A SPREAD INDEX FOR CROWN FIRES IN SPRING

by

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Abstract

This Report describes the construction of an index of the relative rate of spread of crowning forest fires during spring and early summer. It depends on the proposition that conifer crowns are more flammable during this period because the moisture content of their foliage is lower then than during mid-summer. The calculations are based on heat transfer theory and on the energy required to heat moist fuel to ignition temperature, and are supported by some field evidence. The starting point is the Initial Spread Index, a component of the Canadian Forest Fire Weather Index.

Résumé

L'auteur décrit la construction d'un indice du taux relatif de propagation des feux de cime pendant le printemps et au début de l'ete. Cet indice est fondé sur la proposition que les cimes de résineux s'avèrent plus inflammables pendant cette période vu que la teneur en humidité dans leur feuillage est plus basse qu'à la mi-été. Les calculs sont fondés sur la théorie du transfert de la chaleur et sur l'énergie requise pour chauffer la matière combustible humide à la température d'ignition; certains faits observés sur le terrain les confirment. Le point de départ est l'indice de propagation initiale, une composante de l'indice canadien forêt-météo.

A SPREAD INDEX FOR CROWN FIRES IN SPRING

C.E. Van Wagner [1/]

Introduction

This Report describes the construction of a Crown Spread Index to warn of the special susceptibility of conifer stands to crown fires during spring and early summer. Canadian forest fire history records many instances of extensive areas burned during this time of year by fires that spread mainly by crowning. For example, the large fires in Alberta in May 1968 (Kiil and Grigel 1969), three of the four important fires described by Stocks and Walker (1973), and the fires in northwestern Ontario in 1974 all fit this description. However, it is not the intention to try to show here whether or not most conifer crown fires occur early in the fire season. Other factors such as weather patterns and the state of minor vegetation on the forest floor certainly influence the seasonal distribution of crown fires. Rather, this index is based on the proposition that, for any given level of fire weather severity, fires in conifer stands will more likely crown in spring than at other times of year, the primary reason being that the foliage has a lower moisture content during this period.

It is well established (Van Wagner 1967 and others) that the common Canadian conifers, at least east of the Rockies, exhibit a seasonal cycle of foliar moisture content (FMC) with a distinct minimum before the new growth flushes. A simple calculation of the energy required to drive off the foliar moisture and raise the crown fuel to ignition temperature suggests that fire would spread through the crowns considerably more easily during this period. Such energy balances follow an accepted principle in fire spread theory. A cured layer of fine surface vegetation would, it is true, permit a more intense surface fire, and thus increase the liklihood of crowning on a given day. Indeed, in some conifer types this effect, at a time when the hardwood understory is still undeveloped, may well reinforce the spring dip in FMC, since all these effects are roughly concurrent. However, brush and minor vegetation vary greatly among conifer types; in some stands the forest floor is mainly evergreen and changes little with season. There is a further factor that could contribute to variation in crown flammability, namely seasonal trends in the amount and kind of solvent-extractable matter such as fats, resins, waxes and terpenes. The two possible effects are 1) a change in the heat of combustion of the foliage, and 2) a change in the ease of ignition. Philpot and Mutch (1971) investigated the seasonal trend in the ether-extractives of Douglas fir and Ponderosa pine foliage and concluded from their data that some conifer foliage is probably more flammable in summer than in spring, which would contradict the effect of the FMC trend. However, their results differ substantially both between the two species and between the two years of observation. The judgement is made here that as yet no solid information exists on which to base an opinion about the possible effects of solvent-extractives on conifer flammability. The spring dip in FMC is,however, a nearly universal effect, and is by itself able to account for the increased liklihood of crowning in spring. It is thus the logical factor on which to base a special spring crown fire index.

Ideal evidence to substantiate this theory would be a set of crown

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fire spread data in some uniform conifer types under similar conditions of weather and surface fuel, foliar moisture content being the only variable. This is a very tall order. The available direct evidence from Petawawa consists of two half-acre experimental crown fires in a clean-floored red pine plantation, both in similar weather but at quite different FMC's. The two fires compare as follows (Van Wagner 1968), and the difference in behaviour is difficult to explain in any other way:

Fire	Foliar Moisture	Rate of Spread	Flame Height
C4	135%	55 ft/min	65 ft
C6	95%	90 ft/min	100 ft

See also Figs. 6 and 7 in the same reference.

To predict the liklihood of a crown fire during the spring period of low foliar moisture requires, first, a means of estimating the current FMC, and, second, a measure of the fire danger due to the daily weather alone. Stashko and McQueen (1973) have developed an index that is intended to follow foliar moisture only; the daily weather must then be accounted for in some other way. The index proposed in this Report combines both features, and provides every day a number that is related to the level of crown fire behaviour to be expected that day.

The starting point is the Initial Spread Index (ISI), one of the two subindexes leading to the Fire Weather Index (FWI) (Anon. 1970). The ISI depends on two factors, fine fuel moisture and wind, without allowance for variation in the amount of heavy, slow-drying fuel (Van Wagner 1974). The fine fuel here is surface litter, and obviously the ISI must refer mainly to surface fires. Nevertheless, since the same weather factors affect both surface and crown fires, the ISI can in its upper range be taken as a measure of crown fire spread as well in any particular conifer type. This will only be realistic, however, if the seasonal variation in FMC is taken into account. Accordingly, the Crown Spread Index (CSI) described here is determined by multiplying the Initial Spread Index by a Crown Spread Factor (CSF) that depends mainly on foliar moisture as it varies throughout spring and early summer. Once the FMC settles down to a normal summer level, the ISI can assume the role of spread index for fires of all kinds.

Seasonal Variation of Foliar Moisture

It is taken for granted that the spring dip in FMC is a normal occurrence in most of Canada. Its three practical properties are: magnitude, timing, and variation from year to year. However, to achieve reasonable success in predicting the spring dip in FMC, whether from day-to-day or from year-to-year, it is almost necessary to know its basic causes. If the process were one of physical drying governed by daily weather and soil temperature, then considerable variation should be expected from year to year. Stashko and McQueen (1973) have built their Foliar Buildup Index on the assumption that, as long as the soil is frozen, the roots are incapable of supplying the needs of transpiration; the FMC then falls every day by an amount dependent on the daily weather; once the soil has thawed, moisture is no longer limiting and the FMC rises steadily to its normal level regardless of daily weather. According to the available scientific evidence, however, the spring dip in FMC is caused primarily by changes in internal metabolism, relatively independent of current weather. Little (1970) tells how, as spring progresses, the over-wintered foliage temporarily increases its dry weight per needle, mainly in the form of increased starch reserves. As the new foliage flushes, this temporary starch buildup is translocated to the developing new tissue. Little did his work on balsam fir in New Brunswick. Pertinent references based on other North American conifers are Kozlowski and Clausen (1965), Pharis (1967), and Gary (1971). The conclusion must be that at least a substantial part of the observed spring reduction in FMC is really due to a temporary increase in the dry weight base rather than to a decrease in the amount of water present in the leaf cells. Such a process, while no doubt somewhat dependent on the temperature trend, should be much less dependent on the whole daily weather pattern than a physical drying process.

As much FMC data probably exists for Petawawa as for anywhere in Canada; here sampling of five common eastern conifers for foliar moisture has been carried out in 6 different years (not all species in all years). Four features of these data are of interest:

- First, Table 1 lists the tree species together with the mean and range of minimum observed FMC. It can be seen that this parameter has generally varied within ± 8 points of the mean.

- Second, the dates of these observed minima have clustered between May 10 and 20, but single dates are not by themselves very informative. The whole spring dip is usually broad and flat with an indistinct beginning and end 2 to 3 months apart.

- Third, the annual FMC minima were tested against the peak values of Stashko and McQueen's Foliar Buildup Index (op. cit.), as well as against the sum of daily drying factors in the Duff Moisture Code for the month of May; no correlation could be detected with either measure of cumulative daily weather.

- Fourth, Figure 1 shows the trend in dry weight of samples of 50 pairs of red pine needles taken throughout spring 1974, along with FMC's of the same samples. It is clear from simple calculation that, for this sample set, the dip in FMC is wholly accounted for by the temporary increase in dry weight.

The observed range in minimum FMC, about ± 8 points, is in part only a measure of intra-species variation, since the same trees could not be sampled every year. By comparison, during the same years the Foliar Buildup Index of Stashko and McQueen varied from 35 to 130, and the sum of May DMC factors from 55 to 90. The lack of correlation with these weather measures suggests that it would take considerably more sampling to establish the exact nature of the annual variations in FMC and to devise a valid, feasible scheme for detecting them. The judgement is made here that, for purposes of the desired index, the annual variations in spring crown condition are of minor importance compared with the much larger 35-point average difference between spring and summer. The practical course, then, is to assume a single standard trend in FMC, based on local observations in the conifer species of interest, thus avoiding the difficulties of trying to distinguish one year from another.

The Crown Spread Factor

There is essentially no specific crown fire theory in the literature on which to base an index to account for seasonal variations in the rate of spread of crown fires. The following derivation of the Crown Spread Factor (CSF) is therefore based on the principle commonly used in theories of surface fire spread, namely, an energy balance on the forward heat flux to the unignited fuel.

Suppose that the crown canopy is a simple layer of fine fuel in which energy to preheat the unburned fuel is transferred horizontally through the fuel layer itself. Then, from the principle of energy conservation, the following more or less standard equation applies:

$$R \propto E/hd \qquad (1)$$

where R is forward rate of spread

E is horizontal heat flux

h is the preheat ignition energy

d is bulk density of layer

In other words, the rate of spread will be:

a) proportional to the horizontal heat flux,

b) inversely proportional to the preheat ignition energy, and

c) inversely proportional to the bulk density of the layer.

Taking these in turn, suppose that the horizontal heat flux is mainly radiation.

Then, $$E \propto (T/1000)^4 \tag{2}$$

where T is absolute temperature. Flame temperature is in turn dependent on foliar moisture content M. A roughly satisfactory expression for T in terms of M is

$$T = 1500 - 2.75M \tag{3}$$

in which 1500 °K is the theoretical flame temperature with bone-dry fuel and an air supply twice the minimum theoretical requirement.[1/] Substituting (3) in (2) gives

$$E \propto \left(\frac{1500 - 2.75M}{1000}\right)^4 \tag{4}$$

The energy h required to preheat fuel to ignition can also be stated as a simple function of foliar moisture content (Van Wagner 1968):

$$h = 110 + 6.2M \tag{5}$$

The third item, the bulk density d of the crown layer, can be simplified to weight W per unit ground area provided the vertical depth of the crown canopy is assumed constant from season to season. In other words, as new branches are formed above, old lower branches die. W will be at a maximum in midsummer when the new growth is more or less fully developed.

Since the purpose of the CSI is to take account of the special state of the crown layer in spring, a standard state must be chosen at which CSI and ISI are equal, and the CSF equals 1. Let E_o, h_o, W_o, and M_o represent the normal values of these parameters in midsummer. Then,

$$CSF = E/E_o \cdot h_o/h \cdot W_o/W \tag{6}$$

Since E and h have been expressed (eq. 4 and 5) in terms of M, E_o and H_o will depend on the choice of M_o. Also, it is more convenient to express W_o/W as W/W_o , the proportion of full summer foliage weight. The CSF can then be found on any day if M and W/W_o are known, and the seasonal trends of M and W/W_o will combine to yield the seasonal trend of the CSF. The actual values will vary with species and region.

The appearance of the foliage weight ratio (W/W_o) as a factor in the CSF deserves comment. Common experience suggests that when a fuel complex is opened up fire spreads through it more quickly. The theory is also quite clear on this point. Of course, this relationship has its limits; certainly,

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1/ Van Wagner, C.E. 1963. Unpublished MS. Petawawa Forest Experiment Station.

when the bulk density of the layer is reduced below a certain level, then fire will not spread at all. It is taken for granted, however, that the normal seasonal variation in crown bulk density lies well above this critical lower limit. There is, therefore, good justification for including this feature in an index that seeks to account for seasonal differences in crown fire behaviour in constant weather.

Setting up the Crown Spread Index

To set up the Crown Spread Index, information on the spring trends of FMC and foliage weight ratio must be available, derived from sampling and phenological observations of the species of interest. The extent of the area that could be served by a single version of the CSI is uncertain. The following version is based on Petawawa data. It would no doubt be valid for at least those parts of Ontario and Quebec within a few degrees of latitude 46N - how much more only observation would tell.

The chosen FMC trend for Petawawa is shown in **Figure** 2a. It is partly a subjective blend of the trends of the five species listed in Table 1, and its minimum value is 94%, the average of the five species minima. A value of 130 was calculated for M_o, the normal midsummer composite FMC of old and new foliage. The maximum difference is thus 36 points, enough to cause a substantial difference in flammability.

The trend of W/W_o , the foliage weight ration, is shown in Figure 2b. It begins with the rise in dry weight observed during the spring FMC dip, which is followed by a short constant period during which the starch reserves are translocated to the newly-flushed foliage. There is then a final rise to the midsummer level. This W/W_o trend is based on the assumptions that the new foliage constitutes on the average about 30% of the midsummer total for the species sampled, and also that the initial spring starch buildup is about 20% of the over-wintered foliage weight.

Given that M_o = 130, a working equation for the CSF can now be derived from eq. 6:

$$CSF = 538 \left(\frac{1500-2.75M}{1000}\right)^4 \Big/ (110 + 6.2M)(W/W_o) \qquad (7)$$

Figure 2c is a graph of this function as it varies throughout the season in accordance with the trends of M and W/W_o. The CSF is tabulated at 5-day intervals in Table 2. The Crown Spread Index is obtained by multiplying the ISI by the CSF:

$$CSI = ISI \cdot CSF \qquad (8)$$

This final calculation is probably most easily done by hand. However, it could be tabulated, the size of the table depending on the allowable coarseness of the jumps from class to class.

A further step could conceivably be taken, namely the determination of a modified FWI using the CSI in place of the ISI. However, the value of such an additional index is probably doubtful.

The Crown Spread Index in Use

The Crown Spread Index described here is relative rather than absolute. Its aim is to provide a realistically higher number in spring than in summer, based on plausible theory and some pertinent data. This index can be used to judge the relative rate of crown spread in conifer stands until the Crown Spread Factor reduces to 1; then the ISI alone will suffice.

From Petawawa experience in jack and red pine stands, a level of about 30 in either CSI or ISI should roughly indicate the onset of crowning. However, calibration is best done in the local conifer types. Higher values would suggest progressively more extreme rates of spread. According to Table 2, crown conditions could exist under which crown fires would be likely at ISI values as low as 10. Such a level is easily attainable in spring with, say, a humidity in the 30's and a wind of 10 or 12 mph, weather that in other seasons would sustain only a moderately intense surface fire.

Acknowledgement

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Table 1. Spring FMC minima for five conifer species at Petawawa

Species	No. of years sampled	Minimum FMC %	
		Mean	Range
Jack pine	6	105	96-112
White pine	5	103	98-114
Red pine	6	91	85-98
White spruce	4	87	83-89
Balsam fir	5	87	78-95

Table 2. CSF trend at Petawawa by 5-day intervals.

Day / Month	5	10	15	20	25	30
April	----	1.73	1.82	1.89	1.96	2.02
May	2.08	2.13	2.17	2.20	2.20	2.20
June	2.18	2.12	1.98	1.94	1.81	1.68
July	1.52	1.37	1.25	1.15	1.08	1.03
August	1.00	1.00	1.00	1.00	1.00	1.00

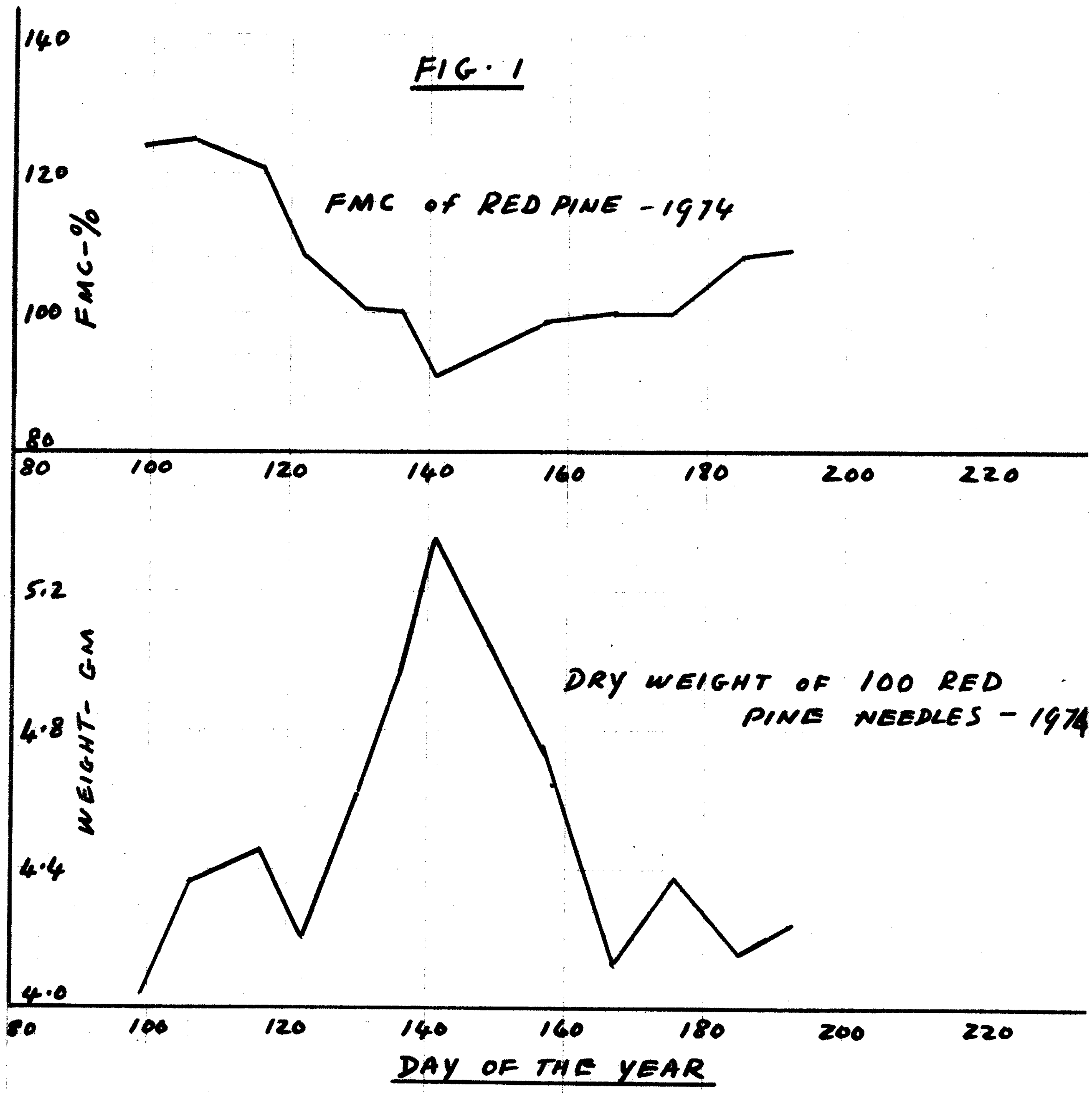

Figure 1. The trends of oven-dry weight (ODW) and foliar moisture content (FMC) for samples of 50 pairs of red pine needles taken during spring 1974.

Figure 2. The normal Petawawa trends of

a) Foliar Moisture Content (FMC)

b) Foliar Weight Ratio (W/W_o)

c) Crown Spread Factor (CSF)

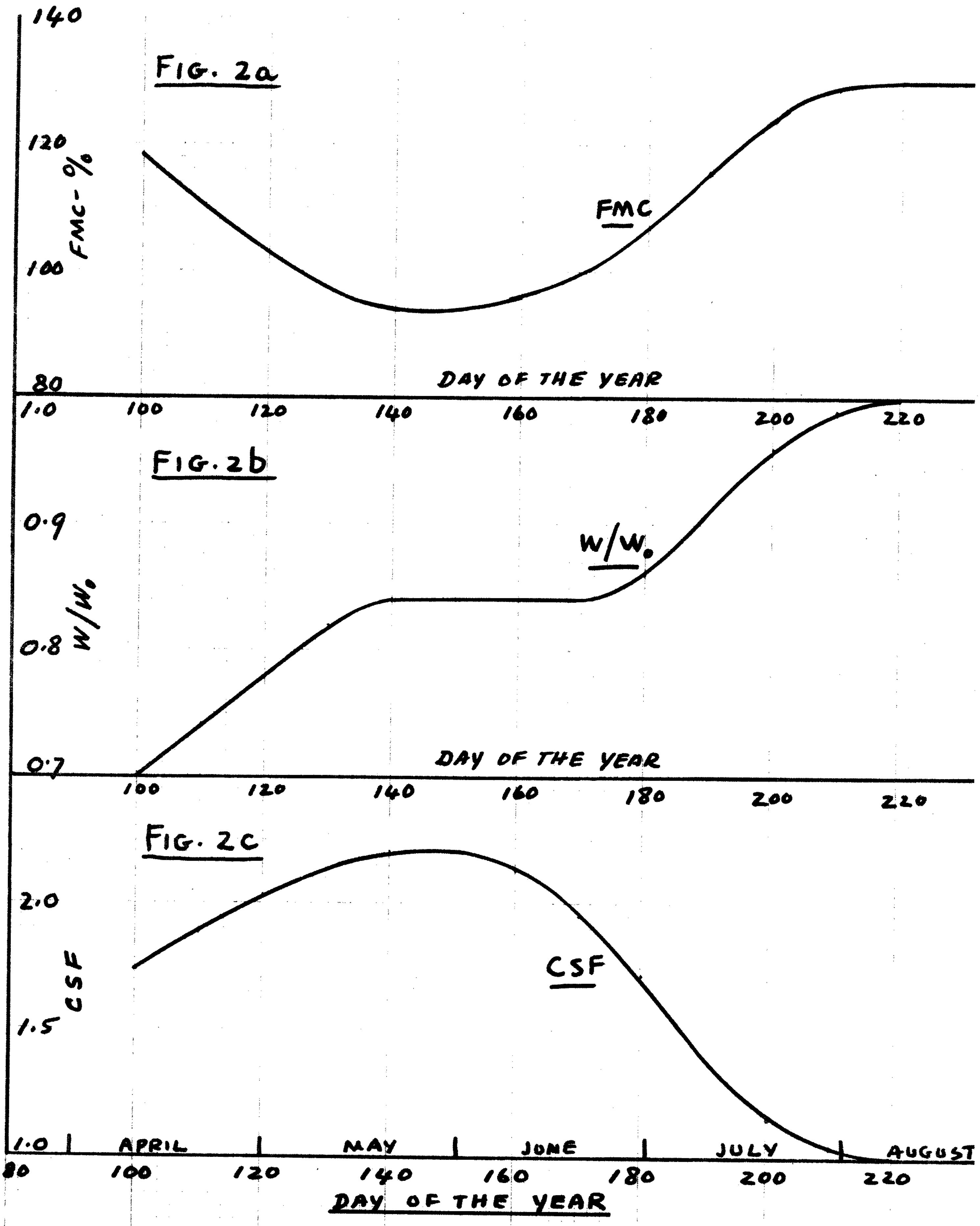
FIG. 2a
140
120
100
80
FMC - %
FMC
DAY OF THE YEAR
1.0
100
120
140
160
180
200
220
FIG. 2b
0.9
0.8
0.7
W/W_0
W/W_0
DAY OF THE YEAR
100
120
140
160
180
200
220
FIG. 2c
2.0
1.5
1.0
CSF
CSF
APRIL
MAY
JUNE
JULY
AUGUST
80
100
120
140
160
180
200
220
DAY OF THE YEAR