MURDOCH RESEARCH REPOSITORY

Fontaine, J.B., Westcott, V.C., Enright, N.J., Lade, J.C. and Miller, B.P. (2012) *Fire behaviour in south-western Australian shrublands: evaluating the influence of fuel age and fire weather.* International Journal of Wildland Fire, 21 (4). pp. 385-395.

TITLE: Fire behaviour in southwestern Australian shrublands: evaluating the influence of fuel age and fire weather.

RUNNING HEAD: Fire behaviour in SW Australian shrublands

Joseph B. Fontaine[1,4], Vanessa C. Westcott[2], Neal J. Enright[1], Janneke C. Lade[2], Ben P. Miller[3]

1. School of Environmental Science, Murdoch University, Perth, WA 6150 Australia

2. School of Geography, University of Melbourne, Melbourne, VIC, Australia

3. Botanic Gardens and Parks Authority, West Perth, WA 6005, Australia;

4. Corresponding author: J.Fontaine@murdoch.edu.au;
ph: +061 08 9360 6075
fax: +061 08 9310 4997

ABSTRACT

Fuel age (time since last fire) is often used to approximate fire hazard and informs decisions on placement of shrubland management burns worldwide. However, uncertainty remains concerning the relative importance of fuel age and weather conditions as predictors of fire hazard and behaviour. Using data from 35 experimental burns across three types of shrublands in Western Australia, we evaluated importance of fuel age and fire weather on probability of fire propagation (hazard) and four metrics of fire behaviour (rate of spread, fireline intensity, residence time, surface temperature) under moderate to high fire danger weather conditions. We found significant support for a threshold effect of fuel age for fire propagation but limited evidence for an effect of fuel age or fire weather on rates of spread or fireline intensity, although surface heating and heating duration were significantly related to fuel age and shrubland type. Further analysis suggested that dead fuel mass and accumulation rate rather than live fuels was responsible for this relationship. Using BEHAVE, predicted spread rates and intensities were consistently lower than observed values, suggesting further refinement is needed in modeling shrubland fire behaviour. These data provide important insight into fire behaviour in globally significant, fire-adapted shrublands, informing fire management and relationships between fire frequency and fire intensity.

SUMMARY

Management of Mediterranean-type shrublands frequently includes application of prescribed fire. This paper examines the use of fuel age (time since fire) and fire weather conditions to predict fire propagation and behaviour in 35 experimental fires in three shrubland types in Western Australia. Model predictions are evaluated against empirical observations.

ADDITIONAL KEYWORDS: sandplain, fire-prone, fuel, fire spread, prescribed fire, management burn, BEHAVE, kwongan

INTRODUCTION

Fire regimes and their management in fire-prone Mediterranean shrublands are of ecological and applied interest due to the high biodiversity values of these ecosystems (Cowling, Rundel *et al.* 1996; Hopper and Gioia 2004), their association with densely settled areas worldwide (Myers, Mittermeier *et al.* 2000), and the propensity for frequent fire at high intensities which often lead to loss of human property and sometimes human life (Cary, Lindenmayer *et al.* 2003; Keeley, Fotheringham *et al.* 2004). High intensity wildfires burning under extreme weather conditions are deemed undesirable given their social and economic costs, as well as their impact on natural resources and biodiversity in fragmented, human-dominated landscapes (e.g. fires in coastal California in 1993 burned large areas utilised by two endangered shrubland bird species, Bontrager, Erickson *et al.* 1995). Frequent anthropogenic ignitions, high fire hazard, and the fire-dependent nature of many plant and animal species eliminates fire exclusion as a reasonable long-term management strategy in most locations. Thus, prescribed fire under moderate fire weather conditions is the most widely applied active management technique to manage fire hazard and maintain populations of fire dependent species in wildlands and peri-urban areas (Cary, Lindenmayer *et al.* 2003; Keeley, Safford *et al.* 2009). A spate of large wildfires in different parts of the world over the past decade (e.g. southeastern Australia 2003 and 2009, California 2007, Canada, Portugal and Russia 2003, Greece 2007) has led to increased concern about the role of global warming in relation to future wildfire risk, and the adequacy of prescribed fire programs aimed at mitigating wildfire risk through fuel reduction (Hughes and Mercer 2009; Stephens, Adams *et al.* 2009; van Wilgen, Forsyth *et al.* 2010).

Debate over the need for prescribed fire, its efficacy in reducing hazard and fire spread rates, and the relative importance of fuel age and weather on fire hazard and fire behaviour in Mediterranean shrublands is ongoing (Keeley and Zedler 2009; van Wilgen, Forsyth *et al.* 2010). Disagreement over the role of fire exclusion, and thus increased fuel age, in contributing to large wildfires has been particularly prominent (e.g. Goforth and Minnich 2007; Keeley and Zedler 2009 and references therein). Mediterranean shrublands generally burn in a crown-fire fashion and much of the scientific debate has centred on how quickly shrubland fuels gain sufficient horizontal and vertical continuity to carry fire under a range of weather conditions (defined as fire hazard or the probability that a fire will successfully propagate). Moritz et al (2004) working in California, found little evidence using fire frequency data to support the hypothesis that young fuels limit fire spread in wildfire situations. In contrast, Baeza et al (2002) and Fernandes et al (2001) found an effect of fuel age in prescribed fire rate of spread and fireline intensity in the Mediterranean Basin. Generalities explaining these conflicting results have not yet emerged, but the importance of fire weather under projected climate change is likely to increase (Williams, Bradstock *et al.* 2009).

Some of the most fire-prone Mediterranean-type shrublands are found in the southern hemisphere, including fynbos in South Africa and kwongan in Western Australia. Both regions are globally recognised biodiversity hotspots (Myers, Mittermeier *et al.* 2000) and possess plant communities characterised by species with fire-surviving traits (including resprouting, serotiny, fire-cued germination, fire-stimulated flowering, Gill 1981; He, Lamont *et al.* 2011). Planned burns for ecological and fire hazard reduction purposes are used in both regions, with some published data examining fire behaviour and fuel age from fynbos (van Wilgen, Forsyth *et al.* 2010; Van Wilgen, Higgins *et al.* 1990; Van Wilgen, Le Maitre *et al.* 1985; Van Wilgen, Richardson *et al.* 1994) and Australian low open woodlands (Bradstock and Auld 1995) (Burrows and McCaw 1990), but little for kwongan (Keith, McCaw *et al.* 2002).

In light of the conflicting results concerning the relative roles of fuel age (fuel accumulation) and fire weather, and likely increases in extreme fire weather associated with a warming climate, we examine to what extent fuel age and weather conditions can be used to predict the probability of fire propagation and four common measures of fire behaviour (rate of spread, fireline intensity, heating duration, temperature at the soil surface). Data from 35 experimental fires in three shrubland types were used to examine these relationships and to address whether commonly applied fire behaviour models used by fire managers (BehavePlus 5.0; Andrews, Bevins *et al.* 2008) accurately predict rates of fire spread and intensity.

METHODS

Study Area

Within Western Australia, high biodiversity shrublands occur extensively through the transitional rainfall zones (400 to 600 mm annual rainfall) on laterite, limestone, and acid sand substrates (Hopper and Gioia 2004). The northern portion of these shrublands is centred in the mid-west region of southwestern Australia near Eneabba (29.82° S 115.27° E), 275 km north of Perth, and is characterised by four broadly defined sub-communities with differing species composition and structure determined by substrate effects on soil depth, nutrient, and water availability (Enright and Lamont 1992; Hnatiuk and Hopkins 1981). Hnatiuk and Hopkins (1981) describe these four vegetation types as (1) tall shrublands on low sandy dunes with deep, unconsolidated acid sands to 5 m; (2) low shrublands on adjacent flat areas comprising shallow, unconsolidated acid sands (to 1 m) over clay; (3) tall shrublands on unconsolidated calcareous sands over Quaternary limestone; and (4) low shrublands with shallow acid sands (<0.5 m) over lateritic gravels rich in iron and aluminium. Reported species richness is high, with observed values of up to 130 species 1000 m^{-2} for tall and low shrublands on acid sands in the South Eneabba Flora Reserve (Hnatiuk and Hopkins 1981). Resprouting shrubs and subshrubs predominate, with non-sprouting (fire-killed) growth forms less common, comprising 20-25% of species in tall and low sandplain kwongan and lateritic kwongan, and up to 40% of species in calcareous kwongan (Enright, Mosner *et al.* 2007). These shrublands are fire-prone, with estimated mean fire intervals of 12-16 years based on plant demographic data (Enright, Marsula *et al.* 1998) and 13 years (range ~5-40 yrs) based on analysis of satellite imagery for the period 1972-2002 (Miller, Walshe *et al.* 2007). Most extant plant species show adaptations to fire, including the ability to recover vegetatively, fire-stimulated germination of soil-stored seeds, and post-fire release of canopy-stored seeds (Enright and Lamont 1989; He, Lamont *et al.* 2011).

We sampled shrublands on three of the four substrates (calcareous, tall and short shrublands over acid sands). Shrublands over laterite, were not sampled due to logistical limitations of adequate fire histories (see below).

Site Selection

Sites on each substrate type were selected within continuous sandplain and calcareous shrublands (i.e. vegetation types 1-3 described above) in designated reserves and unallocated crown lands (i.e. public lands) on the basis of their fuel age (time since last fire) and logistical needs for implementation of prescribed fire (e.g. proximity of fire breaks). Time since last fire (tsf) was determined from remotely-sensed data and records from the Western Australian Department of Environment and Conservation (DEC). As part of a larger project examining the influence of shortened fire intervals on vegetation, we selected sites ranging in age from 3-24 years since previous fire with an emphasis on sites with fuels < 10 years old (Table S1).

Experimental Fires

Experimental fires were conducted in autumn ranging from late March to late May 2006-2009. Ignition occurred mostly around midday (1130-1400, n=31 of 35; range 1130-1600) and was a headfire lit along 1-2 sides, beginning a minimum of 10 m from the plot edge. Fire sizes often were small (median ~0.5 ha) but ranged from 0.25-100+ ha. Weather conditions were generally mild to moderate (mean temperature 27.5°C, Relative Humidity 33.5%, wind speed 8.8 kph; Table S1), representing typical prescribed burning conditions, with mean fuel moistures low because of the time of year (live fuel 37%, litter 4%; Table S2). Fire danger index (see below for details on calculation) values ranged from 8.5-27 (mean 17) corresponding to fire danger ratings of moderate to very high (low: 0-5, moderate: 5-12, high: 12-24, very high: 24-50, Dowdy, Mills *et al.* 2010).

Data Collection

Biomass and fuels. One to four weeks prior to fire, measurements of vegetation and litter within each burn area were made for eight 4 m × 4 m sub-plots nested within a 40 m × 40 m plot, and for five 0.50 m^2 quadrats nested within each sub-plot (n=40 per plot). Within each subplot the identity, canopy height, and 2 perpendicular widths of all (live and dead) plants > 10 cm height was recorded. For quadrats, percent litter cover (10% increments), identity and height-width of all plants was recorded by species. In addition, a systematic grid of 50-100 point intercept measurements were taken at 5 m intervals (Elzinga, Salzer *et al.* 2001). At each point intercept, % litter cover (20 cm × 20 cm area centred on pin), identity, height and canopy width of any plant in contact with the intercept pin, was recorded. Destructive sampling to estimate allometric equations for plot-wide biomass calculations was conducted at the same time outside and downwind from plots. Allometric equations (for a range of species by growth form; grass, herb, resprouting shrub/subshrub, non-sprouting shrub/subshrub) and details of biomass vs. time since fire relationships are given in Westcott (2010) and Lade (2010). At the time of each burn, ~10 samples each of fine live vegetation (leaves and fine twigs <0.6 cm diameter) and litter were collected and placed in airtight ziplock bags. These samples were weighed, dried at 50°C to constant weight and re-weighed to determine fuel moisture content.

Weather conditions. An Ultrasonic Anemometer and climate station (Delta Ohm, model HD2003-HD2003.1, Padova, Italy) was used to measure the weather conditions during fires in 2006-2008. The instrument was erected at 1.5 m height in undisturbed, nearby vegetation and continuously recorded wind direction, wind speed, ambient air temperature and relative humidity at the time of the fires. In 2009, a hand-held kestrel unit (Kestrel 4500, Kestrel Meters, Sylvan Lake, MI, USA) unit was used to record the same variables every few minutes from ignition to fire extinction. In addition to current weather conditions we estimated the Forest Fire Danger Index (FFDI), a widely used fire danger rating system for woody vegetation types in Australia (Luke and McArthur 1986). The FFDI integrates current weather with the Keech-Byram Drought Index (Keetch and Byram 1968) to generate an index of likely fire behaviour which takes into account fuel moisture (i.e. antecedent weather as days since last rain >2mm) and current weather. Details, equations, and evaluation of the FFDI are provided by (Dowdy, Mills *et al.* 2010; Griffiths 1998; Keetch and Byram 1968; Luke and McArthur 1986). Weather data used to calculate FFDI were averages over 15 minutes at time of fire. Data required for calculating the Drought Index, including number of days since last rain and amount of rainfall in most recent event were provided by the Bureau of Meteorology for the weather station at Eneabba (Fig. 1).

Fire Behaviour. We characterised fire behaviour with four separate metrics: rate of spread (RoS), duration of soil heating, mean maximum temperature at the soil surface, and fireline intensity (FI). Each of these components of fire behaviour reflects a slightly different facet of the combustion and heat release process, giving a fuller picture of the fire as it moved through our plots. To measure RoS and soil heating, custom-made 15-channel data loggers (Tain Electronics Pty. Ltd, Box Hill, Australia) were used. From one to three data loggers, each with 15 thermocouple cables (10m in length) protected by steel sheathing were used to sample surface temperature during fires (N=15-45 points of measurement per fire). Cable tips sampled temperatures every 8 seconds (range 0-250°C). The x-y coordinates of each cable-tip were recorded and the time elapsed for fire to spread from one lead to the next in the direction of spread used to estimate RoS. Heating duration was calculated as the mean number of seconds each thermocouple recorded temperatures > 120^{o}C. This threshold value was selected so that results would be comparable with other studies where prolonged exposure of seeds to temperatures > 120^{o}C was found to result in seed death (Auld, Keith *et al.* 2000; Hanley and Lamont 2000). Mean maximum temperature was estimated using ceramic tiles (10 × 10 × 0.7 cm) marked on one side with a series of chromatic thermometer crayons (Faber-Castell Thermochrom, Nurnberg, Germany) which undergo permanent colour changes when exposed to specified temperature thresholds (11 levels ranging from 65-500°C). Each of 35-40 tiles per fire was wrapped in aluminum foil and placed vertically facing into the approaching fire (anticipated based on wind direction) on a 5 × 5 m grid within each plot immediately prior to fire. Following fire, tiles were retrieved, scored for maximum temperature, and the mean plot-wide value used as an estimate of the mean maximum surface temperatures reached during the fire. Finally, fireline intensity was estimated based upon rate of spread and fuel consumption using the Byram equation (Byram 1959):

$$I = Hwr \qquad \text{Eq. 1}$$

where I is fireline intensity (kWm-1), H is the heat yield of the fuel (kJ kg^{-1}), w is the weight of available fuel (t ha^{-1}) and r is the rate of spread (m s^{-1}). RoS was estimated as above and weight of available fuel was assumed to represent 100% of litter and 16% of live vegetation (corresponding to leaves + twigs <0.6 cm). We used a heat yield value of 18,622 kJ kg-1 based upon empirical data for fynbos vegetation reported by van Wilgen et al (1985), corrected for moisture content (Byram 1959).

Data Analysis

Our goal was to evaluate the relative importance of fuel age (time since fire), fire weather (measured as FFDI), and shrubland type in relation to fire propagation and behaviour. We focused on fuel age and FFDI because of their widespread use by fire managers in deciding where and when to ignite management fires. Furthermore, we wanted to evaluate whether modelled fire spread and intensity corresponded to observed field values. To accomplish this we employed a model selection framework where we confronted our data with a set of linear models and evaluated the support for each predictor given the data (Burnham and Anderson 2002). We used AICc to rank models and akaike weights together with 95% confidence intervals of model coefficients to assess importance of predictors. Correspondence of empirical and modelled fire behaviour was assessed from their correlation with one another (see below for details).

Fire propagation. We first assessed the contribution of time since fire, FFDI, and shrubland type in determining whether a lit fire would propagate through each plot (71% of fires successfully propagated). Using logistic regression we considered an all subsets combination of these three predictors allowing for an interaction between time since fire and FFDI. Lack of convergence prevented us from investigating interaction terms between shrubland type and time since fire/FFDI.

Fire Behaviour. For each of our four measures of fire behaviour we employed an all subsets approach to evaluating the importance of time since fire, FFDI, and shrubland type using linear regression. In addition to each term by itself, we allowed for an interaction between time since fire and shrubland type (different cover types regrow at varying rates) and an interaction between time since fire and FFDI (younger fuels would be more likely to burn at higher FFDI values). In all cases we examined the full additive model for fit, homogeneity of variance, and influence of outliers before proceeding with our analyses.

Modeling of Fire Behaviour. Prior to conducting a management burn, fire managers are required to perform some level of fire modeling to anticipate the conditions under which fireline intensities will be controllable and thus risk will be at an acceptable level. Often, part of this process involves the software package BEHAVE (Andrews, Bevins *et al.* 2008) which produces estimates of RoS, FI, spotting distance, containment likelihood, and fire effects for a number of vegetation types, including shrublands. BEHAVE is used extensively in forested systems as well as shrublands in North America and along with other programs like CONSUME (Prichard, Ottmar *et al.* 2006) is increasingly used to predict other outcomes like carbon emissions from fire. Assessments of the chaparral fuel model of BEHAVE have been conducted in California (Keeley and Zedler 2009) as well as in South African fynbos (Van Wilgen, Le Maitre *et al.* 1985), but not in Western Australia to our knowledge (but see Hollis, Matthews *et al.* 2010 for data on Australian woodland fuels). Thus, we examine the predictions made by BEHAVE using customised fuel models initialised from the original chaparral fuel model (Rothermel 1972). We extracted predicted RoS and FI from BEHAVE and compared these against observed values (slope of each line corresponded to reported correlation with values <1 suggesting negative bias and > 1 positive bias). For fires that did not propagate, we used zero as the observed RoS and FI.

RESULTS

Fire Propagation. Over the period 2006-2009, 35 ignitions were attempted with 25 fires that propagated (see supplementary tables S1-S3 for weather, fuels, and fire behaviour data associated with each fire). Fuel moisture levels were generally low, with a mean of 3.7% (range 1-9%) for dead fuels and 36.7% (range 9-54%) for live fuels (Table S1). Live fuel moisture varied significantly by shrubland type ($F_{2,31}=12.1, p<0.001$) with consistently low values in shallow sands (mean 21%) and overlapping values in deep sand (mean 32%) and calcareous shrub types (mean 44%, Table S1). Time since fire was a strong predictor of fire propagation, being present in all top models, with an Akaike weight of 1.0, and confidence intervals not overlapping zero (Fig. 2, Tables 1-2). We found little support in the data for the importance of fire weather (as measured by FFDI) in determining whether a fire would burn within the range of experimental conditions assessed (moderate to very high fire danger, 3-24 years since last fire). Shrubland type was not supported as an important predictor of the probability of fire propagation.

Fire Behaviour. Of the 25 fires which propagated successfully, we obtained data for our four behaviour metrics from 23 (equipment failures occurred for two fires). Fire behaviour (rate of spread, fireline intensity, heating duration, mean maximum surface temperature) varied by shrubland type (Fig 3). Differences among shrubland types were most pronounced in heating duration (calcareous > deep sand > shallow sand; Fig 3c) and broad variance in rate of spread and fireline intensity were observed for deep sand shrublands (Fig 3a-b). None of the weather-based components of FFDI (relative humidity, temperature, wind speed) were related to fire behaviour (Table S4). The most commonly used measure of fire behaviour, rate of spread (RoS), did not vary with either fuel age or fire weather, with the intercept-only model ranked highest (Tables 1-2). Fuel age appeared in 3 of the 5 top models with an Akaike weight of 0.56, but with all parameter estimates overlapping zero in their 95% confidence intervals (Table 2). The top-ranked model for fireline intensity (FI) was shrubland type, with limited evidence for influence of fire weather or fuel age (Table 2). Parameter estimates for the effect of shallow sand vegetation narrowly overlapped zero suggesting that fireline intensities in that shrubland type were lower, consistent with lower biomass estimates (Fig 3, Table S1). Results for mean maximum surface temperature and duration of heating (time >120°C) were similar, with support for more complex models including interactions among fuel age and shrubland type (both response variables, Tables 1-2, Fig. 3) as well as fire weather and fuel age (mean maximum temperature only, Tables 1-2). Effects of shrubland shrubland type and fuel age were strongly supported with parameter estimates not overlapping zero, as well as for interaction terms in the model for mean maximum temperature (Table 2). Further partitioning fuel age into biomass of live and dead components for the two predictors with fuel age in the top model (Table 1, Fig. 4) suggested that the mass of dead fuel was a stronger predictor of fire behaviour than live biomass. Using simple univariate regression, we found strong evidence of a relationship between mean maximum temperature and dead biomass ($t_{1,21}$=4.1, p<0.001) but not for live biomass ($t_{1,21}$=1.0, p=0.33); a similar pattern was repeated for heating duration (t=4.1, p<0.001 for dead biomass) but with some support for live biomass as well ($t_{1,21}$=2.7, p=0.01).

Model Predictions. Using BEHAVE, we generated customised fuel models for each of the 35 management fires and compared predicted and observed RoS and FI (Table 3). Across nearly all shrubland types and both metrics, BEHAVE exhibited negative bias with predicted < observed values (Fig. 5). For shallow-sand vegetation, the estimated slope of the line was zero indicating no relationship between observations and predicted values (however, the small sample, N=5 fires, suggests caution in inferring beyond this study; Table 3). Predicted and observed values had the greatest correspondence for tall shrublands on deep sand with a non-zero slope estimate of 0.31 for RoS and 1.05 for FI (Table 3, Fig. 5). Calcareous vegetation had shallower but also well supported (different from zero based on 95% CI) slope estimates of 0.14 for RoS and 0.37 for FI (Table 3, Fig. 5).

DISCUSSION

We found broad support for the positive association of fuel age and the probability of fire propagation (i.e. fire hazard), as well as an influence on two measures of fire behaviour - but not the two that are most commonly used (RoS, FI), calling into question their use in deciding where and when to place management burns. Similarly, despite estimating forest fire danger index (FFDI) values with time of fire, site-specific meteorological data, we found no evidence supporting use of FFDI in predicting fire propagation or fire behaviour in Western Australian shrublands under the fire (moderate to very high fire danger index) weather conditions measured. Vegetation type (the three shrubland communities) mediated measures of fire behaviour (RoS, FI, heating duration, maximum temperature) but not fire propagation, likely owing to the similarity in vegetation structure in the initial years following fire, with similarly low levels of surface litter and vegetation continuity and differences only emerging later with further vegetation development.

Comparison of biomass levels, RoS, and FI from similar studies worldwide (Table 4) suggests that observed RoS is similar to that for fynbos vegetation in South Africa (Van Wilgen, Le Maitre *et al.* 1985) and for California chaparral (Rothermel and Philpot 1973) but is generally higher than values observed in European maquis (Dimitrakopoulos 2002; Fernandes 2001) or Scottish *Calluna* shrublands (Davies, Legg *et al.* 2009; Hobbs and Gimingham 1984). FI followed a roughly similar pattern with most empirical data from

Europe suggesting lower FI despite generally greater fuel loads (see notes, Table 4). Fynbos vegetation had higher reported FI but lower biomass than for two of the shrubland types in this study (tall shrublands on deep sand, tall shrublands on calcareous sand). One important difference may be the contribution of topography to RoS and FI; the Western Australian shrublands examined here have subdued topography (slopes 0 - 2°) compared with much greater topographic complexity in South Africa and California where steep hills may promote forward rates of spread and fire intensity (Keeley, Brennan *et al.* 2008). Higher RoS and FI observed in this study than for shrublands at higher latitudes may point to different factors limiting fire spread among these shrubland ecosystems. In European shrublands, fuel moisture rather than fuel quantity or arrangement may be the limiting factor at fine scales (Davies, Legg *et al.* 2009), whereas in Western Australia long, hot dry summers and sandy, droughty soils lead to low foliar moisture levels much earlier in the growing season, making fuel quantity and arrangement the greatest limiting factor given an ignition source. For example, Fernandes (2001), working in Portugal, reported mean foliar moisture levels of 85% whereas we recorded mean levels of 21%, 32%, and 44% for shallow sands, deep sand, and calcareous shrublands, respectively. Bilgili and Saglam (2003), working in Turkish maquis recorded similar moisture levels to this study and also reported the highest empirically measured FI for studies from the Mediterranean Basin, suggesting that live fuel moisture limits FI in management burns where fuels may experience relatively less pre-heating and drying than under wildfire conditions. For comparison, Keeley and Zedler (2009) suggest that in Californian chaparral, 60% foliar moisture is the critical level below which ignition of live vegetation occurs easily.

Previous work explicitly evaluating the influence of fuel age on fire behaviour in shrubland vegetation is sparse. Similar to our fire propagation results, Burrows and McCaw (1990) , found that fires were unlikely to carry until at least 4-5 years post-fire in Western

Australian *Banksia* woodlands when fuel accumulation approached 80% of the 20 year fuel level. Baeza et al (2002) used nine experimental fires in 3, 9, and 12 year old Mediterranean gorse shrublands, finding significantly lower RoS and FI at 3 years compared with 9 and 12 years post-fire. They identified live fuel moisture as a key variable limiting fire spread. However, unlike our study where all 35 fires were in autumn (at the end of the summer drought), 5 of their 9 experimental fires were in the spring and were associated with high foliar moisture levels. The lack of observed influence of fuel moisture on fire behaviour (RoS, FI) in our data may be due to generally low fuel moisture and lower variability than observed in spring versus autumn contrasts reported in Baeza et al (2002).

More broadly, the observation that fuel age did not influence RoS or FI under moderate to high fire danger weather conditions has implications for the use of prescribed fire to reduce fuel loads. As fire weather becomes more extreme, the role of fuel conditions in mediating fire behaviour would lessen, as high wind and temperature under low humidity control fire spread (Moritz, Keeley *et al.* 2004). Thus, the lack of an effect of fuel age on fire behaviour under moderate conditions calls into question the assumption that use of prescribed fire influences fire behaviour beyond the initial 4-5 year window where actual propagation is limited. Analysis of fire frequency data from California arrived at similar conclusions, finding little to no evidence of fuel age on the probability of fire occurrence for intervals up to 80 years (Moritz, Keeley *et al.* 2004).

With respect to prediction of fire behaviour, Cruz and Alexander (2010) provide a critique of current knowledge and best practice with a focus on forest fuels and crown fire prediction. They raise two relevant concerns: the application of customised fuel models without empirical fire behaviour observations, and the consistent underprediction of fire behaviour relative to empirical observation. In this study, we found consistent underprediction (with one exception) of fire behaviour by BEHAVE, supporting the forest-based evidence of Cruz and Alexander (2010). This lends weight to the proposition that use of customised fuel models should be done with caution and only when empirical fire behaviour data are available to provide an adjustment term to match prediction with real-world observation. Problematically, this sort of adjustment approach relies on sparsely available empirical data, underscoring a need to substantially refine our collective approach to modeling fire behaviour in the absence of empirical fire behaviour data.

Study Limitations.

The scope of inference of this study is to fire behaviour in shrubland vegetation 3-24 years post-fire under moderate to high fire danger weather conditions (FFDI range 5 – 24) typical of management burns. As such, this study provides important insight into relationships between variables well known to be important in determining fire behaviour (fuel quantity, quality, and arrangement, fuel moisture, etc) but should not be used to infer fire behaviour under wildfire conditions. Additionally, the lighting of a long strip of vegetation along two sides of plots and the relatively small size of burns may have reduced heterogeneity within fires, but also potentially lowered fireline intensities under higher rates of spread. The subdued topography of Western Australia offers the opportunity to study fire behaviour without strong topographic influence, but also limits inference about fire spread in areas with steep, complex topography (e.g. like much of western North America, Southern Africa and south-eastern Australia). Size of experimental fires might also be expected to influence results relative to wildfires which burn under a broader range of temporal and spatial conditions. Thus, it would be expected that the results reported here possess narrower variation than similar observations collected from wildfires. However, like topographic effects, this also offers the opportunity to deepen our understanding fine-scale fire behaviour.

We do make inference to processes influencing landscape-scale patterns such as boundaries between shrubland types or changes in weather conditions over time.

Management Implications.

Fuel age is one of the simplest and most widely used qualitative correlates of fire hazard in fire-prone ecosystems, particularly shrublands. Increased fire frequencies associated with global warming and human population growth have led to increased pressure on managers to balance protection of ecological and human values. Increased fire frequencies may lead to species losses due to inadequate time for reproduction and replenishment of the seed bank or below ground energy reserves necessary for resprouting post-fire (Burrows 2008). Our finding that fuel age is important for determining fire hazard is consistent with a broad fire literature on the subject, and the interval at which fires will propagate in these shrublands (~5 yrs or greater) is far shorter than that recommended to retain a full complement of species, particularly for non-sprouters (Burrows et al 2008, > 10yrs; Westcott 2010, >10 yrs). However, we found little relationship between fuel age or overall fire weather and RoS, suggesting that a more detailed understanding of fuel complexes will need to be obtained by managers tasked with determining fire potentials in a range of shrubland types.

The underestimation of fire potentials by the widely used program BEHAVE also may be problematic in relation to management burns for ecological purposes. Without good tools to predict fire behaviour, managers likely will be overly conservative in their implementation of management fires, leading to application of fires under mild weather conditions not conducive to maintenance of biodiversity. For example, in many fire-prone shrublands it is possible to burn on dry days in winter and early spring when fine surface fuels cure quickly. However, fires during these times of year may not heat the soil sufficiently to break dormancy of soil-stored seeds, and/or may cause seeds to germinate too late in the wet season (late winter – early spring) to establish a deep enough root system to survive the long summer drought. For example, Potts et al (2010) found lower summer survival in *Ceanothus cuneatus* seedlings originating from spring burns than for autumn burns in Californian chaparral. Enright and Lamont (1989) also found lower rates of seedling recruitment after spring than autumn fires, although higher rates of self-thinning among dense seedling stands slowly reduced overall differences.

Finally, while the inferred relationship between fuel age and RoS serves as a major rationale for management objectives aimed at maintaining lower fuel ages and shorter fire rotations, our results call into question any such relationship under conditions typical of management burns, mirroring similar findings from California based on analysis of fire frequencies (Moritz, Keeley *et al.* 2004). Although older fuels may carry fire more readily and exhibit greater surface temperatures or soil heating, we found no evidence for increased RoS with increasing fuel age.

ACKNOWLEDGEMENTS

This research was supported by Australian Research Council Linkage grant LP0775172. Byron Lamont, Mathew Gannaway, Willa Veber, Phil Ladd, Ian Wheatland, Jessica Millet-Riley, Dan Donato, Melanie Stidham, John Campbell and a number of volunteers assisted with fieldwork. We greatly appreciate the help of DEC personnel, David Atkins, Matt Dodd, Sam Hurd (and their staff) in the planning and delivery of the experimental fires.

LITERATURE CITED

Andrews PL, Bevins CD, Seli RC (2008) BehavePlus fire modeling system Version 4.0 User's Guide. In. (USDA Forest Service General Technical Report RMRS-GTR-106WWW)

Auld TD, Keith DA, Bradstock RA (2000) Patterns in longevity of soil seedbanks in fire-prone communities of south-eastern Australia. *Australian Journal of Botany* **48**, 539-548.

Baeza MJ, De Luis M, Raventos J, Escarre A (2002) Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. *Journal of Environmental Management* **65**, 199-208.

Bands DP (1977) Prescribed burning in cape fynbos catchments. In 'Proceedings of the symposium on the environmental consequences of fire and fuel management in Mediterranean ecosystems'. (Eds HA Mooney and CE Conrad) pp. 245-256. (USDA Forest Service Technical Report WO-3)

Bilgili E, Saglam B (2003) Fire behavior in maquis fuels in Turkey. *Forest Ecology and Management* **184**, 201-207.

Bontrager DR, Erickson RA, Hamilton RA (1995) Impacts of the October 1993 Laguna Canyon Fire on California Gnatcatchers and Cactus Wrents. In 'Brushfires in California:

Ecology and Resource Management'. University of California, Irvine. (Eds JE Keeley and T Scott) pp. 69-76. (International Association of Wildland Fire)

Bradstock RA, Auld TD (1995) Soil temperatures during experimental bushfires in relation to fire intensity: consequences for legume germination and fire management in south-eastern Australia. *Journal of Applied Ecology* **32**, 76-84.

Burnham KP, Anderson DR (2002) 'Model selection and multimodel inference: A practical information-theoretic approach.' (Springer: New York)

Burrows ND (2008) Linking fire ecology and fire management in south-west Australian forest landscapes. *Forest Ecology and Management* **255**, 2394.

Burrows ND, McCaw WL (1990) Fuel characteristics and bushfire control in Banksia low woodlands in Western Australia. *Journal of Environmental Management* **31**, 229-236.

Byram GM (1959) Combustion of forest fuels. In 'Forest Fire: Control and Use'. (Ed. KP Davies) pp. 155-182. (McGraw Hill: New York)

Cary G, Lindenmayer D, Dovers S (2003) 'Australia burning: Fire ecology, policy and management issues.' (CSIRO Publishing: Collingwood, Victoria)

Cowling RM, Rundel PW, Lamont BB, Arroyo MK, Arianoutsou M (1996) Plant diversity in Mediterranean-climate regions. *Trends in Ecology & Evolution* **11**, 362-366.

Cruz MG, Alexander ME (2010) Assessing crown fire potential in coniferous forest of western North America: a critique of current approaches and recent simulation studies. *International Journal of Wildland Fire* **19**, 377-398.

Davies GM, Legg CJ, Smith AA, MacDonald AJ (2009) Rate of spread of fires in *Calluna vulgaris*-dominated moorlands. *Journal of Applied Ecology* **46**, 1054-1063.

Dimitrakopoulos AP (2002) Mediterranean fuel models and potential fire behaviour in Greece. *International Journal of Wildland Fire* **11**, 127-130.

Dowdy AJ, Mills GA, Finkele K, de Groot W (2010) Index sensitivity analysis applied to the Canadian forest fire weather index and the McArthur forest fire danger index. *Meteorological Applications* **17**, 298-312.

Elzinga CL, Salzer DW, Willoughby JW, Gibbs JP (2001) 'Monitoring plant and animal populations.' (Blackwell: Malden, Massachusetts)

Enright NJ, Lamont BB (1989) Seed banks, fire season, safe sites and seedling recruitment in 5 co-occurring Banksia species. *Journal of Ecology* **77**, 1111-1122.

Enright NJ, Lamont BB (1992) Recruitment variability in the resprouting shrub Banksia attentuata and non-sprouting congeners in the northern sandplain heaths of southwestern Australia. *Acta Oecologica-International Journal of Ecology* **13**, 727-741.

Enright NJ, Marsula R, Lamont BB, Wissel C (1998) The ecological significance of canopy seed storage in fire-prone environments: a model for non-sprouting shrubs. *Journal of Ecology* **86**, 946-959.

Enright NJ, Mosner E, Miller BP, Johnson N, Lamont BB (2007) Soil vs. canopy seed storage and plant species coexistence in species-rich Australian shrublands. *Ecology* **88**, 2292-2304.

Fernandes PAM (2001) Fire spread prediction in shrub fuels in Portugal. *Forest Ecology and Management* **144**, 67-74.

Gill MA (1981) Adaptive responses of Australian vascular plant species to fire. In 'Fire and the Australian biota'. (Eds MA Gill, RH Groves and IR Noble) pp. 273-310. (Australian Academy of Science: Canberra)

Goforth BR, Minnich RA (2007) Evidence, exaggeration, and error in historical accounts of chaparral wildfires in California. *Ecological Applications* **17**, 779-790.

Griffiths D (1998) Improved formulae for the McArthur forest fire danger meter. In. (Meteorological Note 214. Bureau of Meteorology: Melbourne, Victoria)

Hanley ME, Lamont BB (2000) Heat pre-treatment and the germination of soil- and canopy-stored seeds of south-western Australian species. *Acta Oecologica-International Journal of Ecology* **21**, 315-321.

He T, Lamont BB, Downes KS (2011) Banksia born to burn. *New Phytologist*, doi: 10.1111/j.1469-8137.2011.03663.x.

Hnatiuk RJ, Hopkins AJM (1981) An ecological analysis of kwongan vegetation south of Eneabba, Western Australia. *Australian Journal of Ecology* **6**, 423-438.

Hobbs RJ, Gimingham CH (1984) Studies on fire in Scottish heathland communities. I. Fire characteristics. *Journal of Ecology* **72**, 223-240.

Hollis JJ, Matthews S, *et al.* (2010) Testing woody fuel consumption models for application in Australian southern eucalypt forest fires. *Forest Ecology and Management* **260**, 948-964.

Hopper SD, Gioia P (2004) The Southwest Australian Floristic Region: Evolution and conservation of a global hot spot of biodiversity. *Annual Review of Ecology Evolution and Systematics* **35**, 623-650.

Hughes R, Mercer D (2009) Planning to reduce risk: The wildfire management overlay in Victoria, Australia. *Geographical Research* **47**, 124-141.

Kayll AJ (1966) Some characteristics of heath fires in N.E. Scotlands. *Journal of Applied Ecology* **3**, 29-40.

Keeley JE, Brennan T, Pfaff AH (2008) Fire severity and ecosytem responses following crown fires in California shrublands. *Ecological Applications* **18**, 1530-1546.

Keeley JE, Fotheringham CJ, Moritz MA (2004) Lessons from the October 2003 wildfires in Southern California. *Journal of Forestry* **102**, 26-31.

Keeley JE, Safford H, Fotheringham CJ, Franklin J, Moritz M (2009) The 2007 Southern California Wildfires: Lessons in Complexity. *Journal of Forestry* **107**, 287-296.

Keeley JE, Zedler PH (2009) Large, high-intensity fire events in southern California shrublands: debunking the fine-grain age patch model. *Ecological Applications* **19**, 69-94.

Keetch J, Byram GM (1968) A drought index for forest fire control. In. (USDA Forest Service: Asheville, NC, USA Research Paper SE-38)

Keith DA, McCaw WL, Whelan RJ (2002) Fire regimes in Australian heathlands and their effects on plants and animals. In 'Flammable Australia: The fire regimes and biodiversity of a continent'. (Eds RA Bradstock, JE Williams and MA Gill) pp. 199-237. (Cambridge University Press: Cambridge, UK)

Lade J (2010) The effects of increased fire frequency on calcareous shrubland communities of the Gerladton Sandplain Region, SW Australia. Masters Thesis thesis, University of Melbourne.

Luke RH, McArthur AG (1986) 'Bushfires in Australia.' (Australian Government Publishing Service: Canberra)

Marsden-Smedley JB, Catchpole WR (1995) Fire behaviour modelling in Tasmanian buttongrass moorlands. II. Fire behaviour. *International Journal of Wildland Fire* **5**, 215-228.

McCaw WL, Maher T, Gillen K (1992) Wildfires in the Fitzgerald River National Park, Western Australia, December 1989. In. (Department of Conservation and Land Management, Technical Report no. 26, Perth)

Miller BP, Walshe T, Enright NJ, Lamont BB (2007) Error in the inference of fire history from grasstrees. *Austral Ecology* **32**, 908-916.

Moritz MA, Keeley JE, Johnson EA, Schaffner AA (2004) Testing a basic assumption of shrubland fire management: how important is fuel age? *Frontiers in Ecology and the Environment* **2**, 67-72.

Myers N, Mittermeier R, Mittermeier C, da Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* **403**, 853-858.

Potts JB, Marino E, Stephens SL (2010) Chaparral shrub recovery after fuel reduction: a comparison of prescribed fire and mastication techniques. *Plant Ecology* **210**, 303-315.

Prichard SJ, Ottmar RD, Anderson GK (2006) 'Consume 3.0 users guide.' USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. In. (Research Paper INT-115, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT)

Rothermel RC, Philpot CW (1973) Predicting changes in chaparral flammability. *Journal of Forestry* **71**, 640-643.

Saglam B, Bilgili E, Kucuk O, Durmaz BD (2008) Fire behavior in Mediterranean shrub species (Maquis). *African Journal of Biotechnology* **7**, 4122-4129.

Sauvagnargues-Lesage S, Dusserre G, Robert F, Dray G, Pearson DW (2001) Experimental validation in Mediterranean shrub fuels of seven wildland fire rate of spread models. *International Journal of Wildland Fire* **10**, 15-22.

Smith FR (1983) Responses of four shrub species to timing and behaviour of fire in the Natal Drakensberg. University of Natal.

Stephens SL, Adams MA, Handmer J, Kearns FR, Leicester B, Leonard J, Moritz MA (2009) Urban-wildland fires: how California and other regions of the US can learn from Australia. *Environmental Research Letters* **4**, 1-5.

van Wilgen BW, Forsyth GG, de Klerk H, Das S, Khuluse S, Schmitz P (2010) Fire management in Mediterranean-climate shrublands: a case study from the Cape fynbos, South Africa. *Journal of Applied Ecology* **47**, 631-638.

Van Wilgen BW, Higgins KB, Bellstedt DU (1990) The role of vegetation structure and fuel chemistry in excluding fire from forest patches in the fire-prone fynbos shrublands of South Africa. *Journal of Ecology* **78**, 210-222.

Van Wilgen BW, Le Maitre DC, Kruger FJ (1985) Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. *Journal of Applied Ecology* **22**, 207-216.

Van Wilgen BW, Richardson DM, Seydack AHW (1994) Managing Fynbos for biodiversity: constraints and options in a fire-prone environment. *South African Journal of Science* **90**, 322-329.

Westcott VC (2010) The effect of short inter-fire intervals on the biodiverse, fire-prone, Mediterranean-type shrublands of the Eneabba Sandplain, Western Australia. Dissertation thesis, University of Melbourne.

Westman WE, O'Leary JF, Malanson GP (1981) The effects of fire intensity, aspect and substrate on post-fire growth of Californian coastal sage scrub. In 'Components of productivity of Mediterannean climate regions --Basic and applied aspects'. (Eds NS Margaris and HA Mooney) pp. 151-180. (W. Junk.: The Hague)

Williams RJ, Bradstock RA, *et al.* (2009) 'Interactions between climate change, fire regimes and biodiversity in Australia - A preliminary assessment.' Report to Department of Climate Change and Department of Environment, Water Heritage and the Arts: Canberra.

Wouters MA (1993) Wildfire behaviour in heath and other elevated fuels: a case study of the 1991 Heywood fire. In. (Research Report no. 36, Victorian Department of Conservation and Environment, Melbourne.)

TABLES

Table 1. Best performing models given four measures of fire behaviour relative to fuel and weather conditions from 35‡ experimental fires conducted in shrubland vegetation, Western Australia.

Fire Behaviour Measure	Model	k	AICc	ΔAICc	ω_i	Model R^2
Fire Propagation	tsf	3	32.39	0.00	0.49	0.35†
	tsf + FFDI	4	33.47	1.08	0.29	0.40†
	tsf + type	4	34.93	2.54	0.14	0.41†
Rate of Spread	intercept	2	22.20	0.00	0.27	0
	tsf	3	23.35	1.14	0.15	0.06
	tsf*type	5	23.54	1.34	0.14	0.40
	tsf + type	4	23.65	1.45	0.13	0.24
	type	3	23.99	1.79	0.11	0.12
Fireline Intensity	type	3	432.69	0.00	0.32	0.20
	intercept	2	432.75	0.47	0.25	0
	FFDI + type	4	434.78	2.09	0.11	0.23
Mean Surface Temp	FFDI*tsf + tsf*type	7	258.17	0.00	0.72	0.77
	FFDI + tsf*type	6	260.57	2.40	0.22	0.70
Heating Duration	tsf*type	5	293.23	0.00	0.50	0.73
	tsf + type	4	294.11	0.88	0.32	0.65

Notes: Reported models were those with Akaike weights >0.10; tsf= time since fire, FFDI=Forest Fire Danger Index, type=shrubland vegetation type.

†Pseudo-R-Squared values

‡N=35 for analysis of propagation, N=23 for analysis of fire behaviour

Table 2. Support for predictors based on Akaike weights of models predicting fire behaviour in shrubland vegetation of Western Australia.

Predictor	tsf	FFDI	type	tsf*FFDI	tsf*type
Fire Propagation	**1.00**	0.37	0.14	0.08	NA
Rate of Spread	0.56	0.21	0.45	0.02	0.41
Fireline Intensity	0.23	0.25	0.57	0.01	0.04
Mean Surface Temperature	**1.00**	0.99	**0.98**	**0.73**	**0.94**
Heating Duration	**1.00**	0.18	**1.00**	0.03	0.60

Notes: Bolded values indicated parameter estimates whose 95% confidence intervals did not overlap zero. Abbreviations: tsf=time since fire, FFDI=Forest Fire Danger Index, type=shrubland vegetation type.

Table 3. Relationship (slope, t-value, p-value) between observed and predicted rates of spread (m sec^{-1}) and fireline intensity (kW m^{-1}) for 35 experimental fires across three shrubland vegetation types in Western Australia.

Shrubland Type	N	Rate of Spread			Fireline Intensity		
		slope (SE)	t	P	slope (SE)	t	P
All	35	0.17 (0.09)	1.92	0.06	0.63 (0.12)	5	<0.001
shallow sand	5	-0.25 (0.61)	-0.41	0.71	0.07 (0.09)	0.07	0.95
deep sand	12	0.31 (0.11)	2.92	0.02	1.04 (0.20)	5.34	<0.001
calcareous	18	0.14 (0.08)	1.89	0.08	0.37 (0.14)	2.65	0.02

Notes: A slope of 1 would indicate perfect agreement between observed and predicted values while values <1 suggest positive bias in predictions. Estimates based on simple linear model of observed versus predicted values with the intercept allowed to vary.

Table 4. Comparison of results in current study with similar work in shrubland ecosystems globally.

Region	Vegetation type	Source	Fuel age (yrs)	Prefire biomass (t ha-1)	Rate of spread (m sec-1)	Fire intensity (kW m-1)	N fires
Australia (SW)	Shallow acid sands	This study	4-14	2.9-4.0	0.35-0.48	525-900	5
Australia (SW)	Deep acid sands	This study	4-16	4.8-19.4	0.1-1.57	602-11073	12
Australia (SW)	Calcareous sands	This study	3-24	6.1-22.8	0.08-0.92	776-8857	18
Australia (SE)	Heath-Low Woodland	Bradstock and Auld (1995)			0.008-0.339	151-4561	13
Australia (SW)	Mallee-heath	McCaw *et al.* (1992)	>20		1.1-2.1	25000-35000	wildfire
Australia (S)	Low Heath	Wouters (1993)	5		0.33	9000	wildfire
Australia (SE)	Eastern dry heath	Bradstock, in Keith *et al.* (2002)	5		0.67	25000	wildfire
Australia (SE)	Wet Heath	Marsden-Smedley and Catchpole (1995)	16-25		0.9-0.92	16000-19000	wildfire
South Africa	Cape fynbos	van Wilgen *et al.* (1985)		9.7-34.2	0.04-0.89	515-20709	14
South Africa	Cape fynbos	Bands (1977)		3-10	0.07-1.11	360-18900	
South Africa	Natal Drakensberg shrublands	Smith (1983)		15.4-39.5	0.01-0.20	88-1617	
California	coastal sage scrub	Westman *et al.* (1981)		18.7-20.8	0.05-0.59	1250-10852	
California	Chaparral	Rothermel & Philpot (1973)		43.75	0.04-1.74	380-35000	
Scotland	Heathland	Kayll (1966)		15.9-23.3	0.03-0.12	2430	
Scotland	Heathland	Hobbs & Gimingham (1984)		8.82-27.4	0.003-0.03	40-1100	
Scotland	Heathland	Davies *et al.* (2009)		7.5-16.0	0.01-0.18		27
Mediterranean	Maquis (Turkey)	Bilgili & Saglam		19.3-43.6	0.01-0.15	623-10355	25

		(2003)					
Mediterranean	Maquis (Greece)	Dimitrakopoulos (2002)		25.5-53	0.08-0.83	2900-50900	
Mediterranean	Phyrgana (Greece)	Dimitrakopoulos (2002)		5.7-9.9	0.05-0.32	400-3100	
Mediterranean	Portugal	Fernandes (2001)		4.9-64.9	0.01-0.33		
Mediterranean	*Ulex* Shrublands (Spain)	Baeza *et al.* (2002)	3-12	10.4-46.2	0.004-0.04	69-2310	9
Mediterranean	*Genista* shrubland (France)	Sauvagnargues-Lesage *et al.* (2001)			0.1-0.17		9
Mediterranean	Maquis (Turkey)	Saglam *et al.* (2008)		24.7-51.3		189-5906	18

FIGURES

Fig. 1. Study area (Mid-West region, Western Australia) showing major substrate types and locations of sites subjected to experimental fires 2006-2009.

Fig 2. Fuel age (time since fire) and weather conditions as measured by the Forest Fire Danger Index under which 35 experimental burns were ignited in Western Australian kwongan (shrubland) vegetation. Fires that did not carry across a range of weather conditions were of younger fuel ages.

Fig 3. Means and 95% confidence intervals of four measures of fire behaviour (a: rate of spread, b: fireline intensity, c: mean maximum temperature, and d: heating duration) for three shrubland vegetation types during 35 experimental burns in Western Australia, 2006-2009.

Fig 4. Dead surface fuel mass in relation to (a) heating duration and (b) mean maximum temperature for 35 experimental fires (n=23 for those which successfully burned) in Western Australian kwongan. Mass of dead material was significantly related to both measures of fire behaviour (heating: $F_{1,22}=17.29, p<0.001$; mean max temp: $F_{1,21}=16.79, p<0.001$).

Fig 5. Observed versus predicted values of (a) rate of spread and (b) fireline intensity as modeled from program BEHAVE using customized fuel models and weather data from 35 experimental bushfires over three shrubland vegetation types in Western Australia. Shallow sand plots (N=5) had slope estimates of zero and are not shown.

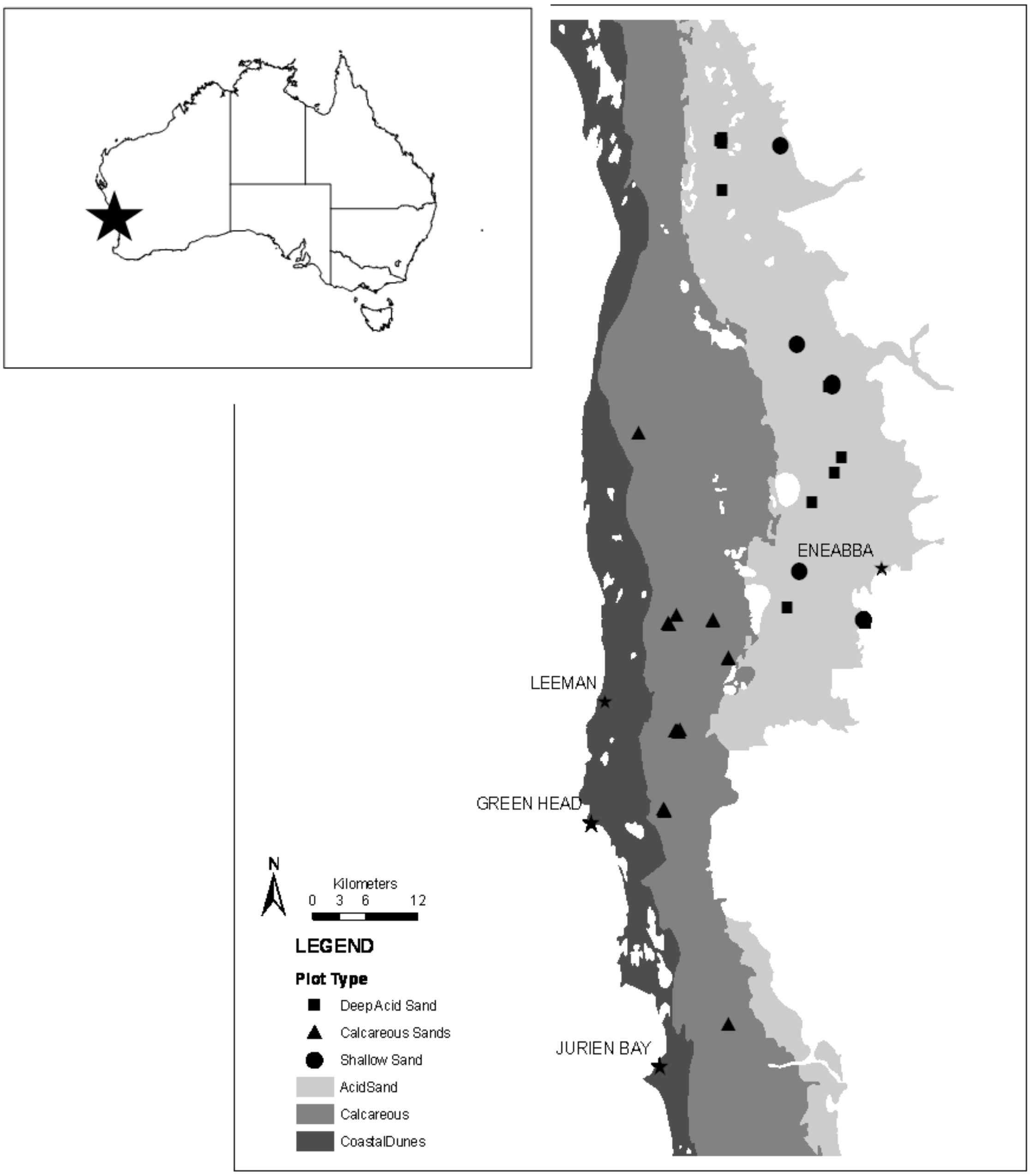

ENEABBA
LEEMAN
GREEN HEAD
JURIEN BAY
N
Kilometers
0 3 6 12
LEGEND
Plot Type
■ DeepAcid Sand
▲ Calcareous Sands
● Shallow Sand
AcidSand
Calcareous
CoastalDunes

Fig 1

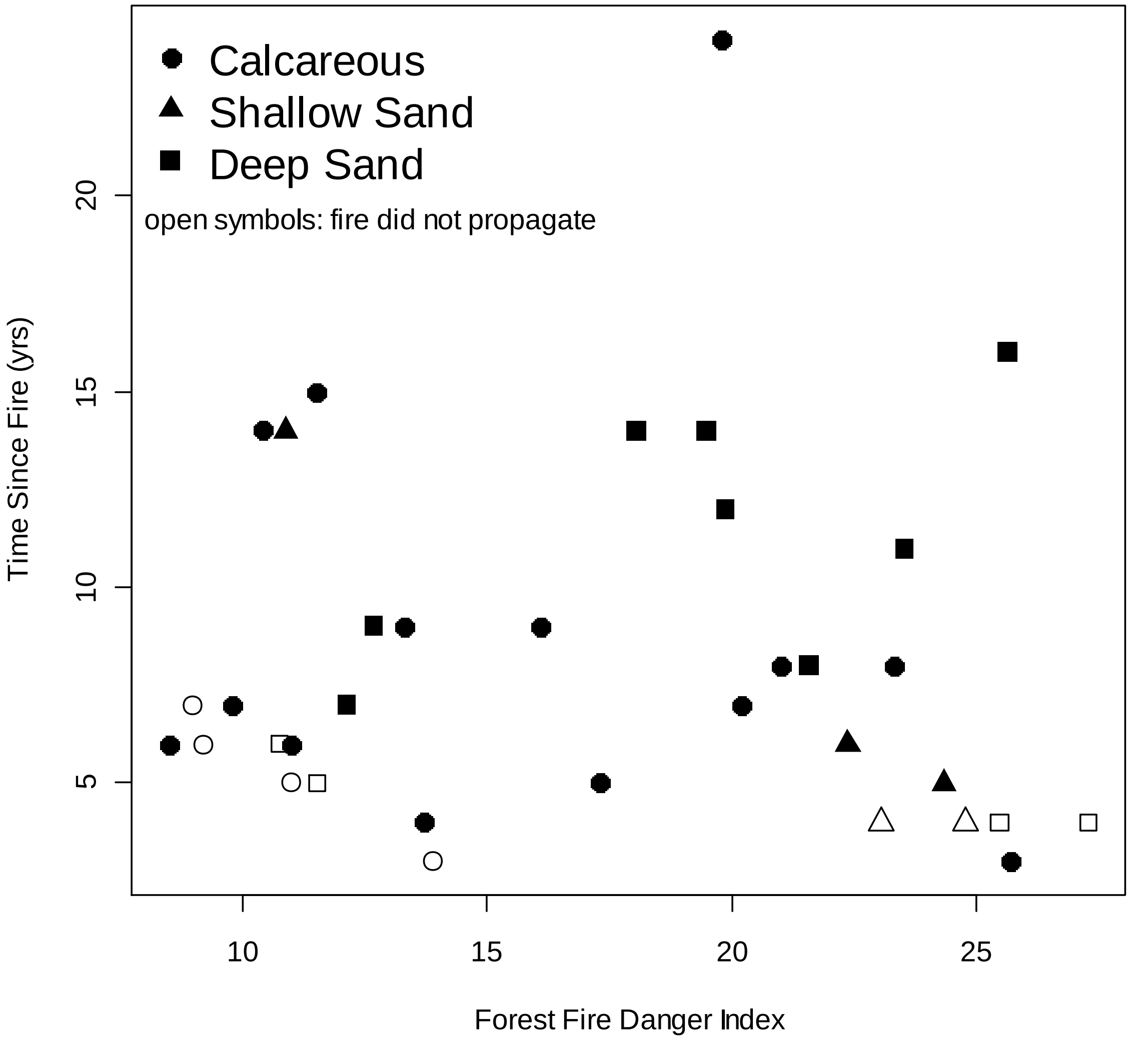

● Calcareous
▲ Shallow Sand
■ Deep Sand
open symbols: fire did not propagate
Time Since Fire (yrs)
5
10
15
20
10
15
20
25
Forest Fire Danger Index

Fig 2.

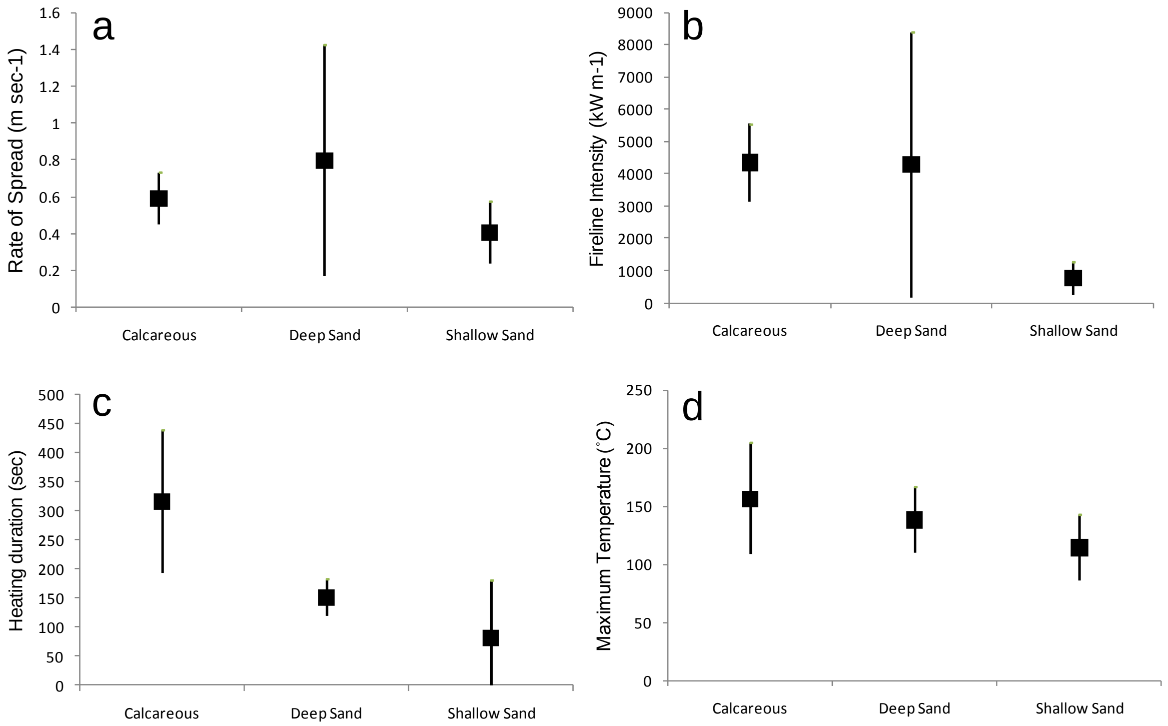

a
Rate of Spread (m sec-1)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Calcareous
Deep Sand
Shallow Sand
b
Fireline Intensity (kW m-1)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Calcareous
Deep Sand
Shallow Sand
c
Heating duration (sec)
0
50
100
150
200
250
300
350
400
450
500
Calcareous
Deep Sand
Shallow Sand
d
Maximum Temperature (˚C)
0
50
100
150
200
250
Calcareous
Deep Sand
Shallow Sand

Fig 3.

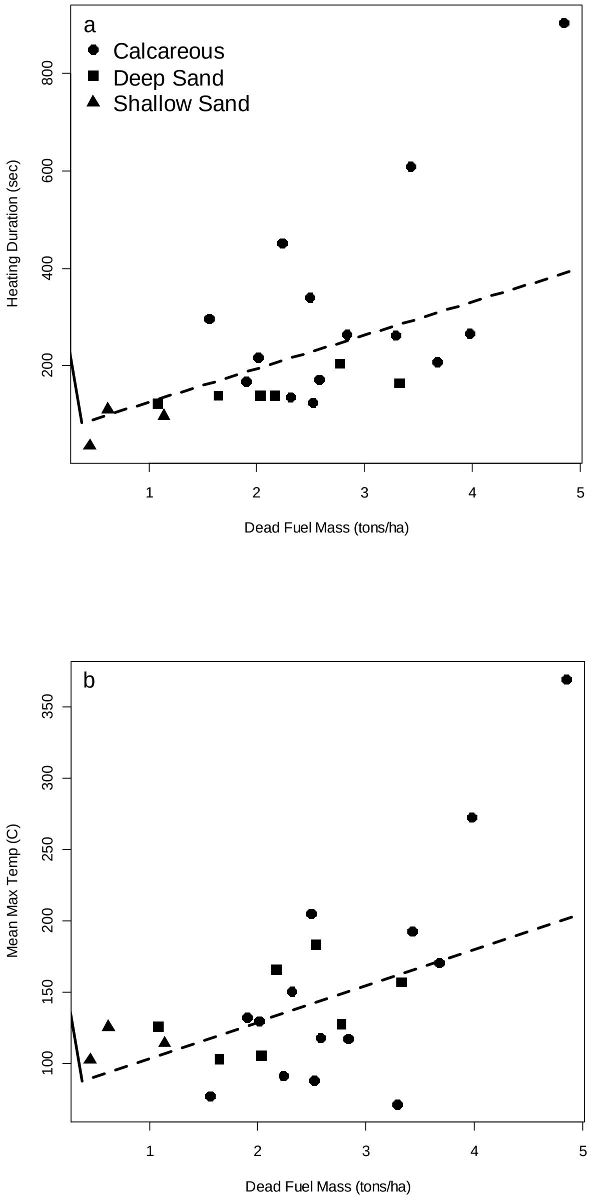
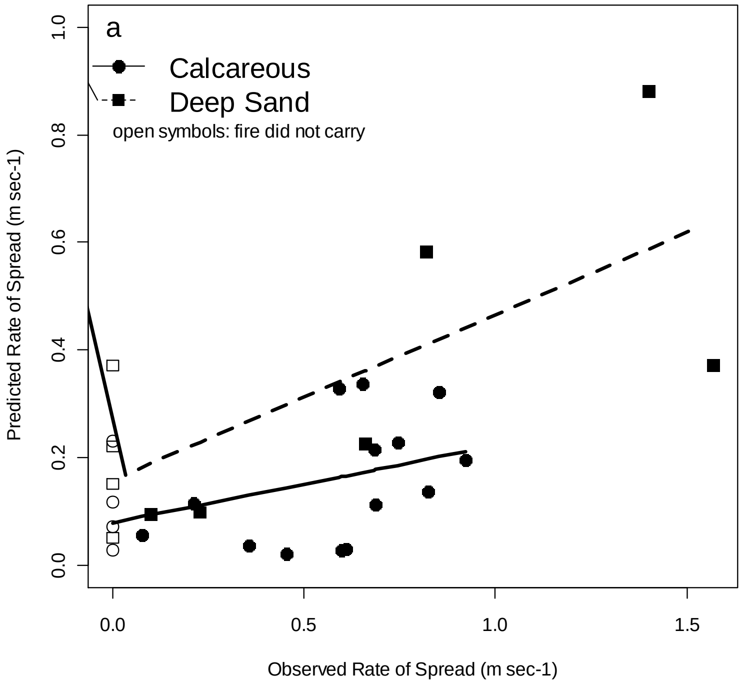

a
Calcareous
Deep Sand
Shallow Sand
Heating Duration (sec)
200
400
600
800
1
2
3
4
5
Dead Fuel Mass (tons/ha)
b
Mean Max Temp (C)
100
150
200
250
300
350
1
2
3
4
5
Dead Fuel Mass (tons/ha)

Fig 4.


a
Calcareous
Deep Sand
open symbols: fire did not carry
Predicted Rate of Spread (m sec-1)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
Observed Rate of Spread (m sec-1)

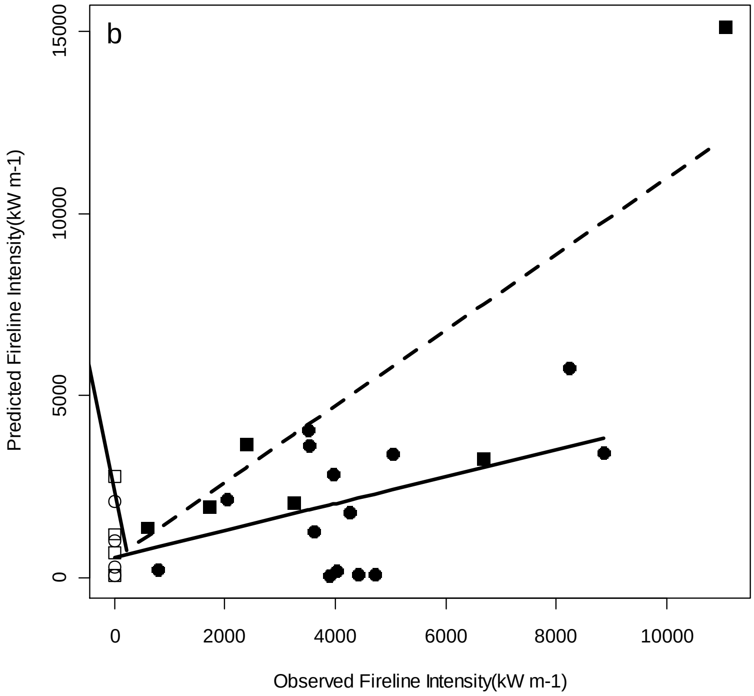

b
Predicted Fireline Intensity(kW m-1)
0
5000
10000
15000
0
2000
4000
6000
8000
10000
Observed Fireline Intensity(kW m-1)

Fig 5.

SUPPLEMENTARY MATERIALS/ONLINE APPENDICES

Table S1. Weather, fuel moisture, and ignition characteristics of 35 experimental fires lit in three shrubland vegetation types of Western Australia 2006-2009.

Shrubland Vegetation Type	Time Since Fire (yrs)	Fire Ran?†	Date of Fire	Time of Ignition	Forest Fire Danger Index	Relative Humidity (%)	Temperature (C)	Mean Wind Velocity (kph)	Litter Moisture (%)	Live Fine Fuel Moisture (%)
Calcareous	3	Yes	12-Apr-07	1154	25.7	17	31.4	8.6	4.0	22.4
Calcareous	3	No	31-Mar-09	1335	13.9	56	25.7	14.0	5.0	46.1
Calcareous	4	Yes	14-Apr-08	1339	13.7	12	33.1	8.3	6.4	48.3
Calcareous	5	No	17-Apr-07	1137	11.0	25	26.8	5.5	6.6	31.8
Calcareous	5	Yes	21-Apr-09	1349	17.3	45	30.5	14.0	5.2	54.2
Calcareous	6	Yes	26-Apr-07	1456	8.5	34	23.3	6.2	9.0	40.8
Calcareous	6	Yes	17-Apr-07	1410	11.0	42	24.3	13.0	6.0	32.2
Calcareous	6	No	05-May-08	1341	9.2	27	33.5	4.5	5.0	45.6
Calcareous	7	No	15-May-07	1230	9.0	33	19.9	8.3	5.2	45.6
Calcareous	7	Yes	09-May-08	1427	9.8	36	27.8	8.2	4.0	44.8
Calcareous	7	Yes	16-Apr-08	1502	20.2	67	25.4	10.7	5.3	40.0
Calcareous	8	Yes	29-Apr-09	1330	23.3	36	28.8	6.0	1.4	54.2
Calcareous	8	Yes	28-Apr-09	1330	21.0	27	30.0	7.0	5.0	48.9
Calcareous	9	Yes	09-May-07	1720	16.1	28	25.7	3.0	5.6	44.0
Calcareous	9	Yes	24-Apr-09	1350	13.3	60	25.0	6.0	1.4	45.5
Calcareous	14	Yes	16-May-07	1240	10.4	35	21.4	6.4	4.8	38.8

Calcareous	15	Yes	07-May-08	1319	11.5	26	30.3	7.0	8.0	53.0
Calcareous	24	Yes	08-May-09	1146	19.8	37	27.0	9.0	3.2	53.3
Shallow Sand	4	No	06-Apr-06	1415	23.0	30	26.0	17.0	1.1	16.1
Shallow Sand	4	No	07-Apr-06	1305	24.8	26	29.4	8.9	2.8	22.9
Shallow Sand	5	Yes	11-Apr-07	1250	24.3	23	27.6	8.6	1.1	12.9
Shallow Sand	6	Yes	15-Apr-08	1334	22.4	31	31.2	11.1	0.8	22.7
Shallow Sand	14	Yes	22-Apr-08	1312	10.9	40	28.0	16.6	8.6	31.5
Deep Sand	4	No	06-Apr-06	1530	25.5	27	27.3	15.1	1.8	20.5
Deep Sand	4	No	07-Apr-06	1455	27.3	24	30.3	9.6	5.0	31.6
Deep Sand	5	No	23-Apr-07	1217	11.5	42	24.5	6.5	2.1	37.1
Deep Sand	6	No	08-May-08	1314	10.8	44	28.4	8.1	1.5	44.8
Deep Sand	7	Yes	24-Apr-07	1226	12.1	46	25.1	13.7	1.8	19.0
Deep Sand	8	Yes	20-Apr-06	1515	21.6	32	32.2	8.9	1.2	44.7
Deep Sand	9	Yes	19-Apr-07	1213	12.7	39	24.4	7.2	1.2	8.6
Deep Sand	11	Yes	27-Apr-07	1305	23.5	29	26.3	14.4	1.9	18.8
Deep Sand	12	Yes	06-May-08	1206	19.9	23	29.0	3.3	0.8	39.0
Deep Sand	14	Yes	08-May-07	1600	19.5	35	25.0	4.1		
Deep Sand	14	Yes	02-May-08	1442	18.0	23	28.3	6.4	2.2	44.2
Deep Sand	16	Yes	08-May-07	1335	25.6	17	28.4	3.0	1.6	39.8

†Fire Ran refers to whether each ignition successfully propagated, burning the entire plot.

Table S2. Fuel characteristics of 35 experimental fires ignited across three shrubland vegetation types in Western Australia.

Shrubland Vegetation Type	Time Since Fire (yrs)	Fire Ran?	Litter Biomass (t/ha)	Live Biomass (t/ha)	Total Biomass (t/ha)	Fuel Bed Depth (cm)
Calcareous	3	Yes	1.9	4.9	6.8	54.8
Calcareous	3	No	1.7	5.4	7.1	31.5
Calcareous	4	Yes	1.6	4.5	6.1	47.7
Calcareous	5	No	2.0	14.3	16.2	77.4
Calcareous	5	Yes	2.5	5.9	8.4	45.0
Calcareous	6	Yes	2.5	12.0	14.5	61.8
Calcareous	6	Yes	2.0	7.2	9.2	35.3
Calcareous	6	No	1.9	5.6	7.4	61.3
Calcareous	7	No	2.9	13.1	16.0	85.5
Calcareous	7	Yes	2.2	16.0	18.2	56.9
Calcareous	7	Yes	2.6	8.8	11.4	41.2
Calcareous	8	Yes	4.0	14.9	18.9	63.0
Calcareous	8	Yes	3.7	12.3	16.0	45.4
Calcareous	9	Yes	2.8	14.7	17.5	107.6
Calcareous	9	Yes	2.3	8.6	10.9	40.5
Calcareous	14	Yes	3.3	23.0	26.3	94.8
Calcareous	15	Yes	3.4	15.7	19.2	113.1
Calcareous	24	Yes	4.8	13.4	18.2	46.6
Shallow Sand	4	No	0.7	1.9	2.5	43.8
Shallow Sand	4	No	0.7	2.7	3.4	45.0
Shallow Sand	5	Yes	0.5	2.4	2.9	45.6
Shallow Sand	6	Yes	0.6	2.6	3.3	42.0
Shallow Sand	14	Yes	1.1	2.0	3.1	46.0
Deep Sand	4	No	0.8	5.6	6.4	59.8
Deep Sand	4	No	1.4	5.2	6.6	64.9
Deep Sand	5	No	1.0	3.9	4.9	57.3
Deep Sand	6	No	1.1	5.3	6.4	56.8
Deep Sand	7	Yes	1.1	4.0	5.0	54.4
Deep Sand	8	Yes	2.5	10.8	13.4	63.5
Deep Sand	9	Yes	1.6	5.3	7.0	72.2
Deep Sand	11	Yes	3.3	7.7	11.0	58.5
Deep Sand	12	Yes	2.8	10.3	13.1	64.1
Deep Sand	14	Yes	4.1	14.8	18.8	71.6
Deep Sand	14	Yes	2.0	5.1	7.1	59.5
Deep Sand	16	Yes	2.2	8.9	11.0	68.8

Table S3. Observed and Predicted measures of fire behaviour in 35 experimental fires conducted across three shrubland vegetation types in Western Australia, 2006-2009.

Shrubland Vegetation type	Time Since Fire (yrs)	Fire Ran?	Time >120˚C	Mean Max Temp (˚C)	Obs RoS (m sec^{-1})	Obs FI (kW m^{-1})	Predicted RoS (m sec^{-1})	Predicted FI (kW m^{-1})
Calcareous	3	Yes	168	133	0.85	3960	0.32	2855
Calcareous	3	No					0.23	2099
Calcareous	4	Yes	297	77	0.92	3603	0.20	1290
Calcareous	5	No					0.03	78
Calcareous	5	Yes	341	205	0.59	3533	0.33	3647
Calcareous	6	Yes	124	88	0.60	4410	0.03	99
Calcareous	6	Yes	218	130	0.65	3500	0.34	4052
Calcareous	6	No					0.12	1036
Calcareous	7	No					0.07	299
Calcareous	7	Yes	453	92	0.61	4711	0.03	116
Calcareous	7	Yes	172	118	0.74	5037	0.23	3426
Calcareous	8	Yes	267	273	0.83	8857	0.14	3460
Calcareous	8	Yes	209	171	0.21	2035	0.12	2172
Calcareous	9	Yes	264	118	0.45	3895	0.02	85
Calcareous	9	Yes	136	150	0.69	4268	0.11	1813
Calcareous	14	Yes	263	71	0.36	4012	0.04	194
Calcareous	15	Yes	609	193	0.08	776	0.06	252
Calcareous	24	Yes	905	370	0.68	8223	0.22	5771
Shallow Sand	4	No					0.76	2333
Shallow Sand	4	No					0.31	1115
Shallow Sand	5	Yes	36	103	0.38	525	0.30	868
Shallow Sand	6	Yes	111	126	0.48	840	0.35	1290
Shallow Sand	14	Yes	97	114	0.35	900	0.78	2351
Deep Sand	4	No					0.05	69
Deep Sand	4	No					0.37	2783
Deep Sand	5	No					0.22	1206
Deep Sand	6	No					0.15	700
Deep Sand	7	Yes	121	125	0.82	2384	0.58	3664
Deep Sand	8	Yes	*	183	*	*	0.25	4340
Deep Sand	9	Yes	138	103	1.57	6679	0.37	3269
Deep Sand	11	Yes	165	157	1.40	11073	0.88	15105
Deep Sand	12	Yes	204	128	0.23	1717	0.10	1946
Deep Sand	14	Yes	*	190	*	*	0.14	3977
Deep Sand	14	Yes	139	106	0.66	3249	0.23	2067
Deep Sand	16	Yes	138	166	0.10	602	0.10	1383

Notes: Blank cells represent instances in which ignition did not result in a forward-spreading fire through plots.

* Instruments failed at two fires, thus heating duration, ROS, and FI were not able to be estimated.

Table S4. Univariate correlations† (Pearson) between measures of fire behaviour and individual components of fuels and weather from experimental fires in shrublands of Western Australia.

		ROS	FI	Mean Temp	Heating Duration
FUELS	Fuel Age (yrs)	-0.25	0.12	**0.50****	**0.55****
	Litter Mass (t ha^{-1})	-0.06	**0.55****	**0.66*****	**0.67*****
	Live Mass (t ha^{-1})	-0.29	0.26	0.21	**0.51****
	Total Mass (t ha^{-1})	-0.26	0.32	0.29	**0.55****
	Litter Moisture (%)	-0.26	-0.17	-0.18	0.21
	Live Moisture (%)	**-0.44***	0.04	**0.45***	**0.58****
WEATHER	FFDI	-0.01	0.09	0.37	-0.14
	Wind (kph)	0.31	0.10	0.02	-0.07
	Relative Humidity (%)	0.20	0.23	0.09	-0.02
	Temperature (˚C)	-0.19	-0.28	0.22	0.14

† * $p<0.05$, ** $p<0.01$, *** $p<0.001$, data from n=23 experimental fires which successfully propagated. ROS= Rate of Spread (m s^{-1}); FI= Fireline Intensity (kW m^{-1}); Mean Temp=Mean maximum surface temperature (˚C); Heating Duration=Amount of time (sec) above 120˚C

Supplementary Figure S1. Fig 4. Observed fire behaviour (Rate of Spread a-b; Fireline Intensity c-d; Mean Surface Temperature e-f; Heating Duration (seconds > 120˚C) g-h) relative to fire danger (a,c,e,g) and fuel age (b,d,f,h) from 23 experimental fires in shrublands of Western Australia. No correlations were statistically significant with the exception of f and h at $P<0.01$, see Table S4 for details.

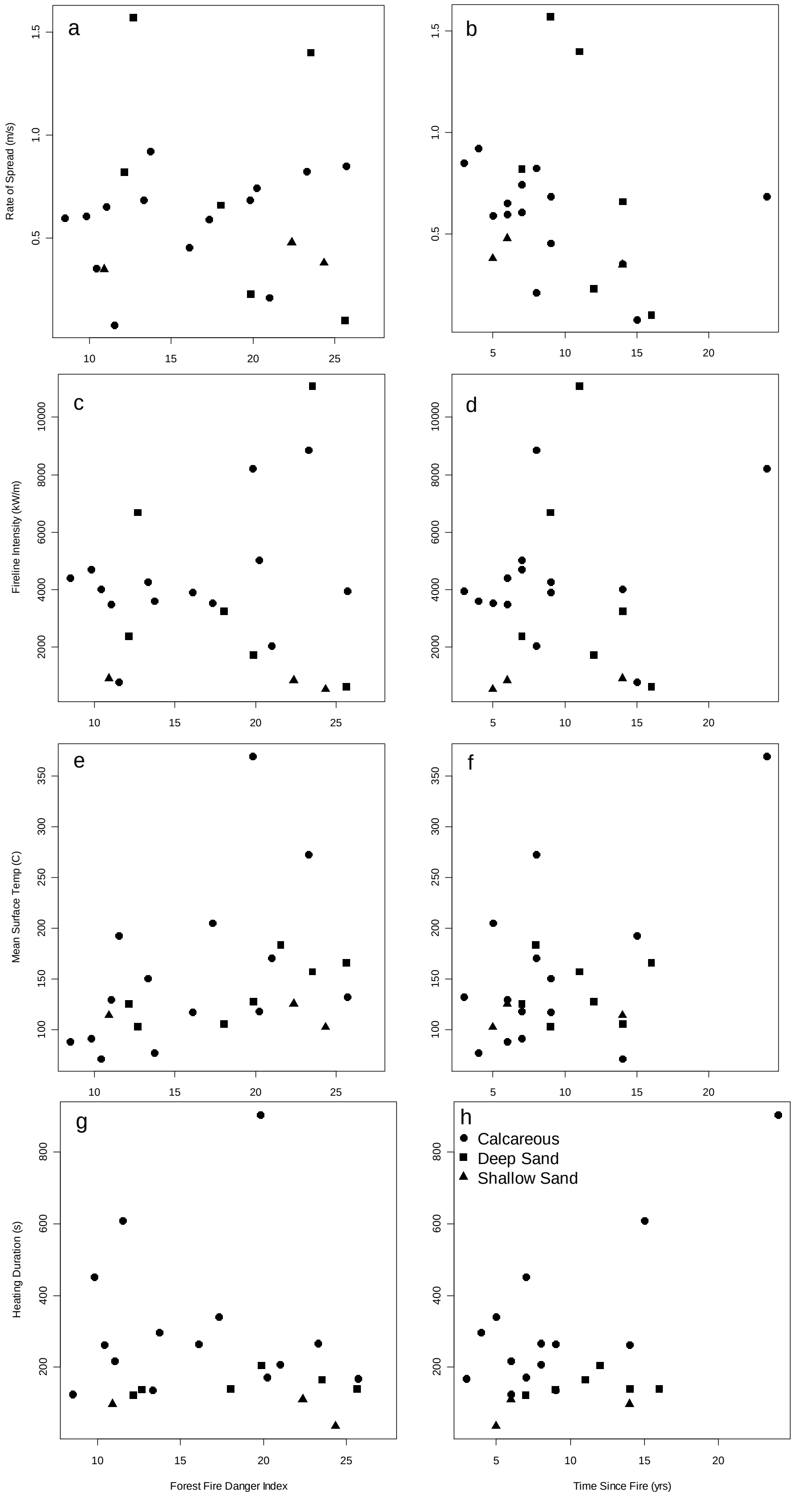

a
b
c
d
e
f
g
h
Rate of Spread (m/s)
0.5
1.0
1.5
Fireline Intensity (kW/m)
2000
4000
6000
8000
10000
Mean Surface Temp (C)
100
150
200
250
300
350
Heating Duration (s)
200
400
600
800
10
15
20
25
5
Forest Fire Danger Index
Time Since Fire (yrs)
● Calcareous
■ Deep Sand
▲ Shallow Sand

Fig. S1