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Research Note

Effects of fuel load and moisture content on fire behaviour and heating in masticated litter-dominated fuels

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Abstract. Mechanical fuels treatments are being used in fire-prone ecosystems where fuel loading poses a hazard, yet little research elucidating subsequent fire behaviour exists, especially in litter-dominated fuelbeds. To address this deficiency, we burned constructed fuelbeds from masticated sites in pine flatwoods forests in northern Florida with palmetto-dominated understoreys and examined the effects of fuel load and fuel moisture content (FMC) on fire behaviour. Flame lengths (49–140 cm) and fireline intensity (183–773 kJ m^{-1} s^{-1}) increased with loading (10–30 Mg ha^{-1}) and were reduced by 40 and 47% with increasing FMC from 9 to 13%. Rate of spread was not influenced by fuel load, but doubled under drier FMC. Fuel consumption was >90% for all burns. Soil temperatures were influenced by both fuel load and FMC, but never reached lethal temperatures (60°C). However, temperatures of thermocouple probes placed at the fuelbed surface reached 274–503°C. Probe maximum temperature and duration at temperatures ≥60°C (9.5–20.0°C min) both increased with fuel load, but were unaffected by FMC. The fire behaviour observed in these unique litter-dominated fuelbeds provides additional insight into the burning characteristics of masticated fuels in general.

Additional keywords: fire hazard reduction, flammability, mechanical fuel treatment, pine flatwoods, saw palmetto.

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Introduction

Mechanical treatment of forest and shrubland fuels has become an increasingly common approach to mitigate potential hazards associated with wildfire in the wildland–urban interface (WUI) and for restoring fire-dependant ecosystems where historical fire regimes have been altered. Mastication (mowing, chipping or mulching) alters understorey fuels by converting shrubs and small trees into dead surface fuels, thereby reducing vertical continuity between fuel strata, reducing fuelbed depth and increasing fuelbed bulk density. However, when fuels are left on site they are only rearranged, without immediate reduction in total fuel loading (Bradley *et al.* 2006; Kobziar *et al.* 2009; Vaillant *et al.* 2009) and often with increases in surface fuels (Kane *et al.* 2009; Kobziar *et al.* 2009). Although these alterations in fuel arrangement may serve to subdue fire behaviour for better control during fire suppression or prescribed burning (Glitzenstein *et al.* 2006), high concentrations of surface fuels may result in unforeseen ecological consequences that conflict with management objectives, when they do burn (Busse *et al.* 2005; Bradley *et al.* 2006; Knapp *et al.* 2011; Kreye *et al.* 2011). Because such treatments are increasingly being implemented, it is important to fully understand their effects on potential fire behaviour and fire effects in order to determine both their effectiveness in reducing fire hazard as well as potential ecological consequences.

The majority of recent mastication research has been conducted in the western US, yet treatments are being increasingly employed in the south-eastern US (Glitzenstein *et al.* 2006; Brockway *et al.* 2009, Menges and Gordon 2010) and in Europe (Molina *et al.* 2009; Castro *et al.* 2011) and will likely occur elsewhere. Although studies at masticated sites have begun to quantify fuel conditions (Bradley *et al.* 2006; Glitzenstein *et al.* 2006; Hood and Wu 2006; Kane *et al.* 2009; Kobziar *et al.* 2009; Battaglia *et al.* 2010), describe fire behaviour (Bradley *et al.* 2006; Glitzenstein *et al.* 2006; Kobziar *et al.* 2009; Knapp *et al.* 2011) and document negative effects from burning (Bradley *et al.* 2006; Knapp *et al.* 2011), very few controlled experiments have been conducted to quantify the effects of their novel fuelbed properties on relevant fire metrics. Because current research has been primarily conducted where surface fuel mass is dominated by woody debris (89%, Glitzenstein *et al.* 2006; 87%, Kane *et al.* 2009; 68–80%, Battaglia *et al.* 2010), controlled experimental burning of constructed fuelbeds has exclusively used masticated woody material (Busse *et al.* 2005; Kreye *et al.* 2011). Fuelbeds resulting from mastication of palmetto–gallberry understoreys in south-eastern US pine flatwoods are dominated by foliar litter (Kreye 2012), and although fuelbed depths are similar to those observed elsewhere, bulk density is much lower. Mastication in these pine flatwoods forests provides an opportunity to conduct manipulative fire behaviour

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experiments to quantify the effects of fuelbed properties on fire behaviour and heating in compact, but foliar litter-dominated fuelbeds.

The objectives of this study were to quantify the influence of fuel loading and fuel moisture content (FMC) on fire behaviour and subsequent heating during the burning of fuelbeds composed of litter and small-diameter shrubs from a pine flatwoods ecosystem. To quantify effects on fire behaviour, we tested the hypotheses that maximum flame length, rate of spread (ROS), fuel consumption and fireline intensity would differ across three fuel loads (10, 20 and 30 Mg ha^{-1}) at two fuel moisture contents (9 and 13%). To evaluate above and belowground heating, we tested the hypotheses that maximum temperature and duration of lethal heating (≥60°C) would increase with fuel loading under both moisture conditions.

Methods

Surface fuels were collected 2–3 weeks after mastication of understorey fuel strata (<20 cm) in pine flatwoods forests in the Osceola National Forest in north-central Florida (30°14′N, 82°36′W). The management objectives of the mastication treatments included reducing fuel loads, reducing competition to increase overstorey tree vigour, and enhancing resilience of overstorey trees in the event of a wildfire. The forest is dominated by mature longleaf pine (*Pinus palustris* Mill.) and slash pine (*P. elliottii* Engelm.) in the overstorey, and by saw palmetto (*Serenoa repens* (Bartr.) Small) – a shrub-form palm – and gallberry (*Ilex glabra* (L.) Gray) in the understorey. Masticated material is primarily derived from shrubs because small trees are rare in the understorey and a midstorey is absent in this ecosystem. Masticated fuel loading across 16 field plots averaged 17.0 Mg ha^{-1} (s.d. 5.7) but ranged from 8.5 to 29.1 Mg ha^{-1}, and fuelbed depth averaged 8.0 cm (s.d. 4.1) but ranged from 2.1 to 20.1 cm. Foliar litter comprised 68% (s.d. 14) of fuelbed mass, whereas woody material comprised 32% (s.d. 14), with the smaller diameter woody material dominating (1-h, 19%; 10-h, 11%; 100-h, 2%).

Fuels were collected from three representative locations within the treatment. At each location, surface debris was collected, at random, into 30-gallon (114-L) paper bags (105 total), transported to the University of Florida, oven-dried and weighed. Because our goal was to evaluate burning properties of masticated material, partially decomposed surface material beneath the newly masticated surface fuels was not collected. Also, 1000-h fuels were rare and not collected for constructing fuelbeds. Each bag of fuel was randomly assigned to a treatment (below) and replicate for constructing fuelbeds. Therefore, constructed fuelbeds were composed of a mixture of randomly collected surface fuels so that fuel composition was better controlled during experimentation.

To conduct experimental burning, 18 fuelbeds were created from collected fuel and burned in May 2010, under conditions relevant for both prescribed burning and wildfires (non-extreme) in this region. Temperatures ranged from 27.8 to 33.9°C, and relative humidities from 46 to 63%, with southern and south-western winds ranging from 0.3 to 1.8 m s^{-1}. Fuelbeds were burned under three fuel loading treatments (10, 20 and 30 Mg ha^{-1}) and two FMC treatments in a 3 × 2 factorial design, replicated three times. Fuelbeds were created within 4-m diameter rings constructed of 15-cm aluminium flashing and located in a treeless opening within a pine flatwoods forest. Soils on which fuelbeds were created were fine sandy textured Grossarenic Paleudults with little organic matter, and surface vegetation (primarily grass) was removed before loading. Fuel was uniformly spread and compacted so that it would approximate fuelbed density measured in the field. Low FMC treatments were burned following loading, whereas higher FMC fuelbeds were moistened with water, covered overnight and burned the following day. Fuel moisture values were 8.9% (s.d. 1.7) in the low FMC treatment and 12.9% (s.d. 5.6) in the high FMC treatment.

Fuelbeds were ignited perpendicular to the wind at 0.5 m from the edge of the ring using a drip torch to create a head fire (Fig. 1). Timing of flame passage was recorded and maximum flame height was estimated from ruled metal rods located at 1.0, 1.2, 2.0, 2.5, 3.0 and 3.5 m from the ignition line. ROS was subsequently calculated, and flame length was determined from observed flame heights and average flame angle (Rothermel and Deeming 1980). Consumption was calculated as the depth of fuel consumed divided by pre-burn depth from four litter pins placed on cardinal directions, 1 m from centre. Temperatures at the fuelbed surface were recorded using three high temperature Type K Thermocouple probes (model CASS-14U-60-NHX, ungrounded, 1/4′ (6.35-mm) sheath, Omega Engineering, Stamford, CT, USA) located at 1.0, 2.0 and 3.0 m from the upwind edge. Soil temperatures were recorded using three bare 30-AWG Type K thermocouples (Omega Engineering) buried to depths of 2.0, 5.0 and 8.0 cm below the soil surface at the centre of each ring. Fireline intensity was calculated as ROS (m s^{-1}) × proportion consumed, fuel load (kg m^{-2}) and fuel heat content (19 678 kJ kg^{-1}, Hough and Albini 1978). Wind speed, air temperature and relative humidity were measured before each ignition.

Flame length, ROS, consumption, fireline intensity, maximum surface temperatures and duration of lethal heating (≥60°C) were compared across fuel load and FMC treatments (main effects and interactions) using a general linear model analysis of variance procedure (SAS version 9.2, SAS Institute Inc., Cary, NC). To evaluate soil heating we tested main effects and interactions of fuel loading and FMC on soil temperatures across the three soil depths. Assumptions of normality and equal variance were respectively validated using the Shipiro–Wilk Test and the Modified-Levene Equal Variance Test. The Tukey–Kramer Test was used to determine differences among fuel loading treatments. Temperature, RH and wind speed were compared across all treatments and tested as covariates in all analyses to account for potential differences in weather conditions.

Results

Constructed fuelbeds were 6.1, 8.9 and 11.9 cm (s.d. 0.8, 1.6, 0.6) deep with bulk densities of 16.7, 23.1 and 25.4 kg m^{-3} (s.d. 1.9, 4.8, 1.4) for the 10, 20 and 30 Mg ha^{-1} fuel load treatments. FMC treatments were low 8.9% (s.d. 1.7) and moderate 12.9% (s.d. 5.6). One 30-Mg ha^{-1} fuelbed was burned at 35.6% FMC, in error, and therefore excluded from analysis. The excluded

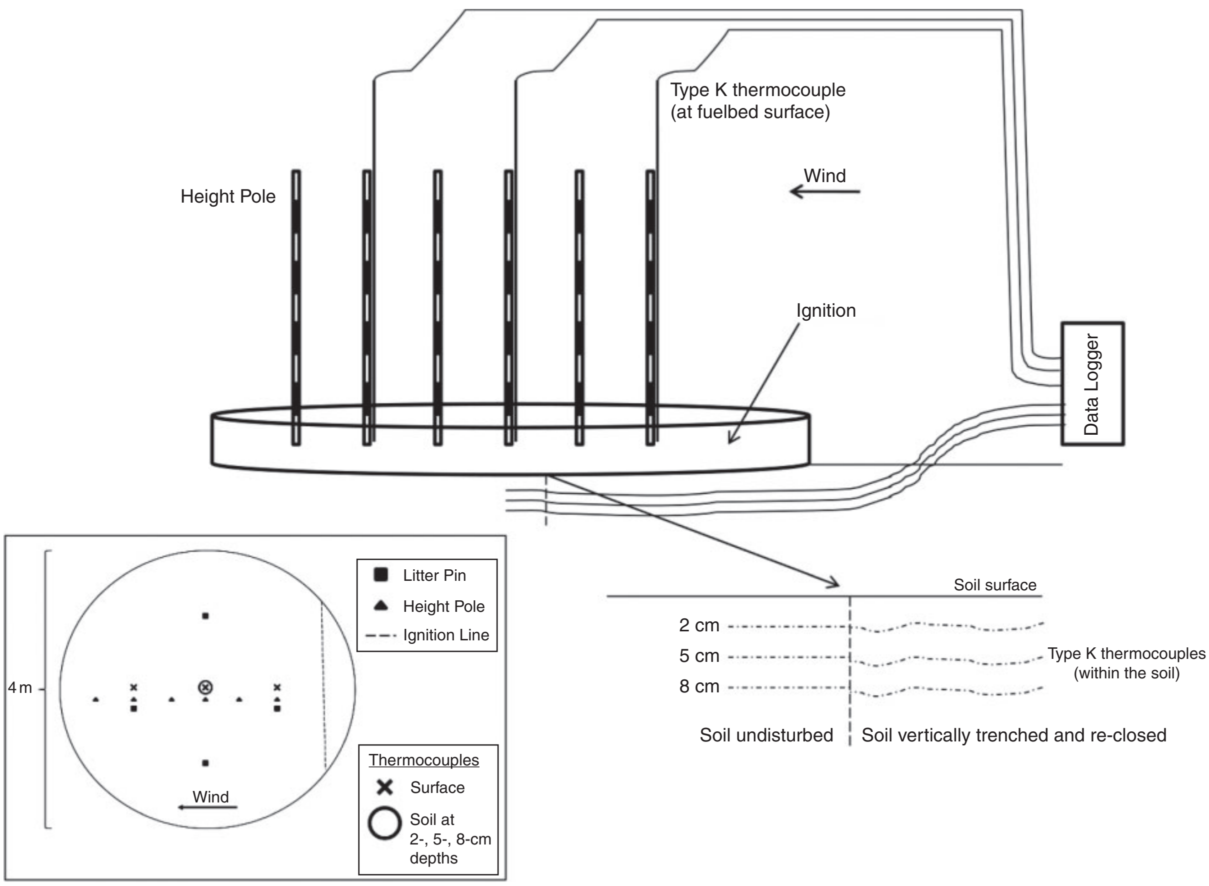

Fig. 1. Experimental setup for the burning of 12.6-m^2 fuelbeds created from masticated palmetto–gallberry-dominated pine flatwoods understorey. Type K thermocouples located at the fuelbed surface at 1, 2 and 3 m from ignition, and at 2-, 5- and 8-cm soil depths at plot centre. Soil thermocouples were narrowly trenched into soil to within 10 cm of plot centre whereby thermocouples were inserted 10 cm into the undisturbed soil profile using a rod. Components are not precisely to scale.

fuelbed burned with low flame lengths (35 cm) and slow ROS (0.20 m min^{-1}), although with high consumption (93%). Wetting fuelbeds did not increase soil moisture ($P = 0.847$), which averaged 9.9% (s.d. 1.1) at 5-cm depth. Air temperature (27.8–33.9°C), RH (46–63%) and wind speed (0.3–1.8 m s^{-1}) did not differ across FMC or fuel load treatments and were not significant covariates in any analysis.

Increasing fuel load resulted in longer flame lengths ($P < 0.001$), higher fireline intensity ($P = 0.003$), higher surface temperatures ($P < 0.001$) and longer durations of lethal heating ($P = 0.002$) (Table 1). However, fuel loading did not influence ROS ($P = 0.446$) or consumption ($P = 0.387$). Effects of fuel loading on fire behaviour metrics were similar across FMC treatments ($P > 0.05$ for all interactions). Higher FMC reduced flame lengths ($P = 0.001$), fireline intensity ($P = 0.029$) and ROS ($P = 0.007$), yet had no effect on consumption ($P = 0.130$), surface temperatures ($P = 0.887$) or duration of lethal heating ($P = 0.547$).

Maximum belowground temperatures differed across soil depth ($P < 0.001$), but lethal temperatures (≥60°C) did not occur. Soil heating increased with fuel loading (Fig. 2*a*, $P < 0.001$) (although 20- and 30-Mg ha^{-1} treatments did not differ) and under drier fuel moisture (Fig. 2*b*, $P < 0.001$). Initial soil temperature (31.8 ± 3.2°C) did not differ across soil depth ($P = 0.560$), FMC ($P = 0.323$) or fuel loading ($P = 0.651$), but was a significant covariate ($P = 0.006$) in the general linear model. No interactions between soil depth, FMC or fuel loading were detected.

Discussion

The results of this experiment quantify the amplifying effect of fuel load on fire intensity and subsequent heating during the burning of compact masticated fuelbeds dominated by foliar litter. Although fuelbed bulk density increased with fuel load, mimicking field observations, the increased compaction did not inhibit combustion or counteract the influence of fuel mass on fire intensity or surface and soil heating. Although lethal temperatures were not reached belowground, thermocouple probes at the surface reached high temperatures and exceeded 60°C (the presumed lethal temperature for live tissue necrosis) for long periods, a result that may indicate the potential for negative ecological effects (including basal heating or potential duff ignition in long-unburnt forests) that exacerbate overstorey mortality (Varner *et al.* 2005). The ability to predict post-mastication fire behaviour and potential ecological effects enhances managers' capacity to utilise mastication treatments.

Table 1. Fire behaviour characteristics from experimental burning of masticated understorey vegetation of south-eastern pine flatwoods across fuel loading and fuel moisture content treatments

Marginal and cell means are listed along with *P* values from GLM ANOVA. Surface temperatures and lethal heating are as indicated by thermocouple probes (see text for explanation). Fuel moisture content (FMC) treatment: low (8.9 ± 0.6%) and moderate (12.9 ± 2.0%). Lethal heating is the duration for which temperatures were equal to or exceeded 60°C. Note: differences in superscript letters within columns indicate that fuel load was significant and similar letters indicate no difference among means from the Tukey–Kramer *post hoc* comparison. Bold formatting indicates statistical significance ($P < 0.05$)

	Flame length (cm) Mean (s.e)	*P*	Rate of spread ($m\,min^{-1}$) Mean (s.e.)	*P*	Consumption (%) Mean (s.e.)	*P*	Fireline intensity ($kJ\,m^{-1}\,s^{-1}$) Mean (s.e.)	*P*	Surface temperature (°C) Mean (s.e.)	*P*	Lethal heating (min) Mean (s.e.)	*P*
FMC												
Low	111 (14)	**0.001**	1.17 (0.12)	**0.007**	93.6 (1.9)	0.130	593 (116)	**0.029**	386 (23)	0.887	14.54 (1.14)	0.547
Moderate	67 (14)		0.61 (0.09)		97.0 (0.7)		317 (83)		392 (24)		13.70 (1.23)	
Fuel load												
10 $Mg\,ha^{-1}$	49 (10)^{A}	**<0.001**	0.75 (0.19)	0.446	94.2 (2.2)	0.387	183 (47)^{A}	**0.003**	274 (19)^{A}	**<0.001**	9.48 (0.73)^{A}	**0.002**
20 $Mg\,ha^{-1}$	91 (10)^{B}		0.98 (0.16)		94.2 (2.2)		487 (81)^{AB}		429 (15)^{B}		14.25 (1.14)^{B}	
30 $Mg\,ha^{-1}$	140 (14)^{C}		1.00 (0.19)		97.6 (0.7)		773 (149)^{B}		503 (16)^{C}		19.93 (0.91)^{C}	
FMC × Fuel load	No interactions were significant											

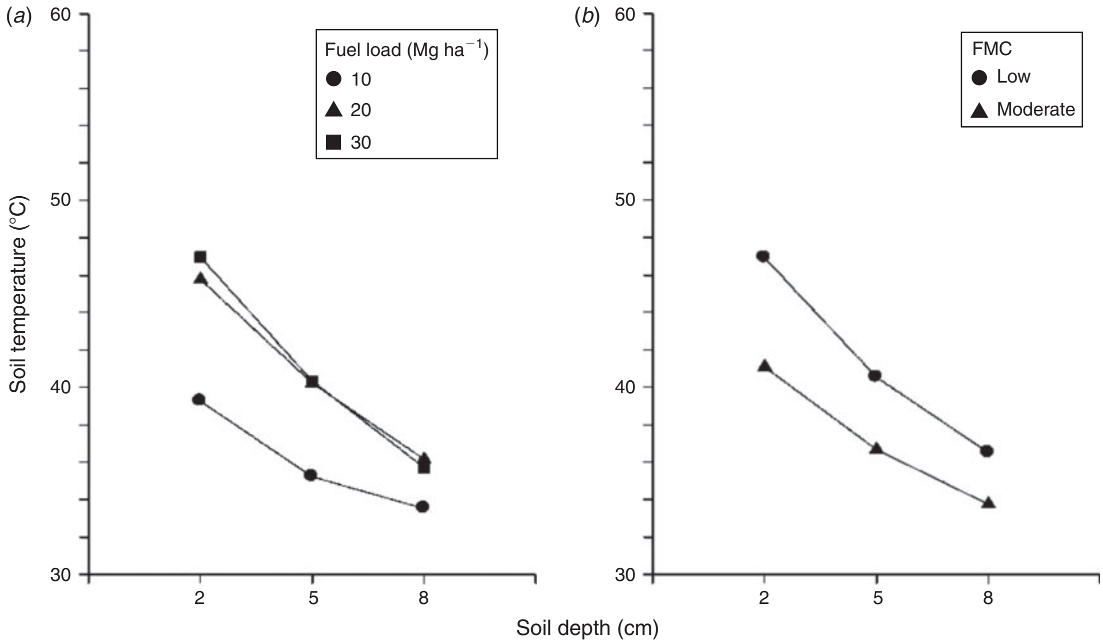

Fig. 2. The effect of fuel loading (*a*) and fuel moisture content (FMC) (*b*) on soil heating at three soil depths during the burning of fuelbeds created from masticated palmetto–gallberry-dominated pine flatwoods understorey. Temperatures differed across all three soil depths, but did not differ between the moderate (20 $Mg\,ha^{-1}$) and the high (30 $Mg\,ha^{-1}$) fuel loading treatments using a Tukey–Kramer *post hoc* comparison of the means. FMC: low (8.9 ± 0.6%) and moderate (12.9 ± 2.0%).

Although observed flame lengths were not unlike those in other controlled experiments where compact masticated fuelbeds were burned (Busse *et al.* 2005; Kreye *et al.* 2011), surface temperatures were somewhat lower and soil temperatures were much lower. Busse *et al.* (2005) developed an empirical model to predict maximum soil temperatures from fuelbed depth, soil moisture and soil depth that drastically overestimates soil heating in our fuelbeds (43–318°C predicted). Directly comparing surface temperatures between studies is done with caution, however, because the temperatures of thermocouple probes differ depending on the properties of the particular probes used, and thermocouple probe temperatures differ from fuel particle or plant tissue temperatures (Bova and Dickinson 2005, 2008). Soil temperatures, which did not reach 60°C even as shallow as 2.5 cm beneath the soil surface in this study, were measured using exposed thermocouples as in the comparison studies. Soil temperatures can be directly compared because the bare thermocouple, being embedded in the soil, provides a good measurement of soil temperature. Although our fuel depths are comparable to those of Busse *et al.* (2005) and Kreye *et al.* (2011), fuel loading in these other studies was substantially higher due to their dominance of woody fuels that likely attributed to higher temperatures as a result of greater total energy release and longer combustion times. The foliar fuel component in masticated palmetto–gallberry fuelbeds results in unique burning behaviour compared with other masticated fuels that have been studied.

Dominance of shredded palmetto in post-masticated fuels likely contributes to a more aerated fuelbed, and thus quicker drying and faster burning rates than those observed in woody-dominated fuelbeds (Kreye *et al.* 2011, 2012). Following mastication of palmetto–gallberry, however, surface fuels become more compacted over time (Kreye 2012) and burning to consume post-masticated surface fuels, while mitigating long-duration combustion, may require strategic timing. These small-scale experiments elucidate how fire behaviour is influenced by fuelbed properties in unique masticated fuels, but field level studies will be required to examine how treatments burn at the operational scale.

In order to better understand fire behaviour and effects from burning masticated fuelbeds, and to develop fuel models to aid in prediction, further research is needed to explore the wide variation of fuelbed characteristics that will likely occur as a result of these treatments. The majority of existing work has been conducted in compact masticated fuelbeds with low fuelbed depths, but where woody material is the primary fuel component. Experimental studies aimed at quantifying burning metrics across a wide range of fuelbed bulk densities, but that also address heterogeneity of fuel particles within the matrix of these compact fuelbeds, will serve to better inform fire behaviour prediction in these widely used fuels treatments. This work provides insight into fuelbed control over fire behaviour in compact foliar litter-dominated fuelbeds that likely represent the upper range of flammability across the spectrum of masticated fuelbeds.

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References

Battaglia MA, Rocca ME, Rhoades CC, Ryan MG (2010) Surface fuel loadings within mulching treatments in Colorado coniferous forests. *Forest Ecology and Management* **260**, 1557–1566. doi:10.1016/J.FORECO.2010.08.004

Bova AS, Dickinson MB (2005) Linking surface fire behavior, stem heating, and tissue necrosis. *Canadian Journal of Forest Research* **35**, 814–822. doi:10.1139/X05-004

Bova AS, Dickinson MB (2008) Beyond 'fire temperatures': calibrating thermocouple probes and modeling their response to surface fires in hardwood fuels. *Canadian Journal of Forest Research* **38**, 1008–1020. doi:10.1139/X07-204

Bradley T, Gibson J, Bunn W (2006) Fire severity and intensity during spring burning in natural and masticated mixed shrub woodlands. In 'Fuels Management – How to Measure Success: Conference Proceedings', 28–30 March 2006, Portland, OR. (Eds PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41, pp. 419–428. (Fort Collins, CO)

Brockway DG, Outcalt KW, Estes BL, Rummer RB (2009) Vegetation response to midstorey mulching and prescribed burning for wildfire hazard reduction and longleaf pine (*Pinus palustris* Mill.) ecosystem restoration. *Forestry* **82**, 299–314. doi:10.1093/FORESTRY/CPP010

Busse MD, Hubbert K, Fiddler G, Shestak C, Powers R (2005) Lethal soil temperatures during burning of masticated forest residues. *International Journal of Wildland Fire* **14**, 267–276. doi:10.1071/WF04062

Castro JA, Allen CD, Molina-Morales M, Marañón-Jiménez S, Sánchez-Miranda Á, Zamora R (2011) Salvage logging versus the use of burnt wood as nurse object to promote post-fire tree seedling establishment. *Restoration Ecology* **19**, 537–544. [Published online early 20 January 2010]. doi:10.1111/J.1526-100X.2009.00619.X

Glitzenstein JS, Streng DR, Achtemeier GL, Naeher LP, Wade DD (2006) Fuels and fire behavior in chipped and unchipped plots: implications for land management near the wildland/urban interface. *Forest Ecology and Management* **236**, 18–29. doi:10.1016/J.FORECO.2006.06.002

Hood S, Wu R (2006) Estimating fuel bed loadings in masticated areas. In 'Fuels Management – How to Measure Success: Conference Proceedings', 28–30 March 2006, Portland, OR. (Eds PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41, pp. 333–340. (Fort Collins, CO)

Hough WA, Albini FA (1978) Predicting fire behavior in palmetto–gallberry fuel complexes. USDA Forest Service. Southeast Forest Experiment Station, Research Paper SE-174. (Asheville, NC)

Kane JM, Varner JM, Knapp EE (2009) Novel fuelbed characteristics associated with mechanically mastication treatments in northern California and south-western Oregon, USA. *International Journal of Wildland Fire* **18**, 686–696. doi:10.1071/WF08072

Knapp EE, Varner JM, Busse MD, Skinner CN, Shestak CJ (2011) Behaviour and effects of prescribed fire in masticated fuelbeds. *International Journal of Wildland Fire* **20**, 932–945. doi:10.1071/WF10110

Kobziar LK, McBride JR, Stephens SL (2009) The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. *International Journal of Wildland Fire* **18**, 791–801. doi:10.1071/WF06097

Kreye JK (2012) Efficacy and ecological effects of mechanical fuel treatments in pine flatwoods ecosystems of Florida, USA. PhD dissertation, University of Florida.

Kreye JK, Varner JM, Knapp EE (2011) Effects of particle fracturing and moisture content on fire behaviour in masticated fuelbeds burned in a laboratory. *International Journal of Wildland Fire* **20**, 308–317. doi:10.1071/WF09126

Kreye JK, Varner JM, Knapp EE (2012) Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuelbed compaction. *International Journal of Wildland Fire* **21**, 894–904. doi:10.1071/WF11077

Menges ES, Gordon DR (2010) Should mechanical treatments and herbicides be used as fire surrogates to manage Florida's uplands? A review. *Florida Scientist* **73**, 147–174.

Molina DM, Galán M, Fababú DD, Garcia D, Mora JB (2009) Prescribed fire use for cost-effective fuel management in Spain. In 'Proceedings of the Third International Symposium on Fire Economics, Planning, and Policy: Common Problems and Approaches', 29 April–2 May 2008, Carolina, Puerto Rico. (Ed. A González-Cabán) USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-227, pp. 370–374 (Albany, CA)

Rothermel RC, Deeming JE (1980) Measuring and interpreting fire behavior for correlation with fire effects. USDA Forest Service, Intermountain Forest and Range Station, General Technical Report INT-93. (Ogden, UT)

Vaillant NM, Fites-Kaufman J, Reiner AL, Noonan-Wright EK, Dailey SN (2009) Effect of fuel treatments on fuels and potential fire behavior in California, USA, national forests. *Fire Ecology* **5**, 14–29. doi:10.4996/FIREECOLOGY.0502014

Varner JM, Gordon DR, Putz FE, Hiers JK (2005) Restoring fire to long-unburned *Pinus palustris* ecosystems: novel fire effects and consequences for long-unburned ecosystems. *Restoration Ecology* **13**, 536–544. doi:10.1111/J.1526-100X.2005.00067.X