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DROUGHT, TIMELAG, AND FIRE DANGER RATING[1]

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ABSTRACT

This paper considers several principles of the construction and presentation of long-term moisture indexes in forest fire danger rating. Five different "drought" indexes are compared as to rate of moisture loss and gain, reservoir size, temperature effect, and whether presented on an absolute or comparative basis. The role of timelag in deciding whether the index should be computed continuously from one fire season to the next is tested. The purpose of the index will determine whether it should be presented in terms of the moisture content of some identifiable component of the fuel complex, or in some other form such as the content of a soil reservoir. Its role in fire danger rating is distinctly subsidiary, and not to be confused with the principal short-term indicators of fire ignition potential and rate of spread.

INTRODUCTION

It is well understood that the incidence and behavior of forest fire depends mainly on short-term weather influences of no more than several days duration. And yet, all through the history of fire danger rating in the United States and Canada, runs a persistent interest in the effects of weather over a much longer term, usually studied under the heading of "drought". Attempts to measure weather's long-term effects produce drought indexes, which are the subject of this paper.

What are "drought indexes"? By thinking of them simply as indexes of long-term weather, the need to define "drought" itself, a vexing problem, is neatly avoided. For present purposes, then, drought indexes are indexes that carry long-term information about weather, whether the trend be wet, dry, or normal. The pertinent further questions are: What kind of information do drought indexes carry? For how long is it carried? How should this information be interpreted?

It is taken for granted that to have any effect on fire, long-term weather must affect some part of the fuel complex. Whatever is dry as a result of drought, if it cannot burn it can obviously not affect fire behavior. The use of a drought index that indicates moisture stored in the mineral soil may have a certain legitimacy in fire danger rating provided correlation with some aspect of fire activity can be demonstrated. However, the physical link in that case remains undefined. Further sections of this paper are devoted to the three last questions above.

A great deal of literature exists on the subject of drought, the main interest being naturally in the field of agriculture. In particular, one detailed publication by the World Meteorological Organization (WMO 1975) provides pertinent background. There is no doubt that rainfall deficiency over a long period is generally accompanied by more and larger fires. In north central U.S., Haines and Sando (1969), Haines et al. (1976), and Haines et al. (1978) have demonstrated the link between shortage of rain and prominent forest fires of the past, including some relationships between fire incidence and the values of several drought indexes. In Ontario, Stocks (1971) found a slight but definite trend toward greater fire occurrence with increasing values of the Canadian Drought Code (Turner 1972); fire occurrence was, however, much more efficiently accounted for by shorter-term indicators. Again, he (Stocks 1974) found good links between fire size and short-term fire danger components, but none with the Drought Code. In British Columbia, Muraro and Lawson (1970) found that the Drought Code (in

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an earlier form) was a good measure of the state of deep organic layers found on the west coast. These references convey a mixed message: that long-term weather has some effect on forest fire activity, but does not provide much information by itself. This paper presents no further field evidence of the above sort, but is intended rather as a contribution to the methods of analysing and interpreting drought indexes with respect to fire.

First, five indexes that are or have been in use to represent long-term weather in fire danger rating are compared, especially as to their timelags. A simple basic index is then used to show the importance of timelag as the principal comparable parameter. Styles of presentation, the other most important index property, are then described, and the paper concludes with some suggestions about interpretation.

BASIC PROPERTIES OF EXISTING DROUGHT INDEXES

The indexes chosen for comparison, with their basic references and abbreviations, are:

1) The Canadian Drought Code (CDC), Turner (1972).
2) The Drought Index of the Atmospheric Environment Service, Ontario Region (AESDI), Loiselle (1984)[3].
3) The American 1000-hour timelag fuel model (1000-HTL), Fosberg et al. (1981).
4) The Keetch-Byram Drought Index (KBDI), Keetch and Byram (1968).
5) The Palmer Drought Severity Index (PDSI), Palmer (1965).

These indexes are chosen to illustrate both similarities and differences, and not to rate one against another. The 1000-HTL is not commonly considered a drought index, although Bradshaw et al. (1983) state that it is an indicator of medium-term drought.

In Table 1 are listed the following properties of these five indexes, as nearly as can be determined from the descriptions and parameters given in their basic references:

[3]An on-line drought index for forest fire management purposes. Int. Rep. SSD-84-2, Ont. Reg., Atmos. Env. Serv. Unpublished.

TABLE 1.--Basic properties of five drought indexes

Item	1000-HTL	AESDI	PDSI	CDC	KBDI
Reservoir capacity Comparison value, mm	3.8 mm (141% MC) 3.8	100-280 mm 200	4-10 in. 203 (8 in.)	100 mm 100	8 in. 203 (8 in.)
Evaporation pattern	NX	1st 40% at max. rate, then NX	1st 25 mm at max. rate, then NX	NX	NX, dependent on annual rainfall
Max. value, 25°C in July	0.19 mm/day	6.2 mm/day	6.2 mm/day	2.1 mm/day	2.3 mm/day at 40 in. rain
Temperature effect, increase in evap. rate between 10 and 30°C, %/°C	Flat	4.0%/°C	4.0%/°C	2.2%/°C	8.3%/°C
Timelag, 25°C in July	19 days	21 days	28 days	48 days	88 days at 40 in. rain
Rainfall effect	By rain duration, diminishing effect with increasing MC	Additive	Additive	Reduced to 83%, then additive	Additive
Material represented	2.7 kg/m² of wood 8 cm in diam.	Mineral soil	Mineral soil	Organic layer, 25 kg/m²	Mineral soil
Presentation style scale type	Absolute - % fuel MC	Relative - inches of departure, current	Relative - inches of departure, cumulative	Absolute - reversed log scale of reservoir content	Absolute - reversed scale of reservoir content
Frequency of calculation	Weekly	Weekly	Monthly	Daily	Daily

- reservoir capacity, including range (if any) and a representative value for illustration purposes,
- evaporation pattern, whether purely negative exponential (NX) or with an initial portion at maximum potential rate,
- potential evaporation rate as at a maximum daily temperature of 25°C in July,
- effect of temperature on the evaporation rate, over a range of 10 to 30°C,
- rainfall effect, whether simply additive or some other,
- material represented, whether organic or mineral, and in quantitative terms if available,
- presentation style and scale form, and
- timelag for the above reservoir capacity and evaporation rate.

Table 1, it should be emphasized, portrays the basic moisture accounting procedures of these indexes only. Each one has its unique presentation style, and, as will be evident, the nature of the index may become radically altered and complicated beyond the simple picture in Table 1. Nevertheless, however each index is presented, the basic accounting procedure lies in the background, and is therefore worth portraying in comparative quantitative fashion along with other indexes intended for broadly similar use. The above properties are taken in turn below, except for timelag, which is dealt with in the next section.

1. Reservoir capacity. Two indexes, AESDI and PDSI, have ranges within which total soil capacity must be chosen. Values of 200 mm (or 8 in.) were used for further illustration. Whenever the material represented is organic matter of known load, the capacity can also be pictured as the maximum moisture content of a potential fuel. Thus, the 1000-HTL has a very small capacity even at its maximum load (2.7 kg/m² according to Bradshaw et al. 1983), and is more readily pictured as a fuel drying down from its maximum moisture content (141% according to Burgan et al. 1977) toward an equilibrium value. Similarly the CDC can be taken as representing a 25 kg/m² fuel layer of maximum moisture content 400%.

2. Evaporation pattern. The negative exponential (NX) form is the general rule; in other words, the instantaneous rate of moisture loss is proportional to the current water content. Two indexes, the AESDI and the PDSI, lose moisture at the maximum rate from an upper layer before reverting to the NX form in the lower layer.

3. Evaporation rate and temperature effect. A temperature of 25°C (daily maximum) was picked as a reasonable representative level at which to conduct the comparison. All indexes but one (the 1000-HTL) vary their evaporation rate with temperature, and the strength of this effect as an average between 10 and 30°C is given. July was chosen because several indexes incorporate a day-length effect. In fact, two of the indexes, the AESDI and the PDSI, base evaporation on the well-known Thornthwaite method (Thornthwaite 1948). The strength of this temperature effect varies greatly among the five indexes, and distinctly affects their behavior.

4. Material represented. The CDC and 1000-HTL represent specific fuels of known loadings. Field verification is therefore readily feasible. The other three indexes represent mineral soils of unspecified quantity. Furthermore, the AESDI and PDSI require a choice of reservoir capacity that depends on the soil texture and normal rooting depth chosen from an agricultural viewpoint. The implication is, then, that some aspect of fire activity is related to these same soil properties as found in the region in question, but field investigation is not straightforward.

5. Rainfall effect. The point of interest with respect to rainfall effect is whether a) the material being wetted absorbs all rain up to the limit of its capacity, or b) only a portion is absorbed, the rest passing through. The 1000-HTL is clearly of the latter type, as befits an index representing a fuel that does not readily absorb rain. The other four absorb all rain, except that the CDC discards a fraction of the rain before it reaches the pertinent layer. The rainfall effect is important because it sets the starting point for each drying period, thus affecting the correlation of the index with true moisture status or reservoir content.

6. Style of presentation. The principal choice of presentation style is between a) an absolute quotation of current water content, perhaps on a special scale, or b) a relative form as departure from long-term normal for the period of measurement. The CDC, 1000-HTL, and KBDI are all of the absolute type, although each has its special scale by which water content is quoted, as shown in Table 1. The AESDI and PDSI are of the relative type, again with a distinct difference. The AESDI is computed weekly and a straight comparison made with the long-term value for that seven-day period. The PDSI, on the other hand, accumulates modified monthly departures from normal, so that a moisture deficit or excess can deepen as a trend continues. The concept of timelag is much compromised by the use of a relative form.

TIMELAG

The timelag is the most important single measure of a drought index, because it is this property that governs the length of weather history that can be stored in the index. Primary comparisons of drought indexes, as with other moisture indexes in fire danger rating, are therefore best made in terms of their timelags.

Given the basic NX evaporation pattern, timelag may be defined as the number of days required to evaporate some initial state down to 1/e of its value; in other words, to lose 63.2% of its initial moisture. The reservoir capacity (C) and the potential evaporation rate (E_o) combine to fix the timelag (τ), which can also be expressed as the length of time required to empty the reservoir if evaporation proceeded at the maximum potential rate. For, by the nature of the negative exponential process, the rate of change (the current evaporation rate E) is proportional to the current content Q. Thus

$$dQ/dt = E = Q/\tau$$

since the proportionality constant is $1/\tau$. When the reservoir is full, Q becomes C and E becomes E_o, the potential evaporation rate. Then

$$\tau = C/E_o$$

if C is in mm and time is measured in days, then τ is in days and E_o or E in mm/day. Thus the timelag is simply proportional to the reservoir capacity, and inversely proportional to the potential evaporation rate. Given the reservoir capacity, any factor that affects evaporation rate will accordingly have an effect on timelag. Such factors are, among the present indexes, daily maximum temperature and daylength. Only in the 1000-HTL is the timelag held constant. Among the other indexes, timelag literally varies from day to day, and comparisons can only be made under specific common conditions.

The next factor affecting timelag is the presence, if any, of an upper layer of the reservoir that loses moisture at the maximum rate, e.g., as in the AESDI and PDSI. A true timelag cannot then be calculated from the whole system. However, it will be found on plotting the trend of water loss well down into the lower (NX) layer that the curve form is not much altered; the overall effective timelag, on the other hand, is considerably reduced.

The last major factor affecting timelag is presentation style, whether absolute or relative. If absolute, the calculation of timelag is, in essence, straightforward. The relative style, however, partially defeats the timelag concept, since the behavior of an index continually compared with a varying reference state is not negative-exponential. The timelag of the basic hydrologic accounting system does, at any rate, play its part both in the determination of the periodic normal values as well as in the current moisture status. Beyond that, each index needs its own special analysis. Following are notes on the timelags of each of the five indexes, in order of increasing timelag, as listed in Table 1.

<u>1000-HTL</u>. The nominal timelag of this index is 1000 h, or 42 days. The effective timelag of 19 days results from the inclusion of a similarity coefficient Z in the basic index equation (Fosberg et al. 1981). It can be computed by recasting the basic equation to yield the slope of the NX curve as follows,

$$1/\tau = 1/\tau_o - (\ln Z)/S$$

where τ is effective timelag,

τ_o is nominal timelag, 1000 h,

Z is similarity coefficient, given as 0.82,

S is the standard timestep, given as 168 h (7 days).

Inserting the given values for τ_o, Z, and S yields 458 h or 19 days. This timelag may very well match the main purposes for which the 1000-HTL is used. It does, however, cast doubt on the suggestion (Bradshaw et al. 1983) that the index is a good indicator of droughts of 4 to 6 months duration.

<u>AESDI</u>. The AESDI would, if its evaporation pattern were wholly NX, have timelags varying from 16 days at 100 mm capacity to 38 days at 280 mm at 25° in July. However, the first 40% of its capacity is lost at the maximum potential rate, so that the effective timelag for the whole reservoir is much reduced. Instead of 32 days at a capacity of 200 mm, the effective timelag is 21 days as measured from the slope of the overall semilog graph. Because its capacity is based on mineral soil properties in the area of interest, the index timelag varies in a manner that may or may not be relevant to local forest fire behavior. The index itself is presented as the difference from normal for the week in question, and the week-to-week changes are therefore difficult to analyse.

The AESDI has a further special feature adapted from Shear and Steila (1972). Although the basic moisture accounting is indicated in Table 1, a surplus or deficit account is run and either added to or substracted from the basic water content. Surplus, if any, is water that would otherwise have run off because the reservoir was full. Deficit, if any, is the unfulfilled evaporative need whenever actual evaporation was less than potential evaporation. This procedure allows the quoted moisture amount to either exceed the stated reservoir capacity or to become a minus quantity, as the case may be. The surplus/deficit account is renewed and cancelled every week, and is superimposed on the basic continuous reservoir account when the weekly index is computed.

<u>PDSI</u>. This index loses a constant amount of water, namely the first 25 mm, from its reservoir at the maximum rate. At 25°C in July and 203 mm (8 in.) capacity, its timelag would be 32 days if wholly NX, but works out to 28 days from the overall semilog graph. Under the same evaporation conditions, by virtue of its variable reservoir dependent on local soil properties, its timelag would vary from 14 days at 4 in. capacity to 35 days at 10 in. capacity. The variation of timelag with soil properties, as with the AESDI, raises the same question of relevance to fire activity. The PDSI is, of course, a widely used and quoted index,

with a relatively complex structure compared with the other four indexes. The index itself accumulates normalized monthly departures from the average long-term moisture status for each period. Since the index thus incorporates both the basic hydrologic accounting plus this cumulative monthly process, its behavior is very difficult to analyse. However, since 0.897 of last month's index value is carried over into the next (Alley 1984), it is possible to compute what proportion of the present index value is contributed by a given month n into the past. This proportion P should be

$$P = (0.897)^n \Big/ \sum_{i=o}^{i=n} (0.897)^i$$

Thus, after 10 months, a particular month should influence the index to the extent of 5% of its original contribution.

CDC. This index has a straightforward timelag that equals 48 days at 25°C in July, and varies in a conservative manner with temperature and daylength.

KBDI. Although this index has a fixed reservoir capacity, its evaporation rate is made to vary with average annual rainfall. This procedure has an effect on timelag analogous to that of varying the reservoir capacity. It is a strong inverse effect; calculating from Equation 18 in Keetch and Byram (1968), the timelag at 25°C would vary from 169 days at 500 mm/yr to 54 days at 1500 mm/yr. The KBDI thus has the longest timelags of any of the five indexes. Furthermore, the additional variation with temperature, the strongest of any (Table 1), produces at low temperatures a very long timelag indeed. At 10°C, for example, and 500 mm of rain annually, the timelag of the KBDI would be 1800 days. This index is mainly useful for keeping track of fairly long-term weather in climates that are moderate and moist rather than cool and dry.

The basic timelags of the five indexes (for the conditions in Table 1) are portrayed in Figure 1, in which are graphed the decreases in reservoir content over time. The variation in reservoir capacity is normalized by quoting each index as a per cent of its full capacity. The figure also indicates the proportion of any past weather effect that is still carried by the index. Thus, in the CDC, a rainfall 80 days ago is presumably still influencing the index to the extent of 20% of its original impact. By contrast, the effect of that rainfall would have almost disappeared in the AESDI accounting system.

BEHAVIOR OF A BASIC DROUGHT INDEX WITH VARYING CAPACITY

Because the five indexes vary so much with respect to special features and presentation style, the effect of timelag is easier to demonstrate with a simpler example. A flexible basic drought index was therefore constructed of the following features:

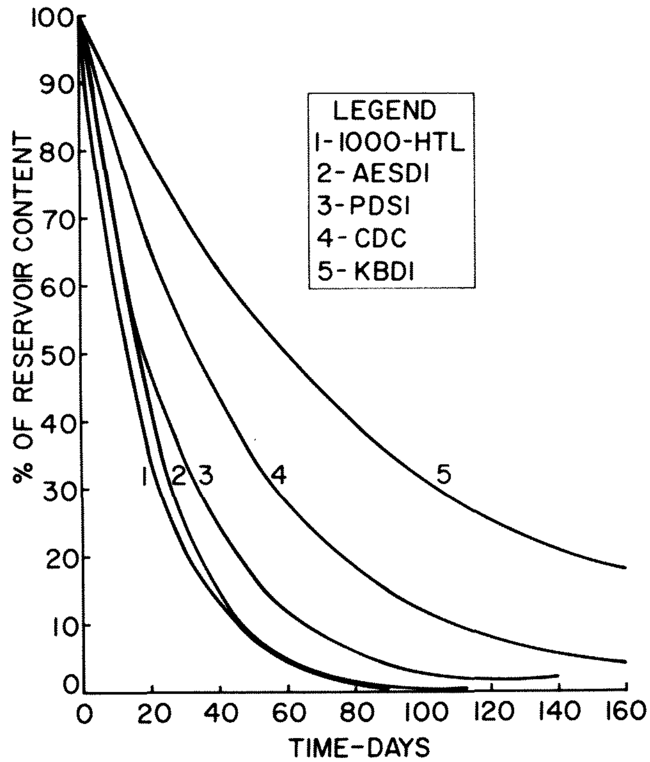

FIGURE 1.--Trends of moisture loss from saturation for five drought indexes, as at 25° C in July. All index scales normalized to 100 at full capacity.

- variable reservoir capacity,
- additive rainfall effect,
- Thornthwaite evaporation procedure, and
- negative exponential evaporation pattern.

The index is expressed as the percentage of capacity currently occupied, normalizing the results for various reservoir capacities. It is computed daily and carried over from one season to the next by the following equations:

$$Q_r = Q_o + R \qquad , Q_r \not> C$$

$$E_o = 0.0154\ TL \qquad , T \not< o$$

$$Q = Q_r\ (1 - E_o/C)$$

$$D = 100\ Q/C$$

$$Q_s = 0.75\ Q_f + 0.5\ P_w \quad , Q_s \not> C$$

where R is daily rainfall, mm

T is daily maximum temperature, °C

L is daylength, h

E_o is evaporation rate at full capacity, mm/day

Q is current reservoir content, mm

Q_r is Q after rain

Q_o is yesterday's Q

C is reservoir capacity, mm

Q_f is Q on the last measured day in the fall

Q_s is starting Q next spring

P_w is winter precipitation during the interval, mm

The evaporation equation appears much simplified because Thornthwaite's Heat Exponent A is nearly 1 at Petawawa, the location on which the index is based.

This index was tested as follows to illustrate the effect of varying the reservoir capacity and thereby the timelag. A 4-yr weather sequence was set up by repeating season 1964 at Petawawa (April 13 to October 31) four times. This was, for Petawawa, a very dry fire season, with only 280 mm of rain. To link the seasons, and to test the carryover effects, winter precipitation of only 100 mm was assumed in each intervening period, about 25% of normal. The basic drought index (BDI) was then run through the 4-yr series with reservoir capacities of 100, 200, 400, and 800 mm. The respective timelags are 16, 32, 64, and 128 days.

The most effective way to demonstrate the differences due to timelag is to compare the behavior of each from year to year during the above artificial series of four identical years, starting each year with the index value resulting from the winter carryover procedure. These results appear in Figure 2 as a set of nested annual trends, one set for each variation of the BDI. The length of time required for the consecutive annual trends to converge is a measure of the timelag effect.

Any moisture index can be overwintered; whether the effect projects long enough into the new season to be worthwhile depends on the timelag. The timelag theory in negative exponential systems governs this principle clearly. So, the proportion of any effect remaining after one timelag period is 36.8%, after two periods 13.5%, after three periods 5.0%, and after four periods 1.8%. The patterns in Figure 2 illustrate this progression well. Taking 5% (three periods) as the practical point of no further concern, then the 16-day timelag version, as expected, carries the overwinter effect about 1½ months into the season. At a 32-day timelag the effect lasts about 3 months, and is all gone by the end of the season. At a 64-day timelag, the effect does penetrate somewhat into the following season, but a 128-day or so timelag is needed for any carryover effect to last more than two seasons.

DISCUSSION AND CONCLUSIONS

The first issue worthy of attention is the question of absolute versus relative drought index presentation. In agriculture, the concept of normality is easy to visualize. Farmers everywhere adjust their crops and cultural methods to a more or less average seasonal climate. Departures from this average cause difficulty, and the wider the departure the greater the difficulty. Problems may result from too much rain as well as from too little. The absolute moisture status has therefore less significance than the question of how the current season compares with normal.

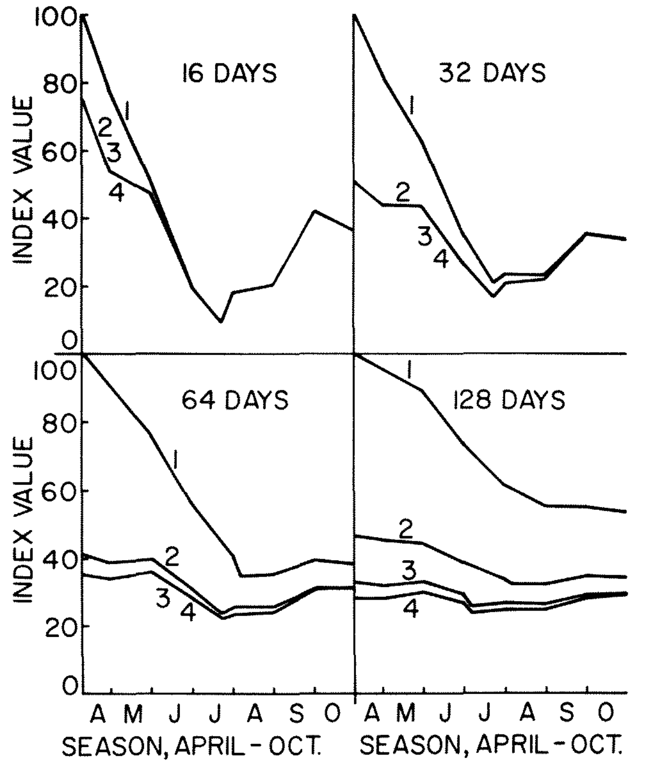

FIGURE 2.--Trends over four consecutive identical years for four versions of the Basic Drought Index at different timelags (16, 32, 64, 128 days), the four annual trends nested vertically in each case. Circled numbers indicate order of years.

In fire danger rating this concept of normality is not present, since the fire management agency has no specific goal except to minimize its activity. An absolute measure of moisture status fits this pattern better than a relative measure. Past fire seasons can indeed be averaged to produce a "normal" picture of the expected amount of fire activity, but this comparison can just as easily be done as a secondary measure. Degrees of daily preparedness and attack strength are themselves on absolute scales, and it makes sense to base them on absolute measures of fire danger. Indeed, all the short-term fire danger indicators are so constructed. Furthermore, as the section on timelags demonstrated, the behavior of an absolute index is more easily analysed and matched with the appropriate feature of fire activity. Still further, the choice of start and end points for accumulating monthly departures as in the PDSI is a difficulty that is not easily resolved (Alley 1984). A related feature of agricultural indexes is the matching of reservoir content with mineral soil properties. Their timelags may therefore vary from place to place in a manner that not only complicates their analysis, but may bear no relation to long-term weather effects on forest fire.

Second is the question of the negative exponential drying principle. It is generally agreed that most organic matter that is potentially combustible dries in this manner. An upper layer that loses moisture freely at the maximum rate may fit a mineral soil situation in which plant roots are the main physical means of extracting the moisture. But in fire danger rating, other short-term moisture models take care of the upper layer of exposed material, and the drought index presumably monitors some deeper layer. Furthermore, the existence of moisture beyond the reservoir's limits, either in the positive or negative sense, as proposed by Shear and Steila (1972) and used in the AESDI, may have some application in agriculture, but it is hard to see how it could apply to any factor affecting fire behavior. The concept of an organic material gaining and losing moisture is best matched by a negative exponential model operating within specified reservoir limits.

In fact, if the NX concept (or one like it) were not operative, there could be no way of discounting the effect of weather as it recedes into the past. A simple accumulation of monthly rainfall deficits, for example, is not a useful measure of long-term weather, since a) it has no convenient starting and stopping points, and b) it portrays a deficit many months into the past as of equal importance with the current one.

The third question has to do with the significance of drought indexes. What do they represent and how should they be evaluated? If a specific heavy fuel exists, either an organic layer or a category of roundwood, for which a moisture model is desired, the problem is no different from that of matching any fuel of known wetting and drying properties. Suppose, however, that the question being asked is whether long-term weather, beyond that represented by the short-term moisture models, somehow affects fire incidence or behavior in a manner whose physical process is not specified. In that case, the foregoing analysis suggests the following procedure.

1. Choose or construct drought indexes of various known timelags.
2. Convert each drought index to some common basis, preferably an expression of moisture or reservoir content.
3. Perform regression or correlations of fire activity with the pertinent short-term weather indicators of fuel moisture and fire behavior in the fire danger system.
4. Try each drought index as an additional independent variable and test for its significance until an appropriate timelag emerges.

With respect to over-wintering, the logic of the timelag concept is inexorable. If the timelag is long enough, failure to carry it through the winter in some rational manner will produce a noticeable distortion following dry winters. About 30 days is the timelag level at which overwintering seems to become logical.

The main point is that no index can be asked to do more than its information content will allow. If its timelag is long, then short-term changes will be highly damped and smoothed. Or, if fire behavior depends heavily on low humidity and high wind, then an index based only on daily temperature and rain cannot record such an effect. For example, when used as a secondary variable, a drought index might demonstrate more or larger fires and more complete burnout within the perimeter when dryness in depth is present than when it is not. And, of course, persistent smouldering and the danger of holdover lightning fires would presumably relate to a long-term index of some sort.

Finally, whatever the concern with long-term weather in the study of forest fire, there is no escape from the importance of timelag as the essential measure of "long term" and its meaning with respect to fire danger rating. Standard conditions must be specified when comparisons are made but the variation in timelag with daily weather and reservoir capacity (if applicable) is a part of this concern. Nor is there any doubt that the role of long-term indexes in fire danger rating is somehow subsidiary to that of the principal short-term indicators of fire ignition potential and rate of spread, and analysis of their significance is best carried out accordingly.

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