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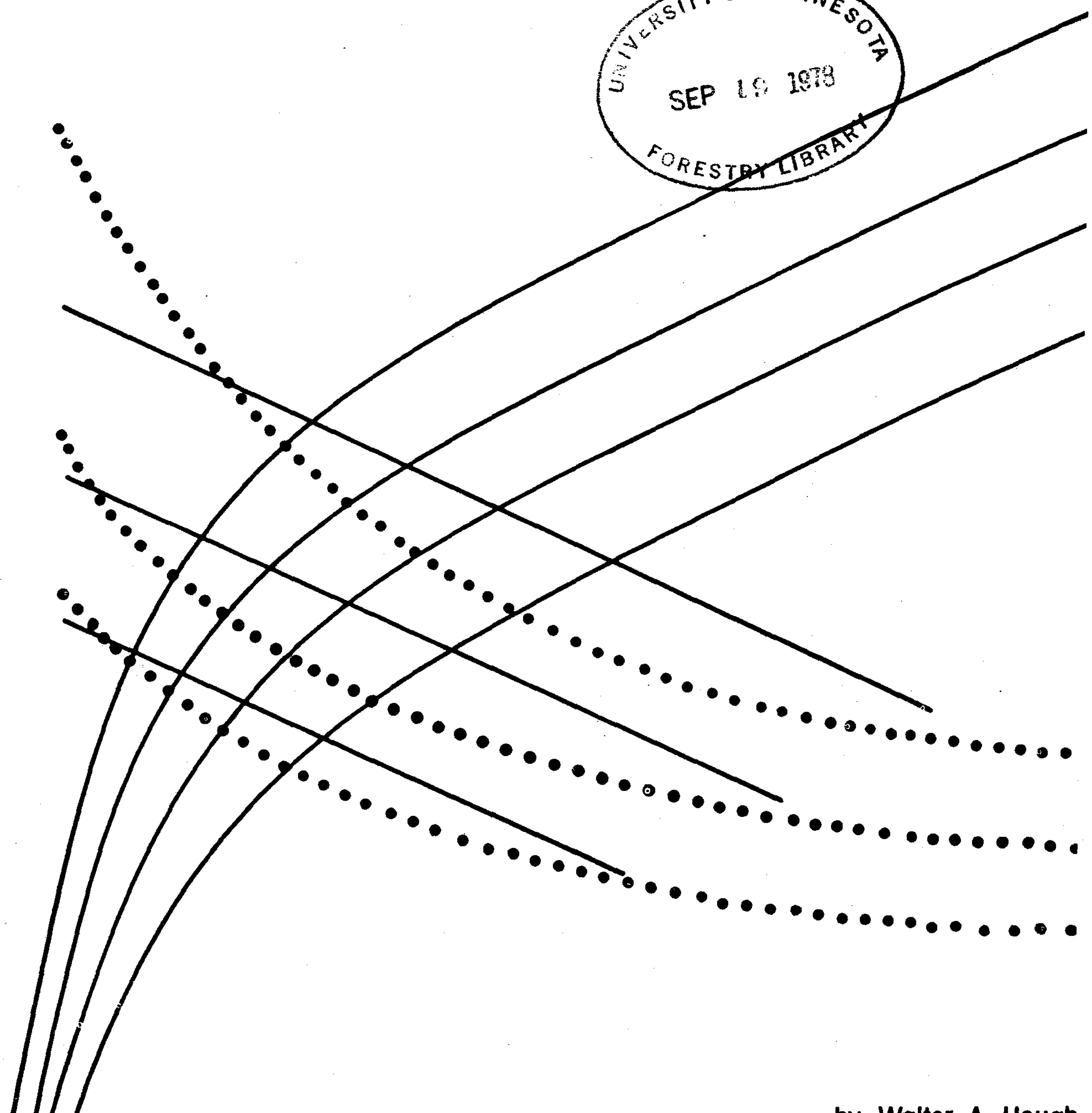

by Walter A. Hough

For the convenience of users, values in this Paper are reported in English units of measure, which are still most commonly used in southern forests. To convert these values to metric units, consult the table below.

To convert from	To	Multiply by
Acres	$meter^2$	4,047
Acres	hectares	0.405
Tons per acre	$kilograms/meter^2$	0.224
Tons per acre	metric tons/hectare	2.242
Pounds per ton	grams/kilogram	0.500
Pounds per ton	grams/metric ton	500
Inches	centimeters	2.540
Feet	meters	0.305
Square feet per acre	$centimeters^2/meter^2$	0.230

Southeastern Forest Experiment Station

Asheville, North Carolina

Estimating Available Fuel Weight Consumed by Prescribed Fires in the South

by

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Abstract.--A method is proposed for estimating the weight of fuel burned (available fuel) by prescribed fires in southern pine stands. Weights of available fuel in litter alone and in litter plus understory materials can be estimated. Prediction equations were developed by regression analysis of data from a variety of locations and stand conditions. They are most reliable for slash pine fuel types but should also provide close approximations for longleaf and loblolly pine types.

Information needed to make estimates includes: stand basal area, time since last disturbance (age of rough), and understory height. With these data, total litter layer dry weight and total understory dry weight can be estimated. Total litter layer moisture content is also needed and can be estimated by a procedure described here. Estimates of available fuel have standard errors of about ± 1.0 ton per acre. However, the accuracy of the method depends on the accuracy of input data. Points of weakness and possible misuse of tables are discussed.

Keywords: Prescribed burning, smoke management.

Forest managers need to predict the weight of fuel consumed by prescribed fires for a number of reasons. This value, called available fuel, is an indicator of fire intensity and the likelihood of the burn meeting the planned objectives, especially for fuel reduction. Available fuel is also needed to estimate smoke production and movement.

Previous work has been done on estimating available fuel in southern pine types (Hough 1968; Sackett 1975), but results are for limited situations and do not cover the needs of the southern forest smoke manager. In earlier work Hough (1968) found significant relationships among fuel consumption, initial fuel weight, and moisture content.

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I report here the results of multiple regression analyses. These results are combined with appropriate assumptions to produce equations for estimating available fuel weight for prescribed burns. The estimating equations were developed initially for the palmetto-gallberry-slash pine fuel type. However, a wider data base was used to permit appropriate predictions to be made in longleaf pine and loblolly pine types. Equations were selected for ease of application to currently available data as well as for accuracy.

EQUATION DEVELOPMENT

AVAILABLE LITTER LAYER WEIGHT

On 1960 and 1961 burns in slash pine stands, a number of variables were statistically related to, and useful for prediction of, amount of available fuel in the various fractions in the litter layer.[2] These fractions consist of the L or litter layer made up of freshly fallen foliage, the F or fermentation layer composed of weathered material whose origin can still be determined, and the H or humus layer made up of well-decomposed organic material.

The weight of available fuel in the combined L&F layers was highly correlated with the initial weight and moisture content of the L&F layers. Available weight in the H layer was significantly related to the initial weight of the H layer and to the amount of fuel burned in the combined L&F layer. Total litter layer weight reduction (L&F&H) correlated best with the initial weight of the total layer and the moisture content of the total layer (total wet-weight/total dry-weight calculations). These relationships were based on measurements from 28 test fires.

A method was needed to estimate litter consumption in a wide variety of prescribed burning situations throughout the South. Therefore, all available measurements that included dry weight and moisture content of the total litter layer before a burn, and fuel dry weight immediately after a burn, were obtained from the files at the Southern Forest Fire Laboratory. All data were from experimental prescribed burns, including backfires and strip headfires of relatively low intensity. Tests were made to see if backfires and headfires differed significantly in total litter layer consumption. Differences were significant: headfires consumed more litter. This finding does not agree with those of others which indicate greater consumption by backfires (Beaufait 1965; Hough 1968). Because our results were confounded by very light fuel weights and low moisture contents on most plots that were headfired, it was not possible to say the difference was due to the type of fire. Therefore, we decided to combine all data so that results could be used for low-intensity headfires as well as for backfires.

Ninety-seven burns were used in the final regression analysis; the year, general location, type of fire, fuel type, and number of burns are given in table 1. The most reasonable fit of the data, one with an R^2 value of 0.78 and a standard error of 0.93 ton per acre, is:

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[2]Data and sampling procedures used in the data collecting are on file at the Southern Forest Fire Laboratory, Macon, Georgia.

$$W_{AL} = 3.4958 + 0.3833 (W_{TL}) - 0.0237 (M_{TL}) - 5.6075 (1/W_{TL})$$

where

W_{AL} = available litter fuel dry weight (tons/acre)

W_{TL} = total litter layer dry weight (tons/acre)

M_{TL} = moisture content of total litter layer (percentage of dry weight).

Table 1.--General information about test burns used in developing estimating equations

Year	Location of burn	Type of fire	Type of fuel	Number of burns
1959	Waycross, Ga.	Backfire	Slash pine-palmetto-gallberry	12
Do.	do.	Headfire	do.	4
1960	do.	Backfire	do.	14
Do.	do.	Headfire	do.	4
1961	do.	Backfire	do.	14
1967	Bainbridge, Ga.	do.	Slash pine-no understory	4
Do.	Charleston, S. C.	Headfire	Longleaf & loblolly pine-titi-gallberry	6
1968	do.	do.	do.	2
Do.	Bainbridge, Ga.	do.	Slash pine-no understory	6
Do.	Lake City, Fla.	do.	Longleaf pine-palmetto-gallberry	2
1969	do.	do.	do.	2
Do.	Bullard, Ga.	Backfire	Slash pine-palmetto-gallberry	5
Do.	Charleston, S. C.	Headfire	Longleaf & loblolly pine-titi-gallberry	6
1974	Cochran, Ga.	Backfire	Slash pine-no understory	4
Do.	do.	do.	Loblolly pine-no understory	1
Do.	do.	Headfire	Slash pine-no understory	1
Do.	Patterson, Ga.	Backfire	Slash pine-palmetto-gallberry	5
Do.	Homerville, Ga.	do.	Slash pine-gallberry	2
Do.	Lake City, Fla.	do.	Longleaf pine-palmetto-gallberry	3

Figure 1 shows available litter fuel values for preburn total litter weights ranging from 1 to 16 tons per acre and total layer moisture contents ranging from 10 to 200 percent. Total layer moisture content is computed using total layer wet and dry weights. It is possible to consume considerable fuel when total layer moisture content is quite high because moisture gradients in forest

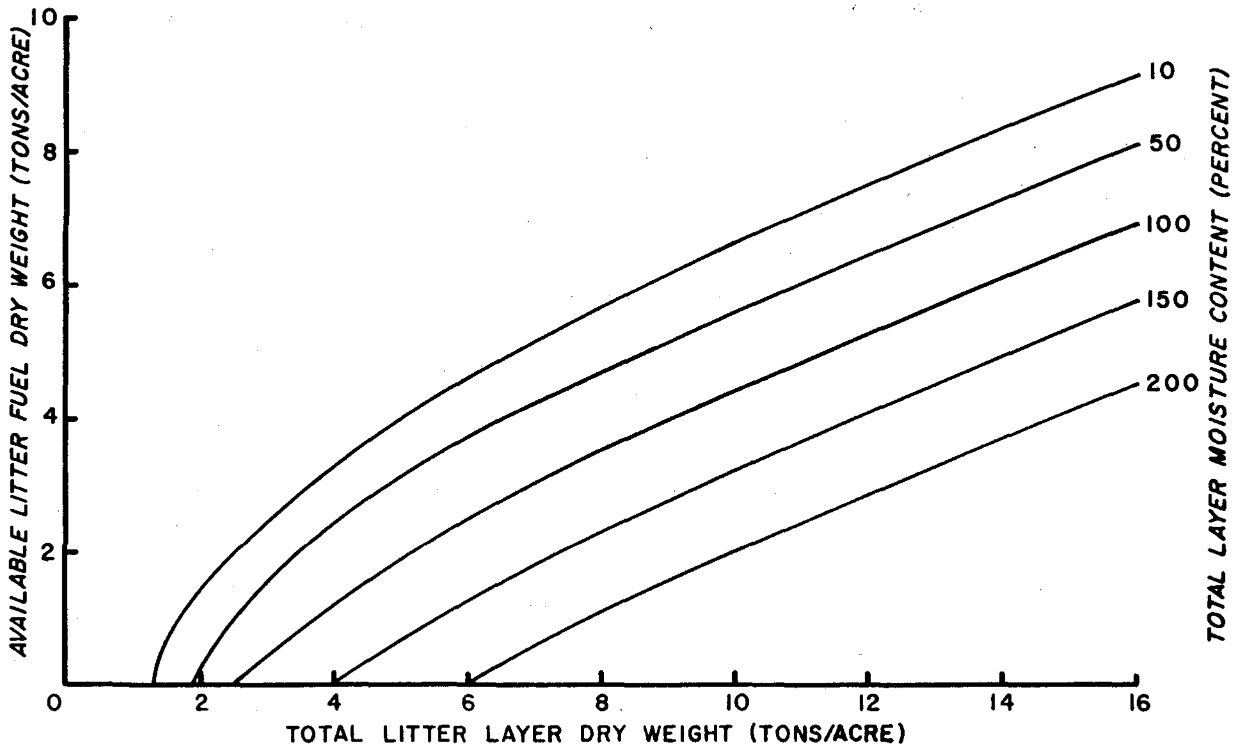

Figure 1.--Weight of total litter layer (L+F+H) consumed by prescribed fires.

floors with well-developed L, F, and H layers are steep. For example, at Waycross, Georgia, moisture content of the L layer was 17 percent, that of the F layer was 34 percent, and that of the H layer was 122 percent. The moisture content of the total layer was 79 percent, but the L and F layers were dry enough to burn while the H layer was too wet to burn. Plots at Cochran, Georgia, had even steeper gradients with the L layer being 20 percent, F layer 80 percent, and H layer 200 percent. The L layer would carry the fire, but that would be about all that would burn.

The nature of our basic data places several limitations on reliability of predictions. Only 2 of the 97 plots had preburn total litter weights above 15 tons per acre, and both of these had fairly high moisture contents. Thus, any litter reduction estimates for initial fuel weights above 15 tons per acre, especially at low total layer moisture contents, are questionable. On plots with a very light total layer (less than 2 tons per acre), moisture content did not exceed 30 percent; therefore, available fuel estimates at higher moisture contents may be in error. Experience has shown that 2 tons or less per acre of litter will not carry a backfire, nor probably a headfire, at moisture contents above 45 to 50 percent (fig. 1).

AVAILABLE LITTER AND AERIAL FUEL WEIGHT

It was necessary to develop a way to estimate available fuel in the understory as well as in the litter. Of the 97 plots used in the litter consumption analysis, 71 had aerial fuel-reduction measurements. Plots at Cochran, Bullard, and Bainbridge, Georgia (table 1) contained only surface fuels. Analyses of covariance indicated only small differences between backfires and headfires. These were again confounded by light understory fuel weights on headfire plots. Differences were not considered important enough to prevent pooling the data.

Multiple-regression analysis indicated possible ways to predict available aerial fuel weights. The first method required direct estimates of average moisture content of standing vegetation; the second did not. Since no convenient technique is available for estimating moisture content of standing vegetation, the second method was explored and adopted.

In the second method, the total litter layer's initial weight and moisture content and the initial weight of the standing fuel are used to estimate the total amount of available fuel. This approach provides the smoke manager with one consumption value that includes both litter and aerial fuel.

The most reasonable fit of the data, one with an R^2 of 0.86 and a standard error of ± 1.0 ton per acre, is:

$$W_{A(L+U)} = 3.2484 + 0.4322\,(W_{TL}) + 0.6765\,(W_{TU}) - 0.0276\,(M_{TL}) - 5.0796\,(1/W_{TL})$$

where

$W_{A(L+U)}$ = available litter plus understory fuel dry weight (tons/acre)

W_{TU} = total understory fuel dry weight (tons/acre).

Figure 2 shows total available fuel weights for preburn understory fuels weighing from 2 to 8 tons per acre and total litter layer weights of from 1 to 16 tons per acre for moisture contents of 10 and 200 percent. Some portions of the curves are extrapolated beyond observed data. For example, the heaviest plot had a standing fuel weight of 5.1 tons per acre; therefore, projections above approximately 5 tons per acre could be in error. Also, the plots with the lowest litter weights (2 tons per acre or less) had very low initial aerial fuel weights (1.1 tons per acre or less). Thus, the estimation of total available fuel for a combination of low litter weight, low litter moisture content, and high aerial fuel weight may be unreliable. Fortunately, very light litter layers with very heavy standing fuel weights seldom occur.

MOISTURE CONTENT OF TOTAL LITTER LAYER

Total litter layer moisture content must be estimated if available fuel is to be predicted. One simple approach would be to use the 100-hour timelag fuel moisture given in the National Fire-Danger Rating System (NFDRS) (Deeming and others 1972). The wetting of 100-hour fuel by precipitation as given in the NFDRS Manual is for stem and branch wood and does not account for the increase in total litter layer moisture content due to rainfall (Fosberg 1971). I therefore developed a new wetting curve reflecting total litter layer moisture contents of 200+ percent after 24 hours of rainfall.

Moisture retention capacity of total forest litter layers has been found to be between 200 and 300 percent of dry weight (Swank and others 1972; Metz 1958; Helvey 1964; Mader and Lull 1968; Van Wagner 1970). Thus, a litter layer weighing between 4 to 10 tons per acre can retain the equivalent of 0.2 inch of rainfall. After this amount has been taken up by the layers, additional rainfall has little effect on moisture content. Metz found that this maximum mois-

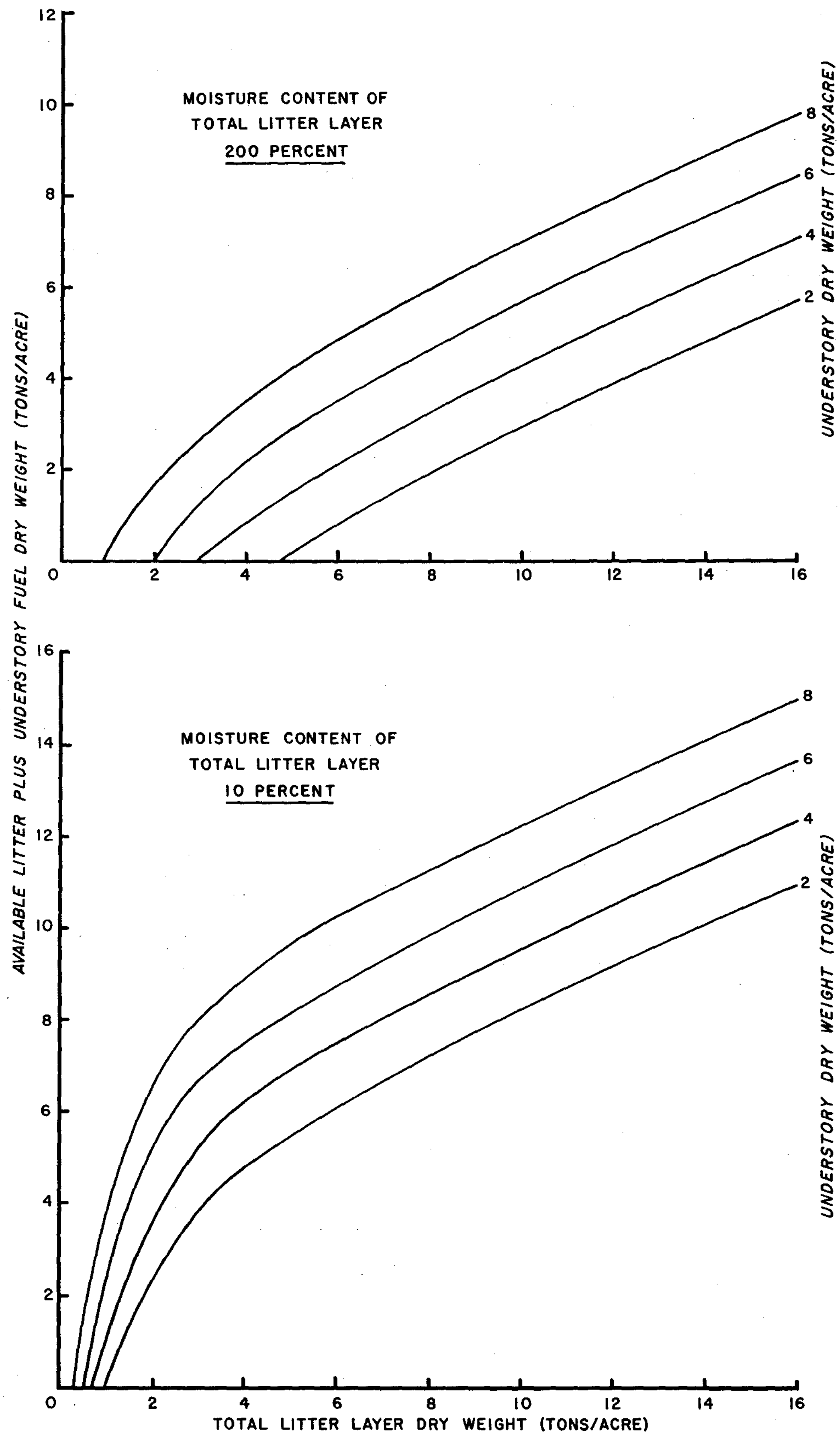

Figure 2. --Available litter plus understory fuel weight varies with initial weight and moisture content of the total litter layer and initial weight of the understory.

ture content was reached only after prolonged rainfall periods--an indication that duration, as well as amount of rain, is important.

Duration effect was also shown by Paul,[3] who studied the effect of rate and amount of rainfall on pine litter moisture content. His data show that water uptake by pine litter begins to level off in 10 to 12 hours, regardless of amount of rainfall. The effect of rainfall on total layer moisture content is not clearly defined by his data. Also, I have found variations of 80 to 100 percent in total litter layer moisture content of square-foot samples collected over a brief period from a slash pine stand. Because the effects of rainfall rate are so unclear, only duration is considered here.

A single curve of total layer moisture content versus duration of precipitation was fitted to Paul's averaged data. I assumed that maximum total layer moisture content would not exceed 250 percent and that this value would be reached after 24 hours of rainfall. Figure 3 shows increases in total layer moisture content from rains of different durations. The equation for this curve is:

$$M_{TL} = 100.2261\,(RD^{0.3027}),$$

RD = rainfall duration (hours).

Fosberg (1975) has developed a theoretical model for predicting the moisture content of litter and duff (F&H layers). Since some of the physical properties of slash, longleaf, and loblolly pine litter layers required by that model are unknown, the model could not be tested.

Drying curves plotted from the NFDRS 100-hour timelag tables are similar to published curves for loblolly pine litter (Metz 1958) and eastern hardwood litter (Helvey 1964). However, the NFDRS curves approach 10 to 15 percent moisture content in about 7 days. These values are lower than total layer moisture contents measured in medium and heavy southern pine litter layers 7 days after a rain. In an effort to account for this difference, all data from experimental burn plots used in developing the available fuel predicting equations were analyzed to see if relative humidity, days since rain, and total weight of litter layer were correlated with total layer moisture content.

Multiple-regression analysis showed that days since rain (DSR) and total litter layer dry weight (W_{TL}) were significantly correlated with total layer moisture content (M_{TL}). Relative humidity was not significantly related to M_{TL} because humidity affects only the uppermost layer of fuel. Moisture content was higher for a heavy layer than for a light layer after the same length of drying following rain.

This difference could result from several factors. First, very light layers were thinner, less compact, and probably have a timelag closer to 10 hours than 100 hours (Nelson 1969). Second, the light layers cannot retain as much rainfall and would not have as high a starting moisture content. Finally, the light layers may have a lower equilibrium moisture content (EMC) than the heavy layers.

[3] Paul, James T. 1968. Influence of rate of rainfall on pine litter moisture content. Special problem in Hydrology, Forestry 845, prepared by author for Dr. J. D. Hewlett, 16 p.

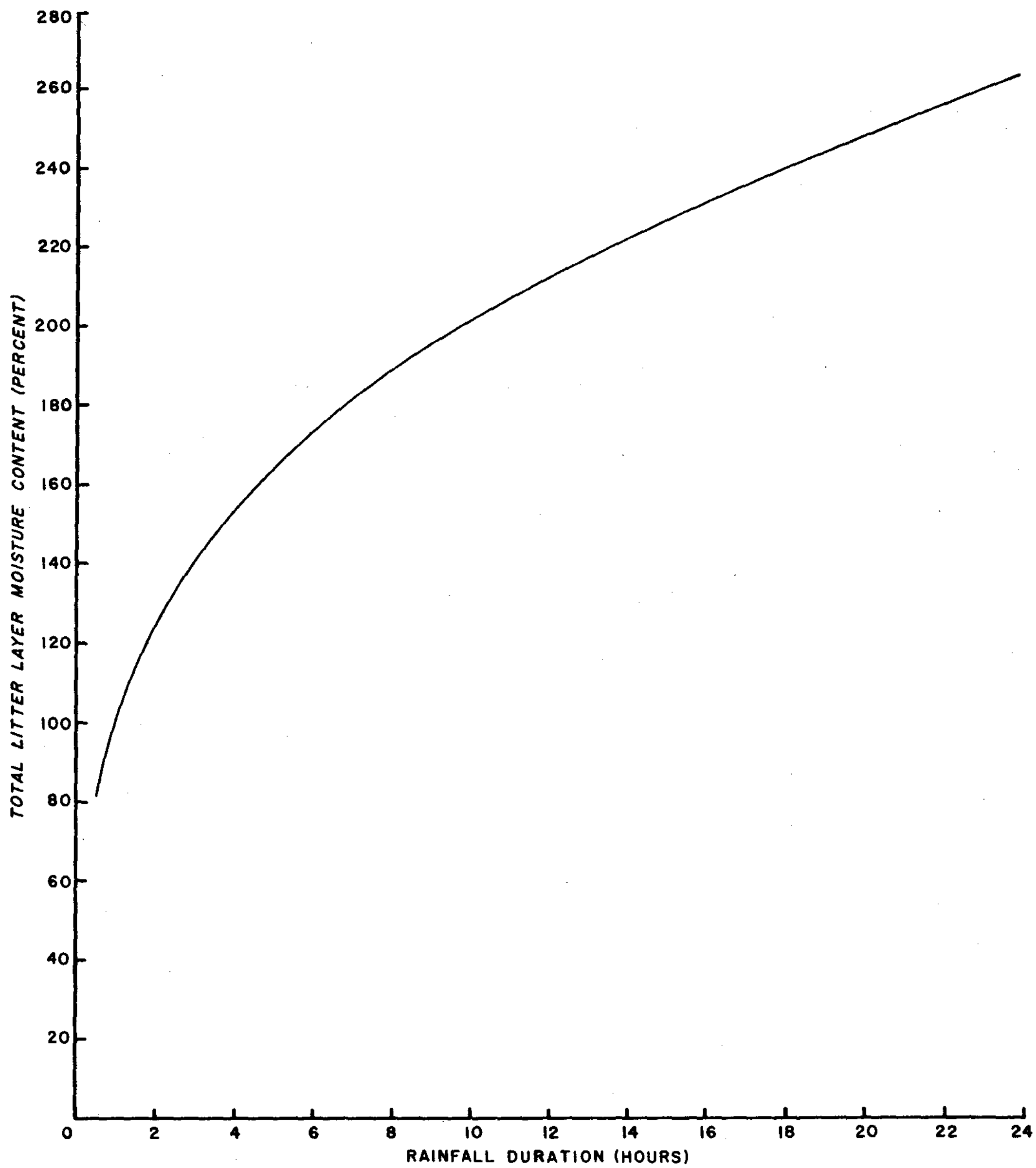

Figure 3.--Effect of precipitation duration on total litter moisture content.

Because the correlation between total layer moisture and total layer weight was highly significant, I developed more than one drying curve. In developing these curves I made a number of assumptions, some of which were best guesses. The best fit of the data through multiple-regression techniques was a straight-line decrease in moisture content following rain (fig. 4).

Since several investigators have shown that drying of forest fuels follows an exponential curve, the linearity I found must have been caused by sampling limitations. I therefore fitted exponential curves for three different total litter weight classes based on a timelag of 100 hours. For light forest litter weights (2.5 tons/acre), such as in 1- to 2-year-old roughs, an EMC of 5 percent was assumed. For moderate loadings (7 tons/acre), as in 3- to 10-year roughs, an EMC of 15 percent was assumed. For heavy fuel accumulations (12 tons/acre) representing 11- to 25-year-old roughs, a 25 percent EMC was assumed. Start-

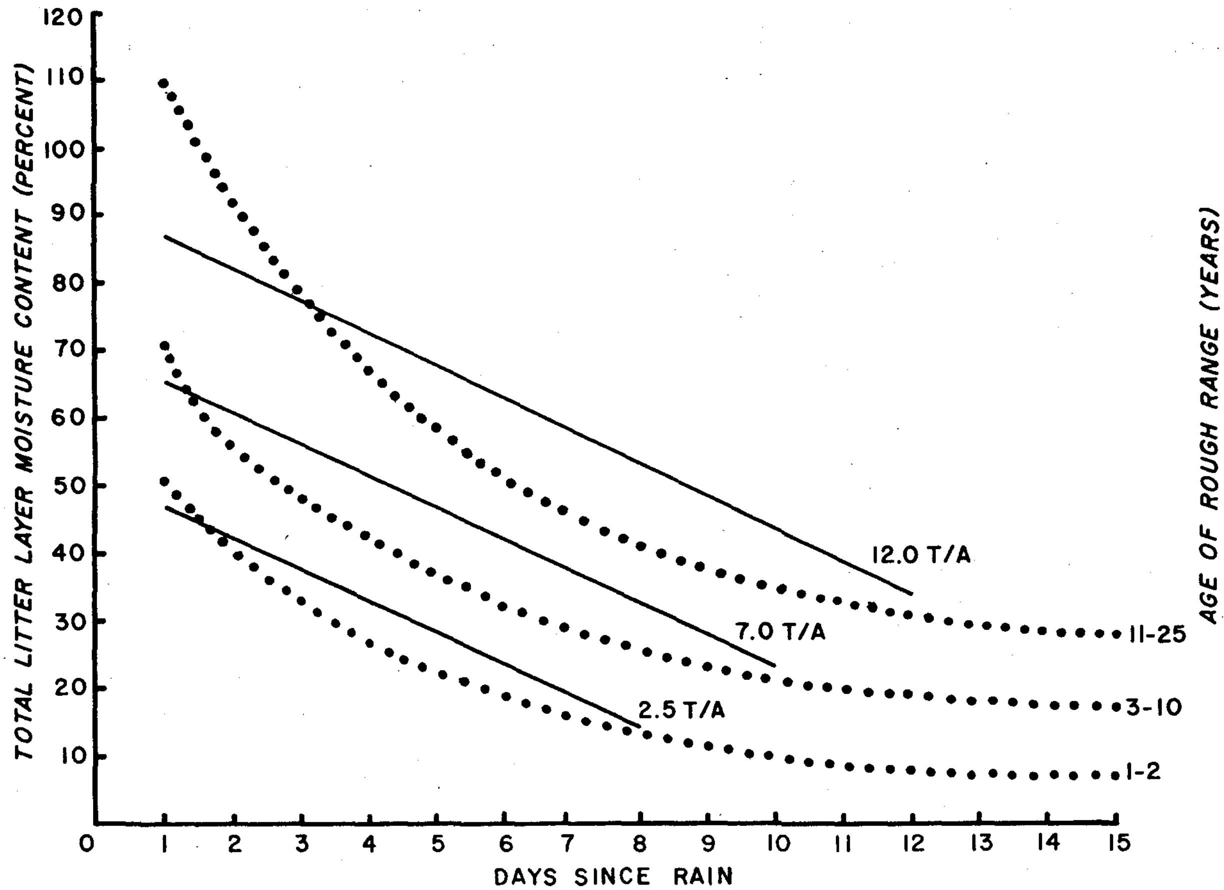

Figure 4.--Drying curves for different litter layer age classes.

ing at 250 percent moisture content, the daily drying curve was calculated from the following:

$$\frac{M_A - M_E}{M_Q - M_E} = e^{-\frac{t}{\gamma}}$$

where

M_A = average moisture content at end of period (percent)

M_E = equilibrium moisture content (percent)

M_Q = initial moisture content at start of period (percent)

e = base of Naperian logarithms (2.718)

t = time (hours)

γ = timelag constant (hours).

A portion of each calculated curve was then selected for an approximate fit of the straight-line produced by the regression equation (fig. 4). Using these curves, the decrease in total litter layer moisture content can be estimated for different ages of rough or fuel weights.

There are limitations on the accuracy of the proposed technique that should be pointed out to the fire manager. First, the method proposed here is based on a small amount of data, and many factors known to influence wetting and drying have been ignored. Second, the maximum moisture content of the total layer is somewhere between 200 and 300 percent, and an upper limit has been arbitrarily set at 250 percent. Third, young stands, very open stands, or stands that have recently been burned will have little or no F or H layer, and therefore total layer moisture content may not reach values of 250 percent. The drying curve for light fuel loading has been calculated to bring the litter layer moisture content closer to the correct values within a day or two after a long period of rainfall.

It should be remembered that fuel moisture usually varies widely from point to point in a forest stand. Therefore, values obtained by this method only roughly approximate values that may be observed at specific points in a stand.

TOTAL WEIGHT OF LITTER LAYER AND UNDERSTORY

Before available fuel can be calculated, two additional values must be estimated: total litter dry weight and total understory dry weight. McNab and Edwards (1976) have developed equations for estimating litter and understory fuel weights from stand characteristics that are relatively easy to measure.

Total litter layer weight can be estimated from age of rough and basal area of the timber stand. Total understory weight can be predicted from age of rough and average height of the understory.

These equations were developed principally from slash pine-palmetto-gallberry fuel data but included some longleaf pine-palmetto-gallberry fuel data and should apply fairly well to that complex. Loblolly pine litter layer weight is much lower than that in a slash pine stand of the same age and density. A separate estimating technique for total litter weight in loblolly stands is needed before available fuel weight can be estimated in this type, and a method is presented in the Southern Forestry Smoke Management Guidebook (SFFL Staff 1976).

DISCUSSION AND CONCLUSIONS

The equations and graphs provided here can be easily programed for computer solution. For those who want to use the method but do not have access to a computer, necessary procedures and tables are presented in the Southern Forestry Smoke Management Guidebook (SFFL Staff 1976).

An attempt was made to compare this method's fuel consumption estimates with published data. It was difficult, however, to find strictly comparable information, especially values needed as inputs for the method presented here.

Fuel consumption on a prescribed burn in a pocosin in North Carolina (Taylor and Wendel 1964) was a good example of the close approximation achieved with this method in a somewhat similar fuel situation. The area had a pond pine overstory, a 5-foot-tall shrub understory--including gallberry--that weighed 6.6 tons per acre, and a total litter weight of 6.5 tons per acre. Organic soil was present but did not burn. Total litter layer moisture content ranged from 90 to 143 percent. Actual fuel consumption on several plots averaged 6.0 tons per acre for litter plus understory. Estimated consumption per plot ranged from 5.6 tons to 7.0 tons per acre, depending on moisture content. Thus, the estimates of total consumption were quite acceptable.

When estimates of available fuel were compared with measurements from other geographic areas, the relationship was very poor. On two plots in ponderosa pine litter (Davis and others 1968), a prescribed burn consumed 3.4 and 6.3 tons per acre. Total litter layer moisture contents were not measured and cannot be precisely calculated from the data given. They were estimated to be 13 and 17 percent for the two plots. Using these inputs, estimated litter consumption would be 6.5 tons per acre for one plot and 9.5 tons per acre for the other. Both estimates are about 3 tons per acre too high.

Data presented by Van Wagner (1972) for jack pine and mixed red and white pine stands indicated that the best predictor of available duff (F&H layers) was duff moisture content. Results are not strictly comparable because only the range and average duff weights were given. Therefore, initial weight of the layer could not be used for individual estimates. It appears that the method for southern pine stands overestimates litter consumption in northeastern pine stands by 2 to 4 tons per acre when moisture content is high and underestimates available fuel by 0.5 to 4 tons per acre when moisture content is low. Obviously, my method does not apply in these pine stands.

There are many unresolved questions concerning the estimation of available fuel weights. However, the estimating equations described in this Paper provide a reasonably accurate way to predict the amount of fuel consumed by prescribed fire in several southern forest fuel types. Under typical prescribed burning conditions (SFFL Staff 1976), the method described here provides greatly improved estimates of fuel consumption and fire effects. The use of the complete method has been described in the Southern Smoke Management Guidebook (SFFL Staff 1976). This is the best method now available for these fuel types, and it will be improved as new research findings become available.

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