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Keywords

eastern, australia, prediction, components, probability, fire, weather, large, fires, sydney, region, south

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Prediction of the probability of large fires in the Sydney region of south-eastern Australia using fire weather

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Abstract. The probability of large-fire (≥1000 ha) ignition days, in the Sydney region, was examined using historical records. Relative influences of the ambient and drought components of the Forest Fire Danger Index (FFDI) on large fire ignition probability were explored using Bayesian logistic regression. The preferred models for two areas (Blue Mountains and Central Coast) were composed of the sum of FFDI (Drought Factor, DF = 1) (ambient component) and DF as predictors. Both drought and ambient weather positively affected the chance of large fire ignitions, with large fires more probable on the Central Coast than in the Blue Mountains. The preferred, additive combination of drought and ambient weather had a marked threshold effect on large-fire ignition and total area burned in both localities. This may be due to a landscape-scale increase in the connectivity of available fuel at high values of the index. Higher probability of large fires on the Central Coast may be due to more subdued terrain or higher population density and ignitions. Climate scenarios for 2050 yielded predictions of a 20–84% increase in potential large-fire ignitions days, using the preferred model.

Additional keywords: climate change, drought, fire danger, fire weather indices.

Introduction

Large landscape fires can have important environmental, social and economic consequences (e.g. death and injuries, destruction of buildings, crops and infrastructure; Moreno 1998; Keeley and Fotheringham 2001; Gill 2005). Such impacts are often severe in peri-urban environments where large populations abut extensive tracts of flammable vegetation. Although large fires represent only a small proportion of the total number of fires, they typically account for the bulk of area burned in many regions (e.g. Reed and McKelvey 2002). An understanding of the factors that govern the incidence and spread of large fires is therefore needed to support effective planning of fire mitigation and suppression, along with planning for ecological and urban interface management (Amiro *et al.* 2004). Such an understanding is required not only to predict their incidence, but also to evaluate how this may shift under global change.

The incidence and size of fires is influenced by a range of factors, such as ignition sources, fuels, terrain, suppression forces and weather. In particular, weather is considered to be a significant influence on the incidence of large fires (Flannigan and Harrington 1988; Carrega 1991; Davis and Michaelsen 1995; Gill and Moore 1996, 1998; Mensing *et al.* 1999; Moritz 2003; Keeley 2004; Peters *et al.* 2004). Formal relationships between the incidence of large fires and meteorological factors or fire-weather indices have been explored in a variety of locations, leading to differing conclusions about the relative importance of different weather components. For example, in Canada, area burned was positively related to low rainfall (i.e. drought), high temperatures and low relative humidity (Flannigan and Harrington 1988). In coastal California, however, large fires were largely determined by incidence of autumn foehn winds rather than antecedent rainfall (Keeley 2004). Viegas *et al.* (1992) and Viegas and Viegas (1994) found area burned in Portugal was related to fuel moisture and seasonal rainfall. In temperate Australia, drought preceding the fire season, in combination with particular meteorological conditions, can result in large fires (Foley 1947; Robin and Wilson 1958; Cheney 1976; Cunningham 1984; Gill 1984).

In contrast to drought, which can be regarded as a relatively long-term influence on fire size, effects of wind, air temperature and humidity at the time of fire are 'ambient' drivers of fire size. Studies using fire danger ratings or indices as predictors of area burned have highlighted the importance of both the ambient and drought components as drivers (Carrega 1991; Goodrick 2002; Preisler *et al.* 2004). Recent research has highlighted links between a changing climate and elevated fire activity in the northern hemisphere (e.g. Pausas 2004; Flannigan *et al.* 2005; Westerling *et al.* 2006). These studies have related differing combinations of increases in temperature, length of fire season and drought to increases in the incidence and area of fire

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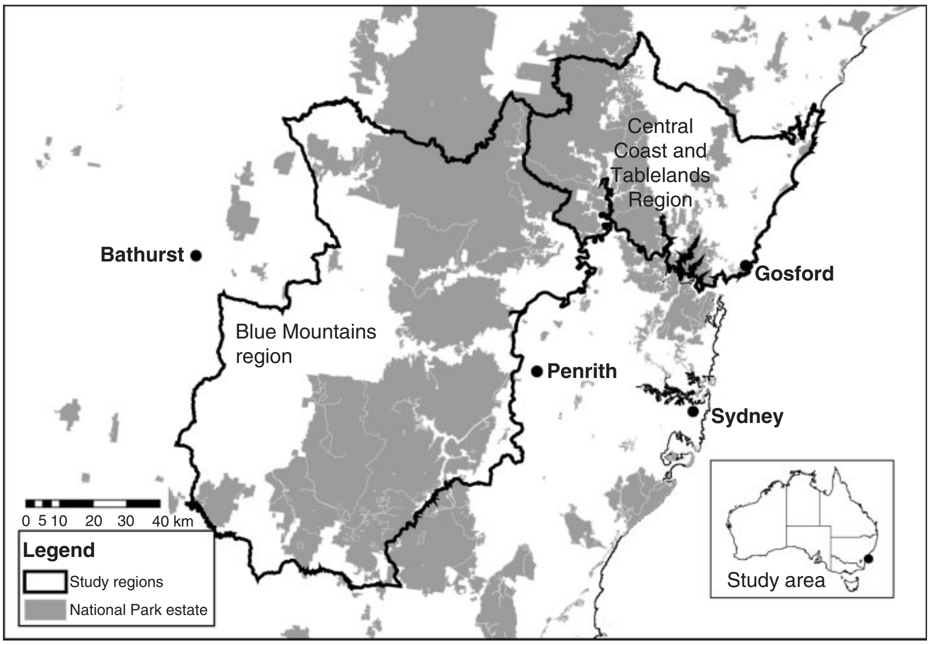

Fig. 1. Location of study areas within the greater Sydney region.

in regions ranging from the boreal to temperate Mediterranean types.

Increases in fire danger indices reflecting, in turn, elevated temperatures, increased evaporation and higher incidence of drought have been predicted for a wide range of regions in Australia under global warming (Williams *et al*. 2001; Hennessy *et al*. 2006). Further insights are required to predict the likely effects of these shifts in fire-weather on fire regimes in Australia. A fundamental understanding of the relationship between area burned and key weather variables offers an empirical basis for predicting the effects of global warming on fire regimes.

The Sydney basin in south-eastern Australia contains the largest urban population centre in the nation. Large fires, causing losses of lives and property, are common in the region (Cunningham 1984; Gill and Moore 1996, 1998; Bradstock and Gill 2001) owing to the large expanse of natural vegetation within and around the greater metropolitan area of Sydney. Much of this is a complex of sclerophyll vegetation dominated by *Eucalyptus* species. Rapid fuel accumulation and high equilibrium fuel loads are a characteristic of this vegetation (Morrison *et al*. 1996). Local combinations of vegetation, terrain and weather can result in a high probability of uncontrollable fire behaviour (Bradstock *et al*. 1998). Bradstock and Gill (2001) estimated that the probability of destruction of property in the region was a positive non-linear function of McArthur's Forest Fire Danger Index (FFDI – the fire danger rating system commonly used in temperate, forested regions of Australia; Luke and McArthur 1978; Noble *et al*. 1980). This trend reflected an underlying positive relationship between incidence of fire and FFDI within major landscapes in the region (Bradstock and Gill 2001).

In the present paper, the aims are to:

(i) Examine the effect of both ambient and drought components of weather in the Sydney region on the probability of large-fire ($\geq$1000 ha) ignition days;

(ii) Apply derived relationships to estimate the level of change in the incidence of large fires that could result from predicted changes in climate by the mid-21st century.

The approach taken differs from many other studies because it concentrates on the weather on the day that large-area fires ignite, rather than a correlation between more general measures of weather and final area burned *per se*. Such an approach has the advantage of offering a predictive capacity for management: i.e. an estimation of the chance of a large-fire event beginning on any given day based on its weather characteristics.

Methods

Study area

The greater Sydney region, in the state of New South Wales, south-eastern Australia, extends from the Hunter Valley in the north to Bateman's Bay in the south and the Blue Mountains in the west, covering ~3.6 million ha. The study areas lie within this basin to the west and north of Sydney and include respectively the Blue Mountains (BM, 1 043 231 ha) and the Central Coast and Tablelands Regions (CCT, 433 471 ha) as defined by New South Wales National Parks and Wildlife Service (Fig. 1). National Park estate predominates in both cases. Historical data on unplanned fire occurrence within these study areas were compiled from official records. Ignition dates and final areas burnt for the periods 1960–61 to 2003–04 (BM) and 1988–89 to 2003–04 (CCT) were collected. These study periods were chosen for their higher data reliability.

The climate of the study areas is temperate (bounded by 34°20′–33°00′S latitude, and 149°50′–151°35′E longitude) with average annual rainfall varying from 600 to 2000 mm. Mean annual temperature ranges from 8.5° to 18.5°C (−2° to 8.5°C,

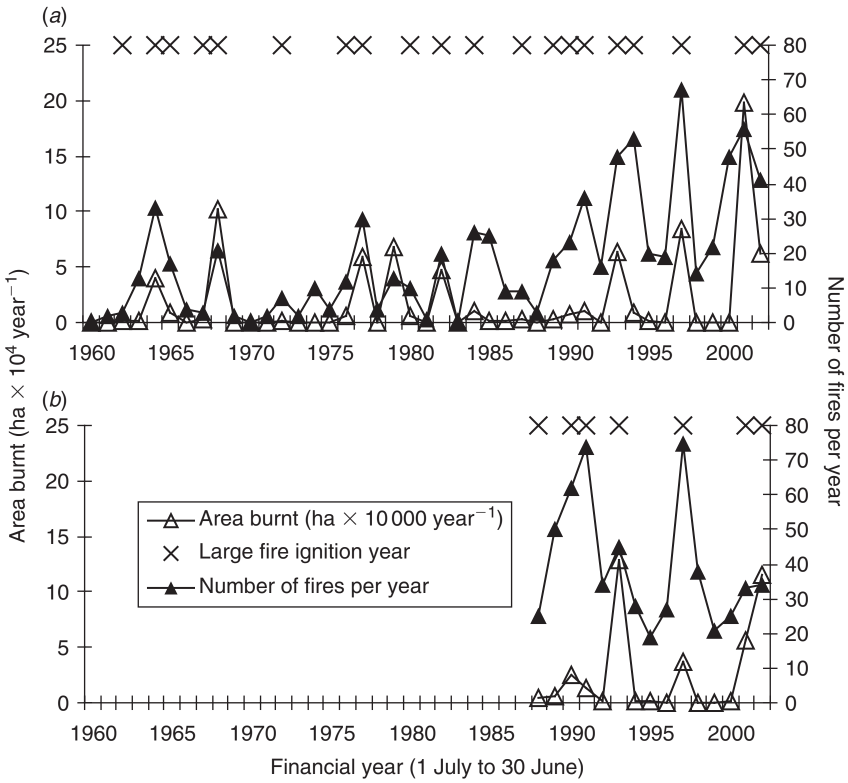

Fig. 2. Annual area burned, number of fires and occurrence of years containing large fire ignition days in the (*a*) Blue Mountains (1960–2003); and (*b*) Central Coast and Tablelands (1988–2003). Years are Australian financial years (e.g. 1960 = 1 July 1960–30 June 1961).

minimum; 20°–29.5°C, maximum) (Australian Bureau of Meteorology). Topography ranges from gently undulating to rugged plateaux with dissected gorges (0 to 1400 m above sea level). The dominant geology is sandstone. Broad vegetation communities include grasslands, heath, woodlands, dry sclerophyll forest with pockets of moister forests, and swamps. Dominant trees are *Angophora*, *Eucalyptus* and *Corymbia* spp. (Keith 2004).

Fire-weather in the region is primarily influenced by temperate dry, cool to hot westerly airstreams and warm, humid easterly subtropical airstreams (Luke and McArthur 1978). From 1960 to 2003, there has been an increase in the annual number of fires in BM, especially since 1993–94 (Fig. 2*a*; years are defined as 1 July to 30 June – which encompasses the spring–summer fire season). Both BM and CCT have shared years with large areas burned: e.g. 1993–94, 1997–98, 2001–02 and 2002–03. In BM, other years with large area burned were 1964–65, 1968–69, 1977–78, 1979–80, 1982–83. Over their respective study periods, a total of 800 500 ha burned in BM and 391 253 ha in CCT (Table 1).

Large-fire ignition days were defined as those on which at least one ignition led to a subsequent burned area of ≥1000 ha (Fig. 2). Small-fire ignition days were all other ignition days (i.e. ignitions resulting in <1000 ha burnt). Predominant ignition sources were human, with lightning being a more significant source of fire in BM than the CCT (NSW Department of Environment and Climate Change, unpubl. data).

Definition of weather indices

The choice of weather observations and procedures for calculation of FFDI and its components followed the methods of Hennessy *et al.* (2006). Daily values of maximum FFDI were calculated from maximum air temperature (T, °C), minimum relative humidity (H, %), maximum wind velocity (V, km h^{-1}) and 24-h precipitation to 0900 hours, using Eqn 1 (Noble *et al.* 1980). FFDI values were capped at a maximum of 100 (see Gill *et al.* 1987).

$$\mathrm{FFDI} = 2 \times \exp(-0.450 + 0.987 \times \ln(\mathrm{DF}) - 0.0345 \times \mathrm{H} + 0.0338 \times \mathrm{T} + 0.0234 \times \mathrm{V}) \quad (1)$$

Precipitation is an input into the calculation of the Drought Factor (DF) along with the Drought Index (Noble *et al.* 1980). DF was calculated using the Keetch–Byram Drought Index (KBDI), (Keetch and Byram 1968) with DF capped at a maximum value of 10 using Eqn 2 (Noble *et al.* 1980).

$$\mathrm{DF} = 0.191 \times (\mathrm{KBDI} + 104) \times (\mathrm{N} + 1)^{1.5} / (3.52 \times (\mathrm{N} + 1)^{1.5} + \mathrm{P} - 1) \quad (2)$$

where N is the number of days since rain and P is the amount of precipitation in the last rain event in mm.

Weather data representative of the BM and CCT districts were taken from respectively Sydney (Sydney Airport) and

Table 1. Numbers of large (≥1000 ha) and small (<1000 ha) fire ignition days and the corresponding area burned for the Blue Mountains (BM) and Central Coast and Tablelands (CCT) for their respective study periods

Study area (period)	No. days Ignitions		Total days	Percentage of days Ignitions		Area burned (ha)		Total ha
	Large	Small		Large	Small	Large	Small	
BM (1960–2003)	51	510	15 692	0.32	3.20	768 223	32 277	800 500
CCT (1988–2003)	23	419	5394	0.39	7.76	359 963	31 267	391 320

Williamtown stations (Australian Bureau of Meteorology) and daily values of KBDI, DF and FFDI were calculated for the historical periods 1960–2003 for Sydney and 1988–2003 for Williamtown. Daily FFDI was then partitioned into relatively long-term (i.e. drought – DF) and short-term, ambient (FFDI with effect of DF minimised) components. The latter, daily ambient component was calculated with DF as a value of 1 (FFDI(DF = 1)) using Eqn 3 (Noble *et al.* 1980), thus minimising the drought effect and allowing coupled effects of temperature, wind and humidity on large-fire ignition to be explored. Values of FFDI(DF = 1) were capped at a maximum of 10.

$$\mathrm{FFDI(DF = 1)} = 2 \times \exp(-0.450 - 0.0345 \times \mathrm{H} + 0.0338 \times \mathrm{T} + 0.0234 \times \mathrm{V}) \quad (3)$$

Statistical modelling

Trends in large-fire ignition days in relation to the various weather indices and their combinations (i.e. DF, FFDI(DF = 1), FFDI and FFDI(DF = 1) + DF – see below) were explored graphically. Large-fire ignition day probability was initially calculated for graphical exploration in 'bins' (single unit size for DF, FFDI(DF = 1) and FFDI(DF = 1) + DF; decile size for FFDI) for each index (i.e. large fire ignition probability = number of large fire ignition days in each bin/total days in each bin in the time series). Non-binned (i.e. continuous) data were used for statistical modelling.

Bayesian logistic regression, with uninformed priors (no prior data), was used to investigate the relationship between large-fire ignition day probability and differing weather components in each study area. The advantage of a Bayesian approach is that the full range of variability in parameter estimates can be accommodated in a preferred model (Ellison 2004; Clark and Gelfand 2006), resulting in a fulsome representation of uncertainty and variability in model predictions.

Four logistic models were fitted to the data from each study area using *WinBUGS* ver. 1.4 (Spiegelhalter *et al.* 2003). The models tested independent effects of DF and FFDI(DF = 1) as well as their product (i.e. FFDI) and their sum (FFDI(DF = 1) + DF) (Table 2). Explanatory variables were centred by subtracting the mean, to reduce correlation between successive samples. Posterior probability distributions on the parameter estimates were sampled from normal distributions. Parameter estimates for the models were based on 20 000 samples after excluding an initial 2000.

The Deviance Information Criterion (DIC) was used to select a preferred model for each study area (Spiegelhalter *et al.* 2003). The change in DIC is indicative of the superiority of the models i.e. values less than three are the better models and those >10 indicate inferior ones. Low values of DIC indicate parsimonious models (i.e. small number of explanatory variables) with a high level of fit to the data. The performance of the models as predictors of large-fire probability was tested by calculation of the ROC (Receiver Operator Curve) and estimation of the area under the curve (AUC). The ROC provides an estimation of performance of binary models based on the ratio of true to false positive predictions (Burnham and Anderson 2002). AUC values close to 1 indicate a model with a high capacity for successful prediction, whereas a value of 0.5 indicates a model that does not perform better than a random coin toss. A predictive, probability surface for large-fire occurrence was derived for the preferred model using least-squares regression (*STATISTICA*, version 7.1).

Effects of climate change

Hennessy *et al.* (2006) estimated a range of scenarios, using a variety of Global Circulation Models (GCMs), for effects of climate change on fire danger and drought indices for a variety of weather stations within south-eastern Australia. Hennessy *et al.* (2006) predicted a general increase (relative to contemporary climate) in average annual sum of daily FFDI in the order of 5–25% and 8–30% for 2050 using two differing GCMs (CCAM Mark 2 and CCAM Mark 3 respectively). Hennessy *et al.* (2006) also provided estimates of change in daily FFDI: for example, the annual frequency of days with Very High to Extreme FFDI in 2050 for Sydney was predicted to rise by 6–75% from a current annual average of 8.7 (Hennessy *et al.* 2006). These predictions were generated from an adjusted 31-year time series of contemporary daily data (Hennessy *et al.* 2006), reflecting effects of 2050 scenarios on the individual parameters (e.g. rainfall, temperature, humidity, wind speed) used in the calculation of daily FFDI.

Effects of climate change on the frequency of large-fire days and total area burned were estimated using the highest and lowest scenarios of change in FFDI and drought indices for 2050 provided by Hennessy *et al.* (2006) based on the CCAM Mark 2 and 3 predictions. The preferred statistical model (see above) was used to generate threshold values of FFDI(DF = 1) and DF that corresponded to differing levels of predicted large fire probability (e.g. 10, 20, 30%). The number of days at or above each threshold was calculated for the contemporary 31-year time series of daily weather data (1974 to 2005) for Sydney and Williamtown (representing BM and CCT respectively – see above). A similar calculation was then performed on the adjusted daily weather data, representing the highest and lowest 2050 scenarios of climate change produced by Hennessy *et al.* (2006). Differences, resulting from climate change, in the number of days corresponding to a particular level of predicted,

Table 2. Bayesian logistic regression models (regression parameter estimates for mean and Bayesian credible intervals) for prediction of effects of weather components (FFDI, DF, FFDI(DF = 1) – see text) on the probability of large fire ignition days in the Blue Mountains (BM) and Central Coast and Tablelands (CCT)

Deviance Information Criterion (DIC) compares models, which are ordered from best to worst (see *Methods*). Parameter a = slope; b = y-intercept for weather component 1; c = y-intercept for weather component 2. Model performance is indicated by estimated area (AUC) under the Receiver Operator Curve (ROC)

Weather component	Mean			Credible intervals 2.5%			Credible intervals 97.5%			DIC	ΔDIC	AUC
	a	b	c	a	b	c	a	b	c			
BM												
FFDI(DF = 1) + DF	−7.80	0.55	0.61	−8.63	0.43	0.39	−7.10	0.68	0.84	560.68	0	0.87
FFDI	−6.24	0.08		−6.60	0.07		−5.90	0.10		587.15	26.47	0.84
FFDI(DF = 1)	−6.68	0.67		−7.09	0.56		−6.30	0.79		607.03	46.35	0.79
DF	−7.21	0.70		−8.06	0.49		−6.52	0.95		613.98	53.30	0.84
CCT												
FFDI(DF = 1) + DF	−10.08	0.61	1.30	−12.62	0.46	0.75	−7.96	0.76	1.91	187.41	0	0.98
FFDI	−6.36	0.09		−7.02	0.07		−5.78	0.10		209.98	20.57	0.96
FFDI(DF = 1)	−6.30	0.71		−6.94	0.57		−5.73	0.85		220.53	33.12	0.92
DF	−8.87	1.25		−10.88	0.89		−7.18	1.75		239.24	51.83	0.93

large-fire probability in BM and CCT were generated by comparing the results yielded from the contemporary and future (2050) weather time series data (high and low scenarios).

Results

Effects of weather on large fires

The daily frequency of each index (i.e. FFDI, DF and FFDI(DF = 1)) declined at higher values (Fig. 3). DF tended toward a bimodal distribution (Fig. 3). The number of large-fire ignition days was relatively low (Table 1), but the resultant area burnt by such fires was very high in both areas: i.e. large-fire ignition days accounted for 96 and 92% of total area burnt in BM and CCT over the respective study periods.

There were positive, non-linear trends in percentages of large-fire ignition days in relation to all weather indices (Fig. 4). In general, the percentage of large-fire ignition days (Fig. 4) was small (e.g. $<0.1\%$) at low values of the weather indices in both areas. High percentages of large-fire ignition days (e.g. $>20\%$) occurred at high values of each index. The exception was DF, where the overall range of percentage occurrence of large-fire ignition days was low ($<10\%$) in both areas. Percentage of large-fire ignition days was generally higher in CCT than BM.

Drought (DF) had an apparent threshold effect on large-fire ignition in both areas (Fig. 4*a*), i.e. large fires only occurred on days where DF > 7 in CCT and mostly above DF > 6 for BM. Large-fire ignition days occurred across a broad range of ambient weather (FFDI(DF = 1)) and FFDI in both areas (Fig. 4*b*, *c*), though trends in percentage occurrence were variable. Trends in percentage of large-fire ignition days in relation to FFDI(DF = 1) + DF were less variable (Fig. 4*d*). The percentage of large-fire ignition days increased markedly when FFDI(DF = 1) was >8 (Fig. 4*c*) and FFDI(DF = 1) + DF > 14 in both areas.

Statistical modelling

The best model for both study areas contained the additive effects of the ambient (FFDI(DF = 1)) and drought (DF) components of FFDI (Table 2). For both study areas, the parameter estimates for FFDI (i.e. the multiplicative effects of drought and ambient components) were significant but this model accounted for a smaller change in the DIC (Table 2) than the additive model, as was expected given trends in the raw data (Figs 3, 4). ROC and AUC values followed a similar trend, with the additive model yielding highest values. The overall ROC and AUC values for all models were relatively high, with the preferred, additive model yielding the maximum (i.e. close to 1), indicating a high capacity for successful prediction of large-fire ignition day probability.

Overall, predicted large-fire ignition day probability based on the preferred mean additive model was constrained by both drought and ambient weather in both areas (Fig. 5*a*), but there was differential sensitivity to these factors between the areas. Large-fire ignition days were predicted (mean) to be absent under low to intermediate values (e.g. 0–6) of both weather components in both areas. Mean predicted probability was less constrained by ambient weather and more constrained by drought in CCT compared with BM, based on the relative position of the 0.1 probability contour (Fig. 5*a*). Mean predicted probability of large-fire ignition days increased with FFDI(DF = 1) and DF, but was sensitive to change at high values of both independent variables (Fig. 5*a*). Overall mean predicted large-fire ignition probability was higher at high values of both weather components in CCT compared with BM. Thus CCT predictions were more sensitive to variations in both ambient and drought components at high values (Fig. 5*a*).

The preferred model, FFDI(DF = 1) + DF, can be used as a large fire probability index (LFPI) with a range of 20, given that both components had a capped maximum value of 10 (see above and Fig. 5). The minimum value of LFPI for each mean large-fire probability decile (Table 3) was estimated from the intercept of each decile with the axes of either DF or FFDI(DF = 1) (i.e. where the value of either index is zero – Fig. 5*a*). Minimum LFPI for each decile of probability was lower for CCT than BM (Fig. 5, Table 3). For example, there was a >50% mean chance of a large-fire ignition day on the Central Coast when LFPI was >18.0 (i.e. FFDI(DF = 1) ≥ 8, DF > 9.1) and in the Blue Mountains when LFPI was >19.4 (i.e. FFDI(DF = 1) ≥ 9.4, DF ≥ 9.6). Over the

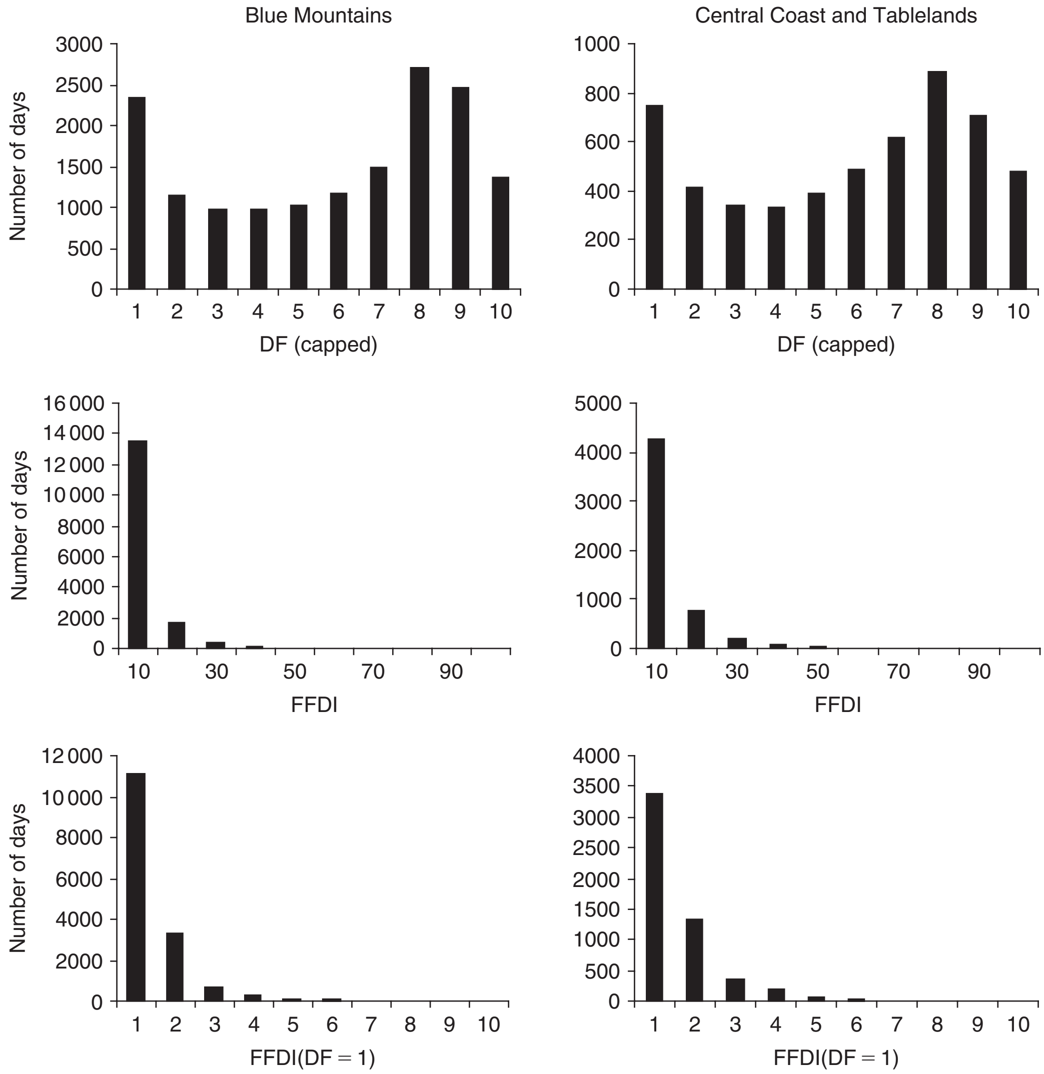

Fig. 3. Frequency of categories of weather indices from Sydney and Williamtown, used respectively for analysis of Blue Mountains (1960–2003) and Central Coast (1988–2003) fire data. Weather indices include Drought Factor (DF), Forest Fire Danger Index (FFDI) with DF = 1 (FFDI(DF = 1)) and FFDI.

period 1974–2003 (10 957 days), these conditions (mean predicted 50% chance of a large-fire ignition day) were rare, being met on 0.01% days (12 days total) on the Central Coast and ~0.001% days (1 day total) in the BM. Lower probabilities of large-fire ignition occurred on appreciably more days in both areas (Table 3).

There was considerable uncertainty around the mean predictions, indicated by the Bayesian credible intervals (Fig. 5*b*, *c*) and their effect on the LFPI. For example, at the upper confidence limit (97.5%), the 50% LFPI was 16.6 for CCT and 17.8 for BM (Fig. 5*b*). At the lower confidence limit, the maximum large-fire probability dropped to ~0.5 for CCT and 0.3 for BM (Fig. 5*c*).

Effects of climate change

The climate change scenarios for 2050 substantially increased the predicted incidence of days suitable for large-fire ignitions, based on minimum LFPI (Table 3). The high-climate-change scenario, as expected, produced a greater increase in predicted large-fire ignition probability than the low-climate-change scenario (Hennessy *et al.* 2006). The average increase in predicted minimum LFPI ranged from 20 (BM) to 34% (CCT) under the low-climate-change scenario, and from 67 (BM) to 84% (CCT) under the high-climate-change scenario (averages were calculated across all LFPI deciles, yielding values of ≥5 days under contemporary climate).

Discussion

Effects of drought and ambient weather

The positive relationship between percentage of large-fire ignition days and the differing weather indices (Fig. 4) reflected the relative rarity of small fires on days with higher values of each index, as well as the overall rarity of such weather conditions (Fig. 3). The exception to this was DF, where the percentage

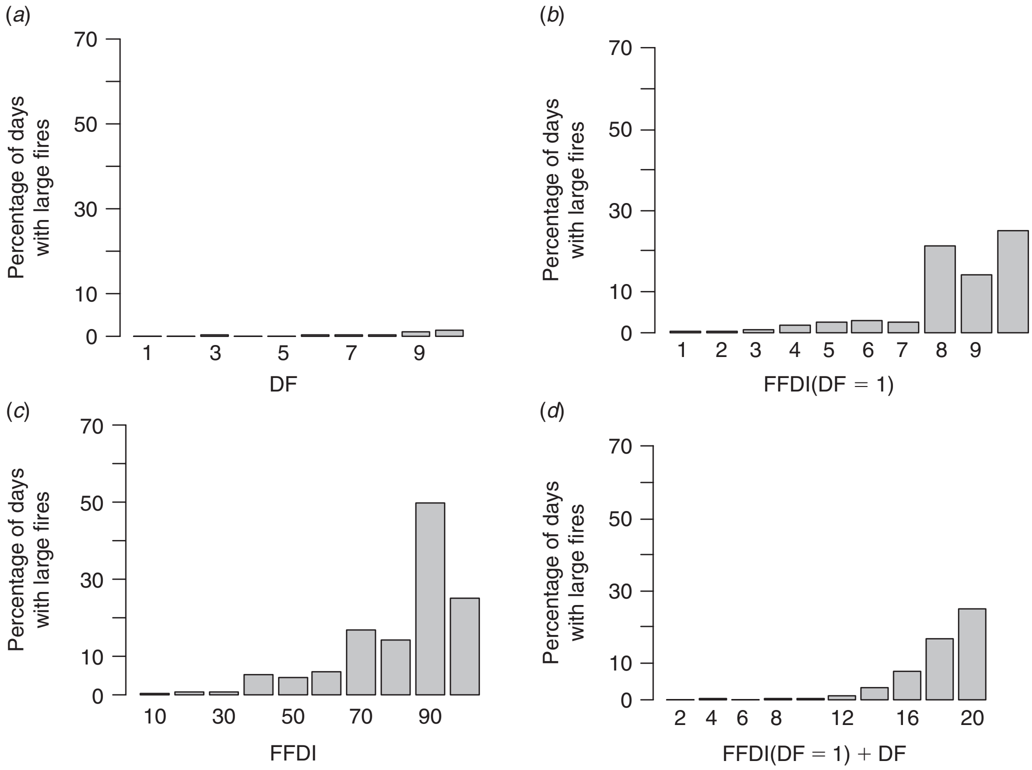

Fig. 4. Percentage occurrence of large fire ignition days in relation to differing weather indices (*a*) Drought Factor (DF); (*b*) Forest Fire Danger Index (FFDI); (*c*) ambient weather (FFDI(DF)); (*d*) additive model (FFDI(DF = 1) + DF) (see text) in the Blue Mountains (BM 1960–2003) and Central Coast and Tablelands (CCT 1988–2003).

range of large-fire ignition days was low, owing to the bimodal distribution of daily DF (Fig. 3). Drought, and to a lesser degree ambient weather, had threshold effects on large-fire ignition day percentage (Fig. 4*a*, *c*). The addition of drought and ambient components (FFDI(DF = 1) + DF) captured these non-linear trends (Fig. 4*d*). Large-fire ignition day probability followed a clearer trend in response to this additive index, compared with FFDI (multiplicative effect) (Fig. 4*b*, *d*). This was reflected in the preferred statistical model (Fig. 5, Table 2).

Drought and ambient weather therefore had interdependent effects on large-fire ignition. Ignition of large fires was only likely in representative landscapes of the Sydney region when drought and ambient conditions of at least 'moderate' severity (e.g. DF > 5, FFDI(DF = 1) > 5, LFPI > 10) co-occurred. Ambient weather (higher temperatures and wind speeds, lower humidity) can realise the opportunity created by drought for large fires to develop if ignitions occur.

The results of the present study quantify trends partially explored in other case studies in the region. Cunningham (1984) found that major fire seasons of fires in the Blue Mountains before 1983 resulted from one or more wet seasons followed by a dry spring, accompanied by specific ambient weather conditions. Large fires in January 1994 affected the Sydney region, resulting in major property loss. These fires and the bulk of resultant property damage occurred under conditions of extreme daily FFDI, though a comparison of wind and drought contributions to FFDI on these days showed no unprecedented values of these variables (Gill and Moore 1996). The contribution of both drought and ambient weather were causal to these fires. Similar circumstances prevailed when large fires burned in the region in December 2001 (Chafer *et al*. 2004; Hammill and Bradstock 2006).

Gill (1984) hypothesised that droughts, because of their regional scale, predispose large areas to fire through drying of fuel, an increase in fuel load and removal of natural barriers to fire spread. Gill (1984) also noted that when droughts are prolonged, there is an increased chance of coincidence of other weather factors that enhance the spread of fire. The overall probability of large fires therefore increases. The results of the present study confirm and extend this hypothesis through quantification of the interactive contributions of drought and ambient weather on probability of ignition of large fires.

Influences of weather on fuel connectivity

Threshold effects of drought and ambient weather on probability of large-fire ignition (Fig. 4) are also evident when cumulative area burned is examined for the study period in both areas in relation to the additive model (i.e. calculated from the final area burned and corresponding FFDI data for each ignition day in the appropriate record – Fig. 6). These results (Fig. 6) are consistent with conclusions from other studies of non-linear distributions of fire area (Reed and McKelvey 2002; Peters *et al*. 2004), i.e. that weather factors operating at meso and macro spatial scales have a predominant influence on the development of large fires through influences on the connectivity of available fuel.

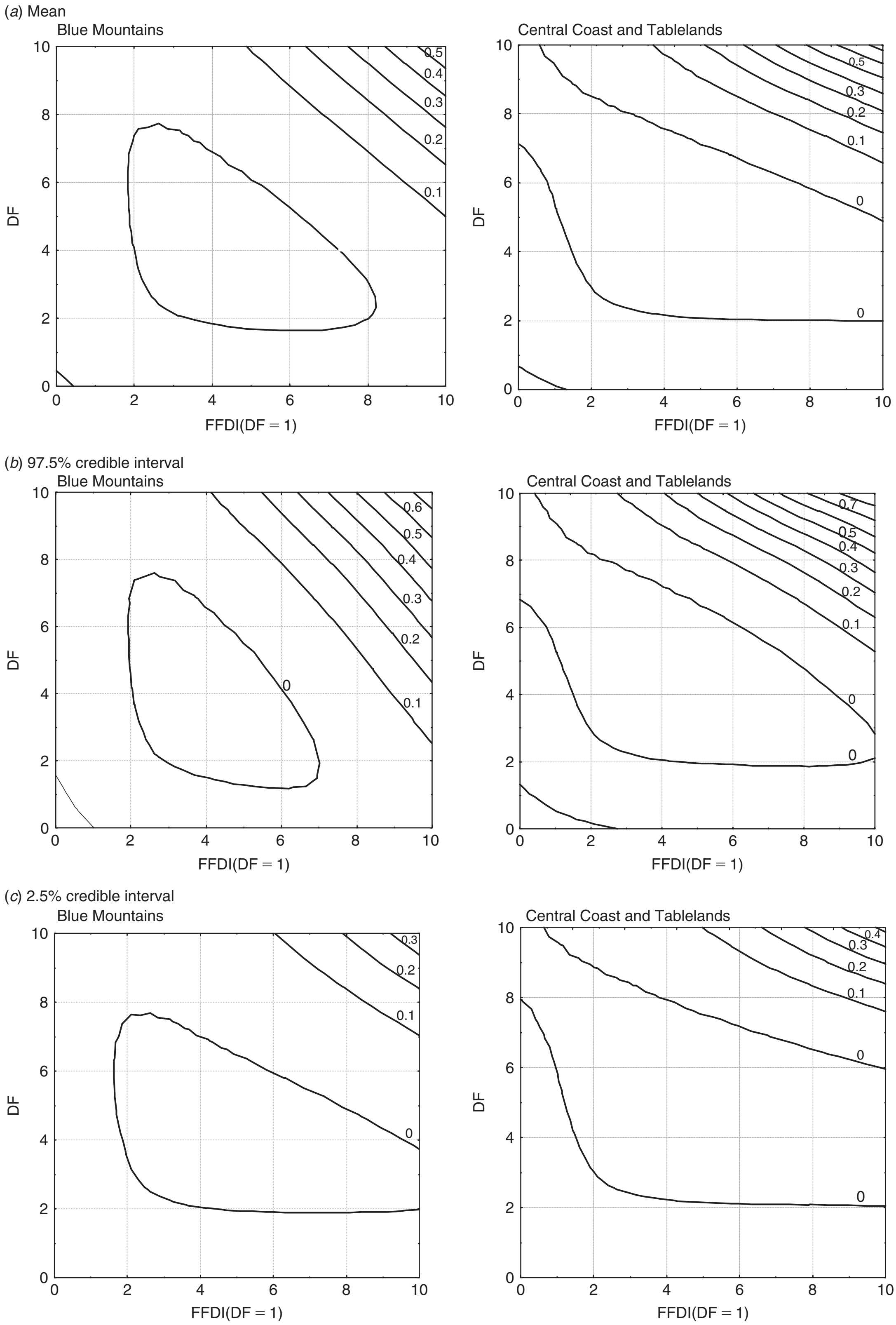

Fig. 5. Prediction of probability of large fire ignition days in relation to drought (Drought Factor (DF) and ambient weather (FFDI(DF = 1))) (FFDI, Forest Fire Danger Index) indices based on historical data from Blue Mountains (1960–2003) and Central Coast and Tablelands (1988–2003). Mean (*a*), 95% (*b*) and 2.5% (*c*) credible intervals are given (see *Methods*).

Table 3. Relationships between mean predicted daily probability of large fire ignition days (LFPI – see text) Drought Factor (DF) and ambient weather (FFDI(DF = 1)), under current (1974–2003) and predicted (Hennessy *et al.* 2006) 2050 climate (low and high scenarios – see text) for the Blue Mountains and Central Coast

Predicted large fire ignition probability Decile	DF	Minimum FFDI(DF = 1)	LFPI	Number of days for current (1974–2003) and predicted 2050 climate (percentage increase for 2050)		
				Current	2050 Low	2050 High
Blue Mountains						
0.1	5.0	4.9	14.9	34	40 (18)	56 (65)
0.2	6.6	6.4	16.4	13	16 (23)	22 (69)
0.3	7.6	7.5	17.5	4	6 (50)	8 (100)
0.4	8.6	8.5	18.5	3	3 (0)	4 (33)
0.5	9.6	9.4	19.4	1	1 (0)	3 (200)
Central Coast						
0.1	6.6	3.8	13.8	135	162 (20)	204 (51)
0.2	7.4	5.1	15.1	70	83 (19)	102 (46)
0.3	8.1	6.2	16.2	39	46 (18)	66 (69)
0.4	8.7	7.2	17.2	23	29 (26)	35 (52)
0.5	9.1	8.0	18.0	12	17 (58)	25 (108)
0.6	9.5	8.8	18.8	5	8 (60)	14 (180)
0.7	9.8	9.7	19.7	4	5 (25)	8 (100)

The thresholds in large-fire ignition (Fig. 4) and resultant cumulative area burned in relation to DF (Fig. 6) may represent a state-transition in landscape-level fuel connectivity, determined primarily by fuel moisture. For values above the threshold, the landscape may enter a state of potential high flammable connectivity where natural controls on fire size break down and where the size of fire will be strongly affected by the ambient component of weather. Such a hypothesis is consistent with the geomorphology of the region: the study landscapes are elevated sandstone plateaux dissected by complex stream systems, often resulting in deep canyons with steep sides (Doerr *et al*. 2006). Thus topography is diverse, leading to strong disjunctions in fuel and complex aspect effects on fuel moisture. We hypothesise that in the absence of drought, fires are relatively small because of the natural variations in continuity of available fuel imposed by the high variation in terrain. In particular, in non-drought conditions, fuel in sheltered southerly and easterly aspects is often too moist to burn. Combined with slope effects, these may impose significant natural barriers to the spread of fires, even when ambient conditions are relatively severe. Such factors are known locally to complement suppression by providing natural containment lines for burning-out operations and prescribed fires.

When drought occurs, these natural controls on fire size may begin to break down, resulting in greater fuel connectivity – effectively a state-transition that increases the spatial scale over which available fuel becomes highly connected. Fires may therefore tend to be less naturally constrained and effective containment opportunities will diminish. When drought is absent, effects of ambient weather are often insufficient for fire to bridge discontinuities. High wind speed may partly allow fires to overcome discontinuities in fuel at landscape scales, via long-distance propagation of embers and ignition of spot fires. This may explain why some large fires are possible (low probability) at low values of DF and moderate to high values of FFDI(DF = 1) (Figs 4, 5). Such a hypothesis is testable through measurement of fuel moisture as a function of slope and aspect combinations under varying degrees of drought. Retrospective analyses of fire perimeters and their relationship between these factors may provide further corroboration.

This hypothesis could partly explain the greater sensitivity of large-fire ignition probability in CCT compared with BM (Figs 4–6). Although there are similarities in geomorphology between these areas, terrain in CCT is substantially more subdued than in BM, where relief and maximum elevation are greater. Thus postulated natural controls on fuel connectivity may be less restrictive and break down more readily in CCT.

In other temperate ecosystems, varying emphases have been placed on drought *v.* ambient conditions (e.g. wind) as principal drivers of large fires. These contrasting and varied emphases need resolution. Gill *et al*. (2002) suggested that interactions of fuel type and climate (a function of latitude and other ecosystem attributes) plus the timing of events that altered the spatial connectivity of fuel can account for the diverse range of fire regimes that prevail across the Australian continent. They distinguished a continuum, in the temperate portion of the continent, spanned by arid and mesic systems. At the arid end of this spectrum, surface fuels that are primarily ephemeral (composed principally of herbs and grasses) predominate, while at the mesic end, litter fuels composed of the foliage of perennial plants and exhibiting regular patterns of accumulation predominate. In arid systems, fuel availability is limited by water availability and its effects on plant germination and growth, whereas in mesic systems, fuel accumulation is relatively rapid and the availability of fuel for burning is constrained chiefly by its moisture content. Fire weather (both drought and ambient components) is not limiting at the arid end whereas fuel is. In contrast at the mesic end, fuel tends not to be limiting but fire weather can be. In the latter case, the occurrence of drought is crucial to fuel availability via effects on fuel moisture.

The Sydney region, along with other ecosystems dominated by forests or shrublands at temperate latitudes, is at the mesic end of this spectrum. If drought is the precursor of large fires, then their occurrence will governed by the frequency of drought over large spatial scales. In temperate Mediterranean-type

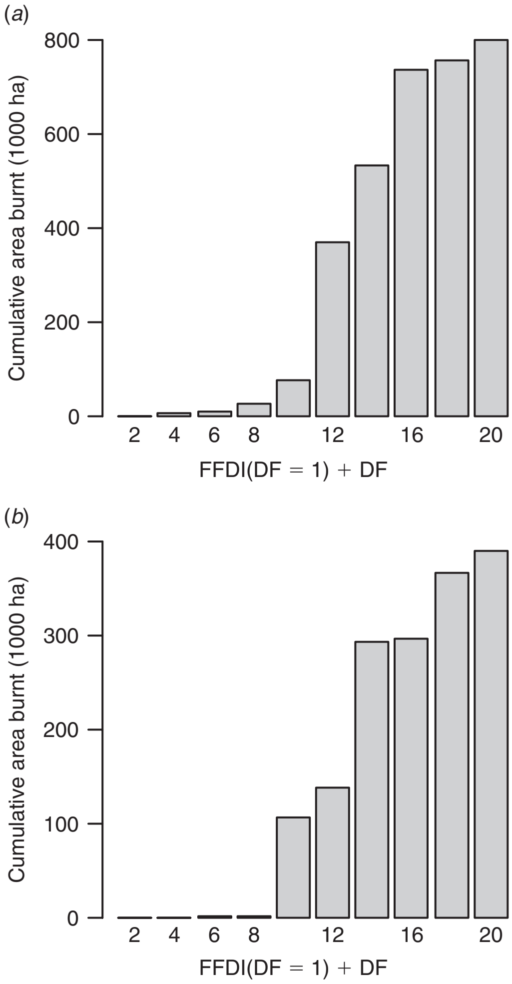

Fig. 6. Relationships between cumulative area burned and FFDI(DF = 1) + DF (DF, Drought Factor; FFDI, Forest Fire Danger Index) for (*a*) Blue Mountains (BM, 1960–2003) and (*b*) Central Coast and Tablelands (CCT, 1988–2003).

ecosystems with a pronounced seasonal summer drought, the conditions necessary for large fires to develop are present every year. In other temperate systems that lack a regular pattern of summer drought (e.g. the Sydney region), appropriate drought conditions occur less frequently and more irregularly. This may explain why wind speed (an ambient weather component) in Californian shrublands (Mediterranean climate with annual summer drought) emerges as the principal determinant of fire size (e.g. Keeley 2004). Thus year-to-year variations in ambient weather (i.e. high wind-speed events) in that environment will have greatest effect on area burned by large fires. By contrast, in a temperate, non-Mediterranean system such as the Sydney region, interannual or even interdecadal variations in drought are likely to have a large effect on area burned, in concert with ambient weather.

Study limitations and consequences for management

The results provide a quantitative basis for predicting the chance of significant fire activity in the region and may be used to refine planning and preparedness based on short-to-medium-term weather forecasting. Existing systems for estimating FFDI could be used for this purpose via an additive reformulation of its components to predict large fire ignition probability (i.e. LFPI – Fig. 5).

Use of an index of this kind must be tempered by appreciation of limitations in the data and analyses. First, the temporal record of fire used in the study is limited – particularly for CCT. More data could be obtained from archives of remote sensing, but the extent to which this approach may augment the record is currently unknown.

Second, ignition of large fires during the study period may have changed owing to human population changes (ignition sources) and changes in fire management practices (i.e. prevention and suppression). These are not considered in the analysis and may contribute to uncertainty in consequent predictions. This study did not attempt to examine influences of varying ignition rates on large-fire probability in time and space. Effects of weather and ignition rates and sources were confounded; hence, the probability of large fires in each region reflected inherent ignition syndromes and the average influence of any historical changes in these syndromes. Trends in the data could therefore be biased. For example, the higher probability of large fires in CCT and BM may be partly due to the higher population density and thus higher rates of anthropogenic ignition in the CCT area (R. A. Bradstock, J. S. Cohn, A. M. Gill, M. Bedward and C. Lucas, unpubl. data). High numbers of ignitions may overwhelm suppression capacity, leading to a large area burned under favourable weather. Data limitations prevented further examination of this effect in this study. Further insights into ignition levels on days with favourable conditions for large fires are required.

Third, the approach does not discriminate between the number of ignitions on an individual day that result in a large area burned, nor does it attempt to more tightly link the weather indices to area burned. This is partly due to data limitations (i.e. insufficient samples of days with differing ignition numbers). Additionally, this limitation results in a relatively coarse representation of the effect of ambient weather in the analysis (i.e. only on day of ignition). In some cases, the area burned on subsequent days was known to contribute substantially to the final total (R. A. Bradstock, J. S. Cohn, A. M. Gill, M. Bedward and C. Lucas, unpubl. data). Such data were not available, however, for all fires, thus precluding the use of a more carefully targeted daily, ambient weather estimate.

Despite these limitations, we suggest that the approach has value for short-to-medium-term prediction of significant fires in the region. Cautious use of LFPI may provide impetus for further refinement to overcome these limitations. We emphasise that the confidence intervals around the mean are wide (Fig. 5), in part owing to the use of data from two weather stations as a predictor of fire activity over a large spatial scale, along with limitations outlined above. These variations would need to be accounted for in any predictive use of LFPI. Local variations in all weather components are likely to account for a substantial part of the variation inherent in the model. We anticipate that the key relationships between weather and probability of large fires (Fig. 5) would have substantially less uncertainty if *in situ* weather data were used to construct the models. The future availability of regional surfaces for drought index and fire danger indices in the region may expedite such improvements.

We also anticipate that other, non-weather factors such as fuel condition and suppression response could be important in determining the probability of occurrence of large fires in this region. There are indications that fuel age affects probability of fire in the region (de Ligt 2005), though interactions with weather and other factors may be significant (Travis 2005). Debate concerning the extent to which fire weather and fuel age contribute to large-fire activity is ongoing (e.g. Moritz *et al*. 2004). This may be better informed by integration of both these key drivers in statistical models that attempt to account for probability of large fires and variation in area burned and severity.

Consequences of climate change

The predicted range of increase in probability of large-fire ignition (~20–84%, Table 3) is wide but sufficient to markedly increase area burned and resultant fire regimes in the region (e.g. shorter inter-fire interval). These estimates overlap with, but exceed at the lower end, the range of increase in average annual daily incidence of Very High and Extreme FFDI (6–75% – see above) predicted by Hennessy *et al*. (2006). They are possibly conservative when extrapolated to effects on area burned and therefore the average interval between fires. For example, changes to the sequence of days with particular characteristics were not considered by Hennessy *et al*. (2006). Such changes may affect the incidence and development of large fires in ways not accounted for here. The probability of rare but significant, extreme events (i.e. multiple days in succession with high wind speed and temperature and low humidity) are unknown. Changes to rates of ignition (not accounted for here) and suppression capacity will further affect the outcome. Despite these limitations, the magnitude of the change in fire regimes indicated by the study has major implications for land management values, ranging from increased probability of property destruction to increased chance of population decline and local extinction of plant species (Bradstock and Kenny 2003).

Further insights will be needed to assess how differing approaches to management will be needed to cope with the changes in fire regimes predicted to result from an increase in the ignition of large fires under climate change. The complexity of this challenge and indeed the responses of fire regimes to alterations in climate may require deeper insights into relationships between weather, fire spread, management effects and indirect feedbacks such as changes in vegetation and fuel structure under climate change and elevated CO_2. Process-based modelling (e.g. Mouillot *et al*. 2002; King *et al*. 2006) may offer one way of exploring the effects suggested by the correlative methods used in the present study.

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