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MCARTHUR'S FOREST FIRE DANGER METER AND THE FOREST FIRE BEHAVIOUR TABLES FOR WESTERN AUSTRALIA: DERIVATION, APPLICATIONS AND LIMITATIONS

N.D. Burrows[1] and R.J. Sneeuwjagt[1]

Abstract

Since early this century, Australian fire control and land management agencies have developed systematic procedures for forecasting levels of bushfire danger and for predicting fire behaviour. Being largely field practitioners with regular bushfire experience, it is not surprising that fire danger rating and fire behaviour prediction systems widely used across the continent were derived from observations and experiments conducted in the field.

Both the Forest Fire Danger Meter and the Forest Fire Behaviour Tables for Western Australia were derived from actual field experimentation over a range of fuel, weather and topographical conditions. While the research methods for developing the two models were similar, the latter tables are based on considerably more detailed research over a wider range of forest and fuel types. Both models have widespread application in forecasting forest fire danger, predicting the spread of forest wildfires and in the planning and implementation of prescribed burns.

The major limitation of both models is that they cannot be reliably used outside the conditions of fuel, weather and topography from which they were derived. An ongoing fire behaviour research program is therefore necessary to allow fire management agencies to meet new expectations and demands in Australian forest fire management.

Introduction

Climate, vegetation and ignition sources dictate that much of the Australian landscape is fire prone. There is ample evidence of a long association between these factors and of the extensive use of fire by Aborigines (Kessell 1928; Hallam 1975; Nicholson 1981; Burbidge 1985) from the coastal forests to the spinifex deserts of Central Australia.

Since European settlement, bushfires have posed a threat to a range of community values. An ability to forecast fire danger, fire hazard and fire behaviour is an essential pre-requisite for planning and

[1]Department of Conservation and Land Management, PO Box 104, Como WA 6152

implementing fire management strategies. While bushfire experience is still an important basis for decision making, more formal, repeatable, reliable and systematic methods for evaluating fire danger and behaviour are necessary. Fire management is becoming increasingly complex and sophisticated to keep pace with increasing demands and expectations.

The first Australian attempt at a formal, somewhat scientific approach to rating forest fire danger was made by the Western Australian Forests Department (Wallace 1936; Foley 1947). Wooden cylinders or 'hazard rods' were used to provide an empirical measure of fire danger, where fire danger approximated the definition of Luke & McArthur (1978). The moisture content of the rods provided a measure of fire hazard which was calibrated against a perceived degree of fire danger. The estimated fire danger was 'based on the intensity, spread and damage which it is considered would be caused by fire burning in two year old jarrah (*Eucalyptus marginata*) leaf litter during the worst period of the day' (Wallace & Gloe 1938). Soon after, similar fire danger rating systems developed across Australia (Cromer 1946; Foley 1947).

In this paper we discuss the derivation of two empirically based forest fire behaviour models widely used in Australia today. The applications and limitations of one of these models, the McArthur Forest Fire Danger Meter, have been dealt with by other authors (Cheney 1968; Luke & McArthur 1978; Cheney 1981; Catchpole 1985; Beck 1988) so will not be dealt with here. Instead, we will discuss the current application of the Forest Fire Danger Tables for Western Australia (also known as the Red Book) and their limitations in fire management.

Australian Bushfire Behaviour Models - Why Empirical?

Bushfire research and the development of danger rating systems in Australia has been based on a semi-empirical approach. The wide diversity of Australian climates and vegetation types, the different needs of managers and State based fire control and land management organisations have thus far precluded the development of a system with national application for all purposes of fire management. The many fire behaviour guides in existence today attempt either to rate fire danger or to predict fire spread for a range of fuel and weather conditions, or both. The guides are mostly in the form of tables, meters or nomograms and predict various descriptions of behaviour for given fuel, weather and topographical parameters. In most cases, the guides have been developed by observing and measuring fire in the field.

Workers in other parts of the world have produced mathematical or laboratory based fire behaviour models (Anderson 1969; Phung & Willoughby 1965; Rothermel & Anderson 1966; Byram *et al.* 1966; Wooliscroft 1968; Anderson 1969; Thomas 1970; Frandsen 1971; Rothermel 1972; Anderson *et al.* 1982). Van Wagner (1967) and others have made useful advances by combining theoretical, laboratory and field methods in an attempt to better define fire behaviour. These workers have mostly attempted to develop national systems, mainly because federal bodies are responsible for fire control over much of the land in North America and Europe.

Whatever the method, the aim has always been to predict fire behaviour and the best system is the one that works for its intended purpose. The required level of resolution, accuracy and reliability of a fire behaviour model depends to a large extent on its application. There are three main applications for which fire behaviour models have been developed. Firstly, to provide a measure of seasonal and daily fire danger, as defined by Luke & McArthur (1978). Generally, this is a numerical index ranking fire danger from conditions when fires cannot spread, to conditions when fires will burn uncontrollably and cause destruction. The index values are often placed in classes

with a descriptive measure of fire danger, such as LOW, EXTREME, etc. As such, a high degree of accuracy is not needed. Daily fire danger rating is commonly used to issue warnings to the public and to set levels of preparedness of fire management authorities.

The second application is to predict rates of wildfire spread. This is valuable support for many aspects of protection planning and wildfire suppression activities (Luke & McArthur 1978; Beck 1988). Predictions of fire behaviour need to be more accurate than those provided by a fire danger rating index system but it is still not essential that they are highly accurate.

The third application is for prescribed burning operations. Here, managers are deliberately setting fire under carefully defined fuel, weather and fire behaviour conditions to achieve a specific purpose. Common examples of this are fuel reduction burns, slash burns following logging operations and various types of burns to regenerate specific plants for habitat. Fire behaviour guides need to be very reliable when land managing authorities are setting prescribed burns. For example, prescribed burning of slash beneath fire sensitive *Pinus radiata* stands can only be safely conducted over a very narrow range of weather and fuel conditions (Burrows *et al.* 1988). Slight inaccuracies in forecasting fire behaviour could result in damage to crop trees. The onus is on managers to control fires deliberately set, to within defined ranges of intensity and spread rate.

The various methods of deriving fire behaviour prediction models to achieve the above, have strengths and weaknesses and have been compared and discussed by others so will not be dealt with in detail here. However, most authors agree that greater control of variables is possible in laboratory studies, but field experiments are more likely to reproduce the actual process of fire spread by integrating the effects of numerous, difficult-to-measure variables. A perfect theoretical model will result in fire behaviour laws with universal application, whereas empirically derived models may only be reliable for the range of experimental conditions. Statistical analyses which are possible with empirical data should at least provide a measure of the variability of dependent variables for given sets of independent variables. Such confidence intervals are useful to managers. Field experiments have provided managers with reliable, accurate fire behaviour guides for conducting very specific prescribed burns (Woodman & Rawson 1982; McCaw 1986; Burrows *et al.* 1988). Mathematical models currently in use are not always suitable for specific fire management needs such as various types of prescribed burning (Rothermel 1987).

There are significant practical limitations on field experimentation such as:

- physical and economical limits to plot size and numbers;
- costs, risks and difficulties of implementing and containing experimental fires, especially under adverse weather conditions;
- legal restrictions on days when experimental fires can be lit, further limiting the range of experimental conditions;
- physical damage to other forest values;
- practical limits on the quantity of data that can be collected and processed; and
- scaling problems associated with large fires such as fire acceleration, spotting, crown fire development.

Peet (1965, 1972) contended that the theoretical and laboratory procedures of Fons (1946) were unrealistic to attempt in Western Australia at the time. Fons' list of fuel variables affecting fire behaviour included film conductance, heat transfer factor for radiation, ignition temperature, particle spacing, surface area-to-volume ratio of fuel particles, specific heat, bulk density and temperature. In reviewing Fons' procedure prior to commencing his own studies, Peet concluded that the special instrumentation and other facilities such as a wind tunnel necessary to conduct laboratory experiments were not available in Western Australia, and were not likely to be. Peet believed that the variables posed by Fons' theoretical model were far too difficult to measure in the field and would not win acceptance among field practitioners.

It was probably for similar reasons that some time earlier, McArthur (1959) had also decided against the theoretical and laboratory techniques being pursued in North America. Instead McArthur, and later Peet, decided to select so called 'indirect variables' (Davis 1959) for measurement under field conditions. These variables were readily identified as affecting fire behaviour and could be relatively easily measured in the field. They included weather (temperature, relative humidity, wind speed and rainfall), fuel factors (fuel load, fuel type, fuel moisture) and topography (slope). Both McArthur and Peet wanted to develop practical, applied fire danger and behaviour prediction systems, consistent with the fire management goals of the day.

Experimental Procedures in the Field - McArthur

In the late 1950s and early 1960s, McArthur conducted over 800 experimental fires over a range of eucalypt fuel types (McArthur 1962, 1967). These fires were allowed to run for 15-60 minutes during which time factors affecting fire behaviour were studied in 'fair detail' (McArthur 1967). Cheney (1968) described the fuels at experimental sites as: 'characteristic of a commercial dry sclerophyll eucalypt forest of mixed species with a fuel quantity of 5 tons per acre (12.5 tha^{-1}). The fuel consisted predominantly of leaf, twig and bark litter with a smaller percentage of grass and low shrubs. The forest characteristics were as found in a commercial dry sclerophyll eucalypt forest; the dominant height was 80 feet (26 m) or more and was well stocked. The topography was flat or gently undulating'.

Data from these experimental fires, together with some opportunistic observations of wildfires, were integrated to produce forest fire danger tables and later meters. The fire danger meters integrate the combined effects of short and long term fuel dryness, and wind speed to produce a basic index, which is further modified by the inclusion of fuel quantity and slope. As has been noted by other authors (Noble *et al.* 1980; Beck 1988) the meters were constructed without functional relationships between variables and without any statistical analyses. Noble *et al.* (1980) fitted equations to the relationships shown on the meters using meter values and not raw data.

McArthur chose rate of spread, flame height and spotting distance as the most useful descriptions of fire behaviour for fire control purposes. He then identified fuel moisture, wind velocity, fuel quantity and slope as the main factors determining rate of spread (McArthur 1967). Fuel size and arrangement were recognized as being important, but no data are presented linking these variables to rate of spread. Likewise, atmospheric stability and spotting were known to influence fire behaviour, but the complexities of these phenomena precluded attempts to implicate them in predicting fire rate of spread. McArthur provided empirical estimates of likely spotting distance and crown fire development.

The experimental method employed by McArthur(as described in a report on experiments conducted in forests near Dwellingup, McArthur 1959) was to mark the fire perimeter at 2-minute intervals with metal tags and later, to survey and map the position of the markers. Maps of fire perimeter at 2-minute intervals enabled linear and area spread rates to be calculated. During the fire, wind speed was measured by a sensitive cup anemometer at 2 m above the ground and in the forest. Notes were made of flame dimensions, smoke colour and other fire behaviour such as spotting and crowning. Fuel quantity (of the surface litter) and fuel moisture content (surface litter) were measured before ignition. Data were analysed by plotting the maximum rate of spread of the fire perimeter against wind speed for each interval (averaged over the same interval), fuel moisture content and slope.

The resulting relationships and a drought factor (days since rain) were then produced on a circular slide-rule type Forest Fire Danger Meter for forecasting forest fire danger and for predicting real time fire behaviour (McArthur 1967, 1973). Fuel dryness, derived from temperature and relative humidity and wind speed were used to determine the basic fire danger index. This was then adjusted using fuel load and slope data to predict rate of spread. McArthur recommended that more precise tables be used for predicting low-intensity, prescribed fire behaviour (McArthur 1962, 1967).

Experimental Procedures - Forest Fire Behaviour Tables for Western Australia

The Forest Fire Behaviour Tables for Western Australia, the Red Book, has been evolving over the last 24 years and has seen input from many fire researchers. However, it was Peet's fire behaviour experiments in the 1960s in the northern jarrah forest near Dwellingup which were the forerunners of the current Red Book. Peet recognized that the fire danger rating system first developed by Wallace (1936) was no longer adequate for the changing fire management needs of the then Forests Department which required a more accurate and effective prediction of fire danger levels and fire behaviour. There had also been dramatic developments in fire suppression equipment and strategies since World War II.

In the period 1961-1964 Peet, in collaboration with McArthur, conducted a series of fire behaviour experiments in mature stands of upland jarrah (*Eucalyptus marginata*) forest near Dwellingup, Western Australia. The purpose was to develop a practical jarrah forest fire danger rating system and to develop means of accurately predicting jarrah forest fire behaviour to facilitate broad-acre prescribed burning for fuel reduction. After an extensive literature review, Peet decided to adopt the experimental techniques of McArthur (1959) for the reasons discussed above (Peet 1965, 1972).

From the outset, Peet aimed at producing fire danger rating and prescribed burning guides which were specific to a defined vegetation structure and landform type within the geographic range of jarrah (Peet 1965). This choice type was influenced by the commercial value and the extent and range of this forest type. Having selected the basic landform units in which fire behaviour studies would concentrate, Peet then set about describing and measuring understorey vegetation in considerable detail, including species present, cover and a measure of understorey flammability. Using these criteria, he further stratified his experimental sites. Details of shrub flammability ratings are provided by McCormick (1966). Peet measured both quantity, depth and type of leaf litter fuels, recognising variations in fuel bed density from field inspections. He also decided to make two measures of litter bed moisture content; the surface litter moisture and the average for the litter profile. The moisture gradient within a litter bed had long been recognized as being important in influencing the quantity of litter fuel available for burning and hence fire spread rate (Gisborne 1928; McArthur 1962; Ashcroft 1967). Peet studied the moisture regime of litter profiles and especially drying rates after rain, in an attempt to develop a fuel moisture prediction system.

An on-site weather station set about 50 m from the experimental burn plots provided regular information about wind speed and direction (at 1.2 m), temperature and relative humidity. Both surface and litter-profile fuel moisture measurements were made before and during the experimental fires. Following McArthur's methodology, fire ignition point was marked and fire perimeter tagged at regular intervals.

Peet identified three main factors in the jarrah forest fire danger equation. These were fuel load, wind speed and fuel moisture content. Direct field measures of fuel moisture content were not practical inputs to a daily fire danger rating system. McArthur integrated temperature and relative humidity to provide for fuel moisture content (McArthur 1962). Initially, Peet chose instead to use the measure of 'fire hazard' already in existence in Western Australia (Wallace 1936) based on the moisture content of hazard rods as explained earlier. Peet (1972) calibrated the moisture content of hazard rods against that of surface litter and related the two variables by a linear equation. Thus, on rain free days, the moisture content of surface litter in the jarrah forest could be reliably predicted using hazard rods. However, a relationship between temperature, relative humidity and surface fuel moisture (Hatch 1969; Peet 1972) was used in preference to hazard rods in the first published Red Book version (Harris 1968). Field staff were finding that problems associated with the biological breakdown of hazard rods were giving misleading results.

Peet recognised that the moisture content of surface litter alone was not entirely adequate for determining fire hazard. He believed that it was also necessary to adjust hazard according to the average moisture content of the litter profile. Further studies were conducted to develop a litter profile fuel moisture prediction system which made allowances for rainfall. As a result, the basic fire hazard could be corrected according to amount of rain, average temperature and the number of days since rain. From experimental fire data, Peet then developed regressions which related fire spread rate and the basic fire hazard, and fire spread rate and wind speed for a range of fuel loads. He then calculated correction factors to the fire hazard based on these equations. By applying corrections for rainfall, wind speed and fuel load, a forward rate of spread could be calculated for specific types of jarrah forest fuels.

The first published version of the Forest Fire Behaviour Tables for Jarrah Forest (Peet 1965) was very similar, in concept and in parameters used, to McArthur's circular slide-rule meters. Fuel accumulation data for both jarrah and karri (*Eucalyptus diversicolor*) litter (Hatch 1955; Loneragan 1961) were incorporated in the Red Book (Harris 1968) together with guides for suppressing wildfires and conducting fuel reduction burns. These early tables were used successfully for the purposes for which they were designed.

Fire control and prescribed burning operations expanded into different forest types. Fire managers and researchers recognized that predictions based on studies conducted in the northern jarrah forests, might not apply to other forests, especially to the tall, wet karri forests of the south-west. In response to management needs, intensive fire behaviour research was carried out in the karri and southern jarrah forests near Manjimup in the early 1970s. These studies concentrated on describing the fuel structure and quantity. Unlike the northern upland jarrah forests, karri and southern jarrah forests are characterised by a tall, dense understorey and often deep litter and trash (suspended, dead vegetation), making a complex fuel. Sneeuwjagt (1971) described six structural types within the southern forests and presented techniques for measuring scrub/fuel structure and quantity. In conjunction with these studies, Sneeuwjagt (*pers. comm.*) carried out several hundred experimental fires in the field. Most of the fires were conducted under relatively mild conditions for safety reasons. Data from these fires were analysed with reliable wildfire data to produce a karri rate of spread index, which is calculated from wind speed and surface fuel moisture content (Beggs 1976).

Sneeuwjagt conducted detailed studies of moisture regimes in deep karri litter fuels and improved the procedure for forecasting fuel moisture for surface and litter profile (Beggs 1976; Sneeuwjagt & Peet 1985).

Surface fuel and litter-profile fuel moisture contents were used to determine the quantity of fuel available for burning. In addition, surface fuel moisture content and wind speed determined the rate of spread index in both standard jarrah and karri fuels. Corrections were then applied depending on total fuel available for burning and slope. McArthur's slope correlation factors were used to adjust rate of spread.

In the last two decades forest fire management has expanded in scope and is demanding reliable, practical fire behaviour prediction systems. For example, using prescribed fire to assist with dieback control (Shea 1975) necessitated the development and validation of prescriptions to enable controlled fires to be safely implemented under warm, dry summer conditions. The requirement of moderate-intensity fires under dry conditions to regenerate animal habitat on specific sites (Christensen 1980) also required field experimentation to develop fire prescriptions which could be implemented with confidence. Extensive fire behaviour studies have been conducted in pine plantations to update the Red Book tables so that they adequately cater for the needs of plantation managers (Ward 1971; McCormick 1973; Burrows 1981; Burrows *et al.* 1988). Valuable stands of karri regrowth required protection and an obvious strategy was to carry out fuel reduction burning. However, young karri are very fire-sensitive and burn prescriptions needed to be precise. A series of studies aimed at measuring fuels and identifying conditions of fuel, weather and fire behaviour suitable for conducting prescribed burns in young karri were carried out (McCaw 1986).

The continued expansion and validation of the Red Book has been in response to changing fire management needs. Fire behaviour prediction systems must be flexible, reliable and responsive to management needs.

Field Application of the Red Book

The Red Book provides reliable estimates of fuel moisture contents and head fire rates of spread for six standard structural forest fuel types common to the south-west of Western Australia. These values which are derived from environmental factors of weather, topography and fuels have important applications to fire prevention and suppression planning and operations.

Moisture Content

The prediction of surface moisture content provides a reliable estimate of the ignition probability of each fuel type. This information is vital in determining the success or otherwise of ignition of prescribed fires such as fuel reduction fires and regeneration/slash fires. The accurate prediction of surface moisture content of the entire range of fuel types is particularly critical in multiple-stage-ignition fires where complex fuel types are progressively burnt over a period of time, sometimes lasting two or three months. Thus, it is possible to gradually burn 70 to 80 percent of a burn area whilst maintaining fire intensities and scorch damage within prescribed limits. The prediction of moisture content differentials between the open fuels of a logged coupe and the adjacent forest fuels is also effectively used to facilitate the control of high-intensity slash fires within their boundaries.

The prediction of a moisture differential is also critical for a number of other burning operations including slash fires under pine (*P.radiata and P.pinaster*) plantations, and 'tops disposal' (i.e. burning the tree crowns left on the ground after logging) in hardwood stands. In these fires, the aerated fuels of the crowns are burnt whilst the litter fuels are only just dry enough to permit fire to run between heaps, but not so dry as to cause fire intensity to exceed prescribed limits and cause damage to the standing crop trees.

The moisture content of surface fuels can be predicted for any time of the day. This information is useful in determining the start time at which ignition can be expected, and the number of hours the fire will continue to burn. The ignition time and the hours of burning dictate the ignition spacing in a fuel reduction fire where it is planned that the individual spot fires will join up in the cooler night conditions, and thereby greatly reduce any potential scorch damage resulting from the interaction of these spot fires.

Headfire Rate of Spread

The surface moisture content and the wind speed are used to calculate the fire danger index for jarrah forests. The index is expressed in terms of the forward rate-of-spread of a headfire (units of metres/hour) burning under specified site conditions which broadly represent those typical of upland jarrah forest carrying a 5-year old fuel, or approximately 8 t ha^{-1} of fuel load. The index can be corrected to allow for cases where fuel load, forest structure or slope depart from those otherwise assumed. Similarly a fire danger index can be determined for karri and associated southern forest types.

Each day, every forest district calculates the fire danger index within nominated weather forecast zones using weather forecasts. The fire manager also calculates, by computer, the headfire spread rates for all the various fuel types, fuel loads and slope conditions that have been identified within each of the major forecast zones. This information provides the basis for planning prescribed burning operations as well as fire preparedness and fire response levels.

The forest fire danger index is displayed on large roadside signs to warn the passing public of the fire danger level and to create in forest users an informed awareness of fire.

The daily fire danger index provides the basis for setting the appropriate detection and fire response levels. Aerial surveillance schedules vary from a single flight at low indices to almost continuous flights which may commence at 7.00 am and finish at dusk. Similarly, pre-set despatch orders will vary from a limited response at low indices, to one where all the forces from within the district and forces from the neighbouring districts are required to be on full alert ready to be despatched to a fire emergency. If the fire danger index exceeds 140 m hr^{-1}, or if three or more departmental fire gangs are committed to the fire, then a large fire organization (LFO) is established. The LFO structure ensures that all the necessary functions required to combat and control a large wildfire are adequately undertaken by trained and accredited personnel.

Limitations of the Fire Behaviour Tables

The Red Book tables, like all other similar fire behaviour prediction systems can only ever be a guide to likely fire behaviour. This is because the inherent biological, spatial and climatic variations within relatively small areas cannot be totally accounted for, even with the most sophisticated monitoring equipment and analysis techniques. Thus, it is always necessary whenever highly accurate estimates of fuel moisture and fire behaviour are required, that these be verified with field tests and samples.

The tables for predicting fuel moisture content in the Red Book are based on field samples collected from Western Australian forests that represented the middle range of their canopy cover extremes, and where terrain was relatively flat. Thus, the table predictions are likely to underestimate the dryness of southern slopes or stands with dense canopies, whilst the opposite is the case for both northern aspects or open stands.

The tables do not account for fuel moisture differences due to variations in soil types although this has not been a major source of error in the eucalypt forests due to the close connection between soil type and forest type in Western Australia. However, this is not the case for pine plantations which have been planted on a wide variety of soil types.

Fuel moisture content predictions are based on the forecast of the weather parameters of temperature, relative humidity and rainfall. Thus the provision of an accurate weather forecast is critical. Rainfall amount is a particularly variable parameter and can affect fuel moisture in numerous ways due to variation in its intensity, duration, periodicity, location and droplet size. To overcome this variability, it is common practice to carry out field measurements within representative forest types. In addition, pre-burn sampling is recommended where it is vital to derive accurate fire behaviour estimates.

Field experience has shown that the fuel moisture content predictions are most reliable during spring and early summer. This is because most of the research data were collected during this period of mild weather when the bulk of the prescribed burn operations are carried out.

Although the seasonal variation in moisture prediction requires further investigation, it is likely that this error may be overcome by linking the moisture content calculations with the Soil Dryness Index which has been adapted for Western Australian conditions (Burrows 1987).

The weather forecasts are derived from observations taken at point sources. Thus the forecasts are best related to these point sources, and any attempt to use these forecasts and derived fuel moisture calculation for areas other than these points may introduce a further error due to spatial variation in weather.

The accuracy of Red Book fire behaviour predictions for the major commercial forest types in Western Australia has been found, by field experience, to be within acceptable limits for most conditions. In particular, predictions of the behaviour of low-intensity fires burning in mild conditions have been remarkably accurate.

Wind speed is the most important variable affecting jarrah forest fire rate of spread, but is the most difficult to predict accurately. Forecast wind speeds are given for standard exposures, but current fire spread predictions are based on wind speed at 1.5 m in the forest. Further research into the affects of different fuel structures and vegetation types on in-forest winds is required to more accurately predict fire spread rate from forecast wind speed.

Until recently, fire behaviour for fires burning under dry soil conditions, or in extreme weather conditions, has tended to be underestimated. This was possibly due to the fact that the bulk of the data for the rate-of-spread calculations were collected from low to moderate-intensity fires. However, the latest Fire Behaviour Tables (Sneeuwjagt & Peet 1985) have incorporated the findings by Burrows (1985) derived from the high-intensity fire behaviour studies (Narrik) associated with the (CSIRO) Aquarius Project. As a result, the current tables have been found to provide reliable fire behaviour predictions for intense forest wildfires that have occurred in Western Australia since

1985. It is expected that further improvements will be introduced once the Narrik fires analyses have been completed.

The Red Book was initially designed to provide only for the Western Australian hardwood forests and pine plantations. Fuel models were determined solely from the local forest fuel types. The six structural fuel types have been found to be a simple and effective representation of the main scrub fuels found throughout the Western Australian forests. These standard fuel types and the fire spread model were not designed for open woodlands and non-forest vegetation types such as the heaths and the spinifex hummock grasslands that cover much of Australia. The Red Book has not been tested for its application to forest types in States outside Western Australia. However, there is every reason to believe that the Red Book may be applied effectively to most of the sclerophyll forest fuels in other Australian States. This can only be determined through intensive sampling of fuel moisture contents and observation of fire behaviour in the various major forest fuel types.

The expansion of the Red Book table format to include fuel characteristics and fire behaviour predictions for other vegetation types will eventually make this table format cumbersome and slow to use. This has been recognized and currently the Department of Conservation and Land Management is developing a computer system to make the various calculations (Beck 1988). The extensive tables and relationships peculiar to empirically derived fire behaviour models is no longer a limitation with modern high speed computers able to handle large data sets.

Conclusion

Fire behaviour models, whether they be empirically or mathematically derived, are not a guarantee for effective fire management. In any event, the models are only guides to planning and decision-making and must be complemented by solid, achievable management objectives, strategies and commitment. Resources to do the job and an ongoing, pertinent research and development program are other necessary ingredients to achieve fire management goals. Computers alone cannot suppress wildfires.

The Red Book has provided a valuable support for fire management in Western Australia. New opportunities for fire management and fire research will ensure the continued growth and application of the Red Book.

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N.P. Cheney & A.M. Gill

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