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Fluctuations in fuel moisture across restoration treatments in semi-arid ponderosa pine forests of northern Arizona, USA

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Abstract. Fuel moisture is an important variable in estimating fire behaviour and wildfire hazard. We measured three replicates each of thin-and-burn, burn-only, and control treatments in semi-arid ponderosa pine forests of northern Arizona, USA to quantify temporal changes and treatment effects on live foliar and dead fuel moisture content. Overstorey structure and canopy bulk density were reduced 40–75% in the thin-and-burn treatment *v.* the burn-only and control treatments. Fluctuations in foliar moisture content varied temporally and across study areas. In 2003, a significant treatment effect was found for two study sites for 1-year-old foliage, but no significant treatment effect was found for new foliage. In 2004, a significant treatment effect was found across all three study sites for both 1-year-old and new foliage. However, no clear pattern existed regarding a specific treatment and its effect on moisture content of old or new foliage. No conclusive evidence was found for a significant treatment effect on the moisture content of fuel particles in the size classes of 0–6, 6–25, and 25–100-mm diameter. Proposals regarding amplified fire behaviour as a consequence of reduced fuel moisture contents in treated *v.* untreated forest stands in semi-arid ponderosa pine forests of northern Arizona therefore appear to be unwarranted.

Additional keywords: American south-west, dead fuel moisture, fire behaviour, foliar moisture content, forest structure.

Introduction

Fire behaviour is impacted by live and dead fuel moisture contents (Rothermel and Anderson 1966; Anderson 1969; Rothermel 1972; Countryman 1974; Burgan 1979) as heat is used to vaporise water in a fuel particle (Brown and Davis 1973). The impact of forest canopy closure on live or dead fuel moisture content has been addressed (Weatherspoon and Skinner 1995; Whelan 1995; Agee 1996; Van Wagtendonk 1996; Scott 1998*a*, 2003; Graham *et al*. 1999, 2004; Scott and Reinhardt 2001; Martinson and Omi 2003; Martinson *et al*. 2003; Fiedler *et al*. 2004), but not rigorously tested. Countryman (1956) proposed that fuels in an open *v.* closed forest should have lower fuel moisture contents, thus amplifying fire behaviour, but Pollet and Omi (2002) did not support this assertion. Open forest stands exhibit (Jemison 1934; Harrington 1982) and do not exhibit (Murphy *et al*. 1965) lower dead fuel moisture contents when compared to closed stands, and such differences might be impractical in fire hazard ratings (Williams 1964). Of microclimate variables studied (e.g. temperature and sunlight penetration), which may influence dead fuel moisture, only sunlight penetration was significantly different across mechanically restored and un-restored forest stands (Meyer *et al*. 2001).

Restoration efforts that extensively modify stand structure and microclimate have been proposed for semi-arid ponderosa pine forests to promote ecosystem functions associated with presettlement forest conditions (Moore *et al*. 1999; Covington 2000) and reduce crownfire hazards (Fulé *et al*. 2001*a*, 2001*b*, 2002). However, the impact of these types of treatments on live and dead fuel moisture is largely unknown. The primary aim of this present study was not to verify our moisture contents to modelling systems such as Nelson's NFDRS model, but to quantify temporal (~2-week intervals) fluctuations and potential treatment effects on live and dead fuel moisture content as a consequence of such forest restoration treatments in semi-arid ponderosa pine forests of northern Arizona. Secondarily, we wanted to develop a localised fuel moisture profile for use in fire behaviour modelling systems as suggested by Scott and Reinhardt (2001). We hypothesised that: (1) live fuel moisture content would significantly increase as a consequence of the thin-and-burn and burn-only forest treatments when compared to the control, and (2) dead fuel moisture content would decrease as a consequence of the thin-and-burn and burn-only when compared to the control.

Methods

Study area

Three replicate study sites (KA Hill, Powerline and Rudd's Tank) within the National Fire and Fire Surrogate study were established in semi-arid ponderosa pine forests of northern Arizona on the Coconino and Kaibab National Forests (Fig. 1). The dominant tree species at all of the study sites is ponderosa pine (*Pinus ponderosa* Lawson var. *scopulorum* Engelm) with minor components of Gambel oak (*Quercus gambelii*) and alligator juniper (*Juniperus deppeana*). Elevations range from 2217 to 2264 m. All three replicate study sites have slopes of ≤5% with little to no variability in aspect. Mean annual precipitation ranges from 546.1 mm at Powerline (35°12.0′33.9″ latitude,

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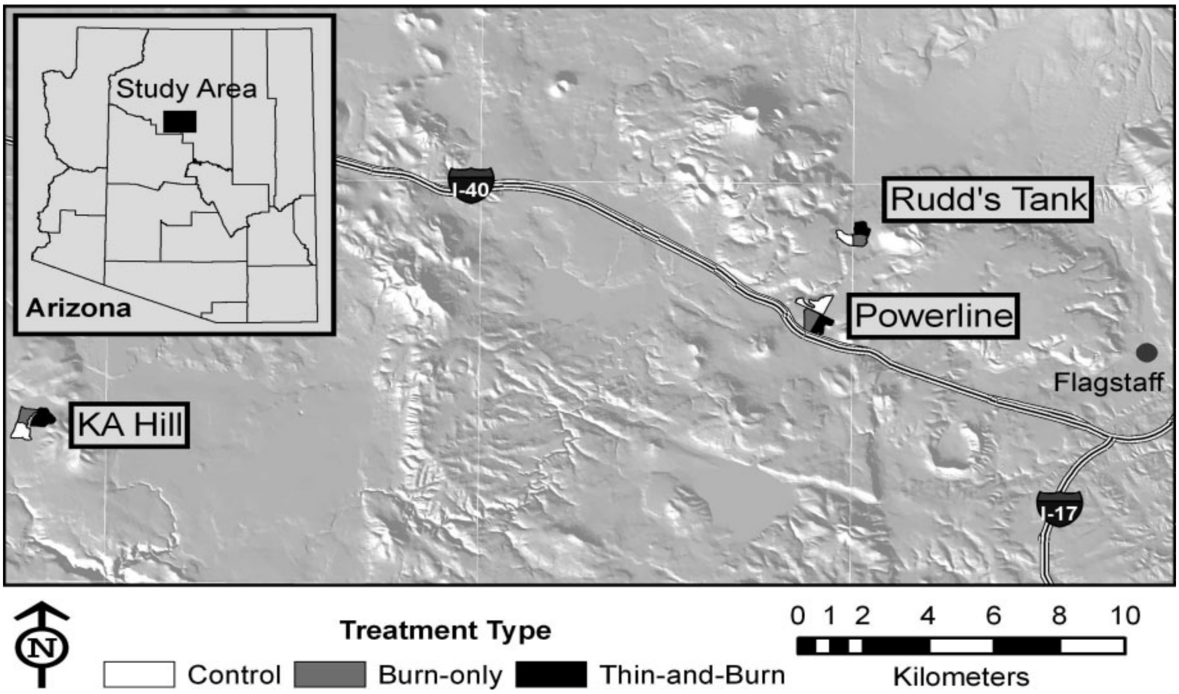

Fig. 1. Arizona Fire and Fire Surrogate study sites locations. Study sites are 11 and 26 km west of Flagstaff, AZ.

Table 1. Monthly study site weather variables for the study period from May to October 2003 and 2004
Weather data were obtained from the National Weather Service. KA Hill weather was taken in Williams, AZ and Powerline and Rudd's Tank were taken in Flagstaff, AZ

Study site	May	June	July	August	September	October
KA Hill						
2003						
Maximum temperature (°C)	21	28	31	27	25	23
Minimum temperature (°C)	6	10	15	12	11	7
Precipitation (mm)	3.3	0.0	42.2	105.2	47.5	7.9
2004						
Maximum temperature (°C)	23	28	29	25	23	15
Minimum temperature (°C)	6	9	12	11	8	3
Precipitation (mm)	0.0	0.25	45.2	114.8	70.9	100.8
Powerline and Rudd's Tank						
2003						
Maximum temperature (°C)	21	26	30	25	24	21
Minimum temperature (°C)	0	1	9	18	3	−1
Precipitation (mm)	3.0	2.0	0	63.8	39.6	0
2004						
Maximum temperature (°C)	21	26	27	25	22	14
Minimum temperature (°C)	−2	2	6	7	2	−2
Precipitation (mm)	0.0	0.0	37.6	108.0	37.3	92.7

111°45.0′32.2″ longitude) and Rudd's Tank (35°14.0′05.9″ latitude, 111°44.0′58.4″ longitude) to 549.1 mm at KA Hill (35°12.0′33.9″ latitude, 111°45.0′32.2″ longitude). Precipitation peaks occur during the monsoonal months of July and August. Average maximum and minimum temperatures range from 27.7 to −11.9°C, with maximums in July and minimums in January. Monthly maximum and minimum temperatures and precipitation rates for the study periods of 2003 and 2004 are provided (Table 1).

Treatments

We focussed on two restoration treatments (thin-and-burn and burn-only), which attempted to lower stem density to 116 trees/hectare with 13 m^2/hectare of basal area, and a control.

Post-treatment stand density targets intended to produce an uneven-aged, patchy forest structure (White 1985) were generated using a group selection approach based on basal area, diameter, and *q*-ratio (BDq) that emulated regional historical data (Cooper 1960, 1961). Mechanical operations began in 2002 and were concluded in the spring of 2003. Prescribed fire operations occurred within a few weeks of late September and early October of 2003 using strip-head fire techniques.

Sampling

Forest overstorey structure

Post-treatment forest overstorey structure was quantified using 10 randomly placed, one-tenth-hectare vegetation plots per treatment. We measured the diameter (0.1 cm) at 1.37 m (breast height), total tree height, and canopy base height for every tree within each overstorey plot. Crown biomass for each plot was generated using regionally derived allometric equations for ponderosa pine (Fulé *et al.* 2001*a*), Gambel oak (Clary 1987), and juniper (Grier *et al.* 1992). Crown volume was calculated using the maximum tree height (top of canopy) minus the average crown base height for each plot, which was multiplied by the plot area (m^2). Crown bulk density was calculated as crown biomass divided by crown volume and numbers reported are averages per treatment.

Live fuel moisture content

We sampled lower crown foliar moisture content in each of the three treatments approximately every 2 weeks between the hours of 1030 and 1630 from May to September (i.e. high, regional fire activity) in 2003 and May to October in 2004. Sampling was cut short in 2003 due to decreases in staffing. A branch containing $\geq$20.0 g of new and 1-year-old foliage was cut from the lower crowns of 10 randomly selected ponderosa pine trees, then dissected, placed in a sealable plastic bag and set into a cooler with ice. Different trees were selected randomly during each sampling date. After collecting 10 samples from each treatment, the foliage was stripped from the branch and field-weighed to 0.1 g. Dead material from the sample was removed to avoid affecting foliar moisture results (Countryman 1974). Current- and previous-year foliage was then oven-dried for 48 h at 70°C (Agee *et al.* 2002) and reweighed. All moisture contents are expressed on a dry weight basis.

Dead fuel moisture content

We also sampled dead fuel moisture content in each of the three treatments approximately every 2 weeks from June to October in 2003 and 2004 between the hours of 1030 and 1630. In 2003, we sampled dead fuel moisture from two sources: (1) natural fuels taken from the forest floor, and (2) standard wooden dowels, in order to test the efficacy of standard wooden dowels as a measure of dead fuel moisture content. Natural fuel moisture content was acquired from sound forest floor fuel particles in two size classes (0–6 and 6–25-mm diameter). Two fuel particles in each size class were collected at five randomly placed dead fuel moisture stations per treatment. The samples from the five stations were bagged and, after collecting 10 from each size class, they were field-weighed to the nearest 0.1 g. Each treatment was completed before continuing to the next, starting with the thin-and-burn, to burn-only, and finishing at the control. Samples were then oven-dried at 70°C until fuel weights equilibrated, which was usually a period of 72 h, and were then reweighed.

We established five randomly placed dead fuel moisture stations in 2003 and 10 in 2004 within each site and treatment using a modified wooden dowel method (Murphy *et al.* 1965). Each station consisted of a 30 × 30 cm piece of chicken wire that was half-folded and stapled to the ground. Dead fuel moisture stations were equipped with wooden dowels in size classes of 0–6 (4-mm diameter precisely) and 6–25 mm (14-mm diameter precisely), which were placed in the bottom rung of the wire perpendicular to the half-folded station. In 2004, we equipped stations with additional 25–100-mm (28-mm diameter precisely) wooden dowels. In 2003, five 4-mm and eight 14-mm diameter dowels were placed in the field and, in 2004, 13 4-mm, 11 14-mm and 11 28-mm diameter dowels were placed in the field. Prior to placement in the field, dowels were oven-dried at 70°C until weights equilibrated and then weighed. In 2003, dowels were field-weighed ($\pm$0.1 g) at each station. However, we were unable to acquire numerous dead fuel measurements due to marginal amounts of moisture, so in 2004 we increased our measuring units to ($\pm$0.01 g). The marginal moisture levels resulted in the pre- and post-drying weights being equal, rendering such data unusable; hence, they were discarded. In both 2003 and 2004, dowels were field-weighed at each station by use of a portable, windproof weighing box and scale. Each treatment was completed before continuing to the next, starting with the thin-and-burn, to burn-only, and finishing at the control. In 2004, because we did not collect natural forest fuels, sampling an entire study site took less than 90 min. All moisture contents are expressed on a dry weight basis.

We tested the reliability of our method used to determine dead fuel moisture contents and concluded that tests for significant differences between dowel and natural fuel moisture in 2003 were primarily rejected and that our method was functional (Table 2). We were obliged to use randomly generated days due to data inconsistencies relating to missing measurements as a consequence of the scale's inability to detect minute amounts of fuel moisture. In 2004, we sampled dead fuel moisture content solely using the wooden dowel method, deemed appropriate from our 2003 trial analysis.

Statistics

We used a MANOVA repeated-measures analysis to test for a treatment effect on foliar and dead fuel moisture content. If a statistically significant treatment effect was detected by the MANOVA, we used a one-way ANOVA for each of the study dates to find where significant differences occurred and then compared treatment means with a Tukey's Honest Significant Difference test. The α level for all of the statistical tests was 0.05.

Results

Live fuel moisture

Differences in post-treatment forest stand structure between mechanical and non-mechanical treatments were significant across all study sites. Mechanical operations significantly reduced basal area and trees per hectare, whereas the

Table 2. Significant differences ($\alpha = 0.05$) and associated *P*-values used to compare the dowel moisture content to the natural fuel stick moisture content

0–6-mm and 6–25-mm dowel moisture contents for the randomly selected day in 2003 are also shown with errors stated parenthetically

Study site	0–6-mm dowel	0–6-mm natural	*P*-value	6–25-mm dowel	6–25-mm natural	*P*-value
KA Hill (26 July 2003)						
Cut-and-burn	6.2 (0.7)	8.0 (0.8)	0.9185	9.3 (0.3)	8.9 (1.0)	0.4308
Burn-only	5.2 (0.4)	8.8 (1.7)	0.1989	8.9 (0.4)	7.3 (0.6)	0.8440
Control	6.4 (0.9)	7.7 (0.8)	0.3162	9.6 (0.2)	8.3 (0.9)	0.7725
Powerline (8 July 2003)						
Cut-and-burn	3.1 (0.1)	2.0 (0.3)	0.0218	1.9 (0.1)	1.8 (0.3)	0.8373
Burn-only	2.8 (0.1)	1.8 (0.1)	0.0011	2.3 (0.2)	1.3 (0.2)	0.0093
Control	2.8 (0.1)	1.8 (0.1)	0.0003	1.9 (0.2)	1.2 (0.1)	0.0062
Rudd's Tank (22 July 2003)						
Cut-and-burn	7.6 (0.8)	9.3 (1.4)	0.5081	12.9 (0.8)	10.7 (1.3)	0.1929
Burn-only	6.3 (0.7)	10.4 (0.9)	0.0401	11.3 (0.7)	11.8 (1.0)	0.7312
Control	6.0 (0.2)	11.6 (1.2)	0.0085	10.9 (0.7)	14.9 (2.0)	0.1076

Table 3. Post-treatment forest structure for each of the Arizona Fire and Fire Surrogate Study locations

Values are stand-level means with standard error stated parenthetically. Within study site significant differences ($\alpha = 0.05$) for each variable are denoted by letter codes and associated *P*-values are given

Study site	Cut-and-burn	Burn-only	Control	*P*-value
KA Hill				
Basal area (m^2 hectare^{-1})	12.8 (1.9)^a	26.5 (2.1)^b	25.7 (1.6)^b	<0.0001
Trees/hectare	110 (18.4)^a	333 (25.4)^b	376 (21.5)^b	<0.0001
Crown bulk density (kg m^{-3})	0.0239 (0.0033)^a	0.0520 (0.0044)^b	0.0507 (0.0027)^b	<0.0001
Powerline				
Basal area (m^2 hectare^{-1})	9.0 (1.5)^a	31.4 (2.5)^b	33.3 (3.2)^b	<0.0001
Trees/hectare	135 (17.1)^a	803 (125.1)^b	883 (131.6)^b	<0.0001
Crown bulk density (kg m^{-3})	0.0190 (0.0026)^a	0.0864 (0.0101)^b	0.0731 (0.0125)^b	<0.0001
Rudd's Tank				
Basal area (m^2 hectare^{-1})	15.9 (3.7)^a	30.8 (2.1)^b	35.0 (2.6)^b	0.0003
Trees/hectare	173 (79.1)^a	472 (53.6)^b	707 (102.4)^b	0.0002
Crown bulk density (kg m^{-3})	0.0286 (0.007)^a	0.0481 (0.0045)^{ab}	0.0611 (0.0061)^b	0.0025

burn-only treatment was primarily ineffective at changing these stand structural variables (Table 3). There was a significant treatment effect on crown bulk density for all three study sites, and significant differences were found between the mechanically *v.* non-mechanically treated areas at KA Hill and Powerline; however, at Rudd's Tank, the burn-only was not significantly different from the thin-and-burn and control.

Fluctuations in foliar moisture content varied between study sites, foliage age, and years (Fig. 2). For all three study sites, the minimum moisture content of old foliage occurred in May of 2003 and 2004, with minimums of 77.1% in 2003 and 99.8% in 2004. There was a 22.5, 22.5, and 25.1% increase in the minimum moisture content of old foliage from 2003 to 2004 at KA Hill, Powerline, and Rudd's Tank, respectively. Peak moisture contents for old foliage were primarily in August, with the exceptions being in early-September at Powerline in 2003 and late-June at Rudd's Tank in 2004. Peak moisture contents for old foliage ranged from 115.0% in 2003 to 132.6% in 2004. Increases in the peak moisture content were also observed from 2003 to 2004 at all three study sites, with a 5.8, 10.7, and 22.6% increase at KA Hill, Powerline and Rudd's Tank, respectively.

Minimum foliar moisture for new foliage also varied across study sites and years; however, across-year comparisons cannot be made definitely for minimum foliar moisture content due to the premature termination of sampling in late-August or early-September in 2003. In 2003, minimum foliar moisture contents were found in August at KA Hill and Rudd's Tank, and in September at Powerline. In 2004, minimums were consistently found in October (Fig. 2). Minimum foliar moisture content for new foliage was 177.2% in 2003 and 138.0% in 2004. Peak moisture content for new foliage was consistently found in July and ranged from 243.8% in 2003 to 239.2% in 2004. Increases in the peak moisture content for new foliage were observed from 2003 to 2004 at KA Hill and Powerline, with a 5.9 and 6.6% increase. However, there was a 4.6% decrease in the peak moisture content of new foliage at Rudd's Tank from 2003 to 2004.

Even though treatment effects were detected throughout the 2003 and 2004 wildfire seasons, no treatment at any of the three study sites consistently had the highest 1-year-old or new mean foliar moisture content throughout the sampling periods (Table 4). For example, the KA Hill control had the highest mean moisture content of 1-year-old foliage throughout the sampling

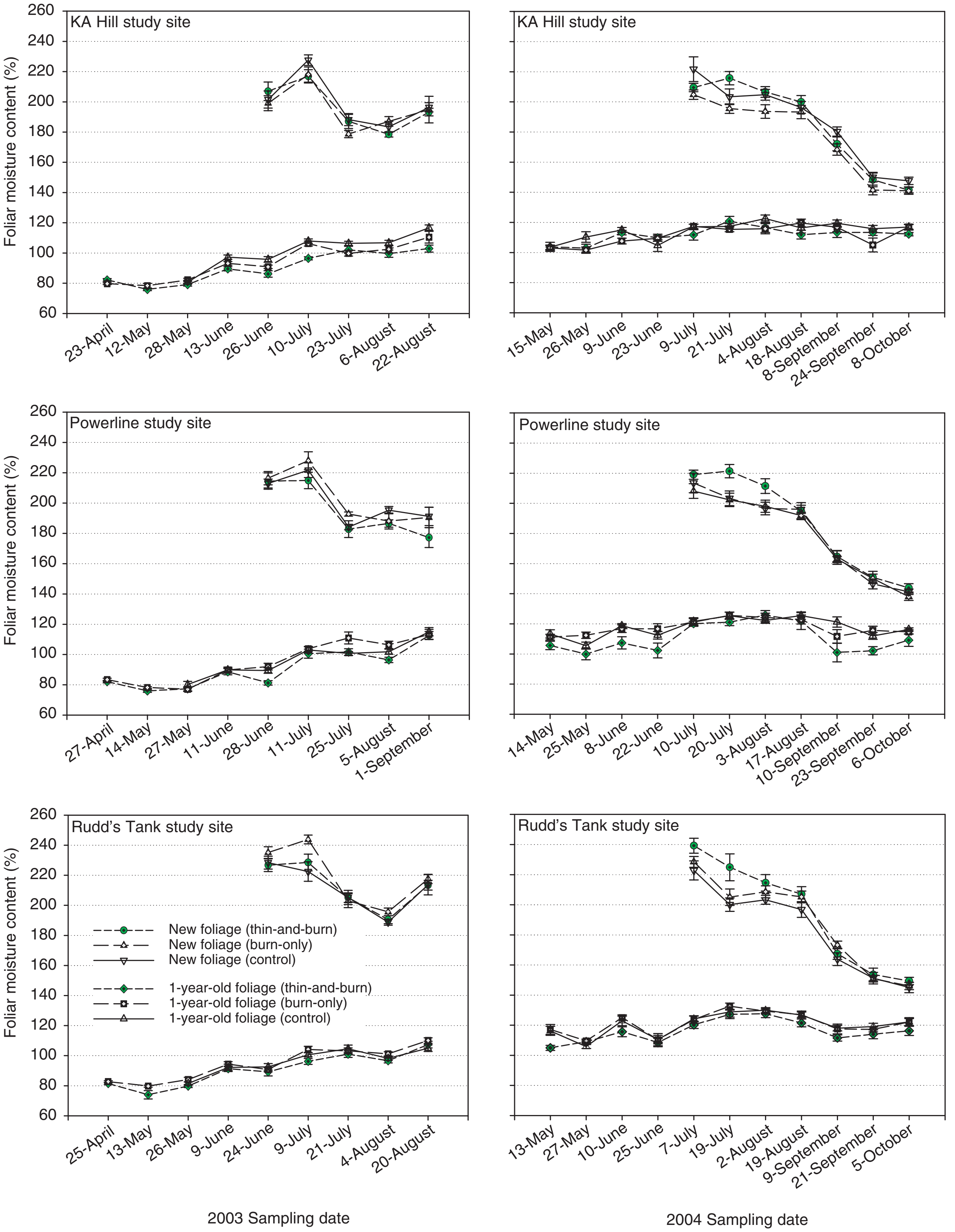

Fig. 2. Fluctuations in 1-year-old and new foliar moisture content in the thin-and-burn, burn-only, and control during the 2003 and 2004 wildfire seasons – KA Hill (top), Powerline (middle), and Rudd's Tank (bottom). Vertical bars represent standard error.

Table 4. Days with detected significant treatment effects on the foliar moisture content for all three study sites during the 2003 and 2004 sampling period

Values are stand-level means with standard error stated parenthetically. Within study site significant differences ($\alpha = 0.05$) are denoted by letter codes and associated *P*-values are given

Study site	Foliage age	Foliar moisture content			*P*-value
		Cut-and-burn	Burn-only	Control	
KA Hill					
13 June 2003	1-year-old	89.5 (1.4)[a]	93.1 (1.2)[ab]	97.2 (1.5)[b]	0.0020
26 June 2003	1-year-old	86.1 (2.1)[a]	90.8 (1.1)[ab]	95.8 (1.9)[b]	0.0025
10 July 2003	1-year-old	96.4 (1.1)[a]	106.2 (1.6)[b]	107.9 (1.5)[b]	<0.0001
22 August 2003	1-year-old	102.9 (2.3)[a]	110.4 (3.0)[ab]	116.7 (1.9)[b]	0.0121
9 June 2004	1-year-old	113.2 (1.5)[ab]	107.9 (1.9)[a]	114.9 (1.7)[b]	0.0128
21 July 2004	New	120.8 (3.2)[a]	115.3 (1.5)[b]	117.3 (1.8)[ab]	0.0089
Powerline					
28 June 2003	1-year-old	81.2 (1.5)[a]	92.0 (2.2)[b]	89.4 (1.8)[b]	0.0010
25 July 2003	1-year-old	101.6 (2.2)[ab]	106.4 (2.5)[b]	101.8 (1.7)[ab]	0.0058
25 May 2004	1-year-old	99.8 (3.7)[a]	112.4 (2.1)[b]	105.5 (2.3)[ab]	0.0136
8 June 2004	1-year-old	107.4 (2.2)[a]	116.8 (2.6)[ab]	118.8 (1.4)[a]	0.0204
22 June 2004	1-year-old	102.3 (4.9)[a]	116.6 (3.5)[b]	112.4 (2.6)[ab]	0.0348
10 September 2004	1-year-old	101.0 (6.2)[a]	111.6 (4.5)[ab]	121.2 (3.4)[b]	0.0235
23 September 2004	1-year-old	102.1 (2.7)[a]	115.6 (2.9)[b]	111.9 (2.3)[b]	0.0036
21 July 2004	New	221.4 (4.4)[b]	202.2 (4.4)[a]	203.4 (4.9)[a]	0.0091
21 July 2004	New	211.5 (4.9)[b]	198.1 (4.0)[a]	196.5 (4.2)[a]	0.0490
Rudd's Tank					
13 May	1-year-old	104.9 (1.7)[a]	117.2 (3.3)[b]	117.2 (3.3)[b]	0.0096
19 July	New	224.9 (8.9)[b]	205.0 (5.0)[ab]	200.0 (4.5)[a]	0.0304

period in 2003 and 2004, but only one sampling day showed significance for new foliage. Powerline and Rudd's Tank showed considerable treatment variation for maximum moisture contents for 1-year-old and new foliage in 2003 and 2004. In 2003, moisture content for 1-year-old foliage was higher without thinning ($P = 0.0006$), but not for new foliage ($P = 0.8380$) at KA Hill over the sampling period (Fig. 2). In 2004, a treatment effect was found for both 1-year-old foliage ($P = 0.0392$) and new foliage ($P = 0.0029$) at KA Hill (Fig. 2), with new foliage moisture content higher with thinning. Similarly, a treatment effect on foliar moisture content was found for 1-year-old foliage ($P = 0.0265$), but not for new foliage ($P = 0.5328$) at Powerline in 2003 (Fig. 2). However, in 2004, the treatment effect was found for both 1-year-old foliage ($P < 0.0001$) and new foliage ($P = 0.0232$). Neither 1-year-old ($P = 0.0886$) nor new foliage ($P = 0.3637$) differed in 2003 at Rudd's Tank, but a treatment effect was found for both 1-year-old foliage ($P < 0.0001$) and new foliage ($P = 0.0013$) in 2004 (Fig. 2).

Dead fuel moisture

Dead fuel moisture contents varied across study sites and the 0–6-mm, 6–25-mm, and 25–100-mm diameter fuel particle classes, but were not influenced by treatments. During the 2004 wildfire season at all three study sites, the minimum moisture content was found in June and maximum moisture content was found in August for the 0–6-mm, 6–25-mm, and 25–100-mm diameter fuel particle classes (Fig. 3). For the 0–6-mm diameter fuel particle classes, minimum moisture contents ranged from 0.6 to 0.8% and the 6–25-mm diameter classes minimum moisture contents ranged from 1.2 to 1.5% – all minimum moisture contents occurred in the thin-and-burn treatment at all three study sites. For the 25–100-mm diameter fuel particle classes, the minimum moisture content ranged from 1.3 to 1.7% and occurred in the thin-and-burn and control at all three study sites. In 2004, there was no treatment effect on the dead fuel moisture content in the 0–6-mm, 6–25-mm, and 25–100-mm diameter fuel particle classes at KA Hill and Powerline (Table 5). At Rudd's Tank there was no treatment effect on the dead fuel moisture content in the 0–6-mm and 6–25-mm diameter fuel particle classes; however, we did detect a significant treatment effect on the 25–100-mm diameter fuel particle class (Table 5), with the control having a significantly higher moisture content than thin-and-burn or burn-only on 24 August 2004 ($P = 0.0093$).

Discussion

Seasonal patterns in the foliar moisture content were similar for all three study sites, with gradual increases in the moisture content of 1-year-old foliage and strong declines in the moisture content of new foliage. Numerous studies have shown similar results for 1-year-old foliage (Russell and Turner 1975; Fuglem and Murphy 1980) and new foliage (Van Wagner 1967; Philpot and Mutch 1971; Springer and Van Wagner 1984; Chrosciewicz 1986; Agee *et al*. 2002). During mid-June of 2003 and 2004 there was a slight decrease in the moisture content of 1-year-old foliage at all sites. However, moisture contents did not drop below the minimum observed each spring and that dip likely resulted from seasonal soil moisture stress (Pharis 1966). Other authors have found that such changes in foliar moisture can be attributed to diurnal fluctuations in relative humidity (Philpot 1965), physiological activity (Countryman 1974) and increases in dry weight associated with starch build-up (Kozlowski and Clausen 1965;

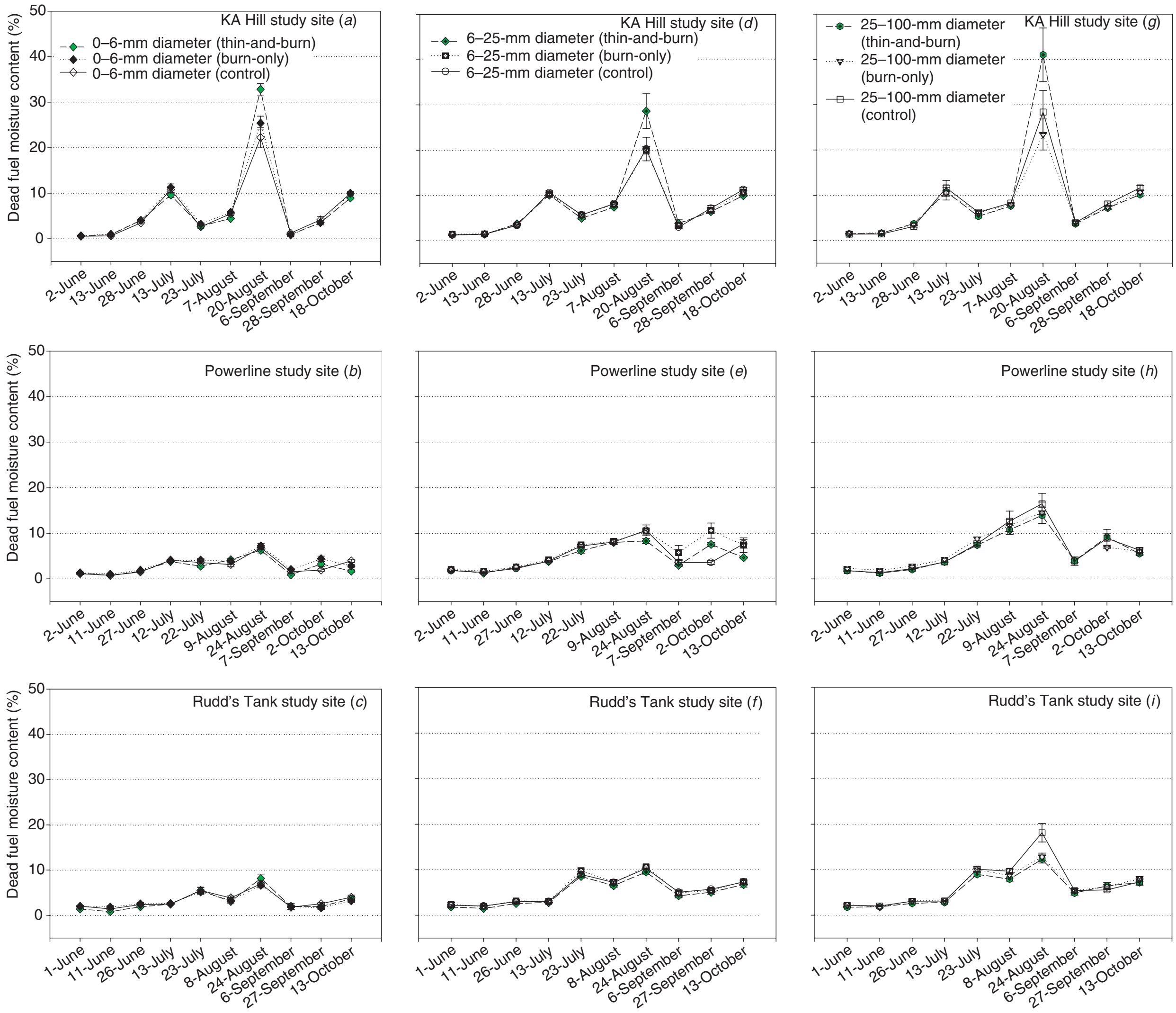

Fig. 3. Fluctuations in dead fuel moisture by 0–6-mm diameter (*a–c*), 6–25-mm diameter (*d–f*), and 25–100-mm diameter (*g–i*) fuel particle classes across treatments during the 2004 wildfire season – KA Hill study site (top), Powerline study site (middle), and Rudd's Tank study site (bottom). The informal beginning of the region's summer monsoon season is during the second week of July. Vertical bars represent standard error.

Little 1970; Gary 1971; Springer and Van Wagner 1984) – parameters that we did not address during this present study.

Increases in the moisture content of 1-year-old foliage as a consequence of the thin-and-burn and burn-only treatment did not occur as hypothesised. In fact, the moisture content of 1-year-old foliage in the thin-and-burn treatment was never higher and often lower than the moisture content in the burn-only and control treatments in both 2003 and 2004, indicating that an open forest structure decreased moisture content of 1-year-old foliage. The weather between study sites was similar within years, with the exception of July 2003, where KA Hill had a sizeable amount of precipitation *v.* none for the remaining sites. No significant treatment effect was found in 2003 on moisture content of new foliage at any of the study sites; in 2004, thin-and-burn treatments showed higher moisture content in new foliage, as hypothesised, in <10% of the measurements. We propose that these trees allocate large amounts of water to bud development and burst, thus moisture contents of new foliage were not shown to be significantly different. In spite of that, mechanical treatments have been shown to alter physiological processes and increase tree vigour (Feeney *et al.* 1998; Cochran and Barrett 1999; Stone *et al.* 1999; Skov *et al.* 2004). Possible treatment impacts over longer time periods cannot be determined from this present study. Small increases in the moisture content of 1-year-old foliage in untreated forests, or new foliage in treated forests, will unlikely provide resistance to surface fires initiating to crownfires in semi-arid ponderosa pine forests. Surface-to-crown fire resistance is likely the result of lower fuel loads and larger spacing between trees in treated *v.* untreated forest stands.

Using foliar moisture content values of ≤100% for modelling exercises during the wildfire season in semi-arid ponderosa pine forests of the American SouthWest is acceptable as deemed by Scott and Reinhardt (2001). When we combined across-study-site datasets for the month of June, the mean moisture content for 1-year-old foliage was 90.8% in 2003 and 112.5% in 2004. However, fire modellers should consider the overall goal of their

Table 5. *P*-values associated with treatment effects on the dead fuel moisture for various time-lag classes at all three study sites during the 2004 sampling period

Study site	Fuel particle class (mm diameter)	*P*-value
KA Hill	0–6	0.0927
	6–25	0.1650
	25–100	0.2549
Powerline	0–6	0.0678
	6–25	0.0531
	25–100	0.4654
Rudd's Tank	0–6	0.8895
	6–25	0.1403
	25–100	0.0480[A]

[A]Detected treatment effect in the 25–100-mm diameter class occurred on 24 August 2004.

exercise and adjust foliar moisture content values to fit the scope of their project. The datasets compiled in this present study provide seasonal foliar moisture content inputs that will aid fire behaviour modellers in our region. Compiling datasets for western conifers regarding trends in foliar moisture content is a useful exercise, even if little consensus regarding the importance of foliar moisture content of crownfire ignition and behaviour has been found (Van Wagner 1977, 1993; Fuglem and Murphy 1980; Xanthopoulos and Wakimoto 1993; Agee 1996; Scott 1998*b*; Cruz *et al*. 2003). Fire modellers should use field-verified data to increase the precision of their modelling exercises, which are a simplification of real-time combustion.

Restoration of forests

Extensive modifications to forest structure, a consequence of proposed forest stand treatments in semi-arid ponderosa pine forests of northern Arizona (Moore *et al*. 1999; Covington 2000; Fulé *et al*. 2001*a*, 2001*b*; Bailey and Covington 2002), will not significantly reduce dead fuel moisture contents. Therefore, concerns regarding increased fire hazards associated with open canopies are unjustified if based solely on depressed dead fuel moisture contents. Increased fire hazard may be created by other fire behaviour factors such as microclimate and/or post-harvesting fuel loads associated with thinning and/or burning treatments. Sunlight penetration has been shown to be significantly different across mechanically restored and un-restored forest stands (Meyer *et al*. 2001), and such a factor would likely play a role in modifying fuel temperature and subsequent fire hazards. Future research should directly address fire behaviour variables such as relative humidity, wind speed, fuel temperature, drying rates, and the impact of herbaceous cover on modifying dead fuel moisture content (Murphy *et al*. 1965; Rothermel and Anderson 1966; Anderson 1969; Agee 1996) across forest canopy closure gradients in treated and untreated stands.

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