crown fire initiation and spread potential is higher in recently attacked forests compared to unattacked forests and that a host of site specific factors such as outbreak severity, timing, and length could have important but as yet unknown impacts based on a set of limited fire behavior observations and re-examination of fire behavior modeling methodology. Due to the limitations of current fire behavior models and lack of quality data we propose that further advances in our knowledge of crown fire potential in recently attacked forests will only be possible if a substantial effort is undertaken to document wildfires, prescribed fires, and/or conduct experimental fires.

As described in Chapter 7, the study of crown fire potential in recently attacked, bark beetle-infested stands will not be able to substantially progress until wildfire observations and/or experimental fires can be used to quantify several important fire behavior metrics, including, rate of spread, fireline intensity, fuel consumption, and residence time, under a variety of weather and stand conditions. Ideally, stands with varying amounts and proportions of bark beetle-altered foliage, distributed spatially in arrangements from random to highly clustered would be subjected to fire in order to quantify the relative impact of both the amount of red foliage and its spatial distribution. This would allow wildland firefighters to identify and rank the relative hazard of stands, in terms of crowning potential, containing the variety of morality levels and spatial arrangements that are found naturally in forested landscapes. For example, we may eventually find that a critical level of red foliage exists such that until that level is reached, bark beetle-caused tree mortality may have little effect on crown fire initiation or spread. Additionally, we may also find that the spatial arrangement of the mortality within a stand (either highly clustered or randomly distributed) may have little overall impact on fire behavior. These questions can only truly be answered in the field, particularly as they relate to wildland firefighter safety and operations, which is where the need for such research ultimately arises.

Conclusions

Bark beetles are a natural disturbance agent in the conifer forests of western North America having caused periods of significant tree mortality for thousands of years (e.g. Brunelle et al. 2008). Thus, the relatively recent tree mortality caused by eruptive outbreaks of these beetles and the direct and indirect effects on forest structure and fire behavior should also be considered a natural part of the life history of these forests (Wright and Heinselman 1973; Brown 1975; Lotan et al. 1985). Although the changes to forest structure, fuel loading, and subsequent fire behavior caused by the tree mortality are considered natural, there are significant consequences of these changes related to human factors such as wildland firefighter safety and fire suppression operations as outlined in Chapter 8. Fire managers and wildland firefighters should be cognizant of the impacts of recent tree mortality on potential fire behavior regardless of whether the changes are considered natural. Therefore it is important that research be undertaken, as presented here and elsewhere, to quantify and understand the various factors affected by bark beetle-caused tree mortality that impact potential fire behavior and the consequences of those changes for wildland firefighters. Given that there are still substantial uncertainties associated with crown fire potential in recently attacked forests, wildland firefighters should continue to be cautious when working in these forests and prepare for fire behavior that is not easily predicted using conventional operational models and guidelines.

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APPENDICES

APPENDIX A

Co-author permission letters

August 28, 2013

Wesley Page
855 North 700 East #29
Logan, UT 84321

Dear Dr. Hebertson:

As co-author of the paper "Fuels and Fire Behavior Dynamics in Bark Beetle-Attacked Forests in Western North America and Implications for Fire Management", I am requesting your permission to include this paper as a chapter in my dissertation, specifically the Introduction. I will include acknowledgements and/or appropriate citations for your contributions. Please advise me of any changes you require.

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Wesley Page

I hereby give permission to Wesley Page to publish the above paper as a Chapter in his dissertation.

Signed Elizabeth Hebertson

Date 9/11/2013

August 18, 2013

Wesley Page
855 North 700 East #29
Logan, UT 84321

Dear Dr. Runyon:

As co-author of the papers "Mountain Pine Beetle Attack Alters the Chemistry and Flammability of Lodgepole Pine Foliage" and "Spruce Beetle-Induced Changes to Engelmann Spruce Foliage Flammability", I am requesting your permission to include these papers as chapters in my dissertation. I will include acknowledgements and/or appropriate citations for your contributions. Please advise me of any changes you require.

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I hereby give permission to Wesley Page to publish the above papers as Chapters in his dissertation.

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CURRICULUM VITAE

Wesley G. Page
855 North 700 East #29 • Logan, Utah 84321, USA
wgp6@hotmail.com

EDUCATION

Utah State University, S.J. & Jessie E. Quinney College of Natural Resources, Logan, Utah
Doctor of Philosophy in Forestry, May 2014
Disturbance Ecology Lab, Advisor: Mike Jenkins
Dissertation Title- Bark Beetle-Induced Changes to Crown Fuel Flammability and Crown Fire Potential,
GPA 4.0 out of 4.0

Utah State University, College of Natural Resources, Logan, Utah
Master of Science in Forestry, May 2006
Disturbance Ecology Lab, Advisor: Mike Jenkins
Thesis Title- Mountain Pine Beetle Effects on Fuels and Fire in Selected Lodgepole Pine Stands within the Intermountain Region,
GPA 4.0 out of 4.0

Northern Arizona University, School of Forestry, Flagstaff, Arizona
Bachelor of Science in Forestry, May 2002
GPA 3.9 out of 4.0, Honors: *Summa Cum Laude*

PROFESSIONAL EXPERIENCE

Utah State University, S.J. & Jessie E. College of Natural Resources, April 2011-Present
Graduate Research Assistant

- Developed methods to determine the influence of different fuel chemical and physical properties on the flammability of foliage from bark beetle-affected conifers.
- Constructed and operated various lab equipment for evaluating flammability, including an oxygen bomb calorimeter and a custom built infrared heating device.
- Supervised at least one lab technician during the summer months.
- Helped write and edit Utah Army National Guard Camp W.G. Williams Fire Management Plan.
- Prepared and published several scientific reports detailing extensive data collection and analyses.

U.S. Forest Service, Prescott National Forest, Prescott, Arizona, March 2008-April 2011
Hotshot Lead Crewmember and Squad Leader (wildland firefighter)

- Supervised the daily activities of a hotshot crew squad (9 people), including, assigning specific tasks and duties to crewmembers, monitoring performance, and ensuring squad safety during all crew operations.
- Made critical fireline decisions as delegated by the Hotshot Captain, including, ensuring that safe and effective wildland suppression tactics were utilized.

- Completed squad performance evaluations, responsible for maintaining and restocking crew cache, and serving in other fireline duties as requested e.g. Firing Boss, Task Force Leader, etc.
- Experience in all size classes and complexities of wildland fires across the United States.

U.S. Forest Service, Mendocino National Forest, November 2005-March 2008
Fire Management Specialist (Prescribed Fire and Fuels)

- Assisted the forest Fuels and Fire Planner with the planning and implementation of hazardous fuel reduction projects across the forest which included prescribed fire and mechanical fuel treatments.
- Provided input as a Fuels Specialist on interdisciplinary planning teams with duties of determining treatment types, locations, and mitigation actions needed to protect sensitive features.
- Played an integral part in the planning of fuels projects on a forest-wide scale through the use of landscape scale fire behavior programs such as FARSITE and FlamMap.

Utah State University, **College of Natural Resources**, January 2004-November 2005
Graduate Research Assistant

- Developed and researched methods to design and implement an extensive field sampling protocol to measure changes in forest fuels (surface, ladder, and canopy) due to bark beetle infestations in Intermountain lodgepole pine forests.
- Supervised two undergraduate students during the summer months.
- Used custom fuel models and fire behavior programs to predict and compare fire behavior in bark beetle-affected stands.

U.S. Forest Service, Fishlake, Santa Fe, and Coconino N.F.s, Summers 1999 to 2003
Assistant Engine Foreman, Engine and Hotshot Crewmember (wildland firefighter)

- Operated wildland fire engine by placing engine in a safe manner and utilizing engine capabilities to safely and efficiently extinguish wildland fires.
- Served as an Engine Boss and Incident Commander of wildland fires.
- Crewmember of a highly trained interagency hotshot crew assigned to suppress the full range of difficulty and complexity of wildland fires across the United States.
- Gained knowledge of fire suppression techniques, fire behavior, and causes of fire for many different fuel types common in the United States.

TEACHING EXPERIENCE

National Wildfire Coordinating Group, Skill Classes, Unit Instructor,

- S-130, Firefighter Training
- S-131, Advanced Firefighter Training
- S-190, Introduction to Wildland Fire Behavior
- S-215, Fire Operations in the Urban Interface
- S-234, Ignition Operations
- S-290, Intermediate Wildland Fire Behavior
- L-280, Followership to Leadership

REFEREED PUBLICATIONS

Page, W.G., M.J. Jenkins, and M.E. Alexander. In review. Models to predict the moisture content of lodgepole pine foliage during the red stage of mountain pine beetle attack.

Page, W.G., M.J. Jenkins, and M.E. Alexander. 2014. Crown fire potential in lodgepole pine forests during the red stage of mountain pine beetle attack. *Forestry* 87: in press.

Page, W.G., M.J. Jenkins, and J.B. Runyon. 2014. Spruce beetle-induced changes to Engelmann spruce foliage flammability. *Forest Science* 60: in press, doi:10.5849/forsci.13-050.

Jenkins, M.J., J.B. Runyon, C.J. Fettig, **W.G. Page**, and B.J. Bentz. 2014. Interactions among the mountain pine beetle, fires, and fuels. *Forest Science* 60: in press, doi:10.5849/forsci.13-017.

Page, W.G., M.E. Alexander, and M.J. Jenkins. 2013. Wildfire's resistance to control in mountain pine beetle-attacked lodgepole pine forests. *The Forestry Chronicle* 89(6): 783-794.

Page, W.G., M.J. Jenkins, and M.E. Alexander. 2013. Foliar moisture content variations in lodgepole pine over the diurnal cycle during the red stage of mountain pine beetle attack. *Environmental Modelling & Software* 49: 98-102.

Page, W.G., M.J. Jenkins, and J.B. Runyon. 2012. Mountain pine beetle attack alters the chemistry and flammability of lodgepole pine foliage. *Canadian Journal of Forest Research* 42(8): 1631-1647.

Jenkins, M.J., **W.G. Page**, E.G. Hebertson, and M.E. Alexander. 2012. Fuels and fire behavior dynamics in bark beetle-attacked forests in western North America and implications for fire management. *Forest Ecology and Management* 275: 23-34.

Jenkins, M.J., E. Hebertson, **W.G. Page**, and C.A. Jorgensen. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *Forest Ecology and Management* 254: 16-34.

Page, W.G., and M.J. Jenkins. 2007a. Mountain pine beetle-induced changes to selected lodgepole pine fuel complexes within the Intermountain Region. *Forest Science* 53(4): 507-518.

Page, W.G., and M.J. Jenkins. 2007b. Predicted fire behavior in selected mountain pine beetle-infested lodgepole pine. *Forest Science* 53(6): 662-674.

NON-REFEREED PUBLICATIONS

Page, W.G., and M.R. Kuhns. 2014. Prescribed fire on public lands. Utah State University, Extension Forest Facts, NR/FF/025. 5 pp.

Page, W.G. 2013. Burning toward uncertainty. *Wildfire* 22(3): 34.

Jenkins, M.J., E.G. Hebertson, **W.G. Page**, and W.E. Lindquist. 2011. A tool to estimate the impact of bark beetle activity on fuels and fire behavior. *Fire Management Today* 71(3): 36-41.

WILDLAND FIRE QUALIFICATIONS
All qualifications are National Wildfire Coordinating Group (NWCG) certified

Faller "B" (Certified sawyer on wildland fires)
Firefighter Type 1 / Squad Boss (Leader of squads of 3 to 10 firefighters)
Engine Boss (Leader of fire engines with 3+ firefighters)
Crew Boss (Leader of crews of 20 or more firefighters)
Firing Boss (Leader of firefighters performing ignition operations on wildland and prescribed fires)
Dozer Boss (trainee) (Leader or dozers on wildland fires)
Incident Commander Type 4 (Commander of multiple resources initial attacking fires)
Fire Effects Monitor (Monitoring fire effects on wildland and/or prescribed fires)
Field Observer (Observe and document fire operations on wildland fires)
Task Force Leader (trainee) (Leader of multiple resources on large wildland fires)
Prescribed Fire Burn Boss Type 2 (trainee) (Commander of type 2 prescribed fires)

HONORS AND AWARDS

Regents Scholarship, Northern Arizona University, full tuition wavier (Fall 1998-Spring 2002)

Northern Arizona University, School of Forestry, Scholarships for Academic Excellence
Raymond Scholarship (1998-2000)
DuBois Forestry Scholarship (2001 and 2002)
Glen Voorhies Forestry Scholarship (2001 and 2002)

Northern Arizona University, Dean's List (1998-2002)

Northern Arizona University, School of Forestry, Applequist Award
Achieving the highest academic average in my forestry class during professional program (2002)

PROFESSIONAL ASSOCIATIONS

Member, Society of American Foresters (Since 2000)
Student Member, International Association of Wildland Fire (2011)

SCHOLASTIC MEMBERSHIPS

Member, Phi Kappa Phi National Honor Society (Spring 2001)
Member, Xi Sigma Pi National Forestry Honor Society (Spring 2002)
Member, Golden Key National Honor Society (Spring 2001)