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Equations for the forest fire behaviour tables for Western Australia

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ABSTRACT

Sneeuwjagt and Peet's forest fire behaviour tables for Western Australia are used to predict fire behaviour for forest types that are common throughout the south-west of the State. This work expresses the data from the tables in the form of equations; bounds are provided for the original research data and for the range of conditions to which the tables have been extrapolated for practical application. A new structure is presented for the methodology of the system to clarify and simplify its use. The equations and the prediction methodology presented provide a succinct and modular system that can be applied to automate the process of predicting fire danger or fire behaviour using a computer.

INTRODUCTION

The forest fire behaviour tables for Western Australia (Sneeuwjagt and Peet 1985) are used throughout the south-west of the State for forecasting forest fire danger and as a guide to predicting forest fire behaviour. The tables provide for predictions of fuel characteristics, and fire behaviour characteristics for the fuel types that occur in forest associations formed by pure and mixed stands of the six major tree species: these are, jarrah (*Eucalyptus marginata* Sm.); marri (*E. calophylla* R.Br.); karri (*E. diversicolor* F. Muell.); wandoo (*E. wandoo* Blakely); radiata pine (*Pinus radiata* D. Don.); and maritime pine (*P. pinaster* Ait.). The tables aim to provide for predictions of: weather conditions, such as daily maximum temperature and minimum relative humidity; total and available fuel quantities; fuel flammability as indicated by fuel moisture; fire danger indices for standard fuels; forward rates of fire spread for given conditions of fuels, weather and topography; scorch heights; indices to support the planning of prescribed burns such as hours of burning time available; and indices to support fire suppression, such as fire fighting resources required.

The tables were derived empirically from fuel, weather and fire behaviour characteristics measured for experimental fires that were conducted in the field. Test fire data were also supplemented with reliable wildfire data to produce the tables (Burrows and Sneeuwjagt 1989). In general, the tables were derived by eye fitting curves or using least-squares procedures (Peet 1971a).

The tables began as a simple, formal, scientific approach to forecasting fire danger, but over the past 25 years they have evolved into a detailed, complex system to support many aspects of fire management (see, for example: Peet 1965; Harris 1968; Hatch 1969; Beggs 1972, 1973, 1976; Sneeuwjagt and Peet 1979). The tables have been updated, and prediction facilities have been expanded, to keep pace with increasing demands and expectations of fire management (Burrows and Sneeuwjagt 1989). As a result of continuing updates and expansions, the tabular format and structure of the prediction system is somewhat cumbersome, slow and confusing to use. This situation will worsen as future research and developments continue to broaden the scope and scale of the prediction system.

The tables cannot be compared readily with other existing fire behaviour prediction systems because they are cumbersome to use, and present discrete rather than continuous predictive functions. Although these problems are largely overcome by computerizing the system, equations that have been formulated to give continuous predictions for continuous inputs would have the added advantage of ease of comparison with other systems. This work presents equations that have been derived to fit the data within each of the tables.

The primary objective of this work has been to fit equations for the tables that are used to predict fire danger and fire behaviour characteristics. The tables that are used locally to predict required dispatch levels, vehicle travel times and fireline production rates in the event of a wildfire, are not dealt with here.

During the process of reviewing the prediction system, which was necessary to derive these equations, it became apparent that the methodology of the prediction system changes with the required accuracy of the predictions. In several cases in Sneeuwjagt and Peet (1985), alternative methods are provided to predict a given parameter, although the circumstances that govern the application of one table over another are not detailed. For example, litter weights can be predicted from the number of annual leaf falls since the last fire (tables 7.1.1., 7.1.2. or 7.1.3.) or litter weight can be predicted from litter depth (table 7.2.1.). In this paper a new structure is presented for the methodology of the prediction system and application procedures are detailed for each table and equation.

The data expressed in the tables given by Sneeuwjagt and Peet (1985) include extrapolations from measured data. These extrapolations are necessary to generate predictions for all situations that are encountered operationally. To date, the limits of the original data have not been available readily because only a proportion of the research work, which is encompassed within the tables, has been published. In conjunction with the equations, the application limits and the bounds of the original research data are presented in an attempt to identify the range of inputs for which predictions should be most reliable, and the limits to which extrapolations have been made.

The accuracy of each equation, with respect to its ability to predict the data in a table, is presented. Predictions using the functions derived describe the table data, but extrapolating the equations beyond their application limits would be completely inappropriate. The equations were designed to predict the data in the tables as accurately as possible and no reference to the accuracy of the tables themselves is intended.

METHODS

Data were taken directly from the tables that were developed by Sneeuwjagt and Peet (1985). Where row or column values represented a range of inputs, mid-point values were used. Where two input options were presented within a table, such that one input may be used in lieu of another, equations were derived from the input that was used most often throughout the tables. An equation was fitted to measured scale displacements for the nomogram used to predict surface moisture content during the day (which is table 4.3.7 in Sneeuwjagt and Peet 1985), and data were taken and used to fit an equation to the graphs used to predict maximum temperature (8.1).

The 1985 edition of the tables (Sneeuwjagt and Peet 1985) was the result of a revision of the 1979 edition (Sneeuwjagt and Peet 1979). Revisions to three of the tables, namely those used to predict the overnight change in surface moisture content in the absence of rain (4.3.2), the basic drying unit (4.3.3), and the day drying correction (4.3.4), were not based on additional data but were made by interpolating and extrapolating ocularly from graphs of the table data (van Didden[1], personal communication). Equations in this paper were fitted to data in the 1979 edition of these tables so that interpolations and extrapolations are mathematically based.

Application bounds for the equations were all extracted directly from the 1985 edition of the tables. Original authors, researchers, internal reports, and publications were consulted to provide bounds for the original data.

Equations describing the relationships between table inputs and predicted outputs were derived using SAS (SAS Institute Inc. 1985). While a few of these relationships are linear, most are not, and non-linear least-squares procedures were used to establish the latter relationships.

A single equation was derived successfully for all tables that depict relationships using two predictor variables, with two exceptions: a single relationship could not be derived for jarrah and karri fuel quantity correction factors (tables 6.8 and 6.13 respectively). Instead, four equations were developed to describe the data within each of these tables.

Equations were not derived for the data of five of the tables. The tables used to assign wind ratios (6.5), scrub flammability factors (7.4.2) and scrub structural types from height density profiles (7.4.3) require qualitative or subjective inputs for which equations are inappropriate. Although equations relating wind ratio (see table 6.5 in Sneeuwjagt and Peet 1985) to tower height could have been fitted for each forest type and canopy, it was considerd that the coarse discrete categories depicted by Sneeuwjagt and Peet (1985) did not merit equations, especially in light of the fact that more sophisicated techniques have been developed to adjust tower wind speeds to forest wind speeds or wind speeds 2 m above open ground (see, for example, Albini and Baughman 1979; Baughman 1981; Durre and Beer 1989).

According to Peet[2] (personal communication), the data from the tables that predict daily minimum relative humidity (8.2) and dew point temperature (8.3) were not based on local research but were extracted from a weather observer's handbook such as that produced by the Bureau of Meteorology (1984). Equations for these two tables were adapted from the work of Murray (1967), Monteith (1973), and Abbott and Tabony (1985), which have been applied by others (Running *et al.* 1987; Beck and Trevitt 1989).

A SUMMARY OF THE PREDICTION SYSTEM

Two tree species dominate the forested areas of the south-west of Western Australia (WA): these are jarrah and karri. In the south-west, the northern jarrah forests are characterized by a shallow (< 20 mm) litter bed and a sparse, low (<1 m) understorey (known as scrub). The wetter karri and jarrah forests in the south are characterized by a dense, tall (sometimes exceeding 5 m) understorey, trash (suspended, dead vegetation) and a deep litter bed (Burrows and Sneeuwjagt 1989). Luke and McArthur (1978) described the northern jarrah and the southern forests as dry and wet sclerophyll forests respectively.

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[1] G.W. van Didden, Fire Protection Branch, Department of Conservation and Land Management, Como WA.

[2] G.B. Peet, Manager, Fire Protection Branch, Department of Conservation and Land Management, Como, now retired.

One of six scrub structural types (Sneeuwjagt 1971a) is assumed or referenced directly in the fire behaviour tables to define a specific fuel complex. For example, northern jarrah is commonly found in association with scrub structural type 6, and karri 3/6 represents a karri overstorey with an understorey of scrub structural type 3 or type 6. Specific fuel complexes and scrub structural types are detailed in Appendix 1.

The forest fire behaviour tables for WA have been developed using the fuel complexes of northern jarrah and karri 4/5 as the bases to predict all fuel moisture and fire behaviour characteristics. In essence, one of two fire behaviour models is used depending on whether predictions are being generated for a jarrah fuel type or a karri fuel type. A fuel type is classified herein as a jarrah type if it carries a sparse, low understorey, or as a karri type if it carries a dense understorey: northern jarrah, pines and upslope wandoo are considered to be jarrah fuel types; and karri fuel types include karri 3/6, karri 4/5, karri 1/2, karri regrowth, southern jarrah and gully wandoo.

In the WA prediction system, four parameters are considered to influence fire behaviour: these are, the moisture content of surface litter fuels; the quantity of fuel that is available for burning; the ground (1-2 m) wind speed in a forest stand; and the slope of the terrain. These four parameters are combined to predict a fire danger index based on either the northern jarrah or karri 4/5 model, according to fuel type. Surface moisture content and wind speed are first used to calculate a forward rate of headfire spread (m h^{-1}), under standard fuel and forest stand structural conditions that are typical of five-year-old jarrah or karri fuels (Burrows and Sneeuwjagt 1989). This spread rate, which is known as a fire danger index, is then corrected to allow for cases where fuel weight, forest stand structure or slope differ from the standard.

The input parameters that are required to derive a fire danger index can be obtained directly or indirectly from measurements conducted in the field, as they were for experimental fires. However, with the exception of terrain slope, which can be obtained from topographic maps, these parameters are not available or measured readily: for example, an available fuel quantity can only be obtained by measuring pre- and post-fire fuel loads; and although ground wind speeds and surface litter moisture contents can be measured directly to predict fire behaviour for prescribed burns, such measurements are not generally possible for wildfires. To overcome these problems, table facilities have been developed to predict these parameters.

A prediction sub-system is used to derive an available fuel quantity. The product of the total litter quantity and the available fuel factor is the available litter weight (Sneeuwjagt 1986). An available fuel factor represents the fraction of the litter bed that has a moisture content below the moisture content of extinction, which is the litter moisture content at which a fire cannot sustain combustion (approximately 25 and 30 per cent for eucalypt forests and pine plantations respectively).

Other tables in the available fuel quantity prediction sub-system include those used to estimate available scrub and trash fuels. Available scrub and trash quantities are derived as a function of scrub structural type and fuel dryness. Available scrub, trash and litter weights are added to yield a total available fuel quantity for a given fuel complex.

Several tables are used to predict litter fuel moisture contents and these constitute another prediction sub-system. The influence of seasonal and diurnal drying trends on dead fuel moisture contents are considered since moisture contents on any given day are derived as a function of those on the previous day. Two models provide the basis of litter moisture content predictions: surface moisture contents are based on the northern jarrah model, and profile moisture contents are based on the karri 4/5 model (see the next section for definitions of surface and profile moisture contents). The predicted surface moisture content for northern jarrah litter and profile moisture content for karri 4/5 litter are then adjusted to estimate surface and profile litter moisture contents for other fuel complexes. Using the moisture content prediction sub-system, litter moisture contents for all fuel complexes are maintained on a daily basis, in a bookkeeping fashion.

Table facilities have been used to estimate ground wind speeds in a forest stand, given a wind speed measured at, or forecast for, a fire tower that is located at a particular height above the stand canopy. A wind ratio is used to relate an unimpeded, tower wind speed to a forest wind speed 1-2 m above the ground. The overstorey, understorey and topographic location of a forest stand are considered for their ability to reduce an open tower wind speed, and wind ratios increase concomitantly with the frictional influence of a given stand (Burrows (1984) discusses the wind ratio concept in detail).

A surface litter moisture content must be derived using the moisture content prediction sub-system before a fire danger index can be calculated. As a result of this calculation sequence, the moisture content prediction sub-system is discussed first and the derivation of fire danger indices is detailed subsequently. The following steps are carried out sequentially to predict a forward rate of headfire spread for non-standard conditions: a fire danger index is calculated; an available fuel quantity is determined; a fuel quantity correction factor is derived; and finally the index is corrected for non-standard fuels and slope giving the spread rate for non-standard conditions. These steps are presented according to the sequence in which correction factors are calculated and applied.

In addition to fire spread rates, scorch heights and the amount of time that is available for prescribed burning can be predicted. These predictions are used primarily to support the planning of prescribed burns although they also provide valuable information during wildfires. Surface moisture contents, available fuel quantities and forward rates of fire spread are required to predict these fire behaviour characteristics, and they are calculated and discussed last.

Descriptions of all variables used are given in Appendix 2, and the tables in Sneeuwjagt and Peet (1985) to which the equations relate are given in Table 6.

MOISTURE CONTENTS

Surface and profile litter moisture contents, which apply to forest conditions of 50 per cent mottled shade, are predicted and recorded in a bookkeeping fashion daily. All moisture contents are expressed as a percentage of oven-dry fuel weight. 'Surface' refers to the top 10 mm of a litter bed, whereas 'profile' refers to the entire litter bed above the mineral soil, the total depth of which exceeds 20 mm. The moisture contents of these litter fuels are required for a number of reasons: surface moisture content indicates the flammability of fine, dead fuels (Underwood *et al.* 1988) and so it is used to predict a fire danger index and a rate of spread; surface and profile moisture contents are used to estimate an available litter fuel quantity, which is required to predict a rate of spread; and moisture contents between 0800 and 1700 hours can be calculated to support predictions of fire behaviour throughout the day.

The moisture content prediction sub-system has been developed to emulate major changes in moisture contents throughout the day, and Figure 1 depicts these changes for surface litter moisture contents. The timing of the daily minimum surface and profile litter moisture contents is a function of the timing of the daily maximum temperature and minimum relative humidity (Luke and McArthur 1978). As fuels dry throughout the day, moisture contents decrease from a daily maximum (at 0800 hours) to a daily minimum (at approximately 1500 hours). The extent of fuel drying is derived as a function of the initial (maximum) surface and profile moisture contents, and the fuel drying potential presented by the weather conditions of a given day.

The relative drying potential for a given day, which is expressed in the basic drying unit, is estimated from the expected daily maximum temperature and minimum relative humidity. Initial moisture contents and the basic drying unit are combined in the day drying correction, which is applied to reduce a daily maximum to a daily minimum moisture content (Fig. 1).

In the late afternoon, surface litter fuels generally absorb moisture as temperature decreases and relative humidity increases. In the absence of rain, surface litter fuel moisture contents increase from an afternoon minimum and reach a maximum early in the morning the next day, largely as a result of increased relative humidities (Luke and McArthur 1978). This overnight change in moisture content, known as the night wetting correction, is added to the minimum surface moisture content of the previous day to derive a maximum surface moisture content for the next day. Surface litter fuels continue to dry overnight occasionally when fuels are relatively moist or when overnight relative humidities are low, and so the night wetting correction may be positive or negative.

In the absence of rain, the overnight change in litter profile moisture content is normally very small (Sneeuwjagt[3], personal communication), and has therefore been set to zero. The minimum (1500 hours) profile

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[3] R.J. Sneeuwjagt, Manager, Fire Protection Branch, Department of Conservation and Land Management, Como WA.

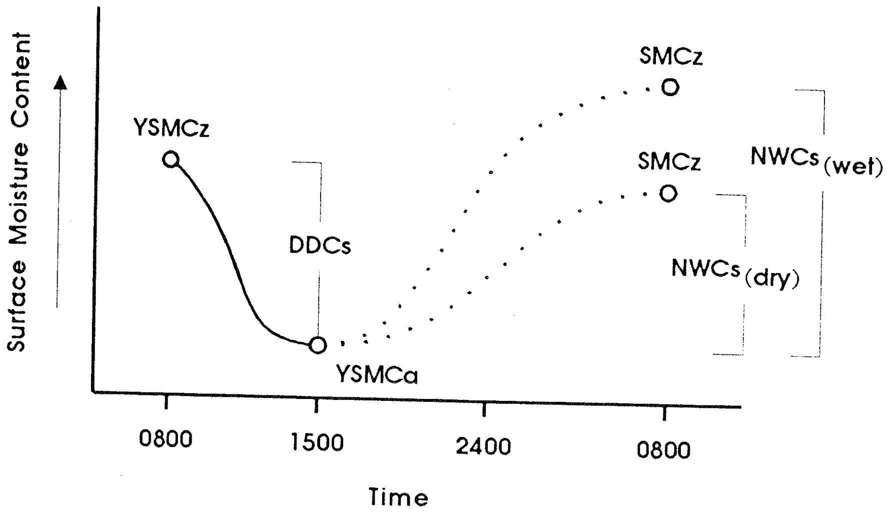

Figure 1. A diagrammatic representation of the major changes in diurnal surface litter moisture content that are emulated by the moisture content prediction sub-system (YSMCa/z is yesterday's minimum/maximum surface moisture content; DDCs is the day drying correction; SMCz is today's maximum surface moisture content; and NWCs is the night wetting correction in the absence of rain (dry) or in the event of rain (wet)).

moisture content on a given day is used to represent the maximum (0800 hours) on the following day.

The occurrence of rain, measured at 0800 hours for the previous 24-hour period, is reflected in the 0800 maximum surface and profile litter moisture contents, and so rainfall is considered to be an overnight wetting factor. McCaw[4] (personal communication) has identified this as a weakness in the current prediction system: if rainfall occurs between 0800 and 1500 hours the increased moisture content is not reflected in the minimum moisture content for that day, but in the 0800 maximum for the subsequent day.

Daily moisture content predictions, for a given fire season, are usually initiated early in September (spring) when fuels begin to dry. Oven drying procedures should be used to initiate the minimum (1500 hours) surface and profile moisture contents from field samples for the first day of the recording season. When oven drying facilities are unavailable, minimum surface and profile moisture contents are initiated at 60 and 100 per cent respectively, when the litter bed is saturated after a rainfall exceeding 10 mm. Values should be field checked by way of a moisture meter, such as the Marconi Moisture Meter, as soon as the predicted surface moisture content drops below 30 per cent.

Maximum Moisture Content

Maximum moisture contents (0800 hours) are calculated for the surface litter of northern jarrah and the litter profile of karri 4/5. These maxima are a function of the minima on the previous day and an overnight wetting correction. Daily moisture content accounting begins by determining the wetting correction, which is a function of the amount of rain in the past 24-hour period (measured at 0800 hours) or, in the absence of rain, the influence of overnight relative humidity on the wetting of fuels.

Night Wetting Corrections for Surface Litter

In the event of rain, the night wetting correction to yesterday's minimum surface moisture content for northern jarrah litter, $NWCs_{(wet)}$, is determined as a function of the amount of rainfall and yesterday's minimum surface moisture content:

$$NWCs_{(wet)} = A / (1 + B\ RAIN^{X}) \qquad [1]$$

where

$A = 121.42 - 94.27 / (1 + 107.55 \exp(-0.037\ YSMCa_{(NJ)}))$

$B = 101.71 / (1 + 17.13 \exp(-0.017\ YSMCa_{(NJ)}))$

$X = -0.84 - 0.62 / (1 + 1087.88 \exp(-0.053\ YSMCa_{(NJ)}))$

$YSMCa_{(NJ)}$ is yesterday's minimum surface moisture content for a given fuel type, which in this case is northern jarrah (NJ)[a] RAIN is the amount of rain (mm), recorded at 0800 hours, for the past 24 hour period

Application Bounds	Original Data[1b]
$5. < YSMCa_{(NJ)} < 200.$	$6. < YSMCa_{(NJ)} < 100.$
$0.1 < RAIN < 65.$	$0.1 < RAIN < 50.$
	$5. < NWCs_{(wet)} < 100.$

TABLE 1

Sources of the original data bounds, which are coded numerically by superscript, for the forest fire behaviour tables for Western Australia.

SUPERSCRIPT	SOURCE
1	R.J. Sneeuwjagt (personal communication)
2	G.W. van Didden (personal communication)
3	Underwood *et al.* (1985)
4	Peet (1971a)
5	N.D. Burrows (personal communication)
6	Peet *et al.* (1971)
7	Peet (1971b)
8	Hatch (1964)
9	Dept. of CALM (1985)
10	Sneeuwjagt (1973)
11	Burrows (1980)
12	Peet (1963)

In the absence of rain, the overnight change in the moisture content of jarrah surface litter, $NWCs_{(dry)}$, is a function of yesterday's minimum surface moisture content, and the intensity and duration of overnight relative humidities, which is reflected in the overnight relative humidity count as detailed by Peet *et al.* (1971):

$$NWCs_{(dry)} = Y\ ORHC + Z \qquad [2]$$

where

$Y = 0.29 / (1 + 1.34 \exp(-0.019\ YSMCa_{(NJ)}))$

$Z = 51.61 - 367.12(0.29/(1 + 1.34 \exp(-0.019\ YSMCa_{(NJ)})))$

ORHC is the overnight relative humidity count that represents the area enclosed by the overnight thermohygrograph trace, to 0800 hours, that exceeds the 70 per cent relative humidity level. The squares below the trace line are counted and one unit is equivalent to 2 per cent relative humidity over a two-hour duration.

Application Bounds	Original Data[1]
$0. < YSMCa_{(NJ)} < 160.$	$6. < YSMCa_{(NJ)} < 100.$
$0. < ORHC < 101.$	$0. < ORHC < 110.$
	$-35. < NWCs_{(dry)} < 15.$

Today's predicted maximum surface moisture content for northern jarrah ($SMCz_{(NJ)}$) is then calculated from:

$$SMCz_{(NJ)} = YSMCa_{(NJ)} + NWCs_{(wet/dry)} \qquad [3]$$

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[4] W.L. McCaw, Senior Research Scientist, Science and Information Division, Department of Conservation and Land Management, Manjimup WA.

[a] Variable subscripts that contain capital letters within parentheses are abbreviated names of fuel types or scrub structural types, and these are detailed in Appendix 1.

[b] Numerical superscripts refer to the source of the bounds of the original data and these sources are summarized in Table 1.

Night Wetting Corrections for the Litter Profile

Today's maximum profile moisture content for karri 4/5 ($PMCz_{(K45)}$) is derived by modifying Equations 1 and 3. In the event of rain, Equation 1 is used to predict the night wetting correction by replacing $NWCs_{(wet)}$ with $NWCp_{(wet)}$. The $PMCz_{(K45)}$ is calculated by replacing $YSMCa_{(NJ)}$, in Equation 1 and 3, with yesterday's minimum profile moisture content for karri 4/5, $YPMCa_{(K45)}$, and substituting $PMCz_{(K45)}$ for $SMCz_{(NJ)}$ in Equation 3.

On rainless nights, today's maximum profile moisture content for karri 4/5 is assumed to be equal to yesterday's minimum profile moisture content. Hence, $NWCp_{(dry)}$ is equal to zero and Equation 2 is not used.

Minimum Moisture Content

A day drying correction is applied to the predicted daily maximum surface and profile litter moisture contents to reduce these maxima to daily minima. Litter fuel drying trends are expressed in the day drying correction as a function of initial (0800 maximum) moisture content and the basic drying unit. Maximum moisture contents having been obtained via Equations 1-3, the basic drying unit must then be determined before a day drying correction can be calculated.

The basic drying unit (BDU) is a relative index that is used to reflect the effects of day-time temperature and relative humidity on the drying of surface litter and the litter profile fuels during the day. The BDU is determined from actual or forecast values of daily minimum relative humidity and maximum temperature.

Maximum Temperature and Minimum Relative Humidity

If forecast values for a particular location are unavailable for minimum relative humidity and maximum temperature, they can be predicted from actual wet and dry bulb temperatures and the time at which they were measured. If clear skies prevail, Equation 4 can be used to predict a maximum temperature, Tz (°C), which is assumed to occur at 1500 hours, from measurements taken between 1000 and 1400 hours, and a 1500 hour maximum can be assumed until 1700 hours:

$$Tz = Tt\,8/t + (Tt - (Tt\,8/t))\,/\,SIN(\pi/2\ 0.92\ (t - 8)\,/\,7.) \qquad [4]$$

where

Tt is the temperature (°C) at time t

t is the time (decimal hours) at which temperature has been measured

Application Bounds	Original Data[2]
$10. < t < 14.$	$t = 10, 12$ and 15
$15. < Tt < 39.$	$14. < Tt < 39.$
$Tt < Tz$	$17. < Tz < 39.$

The equation to predict minimum relative humidity, RHa (%), has been derived by adapting the work of Murray (1967), Monteith (1973) and Abbott and Tabony (1985):

$$RHa = 100\,(273.16 + Tz)\,/\,(273.16 + Tdew)\ \exp\{17.38\,(Tdew/(239.0 + Tdew) - Tz/(239.0 + Tz))\} \qquad [5]$$

Application Bounds

$15. < Tz < 40.$

$-4. < Tdew < 24.$

where

Tdew is the dew point temperature (°C)

The dew point temperature required in Equation 5, can be calculated from wet bulb (Tw) (measured with an Assmann-type forced ventilation psychrometer) and dry bulb (T) temperatures (°C) at any time (t) via Equation 6 (adapted from Murray (1967), Sargent (1980) and Abbott and Tabony (1985)):

$$Tdew = 239.0\,/\,(1.\,/\,(\ln(VP\,/\,6.107)\,/\,17.38) - 1.) \qquad [6]$$

where

$$VP = 6.107\exp(17.38\,Tw\,/\,(Tw + 239.0)) - 0.667\,(T - Tw)$$

Application Bounds

$12. < T < 36.$

$6. < Tw < 36.$

$T > Tw$

$15. < T - Tw$

Basic Drying Unit

Given a maximum temperature and a minimum relative humidity, the basic drying unit can be calculated:

$$BDU = C\,/\,(1 + D\exp(E\,(100 - RHa))) \qquad [7]$$

where

$C = 57.29\,/\,(1 + 1.93\exp(-0.042\,Tz))$

$D = 42.77\,/\,(Tz - 5.80)$

$E = -0.016\,Tz\,/\,(Tz - 5.27)$

Application Bounds	Original Data[1]
$8. < Tz < 48.$	$15. < Tz < 40.$
$0. < RHa < 90.$	$10. < RHa < 70.$
	$8. < BDU < 35.$

Day Drying Corrections for Northern Jarrah Surface Litter

Having determined the BDU, the day drying correction for the surface litter of northern jarrah, $DDCs_{(NJ)}$, is calculated:

$$DDCs_{(NJ)} = F\,BDU + G + 10 \qquad [8]$$

where

$$F = (SMCz_{(NJ)} - 103.79)/((SMCz_{(NJ)} - 103.79)^2 - 12643.93)\ 12.81 - 0.65$$

$$G = (SMCz_{(NJ)} - 99.70)\,/((SMCz_{(NJ)} - 99.70)^2 - 25199.32)\ 3570.12 - 23.26$$

Application Bounds	Original Data[1]
$6. < BDU < 35.$	$8. < BDU < 35.$
$6. < SMCz_{(NJ)} < 200.$	$10. < SMCz_{(NJ)} < 150.$
	$-35. < DDCs_{(NJ)} < 3.$

and applied to determine today's minimum surface moisture content for northern jarrah, $SMCa_{(NJ)}$:

$$SMCa_{(NJ)} = SMCz_{(NJ)} + DDCs_{(NJ)} \qquad [9]$$

Day Drying Corrections for the Litter Profile of Karri 4/5

The day drying correction for the litter profile of karri 4/5, $DDCp_{(K45)}$, is calculated:

$$DDCp_{(K45)} = H\ BDU + I \qquad [10]$$

where

$$H = (PMCz_{(K45)} - 112.15) / ((PMCz_{(K45)} - 112.15)^2 - 21835.42)\ 40.96 - 0.46$$

$$I = (PMCz_{(K45)} - 140.78) / ((PMCz_{(K45)} - 140.78)^2 - 24819.47)\ 298.78$$

Application Bounds	Original Data[1]
$11. < PMCz_{(K45)} < 200.$	$12. < PMCz_{(K45)} < 160.$
$1. < BDU < 35.$	$8. < BDU < 35.$
$-21. < DDCp_{(K45)} < 4.$	$-15. < DDCp_{(K45)} < 2.$

and applied to predict today's minimum profile moisture content for karri 4/5, $PMCa_{(K45)}$:

$$PMCa_{(K45)} = PMCz_{(K45)} + DDCp_{(K45)} \qquad [11]$$

Moisture Contents of Non-standard Litter Fuels

Today's minimum or maximum surface litter moisture content for eucalypt forests other than northern jarrah can be calculated directly from $SMCa/z_{(NJ)}$ using Equations 12-16:

$$SMCa/z_{(SJ)} = 1.12\ SMCa/z_{(NJ)} \qquad [12]$$

$$SMCa/z_{(K36)} = 1.20\ SMCa/z_{(NJ)} + 0.90 \qquad [13]$$

$$SMCa/z_{(K45)} = 1.53\ SMCa/z_{(NJ)} - 0.10 \qquad [14]$$

$$SMCa/z_{(K12)} = 1.61\ SMCa/z_{(NJ)} + 1.70 \qquad [15]$$

$$SMCa/z_{(OS)} = 0.66\ SMCa/z_{(NJ)} + 1.66 \qquad [16]$$

Application Bounds	Original Data[1]
$4. < SMC_{(NJ)} < 50.$	$4. < SMC_{(NJ)} < 150.$
$5. < SMC_{(SJ)} < 56.$	$5. < SMC_{(SJ)} < 150.$
$6. < SMC_{(K36)} < 60.$	$6. < SMC_{(K36)} < 150.$
$7. < SMC_{(K45)} < 74.$	$7. < SMC_{(K45)} < 150.$
$9. < SMC_{(K12)} < 80.$	$9. < SMC_{(K12)} < 160.$
$4. < SMC_{(OS)} < 36.$	$4. < SMC_{(OS)} < 80.$

or by using Equations 17-20 for pine fuels:

$$SMCa/z_{(PP)} = 0.74\ SMCa/z_{(NJ)} + 1.51 \qquad [17]$$

$$AMCa/z_{(PP)} = 0.66\ SMCa/z_{(NJ)} + 1.40 \qquad [18]$$

$$SMCa/z_{(PR)} = 0.86\ SMCa/z_{(NJ)} + 1.02 \qquad [19]$$

$$AMCa/z_{(PR)} = 0.77\ SMCa/z_{(NJ)} + 2.29 \qquad [20]$$

where

AMCa/z refers to the minimum/maximum moisture content of fresh, aerated needles on branches generated from a thinning or pruning operation.

Application Bounds	Original Data[1]
$5. < SMC_{(NJ)} < 80.$	$5. < SMC_{(NJ)} < 100.$
$5. < SMC_{(PP)} < 63.$	$5. < SMC_{(PP)} < 100.$
$4. < AMC_{(PP)} < 56.$	$4. < AMC_{(PP)} < 60.$
$5. < SMC_{(PR)} < 70.$	$5. < SMC_{(PR)} < 120.$
$5. < AMC_{(PR)} < 64.$	$5. < AMC_{(PR)} < 60.$

Today's minimum or maximum profile moisture content for fuel types other than karri 4/5 can be calculated directly from $PMCa/z_{(K45)}$ using Equations 21-25:

$$PMCa/z_{(SJ)} = 0.75\ PMCa/z_{(K45)} + 2.19 \qquad [21]$$

$$PMCa/z_{(K36)} = 0.81\ PMCa/z_{(K45)} + 2.98 \qquad [22]$$

$$PMCa/z_{(K12)} = 1.26\ PMCa/z_{(K45)} + 2.28 \qquad [23]$$

$$PMCa/z_{(PP)} = 1.29\ PMCa/z_{(K45)} - 1.87 \qquad [24]$$

$$PMCa/z_{(PR)} = 1.26\ PMCa/z_{(K45)} + 2.95 \qquad [25]$$

Application Bounds	Original Data[1]
$11. < PMC_{(K45)} < 100.$	As applied
$10. < PMC_{(SJ)} < 80.$	
$11. < PMC_{(K36)} < 85.$	
$16. < PMC_{(K12)} < 125.$	
$13. < PMC_{(PP)} < 125.$	
$16. < PMC_{(PR)} < 125.$	

Day-time Moisture Contents

To predict fire behaviour characteristics at a given time between 0800 and 1700 hours, the surface moisture content at that time is required: there is no provision in the current tables to predict moisture contents, and therefore fire behaviour characteristics, between 1700 hours and 0800 hours the next day.

The surface moisture content for northern jarrah at any time (t) (in decimal hours), $SMC_{(NJ)}$, can be predicted using:

$$SMC_{(NJ)} = SMCz_{(NJ)} - (SMCz_{(NJ)} - SMCa_{(NJ)})\ (14.29\ t - 114.29)/\ 100. \qquad [26a]$$

$$8.0 < t < 15.0$$

$$SMC_{(NJ)} = SMCz_{(NJ)} - (SMCz_{(NJ)} - SMCa_{(NJ)})\ (14.29(30.0 - t)-114.29)/\ 100. \qquad [26b]$$

$$15.0 < t < 17.0$$

Application Bounds	Original data[1]
$6. < SMC_{(NJ)} < 30.$	Source of 26a unknown
$SMCa_{(NJ)} < SMCz_{(NJ)}$	Source of 26b unknown

If predictions are required for a fuel type other than northern jarrah, Equations 12-20 can be employed to calculate the required SMC from that of northern jarrah at time (t).

Profile moisture contents, which are used to calculate available fuel factors for non-standard fuels, are also required for diurnal fire behaviour predictions. There has been no research conducted to address this need specifically, although any one of three methods is employed to approximate the profile moisture contents for karri 4/5 at any time between 0800 and 1500 hours, $PMC_{(K45)}$: the minimum profile moisture content is assumed throughout the day; the profile moisture content at any time is extrapolated linearly from the maximum and minimum and the minimum is applied after 1500 hours; or diurnal profile moisture contents are derived using Equation 26a by substituting $PMCa/z_{(K45)}$ for $SMCa/z_{(NJ)}$ and applying the minimum after 1500 hours. If predictions are required for a fuel type other than karri 4/5, Equations 21-25 are employed.

FORWARD RATES OF HEADFIRE SPREAD

Using the WA Fire Behaviour computer system (van Didden 1985; Beck 1987, 1988), fire danger indices and headfire spread rates are predicted for a number of fuel, stand and topographic conditions that are typical of a given locality, using relevant weather forecasts. This information is applied operationally, for example, to establish standby suppression crew requirements and aerial detection schedules (Burrows and Sneeuwjagt 1989).

Fire Danger Indices

Surface moisture content and wind speed are used to calculate a fire danger index (FDI) for jarrah and karri types by applying one of two models based on a standard northern jarrah (NJs) and karri 4/5 (Ks) fuel complex respectively. A fire danger index actually represents a forward rate of headfire spread ($\mathrm{m\ h^{-1}}$) on level to undulating terrain given the following: stand conditions of northern jarrah and karri 4/5 effecting a 5:1 and 7:1 wind ratio respectively, on an open wind speed measured at (or forecasted for) a height of 15 m above the stand canopy; and an available fuel quantity of 7.5-8.5 and 15.0-19.0 $\mathrm{t\ ha^{1}}$ applying for northern jarrah and karri 4/5 respectively. The standard is intended to reflect the fuel quantity available in five-year-old fuels, which constitute those fuels that have accumulated during a five-year period since the last fire.

Inputs of surface moisture content and wind speed must be estimated for the time at which predictions are required. A fire danger index can be predicted at any time of the day, given inputs that are specific temporally. Planning activities are often carried out for worst case situations to maximize preparedness, and so a minimum SMC and an afternoon wind speed are often applied to predict a maximum FDI for the day.

A fire danger index for standard northern jarrah is calculated from:

$$FDI_{(NJs)} = Yj + Aj \exp(WIND_{fg}\ Nj) \qquad [27]$$

where

$Yj = 21.37 - 3.42\ SMC + 0.085\ SMC^{2}$

$Aj = 48.09\ SMC \exp(-0.60\ SMC) + 11.90$

$Nj = -0.0096\ SMC^{1.05} + 0.44$

$WIND_{fg}$ is the wind speed ($\mathrm{km\ h^{-1}}$) at a height of 1-2 m above the ground in the forest.

Application Bounds

$3. < SMC < 27.$

$0. < WIND_{fg} < 11.2$

and for standard karri:

$$FDI_{(Ks)} = Yk + Ak \exp(WIND_{fg}\ Nk) \qquad [28]$$

where

$Yk = 4.88 - 263.78\ SMC^{-1.80}$

$Ak = 163.40\ SMC^{-1.18}$

$Nk = -0.0059\ SMC + 0.54$

Application Bounds

$3. < SMC < 25.$

$0. < WIND_{fg} < 7.2$

The wind speed required in Equation 27 or 28 can be measured directly, although an open wind speed provided by weather forecasts and tower measurements must be reduced by a wind ratio factor. Standard wind ratio factors (5 for northern jarrah and 7 for karri 4/5), which are assigned according to wind ratio, apply to predict an FDI. The appropriate wind ratio factor for non-standard conditions, which is selected using Table 2 for jarrah types and Table 3 for karri types, should be used to predict a ground forest wind speed:

$$WIND_{fg} = WIND_{t} / WIND_{rf} \qquad [29]$$

where

$WIND_{t}$ is the wind speed ($\mathrm{km\ h^{-1}}$) that is measured at a fire tower at some height above the forest canopy as indicated by a selected wind ratio factor

$WIND_{rf}$ is the wind ratio factor that is assigned according to wind ratio.

To predict a forward rate of headfire spread, a FDI must be corrected if conditions of available fuel quantity or terrain slope, or both, differ from those otherwise assumed. For non-standard available fuel quantities, a FDI is multiplied by a fuel quantity correction factor to generate a forward rate of headfire spread on level to undulating terrain. This fuel corrected rate of spread is then adjusted for slope if topography is neither level nor undulating.

The original data, which were used to establish the FDI relationships and the fuel quantity correction factors, came from experimental fires that sustained combustion. The vast majority of these fires were conducted on level to undulating terrain, since this is the norm for the topography of the south-west of WA. Experimental fires over steep terrain, which might have had a significant impact on fire behaviour, were analysed separately. According to Sneeuwjagt (personal communication), these fires confirmed the slope corrections determined by McArthur (1967).

TABLE 2

Wind ratios (wind ratio factors) for jarrah fuel types (after Sneeuwjagt and Peet 1985).

FOREST TYPE AND CANOPY	WIND RATIOS TOWER HEIGHT ABOVE CANOPY (m)					
	0		15		30	
jarrah-wandoo						
60 per cent canopy						
Ridge	3:1	(3)	4:1	(4)	5:1	(5)
Lower Slopes	4:1	(4)	5:1	(5)	6:1	(6)
30 per cent canopy						
Ridge	2:1	(2)	3:1	(3)	4:1	(4)
Lower Slopes	3:1	(3)	4:1	(4)	5:1	(5)
Flats	1:1	(1)	1:1	(1)	2:1	(2)
pine plantations						
Dense Stands	5:1	(5)	6:1	(6)	6:1	(6)
Thinned Stands	3:1	(3)	4:1	(4)	5:1	(5)

TABLE 3

Average wind ratios (wind ratio factors) for southern forest types that have been derived from the table data provided by Sneeuwjagt and Peet (1985). Tower height is approximately 15 m above the canopy and 30 m above the ground.

FOREST TYPE	AVERAGE WIND RATIO	
southern jarrah	5.5:1	(5.5)
karri 3/6	6.0:1	(6.0)
karri 4/5	7.0:1	(7.0)
karri 1/2	9.0:1	(9.0)
karri regrowth	9.0:1	(9.0)

Bounds depicting the range of fuels, weather conditions and spread rates that were experienced during experimental fires are presented in Table 4. These bounds apply to both fire danger indices and to fuel corrected rates of headfire spread.

Original data bounds are not presented for wandoo since very few experimental fires have been conducted in this fuel type. Operational burns indicate that the jarrah and karri models are adequate for upslope and gully wandoo respectively (Sneeuwjagt, personal communication). Original data bounds for experimental fires in *Pinus pinaster* and *P. radiata* have been grouped because experimental fires in these two fuel types were conducted under similar conditions, although predictive relationships for the two pine species differ.

Experimental fire data were supplemented with data obtained from wildfires such as those discussed by Underwood *et al.* (1985). The range of fuel and weather conditions that were experienced during wildfires include and exceed those experienced during experimental fires. Rate of spread extremes for wildfires that have been considered by Sneeuwjagt and Peet (1985) are also presented in Table 4.

To derive a fuel-corrected rate of headfire spread, a fuel quantity correction factor is applied to a fire danger index. A fuel quantity correction factor is calculated from an available fuel quantity and a surface litter moisture content. The latter of these inputs can be determined *via* the moisture content prediction sub-system. In the next section methods of calculating available fuel quantity are given.

Available Fuel Quantities

An available fuel quantity represents the proportion of a fuel complex that is immediately available to burn in a fire. The available fuel quantity varies as a function of the weight and the moisture condition of a fuel bed, and it is determined by adding the available proportion of litter, trash, scrub and slash fuels for a given fuel complex.

An available fuel factor is used to reduce a total litter weight to that which is available for burning. Litter moisture contents are applied to predict an available fuel factor, and total litter weights can be obtained directly from field samples or predicted from fire history and stand characteristics.

Trash and scrub fuels associated with an understorey influence fire behaviour. The available proportion of these fuel bed components, which is determined according to broad classes of fuel dryness, is added to the available litter fuel, to derive an available fuel quantity.

Pine plantations do not contain scrub or trash components but constitute primarily needle-bed fuels. Thinning and pruning operations are conducted regularly in pines, and the proportion of residual needles and branches (slash fuels) that is available for burning is included in the available fuel quantity in addition to any available litter fuel.

TABLE 4

Original data bounds for experimental fires (extreme wildfire rates of spread) in northern jarrah, karri and pines. The data from these fires were used to derive the rate of spread relationships that are depicted in the forest fire behaviour tables for Western Australia (bound sources are given parentheses and these are detailed in Table 1). Lower bounds for wildfires are unknown.

VARIABLE	NORTHERN JARRAH (1,3,4,5)	KARRI (1)	PINES (1,4,6)
Surface Litter Moisture Content SMC (%)	3.0 - 25.0	6.0 - 25.0	5.0 - 40.0
Ground (1-2m) Forest Wind Speed $WIND_{fg}$ (kph)	1.2 - 10.0	1.0 - 7.0	0.8 - 10.5
Available Fuel Quantity AFQ (t ha^{-1})	1.5 - 15.0	5.0 - 55.0	0.5 - 18.0
Forward Rate of Spread ROS (m hr^{-1})	13 - 660 (3 200)	15 - 200 (2 500)	7 - 85 (1 000)

Available Litter

In forests, the top of a litter bed is normally drier than the bottom, and a moisture gradient exists by which litter moisture content increases from the surface to the bottom of a litter bed (Ward 1971; Luke and McArthur 1978). Ward (1971) illustrated that given a surface and profile moisture content, the moisture content at any depth within the litter bed could be defined. Having quantified moisture content with depth, the proportion of the litter bed with a moisture content below that of extinction, which is known as the available fuel factor (AFF), can be estimated. The available fuel factor can range from 0, which occurs when none of the litter fuel is available, to 1.0, which occurs when the entire litter bed is available.

Shallow litter beds (< 20 mm) under an open stand canopy do not generally exhibit a significant moisture gradient and the moisture content of such a litter bed is assumed to be uniform throughout. The SMC is said to be representative of the moisture content of shallow litter beds, which are typical of northern jarrah forests. If the SMC of a shallow litter bed is below the moisture content of extinction, the entire litter bed is said to be available and an available fuel factor of 1.0 is applied.

Prescribed burning for fuel reduction in northern jarrah is carried out throughout the State forests to maintain fuel loads below 6-8 t ha^{-1} (Underwood 1988). Primarily as a result of this fuel reduction policy, which has been in effect since 1954 (Underwood *et al.* 1985), litter fuels of northern jarrah and upslope wandoo are typically less than 20 mm in depth, and hence a function to derive an available fuel factor from SMC and PMC has not been required for these fuel complexes. On the other hand, litter beds of karri types are typically in excess of 20 mm because they accumulate litter fuels rapidly, and so an available fuel factor must be determined for karri types.

For karri types, an available fuel factor (AFF) can be calculated for any time of the day using moisture contents that are time specific. The available fuel factor for the litter of karri types, which has an extinction moisture content of approximately 25 per cent, is:

$$AFF_{(K)} = 1.0 - (1.0 / (1.0 + P \exp(Q\ PMC)) + R) \qquad [30]$$

where

$P = 0.43 \exp(0.23\ SMC) + 2.0$

$Q = -0.0085\ SMC + 0.024$

$R = 0.013\ SMC - 0.43$

Application Bounds	Original Data[1]
$10. < PMC < 200.$	$10. < PMC < 150.$
$3. < SMC < 30.$	$6. < SMC < 25.$

For pine litter with an extinction moisture content of approximately 30 per cent, the available fuel factor is:

$$AFF_{(PP/PR)} = 1.0 - (1.0 / (1.0 + U \exp(V\ PMC)) + N) \qquad [31]$$

where

$U = 1.07 \exp(SMC\ 0.12)$

$V = -0.00033\ (SMC / 9.77)^{4.20} - 0.045$

$N = (1.67\ SMC / (SMC + 5.79\ )) - 1.56$

Application Bounds	Original Data[1]
$30. < PMC < 200.$	As applied
$5. < SMC < 40.$	

The total litter weight, to which an AFF is applied, is calculated next. One of two methods is used to obtain total litter weight. The first method, which employs input parameters that are obtained readily, is used to predict total litter weight, L (t ha^{-1}), from canopy cover, CC (%), and the number of annual leaf falls that have occurred since the last fire, LF. This first method is used primarily to estimate litter weights for predictions of wildfire behaviour characteristics, when detailed field survey information is unavailable:

$$L_{(NJ)} = (0.18\ CC + 11.06)\ (1. - \exp(-0.086\ LF)) \qquad [32]$$

Application Bounds	Original Data[7,8]
$1. < LF < 25.$	$1. < LF < 30.$
$20. < CC < 80.$	$10. < CC < 80.$
	$1. < L_{(NJ)} < 21.$

$$L_{(K/SJ)} = (0.43\ CC + 22.59)\ (1. - \exp(-0.085\ LF)) \qquad [33]$$

Application Bounds	Original Data[1]
$1. < LF < 25.$	$1. < LF < 25.$
$30. < CC < 100.$	$40. < CC < 75.$
	$5. < L_{(K)} < 45.$

$$L_{(W)} = (0.17\ CC + 1.74)\ (1. - \exp(-0.098\ LF)) \qquad [34]$$

Application Bounds	Original Data[1,9]
$1. < LF < 30.$	$1. < LF < 46.$
$20. < CC < 80.$	CCs are rough estimates
	$0.2 < L_{(W)} < 52.$

The second and more accurate method is used to estimate litter weights when greater accuracy is required to support prescribed burning, for example. Field measurements of litter depth, DP (mm), can be used to estimate total litter weight:

	Application Bounds	Original Data[1,9]	
$L_{(K)} = 0.64\ DP$	$0. < DP < 100.$	$10. < DP < 90.$	[35]
$L_{(M)} = 0.49\ DP$	$0. < DP < 55.$	$5. < DP < 40.$	[36]
$L_{(NJ/SJ)} = 0.53\ DP$	$0. < DP < 55.$	$5. < DP < 30.$	[37]
$L_{(PP)} = 0.47\ DP$	$0. < DP < 100.$	$5. < DP < 100.$	[38]
$L_{(PR)} = 0.39\ DP$	$0. < DP < 100.$	$5. < DP < 60.$	[39]
$L_{(W)} = 0.87\ DP$	$0. < DP < 35.$	$2. < DP < 24.$	[40]

Once the available fuel factor and the total litter weight have been determined for a given fuel type, the weight of available litter, La (t ha^{-1}), is calculated:

$$La = L\ AFF \qquad [41]$$

Available Trash

Dead tree branches and scrub debris, which are known collectively as trash, are common in karri type fuel complexes. Available trash is added to any available litter and scrub fuels to derive total available fuel. One of two trash weights is used to depict an available trash weight, and each of these is derived as a function of trash depth and density (Sneeuwjagt 1973). The amount of available trash, Tra (t ha^{-1}), is assumed equal to the total weight of trash (Trtot) when prevailing weather conditions are expected to result in intense wildfires (SMC < 6), or the weight of trash material that is less than 10 mm in diameter (Trav) is assumed for average conditions of prescribed burning and mild to moderate wildfires (SMC > 6). Trtot and Trav are given by Equations 42 and 43 respectively:

$$Trtot = (60.27 - 10.71\ Tdf)\ Tdepth + (1.0 - 0.041\ Tdf) \qquad [42]$$

$$Trav = (35.35 - 7.76\ Tdf)\ Tdepth + (0.71 - 0.38\ Tdf) \qquad [43]$$

where

Tdepth is the average depth of trash (m), which is the ceiling level that excludes irregularities caused by the occasional tall, dead, individual upright branch or scrub stem (Sneeuwjagt 1973)

Tdf is a trash density factor that is assigned a value of 0, 1 or 2 for dense, medium and sparse trash density classes respectively. Trash density ratings are assigned subjectively: dense trash is found normally in karri types that have not been burnt for 10 or more years; sparse trash is common in karri types that have not been burnt for 5-10 years, and jarrah fuels less than 10 years of age are not apt to carry a significant trash component

Applications Bounds	Original Data[10]
$0.1 < Tdepth < 1.5$	$0.2 < Tdepth < 1.6$
$0. < Tdf < 2.$	$0. < Tdf < 2.$
	$8.0 < Trtot < 98.$
	$3.0 < Trav < 59.$

Available Scrub

Sneeuwjagt (1971a, 1971b, 1973) described six scrub structural types and presented techniques for measuring scrub structure and quantity. Using these field measurement techniques, a height-density profile for a given scrub structural type is assigned (Fig. 2). Scrub weights are estimated from shrub density profiles using the relevant expected height of fuel consumption.

One of three component weights can be assumed to depict an available scrub weight: a total scrub biomass that includes the weight of all branches and foliage is assumed when conditions are expected to result in a high intensity wildfire; a total foliage weight is assumed when conditions are expected to result in a fire of moderate intensity; and the weight of low foliage (< 1.5 m) is assumed when conditions are expected to result in a fire of low intensity. Component weights are determined as a function of scrub density and average scrub top height, Sht (m), and a fire intensity factor, If, is used to identify the applicable scrub weight, SWT (t ha^{-1}): an If of 0, 1 or 2 is assigned for fires that are expected to burn with a high, moderate or low intensity thereby consuming a total scrub, total foliage or partial foliage component respectively:

$$SWT_{(S1)} = (1-If^{0.36}/1.30)(41.80/(1+1117.27\ \exp(-1.44\ Sht)))(1-Sdf^{1.07}/\ 8.84) \qquad [44]$$

$$SWT_{(S2)} = (1-If^{0.25}/1.26)(54.96/(1+\ 48.82\ \exp(-0.86\ Sht)))(1-Sdf^{0.93}/\ 8.36) \qquad [45]$$

$$SWT_{(S3)} = (1-If^{0.36}/1.52)(23.51/(1+\ 19.11\ \exp(-1.25\ Sht)))(1-Sdf^{0.80}/\ 3.34) \qquad [46]$$

$$SWT_{(S4)} = (1 - If^{0.23}/1.24)\ (5.19\ \exp(0.33\ Sht))\ (1 - Sdf^{0.84}\ /3.87) \qquad [47]$$

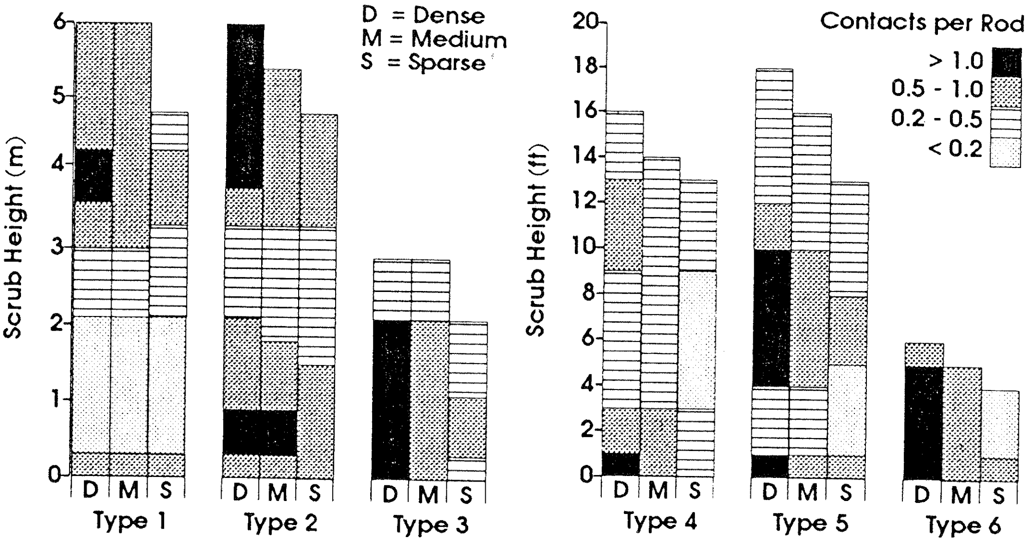

Figure 2. Height-density profiles for six standard structural types (reproduced from Sneeuwjagt and Peet 1985).

$$\mathrm{SWT}_{(S5)} = (1 - \mathrm{If}^{0.19}/1.23)\,(3.10 \exp(0.44\ \mathrm{Sht}))\,(1 - \mathrm{Sdf}^{1.06}/5.08) \qquad [48]$$

$$\mathrm{SWT}_{(S6)} = (1 - \mathrm{If}^{0.58}/2.53)\,(1.29 \exp(1.12\ \mathrm{Sht}))\,(1 - \mathrm{Sdf}^{0.86}/4.46) \qquad [49]$$

where

Sdf is a scrub density factor that is assigned a value of 0, 1 or 2 for dense, medium and sparse scrub density classes, respectively.

	Application Bounds					Original Data[1]				
S1	5.0	<	Sht	<	7.0	4.5	<	Sht	<	7.0
S2	5.0	<	Sht	<	7.0	4.5	<	Sht	<	7.0
S3	1.5	<	Sht	<	3.0	1.3	<	Sht	<	3.5
S4	3.5	<	Sht	<	5.5	3.0	<	Sht	<	6.0
S5	3.5	<	Sht	<	5.5	3.0	<	Sht	<	6.0
S6	0.6	<	Sht	<	1.5	0.5	<	Sht	<	1.8

A scrub flammability factor (SFF), which is assigned using Table 5, is applied to allow for scrub fuels that are non-standard in arrangement. According to Sneeuwjagt (personal communication), the SFF is a crude weighting factor that is applied to scrub loading, although a SFF of 1.0 is normally applied.

The available scrub weight, Sa (t ha^{-1}), is the product of the SWT and a scrub flammability factor SFF:

$$\mathrm{Sa} = \mathrm{SWT}\ \mathrm{SFF} \qquad [50]$$

Available Slash

Although pine plantations do not carry significant trash or scrub components, additional fuels must be considered in pine plantations that have been thinned or pruned. Residual materials (slash fuels) that are left on site consist of stem wood, branch wood and aerated needles. It has been recognized that although thinning and pruning operations reduce the likelihood of crown fires, slash fuels themselves present a fire hazard (McCormick 1973; Burrows 1980; Burrows *et al.* 1988). Prescribed burns can be conducted to remove these fuels if conditions of weather and fuels are such that aerated needles and light branchwood (< 25 mm in diameter) can be consumed without damaging crop trees.

Table 7.5 (Sneeuwjagt and Peet 1985), which is used to quantify the slash fuels of *Pinus radiata* plantations that have been thinned or pruned, has been developed primarily to support such prescribed burns, although it represents a simplification of the work of Burrows and others (Burrows 1980; Burrows *et al.* 1988). Burrows (1980) presented accurate techniques for quantifying the slash fuels of *P. radiata* from average residual top butt diameter and the number of stems removed. Original table data were derived from the relationships that were established by Burrows (1980) by assuming an average butt diameter of 14 cm for an 11-year-old stand that had been thinned commercially. Experimental fires in 14-year-old plantations that had been thinned were conducted without damaging crop trees (Burrows *et al.* 1988), and it was concluded that successful burns could be attained given the following conditions: fire intensities should be less than 200 kW m^{-1}; AMCs must be less than 27 per cent; the soil dryness index (SDI), which was developed by Mount (1972) and adapted for WA by Burrows (1987), should be less than 250 units in the winter or spring, or have fallen by 400 units from its summer maximum in the autumn; the available litter bed should not exceed 3 t ha^{-1}; and the total

TABLE 5

Scrub flammability factors (reproduced from Sneeuwjagt and Peet 1985)

SCRUB FLAMMABILITY	SCRUB FOLIAGE CONDITION		
	YOUNG/GREEN	20% DEAD	50% DEAD
LOW Foliage dispersed; coarse; Sparse; compacted or moist.	0.5	1.0	1.5
MEDIUM Foliage moderately fine; mixed size classes; medium dense;	1.0	2.0	3.0
HIGH Foliage aerated; fine; dense or continuous	1.5	3.0	5.0

available fuel quantity should not exceed 10 t ha^{-1}. These conditions are expected to remove 20 per cent of the total branchwood, Btot, and this fraction of the total represents the available branchwood, Bav, for such low intensity fires.

When an AMC, which is estimated using Equation 20, is less than 27 per cent, all aerated needles are considered to be available for burning. Aerated needles can be fresh or grey depending on the time since thinning or pruning: fresh aerated needles are reddish-brown in colour and have been dead for up to one year, and grey aerated needles have been dead for one to two years. The weight of grey needles (Ng) is 60 per cent that of fresh needles (Nf), which are produced by removing a given number of stems per hectare, SR, in the first commercial thinning treatment of a 10- to 14-year-old plantation of *P. radiata*.

When a plantation has been thinned, the available aerated needle weight, Na (t ha^{-1}), is equal to either Nf or Ng for material that is fresh or grey respectively, and the weight of available branchwood, Ba (t ha^{-1}), is equal to Bav for prescribed burning and mild wildfire conditions, or Btot is assumed for extreme wildfire conditions. In terms of the number of stems per hectare removed, the required available weights are:

$$Nf_{(PR)} = SR\ 0.0085 \qquad [51]$$

$$Ng_{(PR)} = SR\ 0.005 \qquad [52]$$

$$Bav_{(PR)} = SR\ 0.002 \qquad [53]$$

$$Btot_{(PR)} = SR\ 0.01 \qquad [54]$$

and the following quantities are assumed when only pruning occurs:

$$Nf_{(PR)} = 3.0$$

$$Ng_{(PR)} = 1.8$$

$$Bav_{(PR)} = 0.7$$

$$Btot_{(PR)} = 3.0$$

Application Bounds	Original Data[1]
$200. < SR < 800.$	$200. < SR < 750.$

No relationships have as yet been established for *P. pinaster* and, according to Sneeuwjagt (personal communication), for the present it is assumed that the tables for *P. radiata* work adequately for *P. pinaster*.

Given that available litter, trash, scrub and slash fuels have been determined, the total available fuel quantity, AFQ (t ha^{-1}), is determined by adding the weights of the appropriate fuel bed components for a given fuel complex. For example, the AFQ for a northern jarrah type that contains litter, scrub and no trash is:

$$AFQ_{(NJ)} = La_{(NJ)} + Sa_{(S6)} \qquad [55]$$

The AFQ for a *P. radiata* type that has been thinned recently is calculated from:

$$AFQ_{(PR)} = La_{(PR)} + Na_{(PR)} + Ba_{(PR)} \qquad [56]$$

For a karri type with an understorey of scrub structural type 1, the AFQ is comprised of litter, trash and scrub fuel components:

$$AFQ_{(K)} = La_{(K)} + Ta_{(K)} + Sa_{(S1)} \qquad [57]$$

Fuel Quantity Correction Factors

The forward rate of spread of a fire on level to undulating terrain is determined by adjusting a fire danger index for non-standard fuel quantities by way of a fuel quantity correction factor (FQCF). Fuel quantity correction factors are derived from the AFQ and SMC of a given fuel type, and there are separate fuel correction factors for eucalypt forests and pine plantations.

Trends in the table data given by Sneeuwjagt and Peet (1985) illustrate that for jarrah and karri fuel types, there is a threshold value for AFQ below which SMC does not exhibit a direct influence on the FQCF. This portion of both the jarrah hardwood and karri FQCF tables is a theoretical solution that was developed by Sneeuwjagt (personal communication).

The FQCF varies with SMC and AFQ above this threshold AFQ, but attempts to fit a single, accurate function to this portion of the table data failed. Trends given by the table data indicate that FQCFs should increase with decreasing SMCs for a given AFQ, although convergence problems were encountered. These were probably encountered because of the sparsity of SMC data; only three broad categories of SMCs are given in the tables.

Instead of a single function, three equations are presented, one for each SMC class, whereby FQCF varies with AFQ. For northern jarrah and upslope wandoo, fuel quantity correction factors are calculated from:

Application Bounds

$$\mathrm{FQCF}_{(NJ/W)} = 1.02 / (1 + 7266.83 \exp(-1.36\ \mathrm{AFQ}_{(NJ/W)})) + 0.10 \qquad \begin{aligned} 2.5 &< \mathrm{AFQ}_{(NJ/W)} < 8.0 \\ 3.0 &< \mathrm{SMC} < 26.0 \end{aligned} \tag{58a}$$

$$\mathrm{FQCF}_{(NJ/W)} = (6.03 + 5.81\ \mathrm{AFQ}_{(NJ/W)}) / 53.44 \qquad \begin{aligned} 8.1 &< \mathrm{AFQ}_{(NJ/W)} < 25.0 \\ 3.0 &< \mathrm{SMC} < 9.0 \end{aligned} \tag{58b}$$

$$\mathrm{FQCF}_{(NJ/W)} = (11.19 + 2.92\ \mathrm{AFQ}_{(NJ/W)}) / 35.02 \qquad \begin{aligned} 8.1 &< \mathrm{AFO}_{(NJ/W)} < 25.0 \\ 9.1 &< \mathrm{SMC} < 18. \end{aligned} \tag{58c}$$

$$\mathrm{FQCF}_{(NJ/W)} = (0.055 + 0.0023\ \mathrm{AFQ}_{(NJ/W)}) / 0.074 \qquad \begin{aligned} 8.1 &< \mathrm{AFO}_{(NJ/W)} < 25.0 \\ 18.1 &< \mathrm{SMC} < 26.0 \end{aligned} \tag{58d}$$

Original Data[1,4,5]

$1.5 < \mathrm{AFQ}_{(NJ/W)} < 15.$

$3. < \mathrm{SMC} < 25.$

and for karri types, fuel quantity correction factors are:

Application Bounds

$$\mathrm{FQCF}_{(K)} = 0.95 / (1 + 957.74 \exp(-0.52\ \mathrm{AFQ}_{(K)})) + 0.16 \qquad \begin{aligned} 5.0 &< \mathrm{AFQ}_{(K)} < 17.0 \\ 3.0 &< \mathrm{SMC} < 26.0 \end{aligned} \tag{59a}$$

$$\mathrm{FQCF}_{(K)} = (5.08 + 6.26\ \mathrm{AFQ}_{(K)}) / 111.50 \qquad \begin{aligned} 17.1 &< \mathrm{AFQ}_{(K)} < 64.0 \\ 3.0 &< \mathrm{SMC} < 9.9 \end{aligned} \tag{59b}$$

$$\mathrm{FQCF}_{(K)} = (17.35 + 1.70\ \mathrm{AFQ}_{(K)}) / 46.25 \qquad \begin{aligned} 17.1 &< \mathrm{AFQ}_{(K)} < 64.0 \\ 10.0 &< \mathrm{SMC} < 18.9 \end{aligned} \tag{59c}$$

$$\mathrm{FQCF}_{(K)} = (10.88 + 0.46\ \mathrm{AFQ}_{(K)}) / 18.70 \qquad \begin{aligned} 17.1 &< \mathrm{AFQ}_{(K)} < 64.0 \\ 19.0 &< \mathrm{SMC} < 26.0 \end{aligned} \tag{59d}$$

Original Data[1]

$5. < \mathrm{AFQ}_{(K)} < 55.$

$6 < \mathrm{SMC} < 25.$

A single function was derived successfully to describe the FQCFs of each of the pine fuel types, for which eight classes of surface moisture content are given in the tables:

Application Bounds

$$\mathrm{FQCF}_{(PP)} = \mathrm{AFQ}_{(PP)}(-0.0061\ \mathrm{SMC}+0.24) + (1.28 - 0.49/(1+38.96 \exp(-0.25\ \mathrm{SMC}))) \qquad \begin{aligned} 4. &< \mathrm{AFQ} < 25. \\ 3. &< \mathrm{SMC} < 40. \end{aligned} \tag{60}$$

Application Bounds

$$\mathrm{FQCF}_{(PR)} = \mathrm{AFQ}_{(PR)}(-0.0065\ \mathrm{SMC}+0.21) + (1.31 - 0.47/(1+33.99 \exp(-0.36\ \mathrm{SMC}))) \qquad \begin{aligned} 4. &< \mathrm{AFQ} < 25 \\ 3. &< \mathrm{SMC} < 35 \end{aligned} \tag{61}$$

Original Data[1,4,6]

$0.5 < \mathrm{AFQ}_{(PP/PR)} < 18.$

$5. < \mathrm{SMC} < 40.$

Fuel and Slope Corrected Spread Rates

A FQCF is applied to the appropriate FDI, which is $\mathrm{FDI}_{(NJs)}$ for jarrah fuel types and $\mathrm{FDI}_{(Ks)}$ for karri fuel types, to determine the fuel corrected forward rate of headfire spread over level to undulating terrain, ROS (m h^{-1}), calculated using the SMC for a given time and fuel type. Note that the original data bounds presented in Table 4 apply to these rates of spread.

Equations 62, 63 and 64 are examples of ROS calculations for non-standard northern jarrah, *P. radiata* and karri 1/2 fuel types respectively:

$$\mathrm{ROS}_{(NJ)} = \mathrm{FQCF}_{(NJ)}\ \mathrm{FDI}_{(NJs)} \tag{62}$$

$$\mathrm{ROS}_{(PR)} = \mathrm{FQCF}_{(PR)}\ \mathrm{FDI}_{(NJs)} \tag{63}$$

$$\mathrm{ROS}_{(K12)} = \mathrm{FQCF}_{(K)}\ \mathrm{FDI}_{(Ks)} \tag{64}$$

The forward rate of headfire spread for a given fuel type must be corrected for slope if the local topography is neither level nor undulating. The table data presented by Sneeuwjagt and Peet (1985) reproduce the work of McArthur (1967), for which Noble *et al.* (1980) derived Equation 65. Hence, the forward rate of spread of a fire on terrain of slope θ degrees, ROS_θ, is:

$$\mathrm{ROS}_\theta = \mathrm{ROS}\ \exp(0.069\ \theta) \tag{65}$$

Application Bounds

$-10. < \theta < 20.$

SCORCH HEIGHTS

Planning activities that support fuel reduction include prescribing conditions that will yield acceptable canopy scorch heights. Maximum scorch heights can be calculated for jarrah or karri types, although scorch heights for each type are predicted using separate and quite different relationships.

From the results of low intensity spring and autumn fires that were lit in northern jarrah, Peet (1963) developed linear relationships to predict average flame height from average rate of spread, and then average scorch height from flame height. Peet's (1963) linear relationships showed that autumn scorch heights were approximately 1.8 times greater than those incurred in the spring. However, it was found that field personnel were underestimating potential scorch height using these relationships (Burrows[5], personal communication), and so further research was conducted.

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[5] N D Burrows, Senior Research Scientist, Science and Information Division, Department of Conservation and Land Management, Como WA.

Preliminary results of experimental fires in jarrah that were conducted by Burrows (personal communication) suggest that scorch height under peak conditions of summer drying is approximately double the average as calculated by Peet for spring scorch heights. As a result of Burrows' work, a new relationship was derived to predict maximum scorch height from rate of spread and total available fuel quantity. It is assumed at present that these relationships are adequate for predicting scorch heights for pines.

The scorch height equations for jarrah types were developed from spread rates that are relatively low. Indeed the tables, and therefore the equations, are limited to predicting maximum scorch height when fuel and weather conditions are typical of mild intensity fires:

$$\mathrm{SCORCHsp}_{(J)} = 0.17\ \mathrm{ROS}_{\theta} + 1.29 \qquad [66a]$$

$$\mathrm{SCORCHau}_{(J)} = 0.306\ \mathrm{R0S}_{\theta} + 2.322 \qquad [66b]$$

where

SCORCHsp is the maximum scorch height, for a given fuel type, in the spring when the SDI is less than 800 units

SCORCHau is the maximum scorch height, for a given fuel type, in the autumn when the SDI is greater than 800 units

Application Bounds	Original Data[12]
$8. < \mathrm{ROS}_{\theta} < 68.$	$10. < \mathrm{ROS}_{\theta} < 75.$
$4. < \mathrm{AFQ}_{(J)} < 16.$	$5. < \mathrm{AFQ}_{(J)} < 18.$
$50. < \mathrm{CC} < 70.$	$50. < \mathrm{CC} < 70.$
	$0.6 < \mathrm{SCORCHsp}_{(J)} < 8.5$
	$0.6 < \mathrm{SCORCHau}_{(J)} < 24.4$

For karri types, Sneeuwjagt (personal communication) established relationships to predict maximum scorch height from fire intensity, as defined by Byram (1959). Using the table given by Sneeuwjagt and Peet (1985), fire intensity is implied given a ROS_{θ} and an AFQ. Sneeuwjagt (personal communication) also found that maximum scorch heights in the autumn were approximately 1.8 time those incurred in the spring:

$$\mathrm{SCORCHsp}_{(K)} = 0.19\ \mathrm{ROS}_{\theta} + (-30.44 \exp(-0.0082\ \mathrm{AFQ}_{(K)}) + 28.98) \qquad [67a]$$

$$\mathrm{SCORCHau}_{(K)} = 0.342\ \mathrm{ROS}_{\theta} + (52.16 - 54.79 \exp(-0.0082\ \mathrm{AFQ}_{(K)})) \qquad [67b]$$

Application Bounds	Original Data[1]
$10. < \mathrm{ROS}_{\theta} < 112.$	$15. < \mathrm{ROS}_{\theta} < 200.$
$5. < \mathrm{AFQ}_{(K)} < 53.$	$5. < \mathrm{AFQ}_{(K)} < 55.$
	$1. < \mathrm{SCORCHsp}_{(K)} < 31.$
	$1. < \mathrm{SCORCHau}_{(K)} < 63.$

AVAILABLE BURNING HOURS

The implementation of a prescribed burn for fuel reduction is supported by predictions of the time at which fuel moisture content is such that ignition could occur, and the amount of time during which fire spread, intensity and scorch conditions are likely to be safe and effective. In general, adequate conditions for fuel reduction burning are said to occur when the SMC of hardwood litter fuels is between 10 and 18 per cent.

When the surface moisture content is predicted to have decreased from the 0800 maximum to less than 18 per cent, safe and effective prescribed burning can start, STARTt (decimal hours) given by:

$$\mathrm{STARTt} = 14.5 / (1 + 10228.05\ \mathrm{SMCa}^{-3.08}) + 7.57 \qquad [68]$$

The time (decimal hours) that is available for prescribed burning a given fuel type in the autumn, $\mathrm{BHava}_{(NJ/K)}$, or in the spring, $\mathrm{BHavs}_{(NJ/K)}$, which assumes that lighting commences at STARTt, is calculated from:

$$\mathrm{BHava}_{(J)} = 17.46 - 25.78 / (1 + 1801.18\ \mathrm{SMCa}^{-2.70}) \qquad [69]$$

$$\mathrm{BHavs}_{(J)} = 14.35 - 25.36 / (1 + 3022.76\ \mathrm{SMCa}^{-2.78}) \qquad [70]$$

$$\mathrm{BHava}_{(K)} = 13.02 - 14.34 / (1 + 137212.87\ \mathrm{SMCa}^{-4.51}) \qquad [71]$$

$$\mathrm{BHavs}_{(K)} = 12.02 - 14.34 / (1 + 137209.12\ \mathrm{SMCa}^{-4.51}) \qquad [72]$$

Application Bounds	Original Data
$8. < \mathrm{SMCa} < 20.$	Unknown
$0. < \mathrm{BHava/BHavs}$	

Equations 68-72 have been fitted to the table data provided by Sneeuwjagt and Peet (1985), although continuous predictions of day-time SMCs, which can be predicted using Equations 26a and 26b, could also be employed to predict start time and available burning hours. The latter method has never been used operationally.

COMPARISON OF TABLE DATA AND EQUATION PREDICTIONS

Each equation has been evaluated for its ability to predict the table data from which it was derived. A root mean square error (RMSE), a coefficient of determination (R^2) and a mean residual (MRE) have been calculated for each equation (Table 6). The MRE yields information about the tendency of the model to under or over estimate, although a small value does not necessarily indicate a good model. It should be noted that the magnitude of a RMSE or a MRE is scale dependent, hence these values are only useful in comparing models which predict the same variable.

TABLE 6
The root mean squared errors (RMSE[a]), mean residual (MRE[b]) and, where applicable, coefficients of determination (R^2) obtained after fitting equations to each of the forest fire behaviour tables for Western Australia.

EQUATION	VARIABLE	TABLE[c]	RME	AME	R^2	UNIT
1	$NWCs/p_{(wet)}$	4.3.1	1.74	0.33	0.99	%
2	$NWCs/p_{(dry)}$	4.3.2	1.21	-1.01	0.99	%
4	Tz	8.1	0.85	0.02	0.99	°C
7	BDU	4.3.3	0.48	-0.28	0.99	.
8	$DDCs_{(NJ)}$	4.3.4	0.40	0.01	0.99	%
10	$DDCP_{(K45)}$	5.3.1	0.33	-0.06	0.99	%
12	$SMCa/z_{(SJ)}$	4.3.5	0.31	0.06	0.99	%
13	$SMCa/z_{(K36)}$	4.3.5	0.28	0.04	0.99	%
14	$SMCa/z_{(K45)}$	4.3.5	0.32	-0.04	0.99	%
15	$SMCa/z_{(K12)}$	4.3.5	0.36	0.03	0.99	%
16	$SMCa/z_{(OS)}$	4.3.5	0.25	-0.01	0.99	%
17	$SMCa/z_{(PP)}$	4.3.6	0.56	0.19	0.99	%
18	$AMCa/z_{(PP)}$	4.3.6	0.40	-0.14	0.99	%
19	$SMCa/z_{(PR)}$	4.3.6	0.39	0.10	0.99	%
20	$AMCa/z_{(PR)}$	4.3.6	0.42	-0.06	0.99	%
21	$PMCa/z_{(SJ)}$	5.3.2	0.34	0.22	0.99	%
22	$PMCa/z_{(K36)}$	5.3.2	0.46	-0.17	0.99	%
23	$PMCa/z_{(K12)}$	5.3.2	1.16	0.02	0.99	%
24	$PMCa/z_{(PP)}$	5.3.2	0.54	0.01	0.99	%
25	$PMCa/z_{(PR)}$	5.3.2	1.87	-0.08	0.99	%
27a	$FDI_{(NJs)}$	6.7	15.07	0.36	0.99	m h^{-1}
27	$FDI_{(NJs)}$	6.7	19.01	6.57	0.99	m h^{-1}
28a	$FDI_{(Ks)}$	6.12	15.99	-2.18	0.99	m h^{-1}
28	$FDI_{(Ks)}$	6.12	12.39	1.42	0.99	m h^{-1}
30	$AFF_{(K)}$	5.4.1H	0.07	-0.01	0.99	.
31	$AFF_{(PP/PR)}$	5.4.1P	0.08	-0.01	0.99	.
32	$L_{(NJ)}$	7.1.1	0.86	0.11	0.97	t ha^{-1}
33	$L_{(K/SJ)}$	7.1.2	1.98	0.43	0.97	t ha^{-1}
34	$L_{(W)}$	7.1.3	0.50	0.03	0.98	t ha^{-1}
35	$L_{(K)}$	7.2.1	0.98	-0.79	0.99	t ha^{-1}
36	$L_{(M)}$	7.2.1	0.40	0.18	0.99	t ha^{-1}
37	$L_{(NJ/SJ)}$	7.2.1	0.27	0.10	0.99	t ha^{-1}
38	$L_{(PP)}$	7.2.1	0.93	0.32	0.99	t ha^{-1}
39	$L_{(PR)}$	7.2.1	0.91	0.40	0.99	t ha^{-1}
40	$L_{(W)}$	7.2.1	0.25	0.09	0.99	t ha^{-1}
42	Trtot	7.3.1	2.59	-0.74	0.99	t ha^{-1}
43	Trav	7.3.1	1.39	-0.37	0.99	t ha^{-1}
44	SWT(S1)	7.4.1	0.24	-0.01	0.98	t ha^{-1}
45	SWT(S2)	7.4.1	0.37	0.01	0.99	t ha^{-1}
46	SWT(S3)	7.4.1	0.57	0.15	0.98	t ha^{-1}
47	SWT(S4)	7.4.1	0.82	-0.02	0.99	t ha^{-1}
48	SWT(S5)	7.4.1	0.38	0.04	0.99	t ha^{-1}
49	SWT(S6)	7.4.1	0.29	0.06	0.95	t ha^{-1}
51	$Nf_{(PR)}$	7.5	0.03	-0.02	0.99	t ha^{-1}
52	$Ng_{(PR)}$	7.5	0.00	0.00	1.0	t ha^{-1}
53	$Bav_{(PR)}$	7.5	0.00	0.00	1.0	t ha^{-1}
54	$Btot_{(PR)}$	7.5	0.00	0.00	1.0	t ha^{-1}
58a & 58b	$FQCF_{(NJ/W)}$	6.8	0.17	0.13	0.99	.
58a & 58c	$FQCF_{(NJ/W)}$	6.8	0.02	0.01	0.99	.
58a & 58d	$FQCF_{(NJ/W)}$	6.8	0.05	0.03	0.99	.
59a & 59b	$FQCF_{(K)}$	6.13	0.02	0.01	0.99	.
59a & 59c	$FQCF_{(K)}$	6.13	0.04	0.01	0.99	.
59a & 59d	$FQCF_{(K)}$	6.13	0.03	0.01	0.99	.
60	$FQCF_{(PP)}$	6.9	0.22	-0.04	0.99	.
61	$FQCF_{(PR)}$	6.9	0.23	0.05	0.99	.
66a & 66b	$SCORCHsp/au_{(J)}$	6.14.1	0.68	-0.12	0.99	m
67a & 67b	$SCORCHsp/au_{(K)}$	6.14.2	2.13	-0.34	0.97	m
68	STARTt	7.7.1	0.20	-0.01	0.99	h
69	$BHava_{(J)}$	7.7.1	0.32	-0.05	0.99	h
70	$BHavs_{(J)}$	7.7.1	0.27	0.01	0.99	h
71	$BHava_{(K)}$	7.7.1	0.28	-0.03	0.99	h
72	$BHavs_{(K)}$	7.7.1	0.28	-0.04	0.99	h

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[a] $RMSE = (\Sigma(Xio - Xip)^2 / n)^{0.5}$

[b] $MRE = \Sigma(Xio - Xip) / n$

where n is the number of observations and Xio (Xip) denotes the ith observation of the observed table (equation predicted) values.

[c] Table numbers refer to Sneeuwjagt and Peet (1985)

Using the equations, the table data are reproduced almost exactly if predictions are expressed with precisions equivalent to those depicted in the tables. Error terms include differences between the decimal precision of the equation predictions and the integer precision of the table data.

Equations that describe linear relationships illustrated extremely strong coefficients of determination (Table 6). In the worst case, 99 per cent of the variation in the predicted table variable is accounted for by the linear relationship with a given input variable.

The equations used to predict fire danger indices (Equations 27 and 28), which are the crux of the fire behaviour prediction system, have been investigated further. In an initial analysis, fire danger indices were predicted solely as a function of ground wind speed, by holding surface moisture content constant. This stage of the analysis proved that table data were best described as a function of wind speed using a modified exponential equation. A modified exponential fit the table data better than any of the many other equation forms tested, and so it was parametrized for each SMC. In lieu of deriving Yj/k, Aj/k and Nj/k in Equations 27 and 28 as a function of SMC, best fit is obtained using the parameters thereof, which are given in Table 7. In effect, the parameters given in Table 7 can be used to replace Equations 27 and 28 with twenty-one and twenty-three new equations respectively.

Error terms for each of the modified exponential equations particular to a given SMC, are presented in Table 7, along with the errors obtained when all of these equations are used in combination to predict the values that are given by Sneeuwjagt and Peet (1985). Error terms illustrate that the accuracy of the equations that were parametrized for each SMC, decreases with increasing SMC, and close examination of the table data explains why this is so.

The precision of the data expressed in the forest fire behaviour tables decreases with increasing fire danger index: fire danger indices between approximately 1-100, 100-300, 300-1000 and greater than 1000 are expressed to the nearest 1, 5, 10 and 50 m h^{-1}, respectively. The frequency of high FDIs increases with decreasing SMC, and so rounding errors will also increase with decreasing SMC. In essence, the table data depict that the error in predicted forward rates of headfire spread (FDI) increases with increasing wind speed and decreasing surface moisture content. Indeed our ability to predict fire behaviour characteristics decreases with the advent of extreme conditions. Weighted fitting techniques have therefore been used to favour those data with small errors.

A variance (σ^2) is required to calculate a weight for a given FDI. Assuming errors are roughly uniformly distributed over a range, the variance over these table data can be estimated from:

$$\sigma^2 = a^2 / 3.0 \qquad [73]$$

The variance has been calculated from estimates of **a** given by 0.5, 2.5, 5.0 and 25.0 for FDIs from 0-100, 101-300, 301-1000 and 1000+, respectively, and models have been developed to estimate the variance (Si^2) for each cell of the table as a function of wind speed and surface moisture content. Using the standard statistical equation (Myers 1989) to predict weights (Wi):

$$Wi = 1/Si^2/(\Sigma\ 1/Si^2) \qquad [74]$$

and replacing Si^2 with the models derived and $\Sigma\ 1/Si^2$ with the values calculated, the following were used to weight the table data for standard northern jarrah and standard karri respectively:

$$Wi = 1 / \exp (4.08 + 0.20\ SMC - 2.68\ SMC^{0.5} + 0.037\ WIND^2) / 2849.15 \qquad [75a]$$

$$Wi = 1 / \exp (2.72 + 0.14\ SMC - 2.04\ SMC^{0.5} + 0.066\ WIND^2) / 2085.42 \qquad [75b]$$

A non-linear, iterative weighting procedure in SAS (SAS Institute Inc. 1985) was used to parametrize the equations. Hence, Equations 27 and 28 should be replaced with the following:

$$FDI_{(NJs)} = Yj + Aj \exp (WIND_{fg}\ Nj) \qquad [27a]$$

where

$Yj = 27.29 - 2.38\ SMC + 0.045\ SMC^2$

$Aj = 47.56\ SMC \exp(-0.58\ SMC) + 6.67$

$Nj = -0.0013\ SMC^{1.60} + 0.43$

and

$$FDI_{(Ks)} = Yk + Ak \exp (WIND_{fg}\ Nk) \qquad [28a]$$

where

$Yk = 3.39 - 155.41\ SMC^{-3.34}$

$Ak = 103.95\ SMC^{-1.04}$

$Nk = -0.0084\ SMC + 0.59$

The combined errors obtained using the models parametrized by SMC (Table 7) can be compared with those obtained using Equations 27a and 28a. The accuracy with which the table data are predicted is not improved greatly by applying twenty-one (RMSE=9.64, MRE=4.73) and twenty-three (RMSE=12.70, MRE=5.45) models in lieu of Equations 27a (RMSE=15.07, MRE=5.60) and 28a (RMSE=15.99, MRE=5.98) respectively. It should also be noted that Equation 28a is not an improvement on the original Equation 28.

Despite the relative size of the error terms of Equations 27a and 28a, these equations should predict table data with an accuracy sufficient for the application of most predictions. Any increase in accuracy generated as a result of producing one equation to predict a fire danger index for each SMC as a function of wind speed, is not apt to justify using 44 equations in lieu of two. Indeed the combined errors given in Table 7 illustrate that a relatively large error is inherent despite the technique employed to calculate a fire danger index.

TABLE 7

The parameters, root mean squared errors (RMSE) and average mean errors (MRE) for the modified exponential equations that optimize the prediction accuracy of fire danger indices (FDIs) for jarrah (NJs) and karri (Ks), which vary as a function of forest ground wind speed ($WIND_{fg}$) for a given surface litter moisture content (SMC).

	$FDI_{(NJs)} = Yj + Aj\ EXP(WIND_{fg}\ Nj)$					$FDI_{(Ks)} = Yk + Ak\ EXP(WIND_{fg}\ Nk)$				
SMC	Yj	Aj	Nj	RMSE	MRE	Yk	Ak	Nk	RMSE	MRE
3	12.82	36.84	0.41	16.30	12.75	-32.76	44.91	0.53	47.20	34.02
4	2.62	30.54	0.40	20.81	14.84	-8.24	28.86	0.52	24.78	18.85
5	-9.36	28.64	0.37	25.64	16.51	-11.75	22.87	0.52	18.30	13.08
6	11.38	16.44	0.40	9.80	2.63	-5.71	19.08	0.51	11.76	9.06
7	10.20	13.82	0.39	12.78	8.47	-6.70	18.08	0.49	7.99	7.21
8	7.80	11.87	0.38	6.42	4.39	-4.24	16.20	0.48	9.20	6.67
9	5.32	10.92	0.37	4.63	3.60	-0.70	13.66	0.48	8.56	6.37
10	5.60	9.42	0.36	9.23	6.24	-0.66	12.61	0.46	5.25	4.45
11	4.19	8.76	0.36	15.60	5.54	0.05	11.32	0.46	4.26	3.70
12	3.43	8.14	0.35	6.63	4.53	1.04	10.46	0.45	5.44	4.01
13	3.55	7.40	0.34	4.00	2.87	1.01	10.08	0.43	2.72	2.33
14	4.24	6.27	0.35	0.97	0.84	1.70	8.55	0.44	3.52	2.66
15	2.06	6.52	0.34	5.25	3.59	4.74	6.11	0.47	2.71	1.73
16	2.16	5.99	0.33	1.52	1.26	2.80	6.65	0.44	2.84	2.21
17	1.24	5.92	0.32	1.40	1.05	3.00	6.11	0.43	1.23	0.95
18	2.54	5.04	0.32	1.86	1.34	2.00	6.09	0.41	2.65	1.88
19	3.26	3.72	0.34	1.26	1.00	4.51	4.05	0.46	0.59	0.51
20	1.52	4.26	0.31	0.64	0.51	4.04	3.92	0.44	1.57	1.14
21	.	.	.	.	.	4.59	3.23	0.46	1.42	1.04
22	0.09	4.40	0.29	1.32	0.84	4.39	3.02	0.45	0.64	0.53
23	.	.	.	.	.	3.54	3.11	0.43	0.96	0.74
24	-2.59	5.49	0.24	0.85	0.74	3.61	2.87	0.43	0.41	0.32
25	.	.	.	.	.	2.95	2.92	0.42	1.03	0.78
26	-0.86	5.30	0.20	0.45	0.34	.	.	.	.	.
Combined				9.64	4.73				12.70	5.45

DISCUSSION

Sneeuwjagt and Peet's (1985) tables are a significant contribution to fire behaviour forecasting in WA. The methodology of this prediction system is sufficiently modular to incorporate facilities to predict fire behaviour for most of the forest fuel types throughout Australia (Burrows and Sneeuwjagt 1989). Although it would be necessary to establish new empirical relationships for other pine and eucalypt forest types, such an expansion is feasible because the system takes into account the presence or absence of a deep litter bed, trash, scrub and slash fuel components for a given fuel complex. Any further expansion of the current tables, however, will render them even slower and more cumbersome to use.

Seventy-two equations have been developed to perform the majority of the predictive functions that are encompassed within the forest fire behaviour tables for WA. In the present work, the equations for the tables have been organized according to the sequence in which calculations are made to generate a fire danger index and a forward rate of headfire spread for non-standard conditions. Two prediction sub-systems have been developed, which support the prediction of litter moisture contents and available fuel quantities, to help structure calculation procedures that are quite complex. This restructuring has been carried out to clarify and simplify the prediction methodology that was presented in the 1985 edition of the tables. The essence of the prediction process has not been altered, it has simply been reorganized and procedures have been stated explicitly.

Equations alone do not necessarily eliminate the need for a manual, tabular system to support calculating fire behaviour in the field. Nonetheless, the 1985 edition of the tables could be restructured and proper application of the tables could be detailed explicitly. These improvements would simplify the manual, tabular system and clarify its use and limitations, thereby increasing the overall effectiveness of the system.

Each equation is as suitable for generating predictions as the table from which it originated. The equations provide predictions that are no more accurate than the tables from which they were developed. Any assumptions and limitations that are relevant to the use of the tables also apply to the equations. Actual rather than forecasted input values should be used when increases in prediction accuracy merit any additional cost or effort involved.

The application bounds provided for each equation must be observed. Although these limits have met with success operationally for a number of years, predictions within the bounds of the original data should be most accurate. The most reliable predictions are attained within the bounds of the fuel, weather and fire behaviour characteristics that have been experienced during experimental fires (Table 4), and the relationships between fuel, weather and fire behaviour characteristics are probably better understood for northern jarrah than for karri fuel complexes, and least understood for pine fuel complexes in WA.

The equations derived represent a significant advancement by which predictions of fire danger and fire behaviour characteristics can be compared with those of other prediction systems, and predictions can be automated readily using a computer. The prediction sub-systems and the equations provided herein should facilitate the process of incorporating any future developments into the prediction system because they can be modified or replaced easily. The equations have been used in the Wildfire Threat Analysis System (Underwood 1988; Beck and Muller 1989; Muller 1993), and can be applied by way of personal computer software that has been produced by REMS Research Ltd (1991).

It would have been far more sensible to develop equations, and probably more simple ones, from the original experimental data. In some cases these data have been lost, are currently being re-analysed (Burrows, personal communication) or were otherwise unavailable. Despite its operational success, the incompleteness of published data behind the WA fire behaviour prediction system detracts from its scientific credibility. It is hoped that this work will be followed by improved equations based on published data.

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