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LD50, A TOOL DESCRIBING THE RELATIONSHIP BETWEEN
FIRE ENERGY RELEASE RATE AND TREE MORTALITY

by

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ABSTRACT

The toxicological concept of LD50, a relationship between dose and response, has been borrowed to describe the effect of fire energy release rate upon tree mortality. Five experimental sites from Point Sublime, Grand Canyon National Park, were burned and energy release rates were measured by radiometric analysis. Tree kill percentages from four coniferous taxa, ponderosa pine (Pinus ponderosa), Douglas-fir (Pseudotsuga menziesii), white fir (Abies concolor), and spruce spp. (Picea engelmannii, P. pungens) were plotted against diameter class and statistically fitted to the appropriate curve type. LD50 is correlated with energy release rate for all taxa ($R^2 = 0.94$). The tree diameter class in which 50% mortality will occur can be predicted. A direct relationship between prescription burning parameters and tree mortality by fire may be established.

Key words: Prescription burning, Ponderosa pine, white fir, Douglas fir.

LD50, A TOOL DESCRIBING THE RELATIONSHIP BETWEEN FIRE ENERGY RELEASE RATE AND TREE MORTALITY

Introduction

Many fire prescriptions used in the United States are primarily designed to predict fire behavior. They do not predict the effect of fire on ecosystems. Examples of current fire behavior predictive prescriptions are the National Fire-Danger Rating System (NFDRS) and its associated model, AFFIRMS (Deeming 1972 and 1977). These systems were developed to meet the needs identified by managers whose major concern is fire control. Where emphasis is to be placed on manipulation of ecosystems, fire behavior prescriptions are inadequate. A prescription that predicts tree mortality resulting from burning is necessary to predict effects of fire on forest ecology. An important element in the NFDRS and other similar systems is the energy release rate of fire which is instrumental in evaluating fire propagation. This paper reports the results of work done to establish a relationship between fire energy release rate and the mortality of four common species of coniferous trees, ponderosa pine (Pinus ponderosa), Douglas-fir (pseudotsuga menziesii), white fir (Abies concolor), and spruce spp. (Picea engelmannii, P. pugnans), linking fire behavior with forest ecology using LD50 as a descriptive tool.

Literature Review

Trevan, a toxicologist, described the dose-response relationship of toxicology in his introduction of LD₅₀ (Trevan 1927). He determined that at low drug dosage levels some subjects responded but many did not. At high drug dosage levels most subjects responded but a few did not. At some certain dosage level 50% of his subjects responded and 50% did not. He introduced the term "LD₅₀" to describe this 50-50 situation, literally "Lethal Dose 50." He found that by plotting dose-response data for a large number of individuals, a sigmoid curve developed. The LD₅₀ is both the median value of the data and the point of inflection of the curve. Jensen and Homeyer (1970) offer an exposition of the properties of sigmoid curves, and the importance of knowing the point of inflection in fitting curve to data. In general, Trevan found it impossible to

predict a dosage level where no subjects would show response and the dosage level where all subjects responded. Thus a completely safe or completely lethal dose cannot be established. But the LD₅₀ proved to be a useful statistic for the comparison of toxicity of various drugs. Fire can be considered as 'dose' and tree mortality as 'response' and LD₅₀ applied to trees; thus forming a statistic for the description and prediction of tree kill by fire. In this paper, 'LD50' will stand for that diameter class at which 50% of the trees are killed by fire, i.e., Lethal Diameter 50.

Ahlgren (1974), Little (1959), Weaver (1957), and many others report that excessive heating of phloem, cambium, and leaf tissues are important causes of fire kill. There is a positive correlation between bole diameter and tree survival in forest subjected to ground fire of moderate intensity (Cooper 1960, Kayll 1963, Weaver 1951, 1957, and 1967, Wahlenberg 1960, West 1969 et al.). The barks of ponderosa pine (Pinus ponderosa), Douglas-fir (Pseudotsuga menziesii), white fir (Abies concolor), and Engelmann spruce (Picea engelmannii) become thicker and more cork-like with age and increased size (Coulter and Chamberlain 1917), providing increased protection for phloem and cambium tissues. Fahnstock and Hare (1964) investigated the heating of tree trunks by headfires and by backfires. Measurements were taken on both windward and leeward sides of trunks. Cambium mortality was found to be related both to wind direction and bole diameter. Darby and Gates (1966) derived a mathematical model indicating that a relationship exists between heat penetration and stem diameter. Van Wagner (1970), Cooper (1960), and Weaver (1967a) remark that the foliage of taller trees is less subject to fire damage, perhaps because it is heated less intensely.

METHODS

Study Area

Point Sublime has been designated as a fire study area by Grand Canyon National Park, Arizona. It extends from the Kaibab Plateau into the Grand Canyon and ranges in elevation from 2300 m to 2740 m (7500 - 9000 ft.) at its highest point. The hot, dry canyon and the sub-alpine pla-

teau permit development of a mosaic of plant associations separated by broad ecotones. Annual precipitation is bimodal, peaking in February and August. Snowfall accumulation may exceed 2 m during the winter months. Summer rains are violent in nature and fall chiefly in late July and August. Mean annual precipitation is 70 cm (27.5 in.) and mean annual temperature is 6°C (42.8°F).

Experimental Site and Plot Selection

Sites considered as research target areas were selected empirically on the basis of ecological, topographical, and fuel diversity; safety; and representativeness of forest associations available for experimental work. This was done to ensure that a single fire would generate a wide variety of burning conditions and energy release rates. Five sites were selected (Table 1). Each site was surrounded by a fire line and the entire area within this line was eventually burned.

Each experimental site was mapped and map overlays showing fuel loadings and cover type were prepared. Nested sample plots were randomly selected. The number of plots needed was determined by the method of statistical analysis to be employed, the size of the vegetation or fuel unit to be sampled, and homogeneity of the unit (Fig. 1). Overall, 127 plots, each 900 m², were used in this project to achieve uniformity at the 95% confidence level. See Table 1 for plot distribution.

SAMPLING PROCEDURE

Trees

All living trees were inventoried on each 900 m² plot. Diameter breast high was measured for trees of more than 5 m and trees of less than 5 m were measured using basal diameter. Diameter measurements were made with diameter tape. The data were stratified according to species.

Fuels

Dead fuels were classified by particle diameter into three categories: (1) fine fuels (less than 1 cm diameter, including litter and duff), (2) medium fuels (more than 1 cm but less than 8 cm diameter), and (3) heavy

fuels (more than 8 cm diameter). Fine and medium fuels were collected from a 25 m² subplot at each corner of the plot prior to burning, depths and weights were measured, and the samples retained for subsequent analyses. These denuded subplots were "restored" with material from outside the sample plots to minimize any possible alteration of fire behavior.

The heavy fuels and standing dead fuels were not moved or disturbed. That portion of heavy fuels lying within 100 m² square centered along the north and south boundaries of the plots was measured for length and diameter so that fuel volume within the subplot could be determined. Heavy-fuel weight was estimated by multiplying this volume by a density statistic derived from 64 cross-sectional slices taken from within the subplot. Accuracy of heavy-fuel estimates was verified by removing manageable sized pieces from outside the sample sites and drying and weighing them.

Postburn fuel measurements were made in the same manner as preburn measurements on adjacent and undisturbed subplots of equal area within the sample plot. The difference between the preburn and postburn measurements was used to estimate the weight and depth of fuel consumed.

Pre- and postburn fuel samples were subjected to calorimetric analysis. After drying, the samples were repeatedly quartered until a 500 g subsample was obtained. Subsamples were ground in a Wiley mill to pass a 20-mesh screen. Samples were pelleted with a 0.95 cm punch and die under 350 kg/cm pressure to give a pellet weighing between 0.8 and 1.0 g as recommended in Parr's Specification no. 2811 (1969). A sufficient number of pellet replicates was analyzed for caloric content in a Parr 1241 adiabatic oxygen bomb calorimeter to yield a standard deviation of the mean less than 0.001 kcal/g. The analyses were done in accordance with ASTM Standard D 240-64 using 20 atm oxygen pressure. Results were reported in kcal/g at the 95% confidence level with acid, sulfur, and fusewire corrections applied.

Energy Release Rate Measurement

The energy release rate was measured on each plot during burning. Two

different methods were used, radiometric and fuel consumption rate; each with two variations (Table 2).

Radiometric: groundbased. An Epply R413 radiometer masked for 15° field of view was suspended perpendicularly over each plot center. The radiometers were connected to a 24-point sampling potentiometer strip chart recorder. The results were reported in $\text{kcal/m}^2/\text{s}$.

Radiometric: aerial. An airborne infrared scanner was flown 600 m above ground level for 3 hours during the burn on site C. A pass over the fire area was made every 15 minutes. The data were recorded on magnetic tape and interpreted digitally. These data were compared to groundbased data.

Fuel Consumption: weight. The total weight of fuel consumed was determined (preburn estimated weight less actual postburn weight), multiplied by the caloric content of the fuels, and divided by the entire time of the burn to give the mean energy release rate during the entire burn.

Fuel Consumption: volumetric. The reduction of fine-fuel depth during the active flaming period and the rate of flame advance were measured to give the volume of fuel consumed per unit of time. Using the mean fuel-bulk density (weight divided by volume) multiplied by the caloric content of the fuel, the energy release rate could be determined for relatively short time periods.

Tree Death

Death of coniferous trees caused by fire is difficult to evaluate over a short period of time. A tree was defined as killed when: (1) 75% of the foliage was brown and deciduous one year after the fire; (2) no viable growth tips could be found; and (3) the bark of twig internodes showed distinct longitudinal furrowing caused by drying and shrinking of the succulent tissues beneath. Trees within the test plots were inventoried in detail one year following the fire. The results were verified each year for the following two years, giving a three year period of assessment before the trees were declared dead.

RESULTS

Fire Intensity

Measurements of fire intensity made by the radiometric and the fuel consumption rate methods showed widely disparate results. The causes of the variability have not been isolated.

Radiometric: groundbased. The Epply radiometer method was judged best for determining the energy release rates. The data correlated best with LD50 data. Precision of measurement was relatively good with one standard deviation being 23% of the mean. Variability in energy release rates measured over a 15 minute period (22 to 63 kcal/m²/s) for a fuel bed of uniform depth and moisture content is greater than might be expected. Fine-fuel beds that are rough in surface texture emitted less radiation than those of a smoother texture. This effect was attributable to having some short-wave radiation blocked by other burning, but nevertheless opaque, particles. In addition, the radiometer's protective glass envelope was subject to accumulations of debris condensed from the smoke plume. These two effects contribute to the variability of the data.

Radiometric: aerial. The airborne Texas Instruments scanner gave the next best precision of measurement in large forest openings. This sensing method was used only on site C due to high cost of operation and obstruction by the tree canopy and smoke plume. The data taken from site C are summarized in Table 2. When flown at 600 m altitude, the scanner has a minimum view of 9 m² per data point. Each data point represents an average of the radiation received. Interference by the canopy or smoke plume depends upon the flight path of the aircraft which cannot be exactly duplicated. Therefore variability is introduced into measurements under forest cover. The standard deviation was 43% of the mean, a value twice as unsatisfactory as that of the radiometer-measured method.

Fuel Consumption: weight. This gives the more precise results of the two fuel consumption variants. The standard deviation was 61% of the

mean. One problem with this method is that the preburn fuel weight and particle size distribution can only be estimated from a sample taken from a different subplot, since disturbance of the subplot to be burned would likely alter the fuel burning characteristics. The total time of burning varies directly with the fuel-bulk density. Fuels with higher bulk densities burn longer. Perhaps less serious is the variability introduced by differences in the energy content of the fuels between the sampling and burning subplots. Generally, energy release is high during the actual flaming period when the superficial layers of the fuel are being consumed, but drops to a low level as the compacted higher bulk density duff is being burned. The duff may burn so slowly that the fire persists for a week or more. Because the energy release calculated by this method is averaged over this extended time, the energy release rate is apparently quite low. The initial flaming period is most responsible for tree stem heating death. Slow consumption of the duff layer does not have this effect. This method of energy release measurement does not seem to be as well related to tree kill as methods which emphasize measurement of the higher initial burning rate.

Fuel Consumption: volumetric. This variant is less precise than the weight variant, yielding a standard deviation of 67% of the mean. This method produces higher values because of an increased energy release rate during the active flaming period. The measurements are subject to considerable error since they are made partly by estimation. Employing this method is difficult when working with low intensity fires and nearly impossible, and dangerous, when working with intense ones.

The correlation between LD50 and method of measurement is presented in Table 3. Figure 2 presents a histogram of the energy release rates for all experimental sites and all plots.

Fire Intensity and LD50

LD50 is correlated with energy release rate for all fires ($R^2 = 0.94$). The LD50 data and energy release rates are summarized in Table 4 and Figure 3. These data were fitted to the polynomial:

LD50 (ponderosa, diam. cm) =

$$0.42978Q - 1.32435 \times 10^{-3}Q^2 + 3.326019 \times 10^{-6}Q^3 - 4.368027 \times 10^{-9}Q^4 + 2.2745824 \times 10^{-12}Q^5 \quad \text{Eq. [1]}$$

$$R^2 = 0.94$$

where Q is the energy release rate (kcal/m²/s)

Tree kill percentages were plotted against each diameter class, given a known LD50. Each taxon of tree gave a different shaped curve (Figs. 4-7). The ponderosa pine data are best described by an exponential equation. Douglas-fir, white fir, and spruce appear to fit sigmoid curves. The data for each taxon were fitted to the appropriate curve type, generating a curve for each LD50 encountered in the experimental burns. The curves presented are interpolations of the experimental data. The equations derived from fitting the data to these curves are:

$$\text{Kill percentage (ponderosa)} = 100 \times \exp(-P \times 0.3937D) \quad \text{Eq. [2]}$$

$$P = -4.52965 \times 10^{-3} + \frac{2.03208}{LD50} \quad \text{Eq. [3]}$$

$$R^2 = 0.93$$

where D = diam. in cm

Douglas-fir, white fir, and spruce spp. kill percentages are modeled in a similar manner except that second order sigmoid curves are used.

$$\text{Kill percentage} = A + B \times P \quad \text{Eq. [4]}$$

$$P = \frac{\exp\left(-\left(\frac{\frac{C-0.9337D}{C} - 1}{K-1}\right)^2\right) - N}{1-N} \quad \text{Eq. [5]}$$

$$N = \exp\left(-\frac{1}{K-1}\right) \quad \text{Eq. [6]}$$

$$K (\text{Douglas-fir}) = 1.02702 - 1.3825 \times 10^{-2}LD50 + 3.72501 \times 10^{-4}LD50^2 - 1.13417 \times 10^{-5}LD50^3 + 1.61355 \times 10^{-7}LD50^4 - 1.12146 \times 10^{-9}LD50^5 \quad \text{Eq. [7]}$$

$$K \text{ (white fir)} = 0.81108 + 0.035041LD50 - 4.2811 \times 10^{-3}LD50^2 + 1.95437 \times 10^{-4}LD50^3 - 4.70726 \times 10^{-6}LD50^4 + 5.7513 \times 10^{-8}LD50^5 - 2.8361 \times 10^{-10}LD50^6 \quad \text{Eq. [8]}$$

$$K \text{ (spruce spp.)} = 0.82662 + 0.028981LD50 - 3.13999 \times 10^{-3}LD50^2 + 1.2457 \times 10^{-4}LD50^3 - 2.5674 \times 10^{-6}LD50^4 + 2.6518 \times 10^{-8}LD50^5 - 1.0942 \times 10^{-10}LD50^6 \quad \text{Eq. [9]}$$

where K is a taxon constant at LD50

For all four taxa, D is the diameter class being analysed in cm and LD50 is the particular LD50 for each taxon at a given energy release rate in cm.

Constants for Equations

Species	A	B	C
Douglas-fir	14.6308	85.3692	101.6
White fir	7.6089	92.3911	101.6
Spruce spp.	1.88	98.12	127

The coefficients of determination applicable to all the equation sets are: R^2 (Douglas-fir) = 0.87; R^2 (white fir) = 0.93; R^2 (Spruce spp.) = 0.91.

Using these equations, the investigator may predict the kill percentage for any of the taxa, given the LD50 for the particular fire for the particular taxon.

The LD50 for all four taxa are interrelated. When the LD50 for ponderosa pine and the LD50's for the other tree taxa from all test plots are fitted to polynomials, the following equations result:

$$LD50 \text{ (Douglas-fir)} = 2.49 + 2.5573LD50 + 4.9926 \times 10^{-2}LD50^2 - 5.531262 \times 10^{-3}LD50^3 + 1.340526 \times 10^{-4}LD50^4 - 1.035511 \times 10^{-6}LD50^5$$

$$R^2 = 0.96 \quad \text{Eq. [10]}$$

$$\begin{aligned} \text{LD50 (white fir)} = & -1.66 + 5.0658\text{LD50} - 0.183069 \times 10^{-2}\text{LD50}^2 \\ & + 3.511041 \times 10^{-3}\text{LD50}^3 - 2.42361 \times 10^{-5}\text{LD50}^4 \\ R^2 = & 0.94 \end{aligned} \quad \text{Eq. [11]}$$

$$\begin{aligned} \text{LD50 (Spruce spp.)} = & 4.67 + 5.0553\text{LD50} - 0.16138 \times 10^{-2}\text{LD50}^2 \\ & + 5.56804 \times 10^{-3}\text{LD50}^3 - 1.851997 \times 10^{-4}\text{LD50}^4 + 3.529604 \times 10^{-6}\text{LD50}^5 \\ & - 2.556776 \times 10^{-8}\text{LD50}^6 \\ R^2 = & 0.93 \end{aligned} \quad \text{Eq. [12]}$$

where LD50 in all equations is for ponderosa pine in cm

These relationships are represented graphically in Figure 8.

Discussion

Investigators and prescribed fire managers are urged to apply these results with caution. The approach has been empirical and is only known to be valid for the forests of the North Rim of the Grand Canyon. The ponderosa pine forests there have been isolated from the main gene-pool on a forested "island" surrounded by deserts for a considerable time. It is reasonable to suppose that the ecotypes there are not typical. The trees may be more or less sensitive to fire effects than is typical. Bennett (unpublished ms.) found that the infestation of the forest by mistletoe (Arceuthobium sp.) is much higher on the North Rim than on the South. Infested trees are more subject to fire kill than non-infested ones. There is a host of such complications that could affect the results reported.

That portion of the data and the models that deal with either large LD50's or very high energy release rate should be treated with caution. Fires burning with a release rate around 500 kcal/m²/s or more are very intense, dangerous, fast moving, and impossible to measure with reasonable certainty. These data are representative of locations where fuel loadings were very heavy and consequently fire storms developed. Thus they are isolated cases. In each of these circumstances the radiometers were melted or their connecting wires were burned through. It is not known if the last measurement taken represented the maximum release rate, or how much higher it went. Trees in the 150 cm or greater

classes are rarities in the North Rim forests, consequently derivation of reliable LD50 data for them is impossible using reasonably sized sample areas. The large tree data are included in the models, but the cases are so few that they do not materially affect the shape of the equations fitted to them.

The plotted curves (Figs. 4-7) show the relationship between the tree diameter classes, the percentage of trees killed, LD50, and the early vs. late bark-forming taxa. Each curve line represents a different LD50. The curves demonstrate the difference in fire resistance between the ponderosa pine, which forms thick, corky bark early, and those taxa which form this protection only later. These latter taxa remain less resistant to fire, probably because their foliage position provides an easy pathway for fire to burn up into the crown. It is possible that the degree of resistance may be more due to typically close tree spacing and resultant self-pruning, denying fire access to the crowns, than to the anatomy and physiological fire adaptation.

Figure 8 presents the relationship between the LD50 for ponderosa pine and the LD50 for the other conifers examined. By using the relationship shown or by use of the corresponding Equations [10-12] the LD50 for these trees may be determined on the basis of the LD50 for ponderosa pine. With this information the kill percentage for these taxa may be determined by use of Figures (4-7) or Equations [2-9].

When the size class distribution of a stand is known and the inventory partitioned according to the taxa present, post-fire stand composition may readily be determined given the proposed fire intensity. This is accomplished by determining the LD50 for each taxon relative to the proposed LD50 for ponderosa. Then determine the projected kill percentage for each taxon and each diameter class represented in the stand. The percentage for each kind of tree in each represented diameter class that will be fire killed may be estimated. The predicted kill percentages multiplied by the pre-fire inventory figures will give the number of trees and their sizes. By this means the post-fire composition and size distribution can be predicted prior to burning.

A subsequent paper in press will relate ponderosa LD50 to fuel loadings, fuel moisture, weather conditions, and slope. The ability to predict LD50 as presented, and the means to estimate post-burning forest composition will provide a practical means of incorporating ecological consequences into burning prescriptions.

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Figure 1. (a). Map of a typical experimental site showing locations of fire line, site boundary, and southwest corners of randomly located test plots. + = test plots corners; vhf = very fuel loading; hf = heavy fuel loading; mf = medium fuel loading; lf = light fuel loadings. (b). A typical test plot showing arrangement of fuel sampling subplots. The southwest corner has been located randomly. All plot lines run north-south or east-west.

Figure 2. Histogram of energy release rates for all sites and all plots (n = 127). Energy release rates were plotted to indicate the relationship to tree kill at LD50. The curved line represents Gaussian distribution.

Figure 3. Scatter diagram and fitted curve for energy release rate vs. ponderosa pine LD50 data for all sites and all plots (N = 127).

Figure 4. Relationship between kill percent and tree diameter at LD50 of 8, 15, 30, 60 cm for ponderosa pine. Example: find tree diameter of 28 cm on X-axis, move vertically to intersect desired LD50 (in this case, 15 cm), then horizontally to the Y-axis to read 25.5% tree kill. At ponderosa pine LD50 of 15 cm, 25.5 % of the 28 cm diameter ponderosa will be killed.

Figure 5. Relationship between kill-percent and tree diameter at LD50 of 10, 20, 40, 60 cm for Douglas-fir.

Figure 6. Relationship between kill-percent and tree diameter at LD50 of 8, 15, 30, 60 cm for white fir.

Figure 7. Relationship between kill-percent and tree diameter at LD50 of 8, 15, 30, 60 cm for spruce spp.

Figure 8. Comparison of tree kill curve shapes for all conifers. Kill percentage of ponderosa pine, an early bark forming species, drops sharply in comparison to Douglas-fir, white fir and spruce spp., all late bark forming taxa. Kill percentage of the late bark formers remains high until insulating bark begins to form at approximately 15 cm diameter.

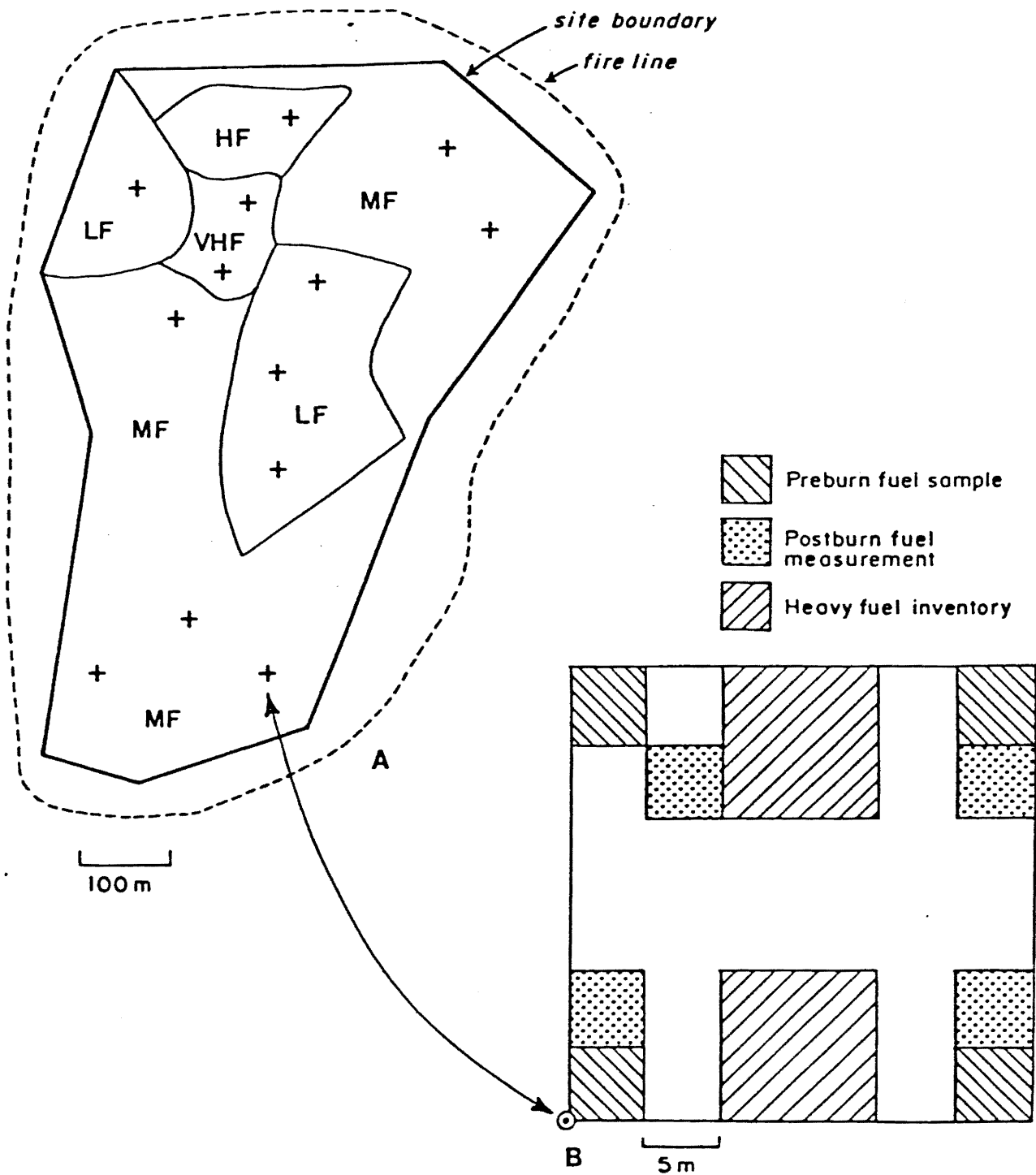


Figure 1a & b
 Bennett/Kunzmann
 LD50, Energy Release Rate

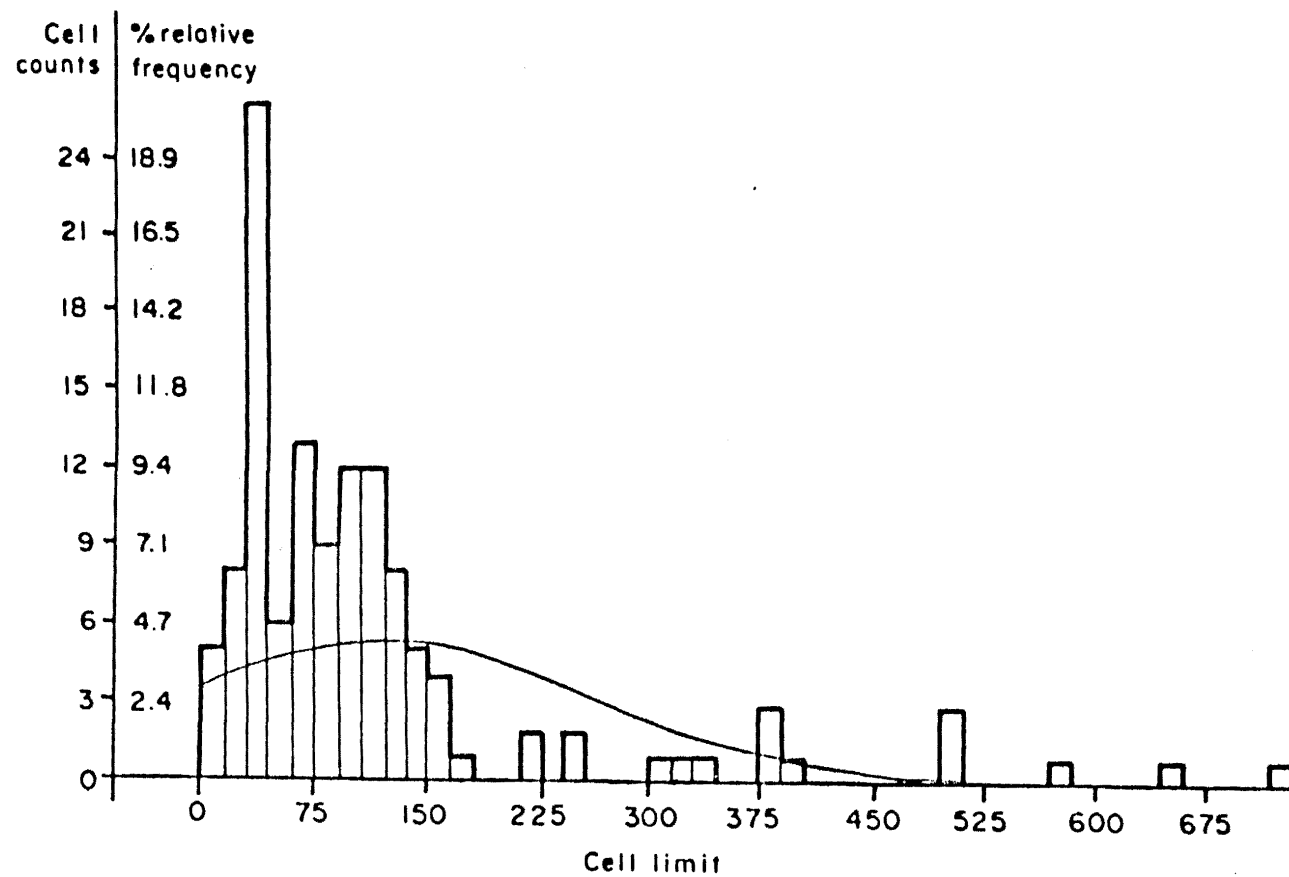


Figure 2
Bennett/Kunzman
LD50, Energy Release Rate

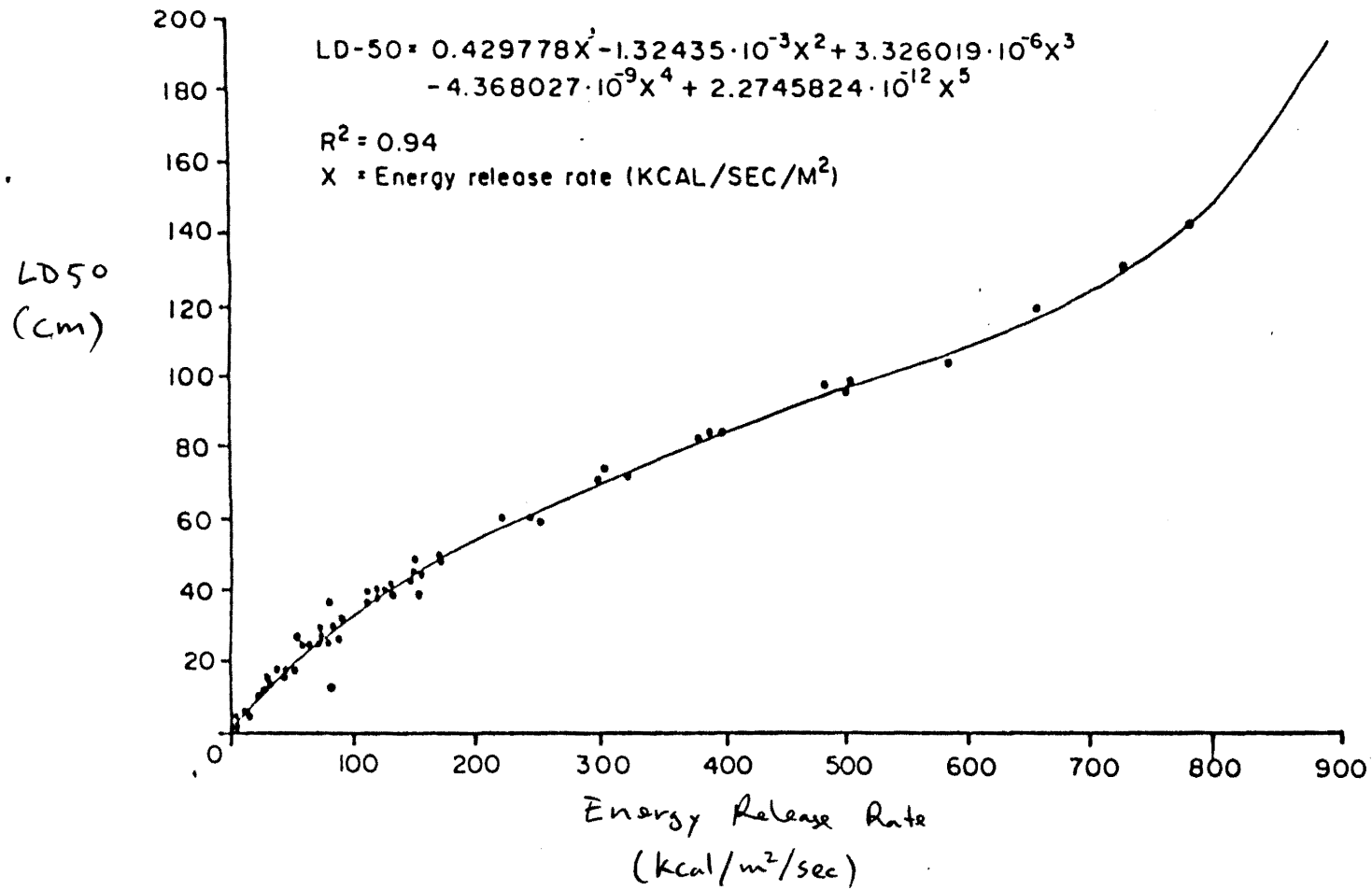
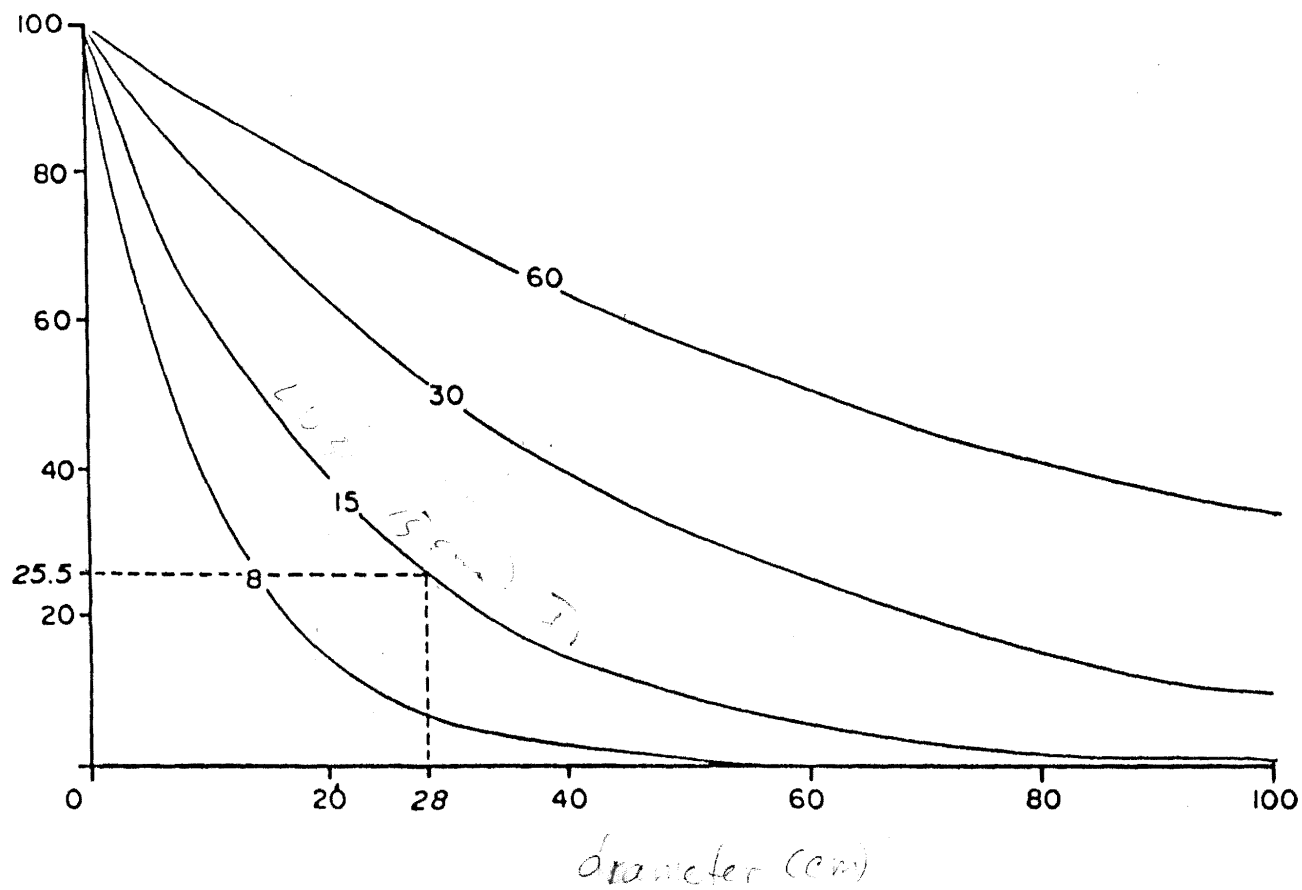


Figure 3
Bennett/Kunzman
LD50, Energy Release Rate



Powder

Figure 4
Bennett/Kunzman
LD50, Energy Release Rate

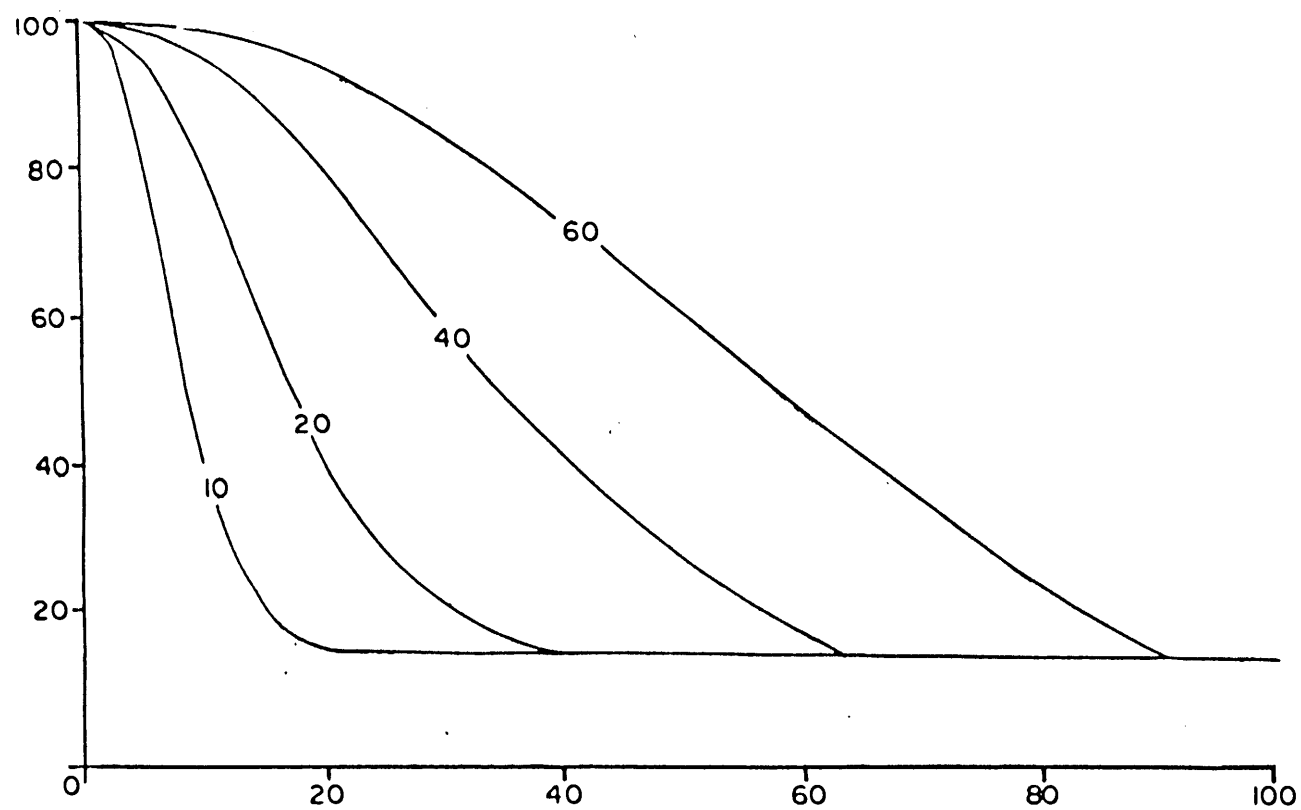


Figure 5
Bennett/Kunzman
LD50, Energy Release Rate

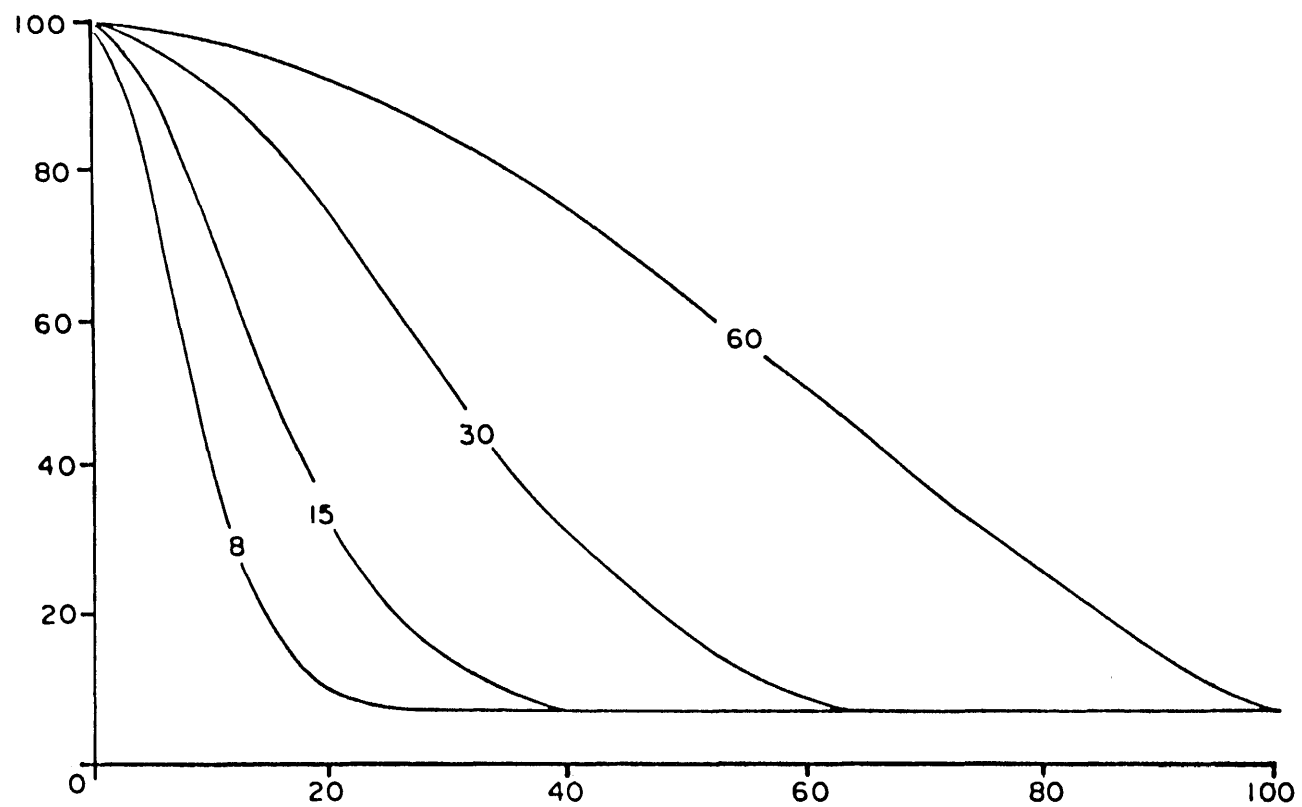


Figure 6
Bennett/Kunzman
LD50, Energy Release Rate

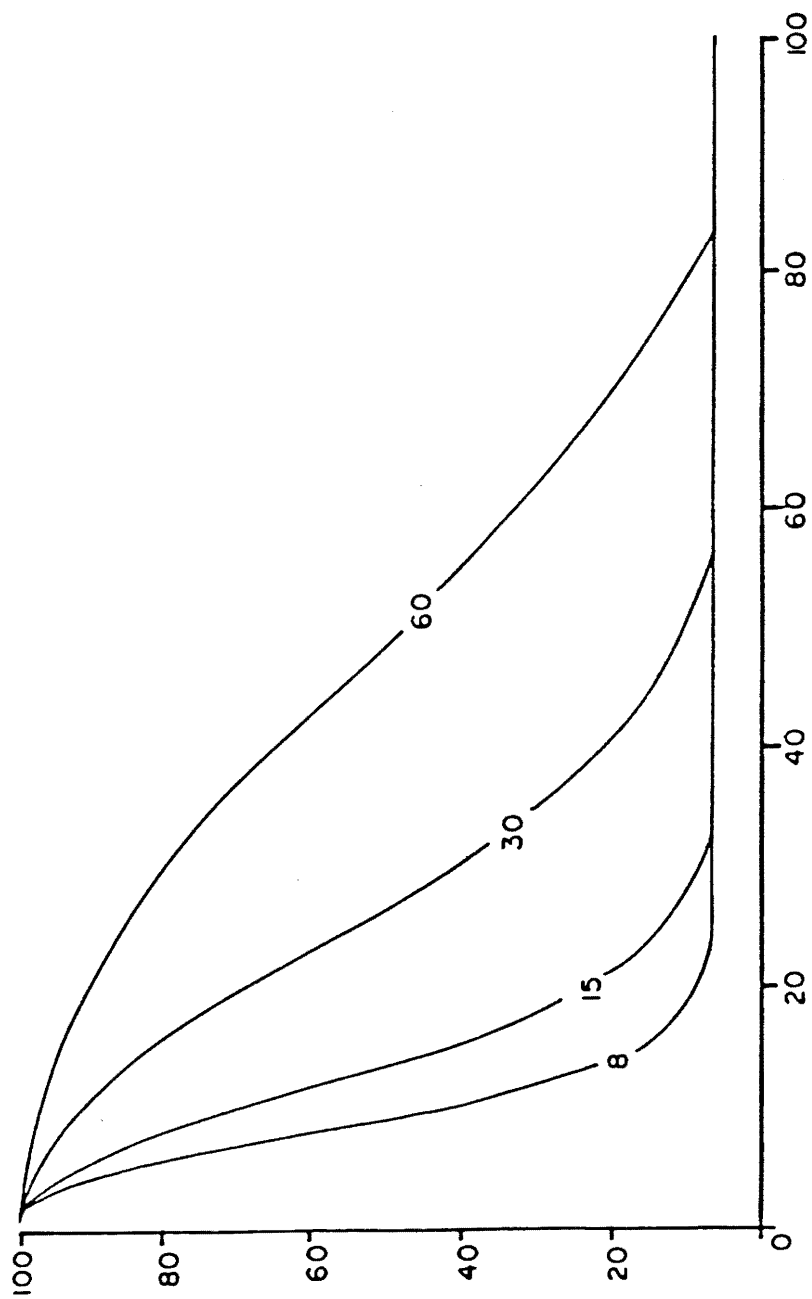


Figure 7
Bennett/Kunzman
LD50, Energy Release Rate

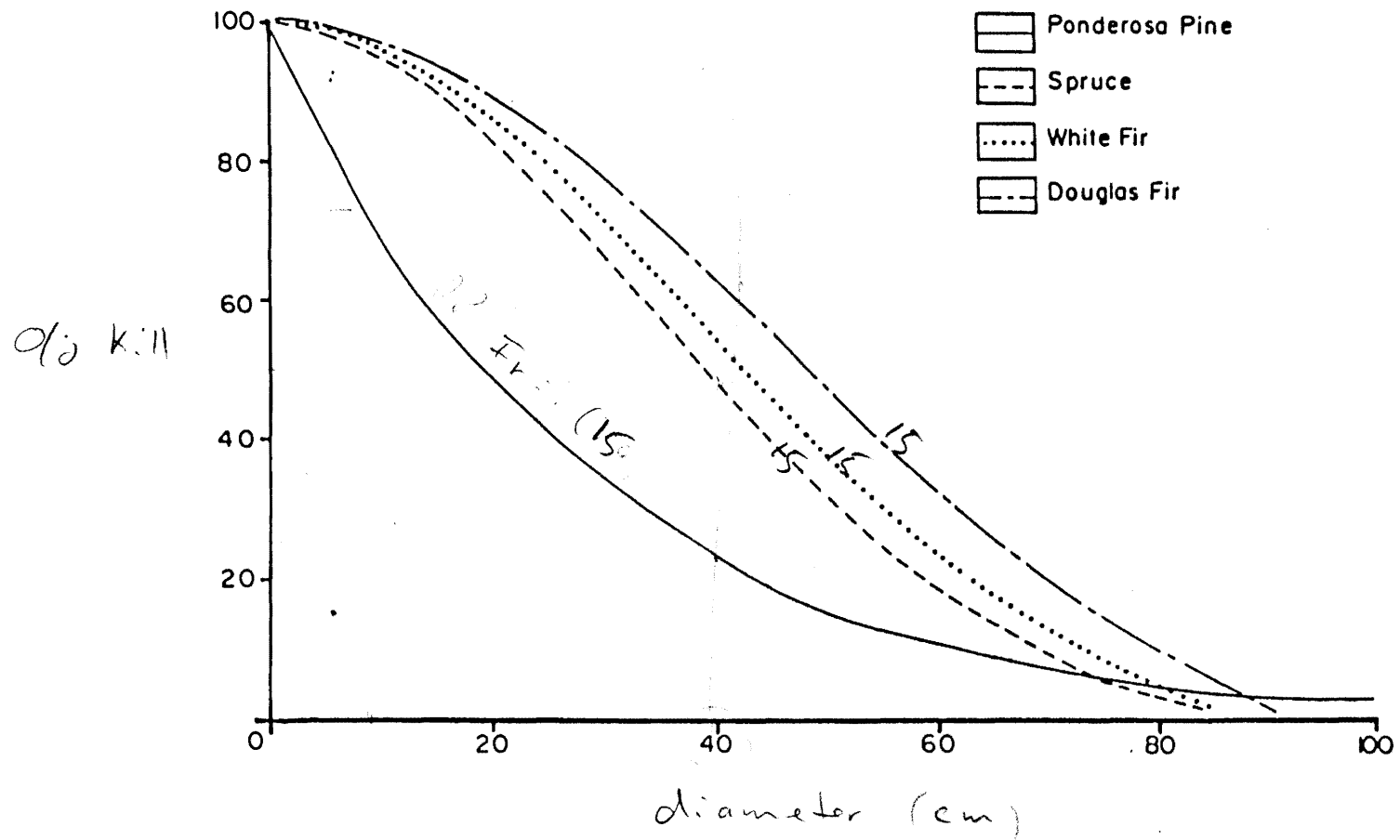


Figure 8
Bennett/Kunzman
LD50, Energy Release Rate

Table 1 -- Characteristics of the Burn Sites

Name	Vegetation	Fuel loadings	No. of plots	Topography	Size / Year burned
SA	<u>Pinus ponderosa</u> - <u>Quercus gambeli</u> ; <u>Pinus ponderosa</u> - mixed grass; and <u>Populus trem-</u> <u>uloides subclimax</u> associations	(c,h,g,a) ^a 6.37 x 10 kg/ha	27	12% max. slope E-W slopes U- shaped canyon	1 ha / 1971
SB	<u>Pinus ponderosa</u> - mixed grass associations	(c,a) ^a 2.88 x 10 kg/ha	26	flat	1 ha / 1973
SC	<u>Pinus ponderosa</u> and <u>Pinus ponder-</u> <u>osa</u> - mixed conifer associations	(g,b,d) ^a 5.74 x 10 kg/ha	30	20% max. slope level, steep canyon	Total 13 ha 7 ha / 1973 6 ha / 1974
SD	<u>Pinus ponderosa</u> ; <u>Pinus ponderosa</u> - mixed conifer; and Douglas-fir - white fir associations	(g,b,d) ^a 5.95 x 10 kg/ha	34	18% max. slope to flat	37 ha / 1975
S1	<u>Pinus ponderosa</u> - mixed conifer associations	(c,a) ^a 3.01 x 10 kg/ha	10	26% max. slope level	2.8 ha / 1971

^a() = NFDRS fuel types.

Table 2
Comparison of Energy Release Rates (ERR) by Two Methods
Site C. 1973 and 1974

Method	ERR in Kcal/m ² /s				Problems
	Min.	$\bar{X}$, SD	Max.	SD% of $\bar{X}$	
Radiometric					
1. Airborne, remote sensing, Texas Instruments scanner 600 m above ground surface.	(14)	38.6±16.5	(42)	43%	View obscured by vegetation and smoke plume, radiation affected by atmospheric conditions, especially water vapor and carbon dioxide. Minimum area for a data point is 9 m ² .
2. Epply radiometer masked for 15° view, parallel to ground surface.	(22)	48.1±11.5	(63)	23%	Measuring element not uniformly sensitive to all wavelengths; incoming energy attenuated by smoking of protective glass envelope; quite sensitive to physical roughness of fuel bed which influences radiation characteristics.
Fuel consumption rate					
1. Based on total fuel consumed during flaming period.	(17)	21.4±13.0	(25)	61%	Burning rate is not uniform during flaming period, most of fuel consumed at low ERR over a long period of time allowing fuel moisture to change by heating.
2. Based on estimated fuel consumed per unit of time.	(9)	32.5±21.9	(68)	67%	Difficulty in estimating weight of fuel consumed when fuel bed is not homogenous.

TABLE 3
CORRELATION OF LD50 DATA WITH ENERGY RELEASE RATE
BY DIFFERENT METHODS OF MEASUREMENTS

Method	R^2
Radiometric: groundbased	0.94
aerial	0.89
Fuel Consumption: weight	0.83
volumetric	0.86

TABLE 4

THE RELATIONSHIP BETWEEN ENERGY RELEASE RATE EXPERIMENTAL
DATA AND THE LD50 FOR VARIOUS KINDS OF TREES.
THESE DATA ARE FROM ALL SITES AND ALL PLOTS
MEASURED BY EPPLY RADIOMETER.

ERR Kcal/m ² /s	LD-50 Pipo	LD-50 Psme	LD-50 Abco	LD-50 Spruce
7.49	2.79	9.13	11.04	17.24
8.44	2.57	8.60	9.61	16.22
11.40	3.74	11.79	13.93	21.09
12.49	4.34	13.50	16.19	23.31
13.65	4.86	15.12	18.57	24.69
16.27	6.62	19.88	23.83	31.20
18.08	6.79	20.37	25.17	31.27
18.62	6.59	20.05	24.32	30.69
21.85	8.71	25.39	30.09	37.59
22.52	8.41	24.72	29.13	36.08
27.49	10.35	29.23	34.52	41.46
27.66	10.25	28.56	34.03	41.18
28.85	10.41	29.51	34.52	41.59
31.57	12.08	32.65	37.75	44.60
31.76	11.60	31.95	36.67	43.87
32.10	11.92	32.30	37.73	44.06
32.64	12.28	33.62	38.78	45.09
33.03	12.26	33.44	28.40	44.34
33.06	12.13	33.08	38.49	44.57
33.07	12.30	33.74	38.00	44.60
33.40	12.29	33.46	38.22	44.50
34.01	12.66	34.06	39.60	45.29
36.30	13.88	36.28	41.07	46.88
36.44	13.60	35.79	41.10	46.46
36.45	13.25	35.29	40.63	46.69
36.59	13.33	35.57	40.13	46.85
36.87	13.89	36.99	40.95	47.20
37.90	14.20	37.41	42.19	48.16
39.39	14.11	37.52	41.92	47.18
41.69	14.87	38.36	42.55	48.96
41.92	15.50	39.37	43.56	49.10
41.98	15.30	39.86	44.12	48.71
42.55	15.40	39.88	44.25	49.59
42.64	15.76	40.58	44.90	49.75
42.68	16.04	41.12	44.52	49.72
43.08	15.46	40.17	44.16	48.84
43.13	16.27	40.96	45.29	49.84
43.44	16.15	41.20	45.02	50.22
44.12	16.12	40.99	44.79	50.06
46.42	16.43	41.07	45.45	50.35
46.67	16.67	42.29	45.95	50.70
51.88	18.51	44.94	48.44	51.93
52.87	18.85	45.82	48.27	51.87

TABLE 4 - CONT.

56.65	19.94	46.52	50.37	52.41
57.21	20.06	46.79	50.34	51.91
61.65	21.42	48.76	52.07	52.45
61.92	22.10	49.35	52.01	52.15
62.20	22.32	49.89	52.59	51.85
62.43	21.52	49.32	52.32	52.58
63.25	22.28	50.28	52.69	52.30
63.42	22.07	49.27	52.37	52.14
65.75	22.51	50.20	52.48	52.39
65.91	23.16	50.75	53.73	51.77
69.10	23.75	51.59	54.35	51.89
69.21	24.13	51.59	54.58	52.31
69.59	24.45	52.03	54.49	52.23
71.81	24.41	52.49	54.83	51.38
72.11	24.38	52.14	54.81	52.34
76.67	26.46	54.12	56.50	51.54
77.24	26.13	53.88	56.42	51.00
77.32	26.48	54.01	57.25	51.26
77.56	26.54	54.04	56.79	51.82
78.16	26.17	54.25	56.97	51.25
80.41	26.61	54.65	56.64	51.04
83.40	27.51	55.28	57.65	51.02
85.11	27.93	56.09	57.98	51.29
88.57	29.25	57.00	59.29	51.01
95.69	30.93	58.65	60.87	50.91
96.33	31.10	58.80	61.47	51.73
96.37	31.28	58.90	61.74	51.23
96.48	31.29	58.99	61.93	51.72
96.92	31.69	58.85	61.48	51.09
98.03	31.45	58.71	61.55	51.19
98.39	32.17	59.76	62.16	51.72
98.84	32.11	59.59	62.66	51.64
100.02	31.68	59.03	61.75	51.74
100.07	31.99	59.62	61.94	51.89
103.13	32.61	60.25	62.84	51.98
103.82	32.76	60.06	62.35	52.19
105.48	33.31	60.41	62.88	51.92
105.55	33.04	60.93	62.82	51.88
105.57	33.16	61.04	63.26	52.48
105.74	33.69	61.30	63.67	52.46
107.90	34.53	61.38	64.97	53.63
108.24	33.81	60.86	64.16	53.21
113.31	35.21	62.11	65.07	54.43
113.97	35.78	63.11	66.17	55.22
115.30	35.90	63.13	66.27	55.06
115.90	35.98	62.95	66.26	55.93
117.28	36.37	63.37	66.41	56.13
117.46	36.01	63.49	65.81	55.66
122.24	36.99	63.98	67.40	57.13
122.76	37.41	64.52	67.25	58.18
125.09	38.08	65.68	68.28	59.99

TABLE 4 - CONT.

125.72	38.05	65.48	68.28	59.59
127.68	38.27	65.12	68.73	60.42
127.85	38.53	65.50	68.58	60.96
134.05	40.36	67.53	70.60	67.04
134.64	39.66	66.80	70.33	64.13
137.49	40.85	67.85	70.81	69.01
138.02	40.61	68.44	70.71	68.41
140.29	41.16	68.13	71.90	70.53
140.73	41.05	68.56	71.63	69.56
141.27	41.48	68.86	72.05	71.35
150.21	43.72	71.46	74.28	83.51
150.25	43.79	71.41	74.21	83.93
156.51	44.19	72.19	74.35	86.34
164.58	46.51	74.79	77.49	103.82
170.22	47.47	75.12	78.04	111.99
222.90	57.26	77.77	86.25	244.52
222.97	57.18	77.41	85.80	243.99
242.35	60.51	81.63	86.57	247.72
249.20	61.41	82.18	91.03	248.34
311.67	71.32	92.48	100.48	258.50
326.36	73.02	94.14	102.86	259.85
331.33	73.85	94.83	103.62	260.96
381.64	80.79	101.90	110.31	267.71
385.01	81.68	102.60	111.04	268.60
388.09	82.43	103.04	111.69	269.90
400.10	84.05	104.25	113.17	270.91
501.36	96.93	118.08	126.62	283.84
508.51	98.22	118.95	128.02	285.04
509.55	98.46	118.79	127.97	285.84
579.57	107.01	128.14	136.18	293.62
645.24	115.83	136.41	145.79	303.17
720.82	129.78	150.02	158.98	316.49
758.61	139.87	160.68	169.25	326.40

55"

63"

66"

129"



IN REPLY REFER TO:

United States Department of the Interior

NATIONAL PARK SERVICE
GRAND CANYON NATIONAL PARK
P.O. BOX 129
GRAND CANYON, ARIZONA 86023-0129

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Jan - make new
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Y14 (GRCA)

JUL 9 1983

Memorandum

To: Chief, Resources Management and Planning

From: Resources Management Specialist Davis

Subject: Review of Bennett and Kunzmann's Fire Study

This is a review of Peter Bennett and Michael Kunzmann's study titled "LD50, a tool describing the relationship between fire energy release rate and tree mortality" written in 1982 following a three year study on North Rim. The study was done on Point Sublime in mixed conifer forest. The purpose was to correlate energy release rate (fire intensity) and tree mortality using information gathered during five prescribed burns.

The concept of the study is reasonable and valid. The authors state that fire prescriptions are primarily designed to predict fire behavior and that current systems defining behavior were developed for suppression purposes. Consequently, they designed a study to establish a relationship between fire energy release rate and tree mortality by size (diameter). The species they tested were ponderosa pine, Douglas fir, white fir, blue spruce, and Engelmann spruce.

In my opinion, Grand Canyon staff should not use the results without field testing them because they were based on only five burns. This is not enough repetitive sampling to accurately evaluate the range of variables that influence tree mortality. Continual field testing to relate intensity with effects would refine the prescription. However, the methods are labor intensive and costly. The authors used four methods to assess intensity: (1 and 2) radiometric (ground and aerial) and (3 and 4) fuel consumption (weight and volume). They concluded that the ground radiometric system was the best, which is basically a network of thermocouples set on trees and the ground to record the heat of the passing flame front.

There are features in this report that cause me to question the results, methods, and interpretation of the work. They are:

1. Several equations are presented in the results section. The authors do not explain how they were developed nor how the numerical values were derived nor what they represent. The reader is simply asked to believe these equations are valid and representative of LD50 or percentage kill. It is not explained how the values for R^2 are determined. Finally, the numbers used are carried out four to seven decimal places. This seems absurd and gives me the impression that the low sampling number is covered by labored mathematics.

2. The authors do not use or convert to common fire language used in America in their writings, so there exists an unnecessary obstacle between the land manager and scientist. For instance, energy release rate is used for fire intensity, kcal/m²/second for BTU/ft/second, and kg/ha for tons/acre. While metric units are used in some countries for fire management operations, the United States still uses English units. The three latter terms are widely used and understood here; so to employ this study, we would need to convert all the numerical results presented in the text, figures, and tables.

3. Table 4 appears to present calculations extrapolated from the field data that are carried out to unrealistic measurements, even though the title states the data is from the study sites. In the final line, the energy release rate is given for large diameter trees, which are not found on North Rim with the possible exception of ponderosa (i.e., ponderosa at 55" dbh, Douglas fir at 63" dbh, white fir at 66" dbh, and spruce at 129" dbh).

4. On page 8 at the lower part of the first paragraph, the authors state "...the initial flaming period is most responsible for tree stem heating death. Slow consumption of the duff layer does not have this effect." In Grand Canyon, litter/duff around the base of trees, especially ponderosa, can be up to two feet deep and cover a radius of 6 feet. The flaming front certainly is a major factor of stem kill, but the authors seem to disregard the effect of longer termed residual heat from slow combustion that can cook the cambium of the stem emersed in duff. Also to be considered is this heating effect on roots.

5. On page 11 in the second paragraph, the authors urge others to use caution applying their results. While they cite the isolation feature of these ponderosa forests, they do not provide sufficient evidence to substantiate that statement.

Currently, Resources Management Specialist John Ray is using fuel and vegetation transects to monitor post-fire effects. Byram's technique of relating flame length with fireline intensity is used during prescribed burns to gage intensity. These are proven and standard methods to evaluate effects. I would recommend that, when possible, he take intensity measurements when the flames actually burn transects so more accurate intensity information is obtained that can be directly related to quantified fuel and vegetation readings.

The weak point in Grand Canyon of developing prescriptions based on observed fire effects (fuel and vegetation data and fire intensity) is in the implementation of the burns. The knowledge gained is not being used to refine prescriptions or attentively apply fire. The knowledge is not incorporated to

improve the program, partly because there are no post-fire onsite evaluations or annual fire reviews. Bennett and Kunzmann are correct that fire effects are integral in refining prescriptions. The transects that Ray has established and the data forthcoming will be an important part of that refinement process someday.

Kathy Davis
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