MANIPULATION OF FIRE INTENSITY TO ACHIEVE MESQUITE MANAGEMENT GOALS IN NORTH TEXAS

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ABSTRACT

Prescribed fire is used to suppress honey mesquite (*Prosopis glandulosa*) encroachment on grasslands in the southwestern United States. The study objective was to examine how frequency, seasonality, and intensity of fire might convert mesquite woodland thickets to grasslands or to savannas. High-intensity fires were hypothesized to facilitate conversion of thickets to grasslands by maximizing reduction of mesquite live height and stand density (expressed as percent topkill and root-kill, respectively). Summer season fires and repeated high-intensity fires were hypothesized to be more effective than single fires in thicket-to-grassland conversion. Low-intensity fires (as headfires) were hypothesized to facilitate thicket-to-savanna conversion by achieving a moderate reduction of live height (20 to 40% topkill) and stand density (20 to 40% root-kill). Repeated low-intensity fires were hypothesized to be more effective than single low-intensity fires or high-intensity fires in converting thickets to savannas. This paper summarizes results from 23 fire treatments (69 total burns) conducted between 1991 and 1996 on two clay-loam sites in north-central Texas.

In thicket-to-grassland fires, single summer fires produced greater average topkill (range 86 to 97%) than single winter fires (range 11 to 70%). Mean topkill increased when plots were burned a second or third time, but whole plant mortality (root-kill) for all treatments remained less than 5%. High-intensity fires thus partially facilitated conversion of thickets to grasslands by reducing live height (topkill), but did not reduce stand density. In thicket-to-savanna fires, single low-intensity winter fires achieved topkills ranging from 7 to 17% which was below the stated goal of 20 to 40%. Mean topkill was 26% following three low-intensity winter fires. Mesquite mortality was less than 5% in all low-intensity fire treatments. Repeated low-intensity fires partially facilitated thicket-to-savanna conversion by achieving a moderate level of topkill, but did not reduce stand density. Low-intensity fires caused taller mesquite to become partially defoliated, with defoliation occurring on the lower portions of the canopy. Trees which retained >30% of foliage (relative to preburn amounts) maintained apical dominance and had few or no basal sprouts. Low-intensity headfires were achieved by burning under relatively cool air temperatures, high relative humidities, low-to-moderate herbaceous fine fuel levels, and moderate wind speeds.

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INTRODUCTION

Historical accounts identified the arborescent legume, honey mesquite (*Prosopis glandulosa* Torr.), as a natural part of grasslands in the southwestern United States (Bartlett 1854, Marcy 1866). Patches of light to moderately dense mesquite were mixed with extensive patches of shrub-free grassland. Increases in mesquite density and distribution during the last century can be attributed to agricultural practices which suppressed naturally occurring fires, enhanced seed distribution via livestock, and reduced grass competition from livestock grazing (Humphrey 1949, Smeins 1983, Archer 1989).

Many efforts to control mesquite during the last 50 years involved repeated use of chemical or mechanical treatments which resulted in above ground mortality (topkill) but had little impact on whole plant mortality (root-kill) (Fisher et al. 1959, Jacoby and Ansley 1991). These treatments created dense woodland thickets because they stimulated regrowth from stem bases and increased stem number per plant and per land area. Dense mesquite thickets reduce understory herbaceous production and visibility for livestock management (Dahl et al. 1978, Scifres 1980). Use of chemical or mechanical treatments to manage mesquite has decreased due to rising costs and environmental concerns. Alternative mesquite management strategies are needed.

Prescribed fire has long been used to treat mesquite (Stinson and Wright 1969). However, the full potential of fire as a management tool for mesquite has not been explored. The management goal of most mesquite-related prescribed fires is to return mesquite stands to open grasslands (Wright and Bailey 1982, McPherson et al. 1986). However, the current treatment of choice—a single high-intensity fire conducted during winter months (when winter-deciduous mesquite is dormant)—produces inconsistent above ground mortality (topkill) and very little whole plant mortality (root-kill) (Wright and Bailey 1982). Thus, a single winter fire will not convert a mesquite stand to a grassland without subsequent treatment.

Repeated high-intensity winter fires, or fires conducted during summer months when mesquite is physiologically active, may be more effective than single winter fires in increasing mesquite topkill or root-kill, and thus facilitate thicket-to-grassland conversion. Repeated fires should more effectively penetrate the protective tissue at the base of a mesquite plant and destroy regrowth buds, than would a single fire. Most plant species are more susceptible to fire injury when physiologically active (Daubenmire 1968). Studies in Arizona indicate that summer fires produced some root-kill in velvet mesquite (*Prosopis velutina*) (Cable 1965). It is reasonable to assume that honey mesquite would have a similar response to summer fires because this species is physiologically active from April to October (Ansley et al. 1991, 1992).

Alternatively, fire may be used to convert mesquite thickets to savannas (i.e., a grassland with a low density of trees) instead of open grasslands (Trollope 1984, Jacoby 1985). The management goal would be to reduce density of thickets to some "moderate" level, yet maintain the upright growth form of the taller mesquite (Ansley et al. 1996). Fire may accomplish such a goal if fireline intensity is low enough so as to not topkill the larger mesquite, yet sufficient to topkill or possibly root-kill the smaller mesquite, as suggested by Wright et al. (1976). The range of fire intensities required to achieve the "thicket-to-savanna" goal are unknown. Lower fire intensities are probably more attainable if burning is conducted during winter months when air temperatures are cooler.

The study objective was to quantify the potential of fire to shift mesquite woodland thickets to grasslands or to savannas by evaluating effects of frequency, seasonality, and intensity of fires on mesquite structure and stand density. Specific hypotheses were: (1) single high-intensity summer fires are more effective than single high-intensity winter fires in converting thickets to grasslands by maximizing reduction of mesquite (a) live height (topkill) and (b) stand density (root-kill); (2) repeated fires (winter or summer) are more effective than single high-intensity fires in thicket-to-grassland conversion by maximizing topkill and root-kill; (3) low-intensity fires will achieve the thicket-to-savanna objective by achieving a moderate reduction of live height (20 to 40% topkill) and stand density (20 to 40% root-kill); and (4) repeated low-intensity fires are more effective than single low-intensity fires or high-intensity fires in achieving the thicket-to-savanna objective.

METHODS AND MATERIALS

Research was conducted from 1991 to 1996 within two fenced exclosures in north Texas: Ninemile pasture on the Waggoner Ranch south of Vernon (33° 51′N, 99° 26′W; elevation 381 meters), and River pasture on the Y Ranch west of Crowell (33° 53′N, 100° 00′W; elevation 472 meters). Mean annual rainfall is 665 millimeters at Ninemile and 450 millimeters at River pasture. Soils at Ninemile are fine, mixed, thermic Typic Paleustolls of the Tillman series which are alluvial clay loams to 3–4 meters depth, underlain by Permain sandstone-shale parent material (Koos et al. 1962). Soils at River pasture are fine-silty, montmorillonitic, thermic Typic Haplusterts of the Hollister series. Livestock grazing was excluded at Ninemile since 1988 and River since 1994.

Vegetation on both sites was dominated by a mixture of native rangeland grasses and a mesquite overstory. Broadleaf forbs and other shrub species comprised less than 10% of the species composition by weight on both sites. Topkilling mesquite herbicides were sprayed on different parts of the Ninemile site in 1965, 1973 or 1974, and over all of the River pasture site in 1983. By 1991, most mesquite at Ninemile were multistemmed regrowth, 3 to 6 meters tall, and occurred at 200–500 trees per hectare. River pasture mesquite occurred at densities similar to Ninemile but had more stems per plant and were shorter (1–4 meters) because they had been treated more recently. About 20% of the mesquite on each site were smaller plants that had emerged from seed since the herbicide treatments. These plants had few stems and were <2 meters tall.

Perennial grasses at Ninemile are cool-season midgrasses, Texas wintergrass (*Nasella leucotricha* [Trin. And Rupr.] Pohl.) and Texas bluegrass (*Poa arachnifera* Torr.); warm-season midgrass, meadow dropseed (*Sporobolus asper* [Michx.] Kunth var. *drummondii* [Trin.]); and warm-season shortgrass, buffalograss (*Buchloe dactyloides*) [Nutt.] Englem.). Perennial grass species at River Pasture are buffalograss and warm-season midgrass tobosagrass (*Hilaria mutica* [Buckl.] Benth.). Grasses were distributed nonuniformly on each site with shortgrasses and midgrasses dominating spaces between mesquite, and midgrasses dominating the understory beneath mesquite canopies. Herbaceous fine fuel amounts were more heterogeneous at River pasture because buffalograss, which generally had the lowest standing biomass, and tobosagrass, which had the greatest standing biomass, made up 80% of the species composition by weight (about 40% each). However, while herbaceous fine fuel varied in amount, it was largely continuous on each site, with bare ground less than 10%. Japanese brome (*Bromus japonicus* Thunb.), a cool-season annual grass, occurred more frequently beneath mesquite canopies at Ninemile than at River pasture.

Fire treatments were initiated at Ninemile in March 1991 and at River pasture in September 1994 after 3 years and 9 months, respectively, of no livestock grazing. Treatments consisted of winter (W) fires burned during January through March, and late-summer (S) fires burned during late August or September. All fires were conducted as headfires. Thicket-to-grassland (GR) treatments included single winter fires in 1991 (GR-W91), 1993 (GR-W93) or 1995 (GR-W95), repeated winter fires (GR-W91+W93 and GR-W91+W93+W95), single summer fires in 1992 (GR-S92), 1993 (GR-S93) or 1994 (GR-S94), repeated summer fires (GR-S92+S94 and GR-S93+S94), and repeated alternate-season fires (GR-W91+S92, GR-W91+S92+W94, GR-W93+S93, and GR-W93+S93+W96). Thicket-to-savanna (SV) treatments included single, low-intensity winter fires in 1991 (SV-W91), 1993 (SV-W93) or 1995 (SV-W95), repeated winter fires (SV-W91+W93 and SV-W91+W93+W95), and repeated alternate-season fires (SV-W93+S93 and SV-W93+S93+W96). Each treatment included three replicate plots. Plot size was 1 or 6 hectares at Ninemile and 1 hectare at River pasture, which was sufficient to assess headfire conditions.

Intensity of GR fires was maximized by burning under relatively high air temperatures and fine fuel loading, and low relative humidities. The SV fires were conducted under higher relative humidity, lower air temperature, and lower fine fuel amount, relative to GR fires, to achieve lower fire intensities. Often GR and SV fires were conducted at different times on the same day with SV fires in mornings and evenings, and GR fires in afternoons.

Air temperature, relative humidity (RH), and wind speed were measured on site a few minutes prior to each fire. Fine fuel amount (litter + standing crop) and moisture content were measured by harvesting within an hour of the burn, five 0.25 meter^2 quadrats of each of the three dominant herbaceous species (as determined by prior evaluation of species composition in each plot) that occurred in interspaces between mesquite trees.

Fire temperatures were measured at 1-second intervals using glass-insulated type K (Chromel-Alumel) thermocouple wire (20 AWG; 0.8 millimeter diameter) overbraided with stainless steel and a Campbell CR7 datalogger placed in a fireproof container (Engle et al. 1989, Jacoby et al. 1992). Temperature was measured at six heights (0, 0.1, 0.3, 1, 2, and 3 meters) at each of three to six locations per plot.

Flame length was estimated by videotaping the flame front as it passed 4 metered metal standards within each plot. Fire intensity was quantified using the flame length equation of Byram (1959): $I = 5.7L^{2.2}$, where I = fireline intensity (British thermal units/feet/second) and L = flame length (feet). Intensity values were converted from British thermal units/feet/second to kilowatts/meter (Roberts et al. 1988). Estimation of fire intensity from scorch height measurements (after Van Wagner 1973) was unreliable because in many trees, smaller branches at the top of the canopy with thinner bark were killed by the convection column, yet axillary meristems along the larger more insulated stems below were released from dormancy.

Fifty to 100 mesquite were evaluated along permanently marked line transects in each plot at the end of the first full growing season following each fire (including each repeated fire). Response variables included percent topkill, percent dead, height of live tissue, amount of canopy foliage remaining in non-topkilled (NTK) trees (visual estimate), and presence or absence of basal regrowth. The relationship between amount of canopy foliage remaining and occurrence of basal regrowth was determined.

Analysis

While the data set included 23 fire treatments and 69 total burns (3 replicates per treatment), not all treatments were used in each statistical analysis. To address Hypothesis 1, single-winter and single-summer fire treatment effects were evaluated at each site using one-way analysis of variance (ANOVA) with fire treatment as the main effect. Fires conducted during the summer and winter immediately before a growing season (example: S92, W93) were compared. Because single fire treatments were conducted during different years at each site (Ninemile 1992–1993; River 1994–1995), it was not possible to analyze site by fire treatment interactions. One-way ANOVAs were used to assess effects of repeated fires (Ninemile only) on thicket-to-grassland (Hypothesis 2) or thicket-to-savanna conversion (Hypothesis 4), with fire treatment as main effect (example: GR-W91 vs. GR-W91+W93 vs. GR-W91+W93+W95). To address Hypothesis 3, one-way ANOVAs were used to compare effects of single low-intensity and single high-intensity fire treatments at each site. An additional two-way analysis was possible (fire treatment and site as main effects) by comparing SV-W95 treatments which were conducted at both sites. Data were pooled within each treatment replicate prior to analysis. Means were separated based on least significant differences (LSD) ($P \leq 0.05$). Percentage data were arcsine transformed prior to analysis (SAS 1982).

RESULTS AND DISCUSSION

Weather, Fuel, and Fire Behavior

Mean air temperature at the time of burning averaged 33.3, 20.8, and 17.3°C for GR- summer, GR-winter, and SV-winter fires, respectively (Table 1). Average relative humidity was highest in GR-summer fires (35.8%), slightly less in SV-winter fires (32.1%), and lowest in GR-winter fires (29.2%). When averaged by GR-winter, GR-summer, and SV-winter groupings, herbaceous fine fuel amount and wind speed were similar. However, among all fires, fine fuel ranged from 1,300 to 4,284 kilograms per acre. Fires that followed a severe summer burn tended to have lower fine fuel (examples: treatments 6 and 13, Table 1). Moreover, as repeated fires reduced mesquite competition in some treatments, fine fuel tended to increase (treatments 9–11 or 17–19, Table 1), but this was not always the case.

Peak fire temperature occurred at 0.1 or 0.3 meters above ground during all fires. Mean peak fire temperature averaged 633, 582, and 530°C for GR-summer, GR-winter, and SV-winter fires, respectively. Mean flame length averaged 3.3, 2.4 and 1.5 meters, and fireline intensity averaged 4042, 2435, and 828 kilowatts/meter for GR-summer, GR-winter, and SV-winter fires, respectively.

Single-Summer versus Single-Winter GR Fires (Hypothesis 1)

Single GR-summer fires produced greater average topkill than single GR-winter fires at the Ninemile site (93 versus 33%, respectively), but not at River pasture

Table 1. Weather, fine fuel and fire behavior data from thicket-to-grassland (GR) or thicket-to-savanna (SV) fire treatments at Ninemile (NM) and River (RV) pastures. For repeated fire treatments (i.e., GR−W91+W93), conditions of the most recent fire are listed. All values are means of three plots.

Site	Treatment Number	Fire Treatment[1]	Air Temp. [C]	RH (%)	Wind (kph)	Herb. Fine Fuel (kg/ha)	Peak Fire Temp. [C]	Flame Length (m)	Fireline Intensity (kW/m)
NM	1	GR-W91 (Set 1)	13.5	33.0	16.1	2354	539	0.8	165
NM	2	GR-W91+W93	20.0	38.3	19.6	3011	661	4.0	5685
NM	3	GR-W91+W93+W95	25.4	26.3	15.0	3083	575	1.9	1105
NM	4	GR-W91 (Set 2)	23.5	24.3	23.6	2578	—	1.2	402
NM	5	GR-W91+S92	33.1	41.3	16.6	4285	631	4.6	7731
NM	6	GR-W91+S92+W94	24.2	32.0	9.1	1300	458	1.5	657
NM	7	GR-S92	33.5	27.0	7.5	2745	664	3.3	3723
NM	8	GR-S92+S94	32.2	45.3	11.5	2991	611	2.8	2594
NM	9	GR-W93	16.8	29.7	15.6	2870	633	3.2	3479
NM	10	GR-W93+S93	35.7	32.3	12.3	1861	638	1.9	1105
NM	11	GR-W93+S93+W96	18.5	28.7	9.4	4824	—	4.4	7011
NM	12	GR-S93	35.0	25.0	20.1	2400	—	—	—
NM	13	GR-S93+S94	32.6	46.7	15.8	1632	537	3.9	5377
NM	14	SV-W91	14.4	29.0	16.1	2450	408	0.9	214
NM	15	SV-W91+W93	19.4	32.0	11.3	2339	660	2.3	1683
NM	16	SV-W91+W93+W95	18.1	30.0	11.3	2779	502	0.8	165
NM	17	SV-W93	18.3	25.0	14.5	1540	443	1.3	480
NM	18	SV-W93+S93	32.2	34.0	12.1	1643	472	1.2	402
NM	19	SV-W93+S93+W96	23.0	35.3	10.5	4805	—	2.5	2021
NM	20	SV-W95	13.0	37.3	15.3	3196	476	0.8	165
RV	21	GR-S94	31.3	33.3	11.0	3803	718	3.3	3723
RV	22	GR-W95	24.1	21.0	13.1	2484	626	1.8	981
RV	23	SV-W95	15.0	36.0	10.2	2585	690	1.2	402
MEAN		GR-Summer (n = 7)	33.3	35.8	13.5	2817	633	3.3	4042
MEAN		GR-Winter (n = 8)	20.8	29.2	15.2	2813	582	2.4	2435
MEAN		SV-Winter (n = 7)	17.3	32.1	12.7	2813	530	1.5	828

[1] W = winter fire (January to March), S = summer fire (August to September).

(Table 2). Root-kill remained less than 3% and was not significantly different between summer and winter fires at either site. Two other sets of single winter fires at Ninemile in 1991 (GR-W91) produced 11 and 30% topkill and root-kill less than 3% (Table 3). An additional single summer fire at Ninemile in 1993 (GR-S93) produced 97% topkill and 3% root-kill (Table 3). These data plus that found in Table 2 lead us to partially reject Hypothesis 1. While single summer fires were more effective than winter fires at reducing live height (topkill) on at least one site, they did not reduce stand density.

While GR-summer fires had greater intensity than GR-winter fires, peak fire temperature was similar between the two (Table 1). Air temperature was greater during GR-summer than GR-winter fires which would have increased fire intensity. Relative humidity was also greater in GR-summer than GR-winter fires, but this would have reduced fire intensity and was therefore likely not a factor that increased topkill in summer fires. We are left to conclude that the high topkill pro-

Table 2. Mesquite response to single summer (S) or winter (W) thicket-to-grassland (GR) fire treatments at two sites.

Site	Fire Treatment	Percent Topkill	Percent Foliage Remain (stand)	Percent Foliage Remain (ntk)[2]	Percent Dead	Treatment Number
NM	GR-S92	93.4 a[1]	1.6 b	26.9 a	0.4 a	7
NM	GR-W93	33.4 b	27.1 a	40.6 a	0 a	9
RV	GR-S94	86.1 a	2.9 a	13.4 b	2.1 a	21
RV	GR-W95	70.1 a	9.8 a	24.6 a	0 a	22

[1] Means within each site followed by similar letters are not significantly different ($P \leq 0.05$).
[2] ntk = non-topkilled trees.

Table 3. Mesquite response to repeated summer or winter thicket-to-grassland (GR) fire treatments at the Ninemile site.

Fire Treatment	Percent Topkill	Percent Foliage Remain (stand)	Percent Foliage Remain (ntk)	Percent Dead	Treatment Number
GR-W91 (set 1)	11.2 b[2]	61.8 a	68.9 a	2.2 a	1
GR-W91+W93	60.0 a	14.4 b	35.7 b	0.9 a	2
GR-W91+W93+W95	68.0 a	11.9 b	31.0 b	3.7 a	3
GR-W91 (Set 2)	30.3 b	45.7 a	62.3 a	0 a	4
GR-W91+S92	82.3 a	2.0 b	8.8 b	0.7 a	5
GR-W91+S92+W94	87.2 a	2.6 b	16.3 b	1.4 a	6
GR-W93[1]	33.4 c	27.1 a	40.6 a	0 a	9
GR-W93+S93	61.5 b	10.0 b	18.7 b	0 a	10
GR-W93+S93+W96	97.2 a	0.7 c	35.0 a	2.1 a	11
GR-S92[1]	93.4 a	1.6 a	26.9 a	0.4 a	7
GR-S92+S94	91.7 a	2.3 a	21.5 a	2.8 a	8
GR-S93	96.7 a	0.6 a	18.3 a	3.3 a	12
GR-S93+S94	98.1 a	0.1 a	2.0 b	3.7 a	13

[1] Treatments 7 and 9 are also found in Table 2. They are included here to illustrate treatment differences related to Hypothesis 2.
[2] Means within each treatment group with similar letters are not significantly different ($P \leq 0.05$).

duced by summer fires was due to higher air temperature and/or more active physiological status of mesquite at the time of the fire, when compared to winter fires. Another factor may be a greater initial vegetation tissue temperature, which would be expected in summer months. Warmer tissue requires less heat input to reach the lethal threshold.

Summer wildfires may have limited mesquite encroachment onto grasslands until this century when European settlers reduced fire frequency through livestock grazing and/or suppression of wildfires (Archer 1989). Studies in Arizona suggest that a significant percentage of velvet mesquite can be killed by summer fires (Humphrey 1949, Blydenstein 1957, Glendening and Paulson 1955, Cable 1965), and it was hypothesized that honey mesquite in Texas would have a similar response. However, our data did not indicate significant honey mesquite mortality from single or repeated summer fires. This may be due to morphological or physiological differences between species, or differences in site characteristics or fire intensity between the regions. We found no studies which contrasted effects of summer and winter fires on mesquite topkill.

Type and condition of understory species may be responsible for the wide range of topkill response (11 to 70%) to single GR-winter fires (Tables 2 and 3). The occurrence of the annual cool-season grass, Japanese brome, beneath mesquite canopies at Ninemile may have retarded winter fires because it was green during the February and March burns. Where Japanese brome was green, there were extensive unburned patches and fire had minimal effects on mesquite. While not compared statistically, this potentially explains why topkill was greater after single GR-winter fires at River pasture than at Ninemile (Table 2). River pasture had primarily warm-season grasses which were dormant (and drier) during the winter. Additionally, single GR-winter fires at River pasture were conducted under warmer mean air temperature (24.1°C) than the GR-W93 fires at Ninemile (16.8°C) and this, along with drier fine fuel, likely increased topkill at River pasture (Table 1). Moreover, River pasture mesquite may have been more susceptible to topkill by fire because they were shorter and had smaller diameter basal stems than Ninemile mesquite.

Single versus Repeated GR Fires (Hypothesis 2)

Mean topkill increased significantly to 60% or more when single winter fire plots were burned a second time with either winter (GR-W91+W93) or summer (GR-W91+S92; GR-W93+S93) fires at Ninemile (Table 3). Topkill was not as great in the GR-W93+S93 (63%) than in the GR-W91+S92 (82%) treatment, even though topkill after the first fire in each treatment was comparable. Fine fuel was lower in the GR-W93+S93 treatment (Table 1), probably because of insufficient time for fuel accumulation just seven months after the winter fires, and this reduced the effect of the second fire. It appeared that the second fire following an initial winter-season fire produced the greatest increase in topkill. Topkill increased significantly following a third fire in only one treatment (GR-W93+S93+W96). There was no significant increase in topkill when single summer fire plots were burned with a second summer fire (GR-S92+S94; GR-S93+S94), but this was because topkill percentages were above 90 after the first fires. While not statistically compared, single winter fires at River pasture were as effective on topkill (70%; Table 2) as three winter fires (GR-W91+W93+W95) at Ninemile (68%) (Table 3). Japanese brome was abundant in 1991 and 1995 at Ninemile and this may explain why, after three winter fires, topkill was only 68%.

Root-kill showed some trends of increasing following repeated GR fires, but remained less than 4% and was not significantly different among treatments. Thus, Hypothesis 2 was only partially satisfied in that repeated fires were more effective than single winter fires in thicket-to-grassland conversion by increasing topkill, but none of the repeated GR fire treatments reduced stand density.

There is little evidence in the literature that single winter fires will kill mesquite. Wright et al. (1976) found that 8 to 50% of mesquite were killed following single late-winter (March) burns on a variety of upland sites in west Texas, which had soils and vegetation similar to our River pasture site. The mesquite in the study by Wright et al. were large trees (2 to 4 meters tall) that had been sprayed with a topkilling herbicide (2,4,5-T), 2 to 5 years prior to burning, and had resprouted to 1 to 2 meter heights at the time of burning. The reason for the high mortality was because the standing dead stems from the herbicide treatment had ignited and burned into live root crowns, killing the buds that would have developed basal sprouts. Mesquite mortality in the study by Wright et al. was much higher when wind speed was greater than 13 kilometers per hour because this enhanced combustion of the standing dead stems. Britton and Wright (1971) and McPherson et al. (1990) found results similar to those of Wright et al. (1976). Because these fires occurred so soon after a herbicide treatment, we view these results as responses to a combined herbicide-fire treatment, rather than to effects of fire alone. The herbicide treatment essentially "primed" the mesquite for the fire treatment to be effective. In our study, mesquite had also been sprayed with herbicides, but fire treatments were not implemented until 17 to 26 years (Ninemile), or 11 years (River) after the herbicides. Because of this delay, most of the mesquite on our sites did not have many standing dead stems from the herbicide treatments. This may explain why root-kill response to fire was so low.

Ueckert and Wright (1974) found that wood borer activity in stems previously killed by fires facilitated stem combustion during subsequent fires. Our low mortality after repeated fires may have resulted from intervals between burns which were too short to allow sufficient borer and decomposer activity in the standing dead stems that prime them to ignite and burn into the crown in later fires.

Table 4. Mesquite response to single and repeated thicket-to-savanna (SV) fire treatments at the Ninemile site.

Site	Fire Treatment g	Percent Topkill[1]	Percent Foliage Remain (stand)	Percent Foliage Remain (ntk)	Percent Dead	Treatment Number
NM	SV-W91	6.9 b; x	76.8 a; x	82.5 a; x	2.8 a; x	14
NM	SV-W91+w93	23.3 a	39.0 b	49.4 b	2.2 a	15
NM	SV-W91+W93+W95	26.4 a	31.5 b	42.5 b	4.9 a	16
NM	SV-W93	13.4 b; x	51.9 a; yz	59.3 a; y	2.3 a; x	17
NM	SV-W93+S93	14.5 b	39.2 a	45.9 ab	0 a	18
NM	SV-W93+S93+W96	77.1 a	5.9 b	22.8 b	1.4 a	19
NM	SV-W95	15.5 a; x	56.5 a; y	66.2 a; y	0.7 a; x	20
RV	SV-W95	16.7 a; x	35.7 b; z	42.4 b; z	0 a; x	23

[1] Means within each treatment group with similar letters (a–c) are not significantly different. Means within each column with similar letters (x–z) are not significantly different ($P \leq 0.05$).

Thicket-to-Savanna (SV) Fires—Hypotheses 3 and 4

Single low-intensity SV-winter fires (three at Ninemile, one at River pasture) achieved low to moderate topkill (range 7 to 17%) (Table 4). Whole plant mortality was less than 3%. Hypothesis 3 was rejected because single SV-winter fires did not achieve the objective of 20 to 40% topkill or root-kill.

Topkill increased to 23 and 26% following two (SV-W91+W93) or three low-intensity winter fires (SV-W91+W93+W95), respectively, but root-kill remained less than 5%. Topkill in the other repeated low-intensity fire treatments did not achieve 20% after two fires (SV-W93+S93) and exceeded 40% after a third fire (SV-W93+S93+W96). Air temperature during the SV-W93+S93+W96 fires averaged 23°C, and fine fuel averaged 4805 kilograms per hectare (Treatment 19, Table 1). These two factors may have yielded a higher fire intensity and produced a greater topkill than was desired. Topkill also exceeded 40% following repeated GR-fires which were burned during the same years as the repeated SV-fires (Table 5).

With these results, part of Hypothesis 4 was not rejected because two of the repeated low-intensity fire treatments (SV-W91+W93 and SV-W91+W93+W95) were more effective than single low-intensity fires or repeated high-intensity fires in achieving a moderate (20 to 40%) level of topkill. However, part of Hypothesis 4 was rejected because the other two repeated low-intensity fire treatments (SV-W93+S93 and SV-W93+S93+W96) failed to achieve the 20–40% topkill goal. Moreover, none of the repeated SV-fire treatments reduced stand density.

Table 5. Mesquite response to repeated thicket-to-grassland (GR) or thicket-to-savanna (SV) fire treatments at the Ninemile site.

Fire Treatment[1]	Percent Topkill	Percent Foliage Remain (stand)	Percent Foliage Remain (ntk)	Treatment Number
GR-W91+W93	60.0 a[2]	14.4 b	35.7 a	2
SV-W91+W93	23.3 b	39.0 a	49.4 a	15
GR-W91+W93+W95	68.0 a	11.9 b	31.0 a	3
SV-W91+W93+W95	26.4 b	31.5 a	42.5 a	16
GR-W93+S93	61.5 a	10.0 b	18.7 b	10
SV-W93+S93	14.5 b	39.2 a	45.9 a	18
GR-W93+S93+W96	97.2 a	0.7 a	35.0 a	11
SV-W93+S93+W96	77.1 a	5.9 a	22.8 a	19

[1] Data in this table are also found in Tables 3 or 4. They are included here to illustrate treatment differences related to Hypothesis 4.
[2] Means within each treatment group of two treatments with similar letters are not significantly different ($P \leq 0.05$).

It was assumed that the thicket-to-savanna goal of 20 to 40% (topkill and/or root-kill) would be achieved if the smaller seedling or adolescent mesquite, which made up about 20% of the mesquite population at both sites, coupled with an additional 10 to 20% of the larger trees in the stand, were topkilled or root-killed. Fire temperatures were high near the ground (>530°C) in both low- and high-intensity fires (Table 1). However, in another study, we found that temperatures of high-intensity fires were 3 to 5 times hotter at 2-meter heights above ground than were low-intensity fires (Ansley et al. 1998). These temperature differences led us to assume that smaller mesquite would succumb to fire of any intensity, while larger mesquite would only be topkilled by more intense fires. We observed in this study that while trees of all heights were topkilled by the GR fires, most trees topkilled by SV fires were shorter than 1.5 meters (data not shown).

Effects of Fires on Mesquite Foliage

As percent topkill of the stand increased with repeated GR-winter or GR-winter-summer fires, foliage remaining per stand and per non-topkilled tree significantly decreased (Table 3). It appeared certain large trees were resistant to further damage from repeated fires. For example, after three fires, foliage remaining on non-topkilled trees was 35% in the GR-W93+S93+W96 treatment, but this represented very few trees in the stand because foliage remaining per stand was less than 1%. Foliage remaining per stand was less than 3% and per non-topkilled tree was less than 27% following single or repeated GR-summer fires.

Foliage remaining per stand ranged from 36 to 77% and foliage remaining per non-topkilled tree ranged from 42 to 83% following single low-intensity SV-winter fires (Table 4). Most trees that were partially defoliated by SV fires retained foliage in the upper portions of the canopy, but lower-positioned canopy growing points and secondary branches were killed. Primary support stems survived, however. The appearance of the partially defoliated trees was similar

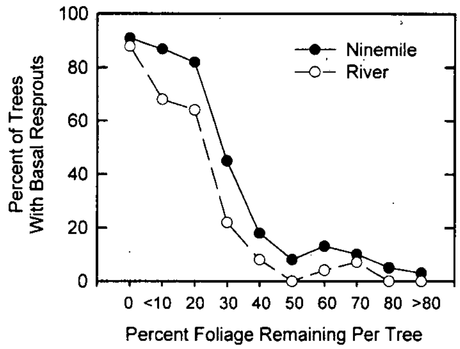

Fig. 1. Percent of trees within each foliage-remaining class (x-axis) that had basal sprouting following low-intensity thicket-to-savanna fires at Ninemile and River pastures. Data from all treatments and replicates at each site were pooled. Over 480 and 140 trees were surveyed at Ninemile and River pasture, respectively. Each point represents responses of 30 to 50 trees (Ninemile) and 10 to 20 trees (River).

to that of a browse-line created by herbivores on trees such as live oak (*Quercus virginiana* Mill). Because the growth form of these mesquite resembled *Acacia tortilis* found in African savannas, with foliage in upper portions of the canopy, they were termed "savanna mesquite."

Amount of foliage buds that survived each fire had direct bearing on whether the trees basal sprouted or maintained apical dominance during the growing season following the fire. A threshold in resprouting response occurred at 30–40% of foliage remaining per tree, and this response was consistent at both the Ninemile and River pasture sites (Figure 1). Below this threshold (i.e., if only 0 to 20% of preburn foliage amounts per tree remained intact), abundant resprouting was common. Above the threshold (i.e., if at least 40% of preburn foliage remained intact), over 80% of the trees had little or no resprouts.

Results from the Ninemile site suggest maintenance of the savanna growth form was possible with repeated low-intensity fires. Foliage remaining on each live tree decreased from 83 to 49 and 43% with second and third winter fires, respectively (SV-W91+W93 and SV-W91+W93+W95), and from 59 to 46 to 23% by a winter-summer-winter combination (SV-W93+S93 and SV-W93+S93+W96) (Table 4). With the exception of the SV-W93+S93+W96 treatment (reasons explained earlier), remaining foliage of non-topkilled trees remained above the 30–40% threshold needed to maintain apical dominance. In contrast, GR-summer fires (Table 3) or repeated GR fires (Table 5) virtually eliminated the "savanna" growth form within a stand.

An illustration depicting effects of repeated high- or low-intensity fires on mesquite foliage and structure is shown in Figure 2. The sequence on the top half of Figure 2 has been observed in the field after numerous repeated high-intensity fire treatments within 3 to 5 years (examples: GR-W91+W93+W95; GR-S92+S94). Mesquite regrowth is continually suppressed and above ground woody tissue, which was mostly killed after the first fire, is gradually consumed by subsequent fires. We found that very little woody tissue was consumed after a first fire, even if percent topkill was high. The sequence on the bottom half of Figure 2 has been observed after repeated low-intensity fires (SV-W91+W93+W95). In this treatment, apical dominance is maintained in most of the taller trees, yet foliage remaining per tree is gradually reduced after each fire (see also data in Table 4).

MANAGEMENT IMPLICATIONS

Mesquite response to fire is variable and has been related to intensity, seasonality, and frequency of fire, or to age and condition of the plant (Cable 1965, Stinson and Wright 1969, Wright et al. 1976, Martin 1983). Most mesquite-fire studies have focused on effects of fire on mesquite mortality (root-kill) because the tra-

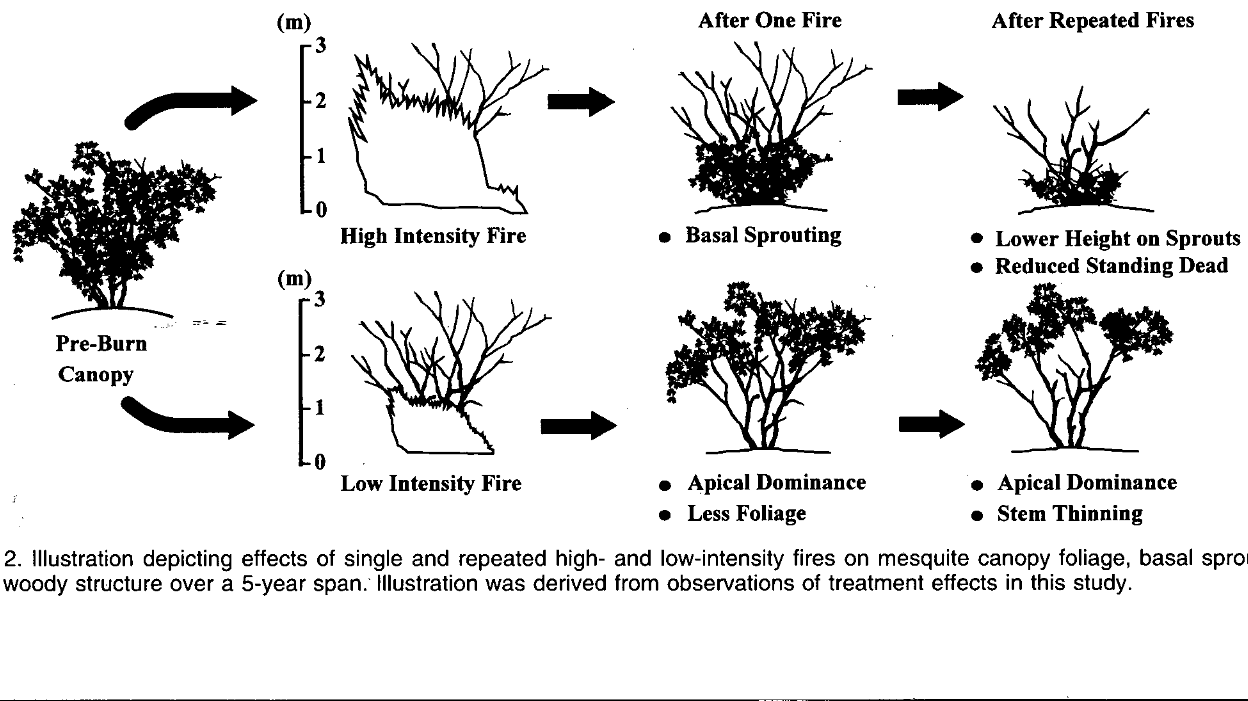

Fig. 2. Illustration depicting effects of single and repeated high- and low-intensity fires on mesquite canopy foliage, basal sprouting and woody structure over a 5-year span. Illustration was derived from observations of treatment effects in this study.

ditional management goal has been thicket-to-grassland conversion. Many of these studies found that fire intensity and mesquite mortality were not well-related. In indirect support of this, Roberts et al. (1988) found no relation between fire intensity and mortality of two grass species in west Texas. Our study agrees with Roberts et al. (1988) in that fire intensity appeared to have little effect on mesquite root-kill. However, we did find that percent topkill and foliage amount per tree were strongly affected by fire intensity. This has clear management implications, especially if the goal is thicket-to-savanna conversion.

Throughout our study, all topkilled trees that were not root-killed resprouted. Such regrowth may create a thicket within 10 to 15 years if no subsequent maintenance practices are employed (Ueckert 1975, Hamilton et al. 1981, Hamilton and Scifres 1982). Thus, a single fire that suppresses above ground growth but does not kill the plant may not serve as a long-term solution for converting mesquite thickets to grasslands. Data from this study suggest that frequent use of high-intensity fires will maintain suppression of mesquite regrowth and at least minimize competitive effects of mesquite on grasslands. Such a management strategy is only possible in livestock-based enterprises if grazing is deferred on a regular basis to allow sufficient accumulation of grass as fine fuel to carry the fires. Recent work in north Texas has suggested that rotational grazing systems which employ a single herd and multiple paddocks provide an opportunity to burn 25% of the land area of each system once every 4 to 5 years (Teague et al. 1997).

Related to Hypothesis 2, our goal was to maximize fire frequency (in one treatment we burned twice within the same year) to determine if such frequencies would weaken mesquite enough to kill the plant. While fire frequencies used in this study were likely too high to be of practical use in rangeland grazing enterprises (3 fires in 5 years, for example), it is not unreasonable to assume that such fire frequencies may have occasionally occurred naturally in southern prairie grasslands prior to white settlement, because the potential for abundant grass growth, high winds, and frequent lightning strikes is high. Thus far, however, we can clearly conclude that none of the high fire frequencies employed in this study significantly reduced mesquite stand density.

Data from this study suggest that, while fire may be fundamental to the development of low-cost and sustainable mesquite management strategies, it cannot be considered the sole means of restoring mesquite thickets to grasslands or savannas, because it did not reduce mesquite stand density. Reducing mesquite density may be achieved by use of herbicides or mechanical removal, either as individual plant treatment, or larger-scale treatments in strips or patches, but at a much higher cost per hectare (Jacoby and Ansley 1991). Once grasslands or savannas are restored, recruitment of new mesquite into these areas may be limited by repeated fires that destroy mesquite beans that are on the ground and kill some mesquite seedlings (Wright et al. 1976), but further study is needed to verify this.

Summer-fire effects on grasses and soils must be further assessed before this management practice can be recommended. Wright and Bailey (1982) suggested that summer fires may harm certain warm-season grasses. We have observed similar responses at our research sites, especially when grasses were clipped to simulate grazing shortly after summer fires (Ansley et al. 1997). We have also observed that summer fires consume more litter than do winter fires. This leaves bare soil patches exposed to erosion or to invasion by weeds such as annual broomweed (*Amphiachyris dracunculoides* DC) (Tunnell and Ansley 1995).

Management for Mesquite Savanna

Repeated low-intensity winter fires appear to be ideally suited as a first step toward conversion of mesquite thickets to savannas. These fires modified the vertical distribution of mesquite foliage by reducing foliage per tree, yet apical dominance was maintained. Such growth form considerations are critical in savanna management because of the capacity of this species to rapidly resprout following topkill. Low-intensity fires achieved a moderate level of topkill, although they did not reduce stand density. As with high-intensity thicket-to-grassland fires, alternate treatments (chemical, mechanical, etc.) may be necessary to reduce stand density in thicket-to-savanna conversion.

Historical accounts differ as to original density and distribution of mesquite in Texas. Bartlett (1854) described much of Texas rangeland as open grasslands with scattered large mesquite (i.e., a mesquite savanna). Marcy (1866) described some upland areas of central Texas as "covered with groves of mesquite trees," and an area in the lower Texas panhandle as "one continuous mesquite flat, dotted here and there with small patches of open prairie." These observations suggest honey mesquite was a natural part of the north Texas vegetation complex prior to white settlement and, apparently in some instances, occurred as dense stands. In other areas mesquite occurred in a savanna setting. There are no descriptions of the presettlement growth form of mesquite, however. It is likely that most of the multistemmed thickets that occur today have greater stem and foliage density than what would have occurred naturally because of human efforts to control mesquite, which stimulated basal sprouting.

While mesquite is often perceived as a noxious plant, the mesquite savanna may offer a good middle ground between maximizing potential benefits while minimizing negative effects of this species (Jacoby and Ansley 1991). Savanna mesquite may enhance ecosystem stability when compared to open grassland by increasing soil fertility through nitrogen fixation and organic carbon additions (Johnson and Mayeux 1990) and increasing herbaceous production (Scifres et al. 1982). The physionomic diversity of a savanna may also enhance wildlife habitat over open grassland (Scifres et al. 1985, Fulbright 1997). The fire-induced "savanna" growth form discussed in this study (Figure 2) may be potentially less competitive with grasses than are thicket-mesquite because of less foliage per tree. Effects of repeated low-intensity "savanna" fires on nutrient cycling, herbaceous understory production, species diversity, and wildlife habitat are as yet unquantified.

Economics of time and labor needed to gather livestock from mesquite thickets when compared to savanna or grassland have not been quantified, but poor visibility through thickets is often cited by livestock managers as a significant and costly problem (Teague et al. 1997). Our data suggest that, when contrasted to mesquite thickets, savanna mesquite increase visibility for livestock management because of reduced foliage per plant and the higher position of the foliage. These trees will also provide some shade for livestock. Moreover, because less fine fuel is needed to support a low- than a high-intensity fire, preburn livestock deferral time would likely be reduced. We hypothesize that a savanna provides sustainable ecological and economical productivity while minimizing management and maintenance costs.

Prescription for Low-Intensity Savanna Fires

Wright and Bailey (1982) and McPherson et al. (1986) identified the best conditions to topkill mesquite. Alternate guidelines are needed if savanna is the management goal. Our goal was to create fires intense enough to topkill or root-kill smaller mesquite and reduce foliage of taller mesquite, yet not of an intensity which would topkill most trees. By destroying the canopy and promoting basal regrowth, an intense fire could limit savanna development for 20–30 years. Conversely, extremely low-intensity fires that have little or no effect on mesquite were also considered unsuitable for savanna development from thickets.

Our experience conducting nearly 70 fires with intentions of manipulating fireline intensities to achieve different mesquite responses has led to some hypotheses regarding weather and fuel conditions necessary to achieve low-intensity thicket-to-savanna headfires. A more detailed account of these relationships is found elsewhere (Ansley et al. 1998). Behavior of winter low-intensity fires appeared to be primarily a function of air temperature, relative humidity (RH), fine fuel moisture content, and fine fuel amount. Winter low-intensity fires that produced the desired "savanna" effect on mesquite (Figure 2) were successfully conducted at the Ninemile site within fine fuel levels of 1500 to 3200 kilograms per hectare, air temperatures between 13 and 20°C (55–68°F), relative humidities between 30 and 40%, and wind speeds from 10 to 16 kilometers per hour (6 to 10 miles per hour) (Table 1). Herbaceous fine fuels greater than 4000 kilograms per hectare, or RH less than 30% under most fuel amounts generated topkilling fires.

Thicket-to-savanna (SV) headfires were usually conducted in mornings or evenings, when air temperatures were cooler and RH higher, than during afternoons. Under low fuels (1000–2000 kilograms per hectare), some savanna fires were successfully conducted in afternoons, or when wind speeds were higher (12–20 kilometers per hour). Conditions required for low-intensity headfires are very similar to those recommended by McPherson et al. (1986) for burning perimeter fireguard areas (i.e., blacklines) prior to burning a large area, with the exception that we desired higher wind speed to move the flame front under these cooler and more humid conditions.

In general, summer fires under most fuel loads topkilled most mesquite and were unsuitable for savanna development. The only low-intensity summer fires we attempted were conducted at mean air temperature 32°C, RH 34%, and wind 12 kilometers per hour. Fine fuel was low (1643 kilograms per hectare) because these plots had been burned in the winter just 7 months earlier. Fire intensity probably stayed low because of the low fuel.

Although low-intensity summer fires may have greater potential than winter fires to reduce mesquite foliage to desired levels and accelerate savanna development, the risk of topkill is also greater. Low-intensity summer fires may have potential for mesquite control in areas dominated with cool-season annual grasses, such as Japanese brome, to reduce the seed source of this species in order to more effectively burn with low-intensity winter fires at a later time. More research is needed on the potential of low-intensity summer fires before they can be recommended.

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