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Is there an inherent conflict in managing fire for people and conservation?

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Abstract. Wildfires are a natural disturbance in many ecosystems, creating challenges for land management agencies who need to simultaneously reduce risk to people and maintain ecological values. Here we use the PHOENIX RapidFire fire behaviour simulator to compare fuel treatment strategies that meet the twin objectives of reducing wildfire risk to human settlements and a fire sensitive endangered species, the koala (*Phascolarctos cinereus*) in south-eastern Australia. The local koala population is in decline and a conservation management plan is being prepared to exclude wildfire for a 10-year period to assist with population recovery. Twelve scenarios developed by the land management agencies were compared using four indicators: wildfire size; burn probability; impact from exposure to fire; and treatment cost. Compared with the current risk setting, three treatment scenarios were found to reduce wildfire size and burn probability concurrently to both people and koalas. These strategies worked by increasing the landscape area treated, which came with increased financial cost. However, the impact from exposure to fire for both property and koala habitat remains high. Additional complementary strategies beyond landscape fuel reductions are needed to reduce impact from exposure in the event of a wildfire.

Additional keywords: fire behaviour, fire simulation, house loss, risk, trade-off.

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Introduction

Wildfires are a natural disturbance in many ecosystems around the globe, with many species dependent on fire to maintain population viability across the landscape (Bradstock *et al.* 2012*a*; Keeley *et al.* 2012). At a landscape scale, species respond to fire regimes rather than individual fires (Gill and McCarthy 1998). A fire regime considers the frequency, intensity, extent, seasonality, heterogeneity and size of fires in a given landscape (Gill 1975; Whelan 1995). Changes to natural fire regimes (or the variability therein) can result in significant ecological impacts on some populations, species and communities (Fox 1982; Russell-Smith *et al.* 2003; Andersen *et al.* 2005; Clarke 2008; Driscoll and Henderson 2008; Nimmo *et al.* 2012; Nimmo *et al.* 2014; Sitters *et al.* 2014).

A range of human factors have resulted in shifts in natural fire regimes (Bowman *et al.* 2009). The presence of humans in the landscape can alter patterns of ignitions (Penman *et al.* 2013*a*; Collins *et al.* 2015; Mann *et al.* 2016), often resulting in an overall increase in the number of ignitions per year (Syphard *et al.* 2007; Syphard *et al.* 2009; Plucinski *et al.* 2014; Price 2015). Fragmentation and manipulation of forests through expansion of agriculture and human settlements has created discontinuities in fuels thereby influencing fire spread patterns (Finney 2007; Price and Bradstock 2010; Salis *et al.* 2014) and surface fire behaviour (Agee *et al.* 2000). Furthermore, fragmentation can increase the flammability of landscapes through changes in vegetation structure along the forest edge and by shifting the vegetation composition from mesic to xeric species (Armenteras *et al.* 2013).

Changes in landscape flammability and fuels have led to altered fire regimes. The largest shift in fire regimes has occurred through the introduction of planned or prescribed burning. Land management agencies undertake planned burning to alter fuel load and structure in an attempt to reduce the extent and impact of future fire. Primarily the focus has been to use planned burning to reduce the risk from fire to human life and property situated within or adjacent to native vegetation (Fernandes and Botelho 2003; Penman *et al.* 2011). However, additional strategies are often adopted by agencies to protect life and property such as mechanical fuel treatments (Syphard *et al.* 2011; Syphard *et al.* 2012; North *et al.* 2015), community engagement (Eriksen and Prior 2013; Penman *et al.* 2015*a*) and fire suppression (Calkin *et al.* 2005; Plucinski *et al.* 2012; Penman *et al.* 2013*b*; Penman *et al.* 2014). Several studies in Australia have found that while planned burning may reduce the extent of wildfire, the net effect is an increase in overall fire extent and frequency (Boer *et al.* 2009; King *et al.* 2013; Price 2015) leading to the emergence of new landscape fire regimes. Land management agencies need to develop fire management strategies that reduce the risk of loss for people and property while maintaining ecological values (Burrows 2008; Penman *et al.* 2011; Thompson *et al.* 2011*a*; McCaw 2013). Strategies are generally limited to addition of fire through planned burning, or attempts at excluding fire to achieve required vegetation growth stages (e.g. Di Stefano *et al.* 2013) with the intent to maximise biodiversity (Parr and Andersen 2006).

Ideally, while developing fire management strategies agencies would explicitly quantify risk trade-offs to identify an optimal approach. Advances in computing and data collection has led to a unique set of tools for studying wildfire behaviour in modern landscapes. Simulation models are used to better understand how individual fires can behave under a set of conditions by varying the inputs of weather, fuel and ignition sources in different landscape settings (Finney 2005; Cary *et al.* 2009; Parisien *et al.* 2010). Combining the results from multiple fires under a range of conditions can be used to build probabilistic wildfire risk profiles for landscapes (Finney 2007; Tolhurst *et al.* 2008). In a research setting, many studies have used fire behaviour simulations and considered theoretical treatment approaches (e.g. nominal percentage landscape treated, reduction in ignition number) to explore ways to manipulate risk from fire in the landscape (Bradstock *et al.* 2012*b*; Haas *et al.* 2015; Calviño-Cancela *et al.* 2016). A common approach is to compare the change in risk between management scenarios using a response group, often human assets and communities (Scott *et al.* 2016) or threatened species (Thompson *et al.* 2011*b*; Ager *et al.* 2012). Very few studies have considered multiple assets in an explicit risk trade-off process (although see Ager *et al.* 2010; Thompson *et al.* 2011*a*; Salis *et al.* 2013; Driscoll *et al.* 2016). In application, few management agencies get to adopt such an approach to risk management and planning. However, there is increasing public pressure for government agencies to quantify risk reduction as a consequence of their actions (State of Victoria 2015).

In this study, we compare fuel treatment scenarios developed by fire management agencies to manage conservation values along with the protection of property. Our conservation values are centred on an isolated but dispersed population of an endangered iconic species, the koala (*Phascolarctos cinereus*). This population is in decline and a new fire management strategy of fire exclusion within koala habitat for the next 10 years has been proposed to allow the population to increase. Surrounding the forest areas where the koalas occur are scattered human properties and small settlements. Research suggests that these properties would be best protected by undertaking planned burning close to the assets (Gibbons *et al.* 2012; Penman *et al.* 2014) however this is not possible due to the presence of the koalas.

The aim of this work was to identify plausible fuel treatment strategies that meet the twin objectives of reducing wildfire risk to the koala population without increasing, and ideally decreasing, the risk to property. To compare treatments we used four indicators: wildfire size; burn probability; impact from exposure to fire; and the cost of treatment (Finney 2005; Ager *et al.* 2007).

Methods

Study area and fire history

The study was set in the coastal forests (~160 000 ha) around the township of Bega in south-eastern Australia (36°7′S, 149°8′E) (Fig. 1). A complex landscape occurs in the area where the river flats contain extensive agriculture (primarily dairy), with native forests managed for either conservation or timber supply in the more rugged terrain. Scattered among the forest and agriculture are several small and medium-sized settlements. Forested areas are dominated by south-east dry sclerophyll forest (as defined by Keith 2004). These forests are dominated by silvertop ash (*Eucalyptus sieberi* L.A.S. Johnson), white stringy bark (*E. globoidea* Blakely) and blue-leaved stringybark (*E. agglomerata* Maiden). The mid-storey is dominated by *Acacia* and *Allocasuarina* spp. with an understorey of sclerophyllous shrubs (Keith 2004). The region receives an average annual rainfall of 600 mm (Bureau of Meteorology Bega AWS weather station number 069139).

The fire regime for this region is characterised by infrequent low intensity surface fires in spring, with medium to high intensity fires in spring and summer (Murphy *et al.* 2013). Wildfire mapping began in the area in 1952. Wildfires were recorded in 1951–52, and 1962–63 and then on an almost annual basis since 1978 with 63 mapped wildfires. Within this set, 18 large fires greater than 100 ha occurred with a mean fire size of 3705 ha (Fig. 2). Planned burning began in 1985 and has occurred since on an almost annual basis with 79 burns recorded. Within this set, 30 large burns greater than 100 ha occurred with a mean planned burn area of 426 ha (Fig. 2).

Property locations and koala habitat

Houses in the region tend to occur towards the coast and along major roadways. Properties used in this study were located along the boundary of the forest reserve and adjacent to koala habitat (Fig. 1). The impact of fire on people and property was measured by using address points, which were provided by the NSW Rural Fire Service (RFS). A 200-m buffer was placed around each address as precise structure locations are not recorded.

Koala habitat has been identified from recent systematic surveys of the region undertaken by the NSW Office of Environment and Heritage (OEH) (State of NSW and Office of Environment and Heritage 2016) (Fig. 1). During early European settlement koalas were widespread throughout the region however significant population declines occurred through loss of forest habitat, overhunting, vehicle collision and dog attacks (Melzer *et al.* 2000). Currently koalas are listed as 'vulnerable to extinction' under the *Threatened Species Conservation Act 1995 (NSW)*. Koalas live in the forest canopy which makes them vulnerable to forest fires that scorch or burn the canopy. The impact of fire on koalas was measured within the footprint of koala habitat identified by the OEH.

Fire simulations

Landscape wildfire risk profiles were developed using the fire spread simulator PHOENIX RapidFire (hereafter PHOENIX) (Tolhurst *et al.* 2008). PHOENIX predicts the spread of fire from ignition points using inputs of weather, fuel load and terrain. PHOENIX simulates two-dimensional fire growth over complex variable landscapes using Huygens' propagation principle of fire edge (Knight and Coleman 1993). In Australian forests the two key drivers for fire propagation are surface fire and convection driven spot fires (McArthur 1967; Gill and Zylstra 2005), both are included in PHOENIX. Surface fire behaviour is

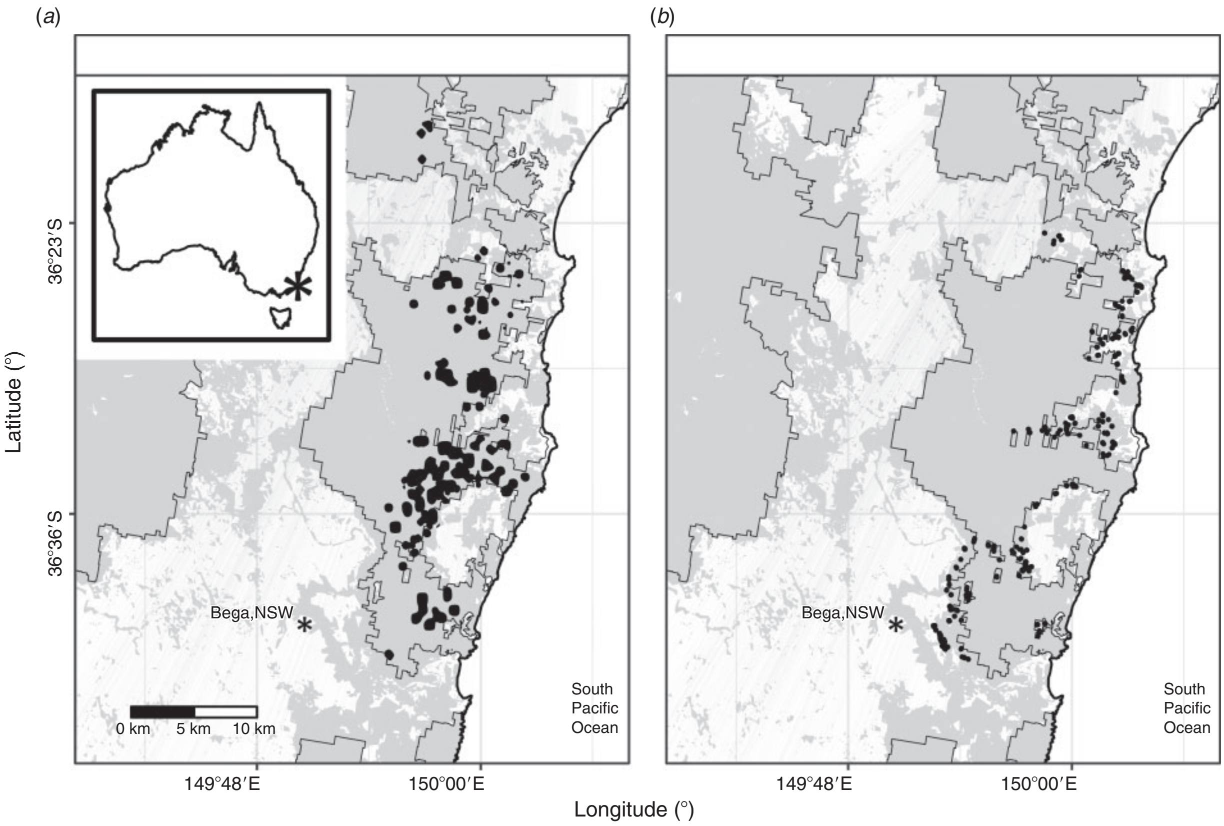

Fig. 1. Study area showing the locations of (*a*) the koala population from surveys and (*b*) property address points with a 200 m buffer. The forest reserve boundary is shown with a black border and forest cover is shown with light grey shading. Non-forested areas have a white background.

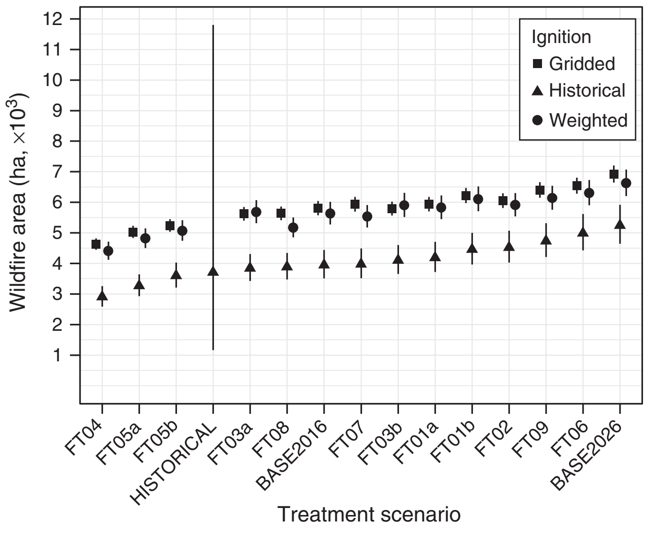

Fig. 2. Variation in median wildfire size between fuel treatment scenarios and ignition approaches. Treatments along the *x*-axis are ordered from smallest to largest mean wildfire area.

based on an adaptation of the CSIRO southern grassland fire spread model (Cheney *et al.* 1998) and McArthur Mk5 forest fire behaviour model (McArthur 1967; Noble *et al.* 1980). The spotting process is modelled using ember propagation coupled with spot fire ignitions (Saeedian *et al.* 2010; Chong *et al.* 2012). PHOENIX is used routinely for operational predictions of fire and strategic risk assessments within state agencies for eastern and southern Australia. Each of these agencies have tested the model and considered PHOENIX to provide an adequate representation of fire behaviour in their jurisdiction.

Weather conditions influence fire behaviour in PHOENIX which requires a weather stream for the simulated fire period. We selected the 10 dates with the highest daily McArthur Forest Fire Danger Index (FFDI) for the period from 1992 to 2011 from the Bega AWS weather station (site number 069139). FFDI is a composite measure that combines temperature, relative humidity, wind speed and a long-term drying index to predict the difficulty of fire suppression (McArthur 1967; Noble *et al.* 1980). An additional five dates from the period 2009–13 were provided by local fire managers as recent dates which presented challenging local fire weather conditions (see Table S1, Fig. S1 and Fig. S2 in online supplementary material). All weather streams covered a 24-h period beginning from midnight, to allow the model to generate stable and realistic estimates of fuel moisture. As the weather streams were taken from the recent past, we have not adjusted for climate change.

Fuel loads were calculated using fire history (time since fire), fuel type and fuel accumulation curves. In PHOENIX, major vegetation types (Keith 2004) are aggregated into fuel types based on similar fuel composition (Fig. 3). Fuel accumulation curves have been developed to model changes in fuel load where

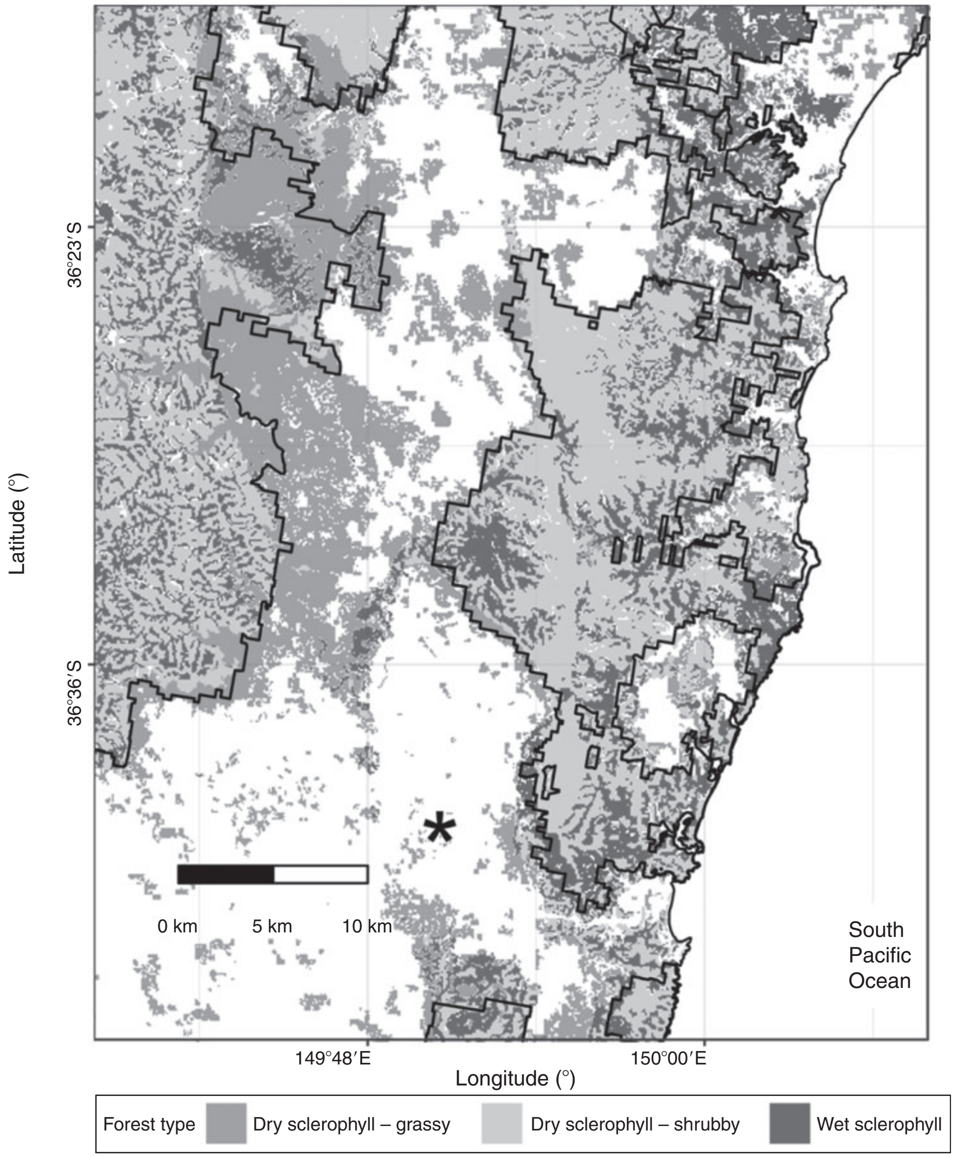

Fig. 3. Major forest fuel types in study area. White areas represent areas cleared for agriculture or urban settlements. The star marks the township of Bega, NSW.

the rate of fuel accumulation decreases with time since fire using a negative exponential equation (Olson 1963). These curves have an increase followed by a plateau in fuel loads resulting in older sites having higher fuel loads. Parameters for fuel accumulation models were developed from a review of empirical literature and field data collected for local forest types by Watson (2011).

Fire histories were varied to represent changing approaches to fuel treatment with maximum fuel reduction occurring across the entirety of each burn block. Treatment blocks and scenarios were developed independently by the three agencies with responsibility for fire management in the study area – NSW OEH, NSW RFS and Forests NSW (Fig. 4). These strategies were designed to represent achievable fuel treatment scenarios under current or slightly increased resource allocation, as well as considering the ecological thresholds of these forests (Kenny *et al.* 2004). Fuel treatments were located on public land within reserve boundaries as a combination of landscape treatments and targeted treatments within koala habitat (Table 1). Landscape treatments were concentrated along the western side of the forest reserve due to koalas and property in the east. Landscape treatments were typically orientated north to south to intercept fires from the west–north-west where the most severe fire weather originates. Treatments within koala habitat were included in four scenarios to examine the effect of targeted treatments on risk reduction.

Fuel reduction and recovery was considered for a ten-year period from 2016 to 2025. Two baseline scenarios were generated for assessment of relative risk and are based on landscape fuel loads. The first represents the current risk setting in 2016

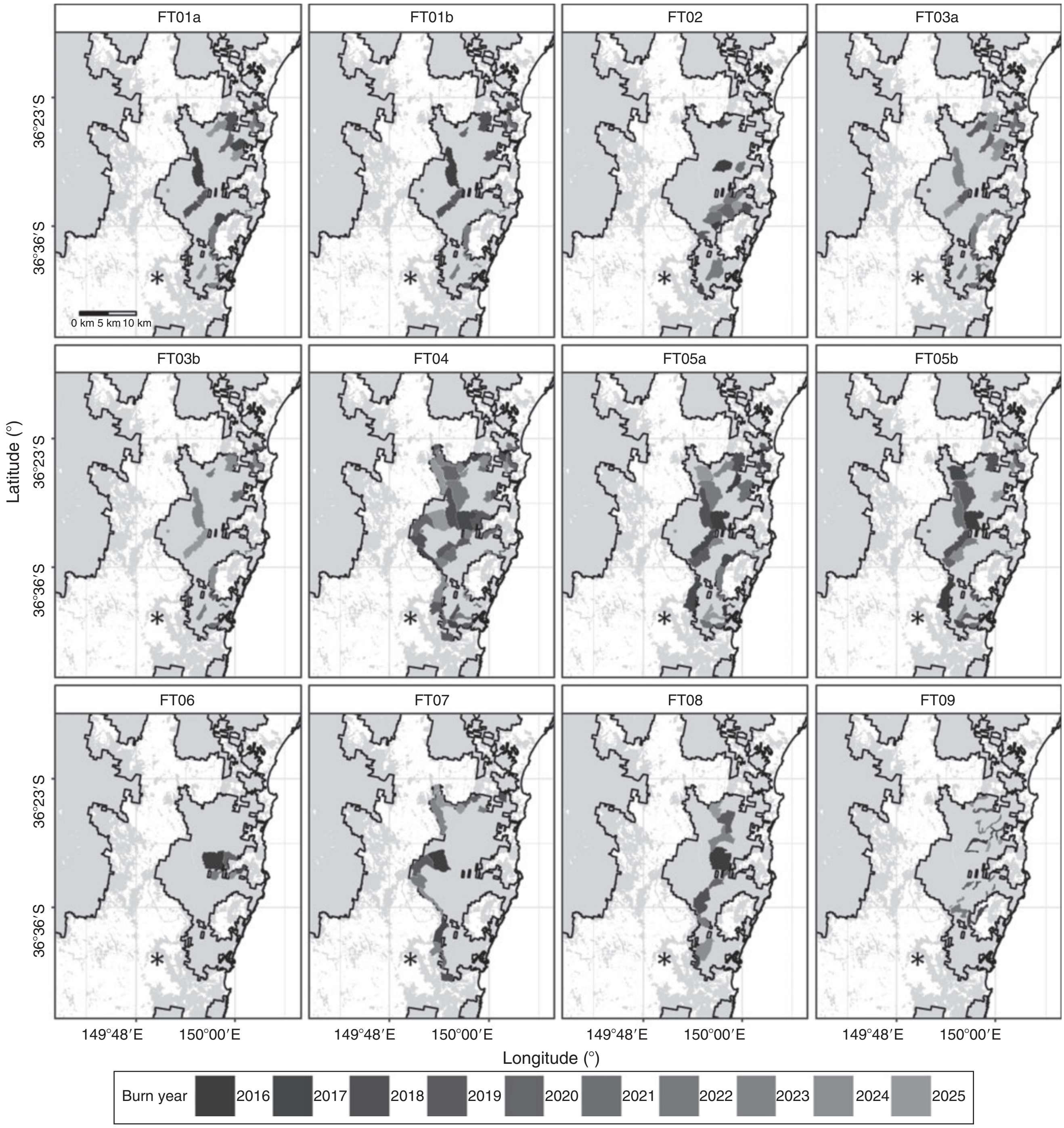

Fig. 4. Fuel treatment blocks and year of treatment are shown for each treatment scenario where treatments occur (FT01a to FT09). All treatments occur within the boundaries of forest reserves. The forest reserve boundary is shown with a black border and forest cover is shown with light grey shading. Non-forested areas have a white background. The star marks the township of Bega, NSW.

based on the contemporary fire history and the second represents future risk in the absence of fuel treatment between the present and 2026. This treatment represents a 'do nothing' scenario where fuel loads will reach maximum levels and we assume maximum risk.

Three ignition approaches were used (Fig. 5) – gridded, historical and weighted. In the gridded approach, we generated a regular 1 km grid of ignitions across the study landscape resulting in 1548 ignition locations. In the historical approach, we used all known historical ignitions ($n = 166$) provided by the

Table 1. Strategies underlying fuel treatment scenarios design

Scenarios were designed for landscape-wide treatments, focusing on koala habitat, or a combination of both. Some scenarios are modifications of the current fire management plan (FMP) whereas other scenarios explore novel treatment configurations and variations in total area treated

Scenario	Rotation period (years)	Landscape treatment	Koala habitat treatment	Description	Treatment area (total ha)
BASE2016				Risk profile in 2016	0
BASE2026				Risk profile in 2026 in the absence of planned burning, fuel treatment and wildfire between 2016 and 2026	0
FT01a	10	x	x	Current FMP	6547
FT01b	10	x		Current FMP, excluding core habitat areas	4861
FT02	10		x	Only burning within core habitat areas	4631
FT03a	7	x	x	Current FMP with adjusted rotation period	6547
FT03b	7	x		Current FMP with adjusted rotation period	4861
FT04	9	x		Hybrid strategy combining FT05b, FT06, FT07.	15 151
FT05a	10	x		Current FMP with wider blocks	11 602
FT05b	10	x		Current FMP with wider blocks, excluding core habitat areas	9505
FT06	10	x		North South Split (managing wildfire spread from northern to southern koala subpopulations)	1912
FT07	10	x		Western Side of Ridgeline	5999
FT08	10	x		Eastern Side of Ridgeline	5722
FT09	10		x	Ridgeline treatments immediately adjacent core habitat areas	2378

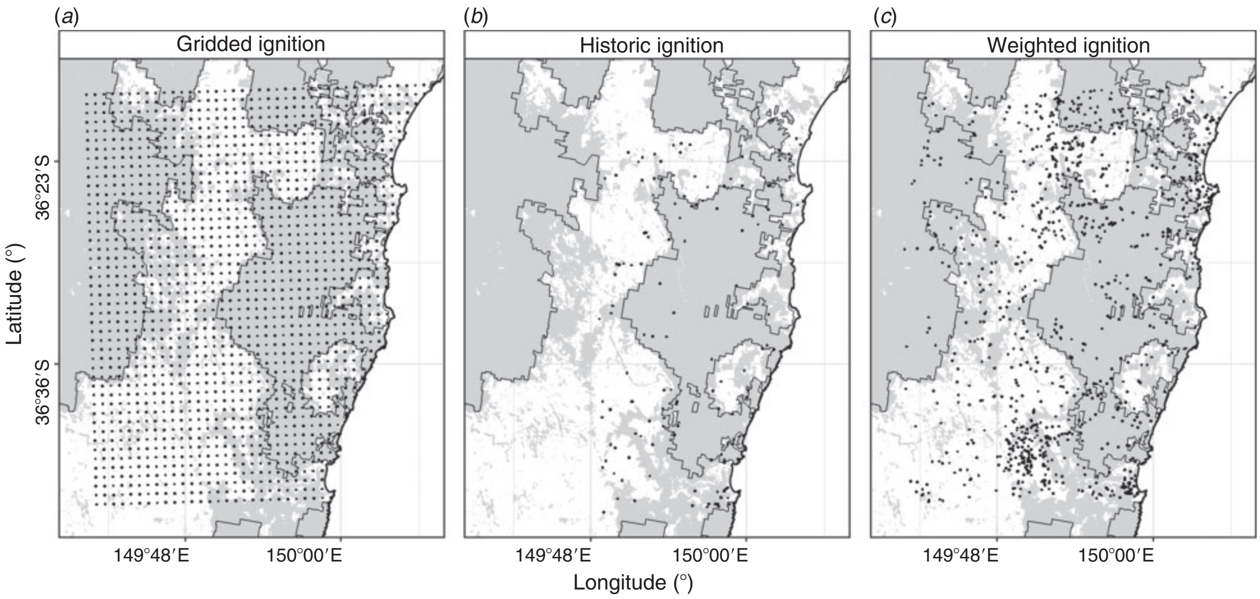

Fig. 5. Three different ignition scenarios were used to examine the effect of ignition scenario choice on risk outcomes. Ignition scenarios examined were (*a*) gridded ($n = 1548$), (*b*) historical ($n = 166$) and (*c*) weighted ($n = 1000$). The forest reserve boundary is shown with a black border and forest cover is shown with light grey shading. Non-forested areas have a white background.

NSW OEH. Finally, in the weighted approach we generated 20 000 random points and calculated ignition probability based on a model developed for similar forest types (Penman *et al.* 2015*b*), and selected the 1000 highest ignition probabilities for use in the analysis. Individual fires were ignited at 1000 hours to allow PHOENIX to generate stable and realistic estimates of fuel moisture pre-ignition. Fires were propagated for 12 h until 2200 hours, unless self-extinguished within this period. For each ignition approach all fires were allowed to run for every combination of weather and fuel treatment. This resulted in 569 940 simulated fires [(166 + 1000 + 1548) ignitions × 15 weather streams × (12 fuel treatments + 2 baseline scenarios)].

Analysis

All simulations were run using 180 m resolution gridded cells to optimise model performance based on the recommendations by Tolhurst *et al.* (2008). For each grid cell the model outputs the following metrics; ember density, convection, intensity and flame length. For each individual fire, PHOENIX reports the maximum value for each metric in each grid cell. For each combination of ignition and fuel treatment scenario, model outputs for each cell were aggregated to generate distributions to capture the combined effects of inputs and controls on landscape fire behaviour. Median cell values were reported as they are less influenced by extreme values when compared with the mean.

Risk was calculated using three metrics – fire size, burn probability and impact from exposure to fire. Fire size was calculated by summing the number of ignited cells by ignition location and treatment scenario. Mean wildfire area and 95% confidence intervals were calculated using a modified Cox's method for log-transformations as recommended by Zhou and Gao (1997). Fires less than 100 ha were removed due to a bimodal distribution in the dataset, as these are considered small in extent compared with the total forest and asset areas. Burn probability was calculated as the number of times a cell burnt divided by the total fires, where total fires were calculated as the number of weather streams by the number of ignitions. Relative burn probability was then calculated by normalising each scenario with the BASE2026 scenario where fuel loads were the highest. Relative burn probability was used to compare ignition approaches to normalise results for differences in ignition densities and patterns.

Impact from exposure to fire was measured differently for each asset. For koalas, impact was measured by flame length, as koalas are predominantly an arboreal species. For property, we used the house loss probability equation of Tolhurst and Chong (2011) to calculate the likelihood for house loss within each cell. House loss is calculated using ember density, flame length and convection and considers the likelihood for house loss through surface fire and spotting processes (Gibbons *et al.* 2012).

We calculated treatment cost using the equations of Penman *et al.* (2014) that predicts a negative log–log relationship between area treated in hectares and cost per hectare. The total treatment cost was calculated by summing the cost of individual blocks over the ten-year period and are not adjusted for inflation. We report the average annual cost per scenario. Model outputs were processed using the R statistical environment (ver. 3.2.3, R Foundation for Statistical Computing, Vienna, Austria, see http://www.R-project.org/, accessed 4 April 2017) and the packages ggplot2 (Wickham 2009), plyr (Wickham 2011), raster (ver. 2.4–20, R. J. Hijmans, see https://cran.r-project.org/web/packages/raster/index.html, accessed 4 April 2017) and rasterVis (ver. 0.41, O. Perpinan and R. J. Hijmans, see http://oscarperpinan.github.io/rastervis/ accessed 13 April 2017).

Results

Indicator 1: wildfire size

Variations in median wildfire size were consistent between ignition approaches, with the gridded ignitions (GI) and weighted ignitions (WI) estimating larger fire sizes than the historical ignitions (HI) approach (Fig. 2). Three treatments resulted in a significantly lower fire size compared with the current risk setting BASE2016 (3948 ha (HI) to 5808 ha (GI)) and the current fire management plan (FMP) FT01a (4185 ha (HI) to 5934 ha (GI)). These treatments were FT04 (2904 ha (HI) to 4630 ha (GI)), FT05a (3266 ha (HI) to 5026 ha (GI)) and FT05b (3597 ha (HI) to 5239 ha (GI)). Treatments FT04, FT05a and FT05b increased the area of fuel reduction burning over the ten-year period by a factor of 2.3, 1.8 and 1.5 compared with FT01a. The largest wildfire sizes occurred where no treatments were under taken in scenario BASE2026 (5242 ha (HI) to 6921 ha (GI)). Using Spearman's rank correlation, wildfire size was negatively correlated with mean annual treatment area for gridded ($r_s = -0.94$, $P = 0.000$), historical ($r_s = -0.93$, $P = 0.000$), and weighted ($r_s = -0.85$, $P = 0.001$) ignition approaches.

Indicator 2: relative burn probability

Changes in relative burn probability were similar between property and koala habitat, although the precise order of treatments and magnitude of change varied between ignition approaches (Fig. 6). Relative burn probability was similar between ignition approaches for the current risk setting BASE2016 for both property (0.72 (HI) to 0.79 (GI)) and koalas (0.70 (HI) to 0.78 (GI)). In addition, relative burn probability was similar between ignition approaches for the current FMP (FT01a) for both property (0.75 (GI) to 0.79 (HI)) and koalas (0.75 (GI) to 0.78 (HI)). This indicates a slight reduction in relative burn probability under the current FMP over the ten-year period. Three treatment (FT04, FT05a, FT05b) consistently resulted in the largest reduction in relative burn probability. Overall, FT04 resulted in the lowest relative burn probability for both property (0.51 (GI) to 0.52 (HI)) and koalas (0.46 (WI) to 0.50 (GI)) (Fig. 7).

Indicator 3: impact from wildfire

The current FMP FT01a resulted in a marginal reduction in median flame length (25.1 m (HI) to 25.9 m (GI)) compared with the current risk setting BASE2016 (26.1 m (HI) to 27.5 m (GI)) (Fig. 8). The longest median flame lengths were reported for the no treatment scenario BASE2026 (28.0 m (HI) to 28.8 m (GI)) with the lowest for a treatment scenario which treated some areas of the koala habitat FT02 (20.8 m (WI) to 21.3 m (GI)). Relative house loss probability had a slight reduction under the current FMP FT01a (0.92 (GI) to 0.93 (WI)) compared with the current risk setting BASE2016 (0.96 (HI) to 0.98 (WI)). The highest relative house loss probability occurred under the no treatment scenario BASE2026. The lower relative house loss probability occurred under FT04, which treated the largest area (0.84 (GI) to 0.85 (WI)).

Indicator 4: cost of treatment

The average annual area treatment ranged from 191 ha to 1718 ha while treatments cost ranged from \$6581 to \$77 298 per year (Fig. 9). Significant correlations exist in all ignition scenarios between relative burn probability of property and treatment area ($r_s = -0.67$, $P = 0.020$ to -0.88, $P = 0.000$) and between the relative burn probability of koala habitat and treatment area ($r_s = -0.55$, $P = 0.071$ to -0.71 $P = 0.013$). As investment increased, risk for both property and koala habitat decreased.

Discussion

We used wildfire simulations to examine the ability of a range of potential fuel treatment strategies to reduce wildfire risk to

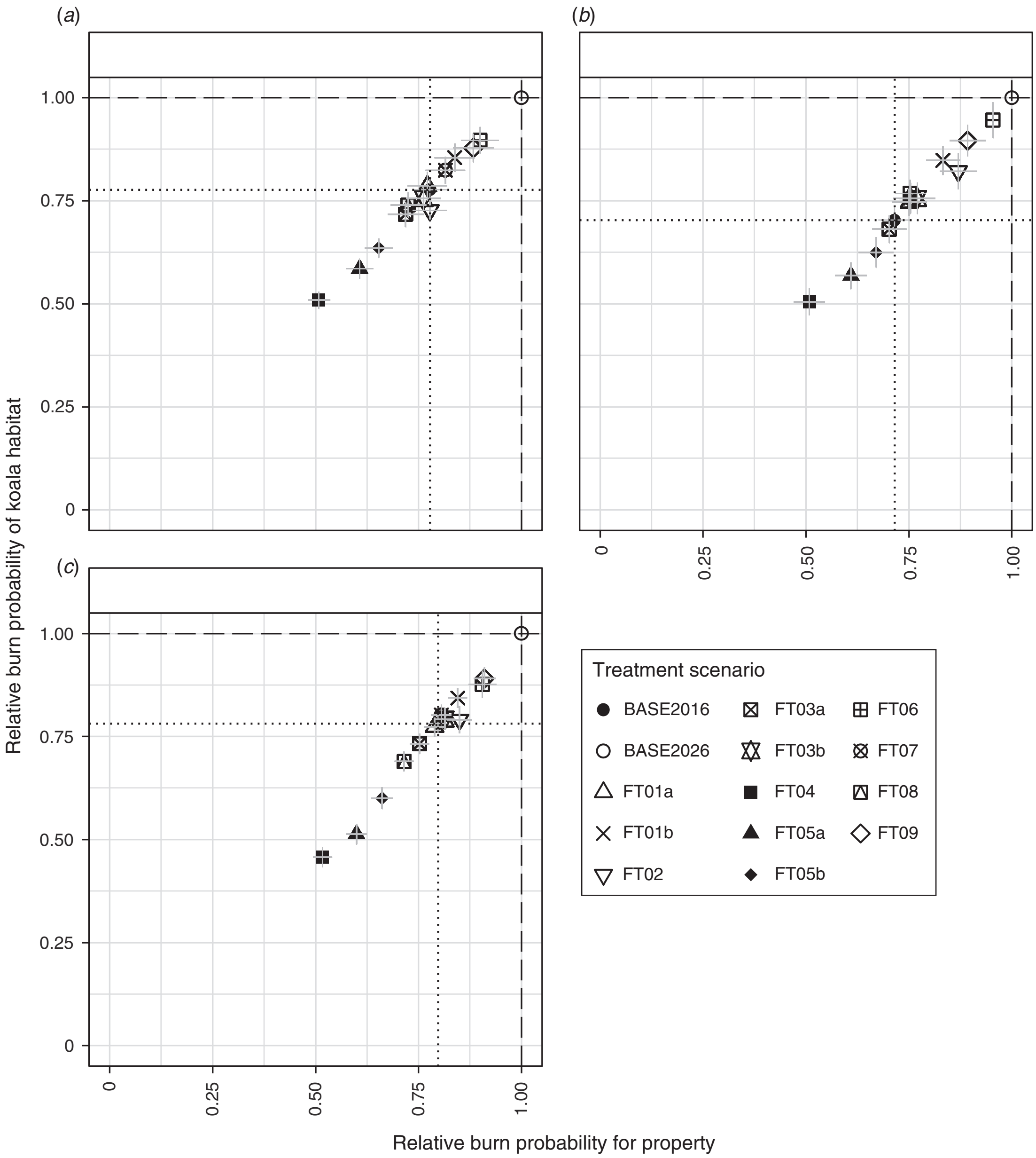

Fig. 6. Change in relative burn probability between property and koala habitat for different fuel and ignition approaches: (*a*) gridded; (*b*) historical; and (*c*) weighted. Current risk values for 2016 (dotted line) and no treatment risk values (dashed line) are highlighted. Probabilities were normalised using the BASE2026 (no treatment) scenario. Median values and 95% CI shown.

property and koala habitat. Consistent with other studies, this study showed that increasing the area of fuel treatment in a landscape resulted in a decrease in future wildfire extent and burn probability to assets (Ager *et al.* 2007; Finney 2007; King *et al.* 2008; Boer *et al.* 2009; Wu *et al.* 2013; Ager *et al.* 2014; Penman *et al.* 2014; Price *et al.* 2015*b*; Salis *et al.* 2016).

Increasing the area treated through planned burning and generating a measurable reduction in wildfire extent has been previously referred to as leverage (Loehle 2004). Leverage varies according to the annual extent of wildfire, extent of fuel treatment and the rate at which fuel loads recover (Price 2012). Leverage has been analysed on individual burns (Loehle 2004) and across landscapes (Boer *et al.* 2009; Price *et al.* 2012; Price *et al.* 2015*a*). In a bioregional analysis of south-eastern Australia, Price *et al.* (2015*b*) found no evidence of leverage within the study area's bioregion for the period 1970–2010. However, they did not consider the extensive logging in the bioregion that would have had a substantial influence on the nature of fuel loads. In addition, the bioregion had very few years in which wildfire occurred. While our study considered a smaller spatial domain than Price *et al.* (2015*b*), our results suggests leverage is possible in this region as fuel treatments played a role in reducing wildfire size. Consideration is required as to how this change affects fire regimes at the decadal scale.

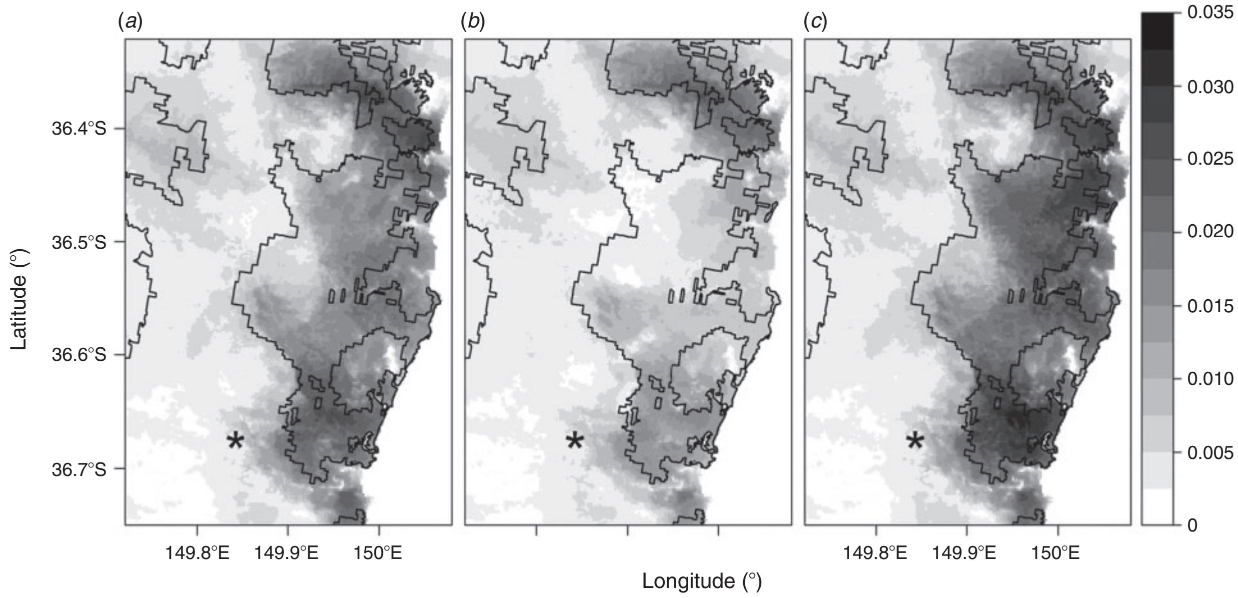

Fig. 7. Burn probability maps comparing fuel treatment scenarios for (*a*) the current risk setting BASE2016, (*b*) the treatment scenario with the greatest reduction in burn probability FT04, and (*c*) the future risk setting BASE2026 where no treatment occurs and fuel loads are highest in the landscape. Burn probabilities shown are for the weighted ignition approach. The forest reserve boundary is shown with a black border. The asterisk marks the township of Bega, NSW.

The spatial arrangement of treatment blocks is one of the key factors in influencing the effectiveness of encountering a wildfire where fuel loads are reduced (Price and Bradstock 2010). When a wildfire encounters a treated area with reduced fuels it is expected to reduce fire intensity and rate of spread (McCaw 2013). Treatments are considered more effective when they are placed adjacent to existing fuel breaks (e.g. roads and rivers). Lowering fuel loads is predicted to interrupt the propagation of a wildfire front (Price and Bradstock 2010). In this study, treatment strategies that produced the largest reductions in risk had a concentration of large burn blocks immediately to the west of koala habitat areas. The need for the spatial arrangement of blocks to the west was 2-fold. First, higher ignition probabilities occur in the west of the study area due to lighting along ridgelines and the higher likelihood of ignitions from roadways and human settlements, as shown in the historical and weighted ignition approaches. Second, the direction of severe fire weather in the region is from the west–north-west and is associated with hot, dry inland winds. A combination of these factors played a role in generating leverage under simulated conditions in this landscape during severe fire weather conditions.

Many treatments did not include planned burning within the koala habitat, which were often immediately adjacent to property, and high fuel loads remain in the eastern side of the forest. Even those treatments that included planned burning within some of the koala habitat resulted in little change in impact from exposure to fire. This result was due to the fact that the koala population area was larger than the fuel treatments within koala habitat. While treatment of larger areas can reduce the likelihood of a fire spreading, under more severe fire weather conditions the amount of fuels becomes less important than weather, as wildfires can still spread through areas with low fuel loads (Cary *et al.* 2009; Bradstock *et al.* 2010; Collins *et al.* 2014). While the probability of fire is reduced for property and koalas, the impact from exposure to fire remains high for both koalas and property. Fuel loads, topography and fire weather resulted in predicted flame lengths greater than 20 m in koala zones under all treatments. Similar high severity fires have been reported in nearby forests by Collins *et al.* (2014). Overall, our results are consistent with other studies that show the placement of treatments nearest to assets provides the greatest reduction in risk (Safford *et al.* 2009; Ager *et al.* 2010; Penman *et al.* 2014).

Planned burning is only one option to achieve risk reduction and when used in conjunction with other approaches it may improve risk outcomes. While scenarios that treat large areas have a better chance of intercepting and reducing the spread of wildfire, in this region they come with increased financial costs. Here we only compared the cost of fuel treatment; however, more cost effective risk mitigation may be achievable through integration with other strategies. These may include mechanical fuel management, ignition management, initial attack and community engagement. Mechanical removal or thinning can reduce fuel loads and alter fuel structure adjacent to property or within koala habitat to manage exposure from fire due to local high fuel loads (Penman *et al.* 2015*a*). In a simulation study Cary *et al.* (2009) found ignition management to have a significant influence on wildfire extent. Natural ignitions cannot be prevented, however the majority of ignitions in the study region originate from human sources which concentrate around human settlements and infrastructure (Penman *et al.* 2013*a*). Ignition management strategies such as increasing awareness and vigilance have been shown to reduce the number of ignitions in some locations (Plucinski 2014) but it is a complex societal issue that requires complex policy beyond the reach of fire management agencies (Prestemon and Butry 2008; Dickens *et al.* 2012). A feasible alternative to fire agencies is investing in initial

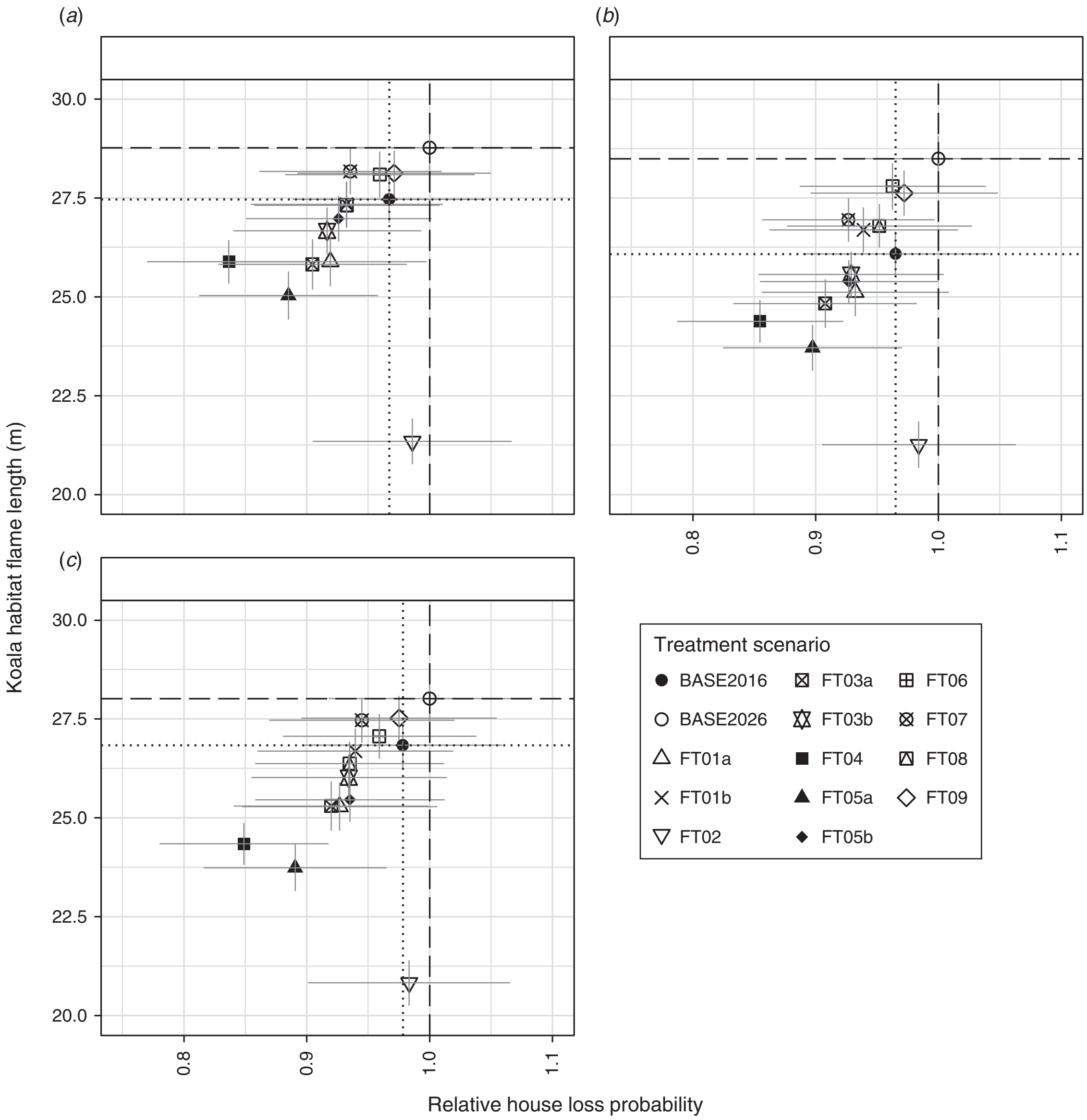

Fig. 8. Change in median relative house loss probability function of convection, intensity and ember density for property and median flame length in koala habitat for different fuel treatment and ignition approaches: (*a*) gridded; (*b*) historical; and (*c*) weighted. Current risk values (dotted line) and future risk values (dashed line) are highlighted. House loss probability was normalised using the BASE2026 (no treatment) scenario. Median values and 95% CI shown.

attack. Initial attack is most successful with rapid response times and low fuel loads (Plucinski 2012) indicating an interaction with fuel treatment efforts (Penman *et al.* 2013*b*; Salis *et al.* 2014). Community engagement with householders encourages better preparation (Penman *et al.* 2013*c*) and increases the probability of structures surviving (Gibbons *et al.* 2012). However, the degree of involvement by property owners is linked to their perceived levels of wildfire risk (Gill *et al.* 2015; Penman *et al.* 2016). All these strategies have the potential to work independently or interactively with the fuel treatments tested here. It was beyond the scope of the study to quantify the effects of the combinations of complementary approaches.

The modelling approach was found to be useful in quantifying risk reductions from various treatments; however, there are limitations to the model. Heterogeneity within historical fire boundaries is not mapped, meaning fuel reduction from past fires is often overestimated (Penman *et al.* 2007). In addition, fuel treatments in the model result in a greater reduction in fuels than would be expected in reality. Furthermore, the model assumes fuel loads increase with time since fire following a negative exponential equation (Olson 1963). These curves assume an ongoing increase or a plateau in values, that is, older sites have more fuel (Watson 2011). However, few studies have attempted to quantify this. Of those that have some suggest support (McCaw *et al.* 2002) while others suggest a short-term increase in fuels (particularly elevated fuels) followed by an ongoing decline (Sturtevant *et al.* 2004; Zylstra 2013). How fuel loads accumulate and the influence of past forest disturbances

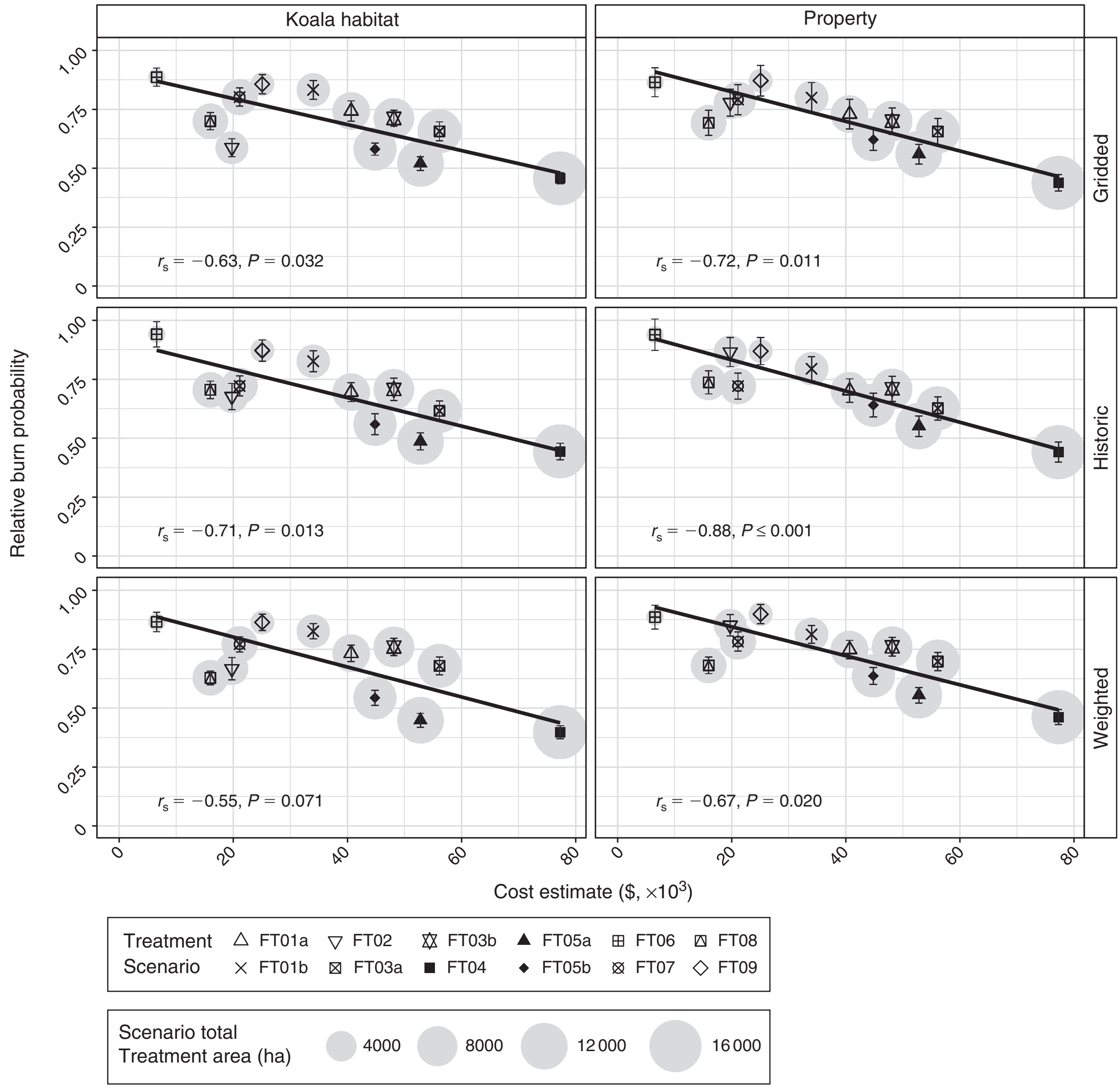

Fig. 9. Cost benefit analysis showing change in relative burn probability versus average annual cost of treatment by ignition scenario versus asset. Cost is a function of area treated. Differences in the total area for each treatment scenario are illustrated using bubbles proportional to treatment area. Spearman's rank correlation (r_s) shown.

such as logging are unknown and require further research. We overcame these limitations by taking a relative risk approach rather than analysing absolute values.

Conclusion

We have used a fire behaviour simulation model to compare change in wildfire risk to adjacent fire sensitive populations of people and koalas in a coastal forest of NSW, Australia. The study objectives were to identify treatment strategies that reduced risk to both people and koalas. Treatments were identified that reduced burn probability and fire size by increasing treatment area in the landscape, albeit at greater financial cost. However, the impact from exposure to fire to property and koala habitat will remain high within asset areas due to the remaining high fuel loads. Additional complementary strategies beyond landscape fuel reductions are needed to reduce impact from exposure in the event of a wildfire.

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