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DIRECT ESTIMATION OF SURFACE FUEL BULK DENSITY AND LOADING IN WESTERN MONTANA AND NORTHERN IDAHO

by

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ABSTRACT

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Direct estimation of surface fuel bulk density and loading on western Montana and northern Idaho (85 pp.)

Director: Dr. Hans Zuuring H. Z.

Bulk density of forest fuels for fire algorithms is a measurement of weight per unit volume of fuel available for fire spread. Currently, fire algorithms use average fuel depth and loading to calculate bulk density, but these two field measurements are subjective and difficult to measure. This study examined the variability of direct estimates of bulk density, hypothesizing that bulk density did not vary significantly over a wide range of fuel conditions, and a small data file of bulk density constants could be determined and stored in fire algorithms. These constants would eliminate the field measurement of fuel depth. To test this hypothesis, eight habitat types that covered a wide range of fuel conditions were sampled to determine mean bulk densities for two fuel strata--litter and grass/forb. The geometric means, rather than the arithmetic means, were considered to be the best measure of central tendency. The litter stratum bulk density did not differ significantly between habitat types, and a bulk density of 1.46 lbs/ft^3 (0.0228 g/cc) was considered representative for much of western Montana and northern Idaho. The grass/forb stratum bulk density did differ significantly between habitat types. However, seven of the eight habitat types were put into three groups each group being represented by a constant bulk density--0.18, 0.11, and .065 lb/ft^3 (0.0029, 0.0018, 0.0010 g/cc).

Stepwise regression of grass/forb, subshrub, and litter loadings on six habitat type characteristics did not give any reliable loading predictive equations.

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INTRODUCTION

Several analytical fire simulation models are presently being used, by State and Federal agencies, to facilitate management of lands in their jurisdiction. The use of these models range from (1) training firefighting personnel, to (2) simulating fire potentials in wildland and harvesting areas, to (3) making more efficient use of firefighting suppression resources.

For example, FIRESCOPE is a cooperative Federal-State-County program aimed at making wildland firefighting more effective in southern California (Albini 1976).

The National Fire-Danger Rating System (Deeming and others 1974) is used nationally by State and Federal agencies for administration and coordination of fire control efforts. This system is used in contractual clauses involving timber harvesting activities (i.e., closures and working hours) and in estimating wildland fire danger which can lead to public land closure.

Also, the Hazard Appraisal Program (Albini 1976) assesses fire potentials for proposed harvesting areas in western Montana and northern Idaho forests. This program uses analytical fire models to simulate various fire situations created by harvesting methods before harvesting has commenced.

FIREMOD (Rothermel 1972) and FOCUS (Fire Operational Characteristics Using Simulation)(Albini 1976) are two other models used to assess fire potentials in differing situations.

The trend of mathematical models indicates that such models are becoming increasingly important in management of lands under the Federal and State jurisdiction. However, simulations generated by these analytical models can be no more reliable than their inputs, and the major inputs are attributes of the pertinent fuels; for example--fuel loading[1/] and bulk depth, surface-area-to-volume ratio, particle density, mineral content, etc. To this point, fire behavior simulation has been the major topic of discussion, but as brought out in the previous sentence, fuel is the all-important entity that must be understood. Wildfire management is literally impossible without fuel management.

The State and Federal agencies currently using the fire simulation models could use them more widely if two of the fuel parameters--fuel loading and bulk depth--were more easily estimated. Currently, these two fuel parameters restrict fire modelling use. However, if the proposed methodology is successful then these two fuel parameters will become easier to appraise and make fire modelling more successful. The ability for State and Federal agencies to use fire modelling more extensively--due to more efficient fuel appraisal techniques--would save both time and money in fire hazard appraisal.

[1/] For technical terms see Appendix I.

PROBLEM

Existing analytical fire models are capable of estimating fire behavior when parameters such as fuel loading, bulk depth, and moisture content are provided.[2] Other fuel parameters are needed but are usually stored as constants. The problem is that fuel loading and bulk depth are costly to measure with present sampling methods, which limits the use of existing fire models. To resolve this dilemma, a technique is needed to estimate these fuel parameters from easily recognizable forest characteristics such as vegetative types,[3] age, percent tree crown closure, aspect, elevation, etc. The fuels that must ultimately be quantified are duff, litter, grasses and forbs (live and dead), tree regeneration, shrubs, and timber (live and dead). If all or part of these fuels could be estimated from forest characteristics, the time and money spent in collecting fuel information would be reduced signficantly, and the fire models would become more economical to use.

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[2] It must also be assumed that all other requirements such as constant wind direction, speed, and homogeneous fuel beds are met.

[3] A vegetative type is described by its overstory and understory composition; for example, short needle conifer overstory with grass/forb understory.

STATEMENT OF OBJECTIVES

As mentioned previously, there are two fuel parameters that are estimated in the field that cause problems with fire modelling; these are fuel bulk depth and loading. Fuel bulk depth is used to calculate fuel bulk density within the fire models. Bulk density is defined as fuel weight per unit volume. Close examination of the bulk density formula shows that it should remain constant for many different types of fuel loadings and depths. The reason for this possible consistancy is that, as fuel loading increases so should fuel depth (indications of this can be seen in Albini and Brown 1978), resulting in constant bulk densities. This example illustrates that bulk density probably varies much less than does fuel depth, therefore, instead of measuring fuel depth in the field, bulk density should be measured directly. However, estimates of bulk density still require a depth measurement, which means that if the bulk density concept is to be successful, constant bulk densities representing large land management units would need to be developed. To test whether it is possible to develop such constants, habitat types from western Montana and northern Idaho were selected as suitable management units.

Ninety-five habitat types and phases (Pfister 1977) were separated into eight distinct fuel complexes, which will be called vegetative types. One habitat type from each of the eight vegetative types was selected to represent that fuel complex. This leads to the primary objective of the study, which was to examine a procedure that would eliminate direct field measurement of fuel depth. This procedure was to directly sample the bulk densities of these eight distinct vegetative types, which cover a wide spectrum of fire hazard levels, and determine if there were any significant differences between their bulk density means. If the differences were small, then it would seem logical that a small data set of constant bulk density means representing all vegetative types could be developed and stored within the fire models. This would eliminate the expensive and difficult fuel depth measurement from the field.

Fuel loading is less of a problem than fuel depth for fire modelling, but is still an expensive parameter to estimate. Since fuel loading had to be obtained for bulk density determinations, this study lent itself well to preliminary investigation of possible correlations between fuel loading (grass/forb, subshrubs, and litter) and forest (stand) characteristics. Therefore, as a secondary objective fuel loading and habitat type characteristic relationships were studied via stepwise regression analysis. An indepth regression analysis is beyond the scope of this thesis, but any preliminary findings were thought to be useful.

METHODS

Current fire models estimate fire rate of spread from one fuel stratum. However, most forest structures contain more than one stratum. To illustrate, consider the forest fuel continuum of: duff, litter, grass/forb and subshrub, shrub, saplings and larger trees; each sequential step provides a separate stratum. When fuels from more than one stratum are estimated and put into fire models, they are homogenized into one stratum before rate of spread is calculated. However, current research is investigating the possibilities of estimating rate of spread from more than one stratum. To assure that the data from this study could be used with either of these approaches, the two fuel strata investigated (litter and grass/forb) were measured separately.

The litter stratum, is defined as all dead nondecomposed horizontally oriented organic material lying in a continuous stratum just above the forest duff layer. Litter is composed of dead grasses and forbs, bark flakes, leaves, needles, down and dead woody material less than 1 inch, cones, and any moss that can be gathered without exposing its roots. The grass/forb stratum consists of those fuels vertically oriented, both living and dead, which form the next sequential stratum just above the litter (see Appendix II). This stratum is primarily composed of grasses, forbs, cones, subshrubs, reproduction, and dead and down woody material.

Bulk densities were determined (for both the litter and grass/forb strata) for eight separate vegetative types. The vegetative types were selected by use of Pfister and others(1977) constancy and average percent coverage tables. Pfister's tables represented 10

National Forests and 95 different habitat types and phases located in Montana. The constancy and percent ground cover figures were used to build tables that summarized the average ground cover of trees, shrubs, subshrubs, grasses, and forbs by species and habitat type. From these summarized tables, it was possible to derive the relative percent ground cover of:

1. Long-needled overstory, e.g., *Pinus ponderosa,*
2. short-needled overstory, e.g., *Pseudotsuga menziesii,*
3. intermediate-needled overstory, e.g., *Pinus contorta,*
4. shrubs, e.g., *Physocarpus malvaceus,*
5. subshrubs, e.g., *Arctostaphylos uva-ursi,*
6. forbs, e.g., *Linnaea borealis,* and
7. grasses, e.g., *Calamagrostis rubescens*

for each of the 95 habitat types and phases.

Once these percents were summed for each habitat type, it was possible to categorize each habitat type under one of the vegetative types listed in Table 1. The next step was to select a particular habitat type that best fit the structure of the vegetative type in question and also represent a significant amount of acres. For example, if the structure was a long-needle overstory with grass understory, then the habitat type that was selected had to contain a major percent of both the indicated understory and overstory. The National Forest Region One office was able to supply approximate acres for each habitat type for five National Forests in western Montana. Armed with the information described above, the habitat types shown in Table 1 were selected to represent their corresponding vegetative type.

Table 1--Habitat types used to represent different vegetative types.

Habitat types[1/] representing vegetative type	ADP code	Vegetative type	
		Overstory	Understory
1) PIPO/PUTR/FEID	162	long needle	shrub/grass/ subshrub
2) ABLA/VACA	640	intermediate needle	shrub/grass/ subshrub
3) PSME/PHMA/PHMA	216	short needle	shrub/grass/ subshrub
4) ABLA/VASC/VASC	732	intermediate needle	subshrub
5) ABLA/LIBO/XETE	662	short needle	subshrub
6) PIPO/FEID/FESC	142	long needle	grass
7) PSME/CARU/CARU	323	short needle	grass
8) ABLA/CLUN/CLUN	621	short needle	shrub/forb/litter

[1/] For definitions see Appendix I.

Field Procedures

Selection of sample areas for each habitat type was subjective. This was done in hopes of assuring a representative sample of the variability within a given habitat type. To achieve this, four areas were deliberately selected that were (four for each habitat type) far enough apart so that any local environmental condition of one area would not have affected the development of the other. Any area that did not clearly represent the habitat type in question was not sampled. Areas were also selected on the basis of overstory percent crown closure to assure a representative sample of the crown closure gradient (0 to 100 percent closure).

Sample plot centers were located within areas by pacing a predetermined distance (far enough to avoid road-edge effects) along a selected azimuth. The azimuth was selected to insure that the plots were located across the variation of the area. Once a plot center was located, the investigator determined whether or not the plot was representative of the habitat type, for instance, was the plot conspicuously nonhomogeneous? in an obvious opening? or in an unusual mycrosite--swale, seep, rock outcrop? If the plot was atypical of the habitat type an alternate plot was located.

The sampling plot was circular, an 1/20th acre in size. The size was thought to be large enough to accurately estimate tree crown closure and small enough to adequately sample its loading and bulk density.

The sampling design used was a nested one. This design was selected to effectively investigate the components of variance of each habitat type's bulk density. The sampling intensity was determined by the available man-power and money. An example of one habitat type's sampling intensity will depict the nested design.

- Habitat type (8 habitat types)
    - Areas within the habitat type (4 areas)[4/]
        - Plots within areas (5 plots)
            - Quadrats within plots (12 quadrats)

This totals to 240 quadrats per habitat type. However, bulk density measurements were taken on only 80 of these. The remainder were used to employ a double sampling technique (Cochran 1977) to inexpensively

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[4/] Habitat type 142 had five areas.

expand the loading sample size.

The retangular quadrat used for the actual loading and bulk density determinations was a 30 X 60 cm quadrat. The size was thought to be large enough to reduce "edge effect" when collecting the clippings of grasses, forbs, subshrubs, etc., but small enough so that loadings collected could be easily handled. Also, by hinging the four corners of the rectangular quadrat, it was possible to collapse it for transportation purposes. Circular plots, although more efficient for reducing "edge effect," are more costly to construct and not as easily carried through and around large shrubs and dangling tree limbs.

The double sampling was done to increase the loading sample size for litter, grass/forbs, and subshrubs. It was for these three classes of material that loading and habitat type characteristic relationships were to be investigated. To implement the double sampling, one-third (80) of the 240 quadrats had their litter, grass/forbs, and subshrub loading (first) visually estimated and (second) collected. The collection process was merely the clipping of litter, grass/forb, and subshrubs from the quadrats and then putting the clippings in a paper sack for transportation to the laboratory for drying and weighing. For the remaining 160 quadrats only visual estimates of the litter, grass/forb, and subshrub loadings were made.

Making visual estimates of the many types of forest grasses, subshrubs, litter, and size classes of down-woody material are difficult. Three methods were employed to try and increase the consistancy of the visual estimates. (1) Prior to each day's data collection, the observers would estimate, clip, and weigh several bunches of typical plants found in that day's area. This would continue until each observer felt confident that he/she could consistently and accurately estimate the grass/forb, subshrub, and litter's loading for the quadrats. (2) Initially, two independent visual estimates were made (one from each of the two observers), and the average of these two estimates was recorded as the final estimate. As the observers became more experienced at estimating loadings, it was felt that one estimate was probably as accurate as the average of two independent estimates. To test this, each observer recorded their loading estimates. Each observer's estimates were plotted against the actual weights, as were their averages. Linear regression lines were fit to each of the data sets for nine separate trials. Four times the Standard Error (SE) was smaller for the average, three times observer one had the smaller SE and two times observer two had the smaller SE. From these findings it was decided to continue with just one estimator. This helped speed up the data collection. (3) As Hutchings and Schmautz (1969) pointed out, an observer has difficulty remembering unit weights of various plant types over a period of time, especially when the observer is fatigued or has attitude changes. To help resolve this dilemma, at the start of every area the observer would estimate unit[5/] weights of typical plants found in the area. The units of plants were then weighed on spring scales in the field. Their weights were recorded and carried with the observer doing

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[5/] Unit = Observers average hand full of any particular plant.

the estimating for the day. Once at an actual quadrat to be estimated, it was a simple procedure to visually estimate units of plants or litter, and then mentally multiply these units by the unit weights that were recorded earlier.

For every 1/20th acre plot a verbal description was recorded on a portable tape recorder. The tapes were typed and kept as a permanent record that was used during data analyses to help interpret results. They helped in understanding any "wild" variability within the data.

Once a plot center had been located (as described earlier), it was divided into four equal quadrants (see Appendix III). To eliminate personal bias in dividing the circular plot into four equal quadrants, one of the two perpendicular diameters always pointed uphill.

Once three of the 30 X 60 cm quadrats had been placed in one of the four quadrants the following procedures were used:

A) A dice was thrown to select a quadrat for actual determination of loading and bulk depths.

B) The following information was taken from the selected quadrat:

    1) Six bulk depth measurements were taken for each of the two strata--litter and grass/forb.

    2) Separate visual weight estimates were made of the litter, grass/forbs, and subshrubs.

    3) All cones and 0-1-inch twigs were collected, and bagged separately.

    4) Subshrubs, grass/forbs, and litter were gathered and bagged separately.

C) The litter, grass/forb, and subshrub loading in the other two quadrats were only estimated (depths were not taken).

D) The d.b.h. of every tree in the quadrant was recorded by 2-inch classes.

E) An ocular estimate was made of the crown closure.

The same sampling procedure was then applied to the remaining three quadrants.

For each 1/20th acre plot the following area characteristics were taken: aspect (±1°), elevation (±100 ft, ±91.4 m), percent crown closure classes (class 1 = 0-19%; 2 = 20-39%; 3 = 40-59%; and 4 = 60+%), percent slope (±1%), number of trees per acre and age (±1 year; also, see Appendix IV). Age is difficult to assess because most forests are uneven aged. For a better estimate of age, up to three different ages were recorded--1) mature overstory, 2) successional-story if present, and 3) understory if present. Unfortunately, not enough age data was collected for the two understory phases to be used in the regression analysis. Therefore, only the overstory age was used.

Although most current research measurements are recorded in metric units, I found it difficult to comply completely. The d.b.h. tapes used measured in inches; the altimeter measured in feet; and the use of a 1/20th acre plot rather than a equivalent hectare plot was a stigma in the study. All quadrat depth measurements (cm) and weight estimages (g) were in metric units, but when bulk density was calculated in g/cc it was difficult to communicate with fire modellers working in lbs/ft^3. Currently, FIREMOD (the fire algorithm I used) requires input variables in English units. Therefore, all tables and figures are shown as follows: English, with metric conversion given as a footnote.

Laboratory Procedures

All of the litter and grass/forb loadings that were collected in the field were put into drying ovens and dried at 102°C for 24 hours. Oven dry weights were recorded on the BULK DENSITY FIELD FORM to the nearest 0.1 gram. The drying temperature and time used was selected to assure complete dryness and to prevent loss of volatils (Ponto 1972).

Variables and Sources of Variation

Fuel bulk depth has been a difficult variable for scientists to either measure consistently or to predict (Albini and Brown 1978). By definition, bulk depth for fire management is the average depth of fuel that actually contributes to the moving fire front. Therefore, those fuels that add significantly to the depth but not to the rate of fire spread, should be excluded from depth measurements. Herein lies the dilemma, since judging which fuels contribute to rate of spread and which do not is *subjective*. To improve the likelihood of consistent judgments among the study crew, guidelines were developed and are as follows:

1) All material over one-inch in diameter was ignored, since these materials do not add significantly to the spread rate but do add significantly to loading. However, if this large material supports fine fuels, then the depth of these fine fuels was recorded but the large fuels ignored.
2) Fine downed and dead woody material, 0.0-1.0 inch (2.54 cm)

in diameter that projected significantly above the rest of the fuels was ignored, for both height and weight (see Appendix II).

3) Vertical bony shrub stems passing through the grass/forb fuel complex were ignored.

4) Heights of isolated grass seed stalks were ignored, however, their weight was included since the stalk crumbles rapidly in a fire and adds to the moving fire front.

5) Fine branchwood from trees or shrubs that dangled in the grass/forb fuel complex was included in the weight, but the depth for the quadrat was determined by the grass/forb material.

By using the above guidelines to collect bulk depth and loading it was hypothesized that the two variables (bulk depth and loading) would correlate linearily and show bulk density constancy.

Preliminary investigation of loading predictability from area characteristics required the collection of at least the following variables: aspect, elevation, percent slope, age, basal area per acre, trees per acre, and percent crown closure. These variables were thought to be easy for land managers to assess and also have significant influence on the vegetative development of habitat types.

Preliminary study preparation also revealed that visual projection of crown closure to the ground was noticeably subjective. However, work done by Pase and Hurd (1957) showed that percent crown closure did not influence vegetative production significantly beyond 50 or 60 percent.

Considering this and the subjectivity of projecting crown closure to the ground, percent crown closure was categorized as follows: 0-19 percent, 20-39 percent, 40-59 percent, and 60+ percent. By using aerial photos of the 1/20th acre plots, canopy closure can be estimated much more accurately, but this capability was beyond the means of this study. For this reason, percent canopy closure class estimates, as described above, were deemed reasonable and their codes 1, 2, 3, and 4 respectively, were used as dummy variables in the regression analysis.

Analyses

Primary Objective--For the bulk density analyses there were two complete and distinct data sets--one for the litter bulk density and one for the grass/forb bulk densities. Unless specifically noted otherwise the "bulk density" verbiage will relate to both litter and grass/forb.

Using the bulk depth and loading measurements, 80 bulk densities were determined for each habitat type.

$$\rho_{b_{i(jk)}} = \frac{W_{i(jk)}}{V_{i(jk)}}$$

where:

ρ_b = bulk density

W = quadrat fuel loading (g)

V = 30 cm X 60 cm X $\overline{d}$ cm

$\overline{d}$ = average of six quadrat depth measurements (cm)

i = 1,2; 1=litter and 2=grass/forb

j = 1,...,8 habitat types

k = 1,...,80 quadrats[6]

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[6] Habitat type 142 had 100 bulk density determinations.

Before mean bulk densities were determined, histograms were made of each habitat type's 80 individual bulk densities (see Appendix V). It was found that all had lognormal distributions.[7/] To normalize this distribution a transformation of bulk densities was necessary. The procedure used to select this transformation is described subsequently.

By plotting the actual arithmetic mean on the lognormal distribution, it was possible to see that the heavier bulk densities were causing the mean to shift to the right. The median bulk density however, (see Figure 1) more closely approximated the apex of the lognormal distribution and was considered a more plausable value to use for the following three reasons: First, fire spreads through areas with lower bulk densities (Rothermel 1972), and since the median was lower than the mean bulk density it was considered closer to a optimum (for fire spread) bulk density. Secondly, more of the observed values nest around the median than the mean. Thirdly, in theory the geometric mean ($\bar{X}^G$)

$$\bar{X}^G \equiv [\prod_{i}^{n} X_i]^{1/n}$$

where:

n = number of observations

of a lognormal distribution *approximates* the median of the same distribution in arithmetic units. Consequently, the geometric mean could be used to represent the median. And, since the geometric mean equals the mean of a lognormal distribution,

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[7/] The lognormal distribution is skewed to the left with a long tail to the right (see Figure 1, top and bottom caption).

let $\overline{X}$ = mean of $\log_e (x)$ distribution

$$e^{\overline{X}} = X^G \equiv [\prod_i^n X_i]^{1/n}$$

$$\overline{X} = \frac{1}{n} [\sum_i^n \ln X_i]$$

a $\log_e$ transformation was used to normalize the skewed distribution. Table 2 shows a comparison between the bulk density mean, median, and transformed geometric mean for grass/forb and litter bulk densities. All the bulk density distributions show the median and geometric mean to be very close, except for the distribution of litter for ABLA/CLUN/CLUN.

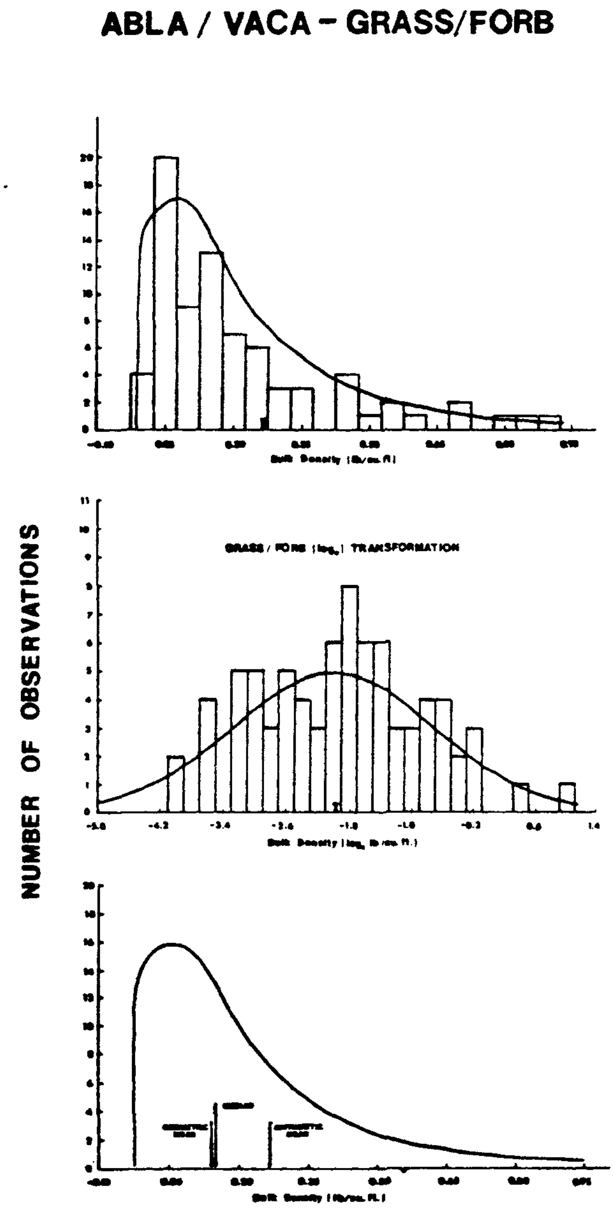


Figure 1--Visual comparison of the arithmetic mean, median, and geometric mean for the ABLA/VACA habitat type.

Table 2--Comparison of three measures of central tendencies for habitat type bulk densities.

Grass/forb (lbs/ft^3)					Litter (lbs/ft^3)		
Habitat type[1]	Code	Mean[2]	$e^{\bar{x}_G}$[3]	Median[4]	Mean[2]	$e^{\bar{x}_G}$[3]	Median[4]
PIPO/FEID/FESC	142	.22	.06	.06	1.43	1.27	1.31
PIPO/PUTR/FEID	162	.18	.07	.07	1.38	1.25	1.20
PSME/PHMA/PHMA	261	.16	.11	.09	1.55	1.34	1.40
PSME/CARU/CARU	323	.26	.11	.11	2.00	1.36	1.43
ABLA/CLUN/CLUN	621	.30	.18	.17	2.06	1.09	2.07
ABLA/VACA	640	.26	.13	.15	1.80	1.61	1.58
ABLA/LIBO/XETE	662	.25	.17	.16	1.73	1.46	1.45
ABLA/VASC/VASC	732	.22	.19	.17	2.59	2.31	2.38

[1] For definitions see Appendix I.

[2] Arithmetic mean bulk densities

[3] Geometric mean transformed back to arithmetic units.

[4] Arithmetic median bulk densities.

The mean bulk density ($\bar{\rho}'$) for each habitat type was calculated as follows:

$$\bar{\rho}'_{ij\ldots} = \frac{1}{nma} \sum_{h=1}^{n} \sum_{k=1}^{m} \sum_{l=1}^{a} \ln \rho_{b_{ij(hkl)}}$$

where:

ρ_b = bulk density

ln = natural (Napeirian) logarithms

i = 1,2; 1=litter and 2=grass/forb

j = 1,...,8 habitat types

h = 1,...,n=4 areas (see footnote 4)

k = 1,...,m=5 1/20th acre plots

l = 1,...,a=4 quadrats

Examination of the litter and grass/forb bulk density distributions show that litter was less skewed than the grass/forbs. The skewness in the grass/forb layer was caused by accumulations of 1/4-1 inch woody material and cones in localized areas within the stand. Hence, whenever the bulk density plot landed in an area where there was a significant amount of 1/4-1 inch diameter woody material or cones, there was very little fuel depth relative to the amount of weight involved. This low fuel depth and heavy weight produced a heavy bulk density that occurred infrequently causing the skewness. Because most of the cones and 1/4-1 inch woody material were collected with the grass/forb layer, the grass/forb distribution was more skewed than the litter distribution. The skewness in the litter layer was mostly due to accumulations of cones within the litter layer and the accumulation of litter in small holes and indentations found on the forest floor. Due to many environmental factors litter tends to smooth over rough surfaces on the forest floor which cause infrequent heavy pockets of litter, which when sampled cause heavy litter bulk densities.

The statistical analysis used in conjunction with this sampling design was a one way analysis of variance with subsampling. The analysis was done in two parts. The first part was a one way analysis of variance with fixed treatment effects (habitat types), which tested whether the mean bulk densities between habitat types were the same. The second part was a nested one way analysis of variance (for each habitat type) that looked at the variance components within each habitat type. The two parts will be discussed consecutively.

The null hypothesis to be tested for the first part is explicitly stated as follows:

$$Ho_i: \mu_{i1} = \mu_{i2} = \mu_{i3} = \mu_{i4} = \mu_{i5} = \mu_{i6} = \mu_{i7} = \mu_{i8}$$

where:

μ = a habitat type mean bulk density

$i = 1,2$; 1=litter and 2=grass/forb

To test this hypothesis, stands within habitat types were considered to be primary sampling units. The selection of stands coincides with fire and fuel management levels. Currently, fire and fuel personnel work with rather large units (generally larger than 10 acres) of land--such as stands within a habitat type or stands of a habitat type. Habitat type as used here has to be defined as a unit of land that has (for all practical purposes) a homogeneous vegetative structure, in which all or part can be managed similarly.

The habitat type areas, although selected subjectively, were considered to be a random sample of all possible areas within a given habitat type. The analysis used was a one way analysis of variance for unequal observations using habitat types as random treatments. The model used is as follows:

$$\overline{\rho}'_{i(jh)} = \mu_i + A_{i(j)} + \varepsilon_{i(jh)}$$

where:

$\overline{\rho}'_{i(jh)}$ = mean bulk density ($\log_e$) of the h th area in the j th habitat type for litter (i=1) or grass/forb (i=2)

μ_i = grand mean ($\log_e$) bulk density of all habitat types for either litter (i=1) or grass/forb (i=2)

$A_{i(j)}$ = effect of j th habitat type within i th fuel category

$\varepsilon_{i(jh)}$ = random deviation of the i(jh) th area from the i(j) th habitat type mean $\sim N(0,\sigma^2)$

σ^2 = variance from a normal population

i = 1,2; 1=litter and 2=grass/forb

j = 1,...,8 habitat types

h = 1,...,n=4 (or 5) areas (see footnote 4)

The analysis of variance is shown in Table 3. An SPSS (Statistical Package for Social Science) program, ANOVA, was used to generate the one way analysis of variance (shown in Table 3). A Bartlett-Box F test (Li 1964) for variance homogeneity was run concurrently. For the grass/forb ($\log_e$) bulk densities the variability within and between habitat types was not significantly different. However, the litter stratum's ($\log_e$) mean bulk densities showed there was heterogeneity of variance within and between habitat types. Figure 2 shows where these variance differences occurred. It appears habitat type 621 (ABLA/CLUN/CLUN) is causing most of the variability differences. The variability of litter bulk density found in 621 was caused by: 1) Isolated pockets of light fuel that were suspended by moss or draped over moss, making it very difficult to measure the depth and then collect the appropriate material. 2) Light loadings were contrasted by isolated pockets of downed and dead woody material which caused heavy fuel loadings relative to their depth. These two circumstances evidently added to the sampling error for habitat type 621 causing the large variability shown in Figure 2.

Although homogeneity of variance was not upheld for the litter stratum's analysis of variance, Figure 2 indicates that the logarithm litter mean bulk densities do not tend to differ substantially. Based on Figure 2 the nonsignificance shown in Table 3 (F=.81), for the differences between habitat type litter mean bulk densities, was deemed reasonable. Figure 2 also substantiates the differences found (F=3.79) between logarithmic habitat type grass/forb mean bulk densities (see Table 3).

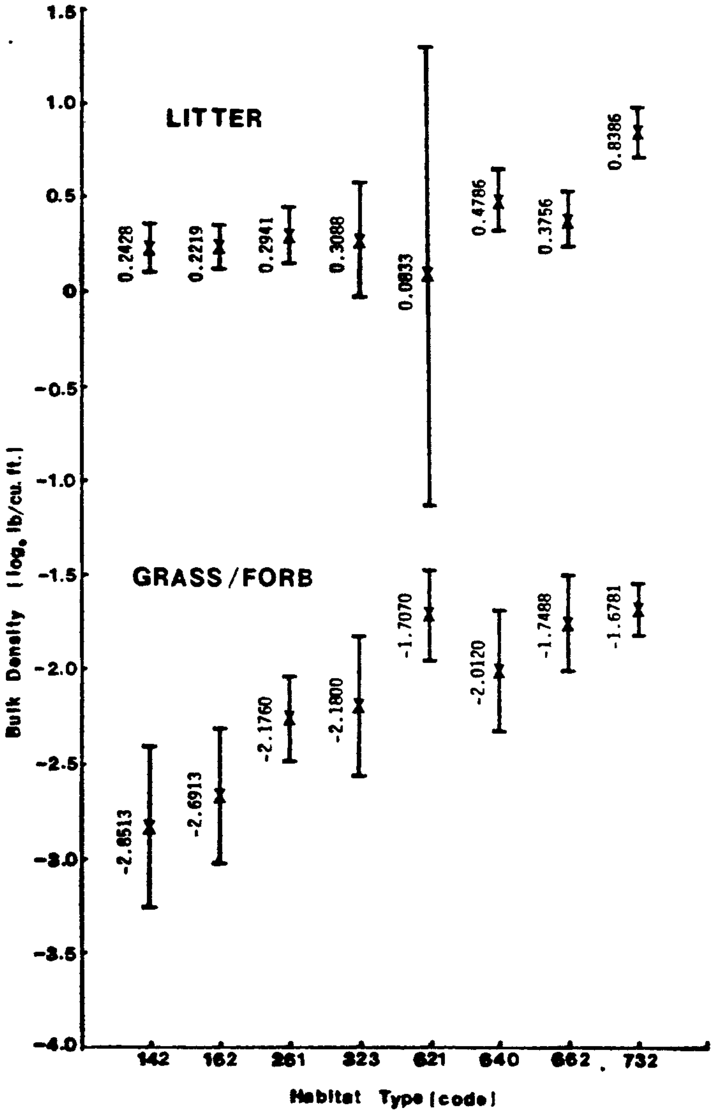
To explicitly summarize the previous paragraph consider the

Table 3--One way analysis of variance comparing the $\log_e$ mean bulk density variability within habitat types with the variability between habitat types.

Source of variation	Degrees of freedom	Sum of squares	Mean square	F
Grass/forb				
Between habitat types	7	6.0334	.8619	3.79**
Within habitat types	25	5.6839	.2274	
Total	32	11.7173		
Litter				
Between habitat types	7	1.4513	.2073	.813
Within habitat types	25	6.3760	.2550	
Total	32	7.8274		

**Significant at the $\alpha_{0.01}$ level.

Figure 2--Habitat type geometric mean bulk densities[1] by habitat type code[2] for plus and minus one standard deviation.



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[1] To change pounds per cubic foot to grams per cubic centimeter, multiply by 0.01602.

[2] Habitat type codes are defined in Table 1.

following: the Ho could not be rejected for the litter stratum, but the Ho could be rejected for the grass/forb stratum.

The null hypotheses to be tested in the second part of the bulk density analyses are as follows:

$$Ho: \sigma^2_{A_i} = 0$$

$$Ho: \sigma^2_{B_i} = 0$$

where:

σ^2_A = error in bulk density due to random selection of areas

σ^2_B = error in bulk density due to random selection of plots

The nested samples--areas, 1/20th acre plots, and quadrats--were considered random for the following reasons: 1) Habitat type areas were random selections from all possible areas within a habitat type (as mentioned on page 24). 2) The 1/20th acre plots within each area were selected along a azimuth which crossed the area variation, and distances between plots were predetermined. And, 3) there were twelve quadrats systematically laid out in each 1/20th acre plot--three in each of the four quadrants. One of the three quadrats was selected at random for bulk density determination, therefore, quadrat determinations were considered random. The model used to represent this nested sampling design is as follows:

$$\rho'_{ij(hkl)} = \mu_{ij} + A_{ij(h)} + B_{ij(hk)} + \varepsilon_{ij(hkl)}$$

where:

$\rho'_{ij(hkl)}$ = observed bulk density of the lth quadrat, within the kth plot, within the hth area for the jth habitat type, for litter ($i=1$) or grass/forb ($i=2$)

μ_{ij} = grand mean bulk density of all quadrats within a habitat type

$A_{ij(h)}$ = random error associated with areas within a habitat type $\sim N(0,\sigma_A^2)$

$B_{ij(hk)}$ = random error associated with 1/20th acre plots within areas $\sim(0,\sigma_B^2)$

$\varepsilon_{ij(hkl)}$ = random error associated with the quadrat determinations of bulk density $\sim N(0,\sigma^2)$

i = 1,2; 1=litter and 2=grass/forb

j = 1,...,8 habitat types

h = 1,...,n=4 areas

k = 1,...,m=5 1/20th acre plots

l = 1,...,a=4 quadrats

σ^2 = variance of a normal population

The F values used to test for rejection of the null hypothesis were calculated as shown below (Snedecor and Cochran 1967):

For Ho: $\sigma_A^2 = 0$ the F was calculated by:

$$F = \frac{s^2 + as_B^2 + ams_A^2}{s^2 + as_B^2}\text{, which estimates } \frac{\sigma^2 + a\sigma_B^2 + am\sigma_A^2}{\sigma^2 + a\sigma_B^2}$$

with (n-1) and n(m-1) degrees of freedom.

Also, for Ho: $\sigma_B^2 = 0$ the F was calculated by:

$$F = \frac{s^2 + as_B^2}{s^2}\text{, which estimates } \frac{\sigma^2 + a\sigma_B^2}{\sigma^2}$$

with n(m-1) and nm(a-1) degrees of freedom.

This type of analysis provides an opportunity to examine the components of variance associated with bulk densities. This is done by testing whether the error contributed by random habitat type areas is negligible ($\sigma_A^2 = 0$), and also by testing whether the error contributed by random plots is negligible ($\sigma_B^2 = 0$). This type of analysis not only gives a glimpse of variance components, but also provides information on where the sampling intensity should be strengthened to improve future bulk density studies. For example, if the variance contributed by areas within habitat types is significantly large then more areas should be sampled in future studies. Also, if the variance of plots within areas is significantly large then more plots should be taken in any future studies. The same would be true for quadrats within plots if the σ^2 was not acceptable to the investigator.

The general form of the nested analysis of variance from the above model is shown in Table 4.

A summary of the nested analyses of variance for both the grass/forb and litter strata are given in Tables 5 and 6, respectively.

Table 4--General analysis of variance used to investigate the bulk density variance components.

Source of variation	Degrees of freedom[1]	Mean square[2]	Parameters estimated
Areas	n-1	$s^2 + as_B^2 + ams_A^2$	$\sigma^2 + a\sigma_B^2 + am\sigma_A^2$
Plots	n(m-1)	$s^2 + as_B^2$	$\sigma^2 + a\sigma_B^2$
Quadrats	nm(a-1)	s^2	σ^2

[1] n=4, m=5, a=4.

[2] s^2 is an estimated variance component of the true population, σ^2, variance component. The subscript A designates error variance attributed by stands within habitat types and B designates the error variance attributed by plots within areas.

Table 5--Nested analysis of variance summary for the eight habitat type's grass/forb stratum.[1/]

Source of variation	HT	DF	MS	F	HT	DF	MS	F
Areas	142	4	8.642	2.66	621	3	1.672	1.95
Plots		20	3.250	1.05		16	0.858	0.97
Quadrats		75	3.107			60	0.888	
Areas	162	3	6.031	4.98*	640	3	6.129	5.06*
Plots		16	1.210	0.51		16	1.212	.75
Quadrats		60	2.396			60	1.626	
Areas	261	3	1.096	1.75	662	3	3.874	5.50**
Plots		16	0.628	0.48		16	0.704	1.24
Quadrats		60	1.300			60	0.566	
Areas	323	3	6.767	4.22*	732	3	0.802	2.63
Plots		16	1.605	1.05		16	0.305	1.42
Quadrats		60	1.524			60	0.215	

[1/] HT= habitat type code, see table 1; DF= degrees of freedom; MS= mean square error.

* Significance at the $\alpha = .05$ level.

** Significance at the $\alpha = .01$ level.

Table 6--Nested analysis of variance summary for the eight habitat type's litter stratum.[1]

Source of variation	HT	DF	MS	F	HT	DF	MS	F
Areas	142	4	0.8350	2.66	621	3	33.3472	3.56*
Plots		20	.3141	1.70		16	9.3714	5.98**[2]
Quadrats		75	.1846			60	1.5675	
Areas	162	3	.8462	4.06*	640	3	1.7074	5.94**
Plots		16	.2083	1.28		16	.2876	2.24
Quadrats		60	.1628			60	.1282	
Areas	261	3	1.1639	4.34*	662	3	1.1090	3.66*
Plots		16	.2682	1.03		16	.3029	.91
Quadrats		60	.2607			60	.3311	
Areas	323	3	2.9638	2.49	732	3	.2564	0.72
Plots		16	1.1887	1.78		16	.3556	1.94
Quadrats		60	.6660			60	.1835	

[1] HT= habitat type code, see table 1; DF= degrees of freedom; MS= mean square error.

[2] One stand had many light loadings which were difficult to measure, and added significantly to measurement error causing this high F value.

* Significance at the $\alpha = 0.05$ level.

** Significance at the $\alpha = .01$ level.

According to the generalized analysis shown in Table 4, the mean square errors shown in Tables 5 and 6, should be in a descending order of magnitude from areas to quadrats. But, since s^2 is an estimate of σ^2 there must be an error associated with s^2, which can cause the discrepancy in the descending flow of mean squares.

Table 5 indicates that for the grass/forb stratum in habitat types 162, 323, 640, and 662 (or one-half the habitats sampled) the error due to different stands is significant at the $\alpha = .05$ level, and Table 6 indicates that for the litter stratum in habitat types 162, 261, 621, 640, and 662 (or five-eights of the habitats sampled) the error due to different stands is significant at the $\alpha = .05$ level. Thus, implying that more areas within these habitats should be sampled. The error variances associated with the ($\log_e$) transformed bulk densities (quads) are difficult to assess due to the close proximity of the actual bulk densities to zero. The reason for this is a very small change in arithmetic units when close to zero causes a relatively large change in the ($\log_e$) transformed units, causing a large error term, and if this error term is untransformed it may appear to be excessively high, which makes it difficult to assess.

For a preliminary measure of how a change in bulk density affects rate of fire spread, two types of test data were run through FIREMOD (Rothermel 1972) for each of the eight habitat types. The basic difference between the two types of data is how fuel depth was estimated. To further explain, presently FIREMOD accepts one fuel stratum which is internally homogenized before estimating fire spread rate. Therefore, the grass/forb and litter stratum loadings had to be combined and a total geometric mean bulk density calculated for each habitat type. FIREMOD does not accept bulk densities directly, rather loading and fuel depth are given and a bulk density is then calculated internally. Average total loadings were calculated for each habitat type. The loadings were graphed, and they also had a skewed distribution (see Appendix VI). To normalize the loading distribution a ($\log_e$) transformation was used to calculate a total geometric mean loading. From the untransformed total geometric mean bulk density and the untransformed total mean loading it was possible to calculate an average fuel depth. The calculated depth corresponds nicely to the arithmetic average as shown in Table 7.

Average fuel depths were also calculated from plus and minus one standard deviation (s_t) and plus and minus one standard deviation of the mean ($s_t/\sqrt{n}$) from the total geometric mean bulk density. Thus, defining the two types of data put through the FIREMOD algorithm. Fuel depth was calculated as follows:

$$\bar{\rho}'_t = \frac{\bar{W}'}{\text{Volume}} = \frac{W'}{L \times W \times \bar{H}} = \frac{W'}{1 \times 1 \times \bar{H}} = \frac{W'}{\bar{H}}$$

$$\bar{H} = \frac{W'}{\rho'_t}$$

where:

$\bar{\rho}'_t$ = total fuel bulk density geometric mean over all fuels (litter and grass/forb)

$\overline{W}'$ = fuel loading geometric mean over all fuels (litter and grass/forb)

L = length, unity or 1

W = width, unity or 1

$\overline{H}$ = arithmetic mean of fuel depth

Table 7--Comparison of actual fuel depth to the calculated fuel depth.[1]

Habitat type[2]	Actual arithmetic average (in)	Calculated average (in)
PIPO/FEID/FESC	1.6	2.2
PIPO/PUTR/FEID	2.6	2.6
PSME/PHMA/PHMA	3.7	3.7
PSME/CARU/CARU	2.7	2.8
ABLA/CLUN/CLUN	3.1	2.8
ABLA/VACA	2.5	2.3
ABLA/LIBO/XETE	3.7	3.7
ABLA/VASC/VASC	4.0	4.1

[1] To change depth to centimeters multiply by 2.54.

All input variables that are allowed in FIREMOD were held constant except for the fuel depth. This was done so that the actual effect of fuel depth on rate of spread could be examined.

[2] For definitions see Appendix I.

Table 8 shows the variation in the rate of spread for 2 and 6 mph wind when $\overline{\rho}_t' \pm s_t/\sqrt{n}$ are used to calculate the fuel depth.

Table 8--Results of FIREMOD when changing $\bar{\rho}_t'$ by ± $s_t/\sqrt{n}$ and holding all other inputs constant.

Habitat type[1]	Wind (mph)	Rate of spread (ft/min)[2]		
		$\bar{\rho}_t' - s_t/\sqrt{n}$	$\bar{\rho}_t'$	$\bar{\rho}_t' + s_t/\sqrt{n}$
PIPO/FEID/FESC	2	3.4	3.1	2.7
	6	13.4	12.0	10.6
PIPO/PUTR/FEID	2	4.0	3.6	3.1
	6	18.1	15.9	14.0
PSME/PHMA/PHMA	2	3.7	3.4	3.1
	6	14.8	13.5	12.3
PSME/CARU/CARU[3]	2	1.8	1.6	1.4
	6	8.6	7.7	6.8
ABLA/CLUN/CLUN	2	2.2	1.9	1.7
	6	6.5	5.7	5.1
ABLA/VACA	2	1.6	1.5	1.3
	6	5.3	4.7	4.2
ABLA/LIBO/XETE	2	2.2	2.0	1.8
	6	7.5	6.8	6.1
ABLA/VASC/VASC	2	2.4	2.2	2.1
	6	9.3	8.7	8.1

[1] For definitions see Appendix I.

[2] Multiply rate of spread values by 0.305 to change to meters per minute.

[3] Due to the large measurement error associated with very light bulk densities they were removed, which significantly reduced this habitat type's bulk density variability, s_t.

Notice, that the variation in rate of spread at the 2 and 6 mph wind is small, both within and between habitat types. However, there appears to be two major groupings between habitat types; the first three and last five. It appears that PSME/PHMA/PHMA and PSME/CARU/CARU should have reverse rates of spread, since the PSME/CARU/CARU is open grown and grassy like the two PIPO habitat types and PSME/PHMA/PHMA is a more closed canopy habitat with shrubs and grasses like the ABLA habitat types. Both the PSME habitats have approximately the same loading for each surface-area-to-volume ratio group. Except, the PHMA phase had 91 percent more subshrub loading which increased its average fuel depth enough (37 percent) to give the same fuel packing ratio[8/] as the PIPO habitat types, and consequently about the same rate of spread. The 0-1/4 inch and 1/4-1 inch loadings for the PSME habitats were significantly greater than for the PIPO habitats (68 percent greater), but the CARU phase had very little subshrubs to increase the fuel depth enough to maintain the same rate of spread as the PIPO and PSME/PHMA/PHMA habitats.

To test the sensitivity of FIREMOD to the variation of bulk density within habitat type areas, the second set of data $(\bar{\rho}_t \pm s_t)$ were put through the FIREMOD algorithm. Fuel depths were calculated from these bulk densities. The variability of the bulk density within an area caused a much greater minimum and maximum fuel depth which caused a

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[8/] Packing ratio = $\frac{\rho_b}{\rho_p}$, where ρ_b = weight per unit volume, ρ_p = oven-dry particle density (Rothermel 1972).

significant change in the rate of spread. This noticeable change in rate of spread (see Table 9) within an area agrees with one's visual picture of a forest fire, where parts of an area are burning hotter and faster than other parts. Obviously, some fuel arrays in an area are closer to a more favorable packing ratio than others which cause "flare-ups" or an increase in fire spread. Whether or not this difference in fuel structure within a given habitat type will significantly influence the average rate of spread for the whole habitat type is unknown. The Northern Forest Fire Laboratory is currently studying the effect of different fuel structures within a stand as they relate to fire rate of spread.

Secondary Objective--The second objective of this study was to examine the possibility of using easily recognizable area characteristics to predict the loadings of 1) subshrubs, 2) grass/forbs, and 3) litter. The area characteristics that were sampled are:

1) number of trees per acre
2) percent canopy cover by plot and by plot quadrants
3) aspect
4) elevation
5) percent slope
6) age

Double sampling was used to inexpensively increase the loading sample size. For every quadrat double sampled, there were two visually estimated quadrats taken. In order to correct the estimated quadrat weights a regression was made of the double sampled quadrats--the

Table 9 --Results of FIREMOD when changing only $\bar{\rho}'_t$ by $\pm\ {}_t$ and holding all other inputs constant.

Habitat type[2]	Wind (mph)	Rate of spread (ft/min)[1]		
		$\bar{\rho}'_t - s_t$	$\bar{\rho}'_t$	$\bar{\rho}'_t + s_t$
PIPO/FEID/FESC	2	8.6	3.1	.8
	6	35.0	12.0	3.1
PIPO/PUTR/FEID	2	10.0	3.6	1.1
	6	46.6	15.9	4.6
PSME/PHMA/PHMA	2	7.4	3.4	1.4
	6	30.7	13.5	5.4
PSME/CARU/CARU	2	14.4	1.58	.53
	6	22.0	7.7	--
ABLA/CLUN/CLUN	2	5.1	1.9	.59
	6	16.0	5.7	1.6
ABLA/VACA	2	3.8	1.5	.46
	6	12.8	4.7	1.4
ABLA/LIBO/XETE	2	4.7	2.0	.72
	6	17.0	6.8	2.3
ABLA/VASC/VASC	2	3.7	2.2	1.3
	6	14.9	8.7	4.8

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[1] Multiply by rate of spread values by 0.305 to change to meters per minute.

[2] For definitions see Appendix I.

actual weight regressed on estimated weight (see Figure 4 for a typical example).

Linear relationships were established between actual and estimated weights for subshrubs, grass/forbs, and litter for every area (33 areas) for a total of 99 regressions. A separate regression was used for each area since all four areas of a particular habitat type were not always done on consecutive days, and there were many different types of fuels from one habitat type to another. Also, the percent moisture content was different (causing unit weights to be different) from one location to another, especially after a rain.

For every 1/20th acre plot there were four quadrants and each had three quadrats, one of which had its loading visually estimated and collected for actual determination (see Appendix III). The other two quadrat loadings were only visually estimated. After the linear regression was complete for each area it was used to correct the samplier bias for the visually estimated plots. Once corrected, all three quadrats within a quadrant were averaged. The average loadings were then used as quadrant loadings and regressed with area characteristics.

Other investigators (Pase and Hurd 1957, and Jameson 1967) have used with varying degrees of success percent canopy cover and basal area to estimate herbage production in ponderosa pine savana stands. Therefore, subshrub, grass/forb, and litter loadings were plotted against percent canopy cover classes[9/] and basal area. The percent canopy cover

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[9/] The class codes are as follows: 1=0-19 percent, 2=20-39 percent, 3=40-59 percent, and 4=60+ percent.

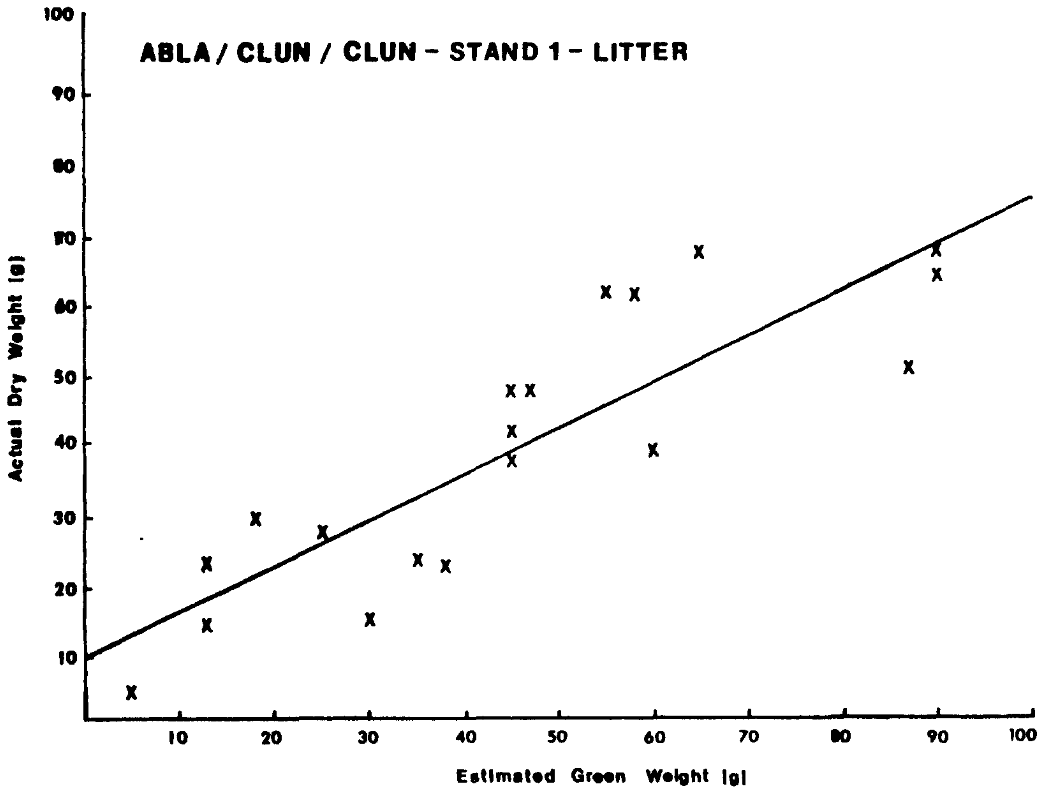

Figure 4--Typical linear regression used to correct visually estimated plots that were taken in conjunction with the double sampling procedure.

class was estimated for each of the four quadrants within 1/20th acre plots, and basal area was estimated from a 100 percent cruise of the 1/20th acre plots.

From scatter diagrams it was possible to ascertain that there was significant variation in loading for all three fuel types within one canopy cover class. Also, there was insufficient slope between (consecutive) percent cover class mean loadings to give good regression results. The only exception was for PIPO/FEID/FESC where the mean litter loading increased from 0.06 $\mathrm{lbs/ft^2}$ (.029 $\mathrm{g/cm^2}$) at 10 percent canopy cover to 0.17 $\mathrm{lbs/ft^2}$ (0.083 $\mathrm{g/cm^2}$) at 60+ percent canopy cover. Also, for this habitat type the grass/forb decreased from a mean of .01 $\mathrm{lb/ft^2}$ (.00488 $\mathrm{g/cm^2}$) to 0.002 $\mathrm{lb/ft^2}$ (0.00098 $\mathrm{g/cm^2}$). This trend agrees with what Pase and Hurd found for their ponderosa pine stands. Despite the significant data variation at the four canopy cover levels, loading was regressed on percent canopy cover classes (using classes as dummy variables) for grass/forb, shrub, and litter. As expected there was no significant relationship between the two variables for any of the habitat types. As an indication of how poor the fits were, the R^2 ranged from .02 to .29. Basal area (BA) scatter plots (loading vs BA) indicated that there was no linear correlation and regressions were not attempted.

The regressions mentioned above used quadrant crown closure estimates (four estimates per 1/20th acre plot). To help reduce some of the local environmental effects, subshrub, grass/forb, and litter loadings were also regressed against average plot (1/20th acre) crown closure. For the most part there was little improvement, however, PIPO/PUTR/FEID did give an R^2 of .55 (see Table 10).

Since percent canopy cover and basal area did not give significant relationships (other than for PIPO/PUTR/FEID), a stepwise regression was used to help determine which of the six area characteristics mentioned on page 39 would best explain loading variation. Table 10 shows which of the six variables entered the stepwise regression first and gave the most significant (at the .05 level) relationship.

For subshrubs there were five habitat types that had no significant estimators. For PIPO/FEID/FESC, PSME/CARU/CARU, and PSME/PHMA/PHMA this was not surprising since these habitat types did not have much subshrub in them. PSME/PHMA/PHMA had a significant amount of *Physocarpus malvaceus* but this species was generally considered a shrub and was not included in the study. However, ABLA/VASC/VASC had the greatest amount of subshrub (*Vaccinium scorparium*) material (.036 lbs/ft^2, (0.0176 g/cm^2)). It appears that *Vaccinium scorparium* is very well adapted to all environmental conditions in which this habitat exists. The four areas sampled had a tree canopy cover range of 16 percent to 61 percent (using midpoints of 10, 30, 50, and 80 percent for canopy closure estimates), an age range of 75 to 150 years, aspect from 27° to 253° and a basal area range from 20.8 (1.93 m^2) to 40.4 (3.75 m^2) square feet per acre. Since ABLA/VASC/VASC has a significant amount of subshrubs

Table 10--Significant independent variables entering loading regression equations and associated statistics by habitat types.

Habitat type[1]	Order of variable entry[2]			$\sqrt{MSE}$ lb/ft^2	R^2	Average loading lb/ft^2[3]	Standard deviation of loading lb/ft^2[3]
	1	2	3				
				Subshrubs			
ABLA/CLUN/CLUN	ELEV	%SLOPE	AGE	.0011	.61	.0020	.0016
ABLA/VACA	ELEV	ASP		.0026	.88	.0120	.00712
ABLA/LIBO/XETE	ELEV			.0035	.73	.0087	.00648
PIPO/PUTR/FEID	NS					.0008	.00118
PIPO/FEID/FESC	NS					negligible[4]	
PSME/PHMA/PHMA	NS					.0063	.00312
PSME/CARU/CARU	NS					.0004	.000619
ABLA/VASC/VASC	NS					.0299	.00696
				Grass/forb			
PIPO/PUTR/FEID	ELEV	%COV		.0040	.65	.0073	.0064
PSME/PHMA/PHMA	ELEV	BA		.0044	.60	.0078	.00649
ABLA/VACA	ELEV	%COV		.0016	.51	.0018	.00221
ABLA/VASC/VASC	ELEV	BA		.0026	.53	.0043	.00354
PIPO/FEID/FESC	%COV	ELEV	BA	.0034	.55	.0070	.0048
ABLA/CLUN/CLUN	ASP	%COV		.0020	.53	.0067	.00269
PSME/CARU/CARU	NS					.0089	.0151
ABLA/LIBO/XETE	NS					.0104	.0067
				Litter			
PIPO/PUTR/FEID	%COV			.0207	.55	.0605	.0301
ABLA/VACA	%COV	ASP		.0072	.51	.0512	.00984
PIPO/FEID/FESC	BA			.0429	.45	.1027	.0567
PSME/PHMA/PHMA	%SLOPE			.0173	.44	.0673	.0226
PSME/CARU/CARU	BA	ELEV		.0139	.44	.0573	.0175
ABLA/CLUN/CLUN	ASP	%SLOPE	AGE	.0095	.71	.0406	.0161
ABLA/LIBO/XETE	ELEV	AGE		.0083	.56	.0336	.0118
ABLA/VASC/VASC	NS					.0649	.0129

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[1] For definitions see Appendix I.

[2] ELEV=Elevation, ASP=Aspect, BA=Basal area, %COV=Percent PSU canopy cover, %SLOPE=Average PSU slope, NS=No significant relationship.

[3] To change loading to g/cm^2 multiply by 0.49.

[4] There were very few quadrats that had any subshrub loading.

that do not vary much with different area conditions a simple arithmetic average would have to be used to estimate the subshrub loading. The mean of .03 lbs/ft^2 (0.0146 g/cm^2) with a standard deviation of .007 lbs/ft^2 (0.00342 g/cm^2; no $\log_e$ transformation was used for this estimate) indicates there is not much variation in the subshrub loading for this habitat type. ABLA/CLUN/CLUN had significant estimators, however, they appeared to be very weak. For ABLA/VACA and ABLA/LIBO/XETE elevation (ELEV) shows a strong correlation.

Elevation appears to be the most significant estimator for grass/forb. It was the most significant for four of the eight habitat types and at least helps significantly with PIPO/FEID/FESC.

PSME/CARU/CARU and ABLA/LIBO/XETE had no significant characteristics that could be used to estimate grass/forb loading. ABLA/CLUN/CLUN was sensitive to aspect and percent canopy closure. *Clintonia uniflora*, one of the major forbs in ABLA/CLUN/CLUN, requires cool moist growing conditions and when this habitat opens up or drys out (on south or west aspects) *Clintonia's* production decreases.

As noted in Table 10 no one habitat type characteristic relates very well to litter loading. To try and explain each variable in each habitat type for litter loading would be an exercise in futility.

Table 10 shows that fuel loadings of subshrubs, grass/forbs, and litter cannot be predicted very well from habitat type characteristics. Even though ABLA/VACA and ABLA/LIBO/XETE show a high R^2 this could be by chance alone. However, Table 10 does show that elevation is at least a significant variable when trying to explain the variation in natural fuel loadings. For subshrubs and grass/forbs it appears first in seven out of sixteen regressions.

RESULTS

Primary Objective--As was shown in Figure 1 and Appendix V, the bulk density distribution is skewed to the left with a long tail to the right. The long tail being caused by infrequent heavy accumulations of woody material (cones and twigs). These accumulations pull the mean bulk density to the right, away from the apex of the distribution. However, the median does lie close to the apex. To prevent the extremely heavy bulk densities from unfairly weighting the mean bulk densities, two alternatives were considered and are as follows: 1) Consider the extremely high bulk densities as outliers and remove them from the analyses, this would tend to normalize the distribution, or 2) leave the extreme values in, and use the median as a measure of central tendency. Because of the following three reasons the second alternative was chosen. (1) The extreme values are part of the bulk density population and should not be discarded. (2) Logarithmic (natural) transformations do normalize the bulk density distribution (which meant the planned analyses could be done). And, (3) the untransformed logarithmic mean approximates the median of the arithmetic distribution, and the median is more closely associated with most of the observed values.

The first part of the analyses tested for mean differences between habitat type bulk densities. The null hypothesis was rejected for the grass/forb stratum but not for the litter stratum. The following discusses these results.

The litter stratum did not have homogeneity of variance between habitat types. However, most of the difference in variance was traced to ABLA/CLUN/CLUN habitat type, where much of the sampling error was caused by very light quadrat loadings. These very light loadings caused large (relative) sampling error in bulk depth measurements which produced very light bulk densities relative to their median, and a small change close to zero on the arithmetic scale causes large changes in the logarithmic scale. Hence, causing the large error found in the ABLA/CLUN/CLUN habitat type. No other habitat type had as many bulk densities so close to zero. Considering this excessive error explained, due to measurement error, homogeneity of variance between habitat types was deemed reasonable. The grass/forb stratum had homogeneity of variance between habitat types.

The habitat type bulk density *means* for the litter stratum did not prove to be significantly different. However, there was a difference found between the grass/forb *mean* bulk densities. Implications from these analyses (for two stratum fire appraisal algorithms) would be litter bulk density does not vary considerably and could probably enter the fire modelling algorithms as constant values representing large land management units. The grand average litter bulk density from the eight habitat types studied is 1.46 lb/ft^3 (0.0228 g/cc), and for fuel and fire planning purposes could be considered typical of the forested land in western Montana and northern Idaho.

Unlike the litter, the grass/forb stratum differs significantly between habitat types. Although, small groups of habitat types show surprisingly similar grass/forb bulk densities, for example: habitat types ABLA/CLUN/CLUN, ABLA/LIBO/XETE, and ABLA/VASC/VASC had 0.181, 0.174, and 0.187 lbs/ft^3 (0.0029, 0.0028, and 0.0030 g/cc) bulk densities, respectively. And, habitat types PSME/PHMA/PHMA and PSME/CARU/CARU both had 0.113 lbs/ft^3 (0.0018 g/cc) bulk densities. These examples show that grass/forb bulk density does vary between habitat types, but as evidenced here, similar habitat types--such as the three ABLA, the two PSME, and the two PIPO (see Table 2) habitat types--can be grouped together. These groups can then be represented by constant bulk densities for use in fire modelling alogrithms.

Although the habitat type mean bulk densities did not appear to vary excessively, the bulk density determinations within a habitat type did, for example: the litter bulk densities in PIPO/FEID/FESC varied from 0.48 to 3.05 lbs/ft^3 (0.0077 to 0.0489 g/cc) and its grass/forb bulk densities varied from 0.02 to 2.90 lbs/ft^3 (0.0003 to 0.0465 g/cc). These large variations in bulk density, that are found within habitat types, probably cause the "flare-ups" or increased rates of fire spread that are noticeable in wildfires. The large fluctuation in bulk density, which appear to cause the large changes in rate of fire spread, can also be seen in Table 9. For the PIPO/FEID/FESC habitat type the rate of spread ranged from 3.1 ft/min (0.95 m/min) to 35.0 ft/min (10.68 m/min). This range in rate of spread was created by calculating the fuel depth parameter (required input for the fire model algorithm) from bulk densities that were plus or minus one standard deviation (s_t) from the mean bulk density, respectively. Discussion here used PIPO/FEID/FESC as an example, but similar results occurred for the other seven habitat types.

The analyses revealed an interesting phenomenon between the two PSME habitat types. Table 2 indicates that the two have the same bulk density, but Tables 8 and 9 indicate their ranges of fire spread are noticeably different, 1.6 ft/min (0.49 m/min) compared to 3.4 ft/min (1.04 m/min). This phenomenon is explained by the different type and structure of fuel that each habitat type contains. In this example the PSME/PHMA/PHMA habitat type contained excessive amounts of sbushrub material which increased its fuel depth, giving a packing ratio similar to the PIPO habitat types but different than the PSME/CARU/CARU habitat type. Thus, even though habitat types have the same (constant) bulk density the rates of spread may be different due to different types of fuel loadings.

To investigate the variation of bulk density within habitat types a nested analysis of variance was done for each habitat type's litter and grass/forb stratum. The nesting consisted of areas within habitat types, plots within areas, and quadrat determinations within plots. The litter stratum analyses indicated that for five-eights of the habitat types the error attributable to areas ($\sigma^2_{A_1} \neq 0$) was singificant ($\alpha = 0.05$, see Table 5). The grass/forb stratum analyses indicated that for one-half of the habitat types the error attributable to areas ($\sigma^2_{A_2} \neq 0$) was significant ($\alpha = 0.05$, see Table 6). None of the habitat types indicated that error attributable to plots within areas ($\sigma^2_{B_i} = 0$)

was significant.[10/] This implies future bulk density studies should examine more areas within habitat types for a better representation of bulk densities.

Secondary Objective--There are many interacting environmental factors that influence production of grass/forb and subshrub loadings and the accumulation of litter. The ability to estimate their loadings via habitat type area characteristics will require indepth study of these interacting environmental factors. This preliminary study yielded little in the way of predictive equations for grass/forb, subshrub, and litter loadings, but much was learned on the type of variables that need further study before reliable predictive equations can be made. Some of the evasive variables are discussed in the discussion section. Relationships similar to those found by Pase and Hurd (1957) in ponderosa pine stands with percent crown cover, basal area, and biomass production were also found in the two ponderosa pine habitat types studied here (see Table 10).

Elevation appears to be an important variable in explaining fuel loading variation (appearing first in eight regression, see Table 10), but much more work needs to be done with the predictability of grass/forb, subshrub, and litter loadings before any conclusions can be drawn about elevation's importance.

[10/] See footnote 2 Table 6.

DISCUSSION

Many variables measured or estimated in this study were evasive and need more investigation. The following discussion should be helpful to future investigators of 1) bulk density and 2) grass/forb, subshrub, and litter loading predictability from habitat type area characteristics.

Many species of grasses, forbs, and subshrubs have different shade tolerances, consequently, as the forest canopy closes some plant species leave and others invade. If the species involved in the tolerant/intolerant change have approximately the same weight per plant, then any correlation with crown closure is lost. The PIPO habitat types were the only ones not having this problem, due to the few species of grasses being able to survive in their harsh environment.

Percent crown closure is a difficult variable to measure. This study estimated tree crown closure only. However, some stands contained large shrub species that commonly grew in openings, and when tree crown closure was estimated (in the openings) the closure percentage would be recorded as being low, but in actuality the large shrubs would be heavily shading the grass/forb layer.

Another problem with estimating crown closure is how it relates to bole length and age. If a loading measurement is made directly beneath an old-growth tree that (whether on steep slope or flat ground) has a long bole, the shading effect of its crown on biomass loading is negligible, although crown closure would be recorded as being high. The light tends to filter through the crown evenly onto the forest floor. The old-growth tree crowns can even tough (90 to 100 percent closed) and have little effect on biomass production, which leads to another evasive forest variable--crown bulk density. Forest crown bulk density, a three dimensional variable, also significantly affects light penetration and biomass production. As mentioned previously, most tree crowns can be touching (100 percent closed, but low crown bulk density) and still allow plenty of light penetration so as not to significantly reduce biomass production. In another area, however, tree crowns can be overlapping (100 percent closed, but high crown bulk density) and greatly reduce light penetration which will significantly reduce biomass production.

The needle mat development in relation to tree crown closure also influences biomass production. It appears that as slope and bole length increase more light and moisture are able to reach the ground directly beneath tree crowns, and needle mat development will occur further downhill from the tree--needles tend to float downhill when they fall. This situation allows plants to germinate and grow directly beneath the tree, but the needle mat development further down slope (which may be in an opening), hinders germination and reduces biomass production. The result of this situation is that as observers sample directly beneath a tree the grass/forb or subshrub production will be the same as an opening, but the percent canopy cover may be recorded as being relatively high (60 percent +). The reverse happens downhill where the litter mat has reduced grass/forb or subshrub production, but the percent canopy cover is recorded as being low. Of course, this phenomena would not occur on nearly flat ground where the needle mat builds directly beneath trees, nor would it occur on steep slopes in dense stands where the needles from uphill trees float downhill beneath other trees.

All the environmental interactions described above need further investigation before loading of grass/forb, subshrub, and litter can be predicted from habitat type characteristics. For future studies of loading predictability it is advised that one habitat type be selected, and the environmental factors mentioned above studied thoroughly. From this one habitat type, perhaps the key interactions can be found and applied to other habitat types.

SUMMARY

Eight different vegetative types that represent many types of forest fuel complexes were selected and represented by eight habitat types. Each habitat type represented many forested acres in western Montana and northern Idaho.

The bulk density of two sequential natural forest fuel layers (see Appendix II), the litter and grass/forb, were measured. The distribution of the measured bulk densities followed a lognormal distribution for both grass/forb and litter. A $\log_e$ transformation normalized the distributions. It was shown that the geometric mean bulk densities were very close to the median values on the untransformed scale. Since the median has a lower bulk density than does the mean on the same arithmetic scale, and since fire generally spreads through areas with lower bulk densities, and since more values nest around the median than the mean in a lognormal distribution, it follows that the geometric mean (or median) of the bulk density distributions should be used in fire model alogrithms.

The mean bulk densities for the litter stratum were found not to differ significantly and was hypothesized that 1.46 lb/ft^3 (0.0228 g/cc) could be considered representative of much of the forest land in western Montana and northern Idaho. The grass/forb stratum, however, did differ between habitat types, but small groups of habitat types were found that did have similar grass/forb stratum bulk densities. For example, the ABLA habitat types could be represented by a 0.18 lb/ft^3 (0.0029 g/cc), the PSME habitat types by a 0.11 lb/ft^3 (0.0018 g/cc), and the PIPO habitat types by a 0.065 lb/ft^3 (0.0010 g/cc) bulk density.

A nested analysis of variance indicated that for future bulk density studies more areas should be sampled within most habitat types. To further examine the wide variation of bulk density found within habitat types, bulk depths were calculated from bulk densities (from $\pm s_t/\sqrt{n}$ and $\pm s_t$) and put through the fire model algorithm. As expected a large variation in rate of spread was found within habitat types, but it is currently not known whether this significant difference in rate of fire spread will noticeably change the overall rate of fire spread for any given area. This is currently being studied at the Northern Forest Fire Laboratory.

Loading was regressed against six easily recognizable habitat type characteristics. There were few significant regressions found. Those that did occur had elevation as the most significant independent variable. Since elevation does not seem like the most logical independent variable, more work must be done to varify and understand its significance. There are many environmental influences that affect forest fuel loadings, and the significant ones change from one habitat type to another. Consequently, no one or two independent variables will work for all habitat types. Each habitat type or vegetative type will need indepth study before pertinent stand characteristics can be found. Until such time fuel loading will have to be estimated by current sampling techniques.

LITERATURE CITED

Albini, Frank A., and J. K. Brown.
1978. Predicting slash depth for fire modeling. USDA For. Serv. Res. Pap. INT-206, 22 p., Intermt. For. and Range Exp. Stn., Ogden, Utah.

Albini, Frank A.
1976. Assessment of fire hazard created by tree cutting activities. Office report on file at the Northern Forest Fire Laboratory, Drawer G, Missoula, Montana, 23 p.

Cochran, W. G.
1977. Sampling techniques. John Wiley & Sons, New York, New York, 428 p.

Deeming, John E., James W. Lancaster, Michael A. Fosberg, and others.
1974. The National Fire Danger Rating System (rev.). USDA For. Serv. Res. Pap. RM-84, 53 p., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Hutchings, S. S., and J. E. Schmautz.
1969. A field test of the relative-weight-estimage-method of determining herbage production. J. Range Manage. 22(6):408-411.

Jameson, Donald A.
1967. The relationships of tree overstory and herbaceous understory vegetation. J. Range Manage. 20:247-249.

Li, Jerome C. R.
1964. Statistical inference I. Edwards Brothers, Inc., Ann Arbor, Michigan, 658 p.

Pase, C. P., and R. M. Hurd.
1957. Understory vegetation as related to basal area, crown cover, and litter production by immature ponderosa pine stands in the Black Hills. Proc. Soc. Amer. For., p. 156-158.

Pfister, R. D., Bernard L. Kovalchik, Stephen F. Arno, and Richard C. Presby.
1977. Forest habitat types in Montana. USDA For. Serv. Gen. Tech. Rep. INT-(in press), Intermt. For. and Range Exp. Stn., Ogden, Utah and Northern Region, Missoula, Mont.

Ponto, R. L.
1972. Procedures for oven drying forest slash components and organic matter; study carried out in Alberta, 1967-71, Canadian Cept. of the Environment, Northern For. Res. Centre, Edmonton, Alberta, Misc. Pap. No. NOR-4-9, 9 p.

Rothermel, Richard D.
1972. A methematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-15, 40 p., Intermt. For. and Range Exp. Stn., Ogden, Utah.

Snedecor, G. W., and William G. Cochran.
1967. Statistical methods. 5th Ed., 593 p., The Iowa State Univ. Press, Ames, Iowa.

APPENDIX I

DEFINITIONS

Fuel bulk density -- Weight of fuel per unit of volume.

Fuel bulk depth -- The average fuel depth.

Fuel loading -- Weight of fuel per unit area.

Optimum packing ratio -- Fuel arrangement at which the fire spread rate is maximized.

Packing ratio -- Fuel bulk density/fuel particle density, dimensionless.

Particle density -- Weight of solid oven-dry material per unit volume.

Stand -- Any given unit of forested land.

Surface-area-to-volume ratio -- Ratio of a fuel particle surface area to its volume.

Litter stratum -- See Appendix II.

Grass/forb stratum -- See Appendix II.

Interpretation of habitat types:

PIPO/PUTR/FEID -- *Pinus ponderosa/Purshia tridentata/Festuca idahoensis*

ABLA/VACA -- *Abies lasiocarpa/Vaccinium caespitosum*

PSME/PHMA/PHMA -- *Pseudotsuga menziesii/Physocarpus malvaceus/Physocarpus malvaceus*

ABLA/VASC/VASC -- *Abies lasiocarpa/Vaccinium scoparium/Vaccinium scoparium*

ABLA/LIBO/XETE -- *Abies lasiocarpa/Linnaea borealis/Xerophyllum tenax*

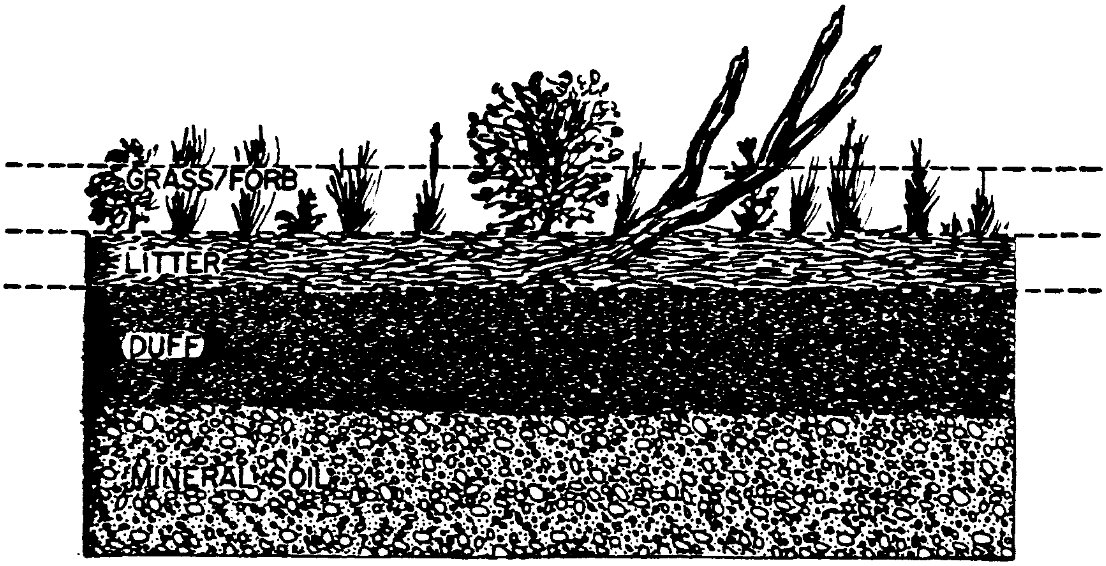
PIPO/FEID/FESC -- *Pinus ponderosa/Festuca idahoensis/Festuca scabrella*

PSME/CARU/CARU -- *Pseudotsuga menziesii/Calamagrostis rubescens/Calamagrostis rubescens*

ABLA/CLUN/CLUN -- *Abies lasiocarpa/Clintonia uniflora/Clintonia uniflora*

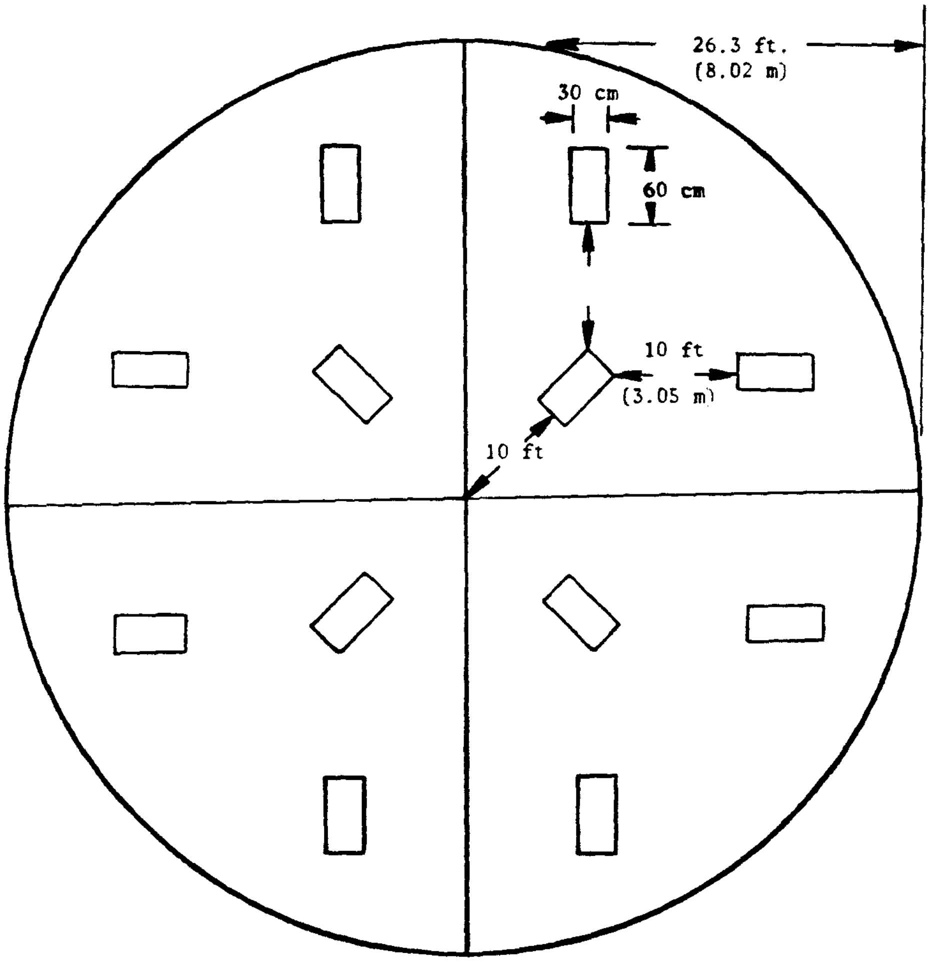
APPENDIX II

The diagram shows the distinct strata of litter and grass/forb. In the bulk density plots, both loading and bulk depth were taken for each strata. Notice that if down woody material, grass/forb, or shrubs extend noticeably above either the litter or grass/forb layers, their height and weight were excluded from any measurements. In this example, the shrub in the center would be cut off at the top of the grass/forb layer and only the lower part included in any measurements. However, any basal stem significantly larger than the fire carrying fuel was not included in any measurement. It was hypothesized that these stems would significantly alter the bulk density and not add to or hinder the fire spread rate. The 1/4-1 inch down and dead woody material was kept, but separated from the rest of the fuels.



APPENDIX III

FIELD LAYOUT OF A 1/20 th ACRE PLOT



APPENDIX IV

Data Recorded on Field Forms

The field form was made so that keypunching could be done directly from it. There were sixteen data cards per plot. The type of data collected and their units of measure are given below:

Habitat code--Eight habitats were sampled and their ADP codes were recorded. (F3.0)[1]

1	PIPO/PUTR/FEID	162
2	ABLA/VACA	662
3	PSME/PHMA/PHMA	261
4	ABLA/LIBO/XETE	640
5	ABLA/VASC/VASC	732
6	PIPO/FEID/FESC	142
7	ABLA/CLUN/CLUN	621
8	PSME/CARU/CARU	323

Stand number--Which of four stands per habitat type. (F2.0)

Primary sampling unit--Which of five per stand. (F1.0)

Aspect--Measured in degrees (0-360°) from hand compass. (F3.0)

Elevation--Measured to nearest 100 feet from altimeter. (F4.0)

Cover type--The tree species that occupied the majority of the forest canopy was recorded by code. (F2.0)

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[1] FORTRAN formats are given for each data entry for future reference.

Cover type

PP--1

DF--2

GF--3

LP--4

WL--5

ES--6

AF--7

Slope--Slope percent was measured with a relaskop. (F2.0)

Habitat position--The general position of habitat on the mountain. (F1.0)

Stand age--If the stand was 1, 2, or 3 aged, each stratum was aged and recorded. 3(F3.0)

Percent canopy cover--The percent crown closure was estimated for each of the four equal quadrants of every plot. Crown closure was estimated by crown closure classes. 4(F1.0)

Class	Canopy cover percent
1	0-19
2	20-39
3	40-59
4	60+

Date--The date that each stand was sampled was recorded and punched.

Overstory cruise--There was a 100 percent cruise taken for each plot. The trees were recorded by 2 inch d.b.h. classes. Species were not recorded. (20F2.0)

Intermediate fuels[2/]--These data were collected in conjunction with, but not for, this thesis.

1) Kind--the type of fuel. 3(F2.0) See Appendix V for code.

2) Void depth--height from ground to the bottom of the intermediate fuel; nearest .1th meter. 3(F2.1)

3) Height--height from ground to the top of the intermediate fuel; nearest .1th meter. 3(F2.1)

Surface fuels--These data were collected in conjunction with, but not for, this thesis.

1) Dominant structure--the orientation of the dominant fire carrying fuels was recorded. (F1.0)

Code	Dominant material
1	Vertical
2	Horizontal
3	Mixed

2) Dominant material--the major fire spreading fuel for each 30 x 60 cm quadrat was determined and coded. 3(F2.0)

3) Percent fuel cover--the percent ground cover of the dominant material was coded. (F1.0)

Primary subshrub--The species of the three major subshrubs were recorded. The standard code of the first two letters of both genus and species were used. 3(A4)

[2/] Intermediate fuel is defined as the next sequential layer of fuel above the grass/forb layer.

Primary grass/forb--The three primary grass/forb species were recorded. The standard code of the first two letters of both genus and species were used. 3(A4)

Surface fuel bulk depth--Measured to the nearest two millimeters. 6(F3.1)

Litter bulk depth--Measured to the nearest two millimeters. 6(F3.1)

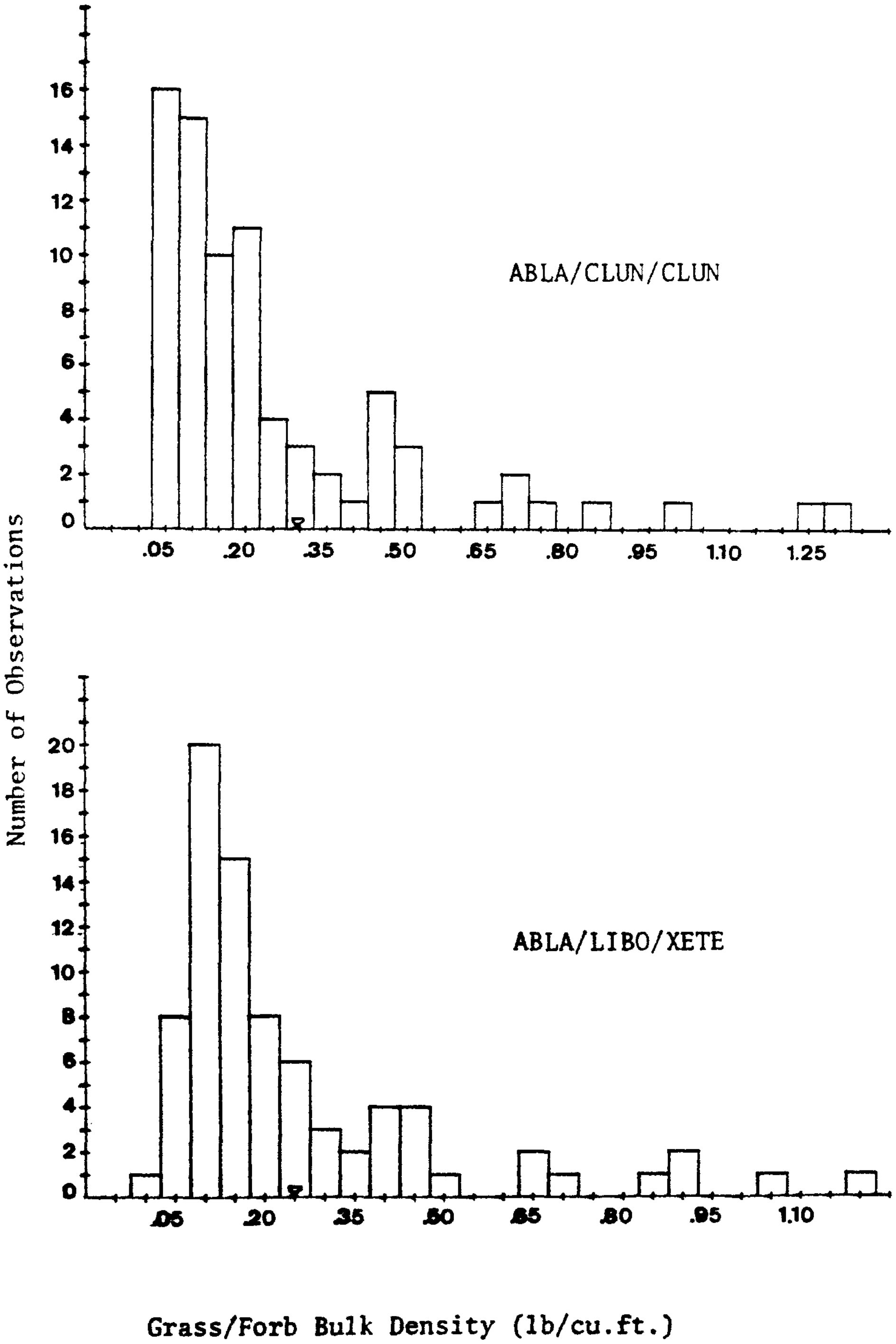
Estimated gree weights--

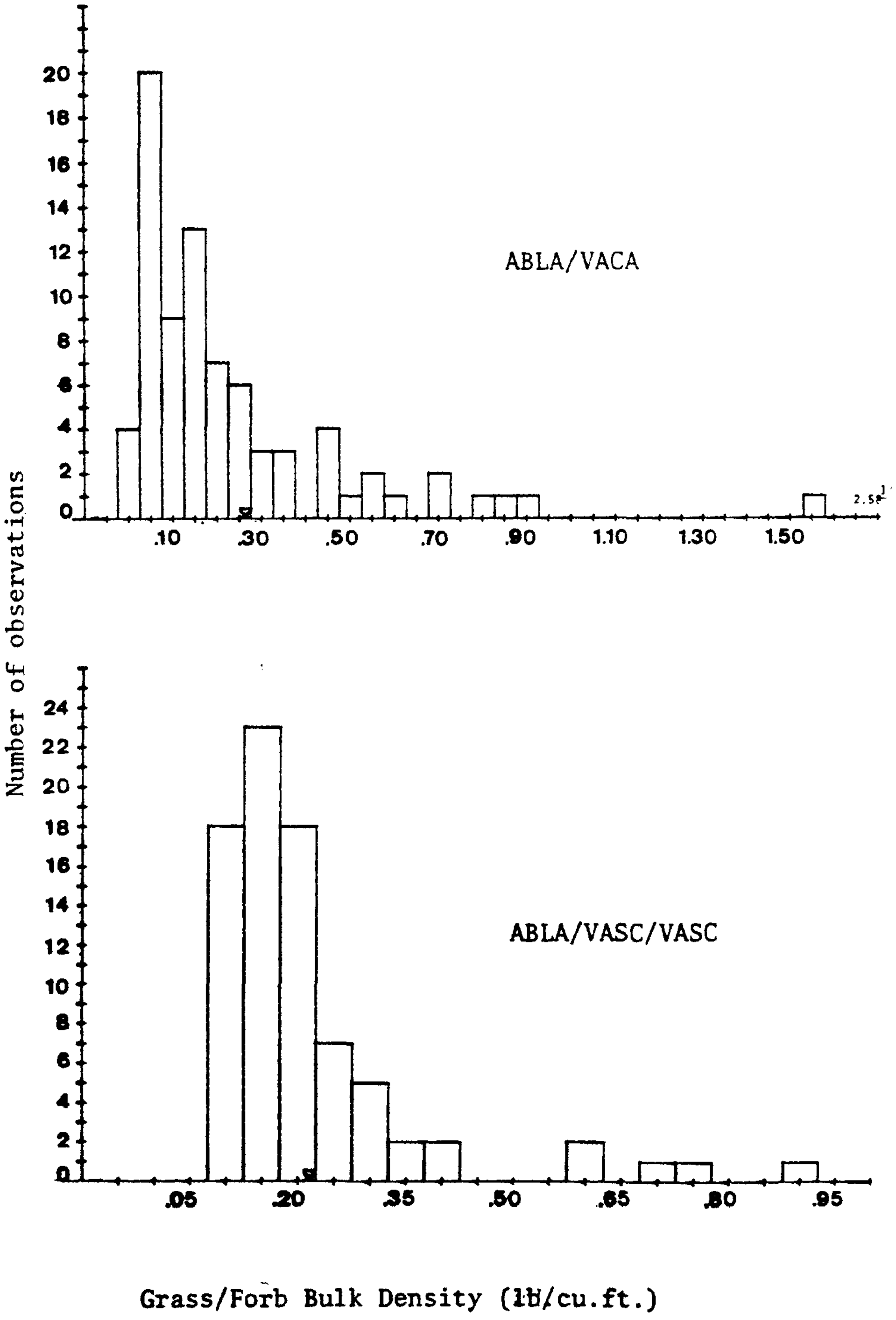
1) Subshrubs--visual weight estimates were made for all quadrats. 3(F4.0)
2) Grass/forb--same.
3) Litter--same.

Dry weights--For the plots that were double sampled the organic material in the plot was separated into subshrub, grass/forb, litter, litter cones, 1/4 inch branchwood, 1/4 inch to 1 inch branchwood, surface needles, and surface cones. Surface needles and cones were those needles that were suspended via needle drape on shrubs and grasses, and the cones were those above the average litter depth.

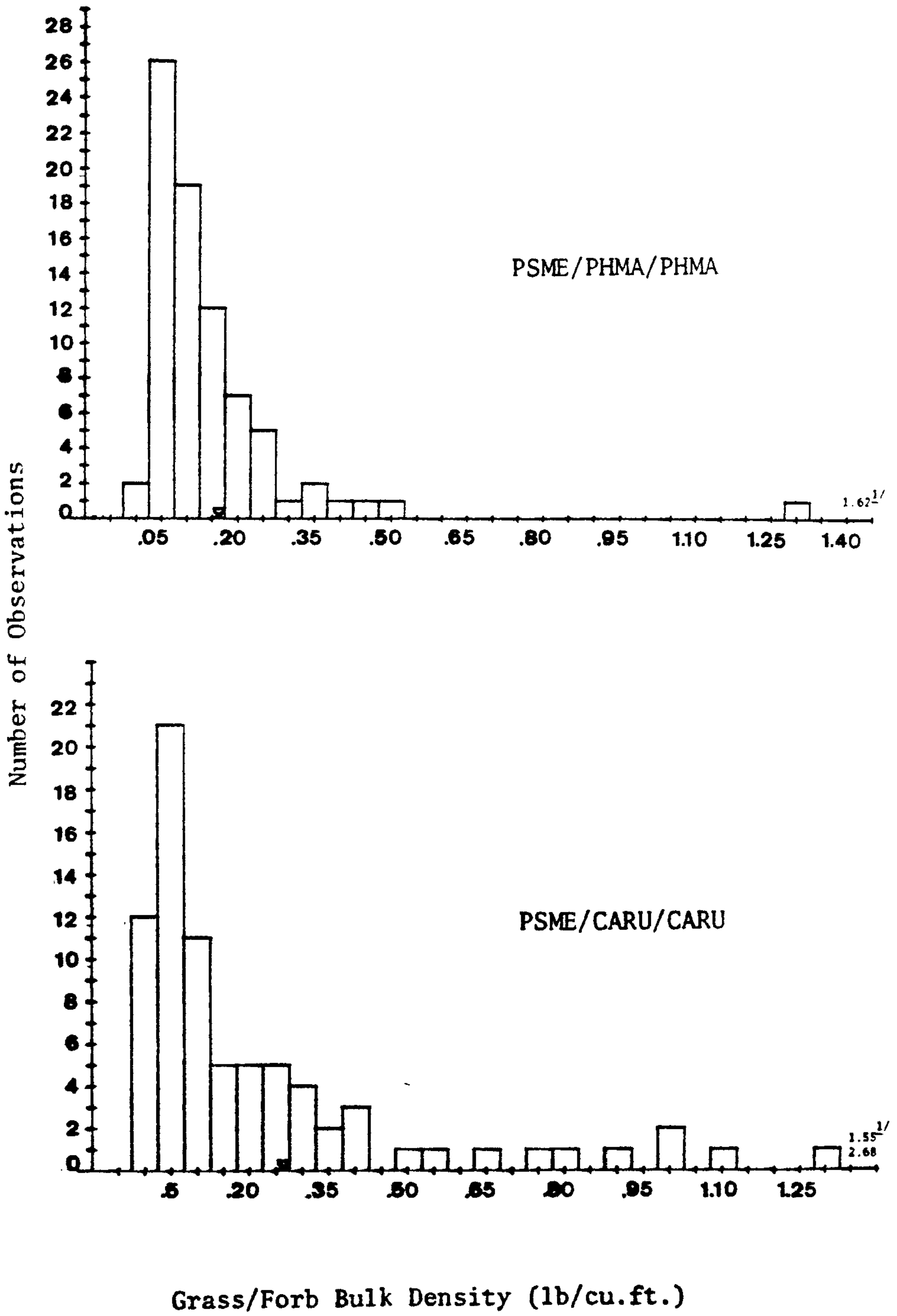
APPENDIX V

Both the litter and grass/forb bulk density distributions are displayed in histograms. To change bulk densities to grams per cubic centimeter multiply histogram values by 0.0160.


ABLA/CLUN/CLUN
16
14
12
10
8
6
4
2
0
.05
.20
.35
.50
.65
.80
.95
1.10
1.25
ABLA/LIBO/XETE
20
18
16
14
12
10
8
6
4
2
0
.05
.20
.35
.50
.65
.80
.95
1.10
Number of Observations
Grass/Forb Bulk Density (lb/cu.ft.)



1/ Values beyond the scale of the histogram.



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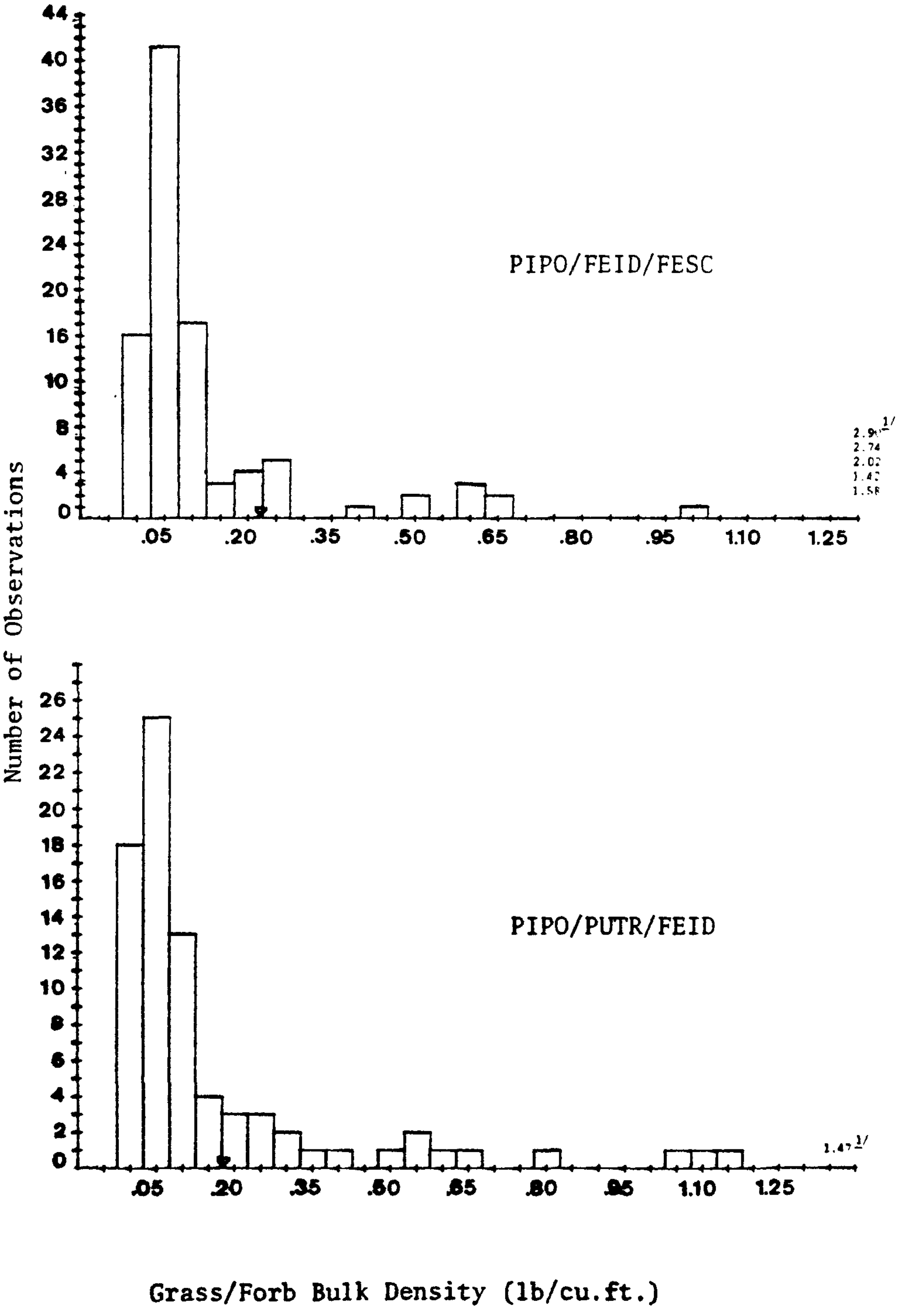

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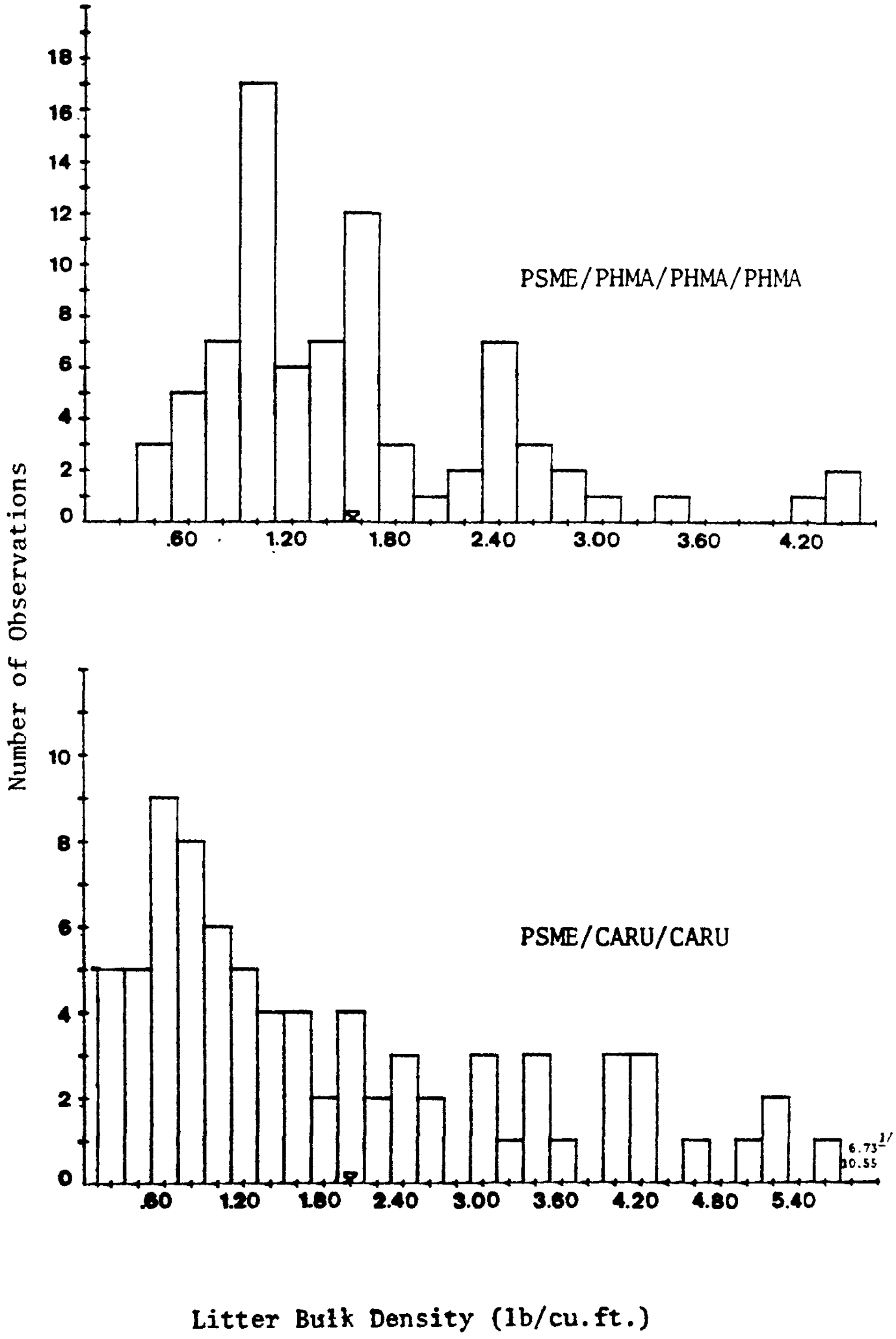

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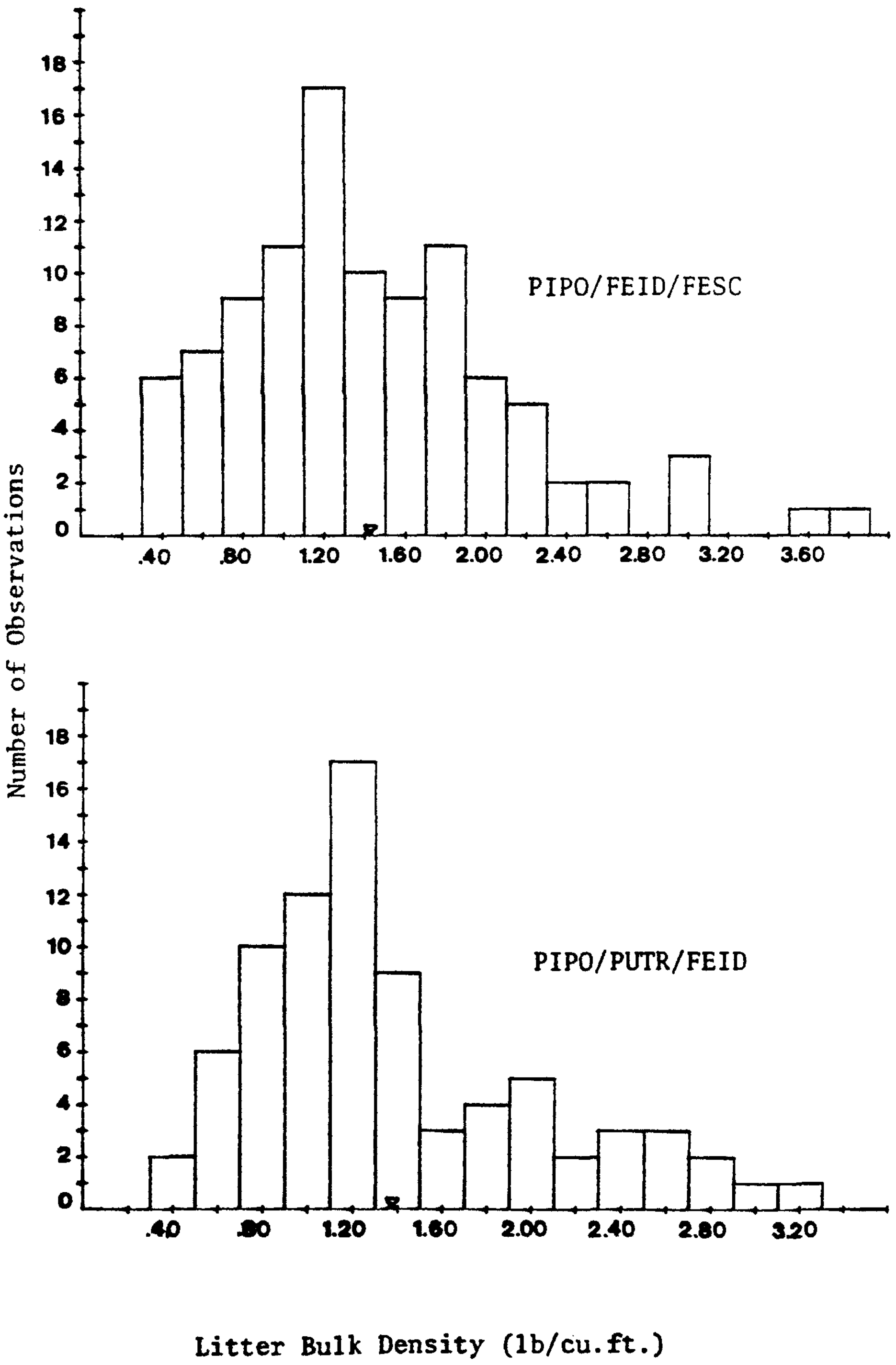
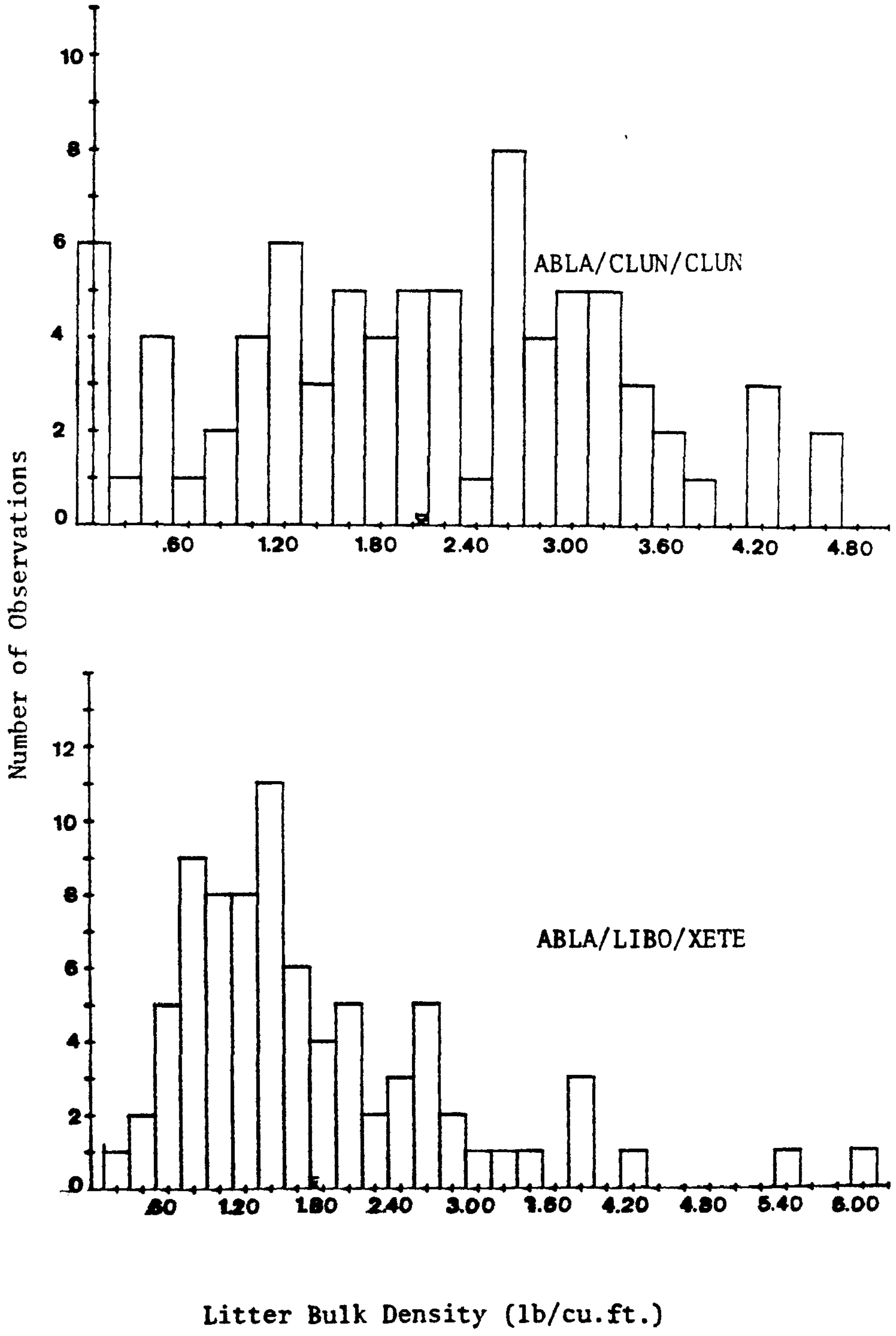
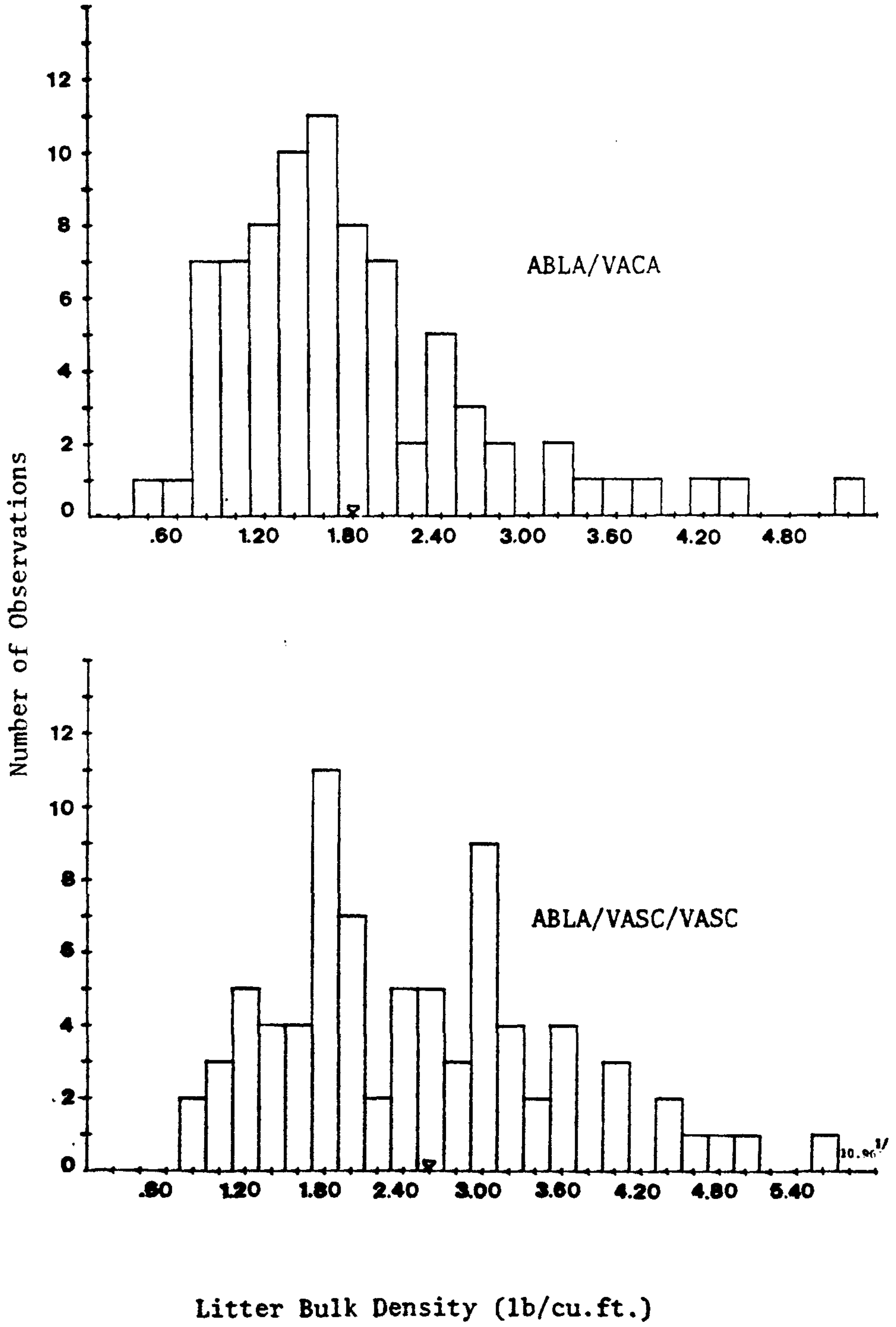
[1] Values beyond the scale of the histogram.


Number of Observations
18
16
14
12
10
8
6
4
2
0
PIPO/FEID/FESC
x̄
.40
.80
1.20
1.60
2.00
2.40
2.80
3.20
3.60
18
16
14
12
10
8
6
4
2
0
PIPO/PUTR/FEID
x̄
.40
.80
1.20
1.60
2.00
2.40
2.80
3.20
Litter Bulk Density (lb/cu.ft.)

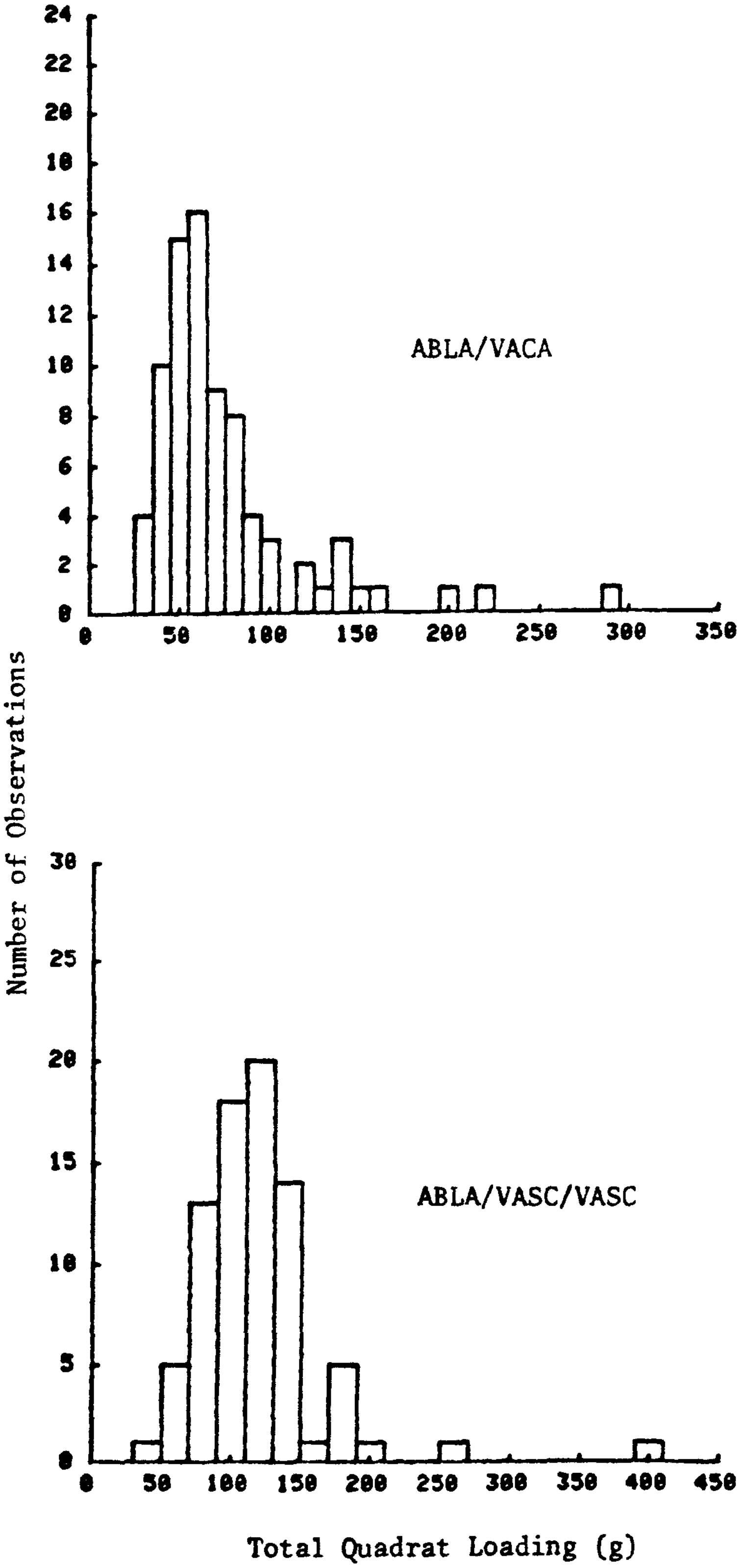

Number of Observations
10
8
6
4
2
0
.60
1.20
1.80
2.40
3.00
3.60
4.20
4.80
ABLA/CLUN/CLUN
12
10
8
6
4
2
0
.60
1.20
1.80
2.40
3.00
3.60
4.20
4.80
5.40
6.00
ABLA/LIBO/XETE
Litter Bulk Density (lb/cu.ft.)

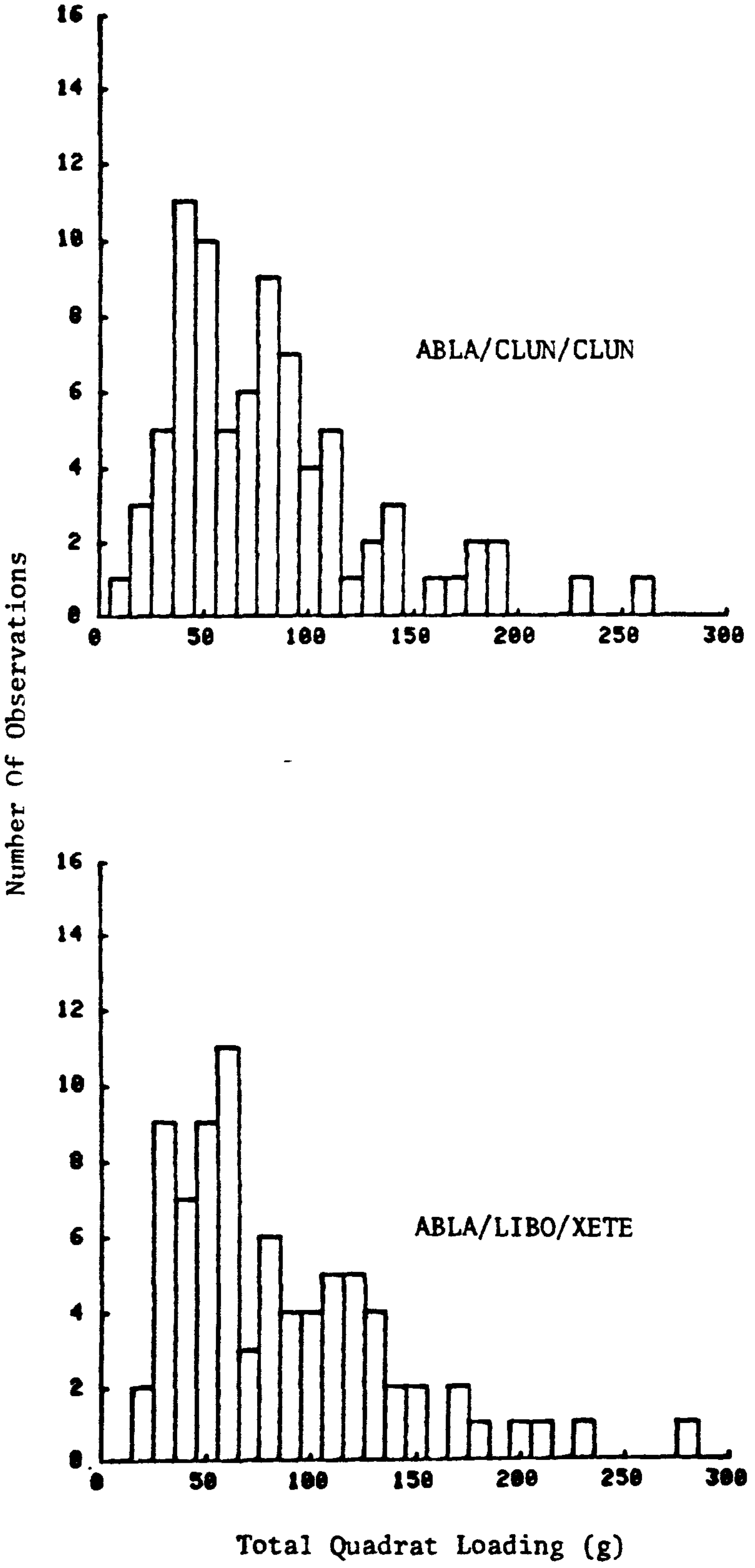


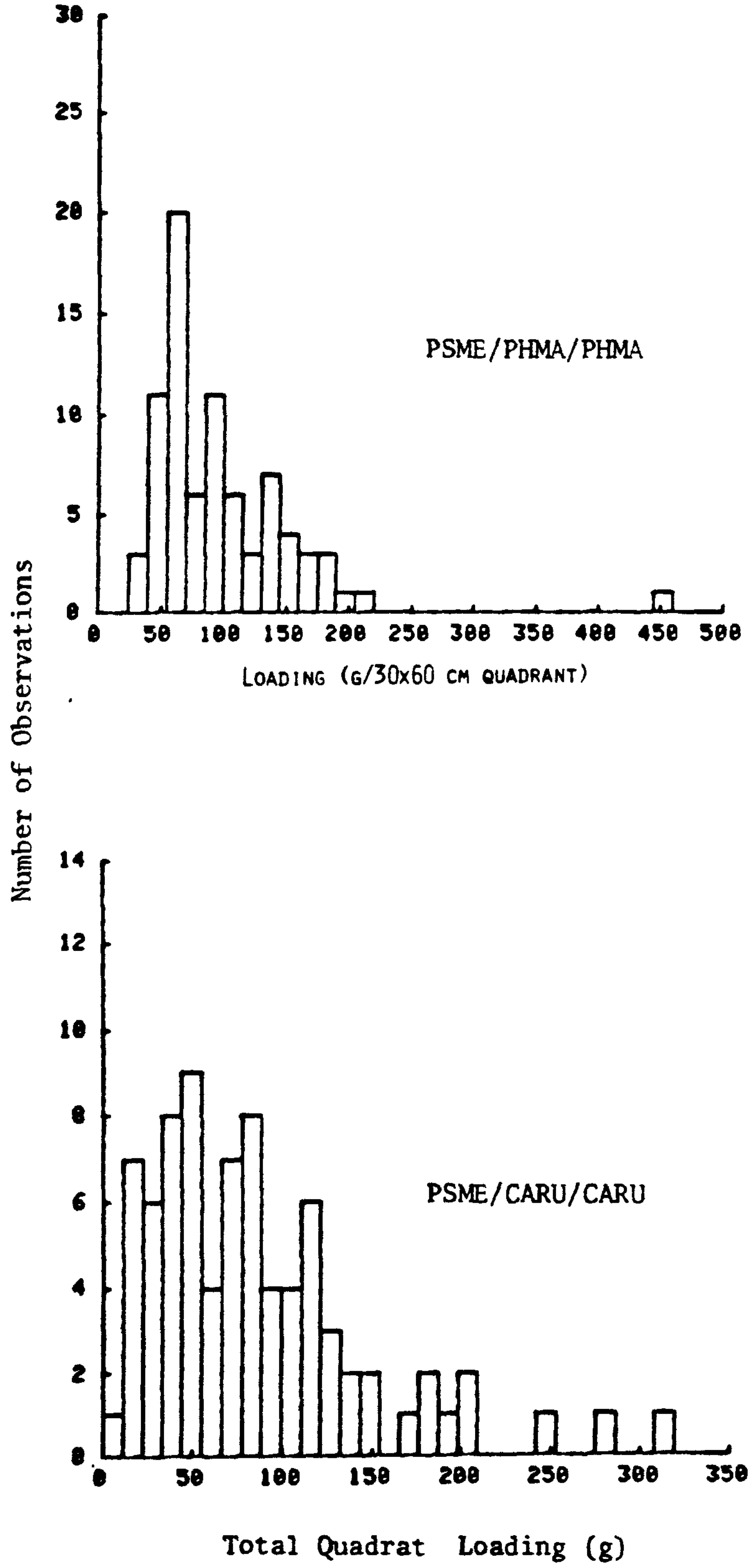
1/ Values beyond the scale of the histogram.

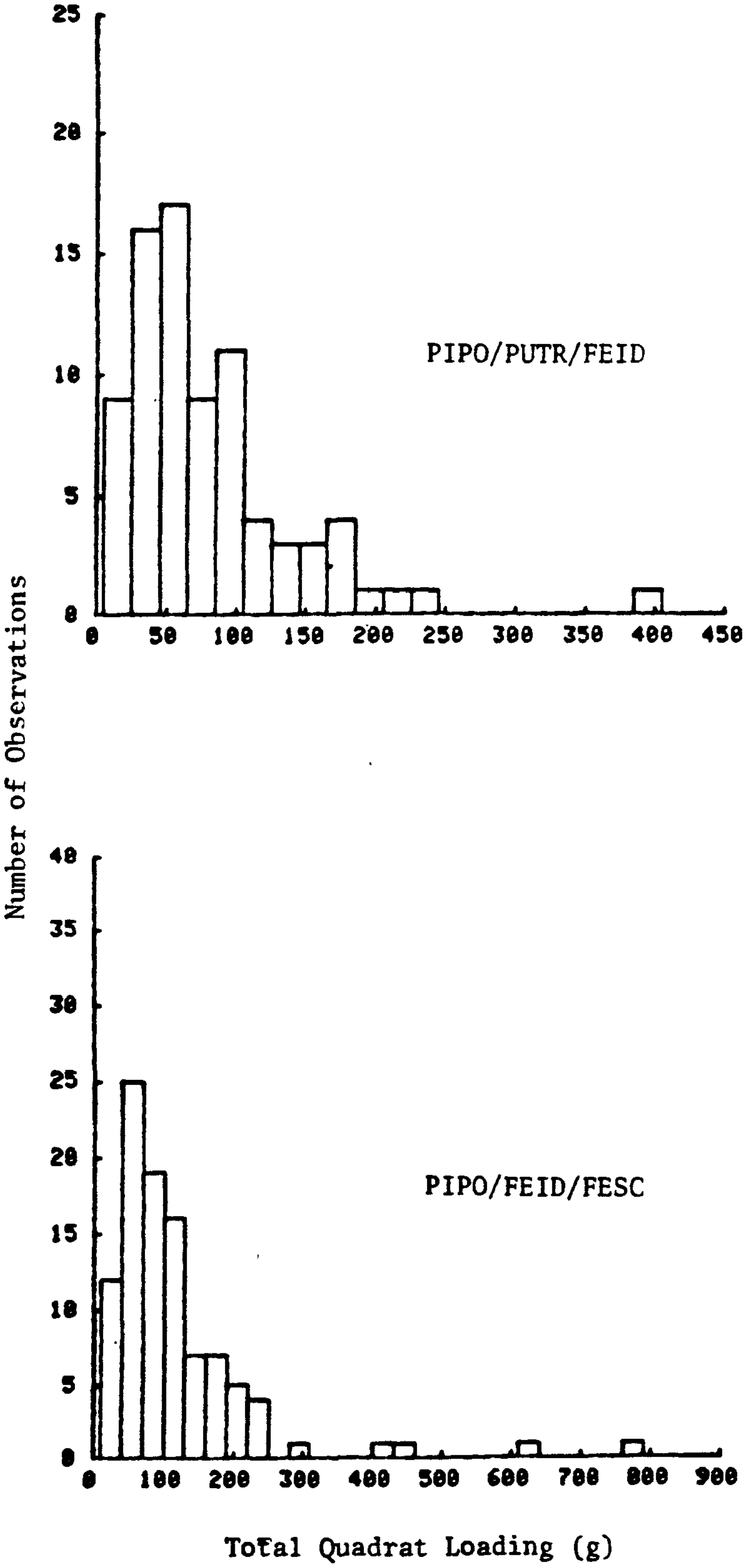
APPENDIX VI

The total quadrat fuel loadings (grass/forb and litter) are displayed in histograms. These total loadings were used to calculate total bulk density, which in turn were used to calculate fuel depth used in the FIREMOD algorithm.


24
22
20
18
16
14
12
10
8
6
4
2
0
0
50
100
150
200
250
300
350
ABLA/VACA
Number of Observations
30
25
20
15
10
5
0
0
50
100
150
200
250
300
350
400
450
ABLA/VASC/VASC
Total Quadrat Loading (g)


Number Of Observations
16
14
12
10
8
6
4
2
0
ABLA/CLUN/CLUN
0
50
100
150
200
250
300
ABLA/LIBO/XETE
Total Quadrat Loading (g)


30
25
20
15
10
5
0
PSME/PHMA/PHMA
0 50 100 150 200 250 300 350 400 450 500
LOADING (G/30x60 CM QUADRANT)
Number of Observations
14
12
10
8
6
4
2
0
PSME/CARU/CARU
0 50 100 150 200 250 300 350
Total Quadrat Loading (g)


PIPO/PUTR/FEID
0
5
10
15
20
25
0
50
100
150
200
250
300
350
400
450
PIPO/FEID/FESC
0
5
10
15
20
25
30
35
40
0
100
200
300
400
500
600
700
800
900
Number of Observations
Total Quadrat Loading (g)