Understanding fire behaviour in different weather conditions and across large, flammable landscapes is important for fire management. In this study, the influences of weather and major landscape variables on fire behaviour were examined following a large fire in the Blue Mountains, near Sydney. Patterns of fire behaviour were inferred from a fire severity map derived using remote sensing and field validation. Fire weather on the day of burning was determined for different parts of the landscape using bureau of meteorology data and fire spread maps compiled during the event. Relative proportions of the landscape burnt by different fire behaviour classes (particularly crown and understorey fires) were determined in a geographic information system. The influence of vegetation type, fuel age and terrain on fire behaviour during two contrasting weather conditions (extreme and moderate fire weather) was examined. The analysis showed that during extreme weather, fire behaviour was dominated by either a crown fire that consumed the canopy or a fire of an intensity that scorched the canopy leaves. In relatively moderate weather, crown fire was almost non-existent and the canopy remained intact over about half of the landscape. Fuel age (time since last fire) of between 1-4 years appeared to moderate fire behaviour relative to fuel ages of 5 to >20 years. Ridge tops and slopes of 15° or less appeared to suffer more crown fire than gullies and slopes of >15°. Surprisingly, aspect did not greatly influence fire behaviour despite strong, directional winds. An important ecological implication may be that fires that occur during severe weather lead to greater landscape homogeneity than fires that occur during more mild weather.

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Variations in environmental conditions (weather, terrain, vegetation) during large, multi-day fires results in complex patterns of fire behaviour across a landscape (Simard, 1991; Catchpole, 2002). Burn patterns, produced by different fire behaviours may be detected and mapped using remote sensing (e.g. Bowman et al., 2003; Chafer et al., 2004). Such patterns are also referred to as fire severity patterns. They enable us to retrospectively examine spatial and temporal variations in fire behaviour. Using a landscape-scale view of fire behaviour generated by remote sensing, questions may be explored such as ‘how does weather on the day influence the occurrence of crown fire’, ‘how does a fire behave in different fuel types and terrain under the same weather conditions’ and ‘what is the spatial arrangement of patches of different fire severity (ie. what size, how close and in what part of the landscape do patches of different fire severity occur)’. Understanding these issues may be useful for fire management by improving predictions about fire behaviour, determining the influence of fuel load and terrain on fire behaviour, and understanding the condition of the post-fire landscape in which plants and animals must survive (e.g. Bradstock et al., 2005).

This paper describes a simple quantitative analysis of fire severity patterns resulting from a large fire affecting part of the Blue Mountains, near Sydney, in the summer of 2001/02. The landscape in which this fire occurred is characterised by rugged, sandstone terrain and variable vegetation. The fire burnt during contrasting weather conditions over many days. Satellite imagery obtained that summer had been used to produce fire severity maps for a number of fires in the region (Chafer et al., 2004). The availability
Areas burnt during different types of fire weather were determined using a combination of fire progression maps produced by the incident management team at the time of the fire (Department of Environment and Climate Change NSW, unpublished data) and Bureau of Meteorology data. Initially, on the 25 December 2001, the main fire front spread rapidly through a forest-dominated landscape driven by hot, dry westerly winds (35°C, ~8% relative humidity, gusts to ~80 km h⁻¹). The maximum forest fire danger index (FFDI, range: 0-100, McArthur, 1967) reached 100 on this day. Moderate weather (FFDI <20) and moist, south-easterly winds occurred on subsequent days, pushing the 25 km northern flank to the north and west towards the urban areas along the highway. During a return of extreme weather (maximum FFDI of 40-90) from 1-3 January 2002, the fire reached the urban-bushland interface in the central mountains. Subsequently, the fire spread into higher altitude areas (700-900 m a.s.l.) to the west where shrubland and low woodland vegetation dominates. Following rain, the fire was extinguished on around 7 January 2002. By combining the fire spread maps with weather information, we have identified parts of the landscape burnt during different weather conditions. This paper focuses on a comparison of areas affected by two of these contrasting weather conditions: (i) the area burnt by the main headfire (FFDI ~100) and (ii) the area burnt during more moderate weather (FFDI ~20) (Fig. 1).

The vegetation in the study area varies from single-layered sedge-swamps and heath (1-4 m) to multi-layered woodlands and forests of varying height (10-50 m). These vegetation types are comprised primarily of various combinations of sedges and other monocots, sclerophyll shrubs and, in woodland and forests, a canopy dominated by eucalypts. Typically, shrubland and woodland occurs on ridges, upper slopes and headwater valleys taller forests occur on mid and lower slopes and in gullies. In this study, vegetation was grouped into three broad types on the basis of structure and height: shrubland (sedge-swamp and heath), sclerophyll woodland/open-forest (trees 10-25 m tall), and tall forest with mesic understorey (trees often >30 m tall). Spatial distributions of these broad vegetation types were derived by pooling vegetation classes identified in recent mapping of the area (Tindall et al., 2004). A digital grid layer representing these distributions across the study area was used in the geographic information system (GIS) analyses.
Data analysis was done using Arcview GIS version 3.2 software. The landscape datasets were converted to grid format with 10 m cell size and spatially aligned with the fire severity map. Fire severity data were intersected with the data for each landscape variable using a ‘combine grids’ function in the Spatial Analyst toolset. The output data were used to calculate the total area and percent of landscape in each severity class in each of the landscape variable categories. The influences of vegetation type, fuel age, slope and aspect on patterns of fire behaviour during the two contrasting weather conditions are presented in graphical format here.

Results and Discussion

The fire severity classes detected using remote sensing, and the inferred fire behaviour classes, are described in Table 1. During the main headfire (FFDI ~100), the canopy was consumed or scorched over the majority (91%) of the landscape. During milder weather (FFDI ~20), crown fire was almost non-existent, however canopy scorch occurred over 43% of the landscape and areas where the canopy remained unburnt comprised about 53% of the landscape. Under both weather conditions, very little of the landscape remained unburnt (1-2%) (Table 1).

During extreme fire weather (FFDI ~100), most (about 70%) of shrubland and woodland/open-forest vegetation was subject to either a crown fire or a high-intensity understory fire and only about 5% was burnt by a low-intensity/patchy fire. In contrast, under the same extreme weather conditions, close to 40% of tall (mesic) forest was burnt only in the understory (Fig. 2a, left). During more moderate weather (FFDI ~ 20), a relatively small proportion of shrubland and woodland/open-forest areas was burnt by crown or intense understory fire (<20%) and about 50% burnt at lower intensity (Fig. 2a, right).

In general, fire behaviour was more severe in shrubland and woodland/open-forest than in tall (mesic) forest, with larger proportions of the former subjected to crown fire or canopy scorch than the latter, irrespective of weather conditions. This difference may have been influenced by vegetation structure and floristics, since shrubland and woodland/open-forest are dominated...
TABLE 1. Remotely-sensed fire severity classes, inferred fire behaviour classes, and percent of landscape burnt in each fire behaviour class during two contrasting weather conditions (forest fire danger index, FFDI). Patterns of these fire severity classes across the area affected by the Mount Hall fire are shown in Figure 1. Data derived from Chafer et al. (2004) and Hammill and Bradstock (in press).

<table>
<thead>
<tr>
<th>Fire severity class (observed)</th>
<th>Fire behaviour class (inferred)</th>
<th>% Landscape burnt</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Crown and understorey leaves consumed</td>
<td>crown fire</td>
<td>20 1</td>
</tr>
<tr>
<td>4. Crown scorched, understorey leaves consumed</td>
<td>intense understorey fire</td>
<td>51 15</td>
</tr>
<tr>
<td>3. Crown and understorey scorched</td>
<td>understorey fire</td>
<td>20 28</td>
</tr>
<tr>
<td>2. Crown intact, understorey scorched</td>
<td>low-intensity understorey fire</td>
<td>4 23</td>
</tr>
<tr>
<td>1. Crown intact, understorey partly scorched</td>
<td>patchy understorey fire</td>
<td>4 30</td>
</tr>
<tr>
<td>Unburnt</td>
<td>no fire</td>
<td>1 2</td>
</tr>
</tbody>
</table>

FIG. 2. Percent of the landscape affected by different fire behaviour classes within (a, b) vegetation type and (c, d) fuel age during contrasting weather conditions (a and c: FFDI~100, b and d: FFDI~20). Details of fire behaviour classes are given in Table 1. The three vegetation types (shrubland, woodland/open-forest and tall forest) represent broad structural categories, within which a number of mapped vegetation classes (see Tindall et al., 2004) have been pooled. Shrubland includes sedge-swamp and heath, woodland/open-forest includes a variety of eucalypt-dominated communities with a variable sclerophyll, shrubby understorey, and tall (mesic) forest includes tall, open eucalypt forest, riparian forest and rainforest. Fuel age is the number of years since the most recent fire (prior to the Mount Hall fire) and may be used as a surrogate for fuel load.
by highly flammable species (sclerophyll shrubs), while tall forest is comprised of many mesic species, especially in the understorey where ferns, herbs and broad-leaved shrubs are common. Also, the tall (mesic) forests occur in gullies and on lower slopes and may have been more sheltered from the high winds driving the worst fire behaviour.

During extreme fire weather (FFDI ~100), young (1-4 years) fuel age was associated with the almost total absence of crown fire, however high intensity understorey fire (causing canopy scorch) still affected about one third of the young fuel areas (Fig. 2b, left). Also during extreme weather, 70-90% of the landscape with older fuels (5+ years) was affected by either crown fire or intense understorey fire (Fig. 2b, left). A similar, although less marked, trend of more moderate fire behaviour in young fuels was found during relatively mild weather (Fig. 2b, right).

In general, while the extent of crown fire during extreme weather was reduced by young fuels, fuel age had a negligible effect on complete canopy scorch (>90% of the landscape, irrespective of fuel age). Could these fuel-related effects on fire behaviour be important for fire management? For instance, is it possible to control a fire of an intensity that scorches the tree canopy, since this level of fire behaviour still dominates in young fuel during extreme weather? Other observations within the study landscape of height of leaf consumption above ground (e.g. Cheney, 1981) indicated that fire intensities beyond known thresholds for effective suppression were achieved in all fuel ages except sites with fuel ages of less than 1 year (Bradstock & Cohn, unpublished data). Also, is a fuel age of 1-4 years achievable for management if required over large areas? Maintaining such young fuel age would have major implications for biodiversity conservation, since a fire interval of 4 years is shorter than the juvenile period of many plant species in these landscapes (Keith, 1996; Bradstock & Kenny, 2003).

During extreme weather (FFDI ~100), fire behaviour was most severe on the ridges and moderate slopes: crown fire affected about 30% of ridges and <15° slopes but less than 20% of gullies and 16° slopes. The distribution of less severe fire behaviour was similar across all slope classes, except that gullies had a greater proportion of low-intensity and patchy
understorey fire (about 20%) than slopes and ridges (5-10%) (Fig. 2c, left). During more moderate weather (FFDI ~20), low-intensity understorey fire was more noticeably affected by slope, with 10-20% of ridges and moderate slopes (<15°) and about 30-50% of steeper slopes and gullies being affected (Fig. 2c, right). The converse of this is that intense fire occurred over far less of the steep (16+°) slopes and gullies than on the ridges and <15° slopes.

Aspect appeared to have little influence over the distribution of the different fire behaviour classes in both extreme and moderate weather. There were roughly similar proportions of each fire behaviour class on north, east, south and west facing slopes (Fig. 2d).

These results need to be considered in view of the inter-dependence of vegetation/fuel and terrain. For instance, steep slopes in the Blue Mountains are characterised by rock outcrops and discontinuous vegetation; vegetation of shorter stature often occurs on the ridges and upper slopes (as compared with taller forest on lower slope and in gullies), and south and east aspects are often characterised by more mesic species (even on upper slopes) due to less exposure to the north-oriented sun. Apparent effects of terrain on fire behaviour are therefore likely to be influenced by these terrain-associated vegetation patterns and fuel characteristics.

**SUMMARY**

This study found that, during extreme (FFDI ~100) head fire conditions, the majority of vegetation was either consumed or completely scorched. There were only small areas where the fire had remained at shrub level, and almost no areas were left unburnt. Areas of unburnt canopy were restricted to tall, mesic forests and steep slopes and gullies under these conditions. Crown fire behaviour was moderated to some extent by vegetation/fuel characteristics. For instance, steep slopes in the Blue Mountains are characterised by rock outcrops and discontinuous vegetation; vegetation of shorter stature often occurs on the ridges and upper slopes (as compared with taller forest on lower slope and in gullies), and south and east aspects are often characterised by more mesic species (even on upper slopes) due to less exposure to the north-oriented sun. Apparent effects of terrain on fire behaviour are therefore likely to be influenced by these terrain-associated vegetation patterns and fuel characteristics.

Understorey fire (about 20%) was more noticeable affected by slope, with 10-20% of ridges and moderate slopes (<15°) and about 30-50% of steeper slopes and gullies being affected (Fig. 2c, right). The converse of this is that intense fire occurred over far less of the steep (16+°) slopes and gullies than on the ridges and <15° slopes.

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**LITERATURE CITED**


