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# Honey Mesquite Canopy Responses to Single Winter Fires: Relation to Herbaceous Fuel, Weather and Fire Temperature

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**Abstract.** Honey mesquite (*Prosopis glandulosa Torr.*) canopy responses to fire were measured following 20 single winter fires conducted in north Texas. Weather conditions during the fires, understory herbaceous fine fuel (fine fuel) amount and moisture content, fire temperature at 0 cm, 10-30 cm and 1-3 m above ground, and canopy responses were compared. Ten fires occurred on a site where fine fuel was a mixture of cool and warm season grasses (mixed site). The other 10 fires occurred on a site dominated by warm season grasses (warm site). When both sites were included in regressions, peak fire temperature at all heights was positively related to fine fuel amount. Fine fuel amount, fine fuel moisture content, air temperature (AT) and relative humidity (RH) affected fire temperature duration in seconds over 100°C (FTD100) at 1-3 m height, but not at ground level. Mesquite percent above-ground mortality (topkill) increased with increasing fine fuel amount, decreasing fuel moisture content, increasing AT, and decreasing RH. Percent foliage remaining on non-topkilled (NTK) trees was inversely related to fine fuel amount and AT, and positively related to fine fuel moisture content. Effect of fire on mesquite topkill and foliage remaining of NTK trees was strongly affected by RH at the warm site ($r^2$ = 0.92 and 0.82, respectively), but not at the mixed site. This difference was due to RH affecting fuel moisture content (and subsequently fire behavior) to a greater degree at the warm than at the mixed site, because of the lower green tissue content in warm site grasses at the time of burning. Under adequate fine fuel amounts to carry a fire, mesquite canopy responses to fire (i.e., topkill vs. partial canopy defoliation) were largely determined by AT and RH conditions during the fire. This has implications if the management goal is to preserve the mesquite overstory for a savanna result instead of topkilling all trees.

Two substudies were conducted during 3 of the fires. Substudy 1 determined mesquite response to fire in 2 plots with different understory herbaceous fuel loads (5,759 vs. 2,547 kg/ha) that were burned under under similar weather conditions. Mesquite topkill was 81% and 11% in the high and low fuel fires, respectively. Under similar weather conditions, fine fuel was an important factor in affecting mesquite responses to fire. However, as demonstrated in the main study, under a variety of weather conditions, AT and RH influenced mesquite response to fire as much or more than did fine fuel. Substudy 2 compared response of mesquite plants with abundant and dry subcanopy fine fuel (3252 kg/ha; fuel moisture 10.4%), or sparse and green subcanopy fuel (1155 kg/ha; fuel moisture 25.9%) to a high intensity fire. All trees were topkilled, including those with low subcanopy fuel, probably from convection heat generated from herbaceous fuel in interspaces between trees. In support of this conclusion, thermocouple data from all 20 fires indicated that canopy responses were more related to fire temperature at 1-3 m than at lower heights. This suggests that the topkill mechanism was due to convective heat within the canopy rather than a girdling effect of fire at stem bases.

**Keywords:** *Prosopis glandulosa*; Texas; Burn; Burning; Savanna

## Introduction

Historical and current theories suggest encroachment of mesquite (*Prosopis* spp.) onto grasslands in the southwest USA is due in part to reduction of naturally occurring fires (Humphrey 1958, Martin 1975, Scifries 1980, Smeins 1983, Fonteyn et al. 1988, Archer 1989). Prescribed fire has gained increased acceptance as a tool to manage grasslands and reduce or retard woody plant encroachment (Scifries and Hamilton 1993). In Texas, prescribed burns that are used to reduce the winter deciduous, arborescent legume, honey mesquite (*Prosopis glandulosa* Torr.), are usually conducted during the winter months of January through March (Wright and Bailey 1982).

Response of honey mesquite to winter fires is variable, ranging from complete above ground mortality (topkill) to little or no effect, and has been related to age and condition of the plants and/or fire intensity (Stinson and Wright 1969, Britton and Wright 1971, Wright et al. 1976). Maximum whole-plant mortality (i.e., root-kill) from any single fire is usually very low (Wright and Bailey 1982). While most research has measured fire effects on mesquite whole-plant mortality, less information is available on fire effects on percent topkill (i.e., percent of individuals in a stand having complete above ground mortality) or, even less, degree of foliage reduction in partially topkilled plants. Variability of mesquite canopy responses to fire may lead to opportunities to create and maintain a savanna physiognomy to accomplish specific management objectives (Ansley et al. 1995, 1996). Knowledge of relations between climate, fuel, fire behavior and mesquite canopy responses are critical to forming a predictive platform for manipulating mesquite growth form with fire.

The physical and physiological mechanism of how fire topkills mesquite needs further elucidation. One hypothesis is that fire destroys cambium at stem bases and physiologically girdles the plant. If this is true then fire temperature near or at the soil surface should be related to topkill. A relationship between understory herbaceous fine fuel amount and peak fire temperature at the soil surface has been quantified on mesquite-dominated grassland (Stinson and Wright 1969). However, the literature has conflicting findings regarding the relation between fuel amount and mesquite response to fire. An alternate hypothesis, which has been found to be true for some coniferous species, is that fire temperature within the canopy (i.e. crown scorch) is fundamental to topkill, and is more important than basal cambial damage (van Wagner 1973). There are virtually no studies of mesquite/grass fires which observed fire temperature at different positions above the soil surface to test the van Wagner hypothesis. At study initiation, we hypothesized that fire interrupts a physiological mechanism in mesquite by destroying phloem at stem bases. The objectives of this study were (1) to determine relationships between fine fuel characteristics and climatic conditions on fire temperature, and (2) relate these factors to topkill or defoliation effects on honey mesquite.

## Materials and Methods

Research was conducted from 1991 to 1995 on 2 sites in the northern Rolling Plains ecological area of Texas: Ninemile Pasture on the Waggoner Ranch south of Vernon (33° 51'N, 99° 26'W; elev. 381 m), and Strip and River Pastures on the Y Experimental Ranch (YER) west of Crowell (33° 52'N, 100° 03'W; elev. 500 m and 33° 53'N, 100° 00'W; elev. 470 m, respectively). The sites are 50 km apart and differ in herbaceous understory species composition. The Ninemile site has an equal mixture of cool and warm-season grasses, while the Y Ranch site is dominated by warm-season grasses. Primary cool-season grass species at Ninemile are perennials Texas wintergrass (*Nassella leucotricha* [Trin. and Rupr.] Pohl) and Texas bluegrass (*Poa arachnifera Torr.*) and the annual grass Japanese brome (*Bromus japonicus* Thunb ex. Murray). Warm-season grasses are perennials buffalograss (*Buchloe dactyloides* [Nutt.] Engelm.) and sand dropseed (*Sporobolus cryptandrus* (Torr.) Gray). Primary grass species at the Y Ranch are warm-season perennials buffalograss, tobosagrass (*Hilaria mutica* [Buckl.] Benth), and sideoats grama (*Bouteloua curtipendula* [Michx.] Torr.)

Mean annual rainfall at Ninemile is 665 mm. Soils are fine, mixed, thermic Typic Paleustolls of the Tillman series which are alluvial clay loams from 0 to 3-4 m depth, underlain by Permian sandstone/shale parent material (Koos et al. 1962). Mean annual rainfall at the Y Ranch is 450 mm. Soils are fine-silty, mixed, thermic Typic Calciustolls of the Quanah series (Strip), and fine, montmorillonitic, thermic Typic Haplusterts of the Hollister series (River) (NRCS-Vernon, pers. comm).

Both sites are dominated by a woody overstory of honey mesquite. Most mesquite are multistemmed regrowth from previous topkilling herbicide treatments. Mesquite at Ninemile were treated in 1973 and were to 2-4 m height at study initiation. Basal stem diameters ranged from 5-12 cm. Mesquite at both Y Ranch pastures (Strip, River) were treated with herbicides in the early 1980's and were 2-3 m height with basal stem diameters 3-8 cm. Livestock (cattle) grazing was excluded at Ninemile since 1988. Livestock grazing was continuous at the Y Ranch sites except for a 4 month deferral prior to burning at Strip Pasture and a 9 month pre-burn deferral at River Pasture.

Fires were conducted during the winter season from late-January to mid-March when mesquite was dormant and void of foliage, warm-season grasses were completely dormant, cool-season perennials were partially green, and cool-season annuals (Japanese brome) were mostly green. Fires were conducted on 10 plots (which ranged in size from 3-7 ha each) at Ninemile, one 10-ha plot in Strip Pasture, and nine 1-ha plots in River Pasture (Table 1). All fires were conducted as headfires according to methods described by Wright and Bailey (1982) and McPherson et al. (1986).

Fire temperature measurements were used to assess fire behavior. Glass-insulated type K (Chromel-Alumel) thermocouple wire (20 AWG; 0.8 mm diam.) overbraided with stainless steel and a Campbell CR 7 datalogger were used to measure and record fire temperatures. A datalogger was placed in a fireproof container near the center of each plot (Jacoby et al. 1992). Thermocouples were extended 50 to 100 m from the datalogger and attached to vertical metal poles at 0, 10, and 30-cm and 1, 2, and 3-m above the soil surface. Two to 6 thermocouple stations (pole + 6 thermocouples) were located in each plot within interspaces between mesquite and at least 2 m from a tree. Stations were located near grass species which

**Table 1.** Plot location, burn date and time, weather, fuel, and mesquite response for each winter fire, 1991-1995.

| Date, Location Time of Headfire | | | | Weather Data | | | Understory Fine Fuel Data | | | Mesquite Response | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Site[1] | Plot | Hour | Air Temp (C) | RH (%) | Avh Wind Speed (kph) | Veg Type at TC Station[2] | Amount kg/ha | % Moist. Cont. | Percent With Complete Topkill | Percent Foliage Remaining (NTK)[3] |
| 04MAR91 | NM | 11B | 1700 | 10.0 | 50 | 5.6 | OPN | 3998 | - | 4 | 94 |
| 07MAR91 | NM | 9B | 1330 | 14.4 | 29 | 16.1 | INT | 2250 | - | 7 | 83 |
| 07MAR91 | NM | 10B | 1330 | 14.4 | 29 | 16.1 | INT | 2850 | - | 11 | 62 |
| 13MAR91 | NM | 7B | 1220 | 18.9 | 20 | 25.7 | INT | 2200 | 25.1 | 15 | 57 |
| 13MAR91 | NM | 8B | 1220 | 18.9 | 20 | 25.7 | INT | 3025 | 22.4 | 26 | 66 |
| 27JAN93 | NM | 11A | 1400 | 20.0 | 21 | 19.3 | OPN | 5759 | 11.2 | 81 | 20 |
| 27JAN93 | NM | 12A | 1400 | 20.0 | 21 | 19.3 | INT | 2886 | 15.2 | 63 | 31 |
| 27JAN93 | NM | 9A | 1600 | 18.3 | 25 | 14.5 | INT | 1037 | 19.4 | 13 | 59 |
| 27JAN93 | NM | 10A | 1600 | 18.3 | 25 | 14.5 | INT | 2547 | 13.4 | 11 | 52 |
| 28JAN93 | NM | 7A | 1200 | 12.2 | 43 | 12.9 | INT | 2367 | 22.5 | 26 | 40 |
| 08MAR93 | ST | 1 | 1450 | 29.4 | 11 | 25.7 | INT | 4968 | 12.9 | 100 | - |
| 08MAR93 | ST | 1 | 1450 | 29.4 | 11 | 25.7 | MC-HF | 3252 | 10.4 | 100 | - |
| 08MAR93 | ST | 1 | 1450 | 29.4 | 11 | 25.7 | MC-LF | 1155 | 25.9 | 100 | - |
| 31JAN95 | RV | 6 | 1300 | 17.8 | 31 | 6.4 | INT | 4384 | 21.2 | 27 | 34 |
| 31JAN95 | RV | 5 | 1450 | 19.4 | 31 | 12.9 | INT | 3197 | - | 38 | 39 |
| 31JAN95 | RV | 3 | 1640 | 18.3 | 25 | 8.0 | INT | 5375 | - | 56 | 20 |
| 01FEB95 | RV | 9 | 1410 | 23.9 | 17 | 8.8 | INT | 4116 | 11.1 | 90 | 11 |
| 01FEB95 | RV | 10 | 1600 | 25.6 | 17 | 11.3 | INT | 4415 | 10.9 | 79 | 21 |
| 22FEB95 | RV | 13 | 1330 | 25.6 | 28 | 17.7 | INT | 3903 | 15.3 | 69 | 33 |
| 22FEB95 | RV | 14 | 1510 | 28.9 | 15 | 17.7 | INT | 4303 | 11.7 | 83 | 23 |
| 24FEB95 | RV | 12 | 1000 | 13.3 | 40 | 7.2 | INT | 2841 | 17.6 | 13 | 45 |
| 10MAR95 | RV | 18 | 1030 | 13.9 | 37 | 16.9 | INT | 1502 | 24.5 | 10 | 48 |

[1] NM = Ninemile Pasture; ST = Strip Pasture; RV = River Pasture.
[2] TC=Thermocouple; INT = Interspace between mesquite; OPN = Open grass areas with few mesquite; MC = under mesquite canopy; HF=high subcanopy fuel;LF=low subcanopy fuel.
[3] NTK= non-topkilled trees

were dominant within each plot. Data obtained from each thermocouple position included peak fire temperature, and fire temperature duration (FTD) in seconds above 100°C (FTD100) or above 200°C (FTD200).

Amount of surface-level herbaceous understory fine fuel (hereafter referred to as fine fuel) was estimated for each thermocouple station location by clipping 3, 0.25 $m^2$ quadrats of vegetation with species composition similar to that occurring at each thermocouple station, but at least 10 m from each station, 30 min. before ignition. Fine fuel moisture content was determined on a wet weight basis [(wet wt.- o.d. wt)/wet wt.] by weighing samples in the field immediately after clipping and again after oven drying at 60° C for 48 hrs. Fine fuel was comprised mainly of grasses, undefined litter, and a few small herbaceous dicots (forbs). Most of the litter was from recently decayed grass tillers. Mesquite wood moisture content was not measured prior to each fire.

Weather variables, air temperature (AT), relative humidity (RH), and wind speed at 2 m height were measured prior to and immediately after each fire using a sling psychrometer and a hand-held wind meter (accuracy ± 3%), respectively. Some adjacent plots were burned simultaneously and were assigned identical weather data (Table 1). However, other variables such as fine fuel, fire temperature and mesquite response were measured separately within each plot.

*Mesquite Evaluations*

Mesquite were evaluated for percent mortality (i.e. root kill), percent topkill (percent of trees in the plot with complete above-ground mortality), and percent foliage remaining per tree of non-topkilled (NTK) trees the growing season following each fire. At Ninemile and River sites, 8 to 15 trees nearest 6 permanent points in a plot were evaluated. The points were marked with metal fence posts located as 2 parallel 3 point transects. Transects were 100 m apart and points within each transect were spaced at 50 m. At Strip Pasture, 80 trees tagged prior to burning were evaluated. Percent foliage remaining was determined by ocular estimate and compared to similar-sized, untreated mesquite in adjacent pastures. Average percent foliage remaining per plot was calculated by averaging partially and completely topkilled trees. Seedling or very small mesquite (< 0.5 m tall) were not included in mesquite response data reported in this paper.

*Statistical Analysis*

Single linear regressions were performed between understory fine fuel or weather (as independent variables) and fire temperature (peak, FTD100, or FTD200 as dependent variables). Single linear regressions were also performed between fine fuel, weather or fire temperature (as independent variables) and mesquite canopy response to fire (percent topkill or percent foliage remaining NTK trees). A stepwise multiple linear regression was performed between fine fuel and weather (as independent variables) and mesquite topkill or foliage remaining (as dependent variables). Per plot averages were used for all regressions. Independent variables were tested for collinearity prior to multiple regressions. Site (Ninemile vs Y Ranch) was tested as a source of variation and regressions were separated by site if there was a significant ($p \leq 0.05$) interaction by site. Since all fires were conducted within a 6-wk span during the winter (27 January to 13 March, 1991-1995), effects of time of year or burn date were not tested. The substudies were unreplicated case studies and not statistically analyzed.

## Results

*Fuel, Weather and Fire Temperature*

Air temperature (AT), relative humidity (RH), wind speed, understory fine fuel amount and fine fuel moisture content ranged from 10.0 to 29.4 °C, 11 to 50%, 5.6 to 25.7 kph, 1037 to 5759 kg/ha, and 11.1 to 25.9%, respectively, across all fires (Table 1). Over all fires and thermocouple stations, average peak fire temperature was 449, 567 and 201 °C, at 0 cm, 10-30 cm and 1-3 m, respectively (Table 2). Fire temperature duration (FTD) in seconds over 100 °C (FTD100) or over 200 °C (FTD200) was greatest at 0 cm (soil surface) and least at 1-3 m heights in most fires. At all heights, FTD100 was greater than FTD200.

**Table 2.** Mean peak fire temperature and fire temperature duration in seconds over 100 °C (FTD100) and 200 °C (FTD200) at 3 thermocouple heights over all fires in the study, 1991-1995. Mean standard errors are in parentheses.

| Thermocouple Height (m) | Peak Fire Temp (C) | FTD100 (Sec) | FTD200 (Sec) | Sample n[1] |
|---|---|---|---|---|
| 0 | 449 (26) | 92 (8) | 53 (7) | 18 |
| 0.1 - 0.3 | 567 (30) | 53 (3) | 32(2) | 20 |
| 1 - 3 | 201 (19) | 20 (3) | 5 (1) | 20 |

[1] All values within each fire plot were pooled prior to mean determination. No thermocouple data from the soil surface (0 cm) were obtained on 2 of the fires.

**Table 3.** Mean time from initiation of fire-induced temperature increase to peak temperature at each thermocouple height. Summary of 39 thermocouple stations (in 20 winter-season fires). Data are from thermocouples placed in interspaces between trees.

| Thermocouple Height (m) | Time Start to Peak (seconds) [1] | Standard Error | Sample n[2] |
|---|---|---|---|
| 0.0 | 37 | 3.6 | 31 |
| 0.1 | 22 | 2.7 | 36 |
| 0.3 | 21 | 1.5 | 35 |
| 1.0 | 25 | 1.9 | 37 |
| 2.0 | 31 | 2.4 | 39 |
| 3.0 | 31 | 2.5 | 37 |

[1] Initiation point of temperature rise was determined when temperature increased 10 °C within a 5 second span.
[2] Sample n varied due to failure of some thermocouples

A typical example of fire temperature at each thermocouple height during a high and a low intensity fire is illustrated in Figure 1. In most fires, including those depicted in Figure 1, peak temperature at any height occurred within 20 to 40 sec of the first indication of a temperature increase caused by the fire (Table 3). Higher thermocouple positions were preheated by the convective column prior to lower ones. Thermocouples at 2 and 3 m heights sensed the fire first and hence had relatively long intervals from initiation to peak (31 sec). The initiation to peak interval was shortest at the 10 and 30 cm heights (22 and 21 sec). Fire temperature at the soil surface rose gradually and had the longest interval from initiation to peak (37 sec). Duration of peak fire temperature at 0 cm was <5 sec in most fires, which agrees with findings of Wright et al. (1976) who burned in mesquite/tobosagrass sites in north Texas.

A positive linear relationship ($r^2=0.50$, $p<.001$) occurred between understory fine fuel amount and peak fire temperature at the soil surface (Table 4 and Figure 2). Slope and intercept of this regression were similar to those reported by Stinson and Wright (1969) for fires in the Rolling Plains in fuel amounts ranging from 3000-8000 kg/ha. Fine fuel amount also influenced ($P<0.01$) peak fire temperature at 10-30 cm and 1-3 m heights above ground, but the relationship between fine fuel amount and peak fire temperature was strongest at ground level and diminished with increasing height above ground (Table 4). There was no relationship between fine fuel moisture or any of the weather variables (AT, RH, wind) and peak fire temperature at any height, except that at the Y Ranch sites only, RH influenced peak temperature at 1-3 m height.

Fine fuel amount influenced FTD100 at 10-30 cm and 1-3 m heights, but not at the soil surface. Understory fine fuel moisture and air temperature (AT) also influenced FTD100 at 1-3 m height. Similar relationships were found between fine fuel amount and FTD200 at 10-30 cm and 1-3 m heights. Air temperature was the only weather variable that influenced FTD200.

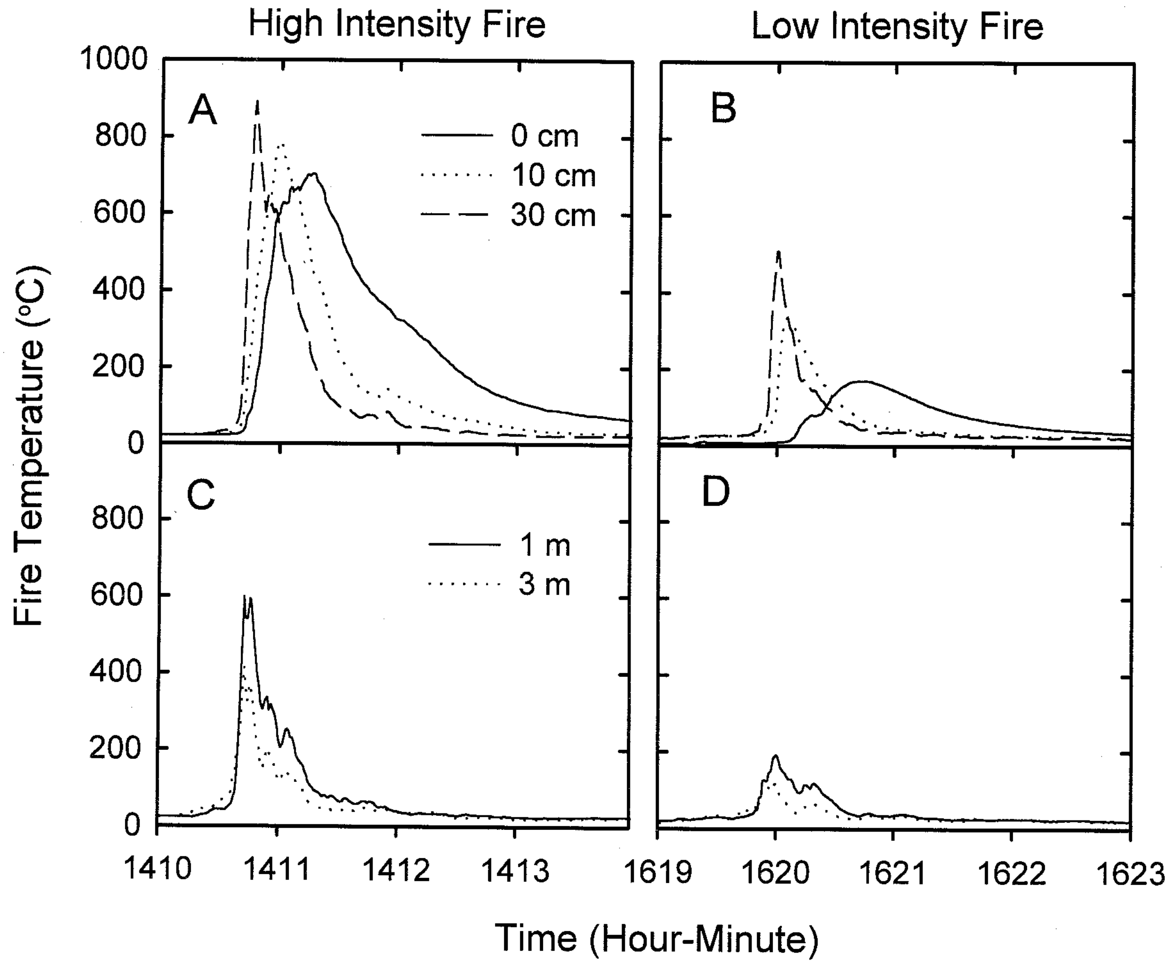


**Figure 1.** Time/temperature profiles of a high (A,C) and a low (B,D) intensity fire at 0, 10 and 30 cm (A,B) and 1 and 3 m (C,D) above ground. Temperature responses at 2 m height were between the 1 and 3 m values in both fires (data not shown). Data are from 2 thermocouple stations (6 points per station) and are not plot means. Fires were conducted in adjacent plots at Ninemile Pasture, Waggoner Ranch, 27Jan93.

**Table 4.** Regressions between fine fuel, weather during the fire, peak fire temperature, and fire temperature duration. Values are $r^2$ of linear regressions. All regressions based on per plot values.

| Independent Variable | Dependent Variable | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Peak Fire Temp | | | Fire Temp Duration (Sec Over 100°C) | | | Fire Temp Duration (Sec Over 200°C) | | |
| | 0 cm | 10-30cm | 1-3m | 0 cm | 10-30cm | 1-3 m | 0 cm | 10-30cm | 1-3m |
| Fine Fuel Amt (kg/ha) | .50** | .43* | .35* | .34 | .48* | .55** | .28 | .51** | .43* |
| Fuel Moisture (%) | .25 | .24 | .30 | .01 | .08 | .54* | .01 | .32 | .22 |
| Air Temperature (C) | .16 | .19 | .18 | .06 | .27 | .37* | .02 | .37* | .14 |
| Relative Humidity (%) | .12 | .06 | .10 | .09 | .25 | .18 | .05 | .17 | .13 |
| RH Ninemile only | .10 | .02 | .01 | .20 | .30 | .03 | .13 | .05 | .03 |
| RH Y Ranch only | .13 | .11 | .44* | .04 | .21 | .63* | .04 | .49* | .39 |
| Wind (kph) | .02 | .01 | .02 | .13 | .01 | .01 | .09 | .01 | .02 |
| Pk Fire Tmp (0 cm) | - | - | - | .29 | - | - | .38* | - | - |
| Pk Fire Tmp (10-30 cm) | - | - | - | - | .36* | - | - | .64** | - |
| Pk Fire Tmp (1-3 m) | - | - | - | - | - | .77** | - | - | .86** |

* = Regressions are significant at p<0.01; ** = significant at p<0.001.

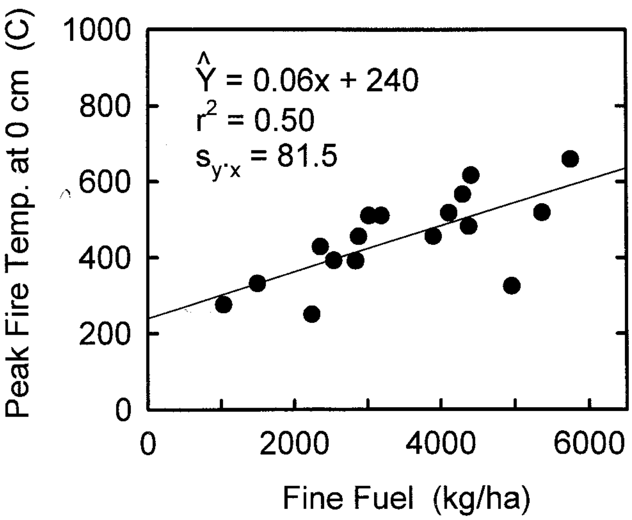


**Figure 2.** Relation between understory herbaceous fine fuel amount and peak fire temperature at 0 cm. Points are means per fire (plot).

Peak fire temperature appeared to be a good predictor of fire temperature duration. The relationship between peak fire temperature and FTD100 or FTD200 increased in strength with increasing thermocouple height, and was strongest at 1-3 m (Table 4 and Figure 3). FTD200 appeared to be more strongly related to peak fire temperature than was FTD100 at all heights (Table 4).

*Mesquite Responses*

Other than some charring on the bark, the appearance of mesquite immediately after each fire was very similar to that prior to each fire, and it was not until the growing season that fire effects on topkill or foliage remaining on non-topkilled trees could be determined. Very little mesquite wood was consumed, probably because of the brief residence time of peak fire temperatures (see Figure 1), and moisture content in the mesquite tissue. Some small twigs (<1 cm diam.) were consumed (unquantified observations) during the most intense fires. However, we are reasonably confident that fire temperatures recorded in the interspaces between mesquite were a function of understory fine fuel and weather variables, and not due to heating or combustion of mesquite wood. Most fire damage to mesquite was probably due to scorching rather than combustion.

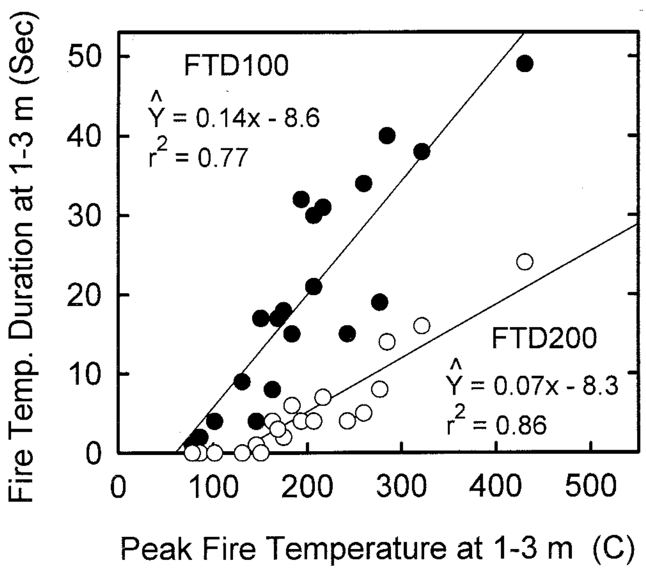


**Figure 3.** Relation between peak fire temperature at 1-3 m heights and fire temperature duration in seconds over 100 (FTD100) or over 200 °C (FTD200) at 1-3 m heights. Points are means per fire (plot).

Average percent topkill and percent foliage remaining per tree of non-topkilled (NTK) trees ranged from 4 to 100 and 11 to 94, respectively, across all fires (Table 1). Trees that were not topkilled usually had portions of their canopy killed by the fire. This was manifest during the following growing season as varying amounts of tree foliage missing. Often defoliation occurred on the lower portion of the mesquite canopy and had the appearance of a browse line (Ansley et al. 1996). The amount of foliage remaining on NTK trees during the growing season following the fire was a negative curvilinear function ($r^2$=0.84) of the percent of trees in the entire stand that were topkilled (Figure 4). Whole plant mortality (i.e., root-kill) varied from 0 to 1% across all fires, and all topkilled trees resprouted from stem bases.

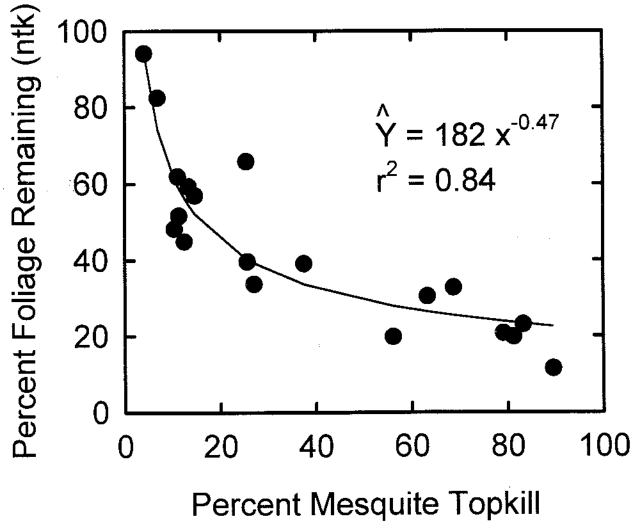


**Figure 4.** Relation between mesquite percent topkill (per stand) and percent canopy foliage remaining per tree (of non-topkilled trees). Points are means per fire (plot).

Linear relationships (p≤0.001) occurred between fine fuel amount, fine fuel moisture content, AT, or RH (as independent variables) and percent topkill (Table 5). There was a strong positive relationship between AT dur-

**Table 5.** Regressions between fine fuel, weather during the fire, peak fire temperaure, fire temperature duration (FTD), and mesquite responses. Values are $r^2$ of linear regressions. Regressions are based on plot means (n= 18-20).

| | Mesquite Response | |
|---|---|---|
| IndependentVariable | Percent Topkill | Percent Foliage Remaining (NTK)[1] |
| Fine Fuel Amount(kg/ha) | .52** | .30 |
| Fine Fuel Moisture(%) | .63** | .56* |
| Air Temperature (C) | .73** | .45* |
| Relative Humidity (%) | .47** | .27 |
| RH at Ninemile only | .17 | .22 |
| RH at Y Ranch only | .92** | .82** |
| Wind (kph) | .03 | .01 |
| Peak Fire Temp (0 cm) | .34 | .60** |
| Peak Fire Temp (10-30 cm) | .45* | .43* |
| Peak Fire Temp (1-3 m) | .55** | .52** |
| FTD; Sec>100°C (0 cm) | .19 | .10 |
| FTD; Sec>100°C (10-30 cm) | .39* | .41* |
| FTD; Sec>100°C (1-3 m) | .74** | .69** |
| FTD; Sec>200°C (0 cm) | .10 | .04 |
| FTD; Sec>200°C (10-30 cm) | .61** | .56** |
| FTD; Sec>200°C (1-3 m) | .48** | .38* |

* = significant at p<0.01; ** = significant at p< 0.001.
[1]NTK = non-topkilled trees

ing the fire and topkill ($r^2$=0.73) (Figure 5). An interaction (p<0.05) occurred between site and effects of RH on mesquite response to fire. A strong negative relationship occurred between RH and topkill ($r^2$=0.92) at the Y Ranch sites (Figure 6), but a relationship between these variables did not exist at the Ninemile site (Table 5). Trees were larger and fine fuel was often quite green due to a greater amount of cool-season grasses such as Japanese brome and Texas wintergrass at Ninemile than on the Y Ranch sites. These factors may have reduced either mesquite sensitivity to fire, or the effect of RH on fire intensity when compared to the Y Ranch sites.

Relations between fuel or weather variables and foliage remaining on NTK trees were the inverse of topkill responses. Foliage remaining was negatively related to AT (Figure 5) and positively related to RH (Y Ranch sites only; Figure 6). Foliage remaining was not significantly related to fine fuel amount ($r^2$=0.30; Table 5), but this was mainly due to a single outlier (Plot 11B; 04Mar91) which had high fuel (3998 kg/ha) but low topkill (4%) due to very green and cool conditions during the fire (Table 1). Removing that point from the regression increased the $r^2$ to 0.55 (p≤0.001). Therefore we conclude that fine fuel and foliage remaining of NTK trees were related.

Stepwise regressions indicated that, when both sites were included in the model, AT and fine fuel amount ex-

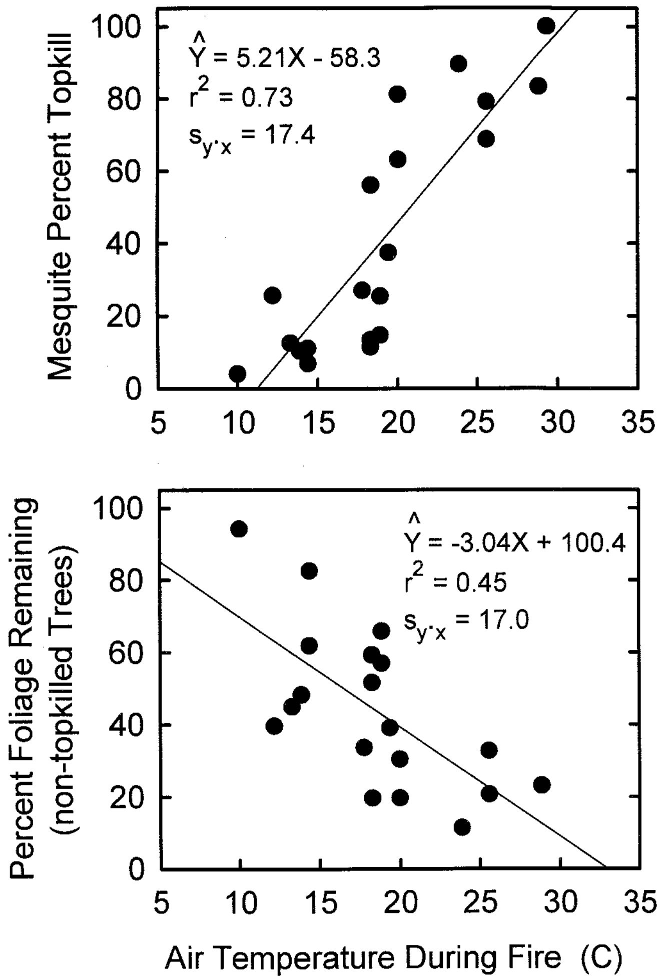


**Figure 5.** Relation between air temperature during each fire and fire effects on mesquite topkill (top), or canopy foliage remaining per tree of non-topkilled trees (bottom). Points are means per fire (plot).

plained most of the variation ($r^2$=0.83) associated with mesquite topkill response to fire (Table 6). Fuel amount and fuel moisture content were the most significant variables affecting foliage remaining of NTK trees. When sites were analyzed separately, fuel amount remained the dominant factor at the Ninemile site, but weather variables AT, RH and wind speed explained most of the variation at the Y Ranch site. Total sample size for the stepwise regressions was reduced because fuel moisture data were not collected during 5 of the fires (see Table 1). When fuel moisture was removed from the model to increase sample N for the regressions, weather variables gained in importance relative to fuel amount at both sites (Table 7). This was especially true at the Ninemile site, where AT became as important as fuel amount in explaining mesquite topkill response to fire.

Mesquite responses to fire temperature variables were generally more related to fire temperature at 1-3 m than at lower heights (Table 5). The effect of peak fire temperature on mesquite percent topkill increased with height

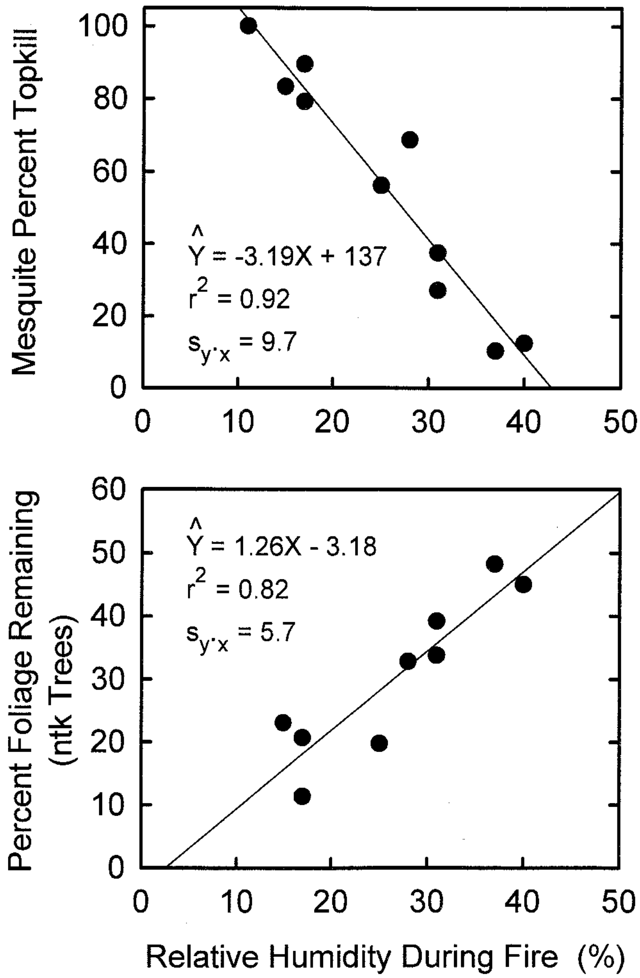


**Figure 6.** Relation between relative humidity during each fire and fire effects on mesquite topkill (top), or canopy foliage remaining per tree of non-topkilled trees (bottom). Points are per plot means (Y Ranch fires only).

and was greatest at 1-3 m. Similar trends occurred between fire temperature duration and mesquite responses, although FTD200 at 10-30 cm and 1-3 m heights had similar effects on mesquite. There was a strong positive relationship between FTD100 at 1-3 m height and mesquite topkill ($r^2$=0.74), and a strong negative relationship between FTD100 at 1-3 m and foliage remaining of NTK trees ($r^2$=0.69) (Figure 7). Mesquite topkill for the stand exceeded 50% if, at 1-3 m above ground, fire temperature was greater than 100 °C for more than 25 sec.

### *Substudies*

Two substudies were conducted during 3 of the fires to further quantify effects of fuel on fire behavior and mesquite response. Substudy 1 was conducted at Ninemile on 27Jan93 in which 2 plots (11A and 9A) with different fuel loads (5759 vs. 1037 kg/ha) were burned under similar weather conditions. In comparing these 2 fires, mesquite topkill was much greater (81 vs. 13%) in the high fuel fire (Table 1). Substudy 2 was conducted during the

**Table 6.** Stepwise regression involving relative effects of fuel amount (FUEL), fuel moisture content (FMST), air temperature (AT), relative humidity (RH) and wind speed (WKPH) on mesquite percent topkill or percent foliage remaining of non-topkilled trees

| Percent Topkill | | | | | |
|---|---|---|---|---|---|
| Sites | N | Independent Variable | Partial $r^2$ | Model $r^2$ | Prob. > F[1] |
| Both Sites | 15 | AT | 0.70 | 0.70 | 0.0001** |
| | | FUEL | 0.13 | 0.83 | 0.0106 |
| Ninemile | 7 | FUEL | 0.69 | 0.69 | 0.0210 |
| Y Ranch | 8 | AT | 0.92 | 0.92 | 0.0002** |
| | | RH | 0.03 | 0.95 | 0.1212 |

| Percent Foliage Remaining (NTK Trees) | | | | | |
|---|---|---|---|---|---|
| Sites | N | Independent Variable | Partial $r^2$ | Model $r^2$ | Prob. > F |
| Both Sites | 14 | FUEL | 0.59 | 0.59 | 0.0014* |
| | | FMST | 0.10 | 0.69 | 0.0841 |
| Ninemile | 7 | FUEL | 0.50 | 0.50 | 0.0746 |
| Y Ranch | 7 | RH | 0.87 | 0.87 | 0.0021* |
| | | WKPH | 0.07 | 0.95 | 0.0800 |

[1] ** = Significant at $P \leq 0.001$;
* = significant $P \leq 0.01$.

08Mar93 Strip Pasture fire to compare effect of subcanopy fuel on mesquite response to fire. Half of 80 tagged trees had abundant and dry subcanopy fine fuel (3252 kg/ha, fuel moisture 10.4%), most of which included dormant midgrasses, 30-50 cm tall. The other 40 trees had sparse subcanopy fuel which consisted of green, cool-season annual grasses about 3-5 cm high (1155 kg/ha, fuel moisture 25.9%). These fuel types occurred within, and did not extend beyond, the canopy margin (dripline). Interspaces between trees were dominated by tobosagrass (4968 kg/ha; fuel moisture 12.9%). The fire was intense (flame length > 6 m; intensity >15,000 kW/m; Byram 1959), driven by high winds (25.7 kph), high AT (29.4 °C), low RH (11%) and moderate fuel loads in interspaces between trees (Table 1). All of the tagged trees were topkilled, indicating that fire effects on mesquite in this particular fire were independent of subcanopy fuel conditions. Peak fire temperatures and fire temperature durations were higher relative to the other fires (Tables 2 and 8). This was especially true at the 1-3 m height, in which peak fire temperature, FTD100 and FTD 200 at all 3 vegetation locations (interspace, subcanopy high fuel and subcanopy low fuel) were much greater that the mean values of other fires in the main study.

## Discussion

### *Factors Affecting Fire Temperature*

Our results agree with Stinson and Wright (1969) and Wright et al. (1976) who found that maximum fire tem-

**Table 7.** Stepwise regression involving relative effects of fuel amount (FUEL), air temperature (AT), relative humidity (RH) and wind speed (WKPH) on mesquite percent topkill or percent foliage remaining of non-topkilled trees. Fuel moisture content was omitted from these regressions.

| Sites | N | Independent Variable | Partial $r^2$ | Model $r^2$ | Prob. > F[1] |
|---|---|---|---|---|---|
| | | **Percent Topkill** | | | |
| Both Sites | 20 | AT | 0.73 | 0.73 | 0.0001** |
| | | FUEL | 0.12 | 0.85 | 0.0014* |
| Ninemile | 10 | FUEL | 0.39 | 0.39 | 0.0521 |
| | | AT | 0.30 | 0.69 | 0.0364 |
| Y Ranch | 10 | RH | 0.92 | 0.92 | 0.0001** |
| | | AT | 0.03 | 0.95 | 0.1098 |

Percent Foliage Remaining (NTK Trees)

| Sites | N | Independent Variable | Partial $r^2$ | Model $r^2$ | Prob. > F |
|---|---|---|---|---|---|
| Both Sites | 19 | AT | 0.45 | 0.45 | 0.0016* |
| | | WKPH | 0.09 | 0.54 | 0.1014 |
| Ninemile | 10 | AT | 0.38 | 0.38 | 0.0593 |
| Y Ranch | 9 | RH | 0.82 | 0.82 | 0.0008* |
| | | WKPH | 0.11 | 0.93 | 0.0258 |

[1] ** = Significant at $P \leq 0.001$;
* = significant $P \leq 0.01$.

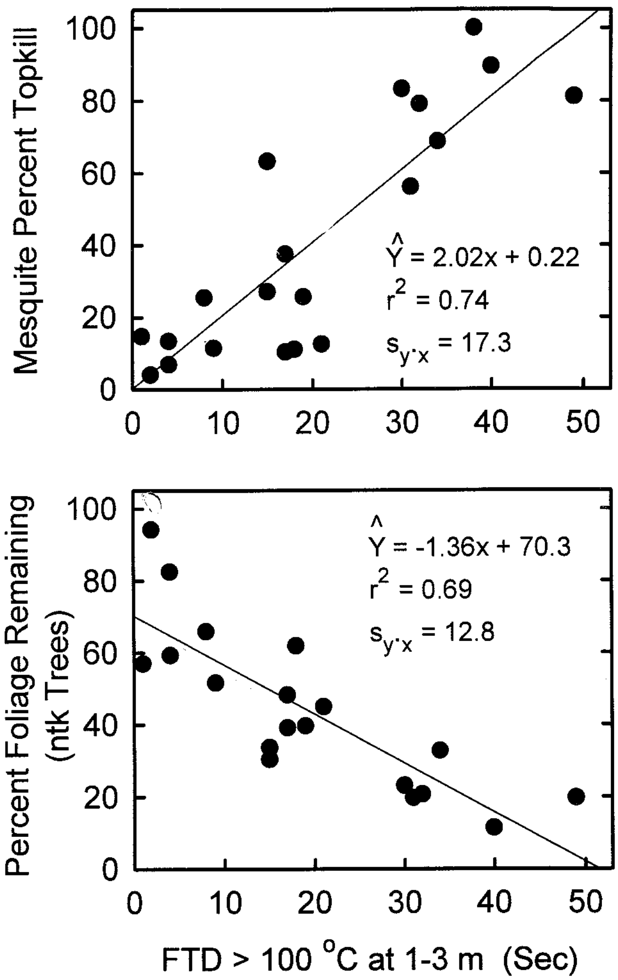


**Figure 7.** Relation between fire temperature duration in seconds over 100 °C (FTD100) at 1-3 m heights and fire effects on mesquite topkill (top), or canopy foliage remaining per tree of non-topkilled trees (bottom). Points are means per fire (plot).

perature at the soil surface increased with increasing fine fuel amount. Trollope (1992a) determined that fire intensity was positively related to fuel, assuming a constant heat yield, and that there was a positive correlation between fire intensity and maximum fire temperature. These results from Africa provide indirect evidence of a relation between fuel amount and peak fire temperature.

Stinson and Wright (1969) found that air temperature significantly affected, and wind speed slightly affected, peak fire temperature at the soil surface. Britton and Wright (1971) found that wind speed and relative humidity were the primary climatic factors which affected fire temperature at the soil surface, but that air temperature and fine fuel were not well correlated with soil surface fire temperature. From our results, fine fuel amount appears to be the dominant factor affecting peak fire temperature, and it may mask potential effects of climatic variables.

*Mesquite Canopy Responses to Fire*

The current study demonstrated that fine fuel amounts and fuel moisture content significantly influenced mesquite canopy responses to fire. Obviously, with much reduced (<1000 kg/ha) or greater fuel amounts (>6,000 kg/ha), we may expect a greater relation between fuel

**Table 8.** Mean peak fire temperature and fire temperature duration in seconds above 100 °C (FTD100) or 200 °C (FTD200) at 3 thermocouple heights and in 3 fuel types; Y Ranch Strip Pasture Fire, 08 March 1993 (sample n=2).

| TC Height (m) | [1/] TC Location | Peak Fire Temp (C) | FTD100 (Sec) | FTD200 (Sec) |
|---|---|---|---|---|
| 0 | INT | 325 | 120 | 54 |
| | MC-HF | 495 | 217 | 169 |
| | MC-LF | 209 | 135 | 13 |
| 0.1-0.3 | INT | 774 | 68 | 49 |
| | MC-HF | 623 | 132 | 79 |
| | MC-LF | 540 | 9 | 42 |
| 1 - 3 | INT | 322 | 38 | 16 |
| | MC-HF | 483 | 42 | 24 |
| | MC-LF | 403 | 36 | 17 |

[1/] TC = thermocouple; INT = Interspace between mesquite, MC-HF = mesquite canopy - high subcanopy fuel; MC-LF = mesquite canopy - low subcanopy fuel.

amount and mesquite response than was found in the current study. Results from substudy 1 (2 burns on same day; different fuel amounts) support the findings of the main study and emphasize that fuel amount is an important factor in affecting mesquite responses to fire. In support of our findings, 2 papers by Trollope (1992a, 1992b) suggest indirectly that fine fuel is related to topkill of some woody species in Africa. Trollope (1992a) indicated a linear relation between fuel load and fire intensity (kJ $s^{-1}$ $m^{-1}$), and Trollope (1992b) found a slight relationship between fire intensity and percent topkill of *Acacia karoo* in Africa. In our study, fine fuel moisture content had as much influence on mesquite response to fire as did fine fuel amount.

Our study demonstrated that air temperature had an equal or greater influence on mesquite canopy response to fire than did fuel amount or fuel moisture content. Mesquite response to fire was also related to relative humidity, but this occurred only at the Y Ranch sites. While fuel moisture was linked to mesquite response to fire at both sites, factors which affected fuel moisture differed between sites. Fuel moisture at the Y Ranch site was affected by air temperature and relative humidity because it was comprised mainly of standing dead tissue. Conversely, the presence of more green tissue in the fine fuel at Ninemile decoupled effects of air temperature and relative humidity on fuel moisture content. Thus, at Ninemile, air temperature and relative humidity did not affect mesquite response to fire because they had little effect on fine fuel moisture content.

At study initiation we hypothesized that fire interrupts a physiological mechanism in mesquite by destroying phloem at stem bases. In this process, fire girdles the stem bases and aerial portions of mesquite are physiologically separated from roots. Our data suggest that this is not the case and that the topkill mechanism is related more to fire conditions within aerial portions of the canopy than at stem bases. The "topkill mechanism" appears to involve convective heat enveloping aerial portions of mesquite rather than destroying stem bases. These results agree with studies on *Pinus* spp. which indicated that the cause of mortality following fire was crown scorch rather than damage to the cambium near the ground (Cooper and Altobellis 1969, Van Wagner 1973). Results from substudy 2 support the concept of convective heat as the primary topkilling factor. In this substudy, mesquite with green, low-growing subcanopy fuel were completely topkilled by an intense fire. These trees were probably topkilled as convection heat generated from fuel in tree interspaces enveloped the branches.

Heat resistance in woody plant tissue is dependent on density and thickness of tree bark (Spalt and Reifsnyder 1962, Hengst and Dawson 1994). Higher moisture content in plant tissue also increases susceptibility to fire (Wright 1980). Aerial portions of mesquite have thinner, lower density bark, and greater moisture content than at the stem base. This would explain why fire temperatures at 1-3 m heights, while always lower and of less duration than temperatures at 0-30 cm heights during the same fire (see Table 2), caused branch mortality in topkilling fires. Most mesquite in our study had basal stem diameters in excess of 5 cm and at least 0.5 to 1 cm thick rhytidome.

One of the reasons why the literature has not shown a strong relation between fire temperature data and woody plant response to fire may be because fire temperature measurements were largely restricted to the soil surface. Another reason may be that peak fire temperature rather than fire temperature duration has been used for comparisons to plant response. In our study, the strongest relationship between fire temperature and mesquite responses involved fire temperature at upper heights rather than at the soil surface, and fire temperature duration in seconds over 100°C (FTD100) rather than peak fire temperature. Fire temperature at upper heights appeared to be more sensitive to weather conditions during the fire than did temperature at ground level (Table 4). The relationship between peak fire temperature and FTD100 was also strongest at 1-3 m heights.

*Canopy Responses vs. Whole Plant Mortality*

Most studies which have related fine fuel and weather variables to mesquite response to fire quantified mesquite whole-plant mortality (i.e., root-kill) and not canopy (i.e., topkill or foliage reduction) responses. Wright et al. (1976), for example, found that honey mesquite mortality in west Texas was independent of fuel amounts ranging from 4500-7800 kg/ha. Cable (1965) found a positive relationship between fine fuel amount and velvet mesquite (*Prosopis velutina*) mortality in Arizona. In another west Texas study, Britton and Wright (1971) found that fuel amount was a better predictor of mesquite mortality than weather variables AT, RH and wind speed. Studies which identified relationships between fuel or weather variables and mesquite root-kill responses to fire may not apply to our study because conditions required to inflict root mortality (i.e., extreme temperatures near dormant regrowth buds at the stem base) may be quite different from those which effect topkill and/or partial canopy defoliation. Somewhat related to our findings, Britton and Wright (1971) indicated that wind speed and RH, and not fine fuel amount, significantly affected burndown of standing dead mesquite, but there was little correlation between air temperature and burndown. Our study suggests that air temperature iis perhaps the most significant weather variable affecting mesquite topkill (Figure 5).

*Mesquite Management with Fire*

While none of the fires in this study root-killed mesquite, other studies have demonstrated fire-induced mortality. Stinson and Wright (1969) and Britton and Wright (1971) reported that fire root-killed up to 32% of medium-sized honey mesquite in the western Rolling Plains of Texas, which is drier than the central or eastern Rolling Plains where our studies were conducted. On dry upland sites in west Texas, Wright et al. (1976) found that 27% of large honey mesquite that had been topkilled with 2,4,5-T before burning were root-killed by fire. Root mortality on lowland sites, however, was less than 8%. Cable (1965) and others found that intense fires root-killed medium-sized velvet mesquite in Arizona.

It appears from these results and those of the current study, that dry, upland conditions are necessary for single winter fires to achieve root mortality in honey mesquite. We hypothesize fire to be progressively less effective at root-killing mesquite as one moves from the drier northwest Rolling Plains region near Lubbock southeast toward more mesic portions of the state (Scifries and Hamilton 1993). It is probably unrealistic to expect fire to achieve significant root mortality in much of the state. This conclusion is similar to that of Trollope (1992b) who indicated that average mortality of 14 of the most common bush species in the Kruger National Park in South Africa was less than 2%. Similar results were found with Mediterranean shrub species (Canadell et al. 1991), Australian shrubs (Bradstock and Myerscough 1988), northern USA shrubs (Leege and Hickey 1971), and some California chaparral shrub species (Keeley and Zedler 1978).

Resprouting following a topkilling fire may exacerbate the mesquite problem in Texas by creating dense stands of thorny, multistemmed plants, similar to responses to topkilling herbicide or mechanical treatments (Fisher et al. 1959, McPherson et al. 1990). Thus, while the emphasis of prescribed fire for mesquite control has been to maximize root-kill and topkill with high intensity fires (Wright and Bailey 1982), an alternative to this approach with fire may be needed for long-term sustainable mesquite management in certain areas (Ansley et al. 1996).

Because mesquite topkill is dependent on fire temperature at higher positions above ground (1-3 m), factors which influence fire temperature at these heights, like air temperature and relative humidity, are as important as understory fine fuel in affecting topkill. The implication is that under adequate understory herbaceous fine fuel amounts to carry a fire, degree of honey mesquite topkill or partial defoliation of non-topkilled plants is largely a function of the air temperature and relative humidity under which the fire is conducted. From results in this study, relative humidity is a more important factor on sites dominated by warm-season grasses, but air temperature appears to be important on all sites. Interestingly, wind speed was not related to mesquite canopy responses. We have observed that flame heights of head fires remain low on relatively windy days in this mesquite/grass fuel medium if air temperature is cool and relative humidity is high.

The variability of mesquite response to fire may enhance opportunities to manipulate growth form and provide alternative management strategies for this species. Knowledge of relations between climate, fuel, fire temperature and mesquite response are critical to forming a predictive platform for manipulating mesquite growth form with fire. This has particular significance if the management goal is not to topkill mesquite but merely to reduce some foliage and preserve a growth form which facilitates savanna development (Ansley et al. 1995, 1996). In this example, it is critically important to understand how fuel and weather influence fire affects on foliage of non-topkilled trees, in addition to the more traditionally measured responses of percent topkill and root-kill of the entire stand. Results from this study suggest that fire behavior and mesquite canopy responses to fire can be manipulated to meet a variety of management goals by burning at selected times when weather and fuel conditions are appropriate.

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