SPATIAL PATTERNS OF FIRE BEHAVIOUR IN RELATION TO WEATHER, TERRAIN AND VEGETATION

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Abstract
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 severe weather, fire behaviour was dominated by either a crown fire or a fire of an intensity that killed the canopy leaves, although tall (mesic) forests were slightly less severity affected. In relatively moderate weather, crown fire was almost non-existent and the canopy remained intact over about half of the landscape. Surprisingly, aspect did not appear to have much influence on fire behaviour. 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.

Introduction
Varying 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. Key *et al.* 1999, Bowman *et al.* 2003, Chafer *et al.* 2004), enabling us to retrospectively examine spatial and temporal variations in fire behaviour. Using a landscape-scale view of fire behaviour, questions may also be explored such as 'how does weather on the day influence the occurrence of crown fires', 'how does 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 an 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 of such data provided an opportunity to examine fire severity patterns across the landscape, and thus infer fire behaviour in relation to weather (forest fire danger index), vegetation (type and fuel age) and terrain (slope and aspect). Here, we present part of an ongoing study which aims to determine the influence of different environmental variables on fire behaviour in the Blue Mountains. Further work using the fire severity data will involve the development of a statistical model to explain and predict fire behaviour in these complex sandstone landscapes.

Study area and fire
The study area is located within Blue Mountains National Park, approximately 50 km west of Sydney, south-eastern Australia. This area consists of dissected terrain formed by erosion of an ancient (Triassic) sandstone plateau (Pickett and Alder 1997). The cliff lines and gorges that characterise the area have been eroded by water over the last 20

million years, and rivers now occupy the bottom of deep v-shaped valleys. Vegetation in the area is dominated by sclerophyll shrublands and eucalypt forests (Keith and Benson 1988; Benson 1992). During December 2001-January 2002, a number of large fires burnt simultaneously across the region, affecting a considerable proportion of the landscape. This study examined fire behaviour patterns of one of these fires, the Mount Hall fire, which burnt about 46 000 ha of the Park after a lightning ignition in a remote part of the Park on 24 December 2001. The fire burnt for 3 weeks through rugged terrain and varied vegetation, across an altitude range of 50 m to 900 m above sea level.

Spatial data used

Fire severity

Fire severity data used in this study were derived from the SPOT (Satellite Pour l'Observation de la Terre) 2 satellite sensor. The method used to map fire severity patterns using this data was based on a vegetation greenness index, the normalised vegetation difference index (NDVI). Patterns of Δ NDVI between a pre-fire and a post-fire image were used to map fire severity following field validation (*ie*. field sampling was used to determine which Δ NDVI values represent which levels of fire severity on the ground). This method has been described in detail elsewhere (Chafer *et al.* 2004, see also Hammill and Bradstock in press). The mapped fire severity patterns are shown in Figure 1.

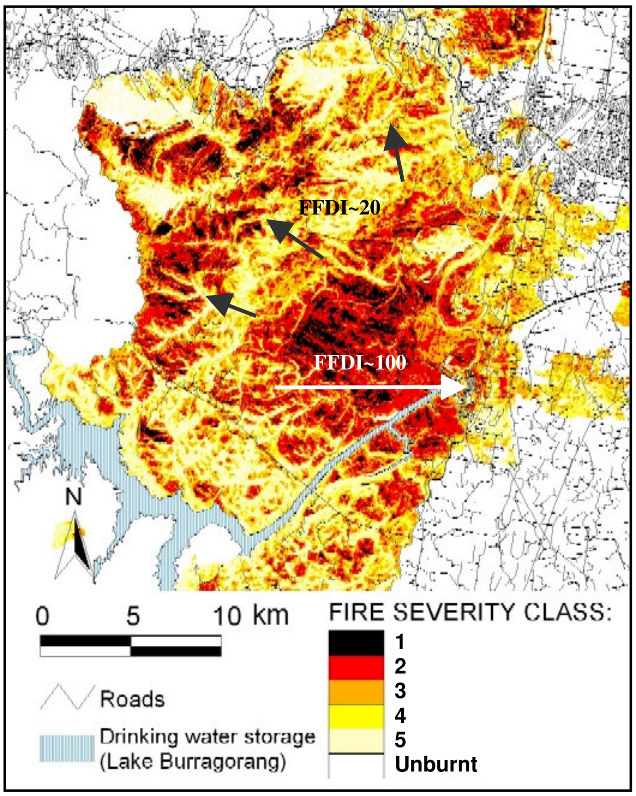

Figure 1. Severity map of the Mount Hall fire derived using satellite imagery (see Chafer *et al.* 2004).
Fire severity and inferred fire behaviour classes are described in Table 1. The dominant forest fire danger index (FFDI) and direction of fire spread (arrows) during two main stages of the fire progression are shown.

Weather

The progression of the Mount Hall fire was mapped by the incident management team at the time of the fire (NSW Department of Environment and Conservation unpublished 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 asl) 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) (Figure 1).

Vegetation

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.

Fuel load
Number of years since the most recent fire (prior to the Mount Hall fire) was derived from historical fire maps (NSW Department of Environment and Conservation unpublished data) and used as a surrogate for fuel load. A GIS layer of time since last fire, which varied in different parts of the landscape from 1 year to more than 25 years, was classified using the following categories: 1-4 years, 5-10 years, 11-20 years, >20 years.

Terrain
Terrain (slope and aspect) classes were derived using a digital terrain model (DEM) and GIS data representing the location of water courses. The DEM was classified into a grid representing the following five slope classes: ridge (≤5°), 6-15°, 16-25°, >25° and gully. Typically, the more moderate inclines occur on the shoulders of ridges and upper slopes, while steeper inclines are further down in the characteristic v-shaped valleys. Gullies were defined using a GIS manipulation of the water course data, in which drainage lines were expanded to a width of 50 m and then incorporated into the classified DEM layer. The DEM was also used to derive a layer representing four aspect classes: north (315-45°), east (45-135°), south (135-225°) and west (225-315°). Ridges and gullies (as defined above) were excluded from the aspect layer.

Data analysis
Analysis of the spatial datasets 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).

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).

Fire severity class (observed)	Fire behaviour class (inferred)	% Landscape burnt	
		FFDI ~100	FFDI ~20
1. Crown and understorey leaves consumed	crown fire	20	1
2. Crown scorched, understorey leaves consumed	intense understorey fire	51	15
3. Crown and understorey scorched	understorey fire	20	28
4. Crown intact, understorey scorched	low-intensity understorey fire	4	23
5. Crown intact, understorey partly scorched	patchy understorey fire	4	30
Unburnt	no fire	1	2

Vegetation type
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 understorey 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 understorey (Figure 2a). During more moderate weather (FFDI ~20), a relatively small proportion of shrubland and woodland/open-forest areas was burnt by crown or intense understorey fire (<20%) and about 50% burnt at lower intensity (Figure 2b).

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 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.

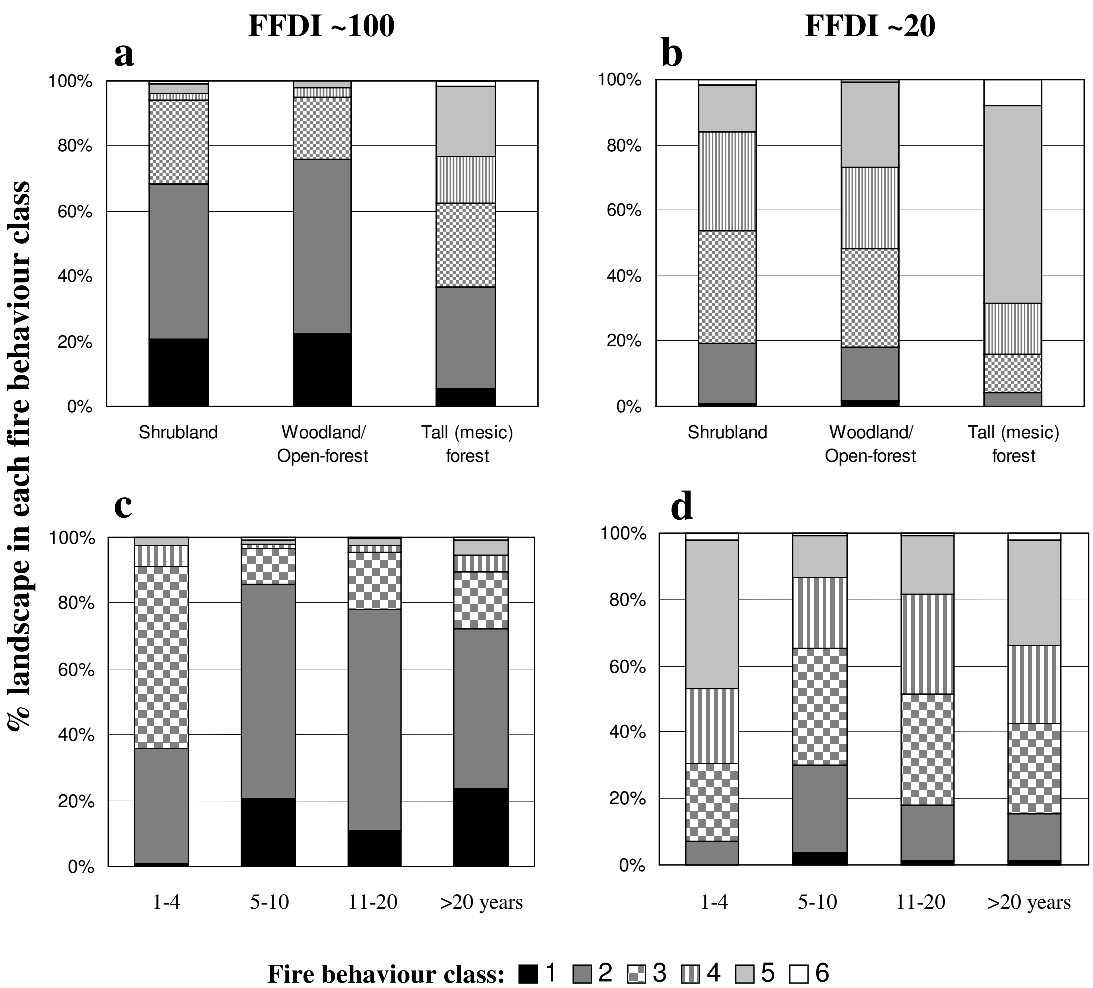

Figure 2. Percent of the landscape affected by different fire behaviour classes within (a, b) vegetation type and (c, d) fuel age during contrasting weather conditions (a and c: FFDI~100, b and d: FFDI~20).
Details of fire behaviour classes are given in Table 1. The three vegetation types (shrubland, woodland/open-forest and tall forest) represent broad structural categories, within which a number of mapped vegetation classes (see Tindall *et al.* 2005) 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.

Fuel load
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 still affected about one third of the young fuel areas (Figure 2c, far left column). Also during extreme weather, 70-90% of the landscape with older fuels (5+ years) was affected by either crown fire or high intensity understorey fire (Figure 2c). A similar, although less marked, trend of more moderate fire behaviour in young fuels was found during relatively mild weather (Figure 2d).

In general, while the extent of crown fire during extreme weather was reduced by young fuels, fuel age had a negligible effect on canopy scorch (>90% of the landscape, irrespective of fuel age). The extent of unburnt and low-intensity/patchy understorey fire was hardly affected (10% 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? Also, is a fuel age of 1-4 years achieveable 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 and Kenny 2003).

Terrain

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%) (Figure 3a). 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 (Figure 3b). 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.

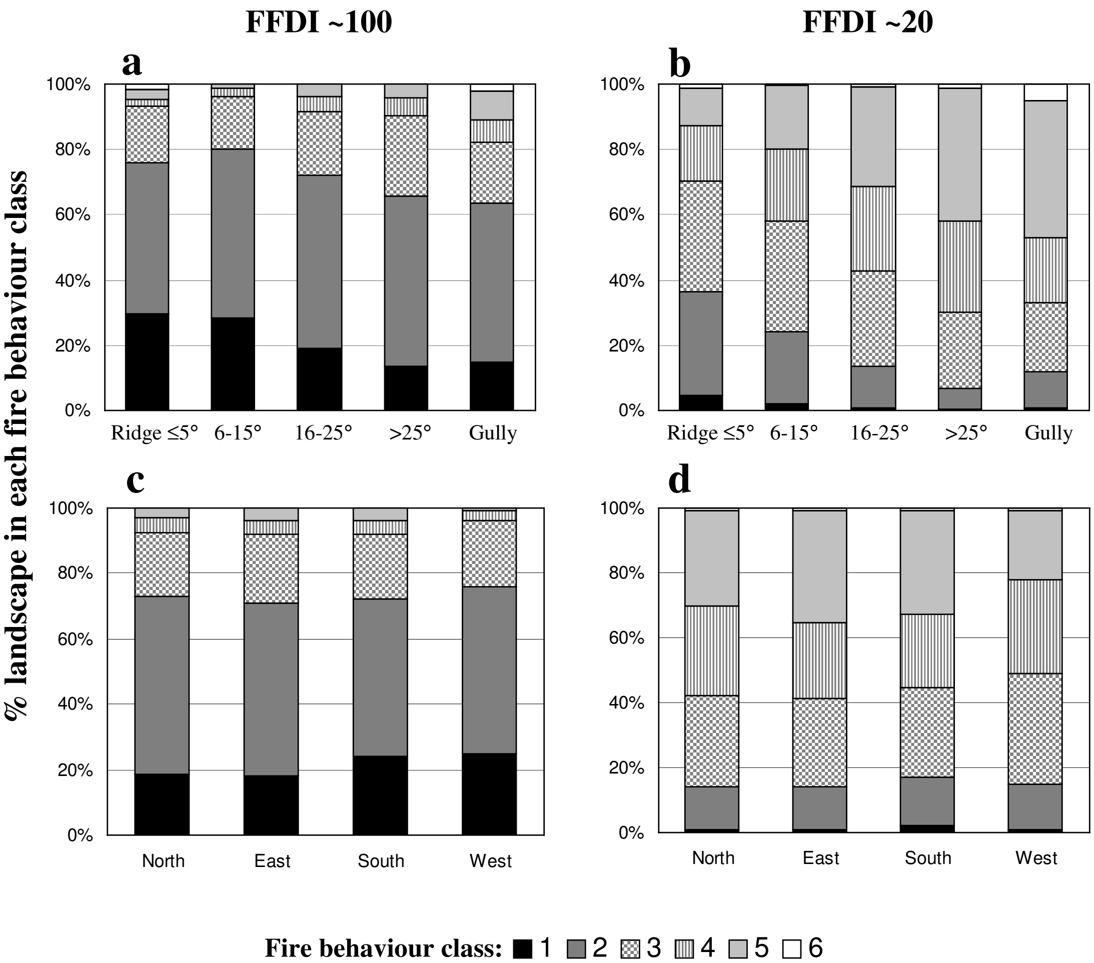

Figure 3. Percent of the landscape affected by different fire behaviour classes on different (a, b) slopes and (c, d) aspects during contrasting weather conditions (a and c: FFDI~100, b and d: FFDI~20).

Details of fire behaviour classes are given in Table 1. The distribution of slope and aspect classes across the study landscape were determined by classification of a digital elevation model (DEM) grid layer combined with spatial data on the location of water courses. Gullies are defined as a 50 m strip spanning water courses. North, east, south and west aspects are restricted to slopes >5° (*ie*. ridges and gullies are excluded from the aspect data).

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 (Figure 3c, d).

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.

Conclusions

This study found that, during extreme weather (FFDI ~100), the majority of vegetation was either consumed or completely scorched by the Mount Hall fire, with almost no area left unburnt and only small areas where the fire remained at shrub level leaving the canopy intact. Areas where the canopy remained intact were largely restricted to tall, mesic forests, steeper slopes and gullies. This severe fire behaviour was moderated to some extent by young fuel age, however the total area of canopy scorch was not reduced. In contrast, during more moderate weather (FFDI ~20), crown fire was almost non-existent and the canopy remained intact over about half of the landscape. Suprisingly, aspect did not appear to have much influence on fire behaviour. These patterns are of relevance to fire management in terms of predicting fire behaviour and understanding its effects in flammable landscapes such as the Blue Mountains. Similar analyses of other large fires would be useful to further explore these findings.

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