Correlation of Weather and Fuel Variables to Mesquite Damage by Fire[1]

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Highlight

Twenty-four 10-acre plots were burned in the Southern Mixed Prairie of Texas under a variety of weather and fuel conditions to determine their effect on ignition, burndown, and mortality of mesquite that had been top-killed by spraying. The number of trees that ignited on each plot varied from 33.6 to 94.9% of the total, whereas the number of trees that burned down varied from 14.4 to 89.1%. Mortality varied from 0 to 24%. Large trees were easier to burn down and kill than small trees. Equations that incorporate wind speed, relative humidity, and total fuel were developed to predict ignition and burndown.

Previous research conducted in west Texas indicates that fire has the potential to burn down—that is to burn standing dead stems off at the base and have them fall to the ground—and kill mesquite (*Prosopis glandulosa* var. *glandulosa*) in a tobosa (*Hilaria mutica*) community (Stinson and Wright, 1969), but prescribed techniques are lacking. This study was designed to measure the range of weather and fuel conditions under which top-killed mesquite with resprouts can be ignited, burned, and killed.

Taylor (1964) expressed concern for the role of weather in fire behavior. He stated that prescribed burning has been attempted throughout a range of fire weather conditions from too wet to too dry. When conditions are too wet, only spotty removal of part of the litter material is accomplished. When conditions are too dry, fire runs uncontrolled through the burn area and is stopped at the control line only by a change in weather.

Relative humidity plays an important role in fire behavior, especially in fine fuels. Countryman (1964) stated, "the moisture content of hygroscopic fuels is very closely associated with relative humidity. In finely divided fuels, the moisture content follows the relative humidity very closely." Fine fuels are usually defined as any material less than ⅛-inch in diameter.[2]

McArthur (1963), in reporting the results of fire behavior studies conducted during the spring months in the grasslands of Central Queensland, noted the following relationships between fine fuel moisture contents for different relative humidities at 80 F:

Relative humidity (%)	Fuel moisture (%)
5	4
50	11

A similar range is reported for higher temperatures, which results in lower fuel moisture at higher relative humidity readings.

Mobley (1967) gave a range of fine fuel moisture which is conducive to efficient controlled burns. He stated that for most prescribed burning, the preferred range of actual fine fuel moisture is from 5 to 10%. When fuel moisture is less than 5%, the fire will be more intense and may cause damage to overstory and soil. When fuel moisture is higher than 10%, fires tend to move irregularly and more slowly. Such burns are often incomplete. Stinson and Wright (1969) reported that the most intensive fire in their study occurred when the air temperature was 80 F, the relative humidity was 25%, and the fine fuel moisture was 19.8%.

Vareschi (1962) reported that the ignition temperatures of the wood and bark of the Chaparro and Chaparro Manteca in a dry state ranged from 290 C to 330 C. On the other hand the ignition

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[2] Personal communication with George R. Fahnestock, Fuel Appraisal Systems, 4507 Univ. Way NE, Seattle, Washington.

temperature of the same species climbed to 500 C or more, if the bark contained sap.

Krueger and Pachence (1961) concluded that wind is the most important weather variable to be considered when using fire in the woods. Wind exerts a substantial influence on temperatures that occur during burns. Whittaker (1961) found that an increase from a slight wind to a moderate one and subsequent fanning of the flames caused a temperature rise of 172 C to 312 C at ground level. When the wind was strong, the equivalent temperature was reduced because the flames swept quickly over the vegetation and did not reach ground level. Nevertheless, fast-moving headfires consistently do more damage to brush and trees than slow-moving backfires (Fahnestock and Hare, 1964).

McArthur (1963) studied the forward progress of headfires as related to fuel moisture content and wind velocity. At a fuel moisture content of 6%, McArthur reported:

Wind Speed (mph)	Rate of Spread (ft/min)
5	29.7
30	561.0

This trend in ranges is present at all observed levels of relative humidity, with the rate of spread decreasing as the relative humidity increases. McArthur (1963) also reported experiments indicating that flame height and fire intensity are directly proportional to fuel quantity as modified by the various weather factors stated above. All the above conditions may be combined to produce maximum temperatures with low fuel moisture content, high wind speed, and fixed fuel quantity. Byram (1958) also commented that an increase in wind velocity results in a subsequent increase in rate of spread, whether fires burn with the wind or against the wind.

After ignition, the fire may influence the occurrence, amount, and behavior of winds. The most favorable condition for fire-caused wind changes in unstable air. Countryman (1964) indicated that fire whirlwinds tend to develop in areas where opposing air currents or eddies occur. Such air flow may result from natural causes or from air currents induced by the fire. Fire-induced whirlwinds appear more likely to develop under unstable rather than stable air mass conditions. Heilman (1967) defined fire whirlwinds as a convection phenomenon and stated that they may occur within the fire itself or high in the convection column. The occurrence of fire whirlwinds in relation to unstable air mass conditions was also reported in Elbert's (1963) analysis of the Hamburg firestorm weather.

The consistency of wind direction previous to a burn is also a factor which influences ensuing fire behavior. Krueger and Pachence (1961) stated that investigators generally agree that burning cannot be safely undertaken unless the wind persists from approximately the same direction for the entire period of the burn. Any material change in wind direction is undesirable, and a change of 90 degrees or more can be disastrous.

Methods and Procedures

Twenty-four 10-acre plots were burned on the Spade Ranch, which is located 20 miles south of Colorado City, Texas. Vegetation consists of almost pure stands of tobosa (*Hilaria mutica*), which is common to the Southern Mixed Prairie. Broomweed (*Gutierrezia dracunculoides*) is also a major species during some years. The plots are on level topography at an elevation of approximately 1600 ft. Mesquite on the plots was sprayed with 2,4,5-T in 1965 and had resprouts 3 to 5 ft tall. The specific mesquite plant here is *Prosopis glandulosa* var. *glandulosa*.

Twenty 2.4 square-foot quadrats were clipped on each plot to determine the quantity of available fine fuel. This is an adequate number of samples to determine the weight of fuel within 10% of the actual mean at the 0.95% confidence level. The weight of fuel was collected by species. Four samples for fine fuel moisture and soil moisture were taken on each plot at the time of each burn. The soil samples were taken within the upper two inches of the mineral soil surface.

Maximum temperatures and durations were recorded with a Speedomax W multipoint recorder. The recorder was powered by a 12-volt car battery with an ATR 12U-RHG Inverter. Six iron-constantan thermocouples were placed randomly in each plot at the mineral soil surface in openings between clumps of grass to measure maximum temperatures.

In preparation for the burn, fire lines were plowed around each area. Large strips of grass were burned on the leeward sides of the plots to allow more flexibility in burning the plots and to reduce the possibility of a fire escape.

All areas were burned as natural head fires. The ignition pattern was a combination of perimeter and strip head firing (Mobley, 1967). On each plot the two windward sides were ignited simultaneously; but, where there was unburned fuel on the leeward side of the plot, the leeward sides were back fired before the windward sides were ignited.

Relative humidity and dry bulb temperature were recorded with a Weather Measure H311 recording hygrothermograph. The collection of these data was initiated 5 hours before ignition and was continued until burning ceased. Wind speed and direction were recorded manually from a Weather Measure W-121 Remote Wind System. Collection of these data was initiated 5 minutes before ignition and was continued at minute intervals until 7 minutes after ignition. All weather sensing and recording devices were located on the windward side, at least 150 ft from the area to be burned. Wind speed and direction were taken 7 ft above the soil surface.

Before burning each plot, 50 live trees were randomly chosen and permanently marked with a metal stake. The number of stems and their basal diameters 6 inches above the soil surface were recorded for each marked tree. Fol-

Table 1. Correlation (coefficients) of fuel and weather variables with ignition, burndown, mortality, and maximum soil surface temperature.

Independent variables	Dependent variables			
	Ignition	Burndown	Mortality	Temperature
Wind speed	0.32	0.56**	0.17	0.30
Air temperature	0.50*	0.50*	0.16	–0.02
Relative humidity	–0.75**	–0.68**	–0.19	–0.17
Total fuel	0.30	0.17	0.38	0.11
Tobosa fuel	0.26	0.25	0.42*	–0.06
Soil moisture	–0.23	–0.35	–0.32	0.09
Fuel moisture	–0.52**	–0.34	0.01	0.08

* Significant at the .05 level of probability.
** Significant at the .01 level of probability.

lowing each burn, observations were made to determine the actual percentage of marked stems which had ignited (stems with charred wood), and burned down (standing stems that burned off at the base and fell to the ground). After one growing season had elapsed, each plot was checked to determine the percent mortality (trees with no resprouts).

The plots were burned between March 7 and April 6, 1969 just before tobosa and mesquite begins growing in the spring. The range of weather variables tested were wind 3 to 21 mph, air temperature 56 to 85 F, and relative humidity 13 to 75%. Total fine fuel varied from 4,070 to 6,969 lbs./acre. Fine fuel moisture varied from 6.4 to 33.1%, and soil moisture varied from 4.6 to 18.1%.

Multiple regression techniques were used to account for variability in the data. The independent variables were: wind speed, air temperature, relative humidity, total fuel (primarily tobosa and broomweed), tobosa fuel, fine fuel moisture, and soil moisture. The dependent variables were: percent ignition, percent burndown, percent mortality, and average maximum soil surface temperature of the burn. A step-wise multiple regression program was used to determine the relative importance of the independent variables in accounting for variation of the dependent variables.

Results and Discussion

Ignition

Ignition on individual tree stems within each plot varied from 33.6 to 94.9%. The most important variable for predicting ignition was relative humidity. It accounted for 55.8% of the total variation. Fine fuel moisture was also a highly significant variable (Table 1), but it is closely related to relative humidity and was not an important variable in the presence of relative humidity. These findings support conclusions by Davis (1959) in which he states "ignition probability increases rapidly with decreasing fuel moisture, hence with decreasing relative humidity."

Wind speed and total fine fuel were the next two most important variables. Wind tilts the flames of a fire and as wind increases more hot gases are carried into direct contact with unburned fuel (Davis, 1959). Also, radiative heat transfer is increased by wind. As total fine fuel increases, the quantity of heat generated by a fire increases and thus mesquite stems are more easily ignited.

The prediction equation developed for ignition is as follows:

$$Y = 25.467 + 1.705 X_1 - 0.764 X_2 + 0.0101 X_3$$

where,

Y = Percent ignition,
X_1 = Wind speed in mph,
X_2 = Percent relative humidity,
X_3 = Total fuel in lb./acre.

This equation accounts for 80% of the total variation with $s_{y \cdot x} = 8.9$.

Size of mesquite stems also affects ignition as shown in the following tabulation:

Size Class	Ignition (%)
2 inches or less	57.7
2–5 inches	71.7
5 inches or larger	81.7

The larger stems may be easier to ignite because of the rougher surfaces, increased borer activity, and possible magnification of "chimney effect" or increased heat on lee side of trees as shown by Fahnestock and Hare (1964).

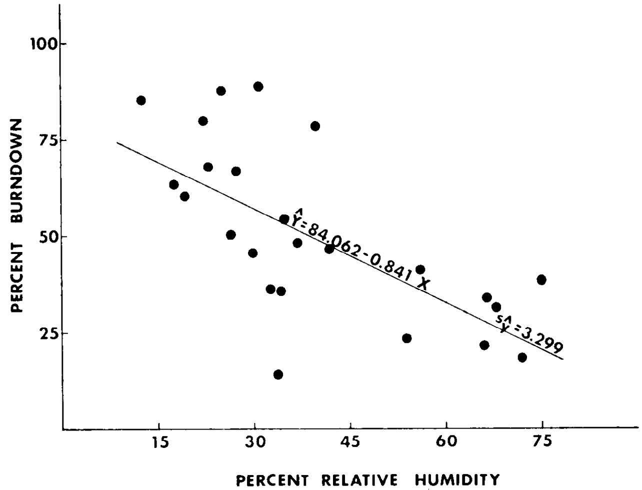

FIG. 1. Percent burndown decreases as relative humidity increases.

Burndown

Burndown on the plots varied from 14.4 to 89.1%. The most important variable for predicting burndown was relative humidity. It accounted for 46.7% of the variation in burndown. The second most important variable was wind speed. Wind speed plus relative humidity accounted for 77.2% of the variation. An increase in relative humidity decreased burndown while an increase in wind speed increased burndown (Fig. 1 and 2). High humidity increases moisture of bark and exposed wood of mesquite which reduced the ease of combustion (Fahnestock, 1953). Wind increases the supply of oxygen to the fire and, as a result, the rate of combustion. Wind also increases heat on the lee side of trees (Fahnestock and Hare, 1964), which increases the rate of combustion.

Another significant variable for predicting burndown was total amount of fine fuel. Adding this variable to wind and relative humidity accounted for 86% of the variation in burndown. These three variables were the most important (Fig. 3) and were incorporated into the following prediction equation:

$$Y = -3.947 + 3.129X_1 - 0.830X_2 + 0.0096X_3$$

where,

Y = Percent burndown,
X_1 = Wind speed in mph,
X_2 = Percent relative humidity,
X_3 = Total fine fuel in lb./acre.

Basically, this equation indicates that 1) an increase of one mph of wind will increase burndown 3%, 2) an increase of 1% relative humidity will decrease burndown 0.8%, and 3) an increase of 104 lbs. of fuel will increase burndown 1%. These variables account for 86% of the total variation in burndown with an $s_{y \cdot x} = 7.6$. Air temperature as a single component was also important (Table 1)

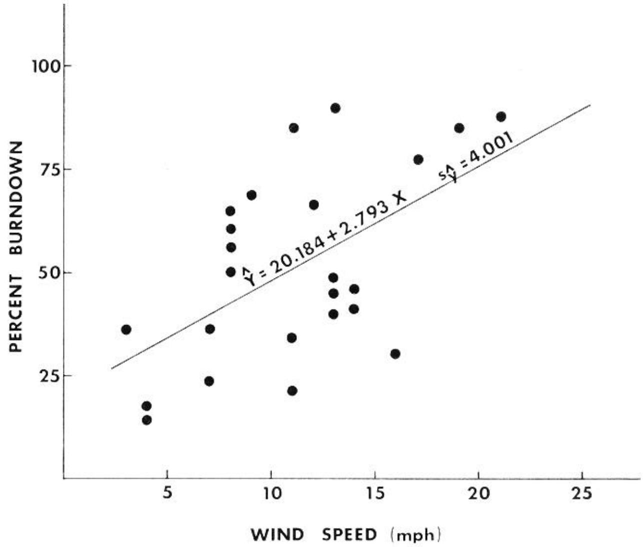

FIG. 2. Percent burndown increases as wind speed increases.

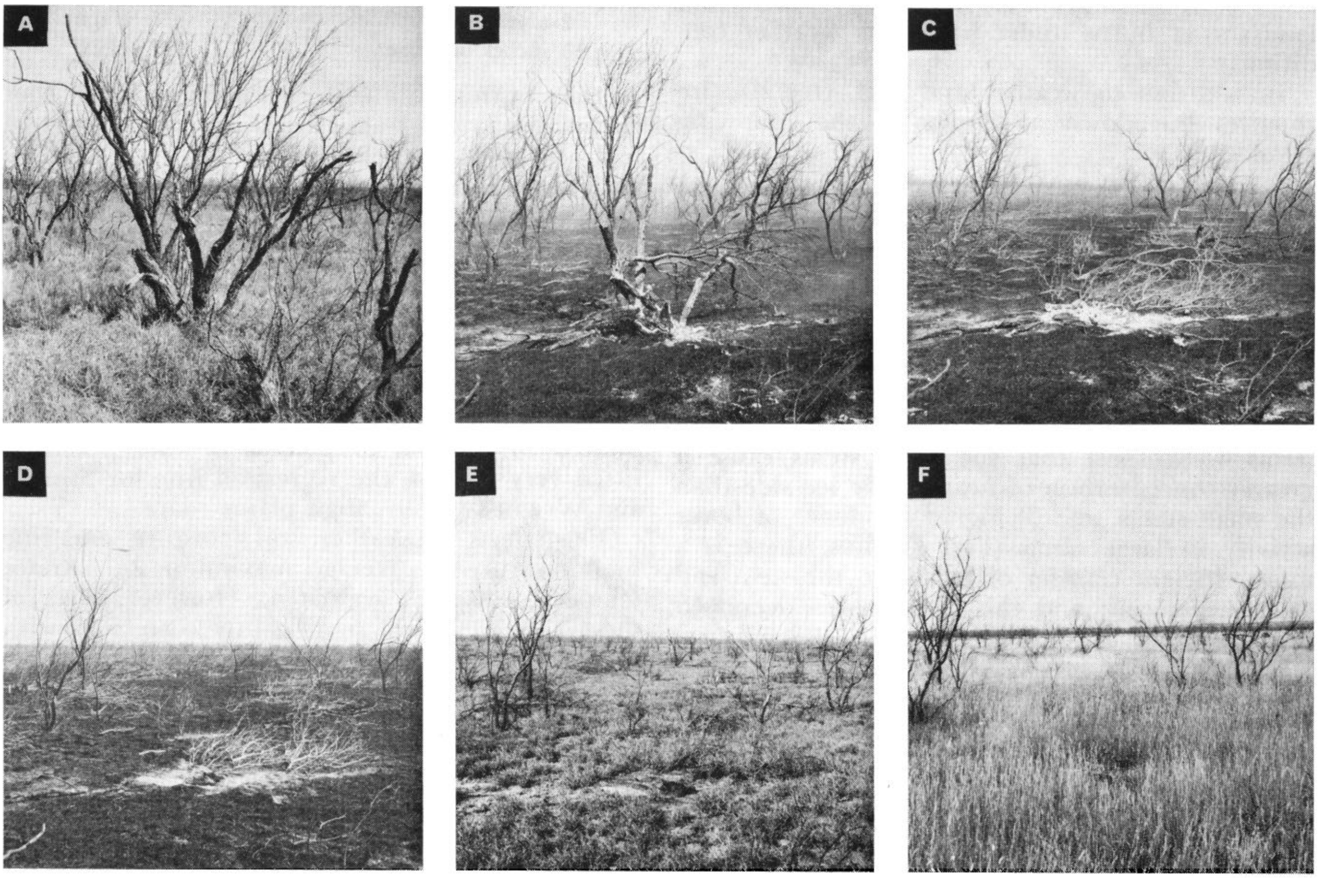

FIG. 3. A sequence of photos in a mesquite-tobosa community before burning until three months after burning: a) Plot before burning on March 20, 1969—4070 lb. of fuel per acre, wind 19 mph, air temperature 69 F, and relative humidity 22%; b) 20 minutes after ignition; c) 60 minutes after ignition; d) 85% burndown one day after ignition; e) grasses growing well one month after burn; f) yields 2,800 lb./acre compared with 1,100 lb./acre on control. Mortality of mesquite was 12%.

but it is inversely related to relative humidity and most of its effect is probably masked in this equation by relative humidity. Fine fuel moisture was not a significant variable for burndown, probably because all but one of the fuel moisture percentages were below 25%. This indicates that if fine fuel moisture is below 25% it is not a major factor in determining the success of burning down dead mesquite stems. We should point out, however, that we are talking about fuel moisture of the grass, not of the mesquite stems.

Prevailing burning conditions can be evaluated by using the equation above. For example, with large amounts of fuel (6,000 to 7,000 lb./acre) a land manager can burn under relatively safe conditions to achieve a 50% burndown. As the amount of fuel decreases, the land manager must burn under more hazardous conditions to accomplish a 50% burndown.

Recommended conditions for burning herbicide treated mesquite trees are: 1) wind = 6–10 mph, 2) air temperature = 70–75 F, 3) relative humidity = 25–35%. These conditions are reasonably safe and effective where fuel is 4,000 lb./acre or greater. When fine fuel is less than 3,000 lb./acre, burning is probably impractical unless the land owner burns under hazardous weather conditions.

In addition to weather and fuel, tree size influences burndown as shown in the following tabulation:

Size Class	Burndown (%)
2 inches or less	38.5
2–5 inches	47.2
5 inches or larger	67.4

This variation appears to be due mainly to three factors: 1) surface characteristics of different stem sizes—the small stems have smooth bark and the large stems have rough or broken bark, 2) size of stems—we suspect that the large stems cause a greater concentration of heat on the lee side than the small stems, and 3) higher incidence of borer activity in large stems (Fig. 4)—thus, there is a more efficient transfer of heat into the stem and gas transfer out; and this results in a decreased ignition time.

Mortality

Mortality on the 24 plots varied from 0 to 24% with an average of 12%. Only the amount of tobosa fuel accounted for a significant amount of variation in percent mortality (Table 1). It accounted for 17.7% of the variation. As tobosa fuel increased, mortality increased. None of the other variables were significantly correlated with mortality which means that death of mesquite trees by burning is extremely difficult to predict.

FIG. 4. Borer activity in dead wood (left center) increases the surface area per unit volume of wood and lowers the ignition time.

Size of mesquite stems, however, as in burndown and ignition, significantly influenced the mortality of trees (Fig. 4). This is shown in the following tabulation:

Size Class	Mortality (%)
2 inches or less	4.3
2–5 inches	9.8
5 inches or larger	26.6

As trees burn and burning continues into the root crown, the larger trees have a greater amount of fuel; they burn for a longer time and release more heat per unit of bud zone. Thus, the buds of large trees are eventually exposed to more heat than small trees. The small trees usually burn for less than half an hour, while the large trees burn for several hours, some burning for several days.

Temperature

Average maximum soil surface temperatures varied from 474 F to 730 F. These temperatures, plotted in relation to pounds of fuel per acre, fitted very well on the regression line for Stinson and Wright's (1969) "high plains" data.

The effects of weather, soil moisture, and fine fuel moisture on average maximum soil surface temperatures were evaluated. However, none of these variables were significantly correlated with average maximum soil surface temperatures (Table 1). Wind had the highest correlation, but it only accounted for 9% of the variation.

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