AN ABSTRACT OF THE THESIS OF

Bruce Roger Meland for the M. S. in General Science
(Name) (Degree) (Major)

Date thesis is presented May 10, 1966

Title A STUDY OF FIELD BURNING UNDER VARYING ENVIRONMENTAL CONDITIONS

Abstract approved [redacted]
(Major professor)

A field study on grass field burning was conducted in the Willamette Valley of Oregon during the summer of 1965. Approximately 243,000 acres of grass fields are burned in the valley during August and September. Serious air pollution problems result from this burning. The purposes of the study were to determine the effect of environmental variables on grass field burning and to determine if conditions exist when significant air pollution reduction can be achieved. The environmental variables investigated were time from harvest to burning, time of day, air temperature, relative humidity, soil and straw moisture, wind speed and direction, and fuel density. The dependent variables measured were particulate emission and size distribution, combustion temperature, burn rate, amount of residue, percent of organics in the particulate, and smoke appearance. The results were analyzed statistically using a correlation

matrix and a stepwise multiple linear regression analysis to determine the significant variables and their relationship.

Environmental variables were found to affect the grass field burning process causing significant differences in some of the dependent variables.

# A STUDY OF FIELD BURNING UNDER VARYING ENVIRONMENTAL CONDITIONS

by

BRUCE ROGER MELAND

A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1966

APPROVED:

[redacted]

Associate Professor of Mechanical Engineering

In Charge of Major

[redacted]

Head of Department of General Science

[redacted]

Dean of Graduate School

Date thesis is presented May 10, 1966

Typed by Marion F. Palmateer

## ACKNOWLEDGEMENTS

I wish to express my appreciation for the careful guidance, freedom of action, and optimum facilities and equipment provided me by my major professor, Dr. Richard Boubel; for generous provision of equipment and assistance in the chemical analysis aspects of the study by Dr. Frank Terraglio; for assistance in providing the wind instrumentation through the Forest Research Laboratory to Dr. William Lowry; and for construction of the instrumentation needed for this project and the many extra hours of assistance during the critical data gathering period, to my assistant John Kellogg.

Thanks to Farm Crops graduate students Dave Schafer and Elmer Stobbe, whose donated time during the data gathering period provided the essential impetus for the success of this study; also to Rex Warren, Extension Farm Crops Specialist, and Dr. David Chilcote for the much needed agricultural assistance and advice.

I would like to thank Mr. Robert Cale, local ryegrass farmer, for allowing the use of his ryegrass land for plot experimentation; also to Mr. Willis Kirk, nearby farmer, for machinery assistance, and Mr. J. Willard Brown, who donated the water for fire control purposes.

Thanks to Mr. Ralph Bjerke, Chief, and the Shedd Fire

Department who donated time and equipment for initial fire control procedures; to Clayton Johnson of the Farm Service, and Mr. Glen Page, Agricultural Engineering, for cooperation in the use of fire control equipment; to Gary Jarman and Dr. Pat Cochran of the Soils Department, for their generous help in instrumentation; and to Robert Black and Richard Johnson of the United States Weather Bureau, Agricultural Service Office, for assistance and use of meteorological equipment for this study.

Sincere appreciation to fellow graduate students James McElroy, Alan Chambers, and Charles Black, for assistance at critical times; also thanks to my uncle, Amos Funrue, for technical assistance; and to my brother Jack, and Neal MacSwan for timely assistance in the data gathering phase of the project.

And last but not least, my sincere appreciation to Professor Fred J. Burgess, project coordinator, and the United States Public Health Service for supporting this research and my graduate studies for the 1965-66 school year.

B. R. M.

TABLE OF CONTENTS

LIST OF FIGURES

# LIST OF TABLES

# A STUDY OF FIELD BURNING UNDER VARYING ENVIRONMENTAL CONDITIONS

## INTRODUCTION

The practice of grass field burning in the Willamette Valley of Oregon contributes a high concentration of pollutants to the atmosphere during a two-month period of August and September each year. These grasses are burned after harvest of the seed. Grass seed from the Willamette Valley fulfills a substantial part of the foreign and domestic market in providing seed for lawn, golf courses, turfs, and pastures. Approximately 243,000 acres of grass-seed land of different varieties are burned after harvest each year (Appendix Figure 1). The time of burn varies for each particular grass. Table 1 indicates total acreages and approximate times of burning each grass. Factors taken into consideration for determining burning time are: (1) time the particular grass variety matures, (2) time the individual farm will complete its harvest, (3) fire hazards to neighboring unharvested fields, (4) weather conditions, (5) availability of labor, and (6) personal preference.

The practice of grass field burning is carried out: (1) to control plant diseases, weeds, and insects, (2) to eliminate surface organic matter which utilizes needed nitrogen during decomposition, and (3) to promote a quick return to the soil of potash, phosphorus, calcium, and some minor elements (4). At the present time there is no satisfactory alternative management practice to replace burning.

Table 1. Acreages of major grass grown in the Willamette Valley and approximate time of burn (9).

| Type of Grass | Acres (Approx. 90% Burned) | Time of Burn (Av. Year) |
|---|---|---|
| Bentgrass | 24, 500 | Sept 10 - Oct 10 |
| Chewings Fescue | 15, 800 | Aug 1 - Aug 25 |
| Red Fescue | 9, 040 | Aug 1 - Aug 25 |
| Merion Bluegrass | 2, 170 | Aug 15 - Sept 15 |
| Kentucky Bluegrass | 8, 000 | Aug 15 - Sept 15 |
| Tall Fescue | 12, 850 | July 20 - Aug 15 |
| English Ryegrass | 40, 000 | Aug 15 - Sept 30 |
| Common Ryegrass | 127, 000 | Aug 15 - Sept 30 |
| Orchardgrass | 4, 000 | July 20 - Aug 30 |
| Total | 243, 360 | |

The fact that a high concentration of air pollutants from field burning are emitted during late summer and early fall each year makes this operation an acute air pollution problem. For example, using an average value of two tons of straw burned per acre of grass and a U. S. Public Health Service figure of 22 pounds of particulate emitted per ton of fuel burned (12), particulate emitted from field burning over this two month period amounts to approximately ten million pounds.

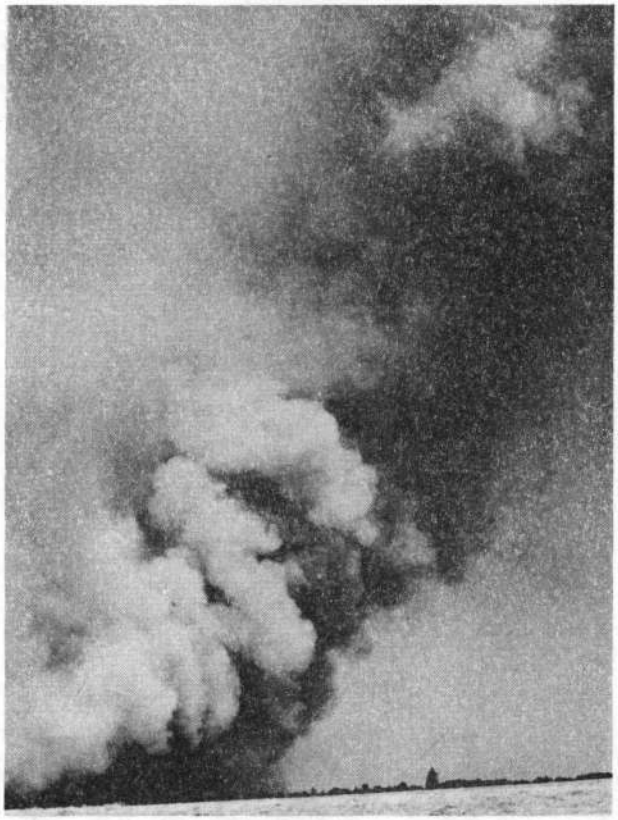


Figure 1. Typical ryegrass field burning.

Some effects of this air pollution are: (1) reduction of visibility, (2) soiling, (3) odor, and (4) fallout on adjoining property.

Agricultural burning is exempt from air pollution control regulations. An agricultural advisory forecast has been operating during the field burning season to inform grass farmers of atmospheric conditions which either favor or inhibit the dispersion of smoke to the upper atmosphere. The farmers are advised to refrain from burning their grass fields during unfavorable dispersion conditions. This program is voluntary, and therefore, some farmers do not follow this advice. Appendix Figures 2-5 illustrate favorable and unfavorable dispersion conditions with corresponding lapse rates.

Further studies on agricultural burning seem justifiable to enable feasible air pollution control measures to be developed. Reasons for additional studies are: (1) increased acreages of grass seed, (2) widespread public concern, (3) limited control measures in effect, (4) relatively high economic returns to Oregon farmers and seed processors[1], and (5) limited information on all aspects of field burning.

## Thesis Objectives

The primary objective of this thesis was to study in detail the effect of environmental variables on grass field burning to: (1) act as a pilot study and help define grass-field burning's contribution to air pollution in the Willamette Valley, (2) determine if environmental conditions exist when significant air pollution reduction could be achieved during the field burning season, (3) provide preliminary information for further studies to find a possible substitute for grass field burning which would check plant disease, weeds, and insects, and (4) test instrumentation and techniques for further air pollution and related research in field burning.

---

[1] Approximately $33,000,000 annually (10).

# PROCEDURE

During the summer of 1965 a local ryegrass field on the Bob Cale farm, ten miles southeast of Corvallis, Oregon, in the heart of the Willamette Valley, was selected as the site for the field burning study. Shortly after the harvest of the ryegrass, a 40 foot wide fire trail was burned around a 14-acre rectangular section. Half of the field was Common (annual) ryegrass, and the other half English (perennial) ryegrass. These two types of grasses were chosen because: (1) they represent two-thirds of the total grass acreage in the Willamette Valley, (2) English (perennial) ryegrass has characteristics of typical perennial grasses with fine texture and regrowth, (3) Common (annual) ryegrass has quite different characteristics with coarse texture, limited regrowth, and characteristics representative of typical cereal grains, and (4) the grasses occurred close to Oregon State University for available study.

Twenty-five plots of each type of ryegrass (10,000 $ft^2$ of area in each plot) were sectioned off using a ten-foot cut wind-rower, followed by a hay baler. This procedure enabled easy fire control when burning each plot, as the short stubble between sections allowed direct wetting with a fire nozzle for easy extinguishability and boundary control.

The individual plots (Figure 2) were burned at different times and measurements of variables were made under the varying environmental conditions of the burning season.

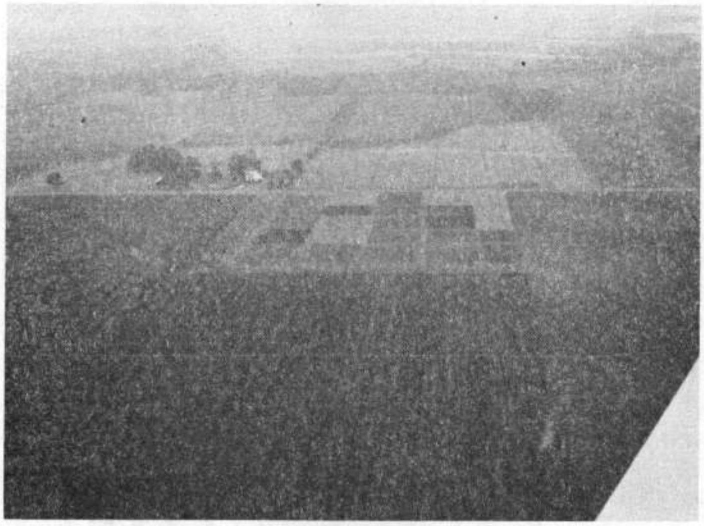


Figure 2. Aerial view of 25 perennial ryegrass plots. (The 25 annual ryegrass plots have been plowed at right.)

Independent Variables Measured for the Study

1. Time between harvest and burning of plot.

2. Time of day.

3. Temperature of air near the ground.

4. Relative humidity of the air near the ground.

   A meteorological instrument shelter was placed at the edge of the plots. Inside was placed a hygrothermograph to continuously record both air temperature and relative humidity.

5. Wind speed and direction (Figure 3).

A field wind indicating system, consisting of two anemometers placed at 10 and 17 feet above the ground and wind vane, was set up and connected to a Esterline Angus wind recorder. Wind data were recorded shortly before, during and after the burning of each plot.

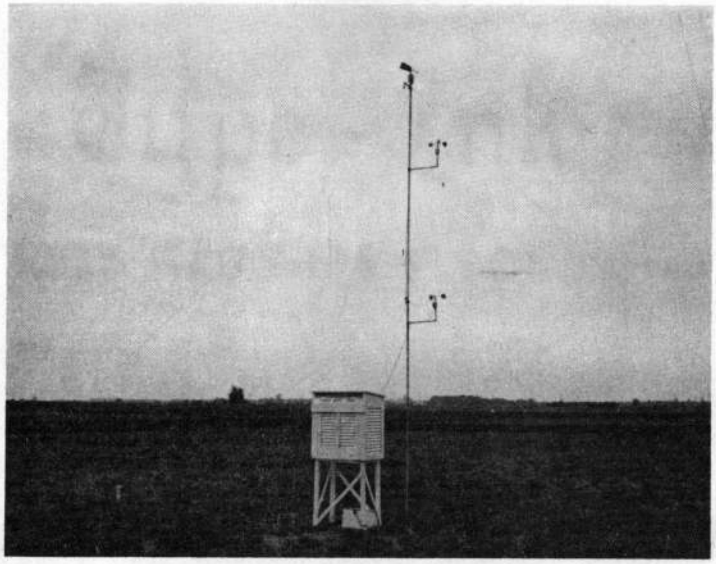


Figure 3. Weather station (instrument shelter and wind system).

6. Soil moisture.

Moisture cans were used in measuring the percent soil moisture by weight. The cans were weighed before and after collecting a soil sample of approximately 150 grams. This sample was obtained from the surface to three-fourths inch in depth. The can was sealed with masking tape to prevent any moisture loss until it was placed in a 105°C oven to dry for 48 hours. The dried soil and can were weighed again and the percent moisture determined. Soil moisture samples were taken before and after burning the plots to provide information concerning soil moisture loss.

7. Straw and stubble moisture.

A sample of approximately 30 grams of straw was placed in a moisture can, and the same procedure followed as that used for soil moisture determination except that the temperature of the drying chamber was maintained at 58°C.

8. Density of fuel.

A standard procedure enabled density measurement of the straw and stubble. As previously mentioned, ten-foot boundary areas, outlining each 10,000 $ft^2$ plot, were cut by the wind-rower and baled. The bales were counted and a representative sample of each type of bale was weighed. Because the surface area cut was known, the determination of pounds of straw per acre could be made. Computations indicated 3,310 pounds of English (perennial) ryegrass per acre and 4,640 pounds of Common (annual) ryegrass per acre. A uniform density for all plots of each particular grass was assumed.

9. Amount of regrowth.

The perennial ryegrass sends up green shoots soon after harvest. The amount of this regrowth depends primarily on the amount of rainfall. Therefore, the longer a farmer waits to burn his fields the greater is the percentage of this regrowth. A rating from 1 to 5 was recorded by Dave Schafer, a Farm Crops graduate student, before each plot burn (1 corresponding to no significant regrowth and 5 to ultimate regrowth).

Dependent Variables Measured for the Study

1. Particulate emissions and size distribution.

To measure the amount of pollutants emitted to the atmosphere, a high-volume sampler was fastened to a metal tripod 16 to 18 feet above the ground. The sampler was positioned upright so the sampling surface of the glass fiber filter would be pointing away from the rising smoke plume. The sampler was placed near the center of the sample plot under calm conditions or placed on the downwind side depending on the wind direction and speed. An electric line, elevated on poles high enough from the fire to prevent burning, was used as a power line for the sampler. The motor generator, supplying power for the thermocouple recorder and high-volume sampler, was away from the sample plot behind a metal shield for protection from extreme temperatures. The high-volume sampler draws air through a glass-fiber filter (Gelman Type A) at approximately 60 cfm, depending on the particulate loading and gas temperature. The sampling time was determined by the period the sampler was in dense smoke. Weighing the filter before and after sampling, recording the air-flow rate through the filter, and time in the smoke gave the concentration of pollutants collected. A one inch diameter Gelman membrane filter was also placed in parallel with the high-volume sampler. Approximately 0.05 cfm was drawn through the membrane filter. The membrane filter was analyzed microscopically for the size distribution of the particulates (Figure 4).

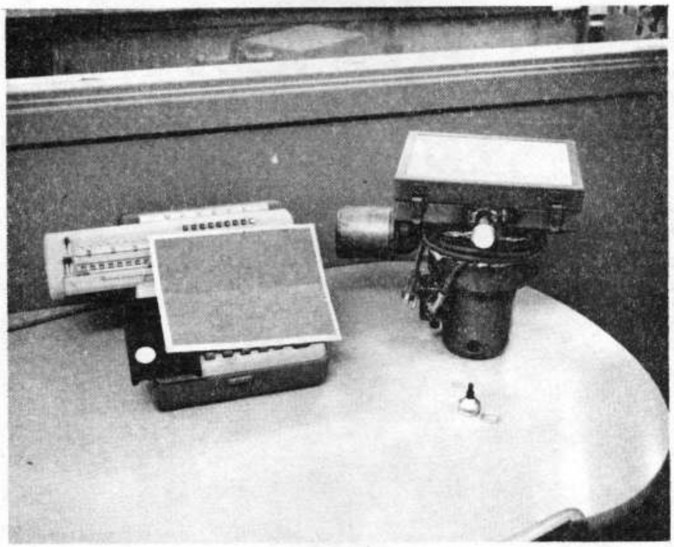


Figure 4. Glass-fiber filter and membrane filter with high-volume sampler.

2. Visual appearance of the burning cycle.

Colored 35mm slides were taken of the individual plots during the burning cycle to study: (1) the color of smoke; a rating of 1 to 5 was given the visual appearance of the smoke (1= white, 2 = gray-white, 3 = gray, 4 = gray-black, 5 = black), (2) amount of smoke emitted, and (3) other visual phenomena.

3. Combustion and soil temperatures.

Temperature measurements were accomplished with four chromel-alumel thermocouples, 60 feet in length, with glass-asbestos-silicon shielding. They were placed at four different levels near the center of each plot: six inches above the soil surface, at the soil surface, one-half inch below the soil surface, and two inches below the soil surface (Figure 5).

Figure 5. Insertion of thermocouple.

Temperatures were recorded continuously on a Honeywell four-channel strip chart recorder. The recorder was turned on ten minutes before the burn and allowed to run 15 minutes after the burning cycle was completed. The temperature response was 12 seconds for full scale travel, and minimum time between points was six seconds (Figure 6).

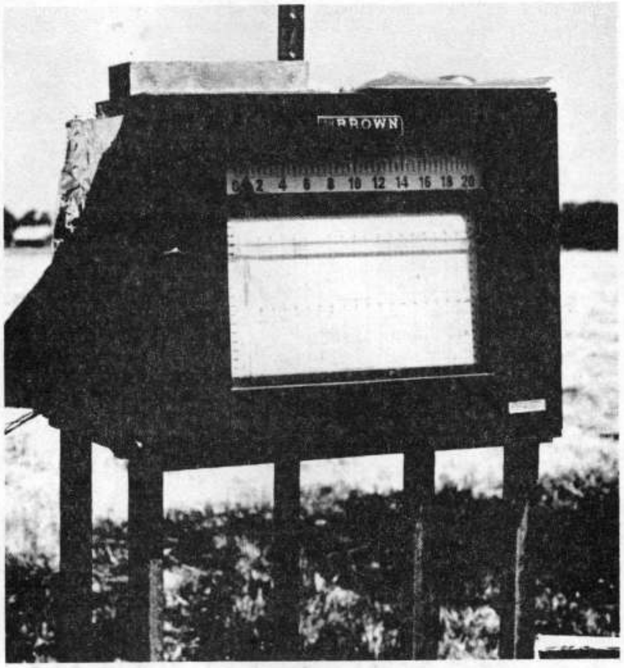



Figure 6. Four-channel temperature recorder.

For a direct comparison of temperature data with other variables, the area under the recorded temperature-time curve, at the soil surface (Figure 10, p. 23), was traced on Albanene tracing paper, cut out and weighed.

4. Burning rate.

The time for the fire to cover a prescribed distance was determined with a stop watch.

5. Residue analysis.

Immediately after the burning cycle, residue of the burning process from a two square-foot area was collected in a plastic bag for analysis.

6. Percent organics.

A Soxhlet extraction, with benzene, of the pollutants collected on the glass-fiber filter gave the percent organics of the pollutants. A diagonal half of the glass-fiber filter was placed in an extraction thimble and extracted for six hours, corresponding to 50 cycles. Weighing the flask before and after extraction enabled determination of the percent organics. A series of blanks were run, showing no significant weight contribution for unused filters (Figure 7).

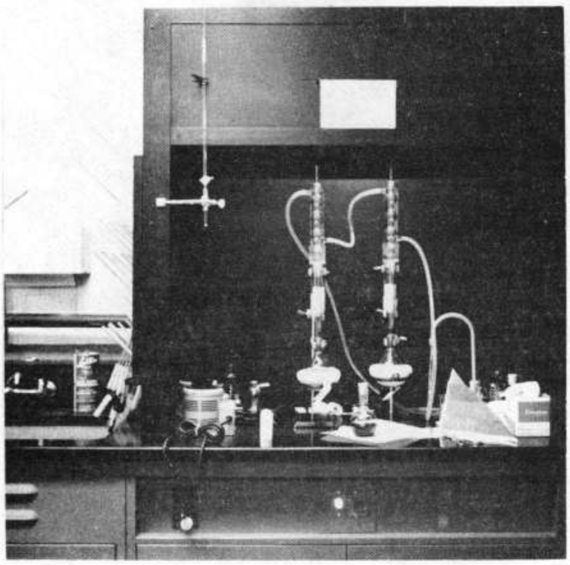


Figure 7. Benzene extraction apparatus for organics.

Brief Burning Procedure for Each Plot

Upon selection of time and plot to be burned, a high-volume sampler was fastened to the top of the tripod. The filters used were a glass-fiber filter and small membrane filter in parallel. The sampler was operated momentarily to get a flow-meter reading with clean filters in place. Thermocouples were inserted at their proper places near the center of the plot and connected to the recorder. A 60-cycle 110-volt generator supplied power for the instruments. Identifying numbers for the plot were set up. Soil and straw moisture samples were taken. Date and time were recorded, and recorders were turned on. Boundary areas were wetted with a pump mounted water tank (Figure 8). The fire was started on the leeward side and lit on the remaining three sides leaving the windward side until last. This procedure provided proper fire control. Pictures were taken at 10 to 15-second intervals. The high-volume sampler was turned on when surrounded by dense smoke and allowed to run anywhere from five seconds to four and one-half minutes depending on the period of maximum smoke density. Burning rate of the flame front was recorded in feet per minute (Figure 9). Upon completion of the burning cycle a soil moisture and residue sample was taken. Another flow reading of the high-volume sampler was taken to enable an average reading to be recorded. The samples and data were taken to the laboratory to be analyzed. After laboratory analysis the data for the 39 different observations were separated into English and Common ryegrass, and tabulated (Appendix Tables 1 and 2).

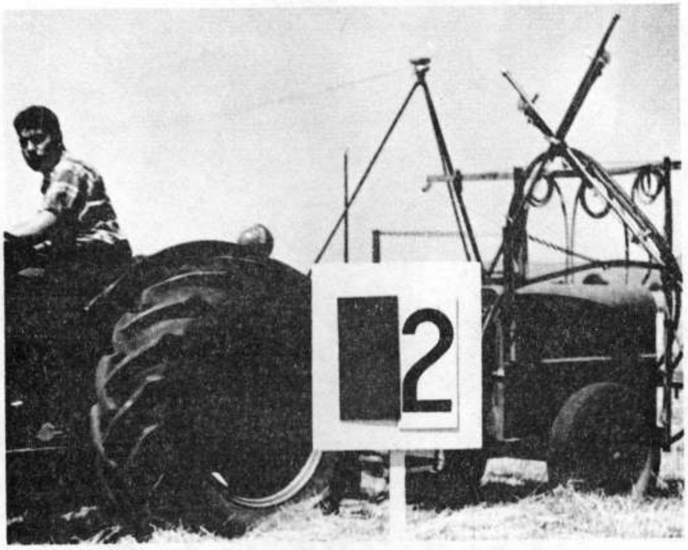



Figure 8. Fire control rig with high-volume sampler on tripod in background.

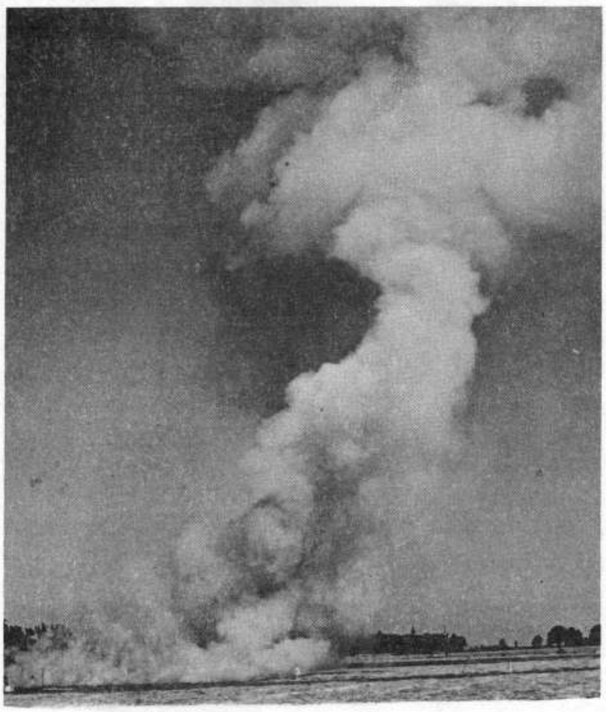


Figure 9. Typical plot burning.

# RESULTS

A correlation matrix program was written to bypass missing data without excluding corresponding significant data (8). Sixteen variables, dependent and independent, were entered in the correlation matrix program. Separate correlations were developed for English ryegrass and Common ryegrass due to the different characteristics of the two grasses. The variables entered were as follows: burn time, days from harvest, air temperature, relative humidity, soil moisture before burn, soil moisture after burn, straw moisture, wind speed, suspended particulate, residue weight, burn rate, surface temperature, percent organics, smoke color, regrowth, and absolute humidity. Table 2 summarizes the significant correlations at the five percent level of significance for both English and Common ryegrass.

Stepwise multiple linear regression analyses of the dependent variables, suspended particulate, residue, burn rate, surface temperature, percent organics, smoke color, and soil moisture loss, on the independent variables, burn time, days after harvest, air temperature, relative humidity, soil moisture before, straw moisture, wind speed, absolute humidity, and regrowth, were run separately for English and Common ryegrass (11).

Table 2. Correlation matrix of variables at the five percent level.

| Variable | Vs | Variable | Correlation |
|---|---|---|---|
| | | English Ryegrass | |
| Days from Harvest (I)[2] | | Air Temp. (I) | -.569 |
| " | | Soil Moist. (b)[1] (I) | .541 |
| " | | Straw Moist. (I) | .596 |
| " | | Residue (D)[1] | .848 |
| Air Temp. (I) | | Rel. Hum. (I) | -.574 |
| " | | Straw Moist. (I) | -.490 |
| " | | Burn Rate (D) | .507 |
| " | | Surface Temp. (D) | .511 |
| " | | Smoke Color (D) | .624 |
| Relative Humidity (I) | | Soil Moist. (b) (I) | .626 |
| " | | Soil Moist. (a)[1] (I) | .708 |
| " | | Straw Moist. (I) | .830 |
| " | | Wind Speed (I) | -.666 |
| " | | Residue (D) | .702 |
| " | | Burn Rate (D) | -.799 |
| " | | Surface Temp. (D) | -.696 |
| " | | Smoke Color (D) | -.786 |
| " | | Abs. Hum. (I) | .836 |
| Soil Moisture (b) (I) | | Soil Moist. (a) (I) | .933 |
| " | | Straw Moist. (I) | .840 |
| " | | Residue (D) | .878 |
| " | | Burn Rate (D) | -.527 |
| " | | Surface Temp. (D) | -.522 |
| " | | Smoke Color (D) | -.613 |
| " | | Regrowth (I) | .536 |
| " | | Abs. Hum. (I) | .462 |
| Soil Moisture (a) (I) | | Straw Moist. (I) | .785 |
| " | | Residue (D) | .730 |
| " | | Burn Rate (D) | -.525 |
| " | | Smoke Color (D) | -.529 |
| " | | Abs. Hum. (I) | .733 |
| Straw Moisture (I) | | Wind Speed (I) | -.527 |
| " | | Residue (D) | .859 |
| " | | Burn Rate (D) | -.745 |
| " | | Surface Temp. (D) | -.696 |
| " | | Smoke Color (D) | -.794 |
| " | | Regrowth (I) | .458 |
| " | | Abs. Hum. (I) | .629 |

[2] (I) independent, (b) before, (D) dependent, (a) after.

Table 2. Continued.

| Variable | Vs | Variable | Correlation |
|---|---|---|---|
| | | **English Ryegrass** | |
| Wind Speed (I) | | Burn Rate (D) | .815 |
| " | | Surface Temp. (D) | .619 |
| " | | Smoke Color (D) | .555 |
| " | | Abs. Hum. (I) | -.609 |
| Residue (D) | | Burn Rate (D) | -.733 |
| " | | Surface Temp. (D) | -.516 |
| " | | Smoke Color (D) | -.676 |
| " | | Regrowth (I) | .784 |
| " | | Abs. Hum. (I) | .530 |
| Burn Rate (D) | | Surface Temp. (D) | .640 |
| " | | Smoke Color (D) | .680 |
| " | | Abs. Hum. (I) | -.662 |
| Surface Temp. (D) | | Smoke Color (D) | .778 |
| " | | Abs. Hum. (I) | -.554 |
| Smoke Color (D) | | Abs. Hum. (I) | -.556 |
| | | **Common Ryegrass** | |
| Days from Harvest (I) | | Soil Moist. (b) (I) | -.600 |
| " | | Soil Moist. (a) (I) | -.818 |
| Air Temp. (I) | | Rel. Hum. (I) | -.610 |
| " | | Wind Speed (I) | .476 |
| " | | Burn Rate (D) | .625 |
| " | | Smoke Color (D) | .544 |
| Relative Humidity (I) | | Wind Speed (I) | -.474 |
| " | | Residue (D) | .501 |
| " | | Burn Rate (D) | -.582 |
| " | | Smoke Color (D) | -.521 |
| " | | Abs. Hum. (I) | .771 |
| Soil Moisture (b) (I) | | Soil Moist. (a) (I) | .931 |
| " | | Residue (D) | .541 |
| Soil Moisture (a) (I) | | Residue (D) | .503 |
| Straw Moisture (I) | | Burn Rate (D) | -.540 |
| " | | Smoke Color (D) | -.720 |
| Wind Speed (I) | | Burn Rate (D) | .698 |
| " | | Smoke Color (D) | .614 |
| Partic. Density (D) | | Organics (D) | .708 |
| Burn Rate (D) | | Smoke Color (D) | .563 |
| Organics (D) | | Smoke Color (D) | -.583 |

The stepwise multiple linear regression analysis revealed the following results.

English Ryegrass

1. The amount of suspended particulate was not significantly dependent on any of the independent variables. (Regrowth nearly showed a significant correlation.)

2. The amount of residue left was dependent upon soil moisture and days after harvest.[3] The equation for the amount of residue left after the burning process is:

$$\text{Residue } (g/2ft^2) = -25.95 + .698 \text{ (days from harvest)} + .393 \text{ (soil moisture, } g/g)$$

Using an average value of residue left on the ground following the burning process as 23.5 $g/2ft^2$, 3310 pounds of burned straw per acre leaves approximately 1125 pounds of residue.

3. The burn rate was dependent upon the wind speed and soil moisture. The equation for burn rate is:

$$\text{Burn rate (ft/min)} = 45.52 - 270.19 \text{ (soil moisture, } g/g) + 5.60 \text{ (wind speed, mi/hr)}$$

---

[3] Five percent level of significance for all statistical results.

4. The surface temperature was dependent upon regrowth, wind speed, straw moisture, soil moisture, relative humidity, and air temperature. The equation for surface temperature is:

$$\begin{aligned}\text{Surface temperature (a-wt)} = & -.069 + .0009 \text{ (air temperature, °F)} \\ & +.0002 \text{ (relative humidity, \%)} \\ & -.202 \text{ (soil moisture g/g)} \\ & -.034 \text{ (straw moisture, g/g)} \\ & +.0007 \text{ (wind speed, mi/hr)} \\ & +.009 \text{ (regrowth, rating)}\end{aligned}$$

5. Percent organics showed no significant dependence on any independent variables.

6. Smoke color was dependent on straw moisture. The equation for smoke color is:

$$\text{Smoke color (rating)} = 4.17 - 6.45 \text{ (straw moisture, g/g)}$$

7. Soil moisture loss showed no significant dependence on any independent variables.

Common Ryegrass

1. The amount of suspended particulate was not significantly dependent upon any of the independent variables.

2. The amount of residue left was dependent upon soil

moisture.[4] The equation for the amount of residue left after the burning process is:

$$\text{Residue } (g/2ft^2) = .78136 + 74.58 \text{ (soil moisture, g/g)}$$

(Note: A positive coefficient for soil moisture implies a positive correlation.)

Using an average value of residue left on the ground following the burning process as 14 $g/2ft^2$, 4,640 pounds of burned straw per acre leaves approximately 670 pounds of residue.

3. Burn rate was dependent upon (1) wind speed, (2) air temperature, and (3) number of days after harvest. The equation for burn rate is:

$$\text{Burn rate (ft/min)} = -152.0 + 1.11 \text{ (days from harvest)} + 2.32 \text{ (air temperature, }^\circ\text{F)} + 2.497 \text{ (wind speed, mi/hr)}$$

4. Surface temperature was not significantly dependent upon any of the independent variables.

5. Percent organics showed no significant dependence on any independent variables.

6. Smoke color, visual rating from light smoke (rating of 1) to black smoke rating (rating of 5), was dependent on straw moisture.

---

[4] Five percent level of significance for all statistical results.

The equation for smoke color is:

Smoke color (rating) = 4.591 - 13.19 (straw moisture, g/g)

7. Soil moisture loss showed no significant dependence on any independent variables.

To obtain a better perspective of the range of variables, Tables 3 and 4 were tabulated.

Figure 10 reveals the differences in temperature profiles at the four different levels of measurement during a typical plot burn.

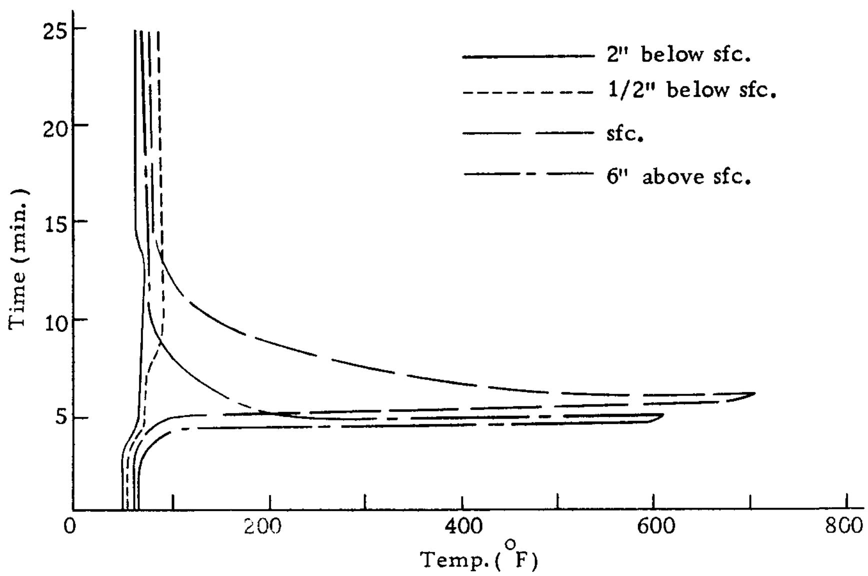



Figure 10. Typical temperature profiles.

The size of the suspended particulate showed a nearly uniform distribution in the submicron range. The mean size of the particulate appeared to be about 0.5 microns. For a detailed study of particle sizes an electron microscope would be desirable because

Table 3. Average and extreme values of English ryegrass variables.

| | Average | Low | High |
|---|---|---|---|
| | | Independent Variables | |
| Burn time (PDT) | 16:29 | 12:40 | 20:55 |
| Days after harvest | 41.8 | 15 | 90 |
| Air temperature (°F) | 73.42 | 64 | 85 |
| Relative humidity (%) | 40.73 | 17 | 66 |
| Soil moisture (g/g) | .0879 | .0349 | .2038 |
| Straw moisture (g/g) | .1818 | .0587 | .3551 |
| Wind speed (mi/hr) | 5.7 | 1.5 | 15.0 |
| Absolute humidity ($g/m^3$) | 8.2 | 2.99 | 12.25 |
| Regrowth (rating) | 2.9 | 1.5 | 5.0 |
| | | Dependent Variables | |
| Suspended particulate ($\mu g/m^3$) | 39,427.5 | 20,435.2 | 56,307.7 |
| Residue wt($g/2ft^2$) | 23.5 | 7.9 | 108.0 |
| Burn rate (ft/min) | 29.71 | 3 | 120 |
| Surface temp. (a-wt) | .01268 | .0020 | .0532 |
| Surface temp. (°F) | 576 | 250 | 1165 |
| 6'' above surface (°F) | 757 | 240 | 1290 |
| 1/2''below surface (°F) | 111 | 68 | 187 |
| 2'' below surface (°F) | 77 | 65 | 85 |
| Organics (%) | 38.83 | 19.89 | 72.78 |
| Smoke color (rating) | 3.0 | 2 | 4 |
| Soil moisture loss (g/g) | .0019 | .0002 | .0298 |

Table 4. Average and extreme values of Common ryegrass variables.

| | Average | Low | High |
|---|---|---|---|
| | | Independent Variables | |
| Burn time (PDT) | 16:13 | 8:30 | 22:53 |
| Days after harvest | 38.00 | 19 | 53 |
| Air temperature (°F) | 69.0 | 55 | 81 |
| Relative humidity (%) | 64.83 | 19 | 80 |
| Soil moisture (g/g) | .0826 | .0466 | .1441 |
| Straw moisture (g/g) | .107 | .0382 | .2301 |
| Wind speed (mi/hr) | 5.6 | 0.0 | 18.0 |
| Absolute humidity ($g/m^3$) | 9.59 | 4.96 | 12.62 |
| | | Dependent Variables | |
| Suspended particulate ($\mu g/m^3$) | 25,603.4 | 11,407.8 | 46,805.1 |
| Residue wt($g/2ft^2$) | 14.11 | 8.6 | 23.2 |
| Burn rate (ft/min) | 64.33 | 18 | 130 |
| Surface temperature (a-wt) | .01932 | .0084 | .0343 |
| Surface temp. (°F) | 831 | 200 | 1670 |
| 6" above surface (°F) | 725 | 180 | 1360 |
| 1/2" below surface (°F) | 116 | 82 | 185 |
| 2" below surface (°F) | 78 | 72 | 90 |
| Organics (%) | 37.36 | 13.30 | 63.93 |
| Smoke color (rating) | 3.16 | 2 | 5 |
| Soil moisture loss (g/g) | .00642 | .0003 | .0209 |

of the small size of the particulate.

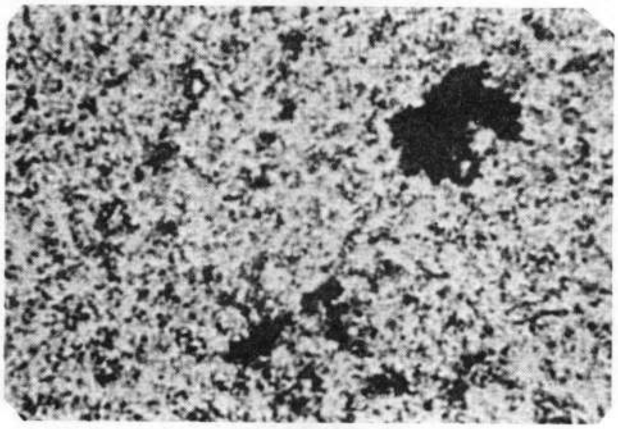


Figure 11. Typical suspended particulate, Polaroid camera, 1000 x magnification. (Approximate size of small, unagglomerated particulate is 0.5 μ.)

# DISCUSSION OF RESULTS

1. The fact that suspended particulate did not correlate significantly with measured variables, with the exception of the positive correlation with percent organics in Common ryegrass and a relation with regrowth in English (perennial) ryegrass, deserves some discussion. Some possible reasons for the lack of correlation are: (1) other variables, not measured, affecting suspended particulate measurements during the burning process, such as air-fuel ratio, (2) the inability to get a representative sample due to wind variations, or the inability to see when the sampler was surrounded by a representative sample of smoke, (3) the possibility that one or more of the variables are nonlinear. For example, straw moisture could, up to a certain point, hinder combustion efficiencies and yield high particulate emissions. Beyond this point excess straw moisture could prevent the burning of stubble and straw, significantly reducing the amount of emissions. The effect of this type of phenomena can prevent significant correlations and therefore hinder the stepwise multiple linear regression analysis.

Suspended particulate correlating positively with percent organics on Common ryegrass indicates combustion efficiencies do affect the amount of suspended particulate produced in the grass field burning process if one assumes that a higher percentage of organics represents less efficient combustion. The characteristic regrowth of English ryegrass might significantly change the combustion process thus producing an insignificant correlation between these two variables for the perennial grass.

Regrowth, although not correlating positively with suspended particulate, did show some value as a predictor. Had the air-fuel ratio been measured and adjustment in gas volumes made, regrowth would probably have shown a positive, significant correlation with the amount of suspended particulate released during a burn. The air-fuel ratio would indicate the amount of air supplied to a known amount of fuel and hence the amount of exhaust gases generated per pound of fuel burned.

Under extreme conditions it was observed that the suspended particulate values were not a true indication of total amounts of pollutants emitted. For example, under rapid burning conditions; no significant regrowth, low straw moisture, low humidity, high wind speed, and high air temperature, a plot will burn in a short time (three-fourths to one and one-half minutes), emitting a high concentration of pollutants as evidenced by the thick bellow of dark smoke. Under other extremes; abundant regrowth, high straw moisture, high humidity, and low wind speed, the plot would burn slowly and give off an extreme amount of gray smoke. Although the particulate samples taken under both extreme burns would be numerically similar (grams of particulate per cubic meter of gaseous effluent), the sample taken during the dark smoke was obviously less diluted by excess air. The real result of this effect was a greater total weight of particulate emitted in the gray smoke even though the particulate loading per unit volume of gas was similar with that of the dark smoke. Multiplying suspended particulate concentrations by the reciprocal of the burn rate is a possible step to adjust for this effect. This adjustment should be verified in future studies.

Observations in the field and from colored slides also revealed that under extreme conditions, abundant regrowth being the chief independent variable, the later in the season the burn is completed, the more total particulate is emitted to the atmosphere. Because of these observational analyses, it can be concluded that green regrowth does contribute to increasing the total amounts of particulate to the atmosphere.

Although Common ryegrass produced an average of about 1300 pounds more fuel per acre, its average suspended particulate emissions were lower than the English ryegrass by a factor of about 30 percent. This fact is quite significant. English ryegrasses' lower combustion temperatures and less rapid burning characteristics, and green regrowth are probably the major contributing factors to this observation.

2. Extreme burning conditions of unusually high wind, low

humidity, and low straw moisture, appeared to damage the grass as evidenced by the crowns of plants burning several minutes after passage of the flame front. Thus, it might not be practical from an agronomic standpoint to burn under these extreme conditions even though from an air pollution standpoint, the conditions seem optimum. Visual observations from an airplane flight in early November indicated that burning under varying environmental conditions did significantly affect the regrowth patterns in the perennial ryegrass. Studies to determine these effects are being carried out by the Oregon State University Farm Crops Department on the plots burned during this study.

3. For English ryegrass it appears that relative humidity rather than absolute humidity more directly affects the combustion process. Such combustion variables more directly affected by relative humidity are the negative correlation of burn rate with humidity, the positive correlation of straw moisture with humidity, and the negative correlation of smoke color with humidity.

4. For English ryegrass the amount of residue left on the ground after the burning process correlates positively with days after harvest, regrowth, soil moisture, straw moisture, absolute humidity, and relative humidity. Keeping residue at a minimum by taking these variables into consideration would help alleviate the air pollution problem due to re-entrainment of residue after combustion.

This would also aid in the efficiency of destroying disease hosts in the straw, and facilitating a more efficient weed spray application through a more direct contact with the soil.

However, one cannot assume in every case that the more residue left on the ground the more will be entrained to the atmosphere. It appeared that Common ryegrass had more residue left capable of being air-borne due to its less dense structure. The residue can be left in such an unburned condition that its air-borne pollution potential is significantly reduced.

For Common ryegrass soil moisture and relative humidity correlated positively with the amount of residue left. Better combustability of Common ryegrass evidently reduced the influence of straw moisture. Residue after the burning process averaged about 40 percent higher for English ryegrass as compared to Common ryegrass. Regrowth appears to be the contributing factor to this phenomena.

The stepwise linear multiple regression analysis for English ryegrass showed residue being dependent upon days after harvest, whereas Common ryegrass residue was dependent on days after harvest and soil moisture. Residue did not show any dependence on straw moisture, a suspected variable. The lag effect of diurnal change in straw moisture is one explanation of this observation.

The best indicator of the amount of residue left at the soil surface after the burning process is soil moisture both in English and Common ryegrass. Some possible explanations of this fact are: (1) soil moisture is not as readily affected by variables under extreme conditions, giving a stable characteristic, (2) significant heat is used up in evaporating the soil moisture, and (3) increased soil moisture gives the soil a higher heat conductivity, thus additional heat is conducted away from the combustion process.

5. In both English and Common ryegrass smoke color, a visual appearance of pollutants emitted to the atmosphere was significantly dependent on the straw moisture, relative humidity, air temperature, and wind speed during the burning process. The extreme dark appearance was related to low straw moisture, low humidity, high air temperature, high wind speed, and lower suspended particulate emissions. For English ryegrass high burn rate, high surface temperature and low residue were dependent variables related to dark smoke.

6. Common ryegrass burns more readily and intensely as indicated by less residue left, and higher combustion temperatures. This burning characteristic of Common ryegrass evidently overshadows the effect of many of the variables related to the burning process. Some of the variables which significantly influenced the combustion of English ryegrass but were unable to influence combustion of Common ryegrass were absolute humidity, straw moisture and wind speed. Possible characteristics of the Common ryegrass causing this phenomena are: (1) coarse texture with less surface

area to be affected by wind speed and soil moisture, (2) more fuel per acre, and (3) no significant regrowth to slow the combustion process.

7. Soil moisture loss from the burning process of Common ryegrass gave an average value of .642 percent loss. Taking into consideration the soil moisture movement in both directions, an average burn will drive into the atmosphere approximately 500 pounds of water per acre from the soil.

A high variability in moisture loss by the soil of English ryegrass makes it practically impossible to come up with a representative value of soil moisture loss from the burning process. Green regrowth seems to be the significant variable modifying or preventing soil moisture loss.

## CONCLUSIONS

1. Many environmental variables do significantly effect the grass field burning process. Thus, farmers should be concerned about environmental variables in achieving minimum pollution and their desired burning objectives for grasses.

2. Burning earlier in the season, whenever regrowth is involved, will facilitate less residue left on the ground which will result in better weed and disease control, and significantly reduce the amount of suspended particulate emitted to the atmosphere.

3. Smoke color is significantly dependent on straw (fuel) moisture. Thus, burning at low straw moisture conditions can significantly lower the visual pollution effect from grass field burning.

4. The combustion process, as indicated by surface temperatures taken during the burning of perennial ryegrass, is affected by air temperature, relative humidity, soil and straw moisture, wind speed, and regrowth. In order not to exceed desired temperature ranges, with resulting plant damage, consideration of these variables is important.

5. One cannot assume that all grasses produce pollutants in proportion to their respective acreages grown. For a pollution study, consideration must be given to the fact borne out in this study, that differences in particulate emissions result from burning

different grasses.

6. The data obtained from the different plots can provide much needed information concerning the effect of burning under variable conditions on the mortality and productivity of the grass. Such a study will be concluded by others through the harvest season of 1966.

7. This study can aid in interpreting the value of field burning and provide preliminary information for finding alternate means of control presently achieved by grass field burning. For example, by studying the mortality and productivity of the plots burned, critical temperatures attained, amount of residue left, and other variables, preliminary work for alternate chemical or physical applications to achieve the desired effects can proceed.

8. Range of values of variables have been defined, many of which were in doubt or unknown before this study. Perhaps through better instrumentation and measuring techniques more representative values will be achieved in future studies.

# RECOMMENDATIONS

1. It is hoped that studies will continue to determine the effect of burning under varying environmental conditions on the mortality and productivity of the grasses burned in this study.

2. It is also hoped that the data and plots from this study can be used in a preliminary investigation concerned with alternate means of weed, plant disease, and insect control. Due to increasing populations in the near future and the agricultural economies involved, a study of this scope seems justifiable. Referring to C. Stafford Brandt's (1) comments on slash burning, "Only a thorough evaluation of the effectiveness of applicable alternative procedures along with air pollution control needs of the community can resolve whether fire should be considered essential to the specific management problem," one can readily see that the day might not be far off when an alternate means of control will be necessary.

3. To obtain more positive results of the effect of environmental conditions on particulate emissions, air-fuel ratios need to be measured, more accurate combustion temperatures need to be recorded using single channel recorders which give continuous temperature-time response, and larger plots, 200' by 200', used in future studies.

4. Farmers should attempt to burn as early in the burning

season as possible especially for perennial grasses because of the regrowth characteristics. Burning early will also help alleviate the dispersion of pollutants as the frequency and intensity of inversions increase as the burning season progresses (Appendix Figures 2-5).

5. Investigations should be made into possible markets and use of straw, leaving only the stubble to be burned, plowed, or chemically treated. This would drastically reduce the pollution emissions but achieve the desired control effects presently provided by grass field burning.

6. A thorough study should be made of all major pollutants emitted from the field burning process along with their effect on the surrounding environment.

7. More qualitative and quantitative analyses should be made of the residue left after burning the plots under the varying environmental conditions.

8. A study should be made of the mechanisms by which the residue is dispersed to the atmosphere during and after the combustion process. Some specific areas of study being: (1) the amounts and fallout pattern resulting from residue entrained during or shortly after the combustion process, and (2) the amount and fallout pattern of residue picked up and carried by winds after the burning process is completed.

9. Similar studies should be made on other major grasses,

contributing to air pollution in the Willamette Valley, due to different individual characteristics.

# BIBLIOGRAPHY


1. Brandt, C. Stafford. Agriculture burning. Journal of the Air Pollution Control Association 16:85-86. February, 1966.

2. California. Dept. of Public Health. Bureau of Air Sanitation. A field study of air pollution in the lower Sacramento Valley during the 1960 fall season. Berkeley, 1961. 66 p. (Processed)

3. Feldstein, M., S. Duckworth, H. C. Wohlers, and B. Linsky. The contribution of the open burning of land clearing debris to air pollution. Journal of the Air Pollution Control Association 13:542-545. November, 1963.

4. Hardison, John R. Justification for burning grass fields. In: Proceedings of the Twenty-fourth annual meeting of the Oregon Seed Growers League, Salem, 1964. p. 93-96.

5. Li, Jerome C. R. Introduction to statistical inference. Ann Arbor, Mich., Edwards Bros., 1964. 658 p.

6. McElroy, John J. Relationships of agricultural burning and air pollution studied in preliminary experiments. California Agriculture 14:3-4. September, 1960.

7. Meland, Bruce R. A study of field burning under varying environmental conditions. Paper delivered at the annual meeting of the Pacific Northwest International Section of the Air Pollution Control Association, Vancouver, British Columbia, November, 1965.

8. Meland, Bruce R. Unpublished correlation matrix program for IBM 1620. Corvallis, Oregon State University, Department of General Science, 1965. 1 p. (Processed)

9. Oregon State University. Cooperative Extension Service Commodity data sheets: all grasses. Corvallis, 1965. Various sheets. (Processed)

10. Oregon State University. Cooperative Extension Service. Commodity data sheets: all grasses and legume seeds, 1960-64. Corvallis, Dec. 6, 1965. 1 sheet. (Processed)

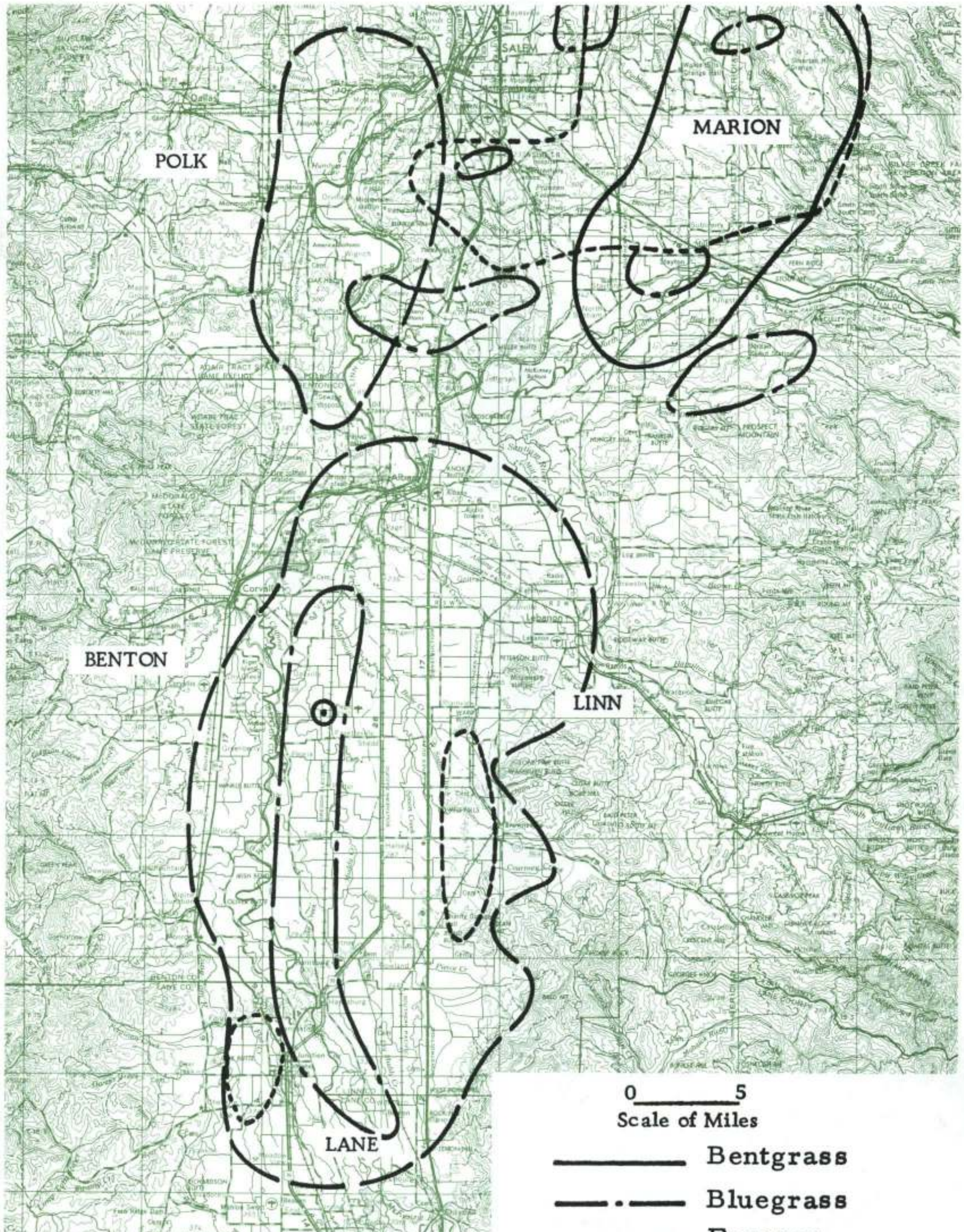
11. Stepwise Multiple Linear Regression Analysis, Computer Program Library for the IBM 1410. Corvallis, Oregon State University, Department of Statistics, 1964.

12. U. S. Public Health Service. Division of Air Pollution. Atmospheric survey training course manual. Cincinnati, Ohio, May 1963.

13. Warren, Rex. Field burning following grass seed harvest. Corvallis, 1965. 1 sheet. (Oregon State University Cooperative Extension Service. Fact sheet no. 96)

14. Yates, Tom, Director, Statistics Computer Lab, Oregon State University. Personal communication. Corvallis, Oregon. December, 1965.

# APPENDIX




Appendix Figure 1. A map of the southern Willamette Valley showing a general geographic distribution of grasses, and site of experimental plots.

## Appendix Table 1

### TABULATION OF DATA
English Ryegrass

| Plot no. | Date (65) | Burn time (pdt) | Days from harv. | Air temp. (°F) | Rel. hum. (%) | Soil mois. (lb/lb)b* | Soil mois. (lb/lb)a¶ | Straw mois. | Wind speed (mph) | Wind dir. (°) | Particulate wt (g) | Air flow (cfm) | Hi-vol time (sec) | Residue wt ($g/2\ ft^2$) | Burn rate (ft/min) | Sfc. temp. (a-wt)§ | Organics (%) | Smoke color (rating) | Regrowth (rating) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8/7 | 11:00 | 15 | 74 | 40 | 0.0360 | ---- | 0.1283 | 2.5 | 225 | 0.0071 | 56.5 | 5 | --- | 40 | 0.0205 | 28.16 | 3 | --- |
| 2 | 8/7 | 13:15 | 15 | 84 | 32 | 0.0349 | ---- | 0.0587 | 4.0 | 247 | 0.0299 | 45.0 | 25 | --- | 48 | 0.0348 | 30.10 | 4 | --- |
| 3 | 8/11 | 15:52 | 19 | 76 | 55 | 0.0662 | ---- | 0.2208 | 2.0 | 247 | 0.0747 | 66.0 | 54 | --- | 40 | 0.0140 | 32.66 | 3 | 2 |
| 6 | 8/13 | 14:59 | 21 | 79 | 35 | 0.1040 | 0.0813 | 0.1846 | 5.0 | 315 | 0.0496 | 58.0 | 52 | --- | 60 | 0.0087 | 29.84 | 3 | 2 |
| 7 | 8/13 | 17:21 | 21 | 79 | 34 | 0.1098 | 0.0949 | 0.2327 | 5.0 | 337 | 0.0837 | 57.0 | 57 | --- | 40 | 0.0020 | 53.76 | 3 | 2 |
| 10 | 8/21 | 15:07 | 29 | 76 | 44 | 0.1109 | 0.1245 | 0.1861 | 6.5 | 315 | 0.0747 | 56.5 | 60 | 41.8 | 35 | 0.0055 | 52.48 | 2 | 3 |
| 11 | 8/23 | 16:50 | 31 | 74 | 54 | 0.1052 | 0.1310 | 0.1845 | 6.0 | 292 | 0.0365 | 54.7 | 35 | 9.4 | 50 | 0.0153 | 49.32 | 3 | 3 |
| 14 | 8/24 | 16:15 | 32 | 75 | 45 | 0.0884 | 0.1013 | 0.1310 | 3.8 | 292 | 0.0490 | 55.5 | 59 | 8.4 | 67 | 0.0154 | 43.27 | 3 | 2.5 |
| 17 | 8/26 | 18:55 | 34 | 71 | 55 | 0.1082 | 0.1287 | 0.2422 | 4.6 | 292 | 0.0313 | 59.0 | 55 | 8.4 | 45 | 0.0038 | 35.46 | 3 | 2 |
| 18 | 8/27 | 16:55 | 35 | 69 | 40 | 0.1044 | 0.1109 | 0.1588 | 12.0 | 337 | 0.0535 | 60.0 | 54 | 10.7 | 80 | 0.0167 | 26.17 | 3 | 3.5 |
| 20 | 8/30 | 17:00 | 38 | 82 | 20 | 0.0773 | 0.0893 | 0.1189 | 15.0 | 0 | 0.0542 | 56.5 | 76 | 7.9 | 100 | 0.0532 | 30.26 | 4 | 4 |
| 23 | 8/31 | 12:40 | 39 | 78 | 29 | 0.0655 | 0.0912 | 0.2098 | 5.0 | 22 | 0.0687 | 56.5 | 55 | 10.0 | 64 | 0.0217 | 72.78 | 3 | 3 |
| 24 | 9/2 | 15:20 | 41 | 69 | 40 | 0.0589 | 0.0686 | 0.1617 | 5.7 | 315 | 0.0606 | 61.0 | 95 | 10.4 | 52 | 0.0078 | 33.00 | 3 | 1.5 |
| 27 | 9/7 | 20:55 | 46 | 64 | 43 | 0.0478 | 0.0502 | 0.1709 | 5.0 | 337 | 0.1119 | 60.5 | 77 | 10.3 | 80 | 0.0120 | 42.36 | 2 | 3 |
| 29 | 9/9 | 13:10 | 48 | 65 | 46 | 0.0508 | 0.0504 | 0.1648 | 3.0 | 337 | 0.1035 | 63.0 | 120 | 11.3 | 17 | 0.0168 | 42.71 | -- | 2.5 |
| 30 | 9/10 | 15:40 | 49 | 73 | 40 | 0.0554 | 0.0519 | 0.1838 | 2.0 | 292 | 0.0989 | 59.5 | 93 | 12.3 | 45 | 0.0155 | 47.52 | 3 | 3 |
| 35 | 9/17 | 13:30 | 56 | 65 | 19 | 0.0479 | 0.0384 | 0.0685 | 7.0 | 0 | 0.0553 | 59.0 | 50 | 14.9 | 72 | 0.0258 | 19.89 | 4 | 4 |
| 36 | 9/23 | 16:35 | 62 | 85 | 17 | 0.0477 | ---- | 0.0699 | 13.0 | 22 | 0.1006 | 54.5 | 90 | 9.5 | 120 | 0.0285 | 22.26 | 4 | 3 |
| 37 | 10/20 | 18:15 | 89 | 65 | 66 | 0.1844 | 0.1782 | 0.3551 | 1.5 | 0 | 0.3426 | 57.5 | 280 | 80.0 | 3 | 0.0042 | 34.44 | 2 | 5 |
| 38 | 10/21 | 15:30 | 90 | 66 | 60 | 0.2038 | 0.1740 | 0.3524 | 2.5 | 45 | 0.1722 | 56.5 | 150 | 108.0 | 4 | 0.0043 | 39.49 | 2 | 5 |
| 39 | 10/21 | 17:40 | 90 | 65 | 74 | ---- | ---- | 0.3726 | 1.5 | 0 | 0.1960 | 56.5 | 160 | 120.0 | 5 | 0.0024 | 39.49 | 2 | 5 |

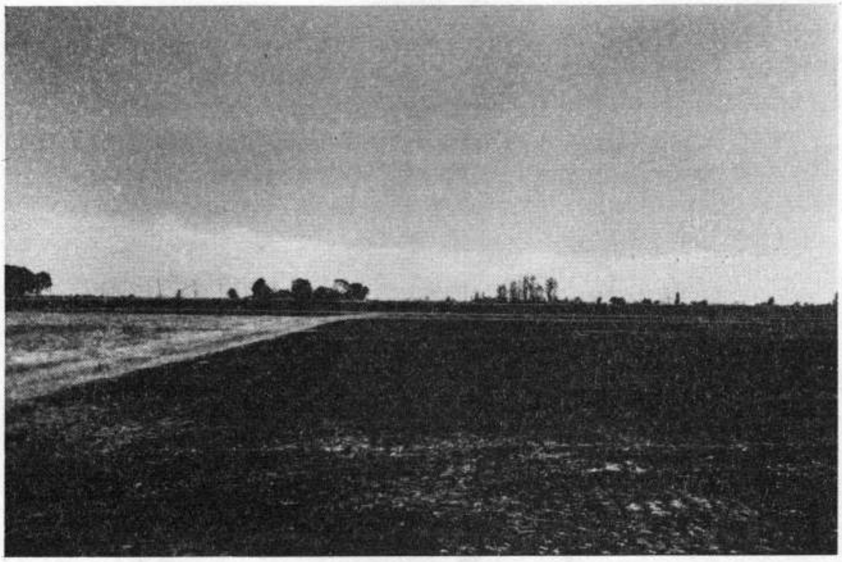
* before burning of plot
¶ after burning of plot
§ weight of area under the surface temperature-time curve in grams

Appendix Table 2

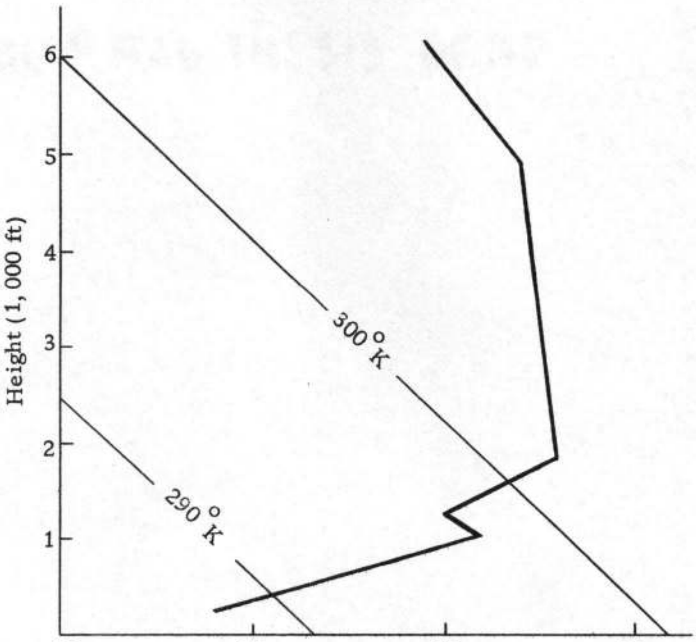
TABULATION OF DATA
Common Ryegrass

| Plot no. | Date (65) | Burn time (pdt) | Days from harv. | Air temp. ($^oF$) | Rel. hum. (%) | Soil mois. (lb/lb)b* | Soil mois. (lb/lb)a¶ | Straw mois. | Wind speed (mph) | Wind dir. ($^o$) | Particulate wt (g) | Air flow (cfm) | Hi-vol time (sec) | Residue wt ($g/2 ft^2$) | Burn rate (ft/min) | Sfc. temp. (a-wt)§ | Organics (%) | Smoke color (rating) | Regrowth (rating) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 8/11 | 17:38 | 19 | 77 | 54 | 0.0516 | ---- | 0.0862 | 2.0 | 202 | 0.0134 | 59.5 | 13 | --- | 50 | 0.0262 | 35.82 | 4 | --- |
| 5 | 8/13 | 12:12 | 21 | 74 | 45 | 0.0833 | 0.0844 | 0.2301 | 3.0 | 22 | 0.0259 | 62.5 | 40 | --- | 60 | 0.0343 | 42.47 | 2 | --- |
| 8 | 8/20 | 19:58 | 28 | 65 | 75 | 0.1441 | 0.1237 | 0.1247 | 4.0 | 240 | 0.0488 | 59.7 | 37 | 23.2 | 50 | 0.0100 | 63.93 | 2 | --- |
| 9 | 8/21 | 12:00 | 29 | 72 | 50 | 0.1263 | 0.1102 | 0.1564 | 5.0 | 337 | 0.0390 | 56.0 | 57 | 18.9 | 50 | 0.0118 | 50.26 | 3 | --- |
| 12 | 8/23 | 19:50 | 31 | 65 | 80 | 0.1181 | 0.1026 | 0.1194 | 8.5 | 240 | 0.0063 | 58.5 | 20 | 21.8 | 45 | 0.0255 | 22.22 | 3 | --- |
| 13 | 8/24 | 14:20 | 32 | 74 | 52 | 0.0934 | 0.1134 | 0.0717 | 4.0 | 225 | 0.0159 | 56.5 | 35 | 11.9 | 60 | 0.0214 | 17.61 | 4 | --- |
| 15 | 8/24 | 19:45 | 32 | 67 | 64 | 0.1143 | 0.0994 | 0.1016 | 8.5 | 315 | 0.0081 | 55.8 | 15 | 15.0 | 60 | 0.0084 | 41.97 | 4 | --- |
| 16 | 8/26 | 16:50 | 34 | 78 | 43 | 0.1133 | 0.0924 | 0.0950 | 8.0 | 292 | 0.0237 | 59.5 | 30 | 10.3 | 80 | 0.0182 | 34.60 | 3 | --- |
| 19 | 8/27 | 18:20 | 35 | 68 | 44 | 0.1037 | 0.1070 | 0.0803 | 12.5 | 292 | 0.0100 | 60.0 | 15 | 12.3 | 80 | 0.0167 | 28.00 | 4 | --- |
| 21 | 8/31 | 8:30 | 39 | 55 | 65 | 0.0724 | 0.0646 | 0.1856 | 1.5 | 225 | 0.0737 | 63.0 | 75 | 8.6 | 18 | 0.0100 | 36.63 | 2 | --- |
| 22 | 8/31 | 10:35 | 39 | 70 | 34 | 0.0779 | 0.0774 | 0.0767 | 5.0 | 67 | 0.0307 | 58.0 | 86 | 12.6 | 90 | 0.0210 | 13.30 | 4 | --- |
| 25 | 9/2 | 16:53 | 41 | 68 | 42 | 0.0661 | 0.0484 | 0.0851 | 6.0 | 292 | 0.0623 | 58.0 | 65 | 9.7 | 50 | 0.0205 | 43.66 | 3 | --- |
| 26 | 9/7 | 16:10 | 46 | 81 | 19 | 0.0580 | 0.0559 | 0.0382 | 18.0 | 0 | 0.0287 | 58.0 | 47 | 11.2 | 130 | 0.0250 | 31.36 | 5 | --- |
| 28 | 9/7 | 22:53 | 46 | 59 | 52 | 0.0537 | 0.0407 | 0.0753 | 0.0 | --- | 0.0535 | 59.0 | 61 | 17.0 | 45 | 0.0188 | 46.73 | --- | --- |
| 31 | 9/14 | 12:25 | 53 | 68 | 58 | 0.0604 | ---- | 0.0908 | 4.0 | 225 | 0.0330 | 67.0 | 54 | 15.7 | 60 | 0.0207 | 47.26 | 2 | --- |
| 32 | 9/14 | 17:00 | 53 | 70 | 59 | 0.0543 | 0.0543 | 0.0913 | 5.0 | 315 | 0.0296 | 62.5 | 40 | 9.3 | 110 | 0.0102 | 40.54 | 3 | --- |
| 33 | 9/14 | 18:40 | 53 | 66 | 73 | 0.0466 | 0.0394 | 0.1040 | 7.0 | 292 | 0.0603 | 59.5 | 67 | 13.7 | 80 | 0.0318 | 41.79 | 3 | --- |
| 34 | 9/14 | 20:00 | 53 | 65 | 78 | 0.0500 | ---- | 0.1311 | 0.0 | --- | 0.0360 | 59.5 | 73 | 14.7 | 40 | 0.0173 | 34.44 | 3 | --- |

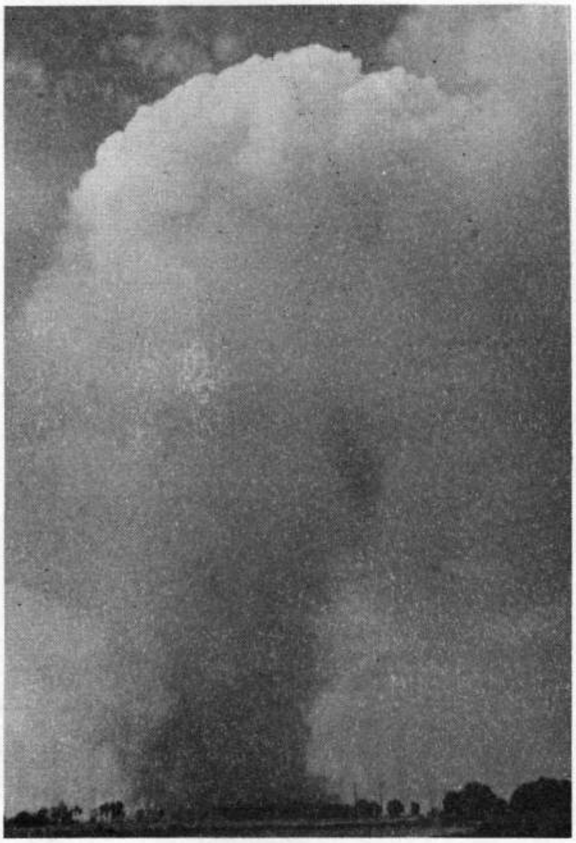
* before burning of plot
¶ after burning of plot
§ weight of area under the surface temperature-time curve in grams



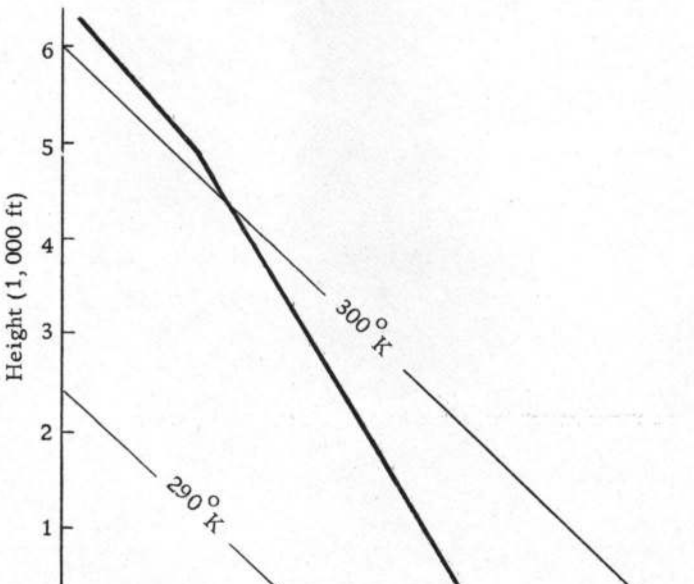
Appendix Figure 2. Characteristic inversion conditions limiting the dispersion of smoke.




Appendix Figure 3. Corresponding lapse rate showing inversion. (4:00 A.M. sounding)



Appendix Figure 4. Characteristic good smoke dispersion conditions without inversion.




Appendix Figure 3. Corresponding lapse rate showing inversion. (4:00 A. M. sounding)