© 1983 Robert G. Clark

THRESHOLD REQUIREMENTS FOR FIRE SPREAD IN GRASSLAND FUELS

by

ROBERT G. CLARK, B.S., M.S.

A DISSERTATION

IN

AGRICULTURE

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

DOCTOR OF PHILOSOPHY

Approved

Accepted

December, 1983

AC
801
T3
1983
No. 12
Copy 2

ACKNOWLEDGMENTS

I thank Dr. Henry A. Wright for his guidance, support, and dedication throughout this study. I also thank committee members Dr. Bill Dahl, Dr. William Portnoy, and Dr. Carlton Britton, all of Texas Tech University, and Dr. James K. Brown of the Northern Forest Fire Lab (NFFL) in Missoula, for their unselfish support and open door policies.

Appreciation is extended to Mr. Richard Rothermel and Dr. James K. Brown of NFFL whose programs provided financial support, and to Dr. Wright and his management of the Texas Brush Line Item. Also, I thank Mr. Bill Masterson of the JY Ranch near Guthrie, Mr. Dan Griffis of the Griffis Ranch near Justiceburg, and Mr. John Anderson of the Borden Spade Ranch near Gail, Texas, who graciously provided sites for this study.

Others to whom I am indebted include David B. Wester and Luke Celentano for assistance with computer programs and data analyses, Gretchen Scott for assistance with chemical analyses, and especially Mr. Fred Roberts who assisted with every test fire conducted during 1982 and 1983, and Mr. Guy McPherson who assisted during 1983.

Finally, I thank Sylvia for everything else.

TABLE OF CONTENTS

ACKNOWLEDGMENTS ii

LIST OF TABLES iv

LIST OF FIGURES vi

I. INTRODUCTION 1

II. FUEL AND WEATHER THRESHOLDS FOR SUCCESSFUL FIRES IN THREE GRASSLAND FUELS 3

Methods 4

Results and Discussion 9

All Variables Included 9

Five Variable Restrictions 14

Use of Equations 18

III. FIRE BEHAVIOR IN THREE WARM SEASON GRASSES 24

Methods 24

Results and Discussion 29

Summary and Conclusions 34

IV. RELATIONSHIP BETWEEN FLAME LENGTH AND FIRELINE INTENSITY IN GRASSLAND FUELS 39

Methods 41

Results and Discussion 43

Headfires 43

Backfires 46

Summary and Conclusions 48

APPENDIX 51

A.1. Range of values used to generate rate of spread and fireline intensity models 52

4.1 Summary of test fires conducted during spring months, 1981 through 1983 40

4.2 Relationship between fireline intensity and flame length on grassland fires in west Texas 44

4.3 Flame length (m) regression models for headfires in three west Texas grass species 45

4.4 Flame length (m) regression models for backfires in two west Texas grass species 47

LIST OF FIGURES

2.1 Sites of test fires conducted during 1981 through 1983 7

3.1 A series of four infrared photographs illustrating the technique used to estimate rate of fire spread in weeping lovegrass 26

CHAPTER 1

INTRODUCTION

Ecologic and economic benefits of prescribed burning have been documented for many rangeland ecosystems. However, increased attempts to use fire have been accompanied by an increased number of failures. Failures are fires that fail to carry, or fires that are of insufficient intensity to satisfy burning objectives. For example, some fires do not generate enough heat to ignite and consume chained woody debris, and other fires do not produce sufficiently long flames to kill elevated buds on shrubs or trees. Further, fires that fail are expensive because fireline preparation, usually the largest direct cost of burning, is completed before the failure of a fire. Failures also disrupt management plans, and delay implementation of alternate treatments.

Fires may fail for several reasons. First, an improper combination of weather factors may have been used such as high relative humidity with low wind speed. Second, an insufficient, or unsatisfactorily arranged, fuel load may have been present. Third, the fire may not have corresponded with the proper stage of plant phenological development, resulting in an attempt to burn with excessive green material in the fuel bed array.

These problems have been largely ignored for grasslands. Much of the published literature on fires in grassland fuels deals with wildfire behavior. Wildfires, however, often occur with weather and fuel conditions that are beyond safety limits for conducting prescribed fires. Grasslands with 340 kg/ha of fine fuel may burn readily under

wildfire conditions but are difficult to burn safely under prescribed conditions. Thus, to conduct satisfactory prescribed fires in grasslands, information is needed on (1) the threshold weather and fuel conditions that allow fire to carry, (2) how fires that are successful behave, and (3) simple, field-oriented methods for practitioners to predict success or failure, and fireline intensity, so that the fire will safely fulfill objectives of burning.

CHAPTER II

FUEL AND WEATHER THRESHOLDS FOR SUCCESSFUL FIRES IN THREE GRASSLAND FUELS

Fire environment is the surrounding conditions, influences, and modifying forces of topography, fuel, and air mass that determine fire behavior (Wein and MacLean 1983). Many variables contribute to the fire environment, and effects of these variables acting simultaneously may be synergetic, synergistic, or antagonistic on fire response to environment. Ultimately, the fire either succeeds or fails. Van Wagner (1983) described three universal principles that apply to successful fires in vegetation. In prescribed burning, two of these variables are paramount. First, there must be sufficient fuel of appropriate size and arrangement. Second, the fuel must be of sufficient dryness to support a spreading combustion reaction.

Despite the dictum that these principles apply to all fuel types, the threshold requirements for fire spread in grassland fuels have not been determined together. For example, Stocks and Walker (1968) examined the effect of green vegetation on surface fire spread without regard for other variables, while Traylor (1961) did not consider green fuel. Some work in the western United States (Sneeuwjagt and Frandsen 1977) and in Australia (Luke and McArthur 1978, Cheney 1981) has been more comprehensive, however. In general, factors that contribute to fire failure have not been reported in the literature. The purpose of this study was to isolate the fire environment variables that determine success or failure of fires in grassland fuels.

Methods

Head and back test fires were attempted during the spring months of 1981 through 1983 (Table 2.1) in uniform stands of three grass species (Fig. 2.1) under a wide variety of fuel and weather conditions. Attempts included 19 fires in buffalograss (Buchloe dactyloides), 55 in tobosagrass (Hilaria mutica), and 44 in weeping lovegrass (Eragrostis curvula). Buffalograss is a short, finely-divided, stoloniferous grass; tobosagrass is a mid-height, coarse, rhizomatous grass; and weeping lovegrass is a tall, fine-leaved, introduced bunchgrass. Fires that carried across the fine fuel portion of the fuel bed, irrespective of fireline intensity or fuel consumed, were considered successful.

Test plots were 20 m or longer in buffalograss, 30 m or longer in the other species, and at least 12 m wide. All plots were on level terrain in uniform stands of grass. Several weather and fuel variables (Table 2.2) were measured. Air temperature and relative humidity were determined within 3 min of ignition with a standard belt weather kit (Anon. 1959) sling psychrometer. Solar intensity was determined with a LI-COR LI-185 Radiometer and LI-200S Pyranometer Sensor (LI-COR n.d.). Wind speed at 0.5 and 2.0 m was determined with totalizing anemometers (Clark et al. 1981). Total precipitation since 1 October and 1 January, and the time since a 20 mm precipitation event occurred were obtained from the National Weather Service records (NOAA 1981-1983) supplemented by local gages and records.

Fuel load data were determined by clipping, to within 1 cm of soil surface, a sufficient number of quadrats on each test fire to estimate fuel load within 20% of the mean at 90% confidence. This was

Table 2.1 Summary of head and backfires conducted in three grassland fuel species, 1981-1983.

Species	Firetype	No. Attempted	No. Successful	No. failed
Buffalograss	headfire	14	8	6
Buffalograss	backfire	5	0	5
Tobosagrass	headfire	31	29	2
Tobosagrass	backfire	24	16	8
Weeping lovegrass	headfire	25	24	1
Weeping lovegrass	backfire	19	12	7
Total	headfire	70	61	9
Total	backfire	48	28	20

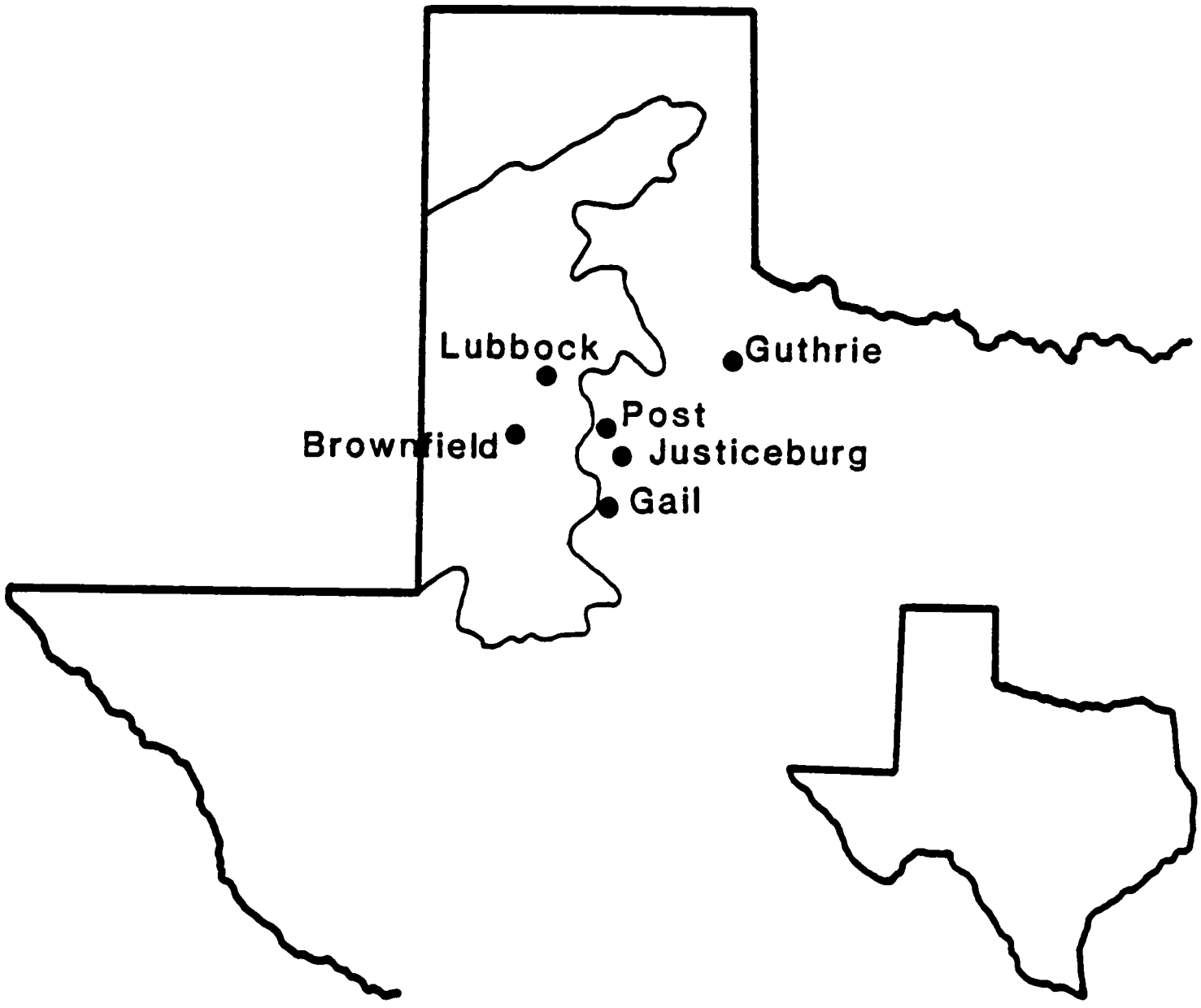

Fig. 2.1. Sites of test fires conducted during 1981 through 1983. Buffalograss fires were conducted at Guthrie and Justiceburg, tobosagrass fires at Guthrie and Gail, and weeping lovegrass fires at Post and Brownfield. The irregular line separates the southern High Plains (west) from the red Rolling Plains of Texas.

Table 2.2. List of variables considered in discriminant analyses of head and back test fires in west Texas.

X_1 = Time since 20mm precipitation event occurred (days)
X_2 = Total precipitation since 1 January of fire year (mm)
X_3 = Total precipitation since 1 October of preceding year (mm)
X_4 = Fuel load, standing litter (kg/ha)
X_5 = Fuel load, green (kg/ha)
X_6 = Fuel load, down litter (kg/ha)
X_7 = Fuel moisture content, standing litter (%)
X_8 = Fuel moisture content, green (%)
X_9 = Fuel moisture content, down litter (%)
X_{10} = Fuel bed depth (cm)
X_{11} = Ratio green fuel load/standing litter load (fraction)
X_{12} = Ratio green fuel load/total litter load (fraction)
X_{13} = Windspeed at 0.5m above soil surface, average (km/hr)
X_{14} = Windspeed at 2.0m above soil surface, average (km/hr)
X_{15} = Solar intensity at ignition (W/m^2)
X_{16} = Ash content, standing litter (%)
X_{17} = Ash content, green fuel (%)
X_{18} = Ash content, down litter (%)
X_{19} = Phosphorus content, standing litter (%)
X_{20} = Phosphorus content, green fuel (%)
X_{21} = Phosphorus content, down litter (%)
X_{22} = Silica content, standing litter (%)
X_{23} = Silica content, green fuel (%)
X_{24} = Silica content, down litter (%)
X_{25} = Low heat content, standing litter (kJ/kg)
X_{26} = Low heat content, green fuel (kJ/kg)
X_{27} = Low heat content, down litter (kJ/kg)
X_{28} = Air temperature at ignition (°C)
X_{29} = Relative humidity at ignition (%)
X_{30} = Fuel particle surface area/volume ratio (cm^2/cm^3)
X_{31} = Packing ratio, fuel bulk density/particle density (cm^3/cm^3)
X_{32} = Fuel load, total (kg/ha)
X_{33} = Fuel moisture content, total (%)

usually ten 0.25-m^2 rectangular quadrats in weeping lovegrass and fifteen 0.063-m^2 rectangular quadrats in buffalograss and tobosagrass. Each quadrat load was separated into green, standing litter, and down litter components and oven-dried to a constant weight at 60°C. Subsamples were weighed in the field immediately after clipping, oven-dried at 60°C to constant weight, than reweighed to obtain fuel moisture content on a dry weight basis. Recorded dry weights also provided ratios of green fuel/standing litter, and green fuel/total litter.

Fuel chemistry was determined using standard laboratory procedures. For the 1981 test fires, all three fuel load components were analyzed for each fire. During 1982 and 1983, three to five samples were randomly selected for each component of each grass species and analyzed to verify the 1981 data. Chemical analyses completed were low heat content determined in a Parr Adiabatic Bomb Calorimeter (Parr Inst. Co., n.d., Van Wagner 1972), and ash, silica, and phosphorus (AOAC 1980).

Surface area/volume ratios were determined for each species (Clark and Wright 1981). Packing ratios, calculated as the ratio of bulk density/particle density (Rothermel 1972), varied little within species. Thus, single values of 0.004130, 0.003461, and 0.005552 were used for buffalograss, tobosagrass, and weeping lovegrass, respectively.

Data were analyzed using the BMDP7M computer program (Jennrich and Sampson 1981) to perform stepwise discriminant analyses that categorized test fire results into success or failure groups. Dual discriminant functions were combined (Morrison 1976) into single equations to simplify use. Jackknifed classifications were used because success or failure of each fire was grouped according to classification

functions computed from all data except the fire being classified. This classification method is more restrictive than normal classification and provides a more realistic estimate of the ability of predictors to disciminate among groups (Tabachnick and Fidell 1983).

Results and Discussion

All Variables Included

Lachenbruch (1975) suggested that when a large number of independent variables are used in stepwise discriminant analysis, only three to five variables can be safely selected without introducing noise. Therefore an attempt was made to select significant functions based on three to five variables.

The use of all variables (Table 2.2) generated a function that correctly grouped 86% of buffalograss headfires (Table 2.3). With buffalograss, success was partially dependent on fuel load; the coefficient for green fuel load was negative and twice as high as that for the down litter fuel load. This suggests that fires occurring after plant growth initiation in the spring are progressively less likely to succeed.

Tobosagrass headfire success was influenced by chemical factors more than was buffalograss, required more variables, and was more difficult to predict. The inclusion of solar intensity, green fuel silica content, and standing litter low heat of combustion resulted in a discriminant equation that, while useful in understanding fire behavior, was not practical for field use. When data from 70 attempted headfires on all species were pooled, the ratio of green fuel load/ total litter fuel load became important. Implicit in ths latter

Table 2.3. Discriminant equations, derived from 33 fire environment variables, for headfires and backfires in three west Texas grasses. Calculated values > 0 predict success at P=0.05.

	Prediction Equation[1]	Correct Prediction (%)
Headfires		
Buffalograss	$-1.0 + 0.016052X_{LFL} + 0.216129X_{AT} - 0.028803X_{GFL}$	86
Tobosagrass	$-1.0 - 0.007323X_{DFM} - 0.002033X_{W2} - 0.000053X_{SI} - 0.028326X_{\%Si} + 0.000086X_{DH}$	81
Weeping lovegrass[2]		
All species	$+1.0 + 0.004038X_{LFM} + 0.012393X_{AT} - 3.191173X_{G/T} - 0.011051X_{DFM} - 0.046475X_{DA}$	92
Backfires		
Buffalograss[3]		
Tobosagrass	$-1.0 + 0.000414X_{DFL} + 0.033117X_{AT} - 0.035597X_{W½} - 0.011206X_{RH}$	80
Weeping Lovegrass	$-1.0 - 1.924821X_{G/O} - 0.008477X_{RH} - 0.007227X_{TIM}$	84
All species	$+1.0 + 0.003741X_{TFL} - 0.097662X_{TFM} - 0.024400X_{W½} - 0.285326X_{RH}$	86

[1] X_{LFL} = down litter fuel load (kg/ha), X_{AT} = air temperature (°C), X_{GFL} = green fuel load (kg/ha), X_{DFM} = standing litter fuel moisture content (%), X_{W2} = windspeed at 2.0 m (km/hr), X_{SI} = solar intensity (W/m^2), $X_{\%Si}$ = green fuel silica content, X_{DH} = standing litter low heat content (kJ/kg), X_{LFM} = down litter fuel moisture content (%), X_{DA} = standing litter ash content (%), X_{DFL} = standing litter fuel load (kg/ha), $X_{W½}$ = windspeed at 0.5 m (kg/hr), $X_{G/O}$ = ratio of green fuel load/standing litter load (fraction), X_{TIM} = time since 20 mm precipitation event (days), X_{TFL} = total fuel load (kg/ha), and X_{TFM} = total fuel moisture content (%).

[2] No reasonable equation generated due to low number of failed headfires in weeping lovegrass.

[3] No buffalograss backfires were succesful.

equation is the contention that, irrespective of the amount of standing or down litter available for combustion, the proportion of green fuel in the fuel bed matrix can influence the success of grassland fires in these species.

In contrast to buffalograss and tobosagrass headfires, weeping lovegrass headfires were usually successful. The only failure in 25 attempts occurred the morning following a 5 cm snowfall. Successful fires were conducted with air temperature -3°C and relative humidity 93%. When total fuel moisture exceeded 30%, combustion was not complete; on one fire a 15 cm stubble remained after burning although the fire carried through standing litter. The weeping lovegrass stands in which most of the fires were conducted were decadent, ungrazed pastures with abnormal accumulations of dead material. Therefore, the discriminant equation in which data from all species was pooled may not be applicable to prescribed burning in properly managed weeping lovegrass pastures.

It is likely that minimum fuel loads required to carry headfires were not determined in this study. Wright and Bailey (1982) suggested that wildfires could carry through fuel loads as small as 340 kg/ha. Since many of the fires in this study were conducted under weather conditions common during wildfires (i.e., relative humidity 11%, air temperature 33°C, windspeed 53 km/hr at 2 m height), it is reasonable to assume that fires should be expected to carry through fuel loads below the minimum used in this study (Table 2.4) under these conditions.

Backfires are rarely used in large-scale prescribed burning except to create blacklines, minimize threat of escape near downwind fire perimeters, and to reduce flame length (see Chapter IV) under canopies.

Table 2.4. Range of selected variables used in discriminant analyses of headfires and backfires in three grass species.

Fire Environment Variable	Buffalograss	Tobosagrass	Weeping lovegrass
Down litter fuel load (kg/ha)	160 to 517	772 to 4469	400 to 3792
Standing litter fuel load (kg/ha)	478 to 1739	1892 to 5136	1572 to 6674
Green fuel load (kg/ha)	188 to 470	50 to 1387	0 to 1133
Total fuel load (kg/ha)	975 to 2401	2791 to 8939	3308 to 8340
Down litter fuel moisture content (%)	1.0 to 104.2	5.1 to 23.8	0.8 to 174.3
Standing litter fuel moisture content (%)	1.0 to 25.6	4.5 to 37.8	2.3 to 181.4
Total fuel moisture content (%)	24.1 to 57.6	14.6 to 59.3	7.3 to 180.8
Ratio green fuel load/standing litter load (fraction)	0.15 to 0.92	0.01 to 0.35	0 to 0.33
Ratio green fuel load total litter load (fraction)	0.13 to 0.47	0.01 to 0.08	0 to 0.18
Standing litter ash content (%)	13.1 to 19.3	8.6 to 13.7	4.8 to 11.4
Green fuel silica content (%)	3.7 to 14.3	4.6 to 13.0	1.8 to 9.5
Standing litter low heat content (kJ/kg)	14766 to 18457	16309 to 17831	16441 to 18434
Time since 20 mm precipitation event (days)	4 to 173	5 to 172	2 to 159
Air temperature at ignition (°C)	8.0 to 31.1	4.7 to 32.8	-2.8 to 30.3
Relative humidity at ignition (%)	14 to 71	11 to 97	12 to 95

Table 2.4. (Continued)

Fire Environment Variable	Buffalograss	Tobosagrass	Weeping lovegrass
Average windspeed at 0.5 m (km/hr)	3.6 to 26.5	3.1 to 25.9	2.7 to 20.4
Average windspeed at 2.0 m (km/hr)	4.7 to 32.1	3.7 to 53.1	6.1 to 39.3
Solar intensity at ignition (W/m^2)	10 to 950	44 to 940	100 to 950

Thus, little information is available in the literature concerning requirements for backfire success. In this study, variables commonly measured on prescribed fires including air temperature, relative humidity, windspeed , fuel load, and fuel moisture content consistantly predicted success of backfires (Table 2.3), even when all variables were used. With tobosagrass backfires, standing litter fuel load was important, and with weeping lovegrass backfires the ratio of green fuel load/standing litter also entered the selected function. When all backfires were combined, total fuel moisture content, windspeed at 0.5 m above the soil surface, and relative humidity were used to correctly classify 86% of the successful and failed fires.

Five Variable Restrictions

For comparison, five easily measured field variables (Table 2.5) including total fuel load, total fuel moisture content, air temperature, relative humidity, and windspeed at 2.0 m were used to determine whether fire success or failure could be correctly classified and thus provide a field-oriented method to predict fire success. Separate analyses were made for headfires and backfires on each species, and for all species combined (Table 2.6).

With headfires, buffalograss success or failure was not predictable (P=.05), and weeping lovegrass data did not provide a reasonable result because only one headfire failed. Success or failure of tobosagrass was predictable, however. Only two variables, total fuel load and total fuel moisture content, provided an 81% correct classification. The influence of tobosagrass data also allowed the combined data for

Table 2.5. Range of five variables used in discriminant analysis of success or failure of three grasses.

Species	Variable	Headfires		Backfires	
		Success	Fail	Success	Fail
Buffalograss	Total fuel load (kg/ha)	975 to 2401	1092 to 2059	---	1076 to 2401
	Total fuel moisture (%)	24.1 to 51.2	27.2 to 51.1	---	24.1 to 57.6
	Air temperature (°C)	8.0 to 31.1	8.9 to 21.9	---	8.9 to 31.1
	Relative humidity (%)	14 to 44	21 to 71	---	14 to 44
	Windspeed at 2m (km/hr)	5.6 to 32.1	4.7 to 21.1	---	5.8 to 30.6
Tobosagrass	Total fuel load (kg/ha)	2791 to 8939	5824 to 6699	3991 to 8939	4860 to 6886
	Total fuel moisture (%)	14.6 to 57.0	39.4 to 59.3	15.5 to 57.1	22.5 to 59.3
	Air temperature (°C)	6.7 to 32.8	11.0 to 19.0	4.7 to 32.5	5.3 to 27.0
	Relative humidity (%)	11 to 97	70 to 84	11 to 77	30 to 97
	Windspeed at 2m (km/hr)	6.1 to 53.1	17.3 to 21.5	3.7 to 49.9	9.5 to 31.7
Weeping lovegrass	Total fuel load (kg/ha)	3308 to 8340	8032 to 8032	3892 to 8340	3744 to 8032
	Total fuel moisture (%)	7.3 to 35.0	180.8 to 180.8	7.3 to 35.0	8.8 to 180.8
	Air temperature (°C)	-2.8 to 30.3	0.0 to 0.0	0.8 to 30.3	-2.8 to 21.0
	Relative humidity (%)	12 to 93	90 to 90	12 to 63	21 to 95
	Windspeed at 2m (km/hr)	6.3 to 39.3	25.8 to 25.8	16.1 to 35.9	6.1 to 26.7

Table 2.5. (Continued)

Species	Variable	Headfires		Backfires	
		Success	Fail	Success	Fail
All species	Total fuel load (kg/ha)	975 to 8939	1092 to 8032	3892 to 8939	1076 to 8032
	Total fuel moisture (%)	7.3 to 57.0	27.2 to 180.8	7.3 to 57.1	8.8 to 180.8
	Air temperature (°C)	-2.8 to 32.8	0.0 to 21.9	4.7 to 35.0	-2.8 to 31.1
	Relative humidity (%)	11 to 97	21 to 90	11 to 77	14 to 97
	Windspeed at 2m (km/hr)	5.6 to 53.1	4.7 to 25.8	3.7 to 49.9	5.8 to 31.7

Table 2.6. Discriminant equations, based on five commonly measured variables, for head and backfires in three west Texas grasses. Calculated values > 0 predict success at P=.05.

Headfires	Prediction Equation[1]	Correct Prediction (%)
Buffalograss[2]		
Tobosagrass	$+ 1.0 + 0.001237X_{TFL} - 0.044305X_{TFM}$	81
Weeping lovegrass[3]		
All species	$+ 1.0 + 0.000437S_{TFL} - 0.058059X_{TFM} - 0.026498X_{WS}$	85
Backfires		
Buffalograss[4]		
Tobosagrass	$+ 1.0 + 0.000377X_{TFL} - 0.037166X_{WS} - 0.049282X_{RH}$	71
Weeping lovegrass	$- 1.0 + 0.000130X_{TFL} + 0.016795X_{AT} - 0.003392X_{TFM}$	79
All species	$- 1.0 + 0.000431X_{TFL} - 0.013111X_{TFM} - 0.028647X_{RH}$	80

[1] X_{TFL} = total fuel load (kg/ha), X_{TFM} = total fuel moisture content (%), X_{RH} = relative humidity (%), X_{WS} = windspeed at 2.0m (km/hr), and X_{AT} = air temperature (°C).

[2] No statistically significant (P=.05) equation generated.

[3] No reasonable equation generated due to low number of failures.

[4] No buffalograss backfires were successful.

three species to correctly classify 88% of the successful and failed fires. The range of fuel loads and fuel moisture contents used to generate the tobosagrass classification function were 2791 to 8939 kg/ha and 15 to 59% respectively. The overall range for all species was 975 to 8939 kg/ha fuel load, and 7 to 181% fuel moisture content.

Backfire success or failure was predictable for tobosagrass and weeping lovegrass but not buffalograss (Table 2.6). No buffalograss backfires were successful. With backfires, these five variables enabled correct classifications ranging from 71 to 80%.

Use of Equations

The discriminant equations (Table 2.3, 2.6) are applicable to the species listed. Due to the diverse morphological differences among the three species, equations for "all species" may be applicable to mixed grassland communities with uniform, contiguous growth patterns on level terrain. Equations determined from five easily measured fuel and weather variables (Table 2.6) are easily applied to field use and should provide guidelines for planning prescribed burns. However, extrapolation beyond the range of variables used in this study should not be done during the planning process. Some calculated field examples are listed in Table 2.7.

It should be emphasized that erratic fire behavior leading to fire whirls or spotting, or horizontal fuel continuity, were not addressed in this study. Also, fuel loads that were used were probably above the threshold requirements for successful fire spread in both backfires and headfires.

Table 2.7. Examples of fuel and weather conditions that will result in fires that carry across fine (0.3 cm) fuel about 80% of the time. These values assume relatively uniform fuel distribution on level terrain.

Headfires	Total Fuel Moisture Content (%)	Windspeed at 2 m (km/hr)	Fine Fuel Load (kg/ha)
	10	10	1000
	20	10	2000
	30	10	3000
	40	10	4000
Backfires	**Total Fuel Moisture Content (%)**	**Relative Humidity (%)**	**Fine Fuel Load (kg/ha)**
	5	10	3000
	10	20	4000
	15	35	5000
	20	30	5000
	15	50	6000
	20	45	6000
	25	40	6000
	30	40	6000

Management Implications

Backfires in all grass species and under nearly all weather conditions moved slowly, removed most of the fine fuel load, and generated low fire-line intensities. Therefore, backfires can be safely and effectively conducted, provided wind shifts do not occur, to widen existing firelines and for burning out small areas near roads or other improvements. Backfires move too slowly, however, to be useful on most broadcast fires.

Backfires are most likely to succeed where the total fine fuel load is at least 3000 kg/ha and is uniformly distributed. Therefore, livestock should be removed from a pasture mid-way through the growing season to allow fuel to accumulate and uniformity to develop. Pastures that contain mixtures of tall and short grasses will burn erratically, and may be difficult to burn with a backfire. Other important factors in backfire success include the total fine fuel moisture content, and the proportion of green fuel. When the entire fine fuel load is dormant it is usually possible to estimate fine fuel equilibrium moisture content from relative humidity (Wright and Bailey 1982). However, if green material is present, relative humidity is a poor estimator and fuel moisture content should be measured. Where the fuel load exceeds 3000 kg/ha, there may be a substantial difference in moisture content between the top and bottom of the fuel bed and again, fuel moisture content should be measured rather than estimated from relative humidity. Backfires do not spread well if total fine fuel moisture content is above 20%, or if green fuel comprises more than 5% by weight of the total fuel load.

Headfires in weeping lovegrass and tobosagrass will almost always carry provided at least 1000 kg dormant fuel/ha is present, uniformly distributed, and fuel moisture content is 20% or less. If spot grazing has occurred, more fuel is necessary and the fire will require more time and effort to complete. With weeping lovegrass and other similar seeded bunchgrasses, the direction of fire spread must be parallel with the drill rows unless inter-row litter is present. If fire is to be used on improved pastures, consideration should be given to planting in the direction which provides the best burning conditions. With both weeping lovegrass and tobosagrass, as total fuel moisture content approaches 30%, a substantial portion of the fuel bed will remain unburned. Thus, if an objective of burning is to remove accumulated litter, total fine fuel moisture content should be 20% or less.

With both head and backfires, success or failure should be judged according to the objectives of burning. Many of the fires that were successful in this study (those that carried across the fine fuel portion of the fuel bed) might be considered failures if objectives had been different. For example, objectives of pasture burning might include 80% mortality of common broomweed (Xanthocephalum dracunculoides) rosettes, or a 50% reduction in honey mesquite (Prosopis glandulosa) canopy cover. In general, headfires will achieve these objectives better than backfires.

LITERATURE CITED

Anonymous. 1959. Belt weather kit. Fire Contr. Notes 20(4):122-123.

AOAC. 1980. Official methods of analysis. Thirteenth ed. Sec. 3.005: sand and silica. Sec. 3.062: phosphorus. Assoc. Official Anal. Chem. Washington, D.C.

Cheney, N. P. 1981. Fire Behaviour, p. 151-175. In A. M. Gill, R. H. Groves, and I. R. Nobel (eds). Fire and the Australian biota. Australian Acad. Sci., Canberra.

Clark, R. G., and H. A. Wright. 1981. Surface area/volume ratios for three Texas grasses. Noxious Brush and Weed Control Highlights 12:19. Texas Tech Univ., Lubbock.

Clark, R. G., A. A. Steuter, and C. M. Britton. 1981. An inexpensive anemometer frame. Fire Manage. Notes 42(3):13-14.

Jennrich, R., and P. Sampson. 1981. Stepwise discriminant analysis, p. 519-537. In W. J. Dixon (ed). Biomedical computer programs, P-series, Univ. Calif. Press, Berkeley.

Lachenbruch, P. A. 1975. Discriminant analysis. Macmillan Pub. Co., NY. 128p.

LI-COR. n.d. Instruction manual for LI-185 quantum/radiometer/photometer. Lambda Inst. Co., Lincoln, NE. 4p.

Luke, R. H., and A. G. McArthur. 1978. Bushfires in Australia. Australian Gov't Pub. Serv., Canberra. 359p.

Morrison, D. F. 1976. Multivariate statistical methods. Second ed. McGraw Hill, NY. 415p.

NOAA. 1981-1983. Monthly climatological data summaries, Texas. Vol. 86-88. Nat. Oceanogr. and Atmos. Admin., Nat. Climatic Center, Asheville, NC.

Parr Inst. Co. n.d. Instructions for 1241 and 1242 adiabatic calorimeter, manual No. 142. Parr Inst. Co., Moline, IL. 23p.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. U.S. Dept. Agr. For. Serv. Res. Pap. INT-115. Intermt. For. and Range Exp. Sta., Ogden. 40p.

Sneeuwjagt, R. J., and W. H. Frandsen. 1977. Behavior of experimental grass fires vs. predictions based on Rothermel's fire model. Can. J. For. Res. 7:357-367.

Stocks, B. J., and J. D. Walker. 1968. The effect of green vegetation on surface fire spread in the laboratory. Info. Rep. PS-X-5. Petawawa For. Exp. Sta., Chalk River, ONT. 5p.

Tabachnick, B. G., and L. S. Fidell. 1983. Using multivariate statistics. Harper & Row, NY. 509p.

Traylor, R. E. 1961. Correlation of weather to fire spread in grass and brush fuels on the Snake River Plains in southern Idaho. Fire Contr. Notes 22(4):118-119.

Van Wagner, C. E. 1972. Heat of combustion, heat yield, and fire behaviour. Info. Rep. PS-X-35. Petawawa For. Exp. Sta., Chalk River, ONT. 7p.

Van Wagner, C. E. 1983. Fire behaviour in northern conifer forests and shrublands, p. 65-80. In R. W. Wein and D. A. MacLean (eds). The role of fire in northern circumpolar ecosystems. John Wiley & Sons, NY.

Wein, R. W., and D. A. MacLean (eds). 1983. The role of fire in northern circumpolar ecosystems. John Wiley & Sons, NY. 322p.

Wright, H. A., and A. W. Bailey. 1982. Fire ecology: United States and southern Canada. John Wiley & Sons, NY. 501p.

CHAPTER III

FIRE BEHAVIOR IN THREE WARM SEASON GRASSES

Fires have occurred on southern Great Plains grasslands for centuries (Wright 1978, Smeins 1980, Pyne 1982), and historical documents indicate that fires moved rapidly over large areas. For example, Haley (1953) described an 1887 fire that traveled 26.6 km in 2 hrs, and another fire during the winter of 1884-1885 that covered over 400,000 ha on the XIT Ranch alone. Duke and Frantz (1961) also reported that these fires could travel 16 to 19 km/hr. Even in grasslands some of these rapid spread rates can be attributed to spotting and intense radiation. Haley (1953) observed grass igniting 5 m ahead of burning material. Haley also noted that "The spread of prairie fires varied with the speed of the wind, the dryness and length of the grass, and its thickness upon the ground."

Because grassland fires reportedly can cross a 61 m fireline (Duke and Frantz 1961), wild and prescribed fires in grasslands have potential for escape. Since containment is of primary concern on prescribed fires, this study was conducted to determine how headfires and backfires behave, under a wide variety of fuel and weather conditions, in three different grassland fuel types.

Methods

Head and back test fires were conducted in three grass species including buffalograss (Buchloe dactyloides), tobosagrass (Hilaria mutica), and weeping lovegrass (Eragrostis curvula). Buffalograss, a short,

finely-divided, stoloniferous grass, and tobosagrass, a mid-height, coarse, rhizomatous grass, provided distinct stands of continuous, uniform fuel. Weeping lovegrass, a fine, leafy, tall bunchgrass, provided a fuel load more typical of row-planted bunchgrasses. Fires in weeping lovegrass were restricted to days with wind flow parallel to the seeded rows to avoid confounding effects of horizontal discontinuity. Fires in buffalograss and tobosagrass were conducted without restriction. All fires were set as line headfires (burning with the wind) or backfires (burning against the wind) with a drip torch. Plots were 20 m or longer in buffalograss, 30 m or longer for the other species, and at least 12 m wide.

Fire behavior data included success or failure of head and backfires (see Chapter II), flame length (see Chapter IV), rate of spread (rate of fire advance), and calculated fireline intensity. Rates of spread and fireline intensities are reported here.

Fireline intensity (Byram 1959, Alexander 1982) was determined by (1) clipping to within 1 cm of the soil surface a sufficient number of quadrats in each test fire plot to estimate fuel load (W) within 20% of the mean at P=0.90, (2) separating the fuel load into standing litter, green fuel, and down litter components, then determining low heat of combustion content of each component in a Parr Adiabatic Bomb Calorimeter (Parr Inst. Co., n.d., Van Wagner 1972) and weighting the contribution of each component to obtain a single heat content value (H) for each fire, and (3) estimating the rate of fire spread (R) with a photographic technique (Britton et al. 1977). Fireline intensity was then calculated according to I=HWR where

I = fireline intensity, kW/m

H = low heat of combustion content, kJ/kg

W = mass of available fuel, kg/m^2

R = rate of fire spread, m/sec

A final reduction correction of 23.9 kJ/kg/% MC weighed moisture content was made to account for the difference between heat content determined in the laboratory with oven-dry samples and the additional moisture contained in each fuel component during the test fires (Van Wagner 1972).

For rates of spread estimation, at least four photographs on high speed infrared black and white negative film were taken perpendicular to direction of fire spread (Fig. 3.1), but seven to ten photographs were used on most fires. Markers were measured to the nearest 0.5 cm in each fire, and the nearest 0.01 cm on each photograph. A slight (3 to 5%) camera parallax error was ignored because only those photographs taken of the central 15 m of fire run were used for analyses.

On successful fires, (fires that carried across the test plots) 33 measured or calculated variables (Table 3.1) were subjected to stepwise multiple regression (Ray 1982) to determine which variables were the best predictors of fireline intensity and rate of spread. The variables were obtained as follows. Weather variables including air temperature and relative humidity were determined using a standard belt weather kit (Anon. 1959). Solar intensity 10 cm above the soil surface was determined with a LI-COR model LI-185 Quantum/Radiometer/Photometer (LI-COR n.d.) and LI-200S Pyranometer sensor. Average windspeeds at 0.5 and 2.0 m were obtained with totalizing anemometers (Clark et al. 1981). Precipitation data were compiled from National Weather Service

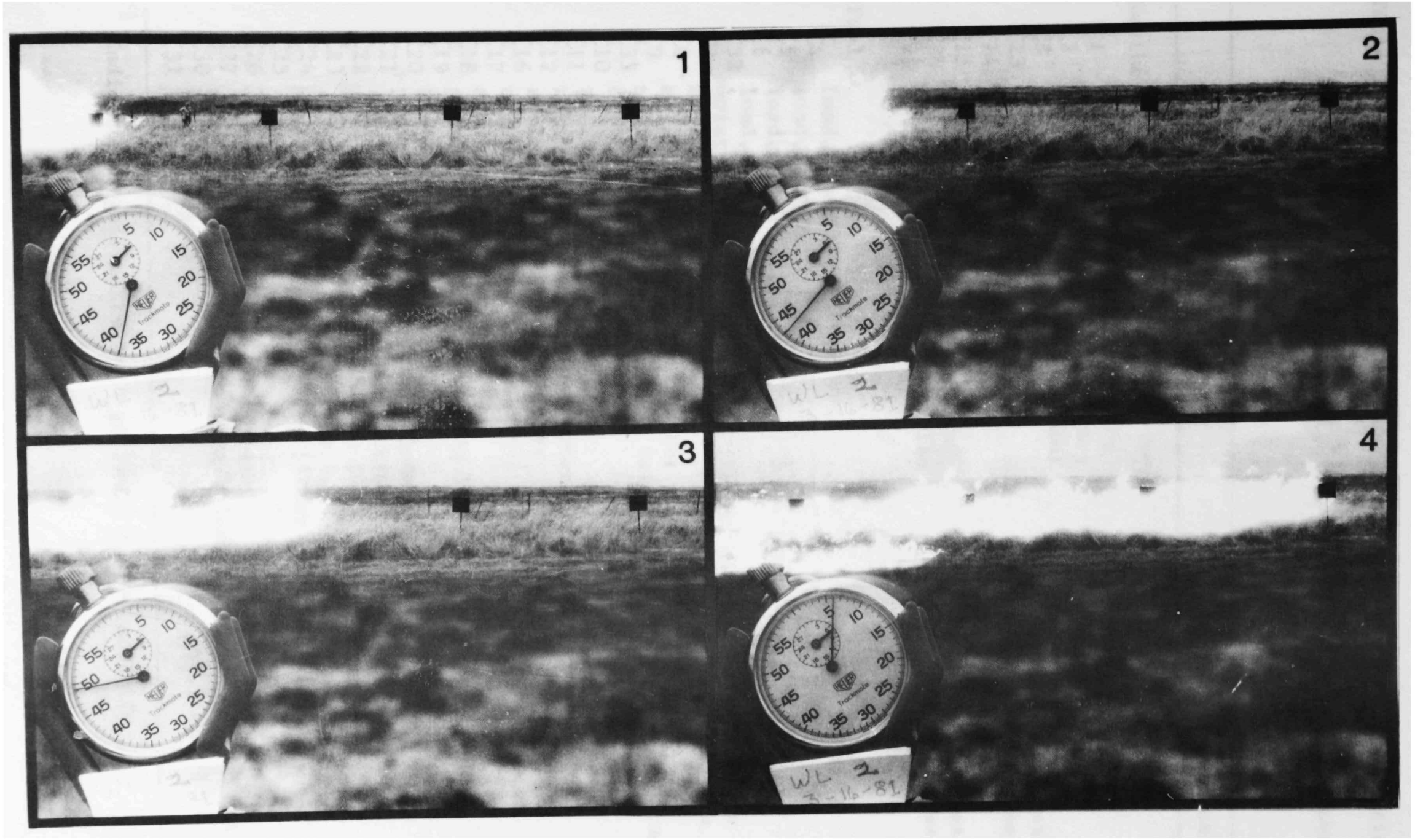

Fig. 3.1. A series of four infrared photographs illustrating the technique used to estimate rate of fire spread in weeping lovegrass. Infrared film was used to penetrate smoke, and a stopwatch recorded elapsed time between photographs. Markers of known dimensions and spacing allowed calculation of rate of fire spread.

Table 3.1. Summary of weather and fuel variables and correlations with rate of spread on 60 successful head, and 28 successful backfires.

Variable		Units	Headfires	Backfires
Weather				
X_1	time since 2cm precipitation	days	0.09	-0.42*[1]
X_2	precipitation since 1 January	cm	-0.08	0.03
X_3	precipitation since 1 October	cm	-0.03	0.38*
X_{13}	windspeed at 0.5m	m/min	0.47**	-0.02
X_{14}	windspeed at 2.0m	m/min	0.56**	0.04
X_{15}	solar intensity	W/m^2	0.16	0.51**
X_{28}	air temperature at ignition	°C	0.31**	0.53**
X_{29}	relative humidity at ignition	%	-0.39**	-0.56**
Fuel				
X_4	load, standing litter	g/m^2	0.16	0.24
X_5	load, green	g/m^2	-0.10	0.31
X_6	load, down litter	g/m^2	0.10	-0.38*
X_{32}	load, total	g/m^2	0.12	-0.03
X_7	moisture content, standing litter	%	-0.25*	-0.69**
X_8	moisture content, green	%	-0.28*	-0.09
X_9	moisture content, down litter	%	-0.18	-0.53**
X_{33}	moisture content, weighted total	%	-0.42**	-0.06
X_{10}	depth fuel bed	cm	0.22	0.55**
X_{11}	ratio green/standing litter	fraction	-0.24	0.06
X_{12}	ratio green/standing plus down litter	fraction	-0.02	0.27
X_{16}	ash content, standing litter	%	-0.15	-0.13
X_{17}	ash content, green	%	-0.16	-0.60**
X_{18}	ash content, down litter	%	0.03	0.39*
X_{19}	phosphorus content, standing litter	%	-0.07	-0.30
X_{20}	phosphorus content, green	%	-0.03	-0.38*
X_{21}	phosphorus content, down litter	%	0.09	0.23
X_{22}	silica content, standing litter	%	-0.21	-0.41*
X_{23}	silica content, green	%	-0.21	-0.45**
X_{24}	silica content, down litter	%	-0.01	0.33
X_{25}	low heat content, standing litter	kJ/kg	0.02	0.04
X_{26}	low heat content, green	kJ/kg	0.22	0.20
X_{27}	low heat content, down litter	kJ/kg	0.01	-0.39*
X_{30}	ratio, particle surface area/volume	cm^2/cm^3	-0.24*	-0.62**
X_{31}	packing ratio	---	0.18	0.61**

[1] Indicates significance by * at P=.05 and ** at P=.01.

Records (NOAA 1981-1983) supplemented with on-site gages and records.

Fuel moisture was obtained from subsamples of fuel load quadrat samples that were weighed in the field immediately after clipping, oven-dried at 60°C to constant weight, then reweighed. Fuel bed depth on each fire was the average of fifteen measurements taken adjacent to the rate of spread markers, and was therefore the average maximum depth of leaf material. Occasional taller seed stalks were ignored because they do not contribute to fire spread (Sneeuwjagt and Frandsen 1977, Wilson, pers. comm. 1981). Ratios of green fuel load/standing litter fuel load, and green fuel load/total litter fuel load were also determined from fuel load samples. Other fuel variables used were surface area/volume ratios (Clark and Wright 1981) and packing ratios calculated from oven-dry bulk density/ovendry particle density (Rothermel 1972).

Chemical properties for fuel load components were determined using standard laboratory techniques. Phosphorus, silica, and ash content (AOAC 1980) were completed in addition to low heat contents. During 1981, each fuel component on each fire was chemically analyzed. During 1982 and 1983 three or more samples from each fuel component in each grass species were randomly selected and analyzed to verify the 1981 results.

Results and Discussion

Fireline intensities and rates of spread were highly correlated ($r=0.92$ for headfires and 0.96 for backfires) because rate of spread was the dominant variable in the calculation of fireline intensity. Weighted low heat contents varied within ± 6% of 16708 kJ/kg, and total

fuel loads varied 8-fold (975 to 8939 kg/ha). However, rates of spread varied 277-fold [0.2 to 55.3 m/min (0.01 to 3.32 km/hr)]. Alexander (1982) stated that low heats of combustion generally vary over a narrow range of about 10% and fuel load consumption over about 10-fold. The variation in rates of spread measured in this study is considerably larger than the 100-fold range suggested by Alexander for forest fires. Low heat contents measured on these grassland fuels were below the value of 18,700 kJ/kg suggested by Alexander.

When all variables were used in headfire analyses, the amount of accounted variation was good for individual species but not for all species combined (Table 3.2). The minimum total fuel loads in successful fires were 975 kg/ha in buffalograss, 2791 kg/ha in tobosagrass, and 3308 kg/ha in weeping lovegrass. Although fine fuel loads of 340 kg/ha will carry wildfires, a minimum of 670 to 1120 kg/ha is necessary to conduct prescribed fires in grasslands (Wright and Bailey 1982). Since many of these fires were conducted outside of weather limits considered safe for prescribed burning in west Texas (Wright and Bailey 1980), the minimum fuel loads for safe prescribed burning may be larger than those suggested by Wright and Bailey (1982). Because the minimum fuel loads on successful backfires were also large (3991 and 3892 kg/ha for tobosagrass and weeping lovegrass, respectively), it is likely that fuel load thresholds for these species were not determined in this study.

Rates of spread on successful headfires ranged between 0.08 and 1.2 km/hr for buffalograss, 0.03 and 3.32 km/hr for tobosagrass, and 0.04 and 3.04 km/hr for weeping lovegrass. Median values were 25- to

40-fold greater in headfires than in backfires.

Regression equations for successful backfires (Table 3.3) accounted for more variation than equations for headfires. In all equations some combination of fuel and weather variables were used. The proportion of green fuel was important with weeping lovegrass but not tobosagrass; this may be due to the nature of the green fuel. The green fuel component in tobosagrass was predominantly annual forbs that were closer to the soil surface and more uniformly dispersed, while green fuel in weeping lovegrass was taller and more concentrated new growth on bunchgrass plants.

Packing ratios entered the model which combined all successful tobosagrass and weeping lovegrass backfires. Packing ratio incorporates surface area/volume ratio, fuel bed depth, and fuel load, and thus varied little within species but greatly between species. Also, packing ratios for these two species were nearly optimum (Rothermel 1982 equation #37), and with the relatively large and uniform fuel loads provided fuel ideally suited to combustion.

Rate of spread analyses were also conducted with the independent variables restricted to five that are easily measured. These variables included air temperature and relative humidity, windspeed at 2 m, total fuel load, and total fuel moisture. Regression models for rate of headfire spread (Table 3.4) varied in accountability from 91% for buffalograss to 29% in weeping lovegrass, and an overall variation of 46%. The high value obtained for buffalograss, although significant (P=0.05), was probably based on twoo few observations to be meaningful.

Rate of spread regression models for backfires, based on five

Table 3.3 Rate of spread (m/min) models for successful backfires in two west Texas grass species.

Species	Model[1]	N	R^2	SE
Tobosagrass	$Y = 1.56 + 0.05X_{17} + 0.03X_{28} - 0.01X_{6} - 8.21X_{20} - 0.01X_{33}$	16	0.90	0.10
Weeping lovegrass	$Y = 0.67 + 0.01X_{15} + 0.08X_{33} - 0.01X_{6} - 4.89X_{11} - 0.01X_{29}$	12	0.94	0.20
Both species	$Y = 0.64 + 0.01X_{5} + 0.01X_{13} + 191.20X_{31} - 4.26X_{11} - 0.02X_{29}$	28	0.77	0.27

[1] X_5 = green fuel load (g/m^2), X_6 = down litter fuel load (g/m^2), X_{11} = ratio green fuel/standing litter (fraction), X_{13} = windspeed at 0.5 m (m/min), X_{15} = solar intensity (W/m^2), X_{17} = green fuel ash content (%), X_{20} = phosphorus content of green fuel (%), X_{28} = air temperature at ignition (°C), X_{29} = relative humidity at ignition (%), X_{31} = packing ratio (g/cm^3 of fuel array/g/cm^3 of particles), and X_{33} = total fuel moisture content (%).

Table 3.4. Rate of spread (m/min) models (P=.05) for successful headfires in three west Texas grasses, restricted to five commonly measured independent variables.

Species	Model[1]	N	R^2	SE
Buffalograss	$Y = 1.39 - 0.03X_{32} + 0.04X_{14}$	7	0.91	3.60
Tobosagrass	$Y = -0.57 + 0.01X_{32} - 0.12X_{33} + 0.05X_{14} - 0.06X_{28} - 0.10X_{29}$	29	0.70	7.65
Weeping lovegrass	$Y = 20.29 + 0.02X_{32} - 0.79X_{33}$	24	0.29	11.66
All Species	$Y = 6.01 + 0.01X_{32} - 0.35X_{33} + 0.04X_{14} + 0.02X_{28} - 0.04X_{29}$	60	0.46	9.59

[1] X_{14} = windspeed at 2 m (m/min), X_{28} = air temperature at ignition (°C), X_{29} = relative humidity (%), X_{32} = total fuel load (g/m^2), and X_{33} = total fuel moisture content (%).

variables, were similar (Table 3.5). All backfires attempted in buffalograss failed. In the weeping lovegrass model, all five variables were required to account for 92% of the variation. An overall model for tobosagrass and weeping lovegrass, based on these five variables, was a significant but poor (R^2=0.41) predictor of rate of backfire spread.

Summary and Conclusions

Sixty successful test headfires in three grassland fuel types and 30 successful backfires in two fuel types were conducted over a three year period, 1981-1983. Thirty-three weather and fuel variables were subjected to stepwise multiple regression to determine if two dependent variables, rate of fire spread and fireline intensity, could be predicted. Measured rate of fire spread and calculated fireline intensity were highly correlated due to the large influence of spread rate, the most variable factor, on fireline intensity.

Rate of spread, based on a model for all headfires, was proportional to down litter fuel load and windspeed at 2.0 m, and inversely proportional to green fuel moisture content, ratio of green fuel load/standing litter fuel load, and relative humidity. This model suggested that a spring headfire in uniform, warm season grasses conducted prior to plant growth initiation and with 10 km/hr windspeed and 25% relative humidity, will move about 1 km/hr.

Rate of spread, based on a model for all backfires, was proportional to the green fuel load, windspeed at 0.5 m, and the packing ratio, and inversely proportional to the proportion of green fuel and relative humidity. This model suggested that in the absence of green

Table 3.5. Rate of spread (m/min) models (P=.05) for successful backfires in two west Texas grasses, restricted to five commonly measured independent variables.

Species				
Tobosagrass	$Y = 0.76 - 0.01X_{33} - 0.01X_{14} + 0.02X_{28} - 0.01X_{29}$	16	0.55	0.21
Weeping lovegrass	$Y = 0.42 + 0.01X_{32} + 0.05X_{33} - 0.01X_{14} + 0.01X_{28} - 0.01X_{29}$	12	0.92	0.22
All species	$Y = 0.88 + 0.01X_{32} - 0.01X_{33} - 0.01X_{14} + 0.02X_{28} - 0.01X_{29}$	28	0.41	0.44

[1] X_{14} = windspeed at 2 m (m/min), X_{28} = air temperature at ignition (°C), X_{29} = relative humidity (%), X_{32} = total fuel load (g/m^2), and X_{33} = total fuel moisture content (%).

fuel and with low windspeed, backfires moved about the same rate as headfires. However, as the fuel load and windspeed increased, headfires moved faster.

The fastest headfire in tobosagrass (3.32 km/hr) occurred with air temperature 30°C, relative humidity 20%, and a 2.0 m average windspeed of 27 km/hr. The fastest weeping lovegrass headfire (3.4 km/hr) occurred with air temperature 31°C, relative humidity 14%, and 2.0 m average windspeed 45 km/hr. Wright and Bailey (1982) stated that prescribed fires on southern Great Plains grasslands should not be conducted with air temperature above 27°C, relative humidity below 20%, or wind gusting greater than 32 km/hr. If the guidelines of Wright and Bailey are adhered to, the maximum rates of headfire spread in these grassland fuels should not exceed 3 km/hr. This is slow enough that grassland fires can be manipulated with experienced and properly equipped fire crews.

LITERATURE CITED

Alexander, M. E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60:349-357.

Anonymous. 1959. Belt weather kit. Fire Contr. Notes 20(4):122-123.

AOAC. 1980. Official methods of analysis. Thirteenth ed. Sec. 3.005: sand and silica. Sec. 3.062: phosphorus. Assoc. Official Anal. Chem. Washington, D.C.

Britton, C. M., B. L. Karr, and F. A. Sneva. 1977. A method for measuring rate of fire spread. J. Range Manage. 30;395-397.

Byram, G. M. 1959. Combustion of forest fuels, p. 61-89. In K. P. Davis (ed). Forest fire control and use. McGraw Hill, NY.

Clark, R. G., and H. A. Wright. 1981. Surface area/volume ratios for three Texas grasses. Noxious Brush and Weed Control Highlights 12:19. Texas Tech Univ., Lubbock.

Clark, R. G., A. A. Steuter, and C. M. Britton. 1981. An inexpensive anemometer frame. Fire Manage. Notes 42(3):13-14.

Duke, C.S., and J. B. Frantz. 1961. 6000 miles of fence: life on the XIT Ranch of Texas. Univ. Texas Press, Austin. 231p.

Haley, J. E. 1953. The XIT Ranch of Texas and the early days of the Llano Estacado. Reprint ed. Univ. Oklahoma Press, Norman. 258p.

LI-COR. n.d. Instruction manual for LI-185 Quantum/Radiometer/Photometer. Lambda Instruments Corp., Lincoln, N. 4p.

NOAA. 1981-1983. Monthly climatological data summaries, Texas. Vol. 86-88. Nat. Oceanogr. and Atmos. Admin., Nat. Climatic Center, Asheville, NC.

Pyne, S. J. 1982. Fire in America: a cultural history of wildland and rural fire. Princeton Univ. Press, Princeton, NJ. 654p.

Ray, A. A. (ed). 1982. SAS user's guide: statistics. SAS Institute, Cary, NC. 584p.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. U.S. Dep. Agr. For. Serv. Res. Pap. INT-115. Intermt. For. and Range Exp. Sta., Ogden. 40p.

Smeins, F. E. 1980. Natural role of fire on the Edwards Plateau, p. 4-16. In L. D. White (ed). Proc. Symp. on prescribed range burning in the Edwards Plateau of Texas. Texas Agric. Ext. Serv.,

College Station.

Sneeuwjagt, R. J., and W. H. Frandsen. 1977. Behavior of experimental grass fires vs. predictions based on Rothermel's fire model. Can. J. For. Res. 7:357-367.

Wilson, R. A., Jr. 1981. Personal communication, March, 1981. Research physical scientist, Northern Forest Fire Laboratory, U.S. Forest Service, Missoula, MT.

Wright, H. A. 1978. Use of fire to manage grasslands of the Great Plains: central and southern Great Plains. Proc. First Internat. Grassland Congr. p. 694-696.

Wright, H. A., and A. W. Bailey. 1980. Fire ecology and prescribed burning in the Great Plains--a research review. U.S. Dep. Agr. For. Serv. Gen. Tech. Rep. INT-77. Intermt. For. and Range Exp. Sta., Ogden. 60p.

Wright, H. A., and A. W. Bailey. 1982. Fire ecology: United States and southern Canada. John Wiley & Sons, NY. 501p.

CHAPTER IV

RELATIONSHIP BETWEEN FLAME LENGTH AND FIRELINE INTENSITY IN GRASSLAND FUELS

Fireline intensity (I) is the rate of energy release from a flaming fireline of unit length, expressed in power units of kW/m (Byram 1959, Alexander 1982). Although its value is debated (Tangren 1976, Van Wagner 1977), It is probably the most widely used descriptor of fire behavior (Alexander 1982). It is usually determined according to I=HWR, where H=low heat of combustion content of available fuel in kJ/kg, W=mass of available fuel in kg/m^2, and R=rate of spread or advance of the fire front in m/sec.

Fireline intensity is a descriptor of fire behavior that is useful in fire control (Rothermel 1972, Cheney 1981) and in predicting some fire effects (Van Wagner 1973, 1983, Norum 1974. 1976, Stocks and Alexander 1980, DeBano 1981) but not others (Roberts 1983). Some researchers (Byram 1959, Thomas 1963, Nelson 1980, Johnson 1983) have determined or used exponential relationships between flame length (F) and fireline intensity (I) of the form $I=kF^x$. These reports indicate that fireline intensity is proportional to flame length but that the exponent may vary about the square of flame length.

The generally accepted relationship is $258F^{2.17}$ kW/m (Rothermel and Deeming 1980). If the relationship is firmly established it provides a reliable method of estimating fireline intensity that is easier than obtaining the data needed to calculate fireline intensity. Because flame length may be the fire descriptor that is most useful for estimating or predicting top kill of shrubs or trees in prescribed

Table 4.1. Summary of test fires conducted during spring months, 1981 through 1983.

Species	Firetype	No. Attempted	No. Successful	No. Failures
Buffalograss	Headfire	14	8	6
	Backfire	5	0	5
Tobosagrass	Headfire	31	29	2
	Backfire	24	16	8
Weeping lovegrass	Headfire	25	24	1
	Backfire	19	12	7
Mixed grass	Headfire	2	2	0
	Backfire	3	2	1
Total	Headfire	72	63	9
	Backfire	51	30	21

fires, confirmation of the relationship between flame length and fireline intensity would also allow estimation of flame length if fireline intensity was previously (Rothermel 1972, Lindenmuth and Davis 1973, Hough and Albini 1978) predicted. The purpose of this study was to establish the relationship between fireline intensity and flame length for headfires and backfires in grassland fuels.

Methods

A total of 72 headfires and 51 backfires were attempted during the spring months of 1981 through 1983. Sixty-three headfires and 30 backfires were successful (Table 4.1). Most of the test fires were conducted in three grass species on several sites (see Chapter II) in west Texas: buffalograss (Buchloe dactyloides), a short, finely-divided stoloniferous grass, tobosagrass (Hilaria mutica), a mid-height, coarse rhizomatous grass, and weeping lovegrass (Eragrostis curvula), a tall, fine-leaved, introduced bunchgrass that is widely seeded on sandy sites in the southwestern United States. Five fires were conducted on mixed grass sites that contained primarily silver bluestem (Bothriochloa saccharoides), sideoats grama (Bouteloua curtipendula), and tobosagrass. Four successful fires in weeping lovegrass were not used in the analysis due to camera malfunction.

All test fire plots were 20 m or longer in buffalograss and 30 m or longer for all other fires. Fires were conducted as line headfires or backfires, at least 12 m wide, under a wide range of weather and fuel condictions (see Chapter II), including air temperature from -3 to 33°C, relative humidity from 11 to 97%, windspeed from 4 to 53 km/hr,

total fuel load from 975 to 3939 kg/ha, and total fuel moisture content from 7 to 181%.

To estimate flame length, at least four photographs on high speed infrared black and white film (Britton et al. 1977) were taken perpendicular to direction of fire spread but seven to ten photographs were used on most fires. Distance between, and dimensions of, four markers installed in each fire were measured to the nearest 0.5 cm in the field and to the nearest 0.01 cm on the photographs. A slight (3 5o 5%) camera parallax error was ignored because rate of spread photographs were taken only on the central 15 m of fire run. At least 5 m of fire run was allowed prior to the first photograph to establish a steady state advance rate. Initial fire photographs for each species were examined for evidence of sustained acceleration (Cheney 1981) to ensure that steady state conditions had been achieved.

Flame lengths were determined from seven to ten measurements on the photographs from each fire. The single flame length value used from each fire was the average longest flame, ignoring occasional gas flashes.

Fireline intensities were determined according to I=HWR (see Chapter III). The relationship between fireline intensity and flame length was determined using a nonlinear (NLIN) procedure to produce a weighted least-squares estimate of the parameters of the model (Ray 1982). The model used assumed that the relationship was of the form $I=kF^{x}$. Also, thirty-three independent fuel and weather variables (see Chapter II) were subjected to stepwise multiple regression (Ray 1982) to determine if the dependent variable, flame length, could be predicted.

Results and Discussion

Headfires

The relationship between flame length and fireline intensity was different for each species (Table 4.2). The relationship was constant for buffalograss, the shortest grass studied. Fireline intensity was slightly exponential with flame length for weeping lovegrass, the tallest species examined, and approached the commonly accepted exponent of 2.17 only with tobosagrass fires. When sixty-one successful headfires were combined, fireline intensity was essentially proportional to flame length, although only 64% of the variation in intensity was explained by this model. The asymptotic standard error of estimate for the exponent was 0.20.

Prediction of flame length of headfires was also variable. When all independent variables were used, reasonably good success was obtained for buffalograss and weeping lovegrass headfires (Table 4.3). A five-variable model for all headfires improved accountability to 69%:

$$F = 8.56 + 0.01X_{TIM} - 2.37X_{G/SL} - 0.01X_{DHL} - 0.01X_{RH} - 0.02X_{S/V}$$

where X_{TIM} = time since 20 mm precipitation event occurred (days), $X_{G/SL}$ = green fuel load/standing litter fuel load ratio (fraction), X_{DHL} = low heat of combustion content of down litter (kJ/kg), X_{RH} = relative humidity (%), and $X_{S/V}$ = surface area/volume ratio of fuel particles (cm^2/cm^3). These models, however, used inputs that are difficult or expensive to obtain and are therefore considered impractical for general field use.

An attempt was made to predict flame length based on five commonly measured fuel and weather variables including total fuel load,

Table 4.2. Relationship between fireline intensity and flame length on grassland fires in west Texas.[1]

Species	Firetype	Model	N	R^2
Buffalograss	Headfire	$I = 280.85F^{-0.0035}$	8	0.59
	Backfire[2]	---	--	----
Tobosagrass	Headfire	$I = 1326.19F^{2.0201}$	29	0.75
	Backfire	$I = 132.08F^{0.6219}$	16	0.92
Weeping lovegrass	Headfire	$I = 1191.11F^{1.1227}$	22	0.65
	Backfire	$I = 166.30F^{-0.0094}$	10	0.89
All species[3]	Headfire	$I = 1488.69F^{1.0066}$	61	0.64
	Backfire	$I = 147.19F^{0.5730}$	28	0.86

[1] I = fireline intensity in kW/m and F = flame length in m.

[2] No buffalograss backfires were successful.

[3] Includes 2 headfires and 2 backfires conducted in mixed grass.

Table 4.3. Flame length (m) regression models for headfires in three west Texas grass species.

Species	Model[1]	N	R^2	SE
Buffalograss	$Y = -0.30 + 1.91X_{11} + 0.05X_{17} - 0.09X_{10}$	8	0.99	0.02
Tobosagrass	$Y = 0.57 + 1.25X_{11} + 0.04X_{18} + 0.01X_{29}$	29	0.47	0.34
Weeping lovegrass	$Y = 2.92 + 0.01X_{1} - 4.49X_{11} - 0.02X_{29}$	22	0.78	0.50
All species[2]	$Y = 4.76 - 0.01X_{5} - 0.01X_{29} - 0.02X_{30}$	61	0.57	0.61

[1] X_1 = time since 20 mm precipitation event (days), X_5 = green fuel load (g/m^2), X_{10} = fuel bed depth (cm), X_{11} = ratio green fuel/standing litter (fraction), X_{17} = green fuel ash content (%), X_{18} = down litter ash content (%), X_{29} = relative humidity at ignition (%), X_{30} = fuel particle surface area/volume ratio (cm^2/cm^3).

[2] Includes two successful headfires on mixed grass sites.

total fuel moisture content, air temperature, relative humidity, and windspeed at 2.0 m above the soil surface. When the flame length routine was restricted to these variables only buffalograss flame length could be successfully predicted. Combining sixty-one headfires resulted in a significant (P=0.05) equation but low coefficient of determination of 0.43. Therefore the use of these variables to predict flame length was not considered adequate for field use.

Backfires

Backfires characteristically have shorter flame lengths and move slower than headfires. This was evident in the magnitude of both the exponent and constant when nonlinear relationships between fireline intensity and flame length of headfires and backfires were compared (Table 4.2). As with headfires, the largest exponent occurred on tobosagrass backfires, but was reduced 3-fold. The exponent from weeping lovegrass data analysis was near zero, suggesting that on these fires the relationship between fireline intensity and flame length was essentially linear. When data from twenty-eight successful backfires were combined the model accounted for 86% of the variation in fireline intensity.

Prediction of backfire flame length from thirty-three fuel and weather variables resulted in models that accounted for 85 and 91% of the variation in flame length for tobosagrass and weeping lovegrass, respectively (Table 4.4). A five-variable model improved the coefficient to 0.80:

$$F = 1.81 + 0.01X_{PPT} - 0.01X_{GFL} - 0.01X_{LFM} - 0.01X_{WS2} - 0.02X_{DLA}$$

Table 4.4. Flame length (m) regression models for backfires in two west Texas grass species.

Species				
Tobosagrass	$Y = 2.68 + 0.06X_{18} - 5.28X_{11} - 13.09X_{20}$	16	0.85	0.14
Weeping lovegrass	$Y = -0.35 + 0.25X_{17} + 0.09X_{23} - 0.01X_{14}$	10	0.91	0.12
All species[2]	$Y = -3.83 + 0.01X_{2} + 0.01X_{25} - 0.01X_{6}$	28	0.59	0.25

[1] X_2 = total precipitation since 1 January (mm), X_6 = down litter fuel load (g/m^2), X_{11} = ratio green fuel/standing litter (fraction), X_{14} - windspeed at 2.0 m (m/min), X_{17} = green fuel ash content (%), X_{18} = down litter ash content (%), X_{20} = green fuel phosphorus content (%), X_{23} = green fuel silica

2 Includes two successful backfires on mixed grass sites.

where X_{PPT} = total precipitation since 1 January (mm), X_{GFL} = green fuel load (g/m^2), X_{LFM} = standing litter fuel moisture content (%), X_{WS2} = wind speed at 2.0 m above the soil surface (m/min), and X_{DLA} = down litter ash content (%). The usefulness of this model is limited however, because data used in these models are difficult to obtain.

Summary and Conclusions

Data from 61 headfires and 28 backfires were used in a nonlinear statistical analysis to establish the relationship between fireline intensity and flame length. Stepwise multiple regression was then used to determine if the dependent variable, flame length, could be predicted from a set of thirty-three measured or calculated variables or from a restricted set of five variables.

The relationship between fireline intensity and flame length in this study differed from that reported in the literature, was different between headfires and backfires, and was different among three grassland fuel species. Based in these data, flame length is not a good, nor consistent, estimator of fireline intensity. Further, flame length is a highly variable dimension of fire behavior and is difficult to predict with commonly measured fuel and weather variables, although reasonably good predictions of flame length can be made from fuel and weather variables that are not routinely measured on prescribed fires. Fireline intensity should be calculated according to I=HWR, and not estimated from flame length, for the most precise data.

LITERATURE CITED

Alexander, M. E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60:349-357.

Britton, C. M., B. L. Karr, and F. A. Sneve. 1977. A technique for measuring rate of fire spread. J. Range Manage. 30:395-397.

Byram, G. M. 1959. Combustion of forest fuels, p. 61-89. In K. P. Davis (ed). Forest Fire: control and use. McGraw-Hill, NY.

Cheney, N. P. 1981. Fire behaviour, p. 151-175. In A. M. Gill, R. H. Groves, and I. R. Nobel (eds). Fire and the Australian biota. Australian Acad. Sci., Canberra.

DeBano, L. F. 1981. Water repellent soils: a state-of-the-art. U.S. Dep. Agr. For. Serv. Gen. Tech. Rep. PSW-46. Pacific Southw. For. and Range Exp. Sta., Berkeley. 21p.

Hough, W. A., and F. A. Albini. 1978. Predicting fire behavior in palmetto-gallberry fuel complexes. U.S. Dep. Agr. For. Serv. Res. Pap. SE-174. Southeast. For. Exp. Sta., Asheville. 44p.

Johnson, V. J. 1983. The dilema of flame length and intensity. Fire Manage. Notes 43(4):3-7.

Lindenmuth, A. W. Jr., and J. R. Davis. 1973. Predicting fire spread in Arizona's oak chaparral. U.S. Dep. Agr. For. Serv. Res. Pap. RM-101. Rocky Mt. For. and Range Exp. Sta., Fort Collins. 11p.

Nelson, R. M., Jr. 1980. Flame characteristics for fires in southern fuels. U.S. Dep. For. Serv. Res. Pap. SE-205. Southeast. For. Exp. Sta., Asheville. 14p.

Norum, R. A. 1974. Smoke column height related to fire intensity. U.S. Dep. Agr. For. Serv. Res. Pap. INT-157. Intermt. For. and Range Exp. Sta., Ogden. 7p.

Norum, R. A. 1976. Fire-intensity-fuel reduction relationships associated with understory burning in larch/Douglas-fir stands. Tall Timbers Fire Ecol. Conf. 14:559-572.

Ray, A. A. (ed). 1982. SAS user's guide: statistics. SAS Institute, Cary, NC. 584p.

Roberts, F. H. 1983. Effect of fireline intensity on grass yield in west Texas. M.S. Thesis. Texas Tech Univ., Lubbock. 86p.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. U.S. Dep. Agr. For. Serv. Res. Pap.

INT-115. Intermt. For. and Range Exp. Sta., Ogden. 40p.

Rothermel, R. C., and J. E. Deeming. 1980. Measuring and interpreting fire behavior for correlation with fire effects. U.S. Dep. Agr. For. Serv. Gen. Tech. Rep. INT-93. Intermt. For. and Range Exp. Sta., Ogden. 4p.

Stocks, B. J., and M. E. Alexander. 1980. Forest fire behaviour and effects research in northern Ontario: a field oriented program, p. 18-24. In R. E. Martin, et al. (eds). Proc. Sixth conf. on fire and forest meterology. Soc. Amer. Foresters, Washington, D.C.

Tangren, C. D. 1976. The trouble with fire intensity. Fire Technol. 12:261-265.

Thomas, P. H. 1963. The size of flames from natural fires. Proc. Symp. on combustion 9:844-859.

Van Wagner, C. E. 1973. Height of crown scorch in forest fires. Can. J. For. Res. 3:373-378.

Van Wagner, C. E. 1977. Readers' forum. Fire Technol. 13:349-350.

Van Wagner, C. E. 1983. Fire behaviour in northern conifer forests and shrublands, p. 65-80. In R. W. Wein and D. A. MacLean (eds). The role of fire in northern circumpolar ecosystems. John Wiley & Sons, NY.

APPENDIX

Table A.1. Range of values used to generate rate of spread and fireline intensity models.

Variable[2]	Headfires[1]				Backfires[1]			UNITS
	BG	TG	WG	ALL	TG	WG	ALL	
X_1	4-155	5-172	2-159	2-172	5-172	2-58	2-172	cm
X_2	3.15-14.88	3.12-15.49	2.03-13.06	2.03-15.49	3.12-15.49	4.98-13.06	3.12-15.49	cm
X_3	10.08-31.11	10.08-16.81	3.89-20.42	3.89-31.11	10.08-16.81	3.89-20.42	3.89-20.42	cm
X_5	18.8-26.7	6.3-138.7	0-113.3	0-138.7	5.0-138.7	0-113.3	0-138.7	g/m^2
X_6	16.0-48.0	77.2-446.9	40.0-379.2	16.0-446.9	77.2-368.0	40.0-154.0	40.0-368.0	g/m^2
X_8	123.4-175.0	118.5-452.6	0-236.7	0-236.7	118.5-452.6	0-236.7	0-452.6	%
X_{10}	4.2-5.9	19.4-30.1	36.6-56.8	4.2-80.1	18.5-30.0	36.6-54.7	18.5-54.7	cm
X_{11}	0.15-0.45	0.02-0.35	0-0.33	0-0.45	0.01-0.35	0-0.21	0-0.35	fraction
X_{12}	0.13-0.30	0.02-0.28	0-0.18	0-0.30	0.01-0.18	0-016	0-018	fraction
X_{13}	72.0-441.9	76.8-382.8	46.4-339.7	46.4-441.9	51.6-431.3	109.8-334.8	51.6-431.3	m/min
X_{14}	93.6-534.8	101.4-654.2	104.8-654.2	93.6-885.2	62.4-831.5	268.2-598.7	62.4-831.5	m/min
X_{15}	20-905	44-940	100-950	20-950	60-920	130-910	60-920	W/m^2
X_{20}	0.13-0.14	0.15-0.24	0.08-0.24	0.08-0.24	0.08-0.24	0.15-0.24	0.06-0.24	%
X_{25}	15363-18457	16309-17831	16441-18434	15363-18457	16481-17344	16441-18344	16441-18344	kJ/kg
X_{28}	8.0-31.1	6.7-32.8	-2.8-30.3	-2.8-32.8	4.7-32.5	0.8-30.3	0.8-32.5	°C
X_{29}	14-44	11-97	12-93	11-97	11-77	12-63	11-77	%
X_{31}	---	---	---	.00346-.00555	---	---	.00346-.00555	---
X_{32}	97.5-240.1	279.1-893.9	330.8-834.0	97.5-893.9	399.1-893.9	389.2-834.0	389.2-893.9	g/m^2
X_{33}	24.09-51.23	14.58-57.01	7.30-35.04	7.30-57.01	15.5257.09	7.30-35.04	7.30-57.09	%

[1] BG = buffalograss, TG = tobosagrass, WG = weeping lovegrass, and ALL = all species combined.

[2] See Table 2.2 for description of variables.

Table A.2. Data from 123 test fires conducted in west Texas. Grassland fuels include buffalograss (BG), tobosagrass (TG), weeping lovegrass (WG), and mixed grass (MG). Dependent (Y) variables on (1) success or failure, (2) fireline intensity (kW/m), (3) rate of fire spread (m/min), and (4) flame length (m). Independent (x) variables are described in Table 2.2

Obs.	Species	Year	Type	Succ. or Fail	Intensity (kW/m)	Rate of Spread (m/min)	Flame Length (m)	X_1
1	BG	81	Head	Succ.	68.6	1.4	0.37	4
2	BG	81	Head	Succ.	643.8	9.9	0.25	10
3	BG	81	Head	Succ.	128.9	2.0	0.17	10
4	BG	81	Head	Fail	0.0	0.0	0.00	12
5	BG	81	Back	Fail	0.0	0.0	0.00	10
6	BG	82	Head	Succ.	605.7	20.2	0.19	151
7	BG	82	Head	Succ.	354.5	10.7	0.19	151
8	BG	82	Head	Succ.	65.5	1.8	0.10	152
9	BG	82	Head	Succ.	109.6	3.5	0.37	155
10	BG	82	Head	Fail	0.0	0.0	0.00	152
11	BG	82	Head	Fail	0.0	0.0	0.00	155
12	BG	82	Head	Fail	0.0	0.0	0.00	155
13	BG	82	Head	Fail	0.0	0.0	0.00	155
14	BG	82	Head	Fail	0.0	0.0	0.00	173
15	BG	82	Head	Fail	0.0	0.0	0.00	173
16	BG	82	Back	Fail	0.0	0.0	0.00	151
17	BG	82	Back	Fail	0.0	0.0	0.00	152
18	BG	82	Back	Fail	0.0	0.0	0.00	155
19	BG	82	Back	Fail	0.0	0.0	0.00	173
20	TG	81	Head	Succ.	570.9	4.3	1.28	5
21	TG	81	Head	Succ.	6907.1	32.1	1.97	10
22	TG	81	Head	Succ.	560.6	3.1	0.56	11
23	TG	81	Head	Succ.	1022.7	4.2	1.21	11

Obs.	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
1	100.8	148.8	1120	220	480	25.6	133.4	20.4	5.9	0.20	0.14	4.32	5.62	20	15.1	17.5
2	100.8	148.8	1739	267	395	20.2	175.0	104.2	5.0	0.15	0.13	14.65	19.84	60	17.6	14.4
3	100.8	148.8	1739	267	395	20.2	175.0	104.2	5.8	0.15	0.13	13.21	20.99	150	17.6	14.4
4	100.8	148.8	1387	320	352	24.8	116.7	82.7	7.5	0.23	0.18	15.95	21.06	400	19.3	17.8
5	100.8	148.8	1739	267	395	20.2	175.0	104.2	5.8	0.15	0.13	12.06	16.06	280	17.6	14.4
6	31.5	294.1	617	198	160	1.0	123.4	1.0	5.3	0.32	0.26	26.51	32.09	760	13.1	9.1
7	31.5	294.1	713	203	160	1.0	123.4	1.0	4.9	0.29	0.23	24.08	25.31	905	13.1	9.1
8	31.5	294.1	717	188	265	7.7	134.7	3.2	5.0	0.26	0.19	5.85	7.73	440	13.1	9.1
9	48.5	311.1	530	238	276	12.4	134.7	4.0	4.2	0.45	0.30	7.02	9.81	810	13.1	9.1
10	31.5	294.1	717	188	265	7.9	134.7	3.2	5.0	0.26	0.19	4.50	5.89	370	13.1	9.1
11	48.5	311.1	754	245	160	14.8	134.7	3.2	4.0	0.33	0.27	10.39	12.87	80	13.1	9.1
12	48.5	311.1	806	236	160	14.2	134.7	3.1	4.1	0.29	0.24	6.22	8.64	400	13.1	9.1
13	48.5	311.1	1169	283	179	13.2	134.7	4.1	4.6	0.24	0.21	3.59	4.67	10	13.1	9.1
14	51.1	313.7	530	470	517	5.0	152.0	3.9	4.1	0.89	0.45	10.94	14.73	790	13.1	9.1
15	51.1	313.7	493	348	251	4.0	152.0	3.9	4.1	0.71	0.47	9.75	12.36	620	13.1	9.1
16	31.5	294.1	713	203	160	1.0	123.4	1.0	4.9	0.29	0.23	26.33	30.60	910	13.1	9.1
17	31.5	294.1	717	188	265	7.9	134.7	3.2	5.0	0.26	0.19	4.57	5.77	370	13.1	9.1
18	48.5	311.1	1169	283	179	13.2	274.7	4.1	4.6	0.24	0.21	5.48	7.06	950	13.1	9.1
19	51.1	313.7	478	438	509	5.0	152.0	3.9	4.1	0.92	0.44	10.00	13.86	900	13.1	9.1
20	100.8	148.8	2916	212	1472	17.7	198.2	7.3	26.3	0.07	0.05	4.61	6.08	730	13.7	13.1
21	100.8	148.8	3648	523	3072	16.1	288.9	21.5	20.6	0.14	0.08	18.68	24.23	640	10.5	11.2
22	100.8	148.8	3232	555	2912	4.5	310.2	13.5	22.8	0.17	0.09	17.35	22.32	650	11.1	15.2
23	100.8	148.8	3925	1387	3627	15.1	285.7	14.9	19.8	0.35	0.18	9.14	13.50	220	9.6	15.7

Obs.	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}	X_{31}	X_{32}	X_{33}
1	22.4	0.09	0.14	0.08	13.4	13.0	20.2	16027	14984	14593	8.0	32	221.3	0.00413	1820	37.3
2	33.0	0.09	0.13	0.08	16.5	10.7	30.0	15363	16249	12823	19.0	40	221.3	0.00413	2401	51.2
3	33.0	0.09	0.13	0.08	16.5	10.7	30.0	15363	16249	12823	18.0	42	221.3	0.00413	2401	51.2
4	25.2	0.08	0.12	0.07	17.5	14.3	22.7	14766	16375	13897	14.0	71	221.3	0.00413	2059	49.0
5	33.0	0.09	0.13	0.08	16.5	10.7	30.0	15363	16249	12823	19.0	40	221.3	0.00413	2401	51.2
6	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	29.4	18	221.3	0.00413	975	25.9
7	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	31.1	14	221.3	0.00413	1076	24.1
8	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	11.7	44	221.3	0.00413	1170	27.1
9	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	23.6	24	221.3	0.00413	1044	38.1
10	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	8.9	44	221.3	0.00413	1170	27.2
11	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	13.3	40	221.3	0.00413	1159	38.5
12	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	16.7	35	221.3	0.00413	1202	36.4
13	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	19.4	29	221.3	0.00413	1631	33.3
14	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	20.8	25	221.3	0.00413	1517	50.2
15	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	21.9	21	221.3	0.00413	1092	51.1
16	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	31.1	14	221.3	0.00413	1076	24.1
17	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	8.9	44	221.3	0.00413	1170	27.2
18	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	19.4	29	221.3	0.00413	1631	57.6
19	17.3	0.07	0.14	0.03	9.9	3.7	11.2	18457	16974	15448	18.3	25	221.3	0.00413	1425	49.8
20	15.5	0.06	0.15	0.08	12.5	8.2	13.7	16310	16928	15948	15.0	28	155.0	0.00346	4600	22.7
21	23.1	0.07	0.19	0.11	8.7	7.4	20.6	16309	17315	14225	26.0	27	155.0	0.00346	7243	38.1
22	23.4	0.07	0.19	0.09	10.4	13.0	21.3	17831	16547	14494	17.0	57	155.0	0.00346	6699	33.7
23	20.3	0.07	0.19	0.06	8.7	11.0	18.0	17344	16559	14253	14.0	75	155.0	0.00346	8939	57.0

Obs.	Species	Year	Type	Succ. or Fail	Intensity (kW/m)	Rate of Spread (m/min)	Flame Length (m)	X_1
24	TG	81	Head	Succ.	2131.8	9.0	1.21	27
25	TG	81	Head	Succ.	1031.9	6.4	0.65	28
26	TG	81	Head	Succ.	351.2	1.8	0.65	28
27	TG	81	Head	Fail	0.0	0.0	0.00	11
28	TG	81	Head	Fail	0.0	0.0	0.00	28
29	TG	81	Back	Succ.	190.0	1.2	1.68	5
30	TG	81	Back	Succ.	112.6	0.7	0.64	10
31	TG	81	Back	Succ.	54.9	0.2	0.40	11
32	TG	81	Back	Succ.	114.2	0.5	0.44	27
33	TG	81	Back	Fail	0.0	0.0	0.00	11
34	TG	81	Back	Fail	0.0	0.0	0.00	28
35	TG	81	Back	Fail	0.0	0.0	0.00	28
36	TG	82	Head	Succ.	2698.8	15.3	1.05	158
37	TG	82	Head	Succ.	5223.2	25.5	1.03	158
38	TG	82	Head	Succ.	4751.7	26.0	2.24	164
39	TG	82	Head	Succ.	1648.9	10.4	1.41	164
40	TG	82	Head	Succ.	2908.2	15.0	1.27	164
41	TG	82	Head	Succ.	3575.7	21.6	1.60	164
42	TG	82	Head	Succ.	85.4	0.5	0.62	165
43	TG	82	Head	Succ.	1083.2	6.2	1.07	165
44	TG	82	Head	Succ.	1424.0	10.6	1.61	165
45	TG	82	Head	Succ.	392.0	2.0	0.67	172
46	TG	82	Head	Succ.	591.4	3.1	1.04	172

Obs.	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
24	106.9	154.9	3573	672	4469	27.5	423.8	20.1	22.8	0.19	0.08	13.14	19.15	120	9.6	10.3
25	106.9	154.9	3040	608	2176	30.6	301.3	19.1	20.2	0.20	0.12	14.15	19.33	860	10.9	13.2
26	106.9	154.9	3467	523	3093	11.1	332.8	11.0	19.4	0.15	0.08	8.17	12.31	940	8.6	11.3
27	100.8	148.8	3232	555	2912	11.3	310.2	18.9	22.8	0.17	0.09	15.19	21.49	800	11.1	15.2
28	106.9	154.9	3040	608	2176	37.8	301.3	21.8	20.2	0.20	0.12	11.77	17.32	380	10.9	13.2
29	100.8	148.8	3488	192	1784	9.0	218.4	12.8	23.1	0.06	0.04	3.10	3.74	920	11.5	15.5
30	100.8	148.8	3264	395	2027	18.1	306.7	23.8	20.0	0.12	0.08	14.36	22.07	470	10.7	13.7
31	100.8	148.8	3925	1387	3627	15.3	285.7	14.9	19.8	0.35	0.18	5.44	8.14	80	9.6	15.7
32	106.9	154.9	4021	747	3680	20.6	293.0	17.4	18.5	0.19	0.10	15.91	23.62	60	11.3	11.4
33	100.8	148.8	3232	555	2912	11.3	310.2	18.9	22.8	0.17	0.09	12.92	18.29	390	11.1	15.2
34	106.9	154.9	3040	608	2176	37.8	301.3	21.8	20.2	0.20	0.12	12.38	18.72	250	10.9	13.2
35	106.9	154.9	3040	608	2176	37.5	301.3	21.1	20.2	0.20	0.12	14.76	20.27	860	10.9	13.2
36	31.2	134.9	3528	331	2178	13.7	118.5	6.2	30.3	0.09	0.06	8.81	15.41	370	9.8	12.2
37	31.2	134.9	4462	270	2293	12.6	118.5	6.2	29.1	0.06	0.04	15.35	22.64	280	9.8	12.2
38	31.2	134.9	3563	507	2219	16.0	118.5	6.2	28.4	0.14	0.09	15.77	26.16	330	9.8	12.2
39	31.2	134.9	3110	487	1887	15.8	118.5	6.0	25.5	0.16	0.10	11.96	19.68	610	9.8	12.2
40	31.2	134.9	3602	576	2475	10.5	118.5	6.0	28.3	0.16	0.10	12.10	18.76	745	9.8	12.2
41	31.2	134.9	2829	608	2213	9.8	118.5	5.9	28.7	0.22	0.12	11.67	16.85	820	9.8	12.2
42	31.2	134.9	3776	515	1765	17.1	118.5	6.9	26.3	0.14	0.09	5.36	9.50	150	9.8	12.2
43	31.2	134.9	3776	515	1765	17.1	118.5	6.9	26.3	0.14	0.09	5.43	9.66	235	9.8	12.2
44	31.2	134.9	2589	475	1549	10.6	118.5	6.2	27.5	0.18	0.12	9.69	14.70	800	9.8	12.2
45	31.2	134.9	4152	582	2102	20.4	258.0	16.4	28.9	0.14	0.09	7.71	12.51	44	9.8	12.2
46	31.2	134.9	4152	582	2102	24.1	258.0	16.2	28.9	0.14	0.09	5.05	8.17	150	9.8	12.2

Obs.	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}	X_{31}	X_{32}	X_{33}
24	17.9	0.06	0.18	0.08	8.9	6.9	16.4	17493	17361	15834	25.0	61	155.0	0.00346	8714	54.3
25	14.1	0.06	0.20	0.08	9.6	7.3	12.4	16919	19196	16632	29.0	54	155.0	0.00346	5824	54.6
26	12.3	0.05	0.16	0.06	7.7	5.0	12.8	17278	17582	17025	30.0	49	155.0	0.00346	7083	34.8
27	23.4	0.07	0.19	0.10	10.4	13.0	21.3	16731	16547	14494	11.0	70	155.0	0.00346	6699	39.4
28	14.1	0.06	0.20	0.08	9.6	7.3	12.4	16919	17196	16632	19.0	84	155.0	0.00346	5824	59.3
29	18.2	0.07	0.15	0.10	10.5	10.2	16.4	17290	17254	16154	16.0	26	155.0	0.00346	5464	17.6
30	14.2	0.06	0.19	0.08	10.2	9.5	12.4	17069	16221	13697	24.0	31	155.0	0.00346	5686	40.2
31	20.3	0.07	0.19	0.06	8.7	11.0	18.0	17344	16559	14253	13.0	77	155.0	0.00346	8939	57.1
32	11.4	0.07	0.18	0.06	10.4	6.2	9.9	16947	17354	16883	25.0	56	155.0	0.00346	8448	43.3
33	23.4	0.07	0.19	0.10	10.4	13.0	21.3	16731	16547	14494	12.0	71	155.0	0.00346	6699	39.4
34	14.1	0.06	0.20	0.08	9.6	7.3	12.4	16919	17196	16632	19.0	88	155.0	0.00346	5824	59.3
35	14.1	0.06	0.20	0.08	9.6	7.3	12.4	16919	17196	16632	27.0	56	155.0	0.00346	5824	58.9
36	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	19.4	34	155.0	0.00346	6037	16.7
37	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	21.7	33	155.0	0.00346	7025	14.6
38	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	20.8	28	155.0	0.00346	6289	20.8
39	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	21.7	26	155.0	0.00346	5484	21.5
40	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	23.9	21	155.0	0.00346	6653	18.2
41	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	26.9	20	155.0	0.00346	5650	20.0
42	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	9.4	40	155.0	0.00346	6056	22.8
43	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	11.9	30	155.0	0.00346	6056	22.8
44	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	19.4	19	155.0	0.00346	4613	20.2
45	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	6.7	97	155.0	0.00346	6836	39.4
46	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	8.9	80	155.0	0.00346	6836	41.6

Obs.	Species	Year	Type	Succ. or Fail	Intensity (kW/m)	Rate of Spread (m/min)	Flame Length (m)	X_1
47	TG	82	Head	Succ.	1273.8	6.5	0.49	172
48	TG	82	Head	Succ.	991.6	4.7	0.95	172
49	TG	82	Back	Succ.	107.8	0.7	0.70	158
50	TG	82	Back	Succ.	100.5	0.5	0.39	158
51	TG	82	Back	Succ.	61.2	0.4	0.41	164
52	TG	82	Back	Succ.	103.2	0.5	0.43	164
53	TG	82	Back	Succ.	129.5	0.8	0.62	164
54	TG	82	Back	Succ.	50.8	0.4	0.34	165
55	TG	82	Back	Succ.	41.2	0.2	0.40	172
56	TG	82	Back	Fail	0.0	0.0	0.00	164
57	TG	82	Back	Fail	0.0	0.0	0.00	165
58	TG	82	Back	Fail	0.0	0.0	0.00	172
59	TG	82	Back	Fail	0.0	0.0	0.00	172
60	TG	82	Back	Fail	0.0	0.0	0.00	172
61	TG	83	Head	Succ.	1596.6	19.5	1.32	53
62	TG	83	Head	Succ.	302.3	2.6	0.74	53
63	TG	83	Head	Succ.	558.2	4.8	1.12	53
64	TG	83	Head	Succ.	645.6	4.8	1.18	56
65	TG	83	Head	Succ.	438.0	3.6	1.15	56
66	TG	83	Head	Succ.	169.6	1.1	0.82	56
67	TG	83	Head	Succ.	4453.4	34.3	1.44	69
68	TG	83	Head	Succ.	8035.6	55.3	1.83	69
69	TG	83	Head	Succ.	1893.0	9.2	0.56	88

Obs.	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
47	31.2	134.9	3675	635	2576	20.0	220.6	16.1	27.9	0.17	0.10	7.51	12.26	210	9.8	12.2
48	31.2	134.9	5136	616	1835	16.2	220.6	15.6	30.1	0.12	0.09	7.26	12.01	210	9.8	12.2
49	31.2	134.9	3406	363	1621	15.6	118.5	6.2	30.0	0.11	0.07	8.45	14.50	300	9.8	12.2
50	31.2	134.9	3984	319	2040	12.2	118.5	5.9	28.6	0.08	0.05	11.77	18.14	160	9.8	12.2
51	31.2	134.9	3275	491	1563	16.0	118.5	6.1	29.0	0.15	0.10	18.65	22.16	560	9.8	12.2
52	31.2	134.9	3602	576	2475	10.5	118.5	6.0	28.3	0.16	0.10	12.39	19.74	910	9.8	12.2
53	31.2	134.9	2829	608	2213	9.8	118.5	5.9	28.7	0.22	0.12	12.62	20.03	770	9.8	12.2
54	31.2	134.9	2589	475	1549	10.6	118.5	6.2	27.5	0.18	0.12	10.29	15.47	555	9.8	12.2
55	31.2	134.9	4256	715	1995	16.2	220.6	15.6	29.0	0.17	0.11	7.08	10.96	690	9.8	12.2
56	31.2	134.9	2971	443	1446	16.1	118.5	6.1	28.1	0.15	0.10	21.85	31.66	240	9.8	12.2
57	31.2	134.9	3776	515	1765	17.1	118.5	6.9	26.3	0.14	0.09	5.36	9.50	150	9.8	12.2
58	31.2	134.9	4152	582	2102	20.4	258.0	16.4	28.9	0.14	0.09	7.24	11.98	49	9.8	12.2
59	31.2	134.9	4152	582	2102	24.1	258.0	16.2	28.9	0.14	0.09	7.30	12.10	205	9.8	12.2
60	31.2	134.9	3675	635	2576	20.0	220.6	16.1	27.9	0.17	0.10	7.82	11.96	158	9.8	12.2
61	68.3	155.4	1892	63	836	19.0	240.9	14.4	23.1	0.03	0.02	11.62	24.14	226	12.0	16.0
62	68.3	155.4	3061	158	772	20.9	240.9	13.9	24.7	0.05	0.04	12.38	14.48	255	12.0	16.0
63	68.3	155.4	3061	158	772	22.1	240.9	14.1	24.7	0.05	0.04	6.35	11.27	405	12.0	16.0
64	68.3	155.4	3199	80	1313	25.4	452.6	16.3	23.4	0.03	0.02	5.21	9.65	320	12.0	16.0
65	68.3	155.4	2932	188	1052	19.0	452.6	12.7	25.5	0.06	0.05	7.48	14.48	855	12.0	16.0
66	68.3	155.4	3569	87	1807	16.6	452.6	17.6	28.1	0.02	0.02	8.00	17.71	310	12.0	16.0
67	75.2	162.3	2662	261	1497	12.5	205.6	5.1	28.0	0.10	0.06	18.05	53.11	570	12.0	16.0
68	75.2	162.3	3233	315	1391	13.0	205.6	8.9	26.2	0.10	0.07	22.97	45.07	310	12.0	16.0
69	81.0	168.1	4073	459	2569	13.0	229.9	8.9	23.4	0.11	0.07	20.70	27.36	875	12.0	16.0

Obs.	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}	X_{31}	X_{32}	X_{33}
47	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	9.4	81	155.0	0.00346	6886	37.0
48	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	9.4	81	155.0	0.00346	7587	32.7
49	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	20.8	31	155.0	0.00346	5390	19.7
50	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	20.3	45	155.0	0.00346	6343	15.5
51	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	20.6	26	155.0	0.00346	5329	22.5
52	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	23.9	21	155.0	0.00346	6653	18.2
53	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	26.1	20	155.0	0.00346	5650	20.0
54	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	16.7	23	155.0	0.00346	4613	20.2
55	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	13.1	67	155.0	0.00346	6966	37.0
56	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	19.2	30	155.0	0.00346	4860	22.5
57	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	5.3	48	155.0	0.00346	6056	22.8
58	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	6.7	97	155.0	0.00346	6836	39.4
59	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	8.9	80	155.0	0.00346	6836	41.6
60	20.1	0.07	0.22	0.04	7.8	5.0	16.1	16481	16601	16559	8.9	80	155.0	0.00346	6886	37.0
61	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	17.5	46	155.0	0.00346	2791	22.6
62	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	22.8	31	155.0	0.00346	3991	28.3
63	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	22.8	32	155.0	0.00346	3991	29.2
64	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	7.2	66	155.0	0.00346	4592	30.2
65	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	11.7	57	155.0	0.00346	4172	37.0
66	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	14.2	51	155.0	0.00346	5463	23.9
67	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	32.8	11	155.0	0.00346	4420	21.4
68	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	31.1	14	155.0	0.00346	4939	24.1
69	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	27.5	17	155.0	0.00346	7101	25.5

Obs.	Species	Year	Type	Succ. or Fail	Intensity (kW/m)	Rate of Spread (m/min)	Flame Length (m)	X_1
70	TG	83	Back	Succ.	63.0	0.5	0.61	53
71	TG	83	Back	Succ.	60.2	0.5	0.46	53
72	TG	83	Back	Succ.	52.9	0.3	0.74	56
73	TG	83	Back	Succ.	124.8	1.0	0.55	69
74	TG	83	Back	Succ.	96.6	0.5	0.38	88
75	WG	81	Head	Succ.	2658.9	16.6	2.43	19
76	WG	81	Head	Succ.	5637.6	29.6	2.33	19
77	WG	81	Head	Succ.	1156.9	11.6	1.96	19
78	WG	81	Head	Succ.	2744.5	16.7	1.54	37
79	WG	81	Head	Succ.	2775.0	16.9	1.88	37
80	WG	81	Head	Succ.	1981.2	17.1	1.03	37
81	WG	81	Head	Succ.	859.1	7.4	1.30	37
82	WG	81	Back	Succ.	85.6	0.7	1.29	19
83	WG	81	Back	Succ.	154.6	0.9	0.93	37
84	WG	81	Back	Fail	0.0	0.0	0.00	37
85	WG	82	Head	Succ.	5568.6	34.5	3.70	126
86	WG	82	Head	Succ.	5823.9	45.2	4.19	126
87	WG	82	Head	Succ.	3406.0	24.4	2.06	149
88	WG	82	Head	Succ.	2823.0	26.6	4.10	159
89	WG	82	Head	Succ.	2045.9	16.3	2.47	2
90	WG	82	Head	Succ.	1278.3	10.2	1.85	2
91	WG	82	Head	Succ.	67.3	0.6	0.42	3
92	WG	82	Head	Succ.	190.5	1.6	0.68	3

Obs.	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
70	68.3	155.4	3040	137	1390	17.5	240.9	13.7	26.2	0.05	0.03	7.99	17.71	505	12.0	16.0
71	68.3	155.4	3061	158	772	22.3	240.9	14.0	24.7	0.05	0.04	6.91	12.88	419	12.0	16.0
72	68.3	155.4	4491	50	894	19.5	452.6	13.7	25.6	0.01	0.01	5.60	14.48	290	12.0	16.0
73	75.2	162.3	2662	261	1497	12.5	205.6	5.1	28.1	0.10	0.06	19.45	33.80	715	12.0	16.0
74	81.0	168.1	4037	459	2569	13.0	229.9	8.9	23.4	0.11	0.07	25.88	49.89	690	12.0	16.0
75	38.9	118.4	2716	444	2036	11.6	93.2	15.1	41.5	0.16	0.09	6.16	8.21	460	6.9	10.1
76	38.9	118.4	2084	252	3792	8.7	119.9	9.2	42.1	0.12	0.04	9.83	15.01	390	6.9	11.0
77	38.9	118.4	1572	296	1440	8.7	150.5	12.5	43.6	0.20	0.10	12.56	19.40	300	5.1	8.9
78	51.1	130.6	3552	388	1540	9.8	145.2	5.5	42.0	0.13	0.08	7.74	17.93	760	4.8	5.3
79	51.1	130.6	3552	388	1540	9.8	145.2	5.5	42.0	0.13	0.08	9.72	16.13	950	4.8	5.3
80	51.1	130.6	1780	588	1488	5.4	128.7	4.2	44.4	0.33	0.18	17.78	26.57	780	7.7	9.5
81	51.1	130.6	1780	588	1488	5.4	128.7	4.2	44.4	0.33	0.18	15.48	25.34	560	7.7	9.5
82	38.9	118.4	2228	428	1236	10.2	92.7	9.7	53.1	0.19	0.12	20.09	33.44	190	6.7	7.2
83	51.1	130.6	3552	388	1540	9.8	145.2	5.5	42.0	0.13	0.08	12.96	19.19	860	4.8	5.3
84	51.1	130.6	1780	588	1488	5.4	128.7	4.2	44.4	0.33	0.18	19.03	26.75	760	7.7	9.5
85	20.3	148.1	4452	0	1160	10.1	0.0	5.1	55.8	0.00	0.00	6.89	14.49	670	8.9	5.0
86	20.3	148.1	3294	0	1143	9.8	0.0	5.1	56.8	0.00	0.00	15.94	20.67	500	8.9	5.0
87	26.2	154.0	3588	162	1164	20.5	58.2	17.7	52.4	0.05	0.03	13.24	18.64	100	8.9	5.0
88	49.8	177.6	2861	305	577	5.0	99.7	10.8	49.0	0.11	0.09	13.19	24.95	710	8.9	5.0
89	49.8	177.6	3373	508	562	2.9	98.2	4.1	42.9	0.13	0.11	4.97	10.78	640	8.9	5.0
90	49.8	177.6	3373	508	562	2.3	98.2	3.1	49.3	0.13	0.11	4.55	9.27	550	8.9	5.0
91	49.8	177.6	3018	554	400	18.8	124.0	21.2	52.7	0.16	0.13	2.78	6.29	210	8.9	5.0
92	49.8	177.6	3018	554	400	12.8	124.0	12.3	52.7	0.16	0.13	8.37	15.65	320	8.9	5.0

Obs.	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}	X_{31}	X_{32}	X_{33}
70	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	20.8	40	155.0	0.00346	4567	23.0
71	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	20.0	37	155.0	0.00346	3991	29.3
72	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	4.7	70	155.0	0.00346	5435	22.5
73	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	32.5	11	155.0	0.00346	4420	21.4
74	20.0	0.10	0.24	0.09	9.6	4.6	13.2	16792	18402	17053	24.2	21	155.0	0.00346	7065	25.6
75	14.9	0.04	0.11	0.06	5.9	8.1	12.9	18434	17696	16438	17.0	36	109.5	0.00555	5196	19.9
76	16.7	0.03	0.08	0.05	6.1	9.5	15.0	17814	17024	15751	19.0	31	109.5	0.00555	6128	13.6
77	12.5	0.03	0.11	0.05	4.3	7.3	11.0	17954	15146	16329	18.0	34	109.5	0.00555	3308	23.0
78	8.7	0.03	0.09	0.05	4.0	4.2	6.6	18344	18563	17097	17.0	39	109.5	0.00555	5480	18.2
79	8.7	0.03	0.09	0.05	4.0	4.2	6.6	18344	18563	17097	18.0	35	109.5	0.00555	5480	18.2
80	12.5	0.04	0.11	0.05	6.5	7.0	10.5	17502	17749	16816	21.0	22	109.5	0.00555	3856	23.7
81	12.5	0.04	0.11	0.05	6.5	7.0	10.5	17502	17749	16816	21.0	19	109.5	0.00555	3856	23.7
82	13.8	0.04	0.06	0.05	5.6	6.2	12.3	17917	18242	16705	18.0	34	109.5	0.00555	3892	19.1
83	8.7	0.03	0.09	0.05	4.0	4.2	6.6	18344	18563	17097	17.0	39	109.5	0.00555	5480	18.2
84	12.5	0.04	0.11	0.05	6.5	7.0	10.5	17502	17749	16816	21.0	21	109.5	0.00555	3856	23.7
85	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	17.2	32	109.5	0.00555	5612	9.1
86	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	16.7	35	109.5	0.00555	4437	8.6
87	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	-2.8	78	109.5	0.00555	4914	21.1
88	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	20.6	38	109.5	0.00555	3744	13.6
89	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	26.4	16	109.5	0.00555	4443	13.9
90	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	27.5	17	109.5	0.00555	4443	13.4
91	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	15.8	93	109.5	0.00555	3972	33.7
92	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	20.0	81	109.5	0.00555	3972	28.3

Obs.	Species	Year	Type	Succ. or Fail	Intensity (kW/m)	Rate of Spread (m/min)	Flame Length (m)	X_1
93	WG	82	Head	Succ.	527.2	4.3	1.15	3
94	WG	82	Head	Succ.	1888.5	9.5	1.39	18
95	WG	82	Head	Succ.	1158.5	6.3	----	33
96	WG	82	Head	Succ.	2193.7	12.0	----	33
97	WG	82	Back	Succ.	121.1	1.0	0.77	2
98	WG	82	Back	Succ.	112.2	0.9	0.51	3
99	WG	82	Back	Succ.	202.3	1.0	0.38	18
100	WG	82	Back	Succ.	474.1	2.6	----	33
101	WG	82	Back	Succ.	365.6	2.0	----	33
102	WG	82	Back	Fail	0.0	0.0	0.00	126
103	WG	82	Back	Fail	0.0	0.0	0.00	126
104	WG	82	Back	Fail	0.0	0.0	0.00	149
105	WG	82	Back	Fail	0.0	0.0	0.00	159
106	WG	82	Back	Fail	0.0	0.0	0.00	3
107	WG	83	Head	Succ.	371.1	2.2	2.13	52
108	WG	83	Head	Succ.	1331.1	6.3	2.47	58
109	WG	83	Head	Succ.	12602.5	50.7	2.90	4
110	WG	83	Head	Succ.	804.3	5.4	2.06	7
111	WG	83	Head	Succ.	3145.6	17.1	1.91	7
112	WG	83	Head	Fail	0.0	0.0	0.00	74
113	WG	83	Back	Succ.	116.5	0.7	1.20	52
114	WG	83	Back	Succ.	159.3	0.8	1.07	58
115	WG	83	Back	Succ.	292.1	1.2	0.92	4

Obs.	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
93	49.8	177.6	3018	554	400	5.3	124.0	6.8	52.7	0.16	0.13	12.19	22.34	730	8.9	5.0
94	51.6	179.4	5310	700	1046	3.2	137.2	3.1	40.3	0.12	0.10	20.38	39.25	695	8.9	5.0
95	51.6	179.4	4244	1133	1223	3.7	186.8	3.2	48.3	0.21	0.16	11.92	21.56	915	8.9	5.0
96	51.6	179.4	4244	1133	1223	3.5	186.8	3.2	46.4	0.21	0.16	11.47	22.58	910	8.9	5.0
97	49.8	177.6	3373	508	562	2.9	98.2	4.8	42.9	0.13	0.11	11.50	16.87	500	8.9	5.0
98	49.8	177.6	3018	554	400	5.3	124.0	6.8	52.7	0.16	0.13	10.91	19.90	680	8.9	5.0
99	51.6	179.4	5310	700	1046	3.2	137.2	3.1	40.3	0.12	0.10	18.30	35.92	495	8.9	5.0
100	51.6	179.4	4244	1133	1223	3.7	186.8	3.2	48.3	0.21	0.16	9.47	17.58	910	8.9	5.0
101	51.6	179.4	4244	1133	1223	3.5	186.8	3.2	46.4	0.21	0.16	10.70	20.54	910	8.9	5.0
102	20.3	148.1	4452	0	1160	10.4	0.0	6.1	55.8	0.00	0.00	7.70	14.49	720	8.9	5.0
103	20.3	148.1	3294	0	1143	10.1	0.0	5.1	56.8	0.00	0.00	7.27	12.54	510	8.9	5.0
104	26.2	154.0	3588	162	1164	20.5	58.2	17.7	52.4	0.05	0.03	12.49	18.34	100	8.9	5.0
105	49.8	177.6	2861	306	577	5.3	99.7	13.0	49.0	0.11	0.09	10.61	19.96	680	8.9	5.0
106	49.8	177.6	3018	554	400	18.8	124.0	21.2	52.7	0.16	0.13	2.72	6.07	130	8.9	5.0
107	69.3	166.4	4841	0	848	7.3	0.0	7.3	54.7	0.00	0.00	16.78	17.71	285	11.4	6.8
108	69.3	166.4	5916	66	1117	12.0	236.7	12.5	40.3	0.01	0.01	7.49	15.29	190	11.4	6.8
109	107.2	204.2	6674	382	1284	4.8	199.2	4.1	47.8	0.06	0.05	17.69	27.36	740	11.4	6.8
110	107.2	204.2	4048	379	602	2.3	210.7	1.8	40.0	0.09	0.08	5.89	17.71	390	11.4	6.8
111	107.2	204.2	4579	384	1216	2.6	210.7	0.8	36.6	0.08	0.07	8.05	14.48	760	11.4	6.8
112	70.9	167.9	6674	74	1284	181.4	236.7	174.3	47.8	0.06	0.05	9.53	25.75	205	11.4	6.8
113	69.3	166.4	4841	0	848	7.3	0.0	7.3	54.7	0.00	0.00	6.59	16.09	438	11.4	6.8
114	69.3	166.4	5916	66	1117	12.0	236.7	12.5	40.3	0.01	0.01	7.15	19.31	130	11.4	6.8
115	107.2	204.2	6674	382	1284	4.8	199.2	4.1	47.8	0.06	0.05	17.47	24.14	810	11.4	6.8

Obs.	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}	X_{31}	X_{32}	X_{33}
93	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	26.7	55	109.5	0.00555	3972	22.0
94	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	20.0	25	109.5	0.00555	7056	16.5
95	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	29.7	12	109.5	0.00555	6600	35.0
96	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	30.3	12	109.5	0.00555	6600	34.9
97	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	25.0	18	109.5	0.00555	4443	14.0
98	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	25.3	61	109.5	0.00555	3972	22.0
99	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	20.0	25	109.5	0.00555	7056	16.5
100	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	29.7	16	109.5	0.00555	6600	35.0
101	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	30.3	12	109.5	0.00555	6600	34.9
102	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	11.4	41	109.5	0.00555	5612	9.5
103	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	16.7	33	109.5	0.00555	4437	8.8
104	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	-2.8	78	109.5	0.00555	4914	21.1
105	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	20.3	38	109.5	0.00555	3744	14.2
106	29.3	0.05	0.12	0.07	6.3	1.8	24.0	16441	17393	15075	15.8	95	109.5	0.00555	3972	33.7
107	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	21.4	25	109.5	0.00555	5689	7.3
108	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	2.2	62	109.5	0.00555	7099	14.2
109	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	29.7	20	109.5	0.00555	8340	13.6
110	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	29.7	17	109.5	0.00555	5029	17.9
111	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	30.3	17	109.5	0.00555	6179	15.2
112	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	0.0	90	109.5	0.00555	8032	180.8
113	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	15.8	39	109.5	0.00555	5689	7.3
114	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	0.8	63	109.5	0.00555	7099	14.2
115	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	29.4	21	109.5	0.00555	8340	13.6

Obs.	Species	Year	Type	Succ. or Fail	Intensity (kW/m)	Rate of Spread (m/min)	Flame Length (m)	X_1
116	WG	83	Back	Succ.	222.5	1.5	1.38	7
117	WG	83	Back	Succ.	198.5	1.1	1.19	7
118	WG	83	Back	Fail	0.0	0.0	0.00	74
119	MG	83	Head	Succ.	1331.0	10.3	1.26	55
120	MG	83	Head	Succ.	296.9	2.7	0.86	55
121	MG	83	Back	Succ.	98.7	0.7	0.71	55
122	MG	83	Back	Succ.	63.7	0.5	0.34	55
123	MG	83	Back	Fail	0.0	0.0	0.00	55

Obs.	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}
116	107.2	204.2	4048	379	602	2.3	210.7	1.8	40.0	0.09	0.08	7.20	17.71	690	11.4	6.8
117	107.2	204.2	4579	384	1216	2.6	210.7	0.8	36.6	0.08	0.07	7.19	16.09	635	11.4	6.8
118	70.9	167.9	6674	74	1284	181.4	236.7	174.3	47.8	0.01	0.01	9.53	25.75	205	11.4	6.8
119	68.3	155.4	2681	100	1647	15.8	86.0	26.9	31.1	0.04	0.02	9.41	17.71	655	8.4	13.1
120	68.3	155.4	2406	283	1101	12.1	86.0	12.4	22.4	0.15	0.10	10.71	16.09	615	8.4	13.1
121	68.3	155.4	2983	56	1722	12.7	86.0	12.4	28.9	0.02	0.01	6.11	16.09	813	8.4	13.1
122	68.3	155.4	2706	415	1347	12.1	86.0	12.4	21.0	0.15	0.10	4.99	15.29	715	8.4	13.1
123	68.3	155.4	2681	100	1647	15.8	86.0	26.9	31.1	0.04	0.02	8.32	12.88	570	8.4	13.1

Obs.	X_{18}	X_{19}	X_{20}	X_{21}	X_{22}	X_{23}	X_{24}	X_{25}	X_{26}	X_{27}	X_{28}	X_{29}	X_{30}	X_{31}	X_{32}	X_{33}
116	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	28.1	18	109.5	0.00555	5029	17.9
117	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	30.0	16	109.5	0.00555	6179	15.2
118	19.7	0.09	0.24	0.13	5.2	2.3	9.8	17889	18203	14303	0.0	90	109.5	0.00555	8032	180.8
119	26.9	0.09	0.18	0.12	7.7	9.8	15.6	17339	16521	15562	6.7	59	161.9	0.00438	4428	21.5
120	26.9	0.09	0.18	0.12	7.7	9.8	15.6	17339	16521	15562	14.4	40	161.9	0.00438	3790	17.7
121	26.9	0.09	0.18	0.12	7.7	9.8	15.6	17339	16521	15562	10.8	48	161.9	0.00438	4761	13.5
122	26.9	0.09	0.18	0.12	7.7	9.8	15.6	17339	16521	15562	14.2	44	161.9	0.00438	4468	19.1
123	26.9	0.09	0.18	0.12	7.7	9.8	15.6	17339	16521	15562	4.2	64	161.9	0.00438	4428	21.5