A GIS-supported model for the simulation of the spatial structure of wildland fire, Cass Basin, New Zealand

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Summary

1. The behaviour of wildland fire in spatially heterogeneous landscapes was simulated using a model (PYROCART) that integrates the Rothermel fire spread model and a geographic information system (GIS).

2. The principal aims of the research were to test the applicability of overseas fire behaviour models to New Zealand ecosystems, and to assess the applicability of GIS to fire spread prediction.

3. The model was validated using an uncontrolled fire that occurred in the Cass Basin, South Island, New Zealand in May 1995. This fire burnt 580 ha across a complex vegetation mosaic comprising shrubland, stands of Nothofagus solandri var. cliffortioides, bog and tussockland.

4. The overall predictive accuracy of the model was estimated to be 80%. Prediction accuracies within different fuel types and slope angles are also presented. Fuel type and slope appeared to be the dominant influences on fire spread. No trends in prediction accuracy by wind speed or direction were apparent. The predicted burnt area and the real burnt area had a similar overall shape. It was found, however, that at high wind speeds the model tended to over-predict rates of fire spread in some directions.

5. The PYROCART model shows potential as a land management tool, especially for the testing of hypotheses concerning land management strategies. However, due to the complex input data and parameterization techniques it requires, it is less suitable for in situ fire management.

Key-words: fire dynamics, fire modelling, geographical information systems, Rothermel model, spatial modelling.


Introduction

New Zealand has a fire history extending back at least 20 million years (Stevens, McGlone & McCulloch 1988). Natural fires were sporadic, but a dramatic rise in charcoal occurrence about 1000 years ago is coincident with Polynesian colonization and indicates a widespread phase of deforestation that reduced New Zealand’s forest cover by approximately 40% (McGlone 1983, 1989). With European settlement a further 20–30% of the primary forest, and much of the regenerating lands, were cleared, burnt and developed for pastoral use (Basher, Meurk & Tate 1990). Fire continues to be used, often in an ad hoc manner, as a cheap and effective means of both stimulating new growth for feed and suppressing unpalatable woody vegetation in tussock grassland and scrub.

Despite the increased importance of fire in post-settlement environments in New Zealand, little research has specifically considered its role in indigenous ecosystems. What literature has been published has been concerned with historical fire regimes as assessed from palynological records (McGlone 1983, 1989) and post-fire vegetation dynamics, especially in montane and subalpine tussock grassland (Payton & Brasch 1978; Payton & Mark 1979; McKendry & O’Connor 1990; Gitay et al. 1991; Mark 1994), with few papers considering the recovery of other ecosystems after fire (Ledgard, Davis & Platt 1987; Timmins 1992) or the effects of...
fire on the native fauna (Patterson 1984). Little research in New Zealand has addressed the mechanics of fire and its behaviour; nor is there a national fire danger rating system, as used extensively in countries such as the USA, Canada and Australia. This lack of information regarding fire dynamics in New Zealand’s indigenous ecosystems hampers fire management, and the consequent paucity of quantitative fire behaviour data (especially for indigenous fuels) makes the use of fire prediction systems developed overseas problematic.

The fire spread model of Rothermel (1972) has been widely used for the prediction of fire behaviour. This model uses a series of flux equations to describe the basic physical and chemical processes of combustion. Fire spread is assessed by a measurement of the differences between the various heat fluxes (Clarke & Olsen 1996). The foundations of fire geometry upon which most subsequent fire modelling has been based were developed by Anderson (1983), who describes the geometry of a wind-driven fire as a double-ellipse, and demonstrates how fire area and total perimeter, as well as maximum width, may be assessed. These relationships are based on the work of McArthur (1966), who showed that the length-to-breadth ratio of a fire is a function of wind speed. The elliptical fire shape model and its derivatives have been used widely in the development of spatial models of fire spread and behaviour (Pyne, Andrews & Laven 1996).

Over the last decade spatial information technologies have been used increasingly to provide information for wildland fire planning. Much of this effort has been aimed at mapping the spatial distribution of fire hazard (Hamilton, Salazar & Palmer 1989; Chuvieco & Salas 1996). The use of geographical information systems (GIS) for the actual simulation of fire behaviour has been comparatively infrequent. However, because most fire models tacitly assume spatial homogeneity in the landscapes in which they are used, GIS, in conjunction with cellular automata models, offer benefits to those modelling fire behaviour in spatially complex landscapes. Examples of the use of GIS to model the spatial behaviour of fire include the FIREMAP system of Vasconcelos (1988), Vasconcelos & Guertin (1992) and Vasconcelos, Periera & Zeigler (1994), the cellular automata model of Clarke, Brass & Riggan (1994) and Clarke & Olsen (1996), and the vector-based FIRE! model of Green et al. (1995).

The research presented here has two principal aims: first, to test the applicability of the Rothermel fire spread model to New Zealand (NZ) ecosystems, and secondly, to assess the role GIS may play in fire spread prediction. The paper is structured in such a way that the conceptualization and development of the model are presented first, followed by a description of the testing and validation of the model. Finally, the limitations of the model and the ways in which it may be improved in the future are considered.

Materials and methods

STUDY SITE

The PYROCART model was parameterized for the natural and semi-natural vegetation types occurring in the Cass Basin, which lies at the northern end of the Craigieburn Range in the middle part of the Waimakiriri watershed, in western Canterbury, central South Island, NZ. The Cass settlement lies at an altitude of 590 m a.s.l., with surrounding land rising to between 1200 and 1800 m (Fig.1). The geomorphic history of the region is complex, with the area having been affected by repeated glacial activity and, since the last glaciation, by intense erosional and fluvial action.

The vegetation of the Cass Basin has been highly modified since human settlement of the area. Much of the plant communities found in the landscape have been ‘induced’ by anthropogenic influences such as repeated burning and grazing. These modifications are thought to have been induced prior to European settlement of the region, probably as the result of a series of catastrophic fires beginning at least 300 years ago and continuing to the present day (Burrows 1960). The plant assemblages found on the west bank of the Cass River may be divided into three broad classes: stands of Nothofagus solandri var. cliffortioides (mountain beech), scrub communities and areas of bog. [Nomenclature of species names follows Allen (1961), Moore & Edgar (1970), Healey & Edgar (1980) and Wilson & Gallaway (1993) where necessary.] The composition of the scrubland that covers the majority of the study area is mixed but dominant species are Cassinia leptophylla (tauhinu), Leptospermum scoparium (manuka), Corokia cotoneaster (korokio) and Discaria toumatou (matagouri). A feature of the glacial gravel deposits that cover the area are the numerous depressions with exposed subsoils; these favour frost heave and thereby prevent the establishment of any vegetation. Swampy areas are characterized by adventive-dominated communities with small areas of the native Carex secta (pukio) present. In some places isolated Schoenus paniculatus tussocks are also found.

In May 1995, a wildfire burnt 580 ha of vegetation on the west bank of the Cass River. The fire occurred during a period of strong north-westerly (fohn) winds. Such conditions would have both dried the fuels and fanned the fire when it was in progress. The most severely burnt areas were stands of tall shrubs such as L. scoparium. The fire
appeared to have been relatively fast moving; there was evidence in places of the ground cover being ignited by fragments falling from the canopies of burning shrubs. Where shrubs were more widely spaced, the fire burnt the canopies and the ground layer immediately underneath them, but the grass between the shrubs was largely unburnt (Kelly 1995).

Outliers of colonizing *N. solandri* var. *cliffortioides* were largely killed by trunk scorching. It was evident, however, that fire failed to spread as successfully in stands of *N. solandri* var. *cliffortioides* compared with the shrubland. For example, in larger stands outer trees were burnt while those nearer the middle remained unharmed. As a result, most of the larger stands escaped serious damage. One stand

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**Fig. 1.** A map of the Cass Basin showing the location of the study site and the extent of the May 1995 fire (west bank of the Cass River).
to the south of Corner Knob remained entirely unburnt as flames swept around both sides of it. In Horrible Bog, fire damage was also relatively minor, with only small amounts of dry plant matter being burnt.

Model Development

This section outlines the development of the fire simulation model by reviewing the Rothermel model, describing the modelling framework and structure, and specifying the fire spread algorithm used.

The Rothermel fire spread model

The mathematical fire spread model of Rothermel (1972) was developed to predict the rate of spread of a fire at the flaming front in an environment specified by fuel, weather and topography descriptors. The Rothermel model is based on that of Frandsen (1971), which considers fire spread through radiative heat transfer and the law of the conservation of energy. The Rothermel model treats the spread of fire as a series of ignitions where the heat transfer from each successive strip of fuel raises the next strip to ignition temperature, thus propagating fire. The primary driving force in the calculations is dead fuels less than 6 mm in diameter; these are the fine fuels that carry the fire. Fuels larger than 76 mm in diameter are not included in the calculations at all (Andrews 1986). The model describes fire spreading through surface fuels (defined as those up to 2 m tall and contiguous with the ground) such as grass, brush and litter. The model is not applicable to crown fires, where fire spreads aerially, independent of the surface fuels; nor does it incorporate spotting.

Rothermel (1972) divides the necessary input variables for the model into three broad classes (Table 1).

Fuel type, fuel moisture content (FMC), wind and slope are assumed to be spatially and temporally constant over the period for which predictions are to be made (Rothermel 1972, 1983; Rothermel & Rinehart 1983; Andrews 1986). However, as wildland fires rarely burn in spatially uniform conditions, the fuel model and the length of prediction are crucial parameters. The uniformity of the landscape greatly influences the length of time over which any predictions of fire behaviour may be accurate. The more uniform the landscape, the greater the length of time over which accurate predictions may be made (Andrews 1986). Partitioning the landscape into a series of internally homogeneous cells and then applying the fire model to each cell can circumvent the assumption of spatial uniformity. It should be emphasized that the model presented here is based solely upon the fire spread model of Rothermel (1972) and not its subsequent refinements in the BEHAVE model (Burgan & Rothermel 1984; Andrews 1986). The development and application of the Rothermel model are described more comprehensively in Perry (1998) and the references contained therein.

Table 1. Classes of input parameters for the Rothermel model

<table>
<thead>
<tr>
<th>Fuel particle properties</th>
<th>Fuel array arrangement</th>
<th>Environmental parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat content</td>
<td>Fuel load (live and dead)</td>
<td>Wind speed</td>
</tr>
<tr>
<td>Mineral content</td>
<td>Mean particle size</td>
<td>Fuel moisture content (FMC)</td>
</tr>
<tr>
<td>Particle density</td>
<td>Mean fuel bed depth</td>
<td>Slope steepness (%)</td>
</tr>
</tbody>
</table>
The spread algorithm

As the Rothermel model only provides an estimation of rate of spread with the wind, it was necessary to correct for those situations where this was not the case. Anderson (1983) and Catchpole, Alexander & Gill (1992) consider the area directly affected by a burning piece of fuel to be an ellipse, in which the source lies in one focus and the major axis is parallel to the wind direction. The eccentricity of such an ellipse increases as a function of wind speed. Green, Tridgell & Gill (1990) give an expression which calculates rate of spread towards an arbitrary direction $y$ (in degrees from north):

$$R_y = \frac{F(1 - e)}{1 - e \cos(y - \omega + 180)}$$  

where $R_y =$ rate of spread (m min$^{-1}$); $F =$ forward rate of spread (m min$^{-1}$); $e =$ the eccentricity of the spread ellipse; and $\omega =$ the direction from which the wind is blowing.

Green, Tridgell & Gill (1990) also provide empirical formulae for eccentricity ($e$) in both forest and grassland fuels:

$$e = \sqrt{[1 - \exp(0.0058 - 0.0324w^{0.5})]} \quad \text{Forest}$$

$$e = \sqrt{1 - 0.826w^{-0.926}} \quad \text{Grassland}$$

where $w =$ wind speed (m min$^{-1}$). In both cases if $w \leq 1$, then $e$ is assumed to be 0.

Thus the expressions above allow calculation of the rate of fire spread in directions other than the direction in which the wind is blowing. The adjusted rate of spread is a function of wind speed (which determines the eccentricity of the ellipse), the forward rate of spread and the difference between the direction from which the wind is blowing ($\omega$) and in which the fire is travelling ($\theta$). The adjustment of rate of spread is at a maximum where the difference between $\omega$ and $\theta$ is $0^\circ$ (i.e. the fire is travelling into the wind) and rate of spread is unadjusted where the difference is $180^\circ$ (i.e. the fire is spreading with the wind). Green (1983) studied the model presented in equation 2 in detail and its validity was confirmed by Green, Gill & Noble (1983), who compared the shapes it produced against the final shapes of a number of experimental fires.

Although the Rothermel model treats fire spread on down-slopes as equivalent to that on flat surfaces, this assumption has been shown to be questionable (van Wagner 1988). Thus, PYROCART adjusts for down-slope rate of spread using the correction factor of van Wagner (1988). Equation 4 yields a minimum of 0.64 (64%) of the level spread rate on down-slopes of $22^\circ$ and regains the level spread rate again at approximately $45^\circ$:

$$SF = 1 - 0.330A + 0.00749A^2$$  

where $SF =$ the downhill spread rate factor, to be applied as a multiplier on the estimated level rate, and $A =$ the slope angle in degrees.

Following calculation of the corrected rate of spread, an evaluation of whether fire spreads into neighbouring unburnt cells occurs. This is a relatively simple, probabilistic procedure. Rate of spread is multiplied by the temporal resolution of the simulation (in minutes). This value is then divided by the model’s spatial resolution, which is corrected for diagonally contiguous cells where appropriate. This value is then compared against a randomly generated number between 0 and 1 and the cell is ignited if this number is exceeded.
MODEL PARAMETERIZATION

This section considers the techniques used to parameterize the PYROCART model such that it could be tested and validated using the fire described above. The techniques used in the evaluation of both physical (wind vector and terrain) and vegetation data are described. As with any model, predictive accuracy was largely a function of the success of the parameterization process, and so parameterization of the PYROCART model proved to be a major component of this research.

Vegetation mapping

A detailed map of the vegetation cover of the fire area was constructed based on a 1:8000 scale pre-fire aerial photograph of the burnt area. Initially polygons were drawn onto the air photograph, based on known vegetation boundaries and its grey-scale texture and shading. These polygons were then ground-truthed, corrected where necessary and allocated to vegetation classes. Eleven vegetation (fuel) types were recognized, ranging from simple monospecific stands of *N. solandri* var. *cliffortioides* to more complex shrubland mosaics containing a number of different species. These fuel types are described in Appendix 1. Finally, the vegetation map was digitized and geo-referenced in Arc/Info using the GPS survey points described earlier.

Topography and wind data collection

The topography of the area of the 1995 fire was evaluated using three-dimensional data obtained through a combination of Global Positioning System (GPS) surveying of the area and stereo-aerial photography. Eighteen control points were surveyed across the data site using the Trimble ProXL GPS (Trimble Navigation Ltd 1996) system. These points were differentially corrected through post-processing. The accuracy of this surveyed data was well in excess of the spatial resolution of the fire spread model (50m). The horizontal accuracy of the control points was estimated to be approximately 1-1 m, with vertical accuracy two to five times worse than horizontal. These data were then imported to Virtuozo (Virtuozo 1996), a digital virtual photogrammetry system that creates a digital terrain model (DTM) and an ortho-photo from a stereo pair of aerial photographs. Virtuozo was used to create a DTM of the fire-scar of the study site, which was subsequently exported to the Arc/Info GIS (ESRI 1996).

The wind field of the study site was analysed (particularly with respect to the influences of topography) under north-westerly conditions similar to those under which the fire took place. Readings of wind speed and direction were taken at 5-min intervals at nine sites across the fire-scar. These sites were chosen such that the range of landscape units found on the fire-scar was represented. From this point wind speed and direction surfaces were interpolated using the quintic interpolation method of Akima (1978) as implemented by Arc/Info. Data layers representing the standard deviation in wind speed and direction across the fire-scar were also created. These were used to simulate random variations in wind speed and direction across the fire-scar.

<table>
<thead>
<tr>
<th>Time lag (h)</th>
<th>Fuel particle diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-6</td>
</tr>
<tr>
<td>10</td>
<td>6-25</td>
</tr>
<tr>
<td>100</td>
<td>25-76</td>
</tr>
<tr>
<td>1000</td>
<td>76-205</td>
</tr>
</tbody>
</table>

Fuel modelling

The Rothermel (1972) fire spread model requires a number of stylized ‘fuel models’ of the vegetation through which fire is spreading. Fuel models are quantitative descriptions of those components of vegetation structure that are important for fire behaviour (Brown 1981). As the Rothermel model had not been previously used in New Zealand, it was necessary to construct fuel models for each of the 11 vegetation types observed.

When fuel models are constructed, any dead vegetation is divided into various ‘time lag’ (TL) classes. Herbaceous and woody fuels are considered separately. Data are collected for each fuel class and type combination and are then aggregated using a complex weighting method that is outlined in Rothermel (1972), Burgan & Rothermel (1984) and Burgan (1987). The TL divisions for the dead fuels are an attempt to simplify the variable rate(s) at which dead fuels dry. Based on their TL periods, four categories of fuel particles and fuel beds were recognized (Table 3). Fuels were committed to one of these categories as a function of their diameter in the case of particles, or their depth in the case of fuel beds. The concept of TL periods is based around that of equilibrium moisture content, the value that the actual moisture content would approach if the fuel particle is exposed to constant atmospheric conditions for an indefinite length of time (Bond & van Wilgen 1995; Pyne, Andrews & Laven 1996).

Burgan & Rothermel (1984) assume three of the nine fuel-related parameters required as input to the Rothermel model to be constant (particle density, and total and effective mineral content). They also
assume the surface-area-to-volume ratios of 10-h TL and 100-h TL fuel particles to be constants. However, for the purposes of this study these surface-area-to-volume ratios were assessed.

Fuel modelling was carried out in the following manner. After the creation of the vegetation map it was necessary to assess the species composition of each fuel class. The basal diameter of 30 specimens of each species represented in any fuel class was measured, the mean basal area calculated and termed the ‘standard unit’ for that species. The only exceptions were exotic grasses (e.g. *Agrostis capillaris* browntop), for which the basal area was based on the average number of upright tillers per 1-m² plot, based on an average of 30 samples. This approach was taken so that fuel models could be built for each species represented in a fuel class. These could then be aggregated, using weighted averages, to create a fuel model for each vegetation class.

Assessment of each vegetation class consisted of surveying the basal diameter of each plant (except exotic grasses, for which the number of upright tillers was counted) within three randomly located 10 × 10-m plots. For especially abundant species, small subsamples were surveyed; for example, this was how the number of upright tillers for grassy species was assessed. After all plots were surveyed, percentage abundance (by basal area) for each species and the number of standard units per plot was calculated and, where appropriate, scaled to the 1-m² level. Within each plot the proportions of herbaceous, woody and dead fuel(s) were assessed, and surface litter was collected.

For each species one specimen was ‘dissected’ in the laboratory in order to assess load, surface-area-to-volume ratio and the fuel moisture content (FMC). The specimen was selected to be as close as possible to the standard unit size so that the data obtained were directly comparable to the data from the survey plots. Before dissection each whole (above-ground) plant was weighed to assess the total load for each species ‘standard unit’. The specimen was then divided into functional categories (e.g. leaves, branches, boles) that were classed according to their TL division. The biomass of each TL size class within each functional category was then calculated. FMC was assessed for each TL division by weighing a sample, drying it for 24 h at 80 °C, then reweighing it and using the weight loss to calculate the moisture content. Although antecedent weather conditions are not included in the fuel moisture assessment required by the Rothermel model, a problem with fuel modelling a posteriori was the adequate parameterization of fuel variables such as FMC. The same is obviously true for an a posteriori reconstruction of the wind field. Despite variables such as fuel load and fuel bed depth being able to be estimated on the basis of an ‘average’ fuel unit, FMC is extremely temporally variable. As a result, FMC was estimated from material that was available at the time of fuel modelling. While it is recognized that there are likely to be differences between FMC and wind as modelled and the FMC and wind at the time of the fire, this was unavoidable.

Estimation of the surface-area-to-volume ratio was also carried out on the basis of functional category and TL division. The expressions of Brown (1970), which estimate the surface-area-to-volume ratio according to whether the particle falls into the class of ‘needles, grasses and lichens’ or ‘hardwood leaves’, were used. Having collected data for each TL category, the characteristic surface-area-to-volume ratio of the species could be calculated using the techniques described by Burgan & Rothermel (1984) and Burgan (1987). These techniques use a weighted averaging system based on the surface area within each TL class as a proportion of the total surface area. Because the largest proportion of the surface area usually falls with the finest (1-h and 10-h) TL classes, they receive the highest weighting. This is appropriate as the Rothermel model considers the passage of the flaming front, which is itself carried by the fine fuel particles. For all woody species, multiple 1-h TL classes were used. This technique is employed where there are different types of particles within one TL class (e.g. twigs and leaves).

Fuel bed depth was assessed by calculating the average height of 30 specimens of each species represented in the fuel models. The final fuel bed depth was estimated to be 70% of the maximum depth as described by Burgan & Rothermel (1984).

Fuel modelling for *N. solandri* var. *cliffortioides* was problematic as it was not possible to dissect and evaluate a specimen of this species. Thus, the fuel model constructed was estimated from data obtained from a variety of sources, such as data on the structure of individual trees at Cass (B.J. Maister, unpublished data; Burrows 1977), from general data on the species in New Zealand (Wardle 1984) and from published US fuel models for natural forest vegetation. The difficulties associated with the accurate modelling of fire spread through this species are considered more fully below.

After fuel models were compiled for one standard unit of each species represented in the various fuel classes, the standard unit values were aggregated on the basis of the number of standard units present per square metre (load) and by percentage abundance based on the basal area (FMC, depth and surface-area-to-volume ratio). All units were calculated in accordance with Wilson’s (1980) metric revision of the fire spread model of Rothermel (1972), although two of these revisions needed to be corrected. The full fuel models for the various fuel classes are presented in Appendix 2.
Post-collection GIS data processing

In order that the data described above could be input into PYROCART, it was necessary that all layers be processed and corrected in Arc/Info. For the vegetation data this involved rasterization of the digitized polygon (vector) coverage of vegetation class (with each grid cell containing one vegetation class). For wind speed and direction, grids were interpolated on the basis of point samples. After the data had been rasterized the four layers were geo-referenced and ‘clipped’ such that the coordinate pairs \((x_{\text{min}}, y_{\text{min}})\) and \((x_{\text{max}}, y_{\text{max}})\) were the same. If ‘NODATA’ were available for a given cell it was coded 9999 and in all cases each cell contained only a single data value.

DATA LAYERS AND PREPARATION FOR MODEL VALIDATION

The following section is concerned with the nature of the data used to simulate a posteriori the Cass fire of May 1995. As such it is not concerned with the methodology used to estimate the parameters, but with the nature of the parameters themselves. Vegetation, slope and wind data are all briefly discussed.

Vegetation data

Although 11 fuel classes were represented in the original vegetation layer, after rasterization to a cell size of 50 m only nine remained. Those omitted were beech–mixed shrub and bare ground (see Appendix 1). The abundance of the nine remaining fuel classes is shown in Fig. 3. The total number of cells in the layer was 5332 (124 rows by 43 columns). Of these, 1892 were coded NODATA; these cells were found predominantly on the east bank of the Cass River. They were all located outside of the possible burn area because of barrier protection by the Cass River and State Highway 73 (Fig. 1).

Slope and wind data

The terrain over which the fire spread is complex, with slope angles ranging from 0° to over 40°, with a mean slope between 10° and 15°. Large flat areas are evident on the grassy flats beside the Cass River and on Waterfall Terrace and Horrible Bog; slopes increase on the flanks of Mounts Misery and Horrible and on Corner Knob.

Data layers representing wind speed and direction were also derived. The wind speed layer is relatively simple, with the highest wind speeds evident on the exposed tops of Corner Knob and the areas of lowest wind speed being those sheltered in the floor of the basin (e.g. Horrible Bog and parts of Waterfall Terrace). Wind speeds range between 1·8 and 6·55 m s\(^{-1}\) (6·5–23·6 km h\(^{-1}\)). The wind direction layer is more complex, with some places exhibiting a high degree of variation in direction within a small area. Such areas are frequently associated with those of low wind speed. Wind directions in the data range from westerly (274°) to north-westerly (319°).

Temporal resolution

The temporal resolution used in the simulation of the fire was crucial. It was estimated by calculating the average rate of spread (ROS) for all fuel types at the maximum possible wind speed (including gusts). This average was divided by the spatial resolution (50 m). The temporal resolution was then estimated analytically such that assuming an average rate of spread at maximum wind speed there was a 50% chance of a fronting fire propagating into a neighbouring cell [i.e. \((\text{ROS} \times \text{temporal resolution})/\text{spatial resolution} (0·5)\)]. On this basis a temporal resolution of 30 s was deemed appropriate.

Results

VALIDATION OF THE PYROCART MODEL

This section considers the validation of the PYROCART model described above. A qualitative description of the fire shapes produced by the model is followed by a more detailed quantitative analysis. Because the model was validated against a single event it was necessary to consider its predictive power within individual fuel classes and on slopes of differing steepnesses. Such analysis may reveal conditions under which the model fails to predict fire behaviour successfully.

Description of the fire shapes produced by the model

Although a temporal validation of the shapes produced using the fire model was not possible, an examination of the way in which the shapes change over time is useful. It would appear that the model
tends to over-predict rates of spread; the temporal extent of the fire simulation was 165 min, whereas in reality the fire lasted considerably longer. Fire shapes at 30-min intervals are presented in Fig. 4, and Fig. 5 plots the cumulative cells burnt against time elapsed.

It was assumed that the fire spread from a single ignition point. Therefore at the start of the simulation this cell was the sole source of fire spread. The simulated fire spread rapidly at first through the light mixed fuel bed on Corner Knob and the mixed scrub on Mount Horrible. Patches of less flammable fuels, such as the stands of *N. solandri* var. *cliffortioides* on Corner Knob and Horrible Bog, remained unburnt. Over the simulation the fire shape became progressively more complex. Both Horrible Bog and the swampy patches at the toe of Corner Knob remained unburnt and the progress of the fire was impeded to some degree by Misery Swamp and the stands of *N. solandri* var. *cliffortioides* extending from Pylon Gully. In one place, however, fire burnt through these strips and moved rapidly into the more flammable *L. scoparium*. By the completion of the simulation, the fire shape had formed a patchwork of burnt and unburnt areas of varying sizes. Horrible Bog remained largely unburnt, as did Misery Swamp. Fire spread was impeded by the *D. toumatou* covered alluvial fan extending from Mount Misery. Apart from these areas, small unburnt patches of *N. solandri* var. *cliffortioides* were visible on Pylon Gully, Betwixt and Waterfall Terrace. The fire was halted by the stand of *N. solandri* var. *cliffortioides* opposite Romulus at the south of the fire-scar.

Figure 5 shows that the fire’s progression (in terms of the number of cells burnt) was temporally (if not spatially) consistent. The only major change in gradient on the graph occurred at about 150 iterations (75 min). It is probable that this slight decrease in the fire’s progression reflects the less flammable fuel beds through which the fire was spreading (e.g. Misery Swamp, Horrible Bog and patches of *N. solandri* var. *cliffortioides*) and the flatter terrain and lower wind speeds of these areas. It has been widely assumed that the perimeter of a free-burning fire increases at a constant rate (implying a quadratic function). However, this constant rate of increase is not reflected in the linear nature of Fig. 5. It is probable that the artificial NODATA boundary surrounding the fire-scar had forced the fire to spread as an irregular line-fire. Such a linear rate of increase in the perimeter of the fire is reasonable given the presence in the landscape of barriers to fire spread, such as rivers and roads.

**Quantitative analysis of the fire shapes**

Sørensen coefficients (Greig-Smith 1983) were calculated in order to compare the shapes predicted by the model with the final shape of the Cass fire. The Sørensen coefficient is used here to test for presence/absence similarity between two landscapes (i.e. real

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Fig. 4. A posteriori simulation of the May 1995 Cass fire. The diagram shows the development of the fire as simulated by the PYROCART fire spread model. Times are in minutes (one iteration = 30 s). These fire shapes are those used to validate the model.

Fig. 5. Cumulative number of cells burnt against iterations (time). The relationship between the number of cells burnt and time elapsed suggests that the perimeter of the fire as modelled may not have increased at a constant rate. That the perimeter of a free-burning fire will increase linearly is a common assumption.
The performance of the model was considered both as a whole and then across the fuel classes and in categories of slope, wind speed and wind direction. Such an analysis allows the strengths and weaknesses of the model’s performance to be more rigorously evaluated.

Table 4 shows that the level of matching between the real and predicted fire shapes was 79.3%. The high level of $b$ indicates that the model tended to over-predict the extent of the fire. However, in isolation these figures are of little value as they convey no information about the nature of the correlation of model predictions and reality in different environmental conditions. The over-prediction of the model may reflect two factors: first, the Rothermel model may over-predict rates of spread in the fuel models used, and, secondly, the lack of an adequate fire extinction routine may cause areas such as the stands of *N. solandri* var. *cliffortioides* on Corner Knob to ‘in-fill’. The high surface-area-to-volume ratios of the fuel bed may have been especially significant in the over-prediction of rates of spread. Gould (1988) found that at surface-area-to-volume ratios similar to those measured, the Rothermel model corrects rate of spread excessively with regard to wind speed. As a result PYROCART may tend to over-predict rate of spread in such conditions. The evaluation of moisture content of extinction was also problematic. Andrews (1980) notes that this parameter is assessed subjectively and Brown (1972) and Sneeuwajt & Frandsen (1977) found that small differences in the moisture content of extinction can exert a significant influence on model predictions. A further important point is that the spread of the fire is constrained by NODATA boundaries (i.e. the edge of the data set); the inability of the fire to spread beyond such boundaries may have artificially elevated the accuracy of the model.

### Prediction accuracy within individual fuel classes

The first set of environmental descriptors that were tested was the fuel classes. The values of the Sørensen coefficient for each fuel class are presented in Table 5. It can be seen that there was a wide range in the coefficient for different fuel types. The highest Sørensen coefficient for an individual fuel type was for wet mixed shrubland (0.945) and the lowest meaningful value was for grassland (0.379). Although wetland had a coefficient value of 0 this was not interpretable as only a single cell contained this fuel type.

Across all fuel types except bog (4), PYROCART tended to over-predict the number of burnt cells (i.e. $c > b$). This is suggestive of the Rothermel model over-predicting rates of spread in the fuel types used.

<table>
<thead>
<tr>
<th>Fuel class</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>SCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet mixed shrubland (2)</td>
<td>43</td>
<td>5</td>
<td>0</td>
<td>0.945</td>
</tr>
<tr>
<td>Mixed shrubland (1)</td>
<td>844</td>
<td>107</td>
<td>33</td>
<td>0.923</td>
</tr>
<tr>
<td>Manuka shrubland (5)</td>
<td>548</td>
<td>272</td>
<td>3</td>
<td>0.799</td>
</tr>
<tr>
<td>Light mixed shrubland (7)</td>
<td>265</td>
<td>156</td>
<td>0</td>
<td>0.773</td>
</tr>
<tr>
<td>Mountain beech (3)</td>
<td>132</td>
<td>66</td>
<td>33</td>
<td>0.748</td>
</tr>
<tr>
<td>Bog (4)</td>
<td>112</td>
<td>40</td>
<td>68</td>
<td>0.675</td>
</tr>
<tr>
<td>Matagouri shrubland (6)</td>
<td>48</td>
<td>70</td>
<td>36</td>
<td>0.475</td>
</tr>
<tr>
<td>Grassland (8)</td>
<td>39</td>
<td>127</td>
<td>1</td>
<td>0.379</td>
</tr>
<tr>
<td>Wetland (9)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5. Sørensen coefficient values for individual fuel classes. The fuel classes are presented in order of their prediction accuracy

SCV, Sørensen coefficient value; $a$, number of cells that were predicted to burn and were burnt in reality; $b$, number of cells that were predicted to burn but did not; $c$, number of cells that were not predicted to burn but which did.
The individual fuel type whose burnt area was most poorly predicted was grassland (8). There was a significant over-prediction of the extent of grassland expected to burn; of the 170 grassland cells 75% were predicted to burn but did not. There were two large expanses of grassland; the largest of these (110 cells; 65%) was found on the flats of the Cass River, with the remaining 60 (35%) located at the southern end of Misery Swamp. Figure 4 shows that PYROCART predicted that these areas would be burnt with the exception of some scattered pockets of unburnt grassland in Misery Swamp. However, in reality the grasslands on the river flats remained completely unburnt, as did much of Misery Swamp. The inaccuracy in predicting fire spread through these areas is probably a reflection of the vegetation abutting the river flats and PYROCART’s over-prediction of flanking and backing rates of spread. An area of high ground moisture supporting bog and wet mixed shrubland is found at the toe of the terrace adjacent to the grassland. Field observation shows that this area was unburnt and may have been influential in preventing fire from spreading onto the river flats. However, these areas of vegetation were not large enough to be included in the fuel layer at the model’s spatial resolution (50 m).

Despite the reasonably high level of predictive accuracy within areas of mountain beech ($s = 0.748$), the construction of a fuel model for this vegetation type was problematic. As described earlier the fuel model was a composite, constructed from a range of data sources, and although PYROCART predicted fire spread within this class reasonably accurately, the fuel model remained unsatisfactory. For example, the model failed to predict the unburnt patches of *N. solandri* var. *cliffortioides* on Corner Knob and over-predicted fire progression through this fuel type in Pylon Gully. The model did, however, predict the inhibiting effects of the large stand of *N. solandri* var. *cliffortioides* at the southern end of the fire-scar. Fundamentally, the problem lies with the use of the Rothermel model to describe fire spread within a forest fuel type. Rothermel (1972, p. iii) describes the model as being designed for the prediction of: ‘rate of spread and intensity in a continuous stratum of fuel that is contiguous to the ground. The initial growth of a forest fire occurs in surface fuels (fuels that are contiguous to the ground). Field observation shows that this area was unburnt and may have been influential in preventing fire from spreading onto the river flats. However, these areas of vegetation were not large enough to be included in the fuel layer at the model’s spatial resolution (50 m).

Thus, the use of PYROCART to describe fire spread within *N. solandri* var. *cliffortioides* breaks one of the fundamental assumptions of the model. Likewise, van Wilgen, le Maître & Kruger (1985) had similar problems with the fuel bed depth parameter when applying the model to mountain fynbos, and Catchpole, Catchpole & Rothermel (1993) found the Rothermel model to be over-sensitive to fuel bed depth in experimental fuel beds.

### Table 6. Sørensen coefficient values for slope classes of differing steepnesses

<table>
<thead>
<tr>
<th>Slope angle (°)</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>SCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
<td>213</td>
<td>211</td>
<td>51</td>
<td>0.619</td>
</tr>
<tr>
<td>5–10</td>
<td>586</td>
<td>193</td>
<td>114</td>
<td>0.792</td>
</tr>
<tr>
<td>10–15</td>
<td>486</td>
<td>140</td>
<td>39</td>
<td>0.844</td>
</tr>
<tr>
<td>15–20</td>
<td>324</td>
<td>81</td>
<td>9</td>
<td>0.878</td>
</tr>
<tr>
<td>20–25</td>
<td>160</td>
<td>62</td>
<td>5</td>
<td>0.827</td>
</tr>
<tr>
<td>25–30</td>
<td>102</td>
<td>34</td>
<td>1</td>
<td>0.854</td>
</tr>
<tr>
<td>30–35</td>
<td>64</td>
<td>13</td>
<td>0</td>
<td>0.908</td>
</tr>
<tr>
<td>35–40</td>
<td>21</td>
<td>11</td>
<td>0</td>
<td>0.792</td>
</tr>
<tr>
<td>40+</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

SCV, Sørensen coefficient value; $a$, number of cells that were predicted to burn and were burnt in reality; $b$, number of cells that were predicted to burn but did not; $c$, number of cells that were not predicted to burn but which did.

### Prediction accuracy by slope steepness

There was a smaller range in the Sørensen coefficient values for slope (Table 6) than for the individual fuel classes (cf. Table 5). Model predictions were least accurate on the shallowest slopes (0–5°), with the highest level of accuracy being found on the steepest slopes (40°+).

Table 6 suggests that PYROCART has greater predictive accuracy on steeper slopes. However, due to the interaction between slope and vegetation type it is difficult to assess the performance of the model solely with respect to slope steepness. On flatter areas, such as Misery Swamp and the Cass River flats, the vegetation mosaic shows greater spatial complexity than on steeper slopes such as the flanks of Mounts Horrible and Misery. Thus, it is necessary to describe the nature of the vegetation on slopes of different steepnesses before trying to interpret the model’s predictions on varying slopes.

Table 7 shows that fuel class diversity decreases with slope. This interaction between slope and fuel class is epitomized by the two extremes of slope steepness (0–5° and 40° +). Fuel class diversity was highest on the flattest slopes, reflecting the greater diversity of the vegetation mosaic on these sites. Furthermore, of those cells with a slope steepness less than 5°, 52% contained either bog or grassland fuels and, as discussed earlier, the model showed a low predictive accuracy within these fuel types (Table 5). These observations make it difficult to attribute the model’s relatively poor performance on flat terrain to slope angle alone.

Conversely, on the steepest slopes diversity was at a minimum; of the 22 cells steeper than 40°, 21 contained *L. scoparium*-dominated shrubland and the other mixed shrubland. Table 5 shows that fire behaviour within these vegetation types was predicted accurately ($s = 0.799$ and $s = 0.923$, respectively).
Prediction accuracy by wind speed and direction

As was the case for fuel type and slope, the model over-predicted burnt areas at most wind speeds, the sole exception being wind speeds between 19 and 23 km h$^{-1}$. However, no clear trends were found for different wind speeds. Although the model’s predictions appeared to be more accurate at each end of the wind speed distribution, this was complicated by the way in which the wind field data were generated. Apart from the model over-predicting burnt area in all wind direction classes except one (275–280°), there were no clear trends and the accuracy of prediction was above 70% for all classes except one (285–290°; $s = 0.584$). It is likely that the lack of clear trends in predictive accuracy in both wind speed and direction reflects problems with the interpolation of point data across the fire-scar rather than more fundamental problems with either the PYROCART or Rothermel models.

Summary of Sørensen analysis

Similarity analysis as outlined above allows an evaluation of the PYROCART model with respect to individual environmental parameters. This is more useful than an overall similarity analysis as it allows the strengths and weaknesses of the model to be analysed more rigorously. This subdivision of the environmental factors is necessary because the model is being validated against a single event (i.e. $n = 1$). Fuel class and slope angle appeared to be the environmental factors with the most influence on the predictions made by PYROCART, while wind speed and direction did not show clear trends in prediction accuracy. Analysis of predictive accuracy on the basis of slope steepness illustrated how the various environmental variables interacted to control fire behaviour.

It is difficult to comment on the relative accuracy of this model compared with other similar models. The only comparable model is the FIREMAP model of Vasconcelos (1988). Although little quantitative information is provided, it is possible to calculate a Sørensen coefficient value of $0.81$ ($a = 218$; $b = 54$; $c = 68$) for Vasconcelos predicted against Vasconcelos observed. These figures indicate that the two models have a similar level of predictive accuracy. However, FIREMAP tended to under-predict fire growth whereas PYROCART tended to over-predict fire growth. Although the overall Sørensen coefficient values for the two models are similar, it is difficult to compare them due to the differences in the two models and the conditions under which they were validated. The most important difference is that the fuel models that Vasconcelos (1988) used were taken directly from the US Fire Danger Rating System and had been tested rigorously in a wide range of fire conditions. This is likely to be significant, because, as described above, errors in prediction by the PYROCART model probably reflect problems in the parameterization of the fuel bed. The only fair comparison between the two models would be to run the data sets used to validate the model on each other and compare the final results.

Discussion

PYROCART is a direct implementation of the Rothermel model and the predictions it makes are subject to the limitations and assumptions of this model. However, there are a number of key differences between the Rothermel model and that presented here. Spatial homogeneity in the fire environment is a fundamental assumption of the Rothermel model. The use of a cellular model to describe the landscape, with the Rothermel model applied to each cell individually, as implemented in PYROCART, allows this assumption to be circumvented. Thus, the approach described here does not violate any of the fundamental assumptions of the Rothermel model and allows fire spread in spatially heterogeneous landscapes to be simulated.
The model as described here would clearly need to be refined to deal with some of the fine-scale temporal variability associated with fire behaviour if it is to be used as an *in situ* fire management tool. Furthermore, considerable research would be needed to validate it in a wider range of vegetation types. As discussed earlier, this validation is made problematic by the lack of quantitative data regarding fire behaviour in New Zealand fuel beds, both exotic and indigenous. However, it should be re-iterated that the model as presented here was not designed as an *in situ* fire management tool, but rather it used time- and space-dependent spread parameters to determine the extent of a wildfire in a spatially complex environment.

The model in its present form still has considerable potential for use as an aid in landscape-scale management in spatially heterogeneous environments, and as such would represent a significant advancement over previous models that have been used to address the influence of spatial heterogeneity on fire spread. For example, Turner *et al.* (1987) and Turner & Dale (1991) have used simple percolation models in binary (flammable vs. non-flammable) landscapes to explore the spread of contagious disturbances such as fire in spatially complex landscapes. Turner *et al.* (1987) found that the spatial configuration of the landscape in terms of patch structure and the proportion of flammable and non-flammable vegetation in the landscape both exert a considerable influence on the way in which contagious disturbances operate in spatially complex landscapes. Turner & Dale (1991) note, however, that such percolation models in binary landscapes are gross simplifications of real landscapes and that the development of better models that incorporate more spatial realism, such as classes of fire susceptibility and non-uniform terrain, could provide useful insights. The PYROCART model presented here could easily be used to this end. The model could be used in a probabilistic manner to examine the influences of landscape structure on fire behaviour over a range of time frames. For example, the proportion of beech forest in the landscape could be varied to explore whether there are critical thresholds above or below which the proportion of low flammability fuel in the landscape significantly influences the pattern of disturbance in the landscape.

A logical progression of this probabilistic landscape pattern approach would be the incorporation of a successional model. An integrated disturbance–succession model, with fire ignitions generated by a Monte Carlo process, could be used to explore the manner in which spatially patchy disturbance events generate spatially complex vegetation mosaics over a long time frame. Another application of a hinged succession–disturbance model could be the development of a fire–vegetation information system such as those described by Kessell & Cattelino (1978), Kessell (1990) and Richardson *et al.* (1994). Such information systems have been used to manage prescribed burning for the rejuvenation of vegetation (e.g. fynbos in South Africa), the reduction of fire hazard, the enhancement of water yields from catchment basins, and the control of invasive plants and shrubs.

A number of improvements could be made to the model that would enhance its functionality for management in the manner described above. Some of these improvements include: (i) inclusion of the capacity to predict spot fire activity; (ii) inclusion of the capacity to predict the onset of crown fire behaviour; (iii) better, more reliable simulation of wind patterns; (iv) inclusion of more realistic fire extinction criteria; and (v) inclusion of the ability to model the effects of firebreaks.

Most of these issues have been considered in the fire behaviour literature and simple empirical models exist for many of them. A notable exception is that of the onset and subsequent behaviour of crown fires. Apart from van Wagner (1977 and 1993), little research has considered this phenomenon. It should also be noted that the use and parameterization of empirical models outside the systems in which they were formulated is not simple.

Acknowledgements

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References


Mark, A.F. (1994) Effects of burning and grazing on sustainable utilisation of upland snow tussock (Chionochloa spp.) rangelands for pastoralism in South


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<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Mixed shrub</td>
<td>This is a widespread and variable fuel class. It comprises a mixture of woody shrubs species such as <em>Cassinia leptophylla</em>, <em>Discaria toumatou</em>, <em>Coprosma</em> spp., <em>Dracophyllum</em> spp. and <em>Leptospermum scoparium</em>. Ground cover is provided by <em>Festuca novae-zelandiae</em> and exotic grass species.</td>
</tr>
<tr>
<td>(2) Wet mixed shrub</td>
<td>This fuel type is similar to (1) but is found in more moist areas such as gullies and south-facing slopes. It is more dense than (1) and contains some additional species, especially <em>Hebe</em> spp. Ground cover is similar to (1) although <em>Schoenus parviflorus</em> is also common.</td>
</tr>
<tr>
<td>(3) Mountain beech</td>
<td>Various aged monospecific stands of <em>Nothofagus solandri</em> var. <em>cliffortioides</em>. Ground cover is similar to (1) if any, woody shrubs present. Standing water is common in this fuel type.</td>
</tr>
<tr>
<td>(4) Bog</td>
<td><em>Schoenus</em>-dominated bog vegetation with few, if any, woody shrubs present. Standing water is common in this fuel type.</td>
</tr>
<tr>
<td>(5) Manuka shrubland</td>
<td><em>Leptospermum scoparium</em>-dominated shrubland. This fuel class covers the flanks of Mountains Horrible and Misery. Other woody shrub species may be present in low densities. Ground cover similar to (1). This fuel type has a significantly higher biomass than either (1) or (2).</td>
</tr>
<tr>
<td>(6) Matagouri shrubland</td>
<td><em>Discaria toumatou</em>-dominated shrubland. Common on the lower flanks of Mount Misery and on the large alluvial fan running from Misery Stream to the Cass River. This fuel type is almost monospecific apart from exotic grasses.</td>
</tr>
<tr>
<td>(7) Light mixed shrubland</td>
<td>Similar species composition to (1) but with a significantly lower standing biomass.</td>
</tr>
<tr>
<td>(8) Grassland</td>
<td>This fuel class comprises some exotic grasses, <em>F. novae-zelandiae</em> and, in some places, <em>S. parviflorus</em>. The dominant species is spatially variable, but the fuel type is characterized by an absence of wood shrubs.</td>
</tr>
<tr>
<td>(9) Wetland</td>
<td>This is a fuel class intermediate between (2) and (4). It is epitomized by low, sparse shrubs (esp. <em>Hebe</em>) growing in thick stands of <em>S. parviflorus</em>.</td>
</tr>
<tr>
<td>(10) Beech/mixed shrub</td>
<td>This is mixed shrubland with a significant component of <em>N. solandri</em> var. <em>cliffortioides</em> present. It is mainly found in those areas where the beech is invading the shrub communities.</td>
</tr>
<tr>
<td>(11) Bare ground</td>
<td>Patches of bare ground. On such patches standing biomass is extremely low. <em>Galtheria antipoda</em> is common, as are stunted shrubs of a number of species including <em>N. solandri</em> var. <em>cliffortioides</em>.</td>
</tr>
</tbody>
</table>
Appendix 2

The fuel models below are those used for the validation of the PYROCART model. The load category includes all fuels in the fuel complex with a diameter of less than 7·25 cm. Surface-area-to-volume ratio was calculated using the formulae of Brown (1970). The table is formatted in a similar style to the fuel models presented in Rothermel (1972).

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>1-h lag</th>
<th>10-h lag</th>
<th>100-h lag</th>
<th>Live fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total load</td>
<td>Load</td>
<td>SAVR</td>
<td>Load</td>
</tr>
<tr>
<td>Mixed shrub (1)</td>
<td>0·42</td>
<td>0·11</td>
<td>77·80</td>
<td>0·15</td>
</tr>
<tr>
<td>Wet mixed shrub (2)</td>
<td>0·49</td>
<td>0·17</td>
<td>71·47</td>
<td>0·14</td>
</tr>
<tr>
<td>Mountain beech (3)*</td>
<td>52·00</td>
<td>45·00</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td>Bog (4)</td>
<td>0·17</td>
<td>0·12</td>
<td>44·28</td>
<td>0·01</td>
</tr>
<tr>
<td>Manuka shrubland (5)</td>
<td>0·76</td>
<td>0·29</td>
<td>92·46</td>
<td>0·25</td>
</tr>
<tr>
<td>Matagouri shrubland (6)</td>
<td>1·93</td>
<td>0·23</td>
<td>33·40</td>
<td>1·04</td>
</tr>
<tr>
<td>Light mixed shrubland (7)</td>
<td>0·13</td>
<td>0·06</td>
<td>87·40</td>
<td>0·04</td>
</tr>
<tr>
<td>Grassland (8)</td>
<td>0·10</td>
<td>0·10</td>
<td>80·98</td>
<td>–</td>
</tr>
<tr>
<td>Wetland (9)</td>
<td>0·15</td>
<td>0·12</td>
<td>51·59</td>
<td>0·1</td>
</tr>
</tbody>
</table>

*Mountain beech fuel model was derived from other sources. See text for further details.

Constants: total mineral content (dimensionless) = 0·0555. Effective (silica-free) mineral content (dimensionless) = 0·001. Particle density (kg m$^{-3}$) = 512.

Abbreviations and units: load is given in kg m$^{-2}$; surface-area-to-volume ratio (SAVR) is given in cm$^{-1}$ (=cm$^2$/cm$^3$) and depth is given in m. Fuel moisture content (FMC) and the FMC of extinction (Ext FMC) are both proportions and are thus dimensionless.