The Soil Dryness Index for Use in Fire Control in the South-West of Western Australia

by N.D. Burrows

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SUMMARY

The dryness of fuels is recognized as one of the most important factors affecting forest fire behaviour. Fire managers must be aware of the seasonal accumulation and degree of moisture of deep forest litter, logs and living vegetation if they are to plan adequately for fire control operations such as fuel reduction burning and wildfire suppression.

The Soil Dryness Index (SDI) and the Keetch-Byram Drought Index (KBI) are two systems used in Australia to determine the seasonal moisture content of soils and forest fuels. To determine which of these systems is best suited to fire control in the south-west of Western Australia, the levels of dryness predicted by both were compared with weekly moisture content measurements of forest soils and logs. Further comparisons were made to determine whether the SDI is a useful guide for conducting control burning operations.

The SDI proved to be superior to the KBI at predicting the rate of spring and summer drying of both soils and forest fuels and can be used as a guide in fire control operations in the south-west of Western Australia: the KBI seriously underestimated drying rates.

INTRODUCTION

It is well accepted that fuel dryness is one of the most significant factors affecting bush fire behaviour and severity. Severe bush fires, such as the Dwellingup fires of 1961 and the Ash Wednesday fires of 1982, mostly occur when very dry fuels are plentiful over a large area. Small and localized wildfires occur almost every summer across Australia but it is the statewide, mass wildfire outbreaks which over-tax fire fighting organisations and cause greatest losses. These fires have almost always occurred during periods of drought. Prolonged drought results in an increase in the quantity of fuel available for burning and a decrease in the moisture content of both living and dead fuels, thus producing a significant effect on fire behaviour (McArthur 1966).

The drying process of fuels such as deep forest litter, living vegetation and large diameter dead woody fuels, is gradual (McArthur 1966). Unless it is carefully measured and evaluated, a state of dangerous fuel dryness may occur unexpectedly. The Keetch-Byram Index (KBI) and a derivation of this, the Soil Dryness Index (SDI), are two models or indices used in Australia for predicting the seasonal status of soil and fuel dryness. These indices do not predict the daily moisture content fluctuations of fine fuel particles such as leaves and small twigs, but instead, are a means of revealing the seasonal dryness of the soil profile, of deep forest litter and of logs lying on the forest floor.

Mount (1972) found that the KBI seriously underestimated the rate of soil and fuel drying in Tasmania. Similar observations have been made in the south-west of Western Australia.

The aim of this study was to examine which of these two drought indices is best suited in fire control management in the south-west of Western Australia and to define the relationship between a drought index and fire control operations.

THE DROUGHT INDICES TESTED

Both drought indices (or models) are based on a simple concept of increases and decreases in soil moisture content. That is, current soil moisture can be determined from soil moisture at a previous time plus additions to soil moisture by rainfall minus various losses of moisture. The greatest difference between the two models is in the ways loss of soil moisture are measured. The mathematical derivation of the models will not be presented here. Instead, a brief summary of the main features of each is presented.

The Keetch-Byram Drought Index (KBI)

The KBI originated in the south-eastern United States of America (Keetch and Byram 1968) and was considered to have application to fire control in Australia (McArthur 1966).

The KBI is calculated using the following steps.

(1) Determining a drought factor [moisture loss by evaporation and transpiration (evapotranspiration)] from daily readings of maximum temperature and rainfall. The mean annual rainfall of the station for which the index is to be calculated determines the appropriate set of drought factor tables to be used.

The daily drought factor decreases for a given temperature as the KBI increases. The soil can only store the equivalent of 200 mm of available moisture (water available for evapotranspiration).

(2) The KBI is reduced by rainfall (5 mm of rain or less is ineffective as it is intercepted by vegetation) to a minimum of 0, which is the point of soil saturation (field capacity).

(3) The KBI rises as moisture is lost from the soil by evapotranspiration and reaches a maximum of 200 mm.

The model is based on the following assumptions:

(1) The rate of moisture loss in a forested area depends on the density and cover of vegetation, which in turn, is a function of rainfall.

(2) The depth of soil is such that the soil has a field capacity of 200 mm of available water.

The Soil Dryness Index (SDI)

The SDI (Mount 1972) is calculated in a similar fashion to the KBI.

(1) An estimable amount of rain fails to reach the soil and is intercepted by the forest vegetation or is unable to be absorbed by the soil and is lost as run-off.

In this study, flash run-off was ignored as the infiltration capacities of the gravelly surface soils is rarely exceeded (Loh *et al.* 1984).

(2) Water entering the soil is evaluated as a reduction in the SDI which reaches 0 when the soil is saturated.

(3) Water loss from the soil by evapotranspiration leads to a rise in the index. The amount of soil water loss can be calculated in millimetres per day from the daily maximum temperature and the current SDI. Evapotranspiration tables can be constructed for each station using mean monthly pan evaporation rates and mean monthly maximum temperature (Mount 1972).

(4) Water can also be lost as run-off which is proportional to rainfall intensity. This is not a feature of the KBI.

(5) The SDI also provides for rainfall which is intercepted by vegetation. The proportion intercepted depends on the

structure and type of vegetation, intensity of rainfall and the quantity of water already held in the canopy from previous rain. One rain-free day is sufficient to dry the canopy. Unlike the SDI, the KBI assumes a constant amount of interception per rainfall event. Both indices are calculated daily using daily rainfall and maximum temperature. The net soil moisture, or the soil moisture budget, is carried over from one day to the next.

METHODS USED TO TEST THE SDI AND THE KBI

Both indices are designed to reflect soil moisture depletion and the drying rates of (1) deep forest litter, (2) living vegetation, and (3) logs. The indices operate on the assumption that soil moisture not only reflects but also affects the moisture contents of these fuels. The following criteria were used to determine which of the two indices is best suited to fire control in the south-west of Western Australia:

(1) the ability of the indices to predict the soil moisture content;

(2) the ability of the indices to predict the moisture content of large logs;

(3) the relationships between SDI values, fire danger and the level of fire control difficulty. The KBI was not tested here.

Soil Moisture

The ability of the SDI and the KBI to predict soil moisture content was appraised by graphing and comparing both indice values with actual soil moisture content measurements. The moisture content of soils beneath three major commercial forest types was measured at weekly intervals over a period of about 18 months.

The three forest types studied were:

(1) Site 1 - Radiata pine (*Pinus radiata*) plantation near Nannup. The period of study was from November 1977 to April 1979. The mean annual rainfall for the site is 1 000 mm.

(2) Site 2 - Mature jarrah (*Eucalyptus marginata*) forest south of Manjimup. The period of study was from December 1978 to June 1980. The mean annual rainfall for this site is 1 150 mm.

(3) Site 3 - Mature karri (*Eucalyptus diversicolor*) forest near Pemberton. The period of study was from June 1979 to July 1981. The mean annual rainfall for this site is 1 250 mm.

The moisture content of the soil profile to a depth of 30 cm was determined from 20 core samples (each about 400 g) taken weekly from each site. Samples were randomly located within an area of about 1 ha. Twenty samples provided a sufficiently low standard error (7 per cent) of the mean soil moisture content. Sampling was standardised to the top 30 cm of soil at all sites because quartz rock at Site 1 hampered sampling to greater depths. It was reasoned that the top 30 cm would be most sensitive to moisture fluctuations, and that this level would best reflect the dryness of deep forest litter and logs.

Soil samples could not be oven dried for moisture content determination due to the varying size and quantity of rocky material present. Soil moisture content was determined indirectly using a filter paper technique (Williams and Sedgley 1965).

A weather station at each site provides daily maximum temperature and rainfall data necessary for daily calculation of both indices. Local evapotranspiration rates, which are necessary to calculate the SDI, were determined from local observations of pan evaporation (supplied by Bureau of Meteorology, Perth) and mean monthly temperature (Western Australia Year Book 1975) using a technique described by Mount (1972).

Log Moisture

Seasonal log moisture content data were obtained for three tree species: marri (*Eucalyptus calophylla*), karri (*E. diversicolor*) and radiata pine using the following procedure (Table 1).

The ends of the logs (Table 1) were painted with a moisture sealant to reduce moisture loss from the end grain. A long gantry was constructed on level ground in the open, near the Manjimup Research Station. A layer of quartz gravel was laid beneath the gantry to prevent rain splashing mud onto the logs. A number of logs (see Table 1) were raised 75 mm above the ground (elevated) by resting log ends on blocks of wood. Other logs were placed onto the quartz gravel (grounded). A chain lift suspended from the gantry and a 100 kg (± 0.01 kg) spring balance were used to weigh the logs. Initial log moisture contents were determined by oven drying small samples from each log. Logs were weighed weekly from September 1976 to May 1979. Knowing the initial moisture contents, weekly moisture contents were calculated from log weights.

Both drought indices were calculated daily over the study period.

TABLE 1: A description of the logs used in a moisture content (P. Jones, unpublished data) comparison study between the SDI and the KBI.

Species	Log Diameter (cm)	Approx. Log Length (m)	Position *(a)*	Degree of Curing *(b)*	No. of logs
Marri	30	1.7	Elevated	Green	4
Marri	30	1.7	Elevated	Green	2
Karri	30	1.7	Elevated	Green	6
Karri	30	1.7	Grounded	Green	2
Karri	30	1.7	Elevated	Dry	2
Karri	30	1.7	Grounded	Dry	2
Pine	30	1.7	Elevated	Green	4
Pine	30	1.7	Grounded	Green	2

(a) Position: refers to whether the log was supported above the ground (elevated) or whether the log was resting on the ground (grounded).

(b) Degree of curing: 'green' refers to logs from trees felled just prior to the log moisture study and 'dry' refers to logs from trees which were felled two years prior to the study.

Fire Danger Rating and the SDI

The SDI values were compared with forest fire danger rating and forest fire control operations, including edging (burning off fuels around the edge of a large forest block), and prescribed burning for fuel reduction. If the SDI could accurately reveal the seasonal buildup of forest fuels then it was reasoned that the index could be used to define limits for carrying out various fire control operations. The KBI had already been used in this way in Australia (McArthur 1966).

Information used to compare the SDI, fire control operations and the daily forest fire danger rating (Sneeuwjagt and Peet 1976) for the Manjimup District were obtained from the then Forests Department records, (now Department of Conservation and Land Management). Records of the forest fire danger rating (FDR) are kept only during the 'fire season', which is the period over which forest fuels are likely to be dry enough to burn. For the Manjimup District, this period is usually from the end of September until April. Records for this period for all years from 1979 to 1984 were examined and compared with SDI values.

Records of 172 prescribed burns over the same period were also examined. Fire behaviour, scorch to trees, difficulty of fire containment and difficulty of mop-up were related to SDI values at the time of the burns.

RESULTS

Soil Moisture Content

Although both the SDI and the KBI predicted soil moisture content trends (Fig. 1), the SDI was superior on all sites (Table 2). Generally, the KBI under-estimated soil moisture drying trends more than the SDI.

Both indices were less reliable following brief periods of rain in summer and following a prolonged cessation of rain during winter (Figs 1-3). Indices were most reliable during uninterrupted drying or wetting cycles.

The mediterranean type climate of cool, wet winters and warm, dry summers experienced in the south-west of Western Australia is well illustrated by the graphs in Figures 1, 2 and 3. Soil moisture content ranged from 4 per cent in summer to 42 per cent in winter. Soils on Site 3, the deeper karri loams, were consistently wetter than the other soils. The soil moisture content and the indice values (Fig. 3) reflect the climate, soil and vegetation differences between the study sites. Site 1 experienced the highest mean monthly temperatures and received the lowest rainfall. Drier climate, shallower soils and the high stocking of trees probably explains the rapid drying of soils on Site 1 from July to December each year.

The best correlation between indice values and soil moisture content was achieved on the wetter site, Site 3 (Table 2). Both indices performed poorest on the drier sites. The correlations between soil moisture content and the KBI were consistently lower than correlations between soil moisture content and the SDI. The strongest correlation between the two indices was achieved on Site 3. The poorest correlation was on the driest site, Site 1. Both indices attempt to model moisture fluctuations in the top 1 m of soil. Only the top 30 cm of soil was examined in this study which probably explains most of the variation between predicted and actual soil moisture contents (Figs 1, 2 and 3).

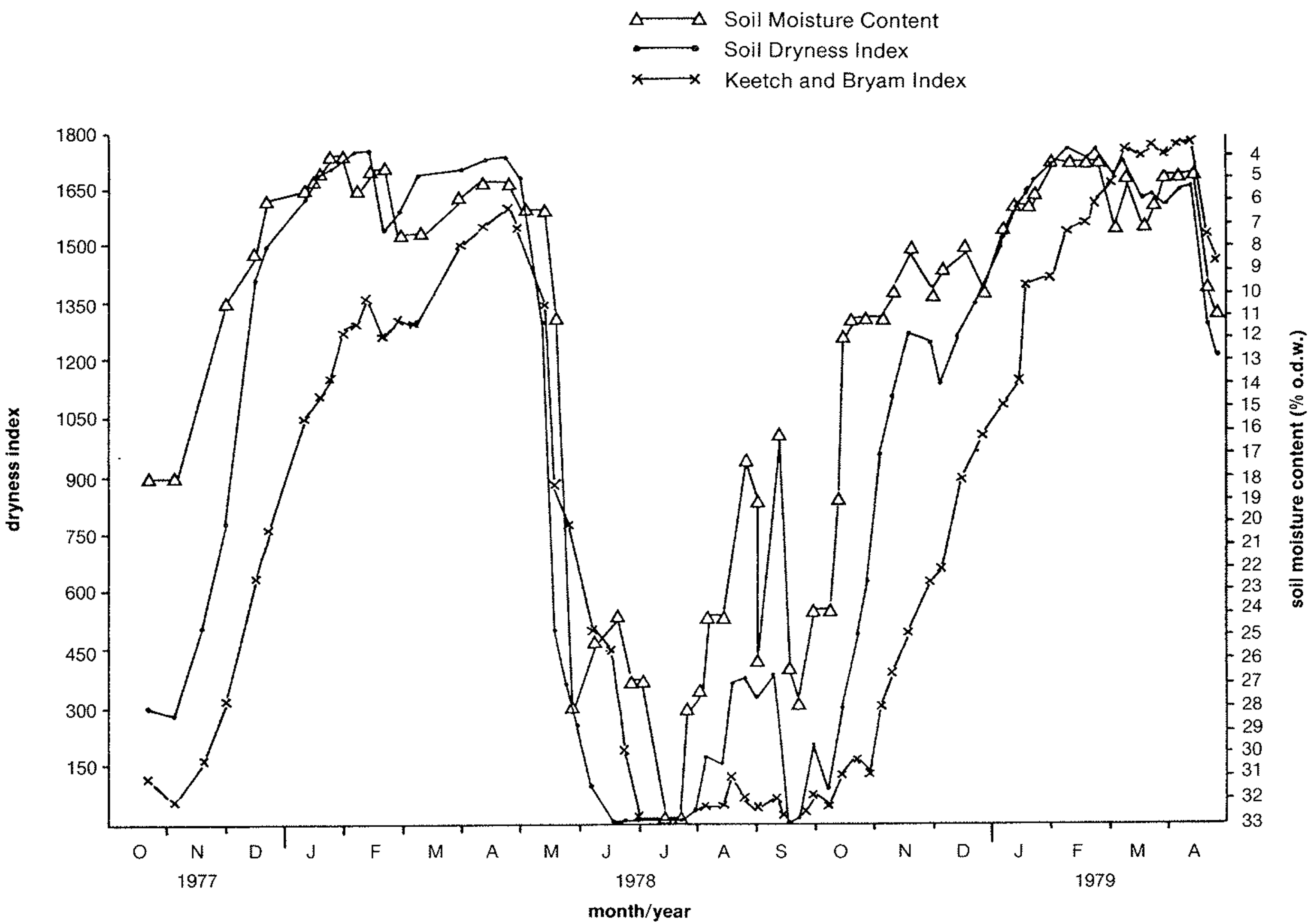

FIGURE 1
The Soil Dryness Index (SDI), the Keetch and Byram Drought Index (KBI) and the profile moisture content of the top 30 cm of soil beneath a **P. radiata** hills plantation near Nannup.

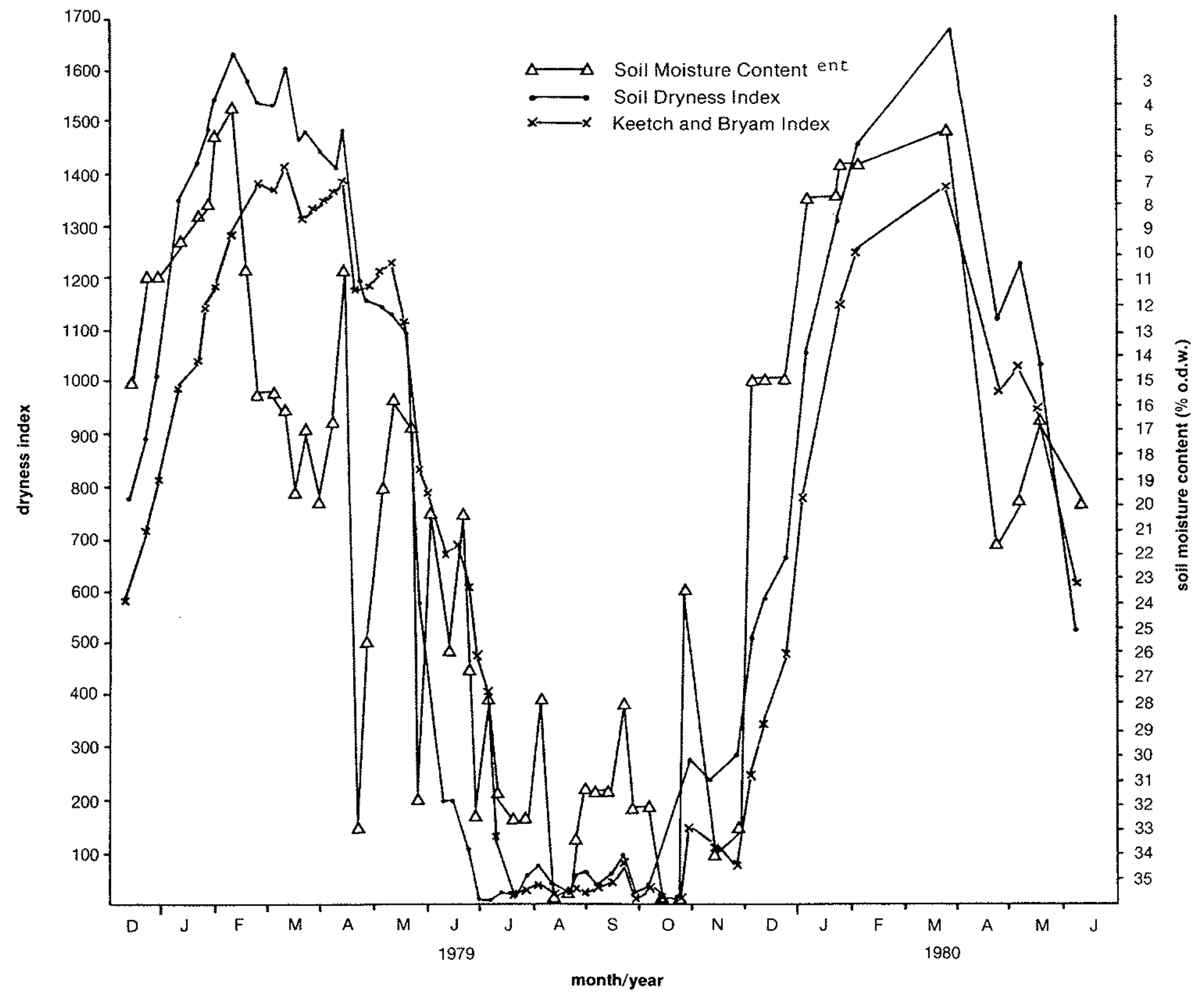

FIGURE 2
The Soil Dryness Index (SDI), the Keetch and Byram Drought Index (KBI) and the profile moisture content of the top 30 cm of soil beneath a jarrah-marri forest near Manjimup.

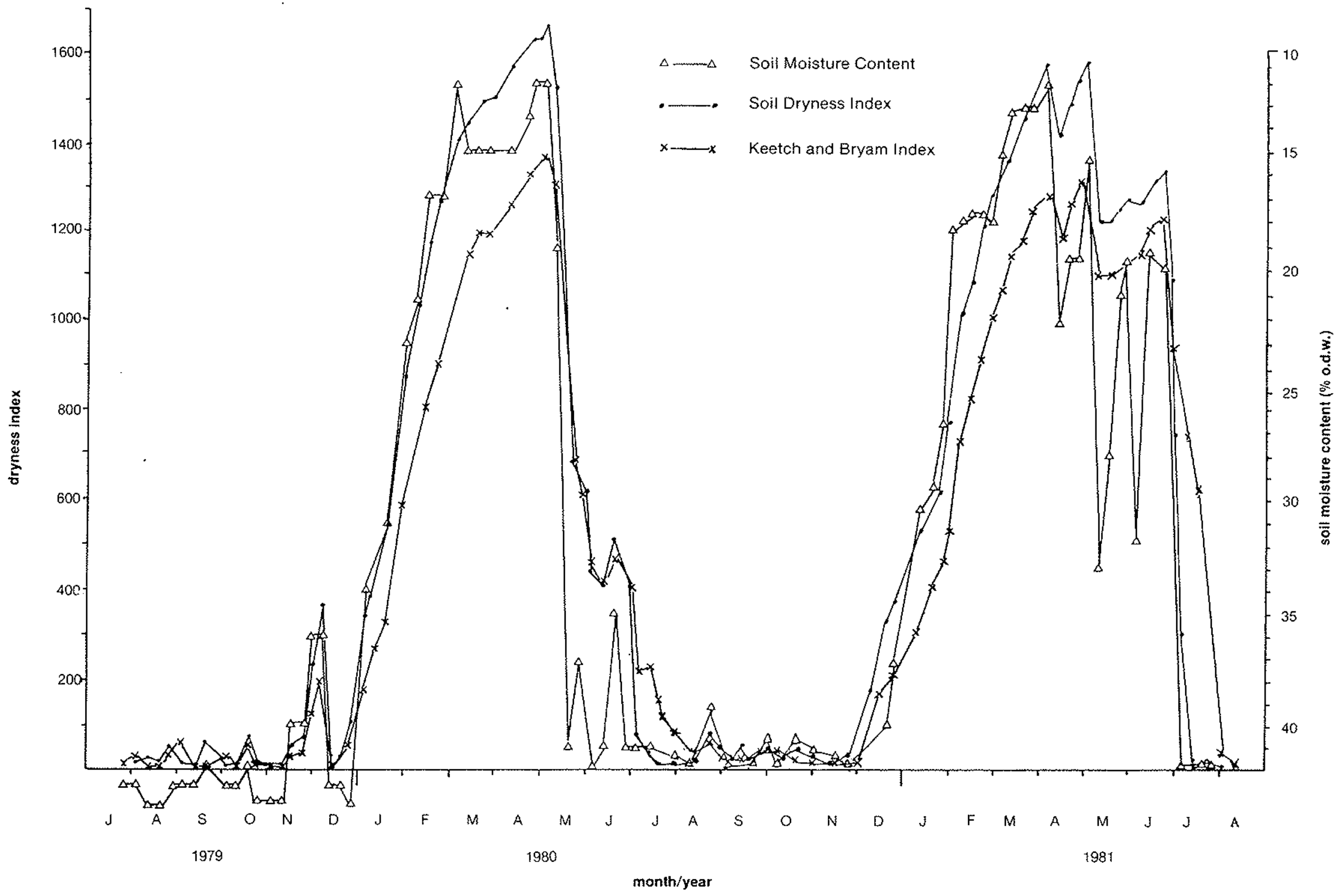

FIGURE 3
The Soil Dryness Index (SDI), the Keetch and Byram Drought Index (KBI) and the profile moisture content of the top 30 cm of soil beneath a karri forest near Pemberton.

TABLE 2: Pearson correlation coefficients for soil moisture content (SMC), the SDI and the KBI for Site 1 (S1), Site 2 (S2) and Site 3 (S3).

Parameters	SDI	KBI	SMC
SDI	1.0		
KBI	0.90 (S1) 0.94 (S2) 0.97 (S3)	1.0	
SMC	-0.93 (S1) -0.83 (S2) -0.95 (S3)	-0.76 (S1) -0.75 (S2) -0.90 (S3)	1.0

Log Moisture Content

At the commencement of the study, the green karri and marri logs had a mean moisture content of about 68 per cent and the green pine logs, 132 per cent. Although the green marri and karri logs showed seasonal fluctuations in moisture content, it was unlikely that they had reached air dry equilibrium by the time the study was completed (Fig. 4). Green karri and marri logs resting on the ground dried out to about 23 per cent in summer 1978 and at the same time, the grounded pine logs reached 7 per cent. The pine logs dried and wetted at a much faster rate than the marri and karri logs. Elevated logs were consistently drier than logs on the ground by 10-15 per cent. The average weekly moisture contents of grounded logs are graphed in Figure 4.

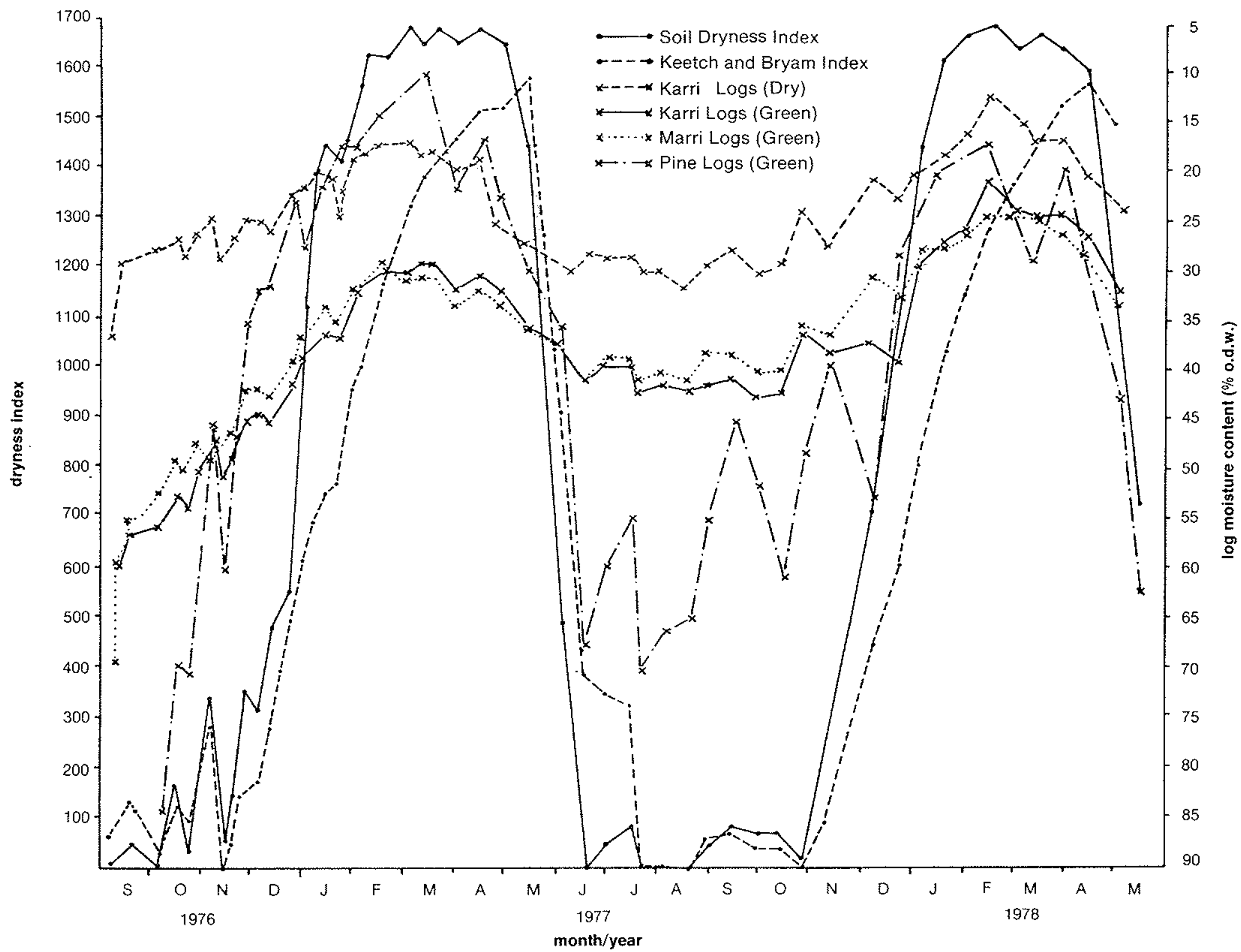

FIGURE 4
Moisture content fluctuation for a range of grounded logs measured in the open at the Manjimup Research Station. Indice values are also graphed.

The correlation between indice values and the moisture content of green logs was poorer than the correlation between indice values and the moisture content of soils (Table 3). The correlation coefficients for both indices and green logs were similar, however, a better correlation existed between indice values and dry logs. As with soil moisture, the moisture content of dried karri logs was best revealed by the SDI (Table 3).

The Fire Danger Rating, Fire Behaviour and the SDI

The FDR was positively related to the SDI for the Manjimup District for the period 15 October to 15 March (1979-1984). When the SDI was low (<250) during this period, an FDR of VERY LOW occurred on 88 per cent of days and an FDR of LOW on the remainder. However, when the SDI was high (1200+), an FDR of VERY LOW or LOW occurred on only 44 per cent of days (Table 5) and an FDR of EXTREME on 2 per cent of days. The proportion of days when the FDR was HIGH, VERY HIGH or EXTREME increased with increasing SDI classes (Table 4). When the SDI was <800, days of FDR in excess of HIGH were unlikely.

The results of 172 fuel reduction burns are presented in Table 5. The decreasing flammability of fuel types, from scrubby treeless flats to karri fuels (Table 5), is reflected in the progressively higher SDI values under which a successful burn was achieved. Jarrah forest edging, scrubby flats and pines were most successfully burnt when the SDI was <250. No successful burning was carried out in these types when the SDI exceeded 600. Prescribed burning in jarrah forest was most successful when the SDI was 251-600.

TABLE 3: Pearson correlation coefficients for various log moisture contents (% oven dry weight), the SDI and the KBI.

Parameter		1	2	3	4	5	6	7	8	9	10
SDI	(1)	1.0									
KBI	(2)	0.90	1.0								
MC% elevated marri (green)	(3)	-0.69	-0.69	1.0							
MC% grounded marri (green)	(4)	-0.79	-0.78	0.97	1.0						
MC% elevated karri (green)	(5)	-0.72	-0.72	0.99	0.98	1.0					
MC% grounded karri (green)	(6)	-0.81	-0.80	0.97	0.99	0.98	1.0				
MC% elevated pines (green)	(7)	-0.62	-0.60	0.98	0.91	0.96	0.92	1.0			
MC% grounded pines (green)	(8)	-0.74	-0.61	0.70	0.83	0.77	0.79	0.60	1.0		
MC% elevated karri (dry)	(9)	-0.93	-0.83	0.69	0.82	0.72	0.82	0.57	0.79	1.0	
MC% grounded karri (dry)	(10)	-0.91	-0.81	0.69	0.82	0.72	0.82	0.56	0.74	0.79	1.0

NOTE: The condition of 'green' or 'dry' refers to the degree of curing of the log at the beginning of the study (See Table 1).

TABLE 4: The percentage of days on which the fire danger rating was: VERY LOW, LOW, MODERATE, HIGH, VERY HIGH or EXTREME for given SDI ranges.

SDI	Fire Danger Rating						Total
	Very Low	Low	Moderate	High	Very High	Extreme	
0- 250	88	12	0	0	0	0	100
251- 400	57	29	7	7	0	0	100
401- 600	40	40	13	7	0	0	100
601- 800	24	40	25	11	0	0	100
801-1200	20	41	25	11	3	0	100
1201+	18	36	22	10	12	2	100

NOTE: (1) These observations were made daily at Manjimup, Western Australia, between 15 October - 15 March during the years 1979-1984 inclusive.

(2) A Fire Danger Rating of MODERATE is generally considered ideal for prescribed burning for fuel reduction (Sneeuwjagt and Peet 1976).

Burning outside this SDI range resulted in a higher proportion of unsuccessful burns. The burns were either too cool and too patchy or were too warm and scorched the overstorey or required considerably more expenditure on mop-up and control (Table 5). Prescribed burning in karri was most successful when the SDI was 601-800. However, a high proportion of the karri fires were rated poor (rating 1). Overall only 44 per cent of the karri prescribed burns were rated ideal (on the first lighting attempt), whereas, 77 per cent of jarrah prescribed burns were rated ideal. None of the karri burns was rated too hot, but 17 per cent of jarrah, 50 per cent of flats and 32 per cent of jarrah edge fires were too hot.

TABLE 5: Number of burns rated according to success (1-4) (*a*) of 172 prescribed burns carried out in different fuel types and over a range of SDI values. Observations were made from forest regions of the south-west of Western Australia over the period 1979 - 1984 inclusive (figure in parentheses is percentage).

Soil dryness index	Forest/fuel type: Jarrah edge fuels (edge burning)				Treeless flats (scrub covered)				Pine needlebed				Jarrah forest litter				Karri forest litter				Total no. burns
	Prescribed burn success rating (*a*)																				
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
0 - 250	2 (6)	15 (49)	4 (13)			6 (38)	1 (6)		3 (14)	12 (58)			3 (4)	4 (5)							50
251 - 600		4 (13)	4 (13)	2 (16)	1 (6)	1 (6)		6 (38)		3 (14)	3 (14)		2 (2)	49 (60)	2 (2)		9 (39)				86
601 - 1000								1 (6)						6 (7)	3 (4)	1 (1)	4 (17)	8 (35)			23
1001 - 1500														3 (4)	4 (5)	4 (5)		2 (9)			13
1500 +																					0
TOTALS	2 (6)	19 (62)	8 (26)	2 (6)	1 (6)	7 (44)	1 (6)	7 (44)	3 (14)	15 (72)	3 (14)		5 (6)	62 (77)	9 (11)	5 (6)	13 (56)	10 (44)			172

(*a*) Prescribed burn success rating;

1 Too cool (intensity <100 kW/m) and burn objectives not met. Poor ignition, less than 50 per cent of area burnt out, patchy fuel reduction, probably need re-burning. No mop-up needed and no control difficulties.

2 Ideal prescribed burn and burn objectives were met. Good ignition, 65 - 70 per cent of the area burnt out, good fuel reduction, little or no scorch to overstorey, little or no mop-up, no control difficulties, burning costs kept low.

3 Burn objectives not met as fire intensity was too high. Some scorch to the overstorey, area completely burnt out, some hopovers, many logs catch alight and require mop-up.

4 Fire intensity too high (350 - 450 kW/m) and considerable mop-up required. Large areas of scorch with some defoliation. Some spotfires and hopovers. Fire escapes require considerable suppression effort and burning costs per unit area are high.

DISCUSSION

Drought indices can provide fire controllers with a continuous scale of reference for estimating the seasonal buildup of soil and fuel dryness. The SDI was superior to the KBI which underestimated the rate of spring and summer drying. This is the most critical period for planning and preparing fire control activities in the south-west of Western Australia.

A feature of the SDI is that it accounts for water loss as overland flow. This has not been observed or quantified for the soils and forests in which this study was undertaken and is a topic for further study. The SDI is probably superior because local evapotranspiration figures are used to determine the rate of moisture loss.

The SDI was also a good indicator of the moisture content of heavy, woody fuels (logs). All else being equal, log moisture content changes will depend on the size of the log (Fosberg 1971). Large logs generally dry slowly. This can be represented by the SDI, but not as well as it represents soil moisture fluctuations. McArthur (1966) suggested that logs are dry at a KBI of 1 000 (mm x 10). In this study, grounded karri logs reached a moisture content of 25 per cent when the SDI was about 600 and reached a minimum moisture content of about 12-15 per cent when the SDI was about 1 700. The KBI was only about 1 200 and rising at this time.

Heavy fuels add to suppression problems when they ignite and can cause extensive damage to nearby crop trees. Very few logs ignited when the SDI was less than 250. When the SDI exceeded 900, a high proportion of logs ignited. McCormick (1966) showed foliar moisture content to be important in regulating the burning rates of scrub foliage. He found that foliar moisture content varied diurnally and between species but the amplitude of seasonal variation was much greater, suggesting seasonal differences in scrub flammability.

Burrows (1984) observed that scrubby creek systems burnt ferociously when the SDI exceeded 1 200. McCormick also reported that plants lost foliar moisture when the KBI exceeded 1 500.

Peet (1969) plotted the moisture content of the outer bark of jarrah trees and found a seasonal trend. Bark was driest in summer and moisture trends corresponded to the KBI. While not tested against the SDI, a better relationship probably exists between the moisture content of outer bark and the SDI. Peet found that the outer bark became flammable when the KBI exceeded 750. This is in keeping with observations made here. When the SDI exceeded 900, fire controllers experienced increasing control difficulties because of bark, standing dead trees and logs catching alight.

The mediterranean type climate experienced in the south-west of Western Australia produces strong seasonal trends of wetting and drying.

Forest fuels and soils dry rapidly during spring and summer, and in most years the summer drought will cause the SDI to exceed 1 600. Wetting commences in autumn, often towards the end of March, and the SDI quickly falls to 0 as fuels and soils reach moisture saturation in winter.

For fire control purposes, the SDI values must be interpreted according to whether the soils and fuels are wetting or drying. The drying of soil and fuels can be considered to occur from the top of the profile. An increasing SDI is equivalent to an increasing depth of soil and fuel dryness. Most fuel reduction burning in Western Australian forests takes place during the drying phase, or in spring when logs, soils, vegetation and deep forest litter are moist. SDI values are a useful guide to the period over which successful fuel reduction burns can be expected. While fire behaviour in light fuels (such as in the jarrah forest) is mostly influenced by day to day weather, the SDI is a useful measure of control and mop-up difficulties and of the level of tree damage likely to be incurred.

Table 6 contains the recommended SDI limits for successfully carrying out various types of controlled burns in Western Australian forests. The range of recommended SDI upper limits for the various types of prescribed burning (Table 6) caters for the varying levels of fire sensitivity of the forest trees and the different structural characteristics of the fuel complexes in the forest types. A description of the fuel complexes is given in *Forest Fire Behaviour Tables for Western Australia* (Sneeuwjagt and Peet 1976).

TABLE 6: The SDI as a guide to fire operations in forest areas of south Western Australia.

SDI UPPER LIMITS		FIRE OPERATIONS
SPRING	AUTUMN (*a*)	
250	SDI to fall by 500 units	Tops disposal, flammable flats, under pine needlebed burning, jarrah edging.
600	SDI fall by 500 units	Fuel reduction burning - northern and eastern jarrah forests and wandoo forest.
700	SDI to fall by 400 units	Fuel reduction burning - southern jarrah forest, karri forest types 3 and 6 (*b*).
800	SDI to fall by 400 units	Fuel reduction burning - karri types 1, 2, 4, and 5 (*b*).
SDI in excess of 1200		Slash disposal and regeneration burns in karri coupes.

(*a*) When autumn burning, allow the SDI to fall by the stated amount from its summer maximum.

(*b*) Karri forest types are described in *Forest Fire Behaviour Tables for Western Australia* (Sneeuwjagt and Peet 1976).

The SDI not only reflects the moisture content of the forest system, but also indicates the types of post-burn weather conditions. For example, conditions of leaf litter, fuel moisture and weather may be ideal for carrying out a fuel reduction burn in open jarrah forest, even though the SDI is high at 1 000. However, it is likely that many logs and standing dead trees will catch alight and that ensuing weather may be warmer and drier. While the burn may appear successful on the day, it may re-ignite or escape later on. Hence, considerably more effort must be spent on mop-up and patrol to secure the burn. Damage to crop trees will also add to the cost of the fire managers protection program.

SPATIAL VARIABILITY OF SOIL DRYNESS .

The two million hectares of State forest in Western Australia is divided into 12 management units or Districts. Weather forecasting and fire behaviour calculations are based largely on meteorological conditions at the District Headquarters. There is often considerable weather variability within a forestry district which results in considerable variability of fuel and soil dryness. In the south-west of Western Australia it is usual for conditions to be warmer and drier in the eastern and northern zones of a forest district.

Measuring variability is difficult because of the dispersed location of meteorological stations. While an experienced person can make intuitive corrections to the SDI for different weather and forest conditions throughout a District, the most reliable means of coping with variability is by establishing remote weather stations at strategic locations and calculating several SDI values accordingly.

The difficulty of measuring climatic variability across a forest division can be partially overcome by increasing the number of meteorological stations, but variation in soil and fuel moisture with topography, vegetation and soil types is more difficult to measure. There is no way of measuring this quickly and effectively. In this instance, a good local knowledge of the forest and an understanding of the variation in fuels and soil moisture contents with site differences is essential for effective fire control. Field measurements to verify fuel moisture content variability should be made prior to controlled burning.

While fuel and soil moisture contents are variable, the usefulness of the SDI is that it is an index of seasonal droughting over a large area. A better method for predicting localized, daily fine fuel moisture contents is available in *Forest Fire Behaviour Tables for Western Australia* (Sneeuwjagt and Peet 1976).

USING THE SDI IN WILDFIRE CONTROL

The KBI is

> 'a number representing the net effect of evapotranspiration and precipitation in producing cumulative moisture drying in deep forest litter, heavy fuel (logs), living vegetation and the upper soil layers' (Keetch and Byram 1968).

This definition also applies to the SDI. The SDI is a good indicator of the quantity of fuel available for burning. As the index rises, the quantity of fuel available for burning increases (McArthur and Cheney 1966). In the south-west of Western Australia, maintaining a continuous graph of the SDI (see Figs 1, 2 and 3) allows fire managers to identify the onset of summer droughting which is important for wildfire preparedness.

As the SDI increases, the fire control organization must correspondingly increase its level of wildfire preparedness. When the index exceeds 1 200, a fire which is not detected early could quickly develop into a large fire. Most severe wildfires have occurred when the SDI is in excess of 1 400. Under these conditions fire behaviour is often severe, crown fires are common and spot fires may develop downwind of the main fire. However, under conditions of low SDI (<600) it is unlikely that wildfires will be severe and they will probably be quickly contained.

Graphed SDI values (as shown in Figs 1, 2 and 3) can be useful for comparing seasonal fire severity from one year to the next and from place to place. A statewide isopleth map of the SDI can be issued to show areas of high and low fuel flammability and should further assist in fire preparedness and resource allocation. Such maps are used by the Tasmanian Forestry Commission for Tasmania.

OFFICE PROCEDURES FOR CALCULATING THE SDI

When to Start

The SDI rarely exceeds 1 750 in forest areas so it can be safely assumed that 200 mm of rain in less than 30 days means that the SDI is zero. Alternatively, if local creeks and catchments are monitored, the index can be set to 0 and calculations commenced when run-off is observed.

The index is calculated from readings of previous days maximum temperature (°C) and 24 hour rainfall (mm). The calculations involve:

(1) Estimating soil moisture loss from evapotranspiration;

(2) Estimating rainfall loss from canopy interception. Mount (1972) also estimates the amount of water lost as flash run-off for KBI. In forested lands of the south-west, this is reported to be negligible, so can be ignored when calculating the SDI.

The index value increases with soil moisture loss from evapotranspiration and decreases with moisture gain from effective rainfall. The amount of effective rain (mm) necessary to restore the soil to field capacity can be calculated at any time by dividing the current SDI by 10.

SDI Equations

$$EFF = P - I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where;
EFF is effective rainfall, P is the 24 hour rainfall (measured at 0800 hours), I is the intercepted loss.

PM(1) - EFF(2) = AM(2) or SCO(2) .... (2)

where;

PM(1) is the SDI value for the afternoon of day 1 and EFF(2) is the effective rainfall as measured on the morning of day 2. AM(2) is the SDI value for the morning of day 2 if EFF(2) is less than PM(1). If it is not, AM(2) is set to zero and the difference is called Soil Capacity Overflow (SCO(2)) or the amount of water flowing out of the soil. The SDI cannot be negative.

AM(2) + ET(2) = PM(2) .... (3)

where;

ET(2) is the evapotranspiration corresponding to the maximum temperature for day 2. ET tables for forest Districts in the south-west of Western Australia are appended (Appendix 1).

SDI Operating Instructions

The SDI recording form is divided into two parts; one part for rainy days and the other for dry days.

Enter record form (Appendix 2) with:

(1) Yesterdays maximum temperature (°C).
(2) 24 hour rainfall (measured at 0800 hours) today.
(3) Yesterdays PM SDI value.
(4) Calculate yesterdays (24 hour) effective rainfall from interception loss - see Table 7.
(5) Adjust yesterdays PM SDI for EFF to obtain todays AM SDI. Note: where PM - EFF results in a negative number set AM = 0.

Adjust todays AM SDI for ET, i.e. AM + ET = todays PM SDI.

Using the Canopy Interception Table

Mount (1972) provides formulae for calculating the quantity of rainfall intercepted by a range of overstorey and scrub types. Table 7 here is a simplication of this and covers the common forest types in the south-west of Western Australia. For fire control purposes, only the interception loss class appropriate to the dominant or most valuable or most flammable forest type need be used. The amount of rainfall intercepted by the forest canopy is a function of canopy height, canopy cover and scrub cover. The following descriptions apply for the four canopy types used here:

(1) Open wandoo (*Eucalyptus wandoo*):
- canopy cover 20 per cent - 40 per cent
- scrub cover - very light (<30 per cent ground cover)

(2) Open jarrah:
- canopy cover 40 per cent - 60 per cent
- scrub cover - very light (<30 per cent ground cover)

(3) Southern jarrah and karri 3 and 6[1]:
- canopy cover 40 per cent - 60 per cent
- scrub cover - moderate (30 per cent - 60 per cent ground cover)

(4) Karri 1 and 2[1] and pines:
- canopy cover 40 per cent - 60 per cent
- scrub cover - dense (60 per cent - 80 per cent ground cover)

  OR for pines;
- canopy cover 60 per cent - 80 per cent
- scrub cover - light (<30 per cent ground cover)

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[1]. Karri forest types are described in *Forest Fire Behaviour Tables for Western Australia* (Sneeuwjagt and Peet 1976).

TABLE 7: Amount of rainfall intercepted by canopies of common forest types in the south-west of Western Australia.

When to Use	Daily Rainfall (mm)	Canopy interception (mm x 10)			
		Open wandoo	Northern jarrah	Southern jarrah, karri 3 and 6 (*a*)	Karri 1 and 2 (*a*) pines
Section A					
(1) First wet day	<1.0	1	2	2	3
(2) Consecutive wet days when daily rain is less than 2 mm after the first wet day	1.1-2.0	2	4	5	6
	2.1-3.0	3	6	8	10
	3.1-4.0	4	8	11	14
	4.1-5.0	5	10	14	18
	5.1-6.0	6	12	17	22
	6.1 +	7	13	20	27
Section B					
(3) Consecutive wet days when each day's rain is greater than or equal to 2 mm after the first wet day	≧ 2 mm after the first	3	5	6	8

(*a*) Karri forest types are described in *Forest Fire Behaviour Tables for Western Australia* (Sneeuwjagt and Peet 1976).

Using Table 7

The total amount of rainfall that can be intercepted (I) by each canopy (canopy capacity) is estimated to be:

6 units (0.6 mm) for open wandoo
13 units (1.3 mm) for open jarrah
20 units (2.0 mm) for southern jarrah and karri 3 and 6
27 units (2.7 mm) for karri 1 and 2 and pines

Section A of Table 7 applies where rain is separated by dry days or I fails to reach canopy capacity which is when daily rain on consecutive wet days is ≤2 mm.

Section B applies when rain occurs on consecutive wet days and I remains at capacity which is when daily rain on consecutive days is greater than 2 mm. I then equals loss from crown evaporation per wet day (W) which is estimated to be:

3 units (0.3 mm) for open wandoo
5 units (0.5 mm) for open jarrah
6 units (0.6 mm) for southern jarrah and karri 3 and 6
8 units (0.8 mm) for karri 1 and 2 and pines

CONCLUSIONS

The KBI underestimated the rate of spring and summer drying of forest soils and of logs. The SDI was better able to reveal soil and log dryness and is recommended for use in Western Australia. Both indices were insensitive to short durations of wetting (rainfall) during a drying phase (spring or summer).

In the south-west of Western Australia, the SDI can be used as a guide to carrying out various prescribed burning operations. If these guides are adhered to, then the cost-effectiveness of fire control operations can be enhanced. Carrying out burning operations outside the recommended SDI limits may result in unacceptable damage to crop trees and high mop-up and control costs.

The SDI cannot be interpreted as an accurate measure of the moisture content of fine fuels nor as a measure of fire behaviour.

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APPENDIX I: Evapotranspiration tables for forest districts in south-west Western Australia.

BUSSELTON, NANNUP, KIRUP

MAXIMUM DAILY TEMPERATURE (°C)

FEB. - JUNE	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+	42+
JULY - JAN.	6+	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+
S.D.I.	Evapotranspiration (ET) in tenths of mm per day											
0+	9	12	15	18	21	25	30	35	40	45	50	55
250+	3	6	9	12	15	19	23	28	33	38	43	48
500+	1	3	5	7	10	14	18	23	28	33	38	43
1400+		2	3	4	5	6	8	9	10	11	12	13
1650+			1	1	2	2	3	4	4	5	5	6

WANNEROO, MUNDARING

MAXIMUM DAILY TEMPERATURE (°C)

FEB. - JUNE	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+	42+
JULY - JAN.	6+	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+
S.D.I.	Evapotranspiration (ET) in tenths of mm per day											
0+	3	8	13	18	23	30	38	45	52	60	68	
250+		5	8	11	16	23	31	38	45	52	59	66
500+		2	4	6	11	18	26	33	40	48	56	64
1400+			2	4	6	8	9	11	13	15	17	19
1650+			1	1	2	3	4	5	6	7	8	9

COLLIE, HARVEY

MAXIMUM DAILY TEMPERATURE (°C)

FEB. - JUNE JULY - JAN.	9+ 6+	12+ 9+	15+ 12+	18+ 15+	21+ 18+	24+ 21+	27+ 24+	30+ 27+	33+ 30+	36+ 33+	39+ 36+	42+ 39+
S.D.I.	Evapotranspiration (ET) in tenths of mm per day											
0	5	13	17	21	27	33	39	44	50	56	62	68
250+	3	8	11	14	19	24	31	37	43	49	55	61
500+	1	4	6	9	13	17	26	32	38	44	50	56
1400+		2	3	5	6	8	9	11	13	14	15	17
1650+		1	1	2	3	3	4	5	5	6	7	8

DWELLINGUP, JARRAHDALE

MAXIMUM DAILY TEMPERATURE (°C)

FEB. - JUNE JULY - JAN.	9+ 6+	12+ 9+	15+ 12+	18+ 15+	21+ 18+	24+ 21+	27+ 24+	30+ 27+	33+ 30+	36+ 33+	39+ 36+	42+ 39+
S.D.I.	Evapotranspiration (ET) in tenths of mm per day											
0	11	14	17	20	25	30	35	40	45	50	55	60
250+	5	8	11	15	19	24	29	34	39	44	49	54
500+	2	4	6	10	14	19	24	29	34	39	44	49
1400+		2	4	5	6	8	9	10	11	13	14	15
1650+		1	1	2	2	3	4	4	5	5	6	7

APPENDIX I cont.

WALPOLE (SOUTH), MANJIMUP (WEST), PEMBERTON

MAXIMUM DAILY TEMPERATURE (°C)

FEB. - JUNE	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+	42+
JULY - JAN.	6+	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+
S.D.I.	Evapotranspiration (ET) in tenths of mm per day											
0		13	17	21	25	29	34	39	44	49	54	59
250+		8	11	14	18	23	27	32	37	42	47	52
500+		4	6	9	12	17	22	27	32	37	42	47
1400+		2	3	5	6	7	9	10	11	12	13	14
1650+		1	1	2	2	3	3	4	5	5	6	7

WALPOLE (NORTH), MANJIMUP (EAST)

MAXIMUM DAILY TEMPERATURE (°C)

FEB. - JUNE	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+	42+
JULY - JAN.	6+	9+	12+	15+	18+	21+	24+	27+	30+	33+	36+	39+
S.D.I.	Evapotranspiration (ET) in tenths of mm per day											
0	9	13	17	21	27	33	39	45	51	57	63	69
250+	3	7	11	15	20	26	32	38	44	50	56	62
500+		2	6	10	15	21	27	33	39	45	51	57
1400+		1	3	5	7	8	10	11	13	14	15	16
1650+			1	2	3	3	4	4	5	5	6	7

APPENDIX II: Monthly record sheet for calculating the S.D.I.

SOIL DRYNESS INDEX FOR FIRE CONTROL

Monthly Record Sheet

Forest Type .... District .... Month .... 19 ....

	Effective Rainfall (EFF) EFF + Rain mm x 10 - I - FR					Determine Soil Dryness Index (A.M.) morning and (P.M.) afternoon			
Date	Rain mm	Rain mm x 10	I	FR	EFF	Max. Temp °C	A.M.	ET	P.M.
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									
26									
27									
28									
29									
30									
31									

N.B. (1) Today's A.M. Soil Dryness Index = Previous Day's P.M. S.D.I. - EFF

If negative, A.M. = 0

(2) Today's P.M. Soil Dryness Index = A.M. + ET

(3) Flash Runoff (FR) is negligable in undisturbed Forest areas so can be set at 0.