# Application of Fire Behaviour to Fire Danger and Wildfire Threat Modelling in New Zealand

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**Abstract**

Information on fire behaviour in different vegetation types is an essential input in wildland fire management system applications. This paper describes how fire behaviour models derived from experimental burning and wildfire documentation have been used as the basis for developing a number of fire management decision support tools in New Zealand. Three separate spatial applications have been produced for modelling current, historical and forecasted fire dangers using the Fire Weather Index and Fire Behaviour Prediction components of the New Zealand Fire Danger Rating System. Historical peak summer fire climate components were defined for use in the New Zealand Wildfire Threat Analysis model within both the Hazard component (Head Fire Intensity) and the Risk component to model the probability of sustained ignition. This information is useful for long-term strategic fire management planning. Current fire weather, fire behaviour and fire danger are updated daily by the National Rural Fire Authority for dissemination via the Internet to fire authorities and the public. The maps are used for short- to medium-term fire management planning applications. The New Zealand Meteorological Service have incorporated the Fire Weather Index System into their forecasting models to produce hourly forecast maps useful for short-term planning and incident management. This is presented to rural fire authorities through their MetConnect web site. These examples are used here to illustrate the essential links between fundamental research on fire behaviour and development of expedient operational fire management solutions.

## Introduction

New Zealand is a country with a land area of 27 million hectares and only 4 million people, so that it can for the most part still be considered rural. It has a generally temperate, maritime climate, yet comprises an extremely diverse range of microclimates, primarily as a result of topography, from semi-arid (rainfall <350 mm/yr) to sub-tropical (rainfall >7000 mm/yr). In a reversal of the widespread land clearing that followed human settlement (during the 1800s and early 1900s), pasture retirement and associated reversion to scrublands or planting with exotic forest species are increasingly resulting in more complex fuel types with higher fuel loads and continuous fuels (Craig 2002). New Zealand does not have one of the most severe fire climates in the world, but still experiences 2500 wildland fires each year that burn around 7000 ha of rural lands[1]. These fires are primarily human-caused, and many continue to occur as a result of escapes from (both permitted and unauthorised) prescribed burning activities. To manage this risk, all aspects of fire management (fire prevention, preparedness and suppression) outside urban fire districts are the responsibility of rural fire authorities. These are largely determined by land ownership, comprising areas managed by the Department of Conservation (state lands), rural fire districts (NZ Defence Force, forestry companies) or

[1] From statistics produced by the National Rural Fire Authority (NRFA) based on the Annual Return of Fires form completed by New Zealand fire authorities.

territorial authorities (local government). In recent times, the trend is increasingly towards fewer, amalgamated rural fire districts covering larger areas, and providing more standardised and professional fire management.

To support the research and development needs of rural fire authorities, a national fire research and technology transfer programme was re-established at the New Zealand Forest Research Institute (formerly FRI, now Forest Research) in 1992 following a lapse of 15 years. Since its inception, Forest Research's rural fire research programme has set about quantifying key features of the New Zealand fire environment and the effect these have on ensuing fire behaviour. The major aim of the programme is the development of the New Zealand Fire Danger Rating System (NZFDRS) (Fig. 1a) by extending the Canadian philosophy and concepts to local conditions. New Zealand adopted the Canadian Fire Weather Index (FWI) System (Fig. 1b) in 1980 as the basis for a national system of rating fire danger in exotic pine plantations (Valentine 1978). This was the precursor to the later adoption and adaptation of the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al. 1989) for use throughout New Zealand (Fogarty et al. 1998).

As knowledge and understanding of fire behaviour and fire danger has increased, there has been an increased demand for tools and applications to utilise this information. Technology such as Geographic Information Systems (GIS) and the Internet have in part enabled fire management agencies to respond to this demand, but have in turn led to calls for more detailed (spatially explicit) information on fire danger and fire behaviour potential. This paper illustrates the link between research on fire behaviour modelling and fire danger rating and the development of a number of new fire management decision support tools in New Zealand. Three separate spatial applications have been produced for modelling historical, current and forecasted fire dangers using components of the (NZFDRS) (see Fig. 1a).

## Fire Danger Rating and Fire Behaviour Prediction in New Zealand

The NZFDRS is used by rural fire authorities to assess the probability of a fire starting, spreading and doing damage. It provides information which supports fire protection decision making (see Fig. 1a) in the areas of fire prevention (e.g., public warnings, permit issue, fuel reduction burning), presuppression (e.g., preparedness and training, initial attack planning) and suppression (e.g., fire behaviour prediction, strategies and tactics). At the core of the NZFDRS, the FWI System (see Fig. 1b) provides numerical ratings of relative ignition potential and fire behaviour, based solely on weather observations recorded by a network of remote automatic weather stations located around the country. Daily observations made at noon local standard time of temperature, relative humidity, wind speed, and 24-hour accumulated rainfall are used to compute values of the three fuel moisture codes and three fire behaviour indexes (Van Wagner 1987). These may be determined from tables (e.g., Anon. 1993) or by computer calculation (Van Wagner and Pickett 1985).

The FWI System was developed to rate fire potential in a reference fuel type (Van Wagner 1987). Therefore, the relative numerical outputs have different meanings in different fuel types, and no absolute measures of fire behaviour are provided. Canadian fire researchers have correlated the FWI System's codes and indices to observed fire behaviour

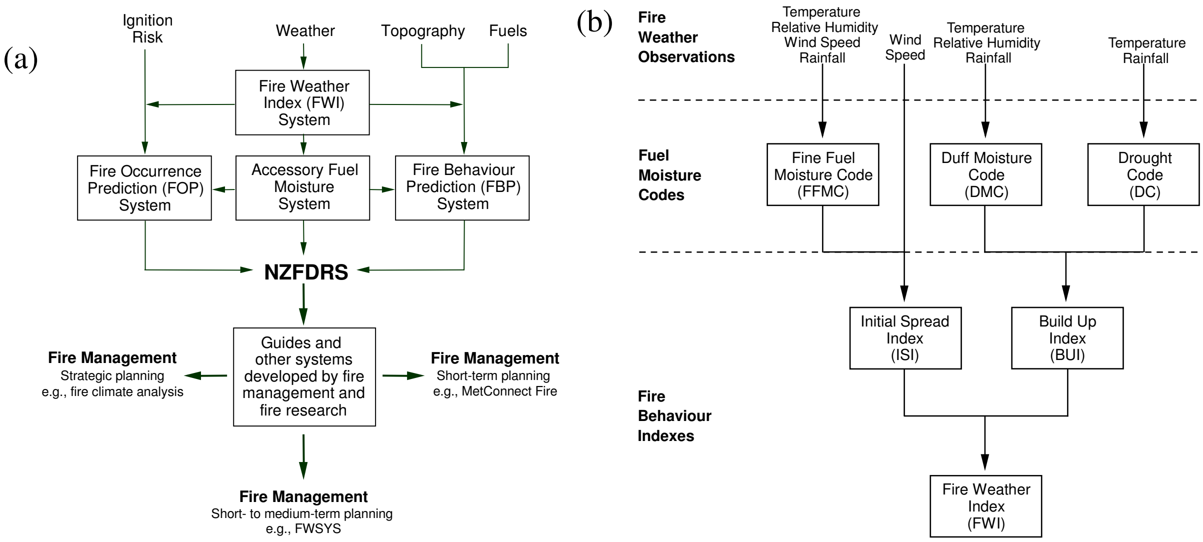


Figure 1. Simplified structure diagrams for: (a) the New Zealand Fire Danger Rating System (NZFDRS), illustrating the linkage to fire management actions (adapted from Stocks et al. 1989); and (b) the Fire Weather Index (FWI) System (after Anon. 1993).

characteristics in many diverse fuel types to produce the Fire Behaviour Prediction (FBP) System module (Forestry Canada Fire Danger Group 1992) of the CFFDRS, based on a minimal number of experimental fires (Alexander and Quintilio 1990) and wildfires (Alexander and Lanoville 1987). The resulting fire behaviour models have been used to derive decision aids for broad-area fire danger rating (e.g., Alexander and De Groot 1989) and associated prevention and preparedness systems (e.g., De Groot 1990).

Within the NZFDRS, the FWI codes and indices are used to determine the fire danger class for forest, grassland and scrubland fuels using the criteria defined by Alexander (1994). This prescribes that difficulty of control, as determined by head fire intensity, be used to define the fire danger classes. The delineation of classes in the classification scheme is based on the effectiveness of various types of resources as fire intensity increases, up to a point (EXTREME) where fires are considered to be uncontrollable using conventional techniques (i.e., >4000 kW/m). In the forest fire danger classification scheme, expected fire behaviour in the Conifer Plantation (C-6) Fuel Type of the FBP System module (Forestry Canada Fire Danger Group 1992) of the CFFDRS (see Fig. 1b) is used to represent fire danger in New Zealand's exotic pine plantations (Alexander 1994). The criteria and associated suppression effectiveness guidelines have been found to correlate well with observed fire behaviour characteristics from a number of significant fires (e.g., Pearce and Alexander 1994). To cater for the increased application of the NZFDRS throughout the country, a fire danger class criteria applicable to grasslands was added using the fire behaviour relationships for the Natural (Standing) Grass (O-1b) Fuel Type in the FBP System (Alexander 1994). This too, has been successfully correlated with observed fire behaviour from a number of historic and recent wildfires (e.g., Rasmussen and Fogarty 1997). More recently, a new fire danger class criteria for scrubland fuels has been produced (NZ Fire Research 2000) and subsequently refined based on observations from experimental burning trials plus several wildfires (Pearce 2001).

To develop and/or validate the models on which these fire danger class criteria are based, it has been necessary to compare the relative numerical outputs of the FWI System with the relevant fire environment or fire behaviour characteristics following the Canadian approach for experimental burning trials and wildfires burning over a wide range of conditions

(McAlpine et al. 1990). Since 1993, more than 100 experimental fires have been carried out by Forest Research in a variety of fuel types, including manuka/kanuka and gorse scrub, tussock grasslands, crop stubble, rank grass, native pakihi wetlands and logging slash (NZ Fire Research 1994-2002, Catchpole et al. 1999). Fire behaviour has also been documented during more than 30 opportunistic wildfire events (Pearce and Alexander 1994, Fogarty et al. 1997, Rasmussen and Fogarty 1997). Results from the research have allowed the National Rural Fire Authority (NRFA) to issue daily fire danger ratings for forest, grassland and, more recently, scrubland fuels, for its network of fire weather monitoring stations (see Fig. 2). The experimental burning program and the development of fire behaviour models remain the main research focus of Forest Research's fire research programme. While research continues on validation of existing models, emphasis is increasingly being placed on development of new models for fuel types distinct to New Zealand.

The availability of improved fire behaviour and fire danger rating capability in New Zealand as a result of this research has lead to a number of new spatially-based decision support tools being developed. These tools combine information on fuels obtained from the New Zealand Land Cover Database (produced by Terralink NZ Ltd) with the weather and fire danger information provided by a network of remote automatic weather stations (RAWS) to predict potential fire behaviour and suppression difficulty in a GIS environment. The RAWS network is at the heart of the New Zealand fire weather monitoring system run by the NRFA, and comprises over 150 weather stations (Fig. 2).

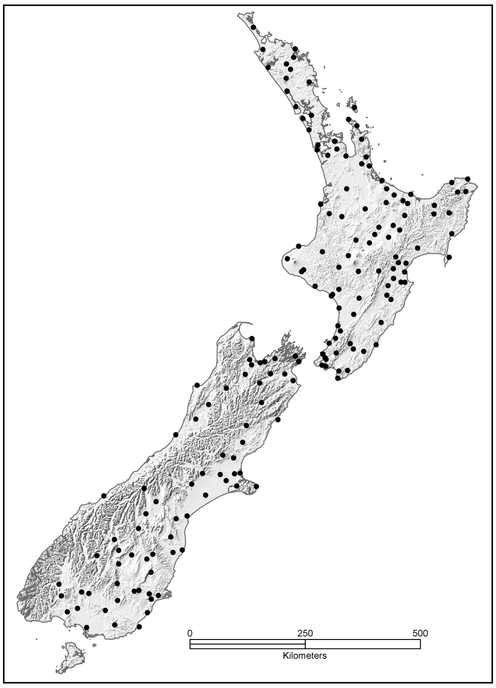


Figure 2. Location of stations within the NRFA's fire weather monitoring network.

Analysing Historical Fire Climate – Fire Behaviour Potential

In 2000, the NRFA contracted Landcare Research to produce maps illustrating the fire behaviour potential across New Zealand (Leathwick and Briggs 2001). A key element of this was production of GIS surfaces representing New Zealand's fire climate. Historical FWI values for 137 stations contained within the NRFA's fire weather archive were summarised to find the worst 20% of days occurring in the fire season (October-April) at each weather station. Average values for each of the FWI System components were then calculated for these 'extreme' days for each station. Mathematical surfaces were fitted to these averages, allowing extreme values for each of the FWI codes and indices to be predicted across all of New Zealand, including at sites remote from weather stations. The fire climate maps therefore describe fire dangers under an "average worst fire season" scenario.

The next step in defining fire behaviour potential was to calculate fuel loads for land cover classes described in the Land Cover Database. Most cover classes were allocated a fixed fuel load (e.g., 3.5 t/ha for pastoral grasslands, 20 t/ha for scrubland; after Alexander 1994, Pearce 2001); however, forest fuel loads were calculated using values for the BUI component of the FWI System (after Alexander 1994) derived from the FWI fire climate layer (Fig. 3). Rate of fire spread was then calculated for each fuel type using the appropriate formulae (after

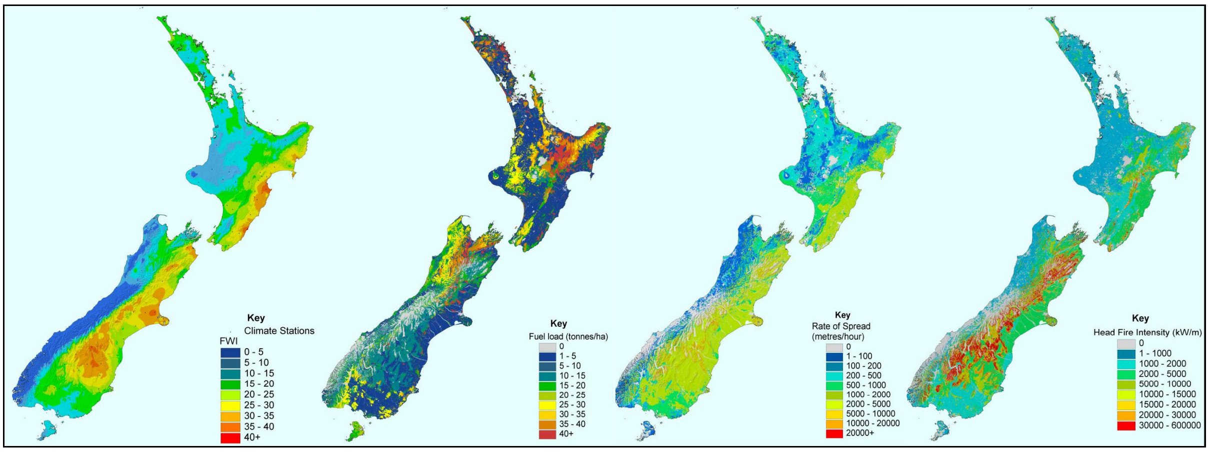

Figure 3. Maps of average FWI, potential fuel load, and head fire rate of spread and intensity, used to define the 'hazard' component in the New Zealand WTAS.

Alexander 1994, Pearce 2001). The rate of spread estimates were then adjusted for the influence of slope using the Slope Correction Factor contained in the Canadian FBP System (Forestry Canada Fire Danger Group 1992). Finally, head fire intensity was calculated by combining estimates of slope-corrected rate of spread and calculated fuel loads (see Fig. 3), using Alexander's (2000) simplification of Byram's formula.

The resulting head fire intensity map aims to depict potential fire behaviour (i.e. 'fire hazard') for the "average worst fire season" scenario. It is an essential component of the New Zealand Wildfire Threat Analysis System (WTAS) which, in addition to this hazard module, also includes modules describing 'risk' (ignition potential[2]) and 'values' (at risk) that are combined using GIS to define the overall wildfire 'threat' (Cameron et al. 2001, Majorhazi 2001). As it uses a single scenario (as opposed to day-to-day weather information), the WTAS is designed to be used as a long-term strategic fire management planning tool. Analysis of the component map layers produced using GIS enables fire managers to drill down to identify the factor(s) contributing to wildfire threat and to develop appropriate mitigation measures. Identification of areas of high risk allows better targeting of fire prevention activities (e.g., public education, enforcement); similarly, identification of areas of high hazard can indicate priority areas for hazard reduction (e.g., prescribed burning, fuels removal) and, for high value areas, potential need for modified suppression response (e.g., resource allocation, response times, suppression tactics for special zones). The New Zealand WTAS methodology is presently being implemented by fire authorities around the country, with a number of local and regional analyses underway.

Monitoring Current Fire Danger – Fire Weather System (FWSYS)

Fire weather monitoring involves collection of weather data from the network of remote automatic weather stations (RAWS) and, in New Zealand's case, calculating the FWI indices to determine daily fire danger in accordance with the criteria produced by Alexander (1994). The NRFA have been monitoring daily fire danger and distributing fire weather reports since 1993. A manually operated system was used at that time and was replaced with an automated system in 1996. This outdated system was replaced in October 2002 with a new Fire Weather System (FWSYS) that utilises the latest GIS and database technology to deliver a greater

[2] The Fine Fuel Moisture Code (FFMC) surface is also used to model the probability of sustained ignition to define the 'risk' component.

range of information to a wider audience. In doing so, it reconises that accessibility and presentation are important elements in helping users understand and utilise daily fire danger information.

In deciding on what path to take for development of the new system, the NRFA looked overseas and, in particular, to Canada due to existing links via the FWI System and fire research. A decision was made to combine the capabilities of two systems developed by the British Columbia Ministry of Forests (BCFS) Protection Branch and Canadian Forest Service (CFS) Fire Research group. The BCFS provided communications software, and data access and query tools, while the CFS provided a customised version of their Spatial Fire Management System (sFMS). An ArcView GIS application for creating maps of fire danger and potential fire behaviour, sFMS has successfully been applied nationally in Canada, as well as in Florida, Mexico and SE Asia (Englefield et al. 2000).

Within FWSYS, current fire weather, fire danger and fire behaviour potential are updated daily based on information collected from the network of around 150 RAWS (see Fig. 2). Polling software downloads the daily (and hourly) data from each station and archives it within the NRFA's fire weather database. As data are collected, the FWI System and fire danger class calculations are performed. Any non-reporting stations receive substitute values from a designated alternate station (this will be replaced by authentic data the next time the station is successfully contacted). sFMS then uses the processed FWI data to create maps for each of the FWI System components, which are subsequently uploaded to the website. The appropriate FWI components and fuel type and load information (after Alexander 1994, Pearce 2001) to produce maps of daily fire behaviour potential for each station location, including head fire rate of spread and intensity, and fire danger class (Fig. 4). The combination of New Zealand's mountainous terrain and clustering of weather stations in dry, windy areas (especially in the South Island; see Fig. 2), meant that use of the standard method for interpolation of data between station locations (inverse distance weighting (IDW); Englefield et al. 2000) contained within sFMS was not appropriate. The method developed by Landcare Research (Leathwick and Briggs 2001) for use in defining the spatial fire climate surfaces was therefore incorporated into sFMS and adapted for creation of daily maps.

Access to the new FWSYS is via several different mechanisms, depending on the level of information required. For the general public, access is through the Internet and the NRFA's website (www.nrfa.fire.org.nz), and includes access to maps of fire danger (see Fig. 4), daily

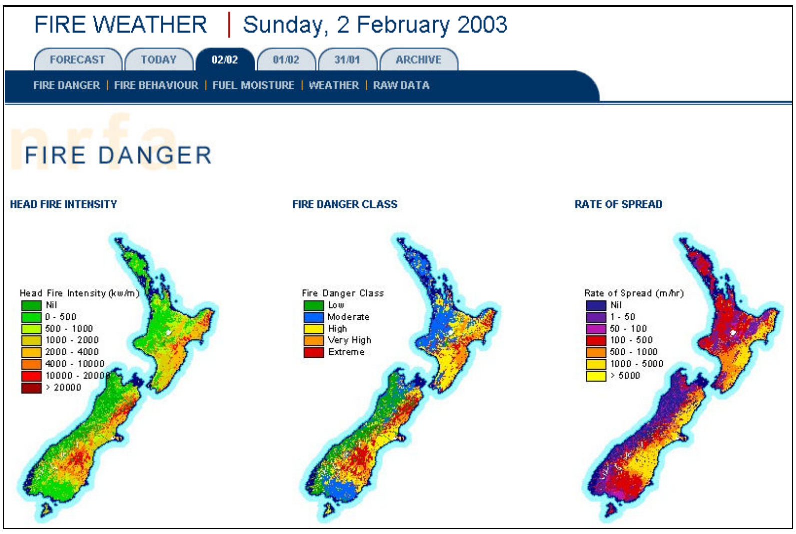


Figure 4. Example screen shot of mapped daily fire danger outputs from the NRFA's Fire Weather System (FWSYS), including head fire intensity, fire danger class and rate of fire spread.

fire weather reports in tabular form, and fire weather forecasts. For fire managers, access is via the NZ Fire Service's "Ruralnet" Intranet system and, as well as the above information, also includes access to data query and analysis tools, graphing capability and data management. A user-definable option allows users to select individual or groups of stations and time periods they wish to view, graph or download data for. The combination of current fire weather and fire danger information and access to the database of historic data makes the FWSYS an invaluable tool for short- to medium-term fire management decision support. Some examples of areas of application include setting of fire season status and restrictions, fire permit issue, lookout manning, preparedness planning and fuel reduction burning, as well as the public notification of fire danger intended by Alexander (1994).

Forecasting Future Fire Danger – MetConnect Fire

Research recently completed by the Meteorological Service of New Zealand Ltd (MetService) has also resulted in production of a fire weather forecasting tool, known as MetConnect Fire, that combines forecasted data from MetService's mesoscale weather prediction model with hourly FWI System calculations (Alexander et al. 1984). The model predicts weather data for a grid across New Zealand (12 km resolution), based on coarse world model data. Model output is used to produce spot forecasts for specific weather station locations. These spot forecasts are then adjusted for elevation and statistically fine-tuned using actual observations from each location. Forecasted hourly values for temperature, relative humidity, wind speed and rainfall are used to calculate both daily and hourly FWI System values for each station location to produce forecasted fire danger data out for a period of 72 hours (3 days). Currently, predictions are being made for 43 station locations. Grid and station data are also interpolated to produce maps of each of the hourly FWI System components (i.e., FFMC, ISI and FWI) that depict the spatial variability of forecasted fire danger across the country.

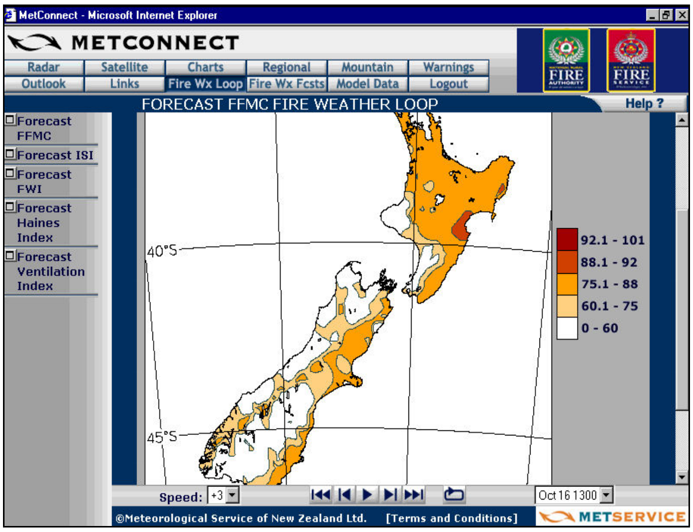

Figure 5. Example screen capture from the MetService's MetConnect Fire package.

The result is displayed on a web browser (Fig. 5) in the form of both animated graphics and text output. Information is updated each time the weather prediction model produces a new forecast (i.e., every 6 hours). Some of the features available through MetConnect Fire are: tabular, mapped and animated forecast FFMC, ISI and FWI; tabular, mapped and animated forecast Haines Index and Ventilation Index; animated satellite images; animated rain radar images; observations from Remote Automatic Weather Stations; regional, mountain and coastal forecasts; Severe Weather Warnings and extended weather outlooks; and animated weather maps. The forecast information provided by MetConnect Fire is extremely useful for short-term planning (preparedness planning, prescribed burning, permit issue) and incident management (fire behaviour prediction).

## Conclusions

Technology such as GIS and the Internet have enabled fire management agencies to produce a range of new tools for displaying spatially explicit information on fire danger and fire behaviour potential. However, the development of three such tools in New Zealand illustrates the essential link required with research on fire behaviour modelling to ensure the validity and accuracy of the resulting fire danger information. An ongoing fire behaviour research programme of experimental burns and wildfire documentation is a critical component of this research, and will ultimately result in improved fire behaviour models for a wider range of fuel and topographic situations. In New Zealand's case, Forest Research is continuing research to validate fire behaviour and fire danger models, and to develop new ones for fuel types not yet covered. Landcare Research and others are working on an enhanced version of the land cover database (LCDB2) which will provide improved definition of vegetation types. However, this will potentially also result in a requirement for improved fire behaviour models covering an even greater range of fuel types.

Advances in several other areas are also likely to lead to further improvements to the tools discussed, together with a number of new developments that will add to the suite of tools available to fire managers. The NRFA is considering use of additional rainfall station data to supplement that from the RAWS network contained within FWSYS in an effort to improve the accuracy of spatial interpolation. The National Institute of Water and Atmospheric Research (NIWA) is also undertaking research to look at RAWS data accuracy, a network analysis of station locations, and spatial interpolation techniques, all of which will potentially improve the quality of output for all the decision support tools in the future. MetService is also investigating the introduction of 14-day FWI predictions based on longer-term weather forecasting techniques. NIWA has been conducting research into the prediction of fire season severity through utilisation of relationships between global and regional climate factors and seasonal severity, as an input into 3-monthly forecasts of regional fire danger and likely fire season severity. Similarly, Forest Research has been investigating the prediction of fire season severity based on comparison with past fire seasons, using the database of historical fire weather and fire danger information archived within the NRFA's FWSYS. This archive was also used by Forest Research to conduct an analysis of long-term averages and extremes of fire climate for stations across New Zealand.

In developing the sorts of fire management decision support tools discussed here, it is also important that fire managers and researchers alike recognise the requirement to balance operational need against scientific rigour (Pearce 2001). Researchers are constantly having to balance the requirements of applying scientific methods to their work with the requirements of practitioners to have the tools and information available for use. Although identified as a key step in the successful implementation of new systems, technology transfer and training is still often overlooked. Researchers therefore need to work closely with end-users in establishing research direction and priorities, and on developing a common understanding of research and its application. There are some applications where practitioners are happy to use tools for which research is still ongoing, particularly if they are better than what is currently available; however, in doing so, they must recognise the inherent limitations of the tool being applied. If tools are put into use before research has been completed and properly tested, then the results could be disastrous. As a final note, fire managers should also remember the old adage – "garbage in, garbage out". The end products developed through applied research are only as good as the underlying data and models on which they are based. It is therefore essential that continuing effort be placed on developing and refining the fire behaviour models on which the tools are based.

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