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# What is the 'appropriate' fuel management regime for the Otway Ranges, Victoria, Australia? Developing a long-term fuel management strategy using the structured decision-making framework

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**Abstract.** The Otway Ranges contain many of the highest-wildfire-risk communities in Victoria, Australia. One of the chief risk mitigation measures in the Otway Ranges is planned burning. The location and amount of planned burning that is undertaken need to consider stakeholder perspectives that can be largely divergent, invoking difficult trade-offs for land-management agencies. The structured decision-making framework was utilised to select the most 'appropriate' 40-year cross-tenure fuel management strategy for the Otway Ranges. This paper details the approach undertaken to develop an optimised set of multi-objective fuel management strategies, identify suitable monetary and non-monetary objectives and calculate risk-weighted consequences using a range of modelling techniques. To underpin clarity in trade-offs and decision making, we emphasise the use of natural measures of performance for each candidate strategy against each objective, such as lives lost, species decline and economic losses associated with wildfire. This paper also highlights the role of stakeholder engagement throughout the decision-making process. We discuss the results of the formal trade-off process that was completed using an additive multi-objective value model to identify a preferred fuel management strategy for the Otway Ranges. The preferred strategy is currently used by local management agencies to guide operational planning and delivery.

**Additional keywords:** decision analysis, economic valuation, life loss, planned burning, risk.

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## Introduction

The policy challenge for modern forest and fire managers involves identifying a fire regime that minimises impacts to society. This requires an understanding of outcomes across a wide spectrum of economic, environmental and social values (Venn and Calkin 2011; Driscoll *et al.* 2016; Rodríguez y Silva and González-Cabán 2016; Bentley and Penman 2017; Thompson *et al.* 2017).

This makes the evaluation of fire regimes a multiple-objective problem that will typically involve trade-offs across uncertain consequences (Driscoll *et al.* 2016; Bentley and Penman 2017).

A common approach to solving multi-objective problems is to utilise multicriteria decision analysis (MCDA) (Richards *et al.* 1999; Failing *et al.* 2007; Driscoll *et al.* 2010; Gregory *et al.* 2012; Vogler *et al.* 2015; Ager *et al.* 2016; Driscoll *et al.* 2016; Fraser *et al.* 2017). An advantage of the MCDA approach is that single-objective modelling outcomes such as those derived from Bayesian networks (BNs) (e.g. Penman *et al.* 2011*b*, 2015; Papakosta *et al.* 2017) or other single-objective methods can be incorporated into multi-objective frameworks.

A second multi-objective approach that is increasingly being used to evaluate the effectiveness of wildfire management treatments is benefit–cost analysis (Mercer *et al.* 2007; Butry *et al.* 2010; Florec *et al.* 2013; Rodríguez y Silva and González-Cabán 2016). Benefit–cost approaches monetise all objectives to enable benefit–cost ratios to be derived.

Although use of MCDA and benefit–cost analysis approaches potentially provides for robust decision making via considered treatment of trade-offs, on its own it does not guarantee outcomes that are acceptable to diverse interests. Enduring solutions are more likely when managers and stakeholders work through problems together (US National Research Council 1996).

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In the environmental sector, the overarching framework of structured decision making (SDM) has been promoted as a useful framework (Marcot *et al.* 2012; Martinez-Harms *et al.* 2015) and has progressively been used to navigate difficult problems involving multiple stakeholders (Failing *et al.* 2007; Gregory and Long 2009; Gregory *et al.* 2012; Moore and Runge 2012; Garrard *et al.* 2017).

There are six steps in SDM. Specifically:

(1) Specify the decision context
(2) Identify fundamental objectives
(3) Nominate alternatives
(4) Estimate the consequences of alternatives against objectives
(5) Articulate trade-offs
(6) Implement the best alternative (and monitor and review outcomes).

The SDM framework utilises the strengths of analytical approaches and emphasises stakeholder deliberation in the setting of objectives, design of candidate solutions, and ultimately in the selection of better solutions via articulation of trade-offs (Gregory *et al.* 2012).

In contrast to benefit–cost analysis, SDM emphasises the use of natural measures that directly relate to objectives. For example, if an objective is to minimise loss of human life, then a natural measure is mortality associated with wildfire. Direct measures make trade-offs more visible and understandable.

Where natural measures are unavailable, constructed scales can be used. Constructed scales enable the inclusion of objectives that are important to stakeholders such as ‘sense of place’ or ‘community support’ (Keeney and Gregory 2005).

The six steps of SDM provide a generic template for approaching problems within which a suite of different analytical tools, such as MCDA and BNs, can be accessed. The combination of analytical rigour and regular stakeholder input helps ensure that outcomes are transparent and repeatable and that competing interests and values are displayed in ways that technical and non-technical stakeholders can understand (Gregory *et al.* 2012).

The present study aimed to identify a fuel management strategy that maximised outcomes for social, economic and environmental objectives while minimising strategy implementation costs. This paper presents the outcomes of the SDM process used to select the current long-term fuel management strategy for the Otway Ranges in south-west Victoria, Australia.

Our approach emphasised local stakeholder involvement in all steps throughout the decision-making process (Fig. 1). Local stakeholders directly contributed to the design of the fuel management strategies, selection of fundamental objectives, completion of values-based judgements for use in the MCDA method and ultimately the selection and adoption of a fuel management strategy.

The alternative candidate strategies varied in the return period of planned burning and the proportion of the landscape treated annually. Evaluation of alternative candidate strategies was undertaken using a range of objectives including loss of human life, fauna species decline, community support, number of towns adversely impacted, cultural heritage impact and economic impacts to a range of local industries and values. Consequences of the strategies were presented based on evaluation of simulated 40-year fire regimes that included planned burning and wildfire. Ultimately, local stakeholders were asked to select their preferred strategies via weighting objectives in an MCDA.

## Methods

### *Study area and fire regime description*

The study area encompassed approximately 1 million ha that includes large tracts of private land used for a diverse range of agricultural purposes. The dominant geographic feature is the Otway Ranges (38°31′S, 143°38′E) (Fig. 2) in the south of the landscape with prominent public forest reserves including the Great Otway National Park, Otway Forest Park, Brisbane Ranges National Park and Port Campbell National Park.

The area has a strong rainfall gradient starting at ~530 mm in the eastern part of the area (Bureau of Meteorology Geelong site no. 087025) through to 1900 mm (Bureau of Meteorology Weeaproinah site no. 090083) along the spine of the Otway Ranges. The variation in rainfall contributes to significant floristic diversity ranging from open heathland and dry forests through to wet forest and small pockets of rainforest in more mountainous areas (State of Victoria 2015*a*). The Otway Ranges also contain the primary water supply catchments for local towns and regional cities.

Peak human population numbers are up to four times higher over the summer months for many coastal townships, with the iconic Great Ocean Road and surrounding area experiencing up to 5.4 million visitors annually in recent years (State of Victoria 2018*a*). This presents challenges for fire agencies as many of these townships are surrounded by flammable forests and road access is limited to the Great Ocean Road. The risk to communities is outlined in the current Barwon Otway Bushfire Management Plan, which identifies several coastal towns, including Lorne and Anglesea, as likely to have significant house loss if exposed to catastrophic wildfires. In terms of house loss potential, these towns were ranked in the top four in Victoria (State of Victoria 2015*a*) with ember attack from high bark loads being a major cause of the potential losses.

Beyond tourism, other industries of note include a diverse agricultural sector consisting primarily of livestock operations and a plantation industry consisting of *Eucalyptus globulus* and *Pinus radiata* plantations. Retail, construction and manufacturing industries also make a significant contribution to the regional economy (State of Victoria 2015*a*).

In the Barwon Otway Bushfire Management Plan area, the fire season extends from October to April, with 69% of fires occurring between December and March and over 95% of destructive fires occurring during this period. On average, there are ~500 grass and forest ignitions per year, with 95% of fires being started by anthropogenic sources (State of Victoria, unpubl. data).

Destructive fires in the study area have been recorded approximately every decade since 1900, with the most notable examples being the Black Friday fire in 1939 (240 000 ha) and 1983 Ash Wednesday fire in the eastern half of the Otway Ranges (42 000 ha, 3 lives and 729 houses lost). More recent examples include the 2015 Wye River Wildfire (~2500 ha, 116 houses lost) and the 2018 Saint Patrick’s Day Fires (~15 000 ha, 24 houses lost) (State of Victoria 2015*a*, 2018*b*; Hinchey 2016).

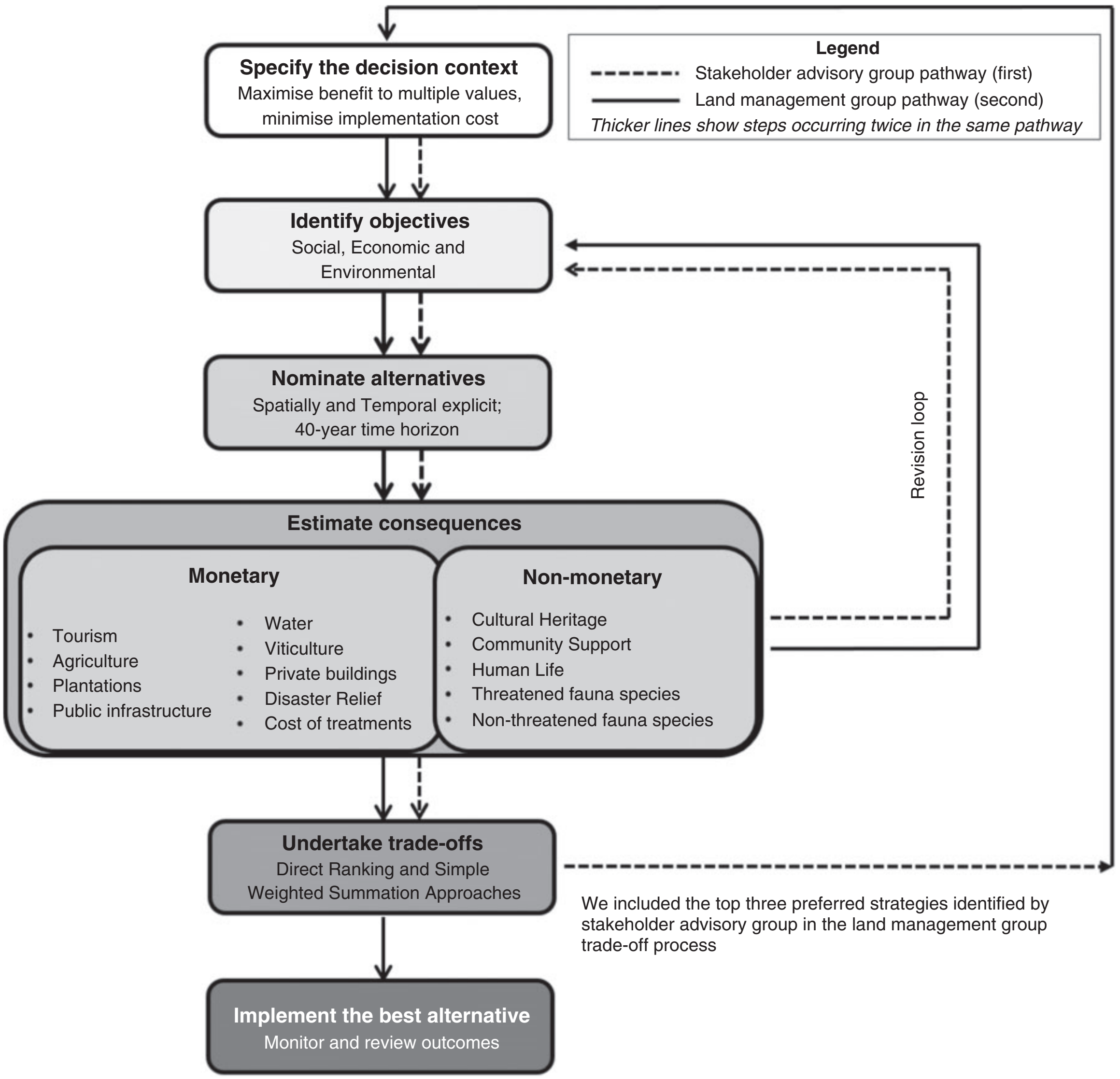


**Fig. 1.** Flowchart of structured decision-making framework and its application in this study.

Mapping of planned burning outcomes on public land has systematically occurred since 1980. Rates of burning between 1980 and 2006 achieved on average less than 1000 ha per annum. Since 2007, there has been an increased focus on the application of planned burning to mitigate wildfire risk and to maintain or improve ecosystem resilience (State of Victoria 2015*a*), with an average of ~4000 ha per annum being treated. The greater focus on township wildfire risk mitigation in the last decade has led to higher areas of private land inclusion in the planned burn program, with up to 10% of the area treated annually being privately owned.

### *Specify the decision context*

Fire management planning in Victoria occurs at state, regional and municipal tiers. It involves bringing together a range of agencies and organisations to discuss, plan and manage fire with the community. Strategic bushfire management planning is guided by two overarching state-wide strategic objectives:

(1) To minimise the impact of major bushfires on human life, communities, essential and community infrastructure, industries, the economy and the environment. Human life will be afforded priority over all other considerations.
(2) To maintain or improve the resilience of natural ecosystems and their ability to deliver services such as biodiversity, water, carbon storage and forest products.

These two objectives provided the basis for the identification of suitable subregional objectives for inclusion in the study.

This study was implemented in two stages (Fig. 1). Stage one involved the convening of a 22-person stakeholder advisory group consisting of management agency representatives, special interest groups and local community representatives to provide input at each of the first five steps in the SDM framework.

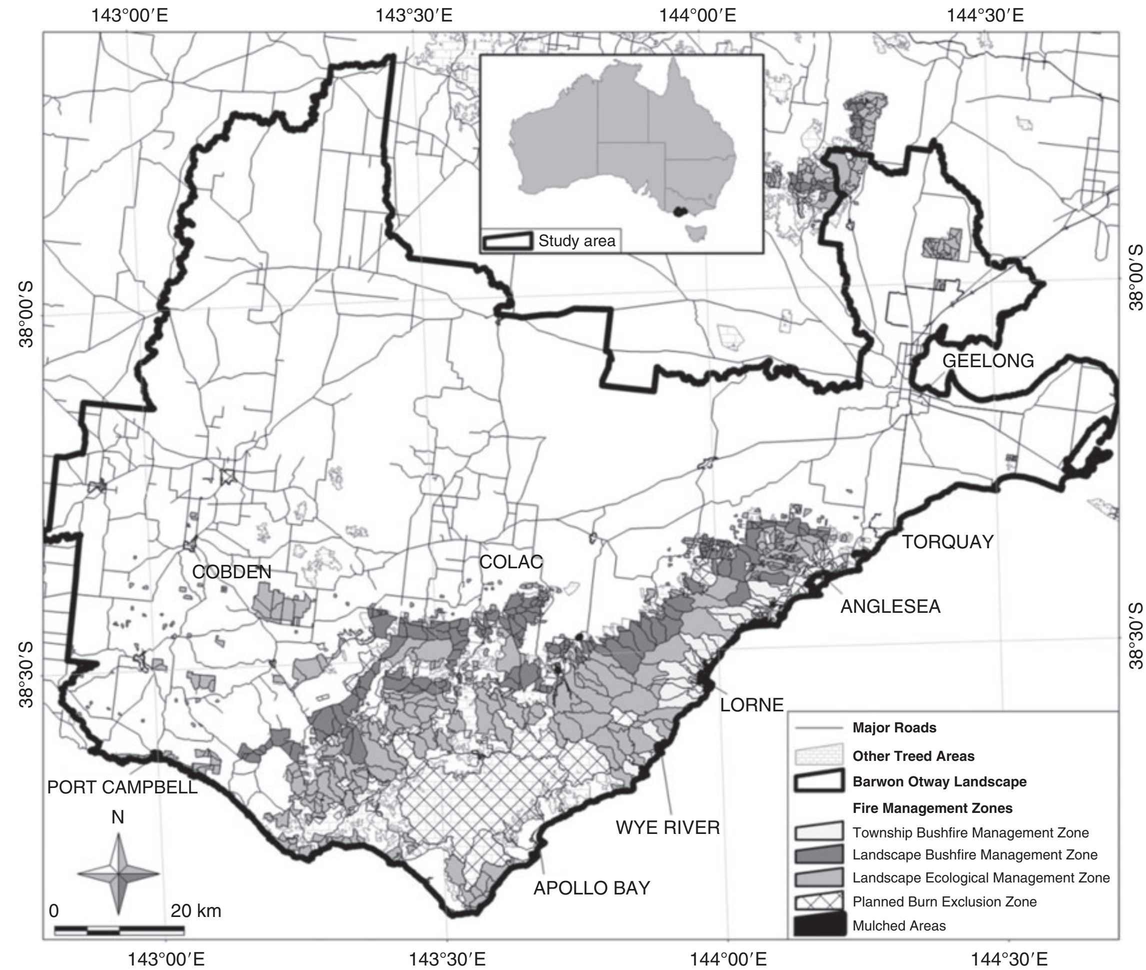


**Fig. 2.** Geographic extent of the study area. Fire management zones are shown for the alternative treatment A1. A1 represents the long-term fuel management strategy that existed at the start of the study. Zones broadly capture the intent of fire application in different parts of the landscape. The Planned Burn Exclusion Zone identifies broad areas of Wet Forest and Rainforest – forest types that are fire-sensitive.

This group reflected on a broader range of treatments beyond fuel management, designing alternative treatments that included suppression and patrol effort, building standards applied to the wildland–urban interface properties and burying of powerlines. The top three preferred strategies identified by the stakeholder advisory group were included in the land-management group trade-off process.

Stage two of the study involved 11 local land managers with direct responsibility for maintaining an appropriate fire regime for the study area. The land-management group focused only on alternative treatments related to fuel management. Insights from the advisory group were utilised by a land-management group in stage two. This paper describes the methods and results from the land-management group.

### *Identify fundamental ends objectives*

A key step is sorting means and ends objectives. Policy-makers often invoke means objectives, such as minimising fuel loads, or maximising building standards. Underpinning our concern for means objectives are more fundamental ends, such as minimising loss of human life and property. To make trade-offs as clear as possible and to avoid double counting in our evaluation of the merit of alternatives across multiple objectives, we need to include only fundamental ends objectives in our analysis (Keeney and Gregory 2005; Gregory *et al.* 2012). Building complete lists of objectives that focus on fundamental concerns is surprisingly difficult (Keeney 2007; Bond *et al.* 2008). We provided a reasonably complete list of fundamental objectives to the stakeholder groups as an initial step using the overarching state-wide strategic objectives as a foundation. The land-management group established nine monetary objectives and six non-monetary objectives (Table 1).

Where possible, we selected performance measures that utilised a natural scale that can be readily interpreted and the causal relationship between the objective and measure is self-evident – for example, the expected number of lives lost or expected dollar cost (Keeney and Gregory 2005; Gregory *et al.* 2005, 2012).

The community support objective was the exception and utilised a constructed scale (Gregory *et al.* 2012) between 0 and

**Table 1. Basic description of the modelling methodologies used to estimate the performance of alternative treatments**

Monetary objectives (1–8) utilised Bayesian networks (BNs) to capture the wildfire exposure and value vulnerabilities. Several BNs also include mitigating and treatment factors. Wildfire exposures were calculated using PHOENIX and captured in a joint distribution based on combinations of ember density (embers $m^{-2}$) and fireline intensity (kW $m^{-1}$) at Year 20 and Year 40. Each network returns the probability of impact to each value at the PHOENIX output cell level. Economic losses for each value were calculated independently from the BN. Economic losses (impacts) represent either lost production or costs associated with wildfire recovery. Objectives 9–15 use other modelling approaches to estimate expected outcomes

| Objectives | Basic description of consequence estimation methodology |
|---|---|
| (1) Economic impact on public property | 16 asset types including roads, rail infrastructure, water infrastructure (not catchments) and public buildings were grouped into four asset groups based on bushfire vulnerability characteristics. Economic loss was calculated by summing the reconstruction costs for each asset impacted by wildfire |
| (2) Economic impact on agriculture | 13 land-use types including livestock, cropping, mixed farming and intensive industries were identified and were grouped into three vulnerability classes to capture seasonal variation and enterprises with and without infrastructure. Annual production losses were calculated for each 180-$m^2$ grid cell and multipliers were added to production losses to account for associated infrastructure and stored produce |
| (3) Economic impact on plantations | Plantations were divided into softwood and hardwood types. Bushfire vulnerability was assumed to be only from direct exposure to the fire front. Harvested plantation production losses were calculated per hectare. Plantation age was not factored in owing to lack of available data |
| (4) Economic impact on viticulture | We refer to wine grapes in this study. Wine production losses were calculated based on production being lost for a 3-year period. The cost of replacing netting was also included based on local vigneron advice. The BN elicited the likelihood of impact from direct exposure to bushfire and bushfire smoke. Smoke exposure was also captured from planned burning. Factors captured in the model include location of the vineyard, time of year of exposure and the nearby planned burn regime. The method ignores vine age and grape type |
| (5) Economic impact on tourism | The tourism model accounted for the magnitude of impact of the bushfire event at the township level with the output an estimate of the number of days of disruption likely to be encountered under peak and non-peak tourism periods. The impact of the planned burn regime was also included in the model. Losses were calculated directly for the township and for surrounding townships in what were termed 'broader perception areas' |
| (6) Economic impact on water provision | Economic losses were calculated based on a reduction in yield from vulnerable catchments and based on changes in water quality. The water yield BN included a vulnerability distribution linked to the vulnerability of forests dominated by an overstorey of *Eucalyptus regnans*. The model calculated the probability of impact for each 180-$m^2$ grid cell. Industry water use was not included. The water quality BN calculates the likelihood of debris flow events occurring within each catchment |
| (7) Economic impact on private buildings | The Bayes net considered the exposure of address points (a proxy for buildings) to fireline intensity and embers, vulnerability of the building based on current building policy and impact of the replacement rate on building vulnerability over time. The probability of building loss was calculated at a 180-$m^2$ cell resolution. Reconstruction costs for houses and businesses were calculated for each local government area and assigned to each cell. Expected reconstruction costs were calculated for each building |
| (8) Cost of disaster relief | The impact probability estimate from the BN for the private buildings objective was also used for this objective. The costs associated with disaster relief were calculated based on data from the 2009 Black Saturday bushfires. Costs were applied to each building impacted |
| (9) Cost of fire management treatments | Treatment costs were included for planned burning and maintenance of cleared areas adjacent to high-risk townships. Suppression costings were also included in all strategies. This included the base costs of equipping firefighters. In addition, a simple suppression costing model was utilised based on wildfire size. Three types of planned burns were costed based on actual costs incurred when delivering planned burning in the study area. Each burn unit was assigned a category from one of: burning adjacent to townships, labour-intensive landscape burns and less intensive landscape burns |
| (10) Impact on cultural heritage | A fire intensity threshold was identified for each Aboriginal site type, based on literature and expert judgements. A site was considered impacted if the fireline intensity exceeded the site's intensity threshold. The expected number of times each site was impacted by the 10 000 bushfire profiles was then recorded. The total number of sites impacted was summed and extrapolated to cover a 40-year period |
| (11) Community support | A constructed scale was developed to measure community support based on the results of ~1200 responses to the Barwon Otway Planned Burning Social Survey 2016 (Australian Survey Research, unpubl. data). Community support was measured on a scale of 0–100, where 0 is no community support and 100 is full community support |
| (12) Number of towns having lower fire risk | Residual risk is currently used by Victorian fire agencies to measure the effectiveness of fuel management activities in reducing bushfire risk to communities (State of Victoria 2015*b*). Modelled house losses are summed under maximum fuel loads. This state provides a baseline to compare how effective fuel management regimes are in reducing bushfire risk. In this project, we used the bushfire profiles to calculate the effectiveness of each alternative treatment in reducing township bushfire risk |
| (13) Impact on threatened fauna species | This project utilised the single-species analysis approach outlined by J. MacHunter, M. Baker, A. Blackett, T. Gazzard (unpubl. data) with enhancements to include bushfire and planned burn changes. Seven threatened fauna species in the study area have been assigned a relative abundance response score based on the growth stage of the vegetation. This enabled the mean abundance to be calculated for each of the 10 000 complete fire regimes in Year 20 and Year 40. We also calculate the mean abundance at the starting year of the analysis (Year 0). The largest decline over three time periods (0–20, 0–40 and 20–40 years) is recorded in the consequence table |
| (14) Impact on non-threatened fauna species | The same approach used for threatened fauna species was applied to this objective; 88 key fire response fauna species are included in the analysis |
| (15) Human life loss | Life loss was indirectly estimated based on the relationship between building loss and lives lost (Blanchi *et al.* 2012). This approach has several limitations (see section on limitations of our work). Expected building losses were calculated using the private building objective BN (see no. 7 above) |

100 to express alternative treatment performance. Constructed scales are created to understand the direct impacts of alternatives and are commonly developed for objectives that are difficult to quantify.

The constructed scale for community support allowed us to develop a narrative about community support or resistance to potential strategies, where support includes both active (engaged, participating) and passive (without active resistance) support, and resistance includes disgruntlement through to organised active opposition. For example, on the scale of 0–100, a score of 20 equals 'There is likely to be active opposition and no active support' whereas a score of 80 equals 'Active support from key community members and others, might be slight opposition from fringes, which should be overwhelmed by active support'. Once this scale was developed, community support scores were determined through an online survey that asked participants to select one preferred strategy and identify their preferred strategy elements (e.g. low township impact or low fauna impact).

### *Nominate alternatives*

Alternative treatments consisted of spatial and temporal variations of planned burning over a 40-year period (Table 2). For the alternative treatment A1 (status quo) and alternative treatment A2, the existing fire management zones were utilised to guide the location and frequency of planned burning in the landscape. Existing fire management zoning consists of three broad landscape-scale zones (Fig. 2). The zones include the Township Bushfire Management Zone (covering an area ~2 km around high-wildfire-risk townships), Landscape Bushfire Management Zone (located in the broader landscape in areas of higher wildfire risk) and Landscape Ecological Management Zone (located in areas predominately focused on achieving ecological outcomes).

The remaining alternative treatments reflected stakeholder narratives around cause and effect and subsequently deviated from the existing fire-management zoning. For example, stakeholders asked for the development of an alternative treatment that 'minimised burning in the Anglesea Heath', an area known to have high biodiversity values, the underlying stakeholder assumption being that regularly repeated planned burning causes negative outcomes for some environmental values. We subsequently identified burn units within the Anglesea Heath and adjusted the burn schedule to limit burning in the area (alternative treatment A5). We then presented the alternative treatment back to the stakeholder group at a follow-up meeting to confirm we had interpreted the narrative correctly. This also presented an opportunity to add in further details such as frequency and width of burning adjacent to townships in the Anglesea Heath area.

We used mixed-integer programming (MIP) within the *Woodstock* program (Remsoft Inc. 2018) to prepare 40-year planned burning schedules (Fig. 3). The use of MIP allows the preparation of realistic burn schedules that meet an objective subject to many constraints. For example, burn units (integer variable) can be scheduled to minimise fuel loads (objective) in areas close to assets while not being burnt below a specified time-since-fire threshold (constraint). A spatially explicit estimate of likely burn coverage was incorporated into the base burn unit dataset. In total, stakeholders developed 12 alternative treatments.

The scheduling of planned burning to meet ecological needs is guided by two ecological resilience concepts – Tolerable Fire Interval (TFI) and Geometric Mean Abundance (GMA) (Cheal 2010; McCarthy 2012; Di Stefano *et al.* 2013). TFI outlines the minimum or maximum recommended time intervals between successive fire disturbance events at a site for a particular vegetation community. In the present study, we utilise the time intervals for each vegetation type as outlined in Cheal (2010). All alternative treatments except A2 were subject to TFI constraints that aimed to minimise the area burnt below TFI. GMA is a biodiversity index used to describe availability of suitable wildlife habitat (McCarthy 2012). In the present study, we developed optimal growth stage targets that maximised the GMA of key fire-response fauna species, following the approach outlined by J. MacHunter, M. Baker, A. Blackett, T. Gazzard (unpubl. data). Alternative treatments A3, A4, A6 and A7 are designed using optimal growth stage targets that aimed to maximise habitat availability.

The remaining seven alternative treatments had a substantial focus on reducing risk to townships, industry and ecosystems vulnerable to repeated wildfires. Contemporary fuel management design principles (Gibbons *et al.* 2012; Tolhurst *et al.* 2013; Driscoll *et al.* 2016; Furlaud *et al.* 2018) were incorporated into the development of the seven fuel management alternatives, with scheduling aiming to either minimise fuel loads or maximise house loss reduction. Alternative treatments A1, A2 and A5 used set planned burn return intervals adjacent to townships in combination with a landscape MIP objective to maximise the annual reduction in fuel load. Alternative treatments A6–A12 were scheduled to minimise the total house loss score annually. A total house loss score was calculated for each burn unit. House losses were calculated for each fire after it had passed through the burn unit. A total house loss score for each burn unit was calculated by summing the house loss scores for all fires that passed through each burn unit. House losses were calculated based on a logistic regression equation of house loss probability (K. G. Tolhurst, D. M. Chong, T. J. Duff, unpubl. data) that includes flame height, ember density and convective strength as model parameters. The MIP objective was to maximise an annual whole-of-landscape house loss score (sum of all individual burn unit scores).

### *Fire modelling approach to inform estimation of consequences*

We enhanced the Monte Carlo simulation methodology outlined by Mason *et al.* (2011) to create 10 000 annual wildfire profiles using the deterministic fire spread simulator PHOENIX RapidFire (henceforth PHOENIX) (Tolhurst *et al.* 2008).

The enhancements to the methodology included the estimation of travel times for all nearby fire stations and bulldozer contractor depots to each ignition point using travel time surfaces derived from the NAVIGATOR model (Duff *et al.* 2015) and assigning the actual resource type (e.g. bulldozer size, fire tanker size,water bombing helicopter type) from a random subset of nearby fire stations and depots to each ignition location. Resource combinations were varied based on whether the ignition started in grass or forest and based on fire danger rating classes (McArthur 1966). Modelled fire outputs were calibrated

**Table 2. Description of alternative treatments**

The average return periods (years) for undertaking planned burning are outlined for three zones with common intent within the study area – Township Bushfire Management Zone (TBMZ), Landscape Bushfire Management Zone (LBMZ) and Landscape Ecological Management Zone (LEMZ). Average annual area treated refers to total planned area within which ignition will take place. The area burnt varies for each burn unit. The average area burnt can be as low as 20–40% in wetter vegetation types to as high as 70–95% in drier vegetation types. All treatments include some private land and include existing mulched areas adjacent to the highest-risk townships. GMA, Geometric Mean Abundance; TFI, Tolerable Fire Interval

| Name | Average annual area treated (average annual private land burnt) (ha) | TBMZ – average return period (years) | LBMZ – average return period (years) | LEMZ – average return period (years) | Alternative treatment descriptions |
|---|---|---|---|---|---|
| A1 | 8800 (800) | 9 | 8 | 43 | Status quo – risk mitigation for townships and industry. Ecologically focused in the LEMZ |
| A2 | 14 300 (1550) | 6 | 8 | 16 | Risk mitigation for townships and industry – high annual area target. Intensive strategy used to capture the perceived maximum possible risk mitigation for township and industry objectives. Note: this level of planned burning is not achievable under current resourcing |
| A3 | 4100 (600) | 17 | 39 | 43 | Maximises fauna habitat outcomes (GMA optimised). Risk mitigation outcomes for other objectives are limited to more frequent burning within 1 km of higher wildfire risk townships |
| A4 | 6900 (650) | 13 | 17 | 32 | Maximises fauna habitat outcomes (GMA optimised). Risk mitigation outcomes for other objectives are limited to more frequent burning within 1 km of higher wildfire risk townships |
| A5 | 8900 (650) | 10 | 13 | 23 | Risk mitigation for townships and industry and no burning in the core of the Anglesea Heath. Prioritises higher frequency burning in the TBMZ and LBMZ and within water catchments in the LEMZ |
| A6 | 7700 (800) | 11 | 20 | 23 | Balances ecological outcomes as the primary driver, while maximising risk mitigation for townships and industry as a secondary driver. Burns frequently within 2 km of high-risk townships |
| A7 | 7600 (750) | 13 | 17 | 25 | Balances risk mitigation for townships and industry (prioritised) with ecological outcomes. Burns frequently within 2 km of high-risk townships |
| A8 | 7600 (1000) | 11 | 14 | 31 | Risk mitigation for townships focused on highest-risk townships. Burns the highest-risk burn units in each locality, irrespective of town risk status. Attempts to maintain TFI as a secondary constraint |
| A9 | 6600 (1000) | 12 | 16 | 36 | Risk mitigation for townships focused on highest-risk townships – reduced annual treated area. Burns the highest-risk burn units in each locality, irrespective of town risk status. Attempts to maintain TFI |
| A10 | 7400 (1000) | 13 | 14 | 31 | Risk mitigation for townships, focusing on maximising the number of townships to reduce residual risk <60%. Targets the highest-risk burn units in each locality in five predetermined landscape areas. Attempts to maintain TFI |
| A11 | 5600 (900) | 13 | 18 | 44 | Risk mitigation for townships focused on highest risk townships – reduced annual treated area. Burns the highest-risk burn units in each locality, irrespective of town risk status. Attempts to maintain TFI. Same as A9, but burns a smaller area each year. |
| A12 | 4600 (800) | 15 | 58 | 22 | Risk Mitigation for townships focused on highest-risk townships – reduced annual treated area. Burns the highest-risk burn units in each locality, irrespective of town risk status. Attempts to maintain TFI. Same as A9 and A11, but burns a smaller area each year. |

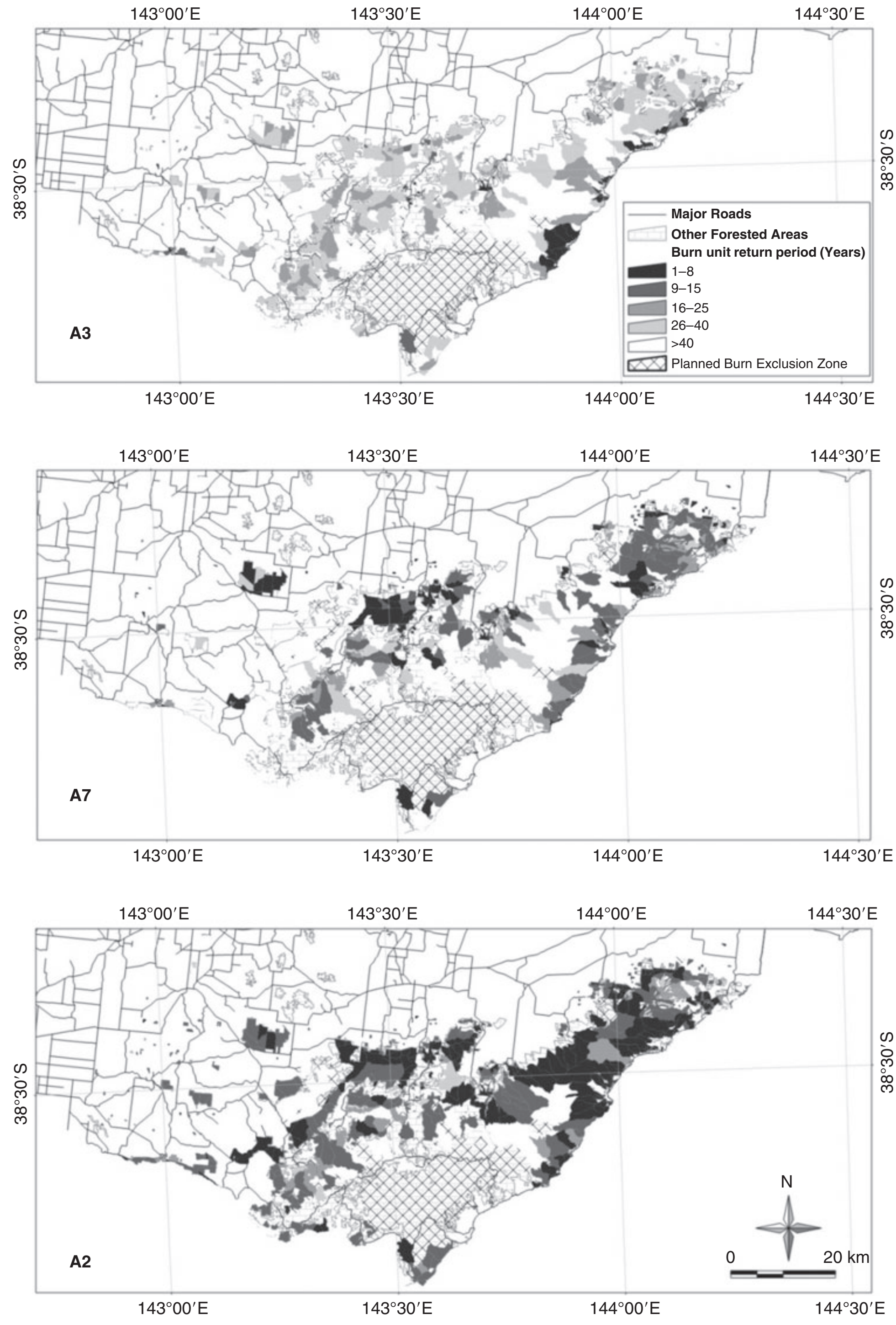


**Fig. 3.** Three alternative treatments showing the average return interval for each burn unit group. A3 represents a lower per annum area strategy with an ecological outcome focus, A7 represents a moderate area strategy that attempts to balance a range of objectives and A2 represents a high area strategy that focuses on community and industry outcomes.

to approximately replicate historical fire size outputs for each fire danger rating – ignition location class (Table 3). Historical fire size outputs were calculated based on datasets maintained by fire agencies within Victoria between 1972 and 2014.

We also added a spatial likelihood weighting to each ignition with ignitions being randomly selected from 19 185 ignition points evenly spaced on a 1 × 1-km grid. Ignition start time was randomly allocated to occur between 1100 and

**Table 3. Percentage variation between historical ignitions and modelled ignition for each fire danger–ignition location–fire size combination**
Combinations with negative numbers indicate that historical ignition numbers were higher than modelled ignition numbers. Positive numbers highlight combinations where the modelled number of ignitions was greater than the historical ignition numbers. For most combinations, modelled fire size outcomes where within 10% of historical fire sizes. Notable exceptions occurred in fire size classes of 0–50 and 3000-ha plus, particularly for ignitions occurring in forested areas

| Fire danger rating (Forest Fire Danger Index range) | Ignition location | Fire size (ha) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0–50 | 50–100 | 100–500 | 500–1000 | 1000–3000 | 3000+ |
| Very high (25–34) | Forest | −19.4 | 0.3 | 5.5 | 5.6 | 6.8 | 1.2 |
| | Grass | −18.2 | 11.4 | 6.2 | −0.4 | 0.7 | −0.3 |
| Very high (35–49) | Forest | −22.5 | 2.2 | 4.1 | 3.9 | 6.1 | 6.3 |
| | Grass | 0.1 | 2.8 | −0.9 | −0.9 | −1.6 | 0.0 |
| Severe (50–74) | Forest | −33.6 | −1.2 | 1.0 | 2.4 | 12.6 | 18.7 |
| | Grass | −4.0 | 7.2 | −4.9 | −0.3 | 1.1 | −0.2 |
| Extreme (75–99) | Forest | −37.8 | 4.6 | −8.9 | 5.2 | 8.4 | 28.6 |
| | Grass | −1.0 | 10.1 | −8.4 | 0.9 | −1.4 | −0.7 |
| Code Red (100+) | Forest | −27.0 | −0.3 | −3.0 | −3.6 | 1.1 | 32.9 |
| | Grass | −4.1 | 10.1 | −1.7 | −3.6 | −1.4 | 0.2 |

1800 hours. Fires were run until 2300 hours to reduce computational run times.

This modelling method limitation (i.e. historical records show some fires continue to spread for significantly longer durations) is offset by the inclusion of a sufficient number of larger fires to approximately match historical fire size outcomes.

Each of the 10 000 annual wildfire profiles was intersected with each of the candidate planned burn strategies at Year 20 and Year 40 to create 20 000 complete fire regimes for each alternative treatment. All PHOENIX simulations produced $180 \times 180$-m cell outputs (Tolhurst *et al.* 2008; State of Victoria 2015*b*).

### Estimate the consequences of each candidate alternative against each objective

For each alternative treatment, we estimated consequences against each objective. Methodologies are briefly outlined in Table 1. Detailed descriptions of the methodologies are provided in Deloitte Access Economics (unpubl. data) and T. Walshe, T. Gazzard, P. Galvin, M. Baker, B. Cross (unpubl. data).

### Articulate trade-offs

Our approach used two complementary methods to identify preferred alternative treatments with each stakeholder group. The first method appeals to fast and frugal System 1 thinking (Kahneman 2011; Gregory *et al.* 2012). Individual stakeholders simply ranked each of the alternatives in order of perceived merit on the basis of the information contained in the consequence table (Table 4). Direct ranking of complex problems involving multiple objectives and multiple trade-offs can be challenging (Hawkins 1994; Luce *et al.* 1999). So before undertaking the ranking exercise, we sought to simplify the consequence table by removing any of the alternatives that were dominated (i.e. had equal or lesser performance on all attributes then another alternative) (Driscoll *et al.* 2016). We likewise explored with the stakeholder groups whether any objectives were redundant because of limited variation across the alternatives.

The second method involves slow and deliberate System 2 thinking. As a basis for comparative insight, we employed a weighting method using an additive MCDA value model (von Winterfeldt and Edwards 1986; Bedford and Cooke 2001; Keeney 2007) to encourage a more detailed evaluation of trade-offs. More explicitly, to account for the range of consequences under each objective in the MCDA, we elicited compensatory weights from each stakeholder (von Winterfeldt and Edwards 1986), such that weights reflected the magnitude of gain on one objective that would be required to compensate a loss on another objective. Decision scores for each participant and each alternative were obtained, where the decision score $V$ for alternative $i$ is

$$V_i = \sum_{j=1}^{n} W_j X_{ij}$$

where $w_j$ = weight for criterion $j$, $n$ = number of criteria and $X_{ij}$ = normalised score for alternative $i$ on criterion $j$.

### Human life loss sensitivity analysis

Taboo trade-offs are those involving a sacred value and a secular value (Tetlock *et al.* 2000). In our study, the trade-off between human life (a sacred value) and monetary loss (a secular value) meets the definition of a taboo trade-off. Taboo trade-offs have been demonstrated to leave the decision maker feeling compromised (Baron and Spranca 1997; Tetlock 2003) and decision makers tend to avoid the internal conflict they incite. A common avoidance strategy is to resist a considered response to the question of willingness to pay and instead provide loose judgments that deny the realities of constrained resources (Tetlock 2000). We tested the sensitivity of preferred alternatives to weights assigned to human life.

For any individual participant, the weights assigned to monetary consequences and human life can be used to calculate an implied value for a single statistical life. For example, if the range for loss of life across alternatives was 100 lives, the range for monetary losses was AU$100 million, and the magnitude of the weight assigned to life was twice that assigned to monetary

**Table 4. Consequence table presented to the land-management group outlining the performance of each alternative for each objective**

Arrows represent whether more (▲) or less (▼) is better for each objective. All results represent outcomes for a 40-year period. The majority of the results reflect probability-adjusted estimates of consequences (i.e. expected consequences). The objectives of community support and the number of towns having lower fire risk are the exceptions. A1 represented the existing strategy (status quo). Light grey shading represents a 10% worse performance than the status quo (A1). Darker grey shading represents a 10% improvement over the status quo. Stakeholders were not presented with A13 in the trade-off workshop. A13 was developed based on stakeholder preferences to capture additional operational and delivery design considerations and is the currently endorsed fire management strategy for the Barwon Otway area

| Objective | Performance measure (preferred direction) | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | **A13** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Economic impact on agriculture | Millions of $ (▼) | 163 | 141 | 187 | 173 | 170 | 164 | 161 | 171 | 176 | 166 | 182 | 192 | 165 |
| Economic impact on plantations | Millions of $ (▼) | 47 | 37 | 58 | 46 | 44 | 46 | 47 | 47 | 51 | 45 | 56 | 60 | 47 |
| Economic impact on tourism | Millions of $ (▼) | 134 | 115 | 165 | 148 | 147 | 137 | 131 | 131 | 138 | 130 | 146 | 153 | 137 |
| Economic impact on viticulture | Millions of $ (▼) | 0.81 | 0.77 | 0.85 | 0.83 | 0.86 | 0.82 | 0.76 | 0.77 | 0.81 | 0.75 | 0.83 | 0.84 | 0.83 |
| Economic impact on private buildings | Millions of $ (▼) | 136 | 120 | 206 | 184 | 182 | 117 | 125 | 119 | 130 | 128 | 138 | 149 | 124 |
| Cost of disaster relief | Millions of $ (▼) | 55 | 49 | 83 | 74 | 73 | 48 | 51 | 49 | 53 | 52 | 56 | 61 | 50 |
| Economic impact on water provision | Millions of $ (▼) | 0.38 | 0.35 | 0.43 | 0.38 | 0.36 | 0.37 | 0.37 | 0.38 | 0.39 | 0.39 | 0.42 | 0.43 | 0.38 |
| Economic impact on public property | Millions of $ (▼) | 34 | 28 | 52 | 42 | 43 | 32 | 30 | 31 | 34 | 32 | 38 | 42 | 33 |
| Cost of fire management treatments | Millions of $ (▼) | 2382 | 2533 | 2264 | 2308 | 2379 | 2348 | 2318 | 2358 | 2327 | 2344 | 2301 | 2276 | 2344 |
| Community support | Constructed scale: 0 = worst, 100 = best (▲) | 77 | 57 | 39 | 66 | 64 | 82 | 82 | 77 | 79 | 79 | 79 | 69 | 83 |
| Impact on cultural heritage | Number of sites adversely impacted (▼) | 56 | 43 | 74 | 75 | 83 | 56 | 50 | 43 | 46 | 42 | 48 | 51 | 52 |
| Impact on threatened fauna species | Number of species with a 20% or greater decline (▼) | 4 | 5 | 1 | 3 | 4 | 1 | 3 | 5 | 5 | 5 | 5 | 5 | 2 |
| Impact on non-threatened fauna species | Number of species with a 20% or greater decline (▼) | 8 | 23 | 1 | 1 | 5 | 1 | 1 | 7 | 4 | 5 | 3 | 1 | 1 |
| Impact on human life | Number of lives lost over 40 years (▼) | 50 | 42 | 82 | 71 | 70 | 41 | 45 | 42 | 48 | 46 | 52 | 57 | 44 |
| Number of towns having lower fire risk | Number of towns below an average of 60% residual risk (▲) | 15 | 17 | 4 | 8 | 9 | 14 | 17 | 14 | 12 | 15 | 12 | 10 | 17 |

loss, we can say that the implied value of a statistical life is AU\$2 million.

A meta-analysis of Australian studies that estimated the monetary value of a statistical life yielded an average AU\$6.0 million in 2006 dollars (Australian Safety and Compensation Council 2008). Acknowledging the considerable variation encountered, the authors of the meta-analysis suggest a range for sensitivity analyses of AU\$3.7 million to AU\$8.1 million.

We conducted a sensitivity analysis whereby the weights for each stakeholder were manipulated by adjusting the implied equivalent of a statistical life to AU\$3.7 million (lower bound), AU\$6 million (best estimate) and AU\$8.1 million (upper bound) (Australian Safety and Compensation Council 2008).

## Results

### *Direct ranking approach*

When all 15 objectives were included, the only dominated alternative was A1, which was dominated by A7. That is, A7 outperformed A1 on all objectives; however, the differences were very small for many of the objectives. To account for uncertainty in the modelling outcomes, a more common approach is to compare alternatives that differ by ±10% (Driscoll *et al.* 2016). When using this approach, all alternatives were non-dominated on at least one objective and were subsequently retained in the consequence table.

The range of deviation for viticulture and water provision objectives across the range of alternatives was within AU\$100 000. In comparison with the other monetary objectives, the economic impact was small, with expected losses of less than AU\$1 million. Nevertheless, the viticulture and water provision objectives were retained in analysis to capture the complete set of impacts.

The direct ranking approach showed strong support from most stakeholders for A6 and A7 and moderate support for A8 and A9 (Fig. 4). Most stakeholders ranked A2, A3 and A5 as the least-preferred alternative treatments.

### *Simple weighted summation approach*

Examples of decision scores for two participants are shown in Fig. 5. Despite considerable differences in emphases

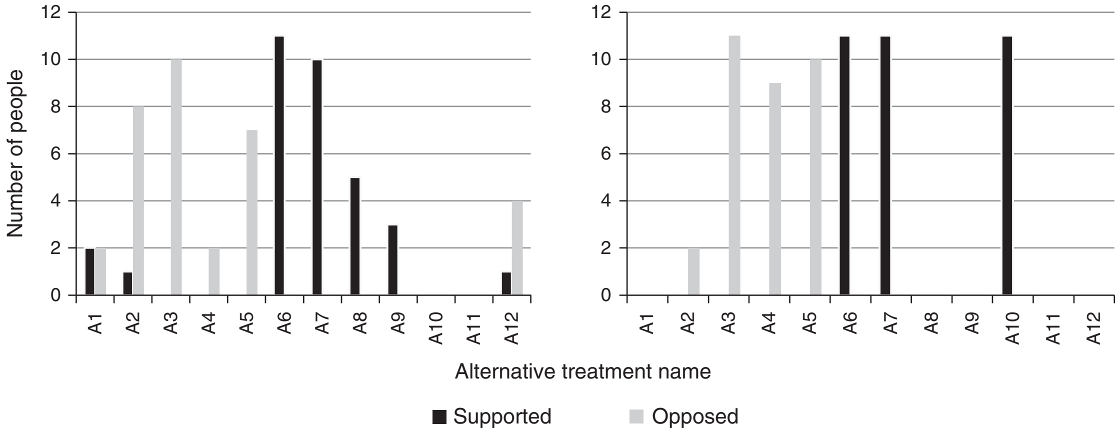


**Fig. 4.** Stakeholder preferences for alternative treatments using a direct ranking approach (left), and simple weighted summation approach (right). For any single participant, an alternative was considered 'supported' if it ranked in the top three and 'opposed' if it ranked in the bottom three. The total number of stakeholders involved in the trade-off analysis was 11.

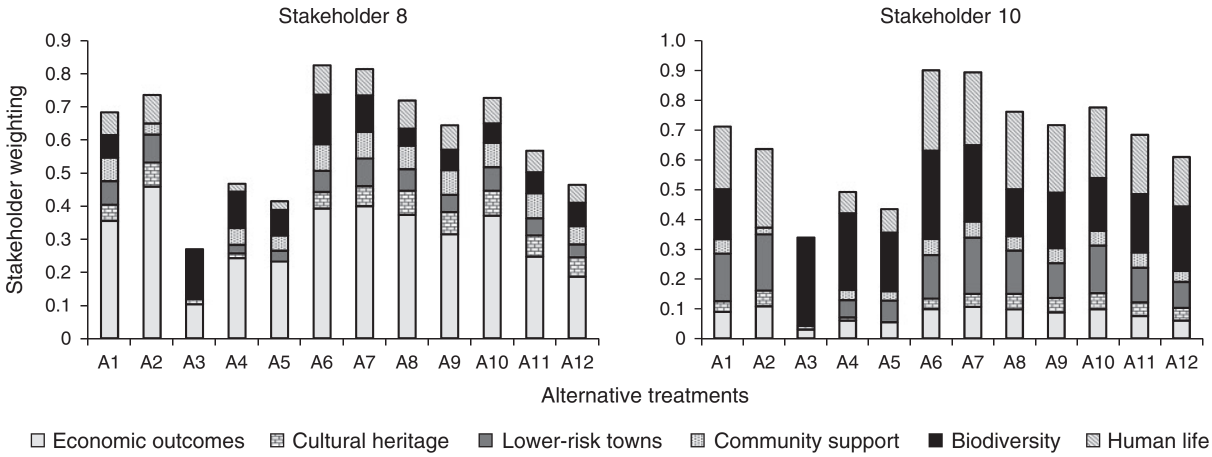


**Fig. 5.** Decision scores from the simple weighted summation method for two participants. Stakeholder 8 weighted monetary outcomes highly whereas stakeholder 10 emphasised a preference for human life and biodiversity outcomes. Despite the differences in emphasis between stakeholders, A6 and A7 were preferred by both stakeholders.

across objectives, both participants rated alternatives A6 and A7 highly.

The collective outcome of the simple weighted summation approach across all 11 participants is shown in Fig. 4. The support for A6 and A7 illustrated in Fig. 5 for two participants is broadly evident in the trade-off judgments of the full stakeholder group. A6 was the top-ranking alternative for eight participants and A7 the best for three participants. A10 was also well supported. The minimalist fuel reduction burning strategy A3 performed worst. A4 and A5 were also judged poorly.

Objectives with the greatest influence on outcomes are those associated with both high variability and high weights. Table 5 collates objective-specific variability in consequences across all alternatives, together with summary statistics on how each objective was weighted. In general, stakeholders assigned high weights to human life and biodiversity. A3 was the worst alternative for human life and A2 performed weakly on biodiversity (Table 4).

### *Human life loss sensitivity analysis*

The average implied monetary equivalent of a statistical life for all stakeholders was AU$2.34 million (range of between AU$0.27 and AU$6.48 million). This is less than half the best estimate of the Australian Safety and Compensation Council (2008) of AU$6 million. The sensitivity analysis showed that A8 would become increasingly supported had participants placed less emphasis on monetary losses and more on human life, all else being equal, whereas support for A10 is eroded at higher valuations. Alternative treatments A6 and A7 remain strongly supported irrespective of the mean value assigned to a statistical life.

### *Selection of a preferred strategy based on stakeholder preferences*

The most supported strategies identified an acceptable performance goal for each objective (Table 4). This enabled the

**Table 5. Variability in raw consequences across all alternatives**

To enable a comparison across multiple units (e.g. dollars, human lives lost, number of species declining), the coefficient of variation, mean weight and weight range were calculated. Objectives with higher weights and a higher coefficient of variation score have the most influence on which alternative treatments will be preferred

| Objective | Coefficient of variation (%) | Mean weight | Weight range |
|---|---|---|---|
| Economic impact on agriculture | 8 | 0.03 | 0.01–0.09 |
| Economic impact on plantations | 13 | 0.01 | 0.00–0.03 |
| Economic impact on tourism | 9 | 0.03 | 0.01–0.06 |
| Economic impact on viticulture | 4 | 0.01 | 0.00–0.04 |
| Economic impact on private buildings | 21 | 0.03 | 0.00–0.08 |
| Cost of disaster relief | 20 | 0.03 | 0.00–0.10 |
| Economic impact on water provision | 7 | 0.01 | 0.00–0.05 |
| Economic impact on public property | 19 | 0.05 | 0.00–0.11 |
| Cost of fire management treatments | 3 | 0.08 | 0.00–0.16 |
| Community support | 18 | 0.07 | 0.01–0.16 |
| Impact on cultural heritage | 25 | 0.06 | 0.01–0.14 |
| Impact on fauna species currently listed as threatened | 40 | 0.12 | 0.05–0.18 |
| Impact on fauna species currently not listed as threatened | 124 | 0.16 | 0.07–0.22 |
| Impact on human life | 25 | 0.17 | 0.09–0.27 |
| Number of towns having lower fire risk | 32 | 0.13 | 0.05–0.20 |

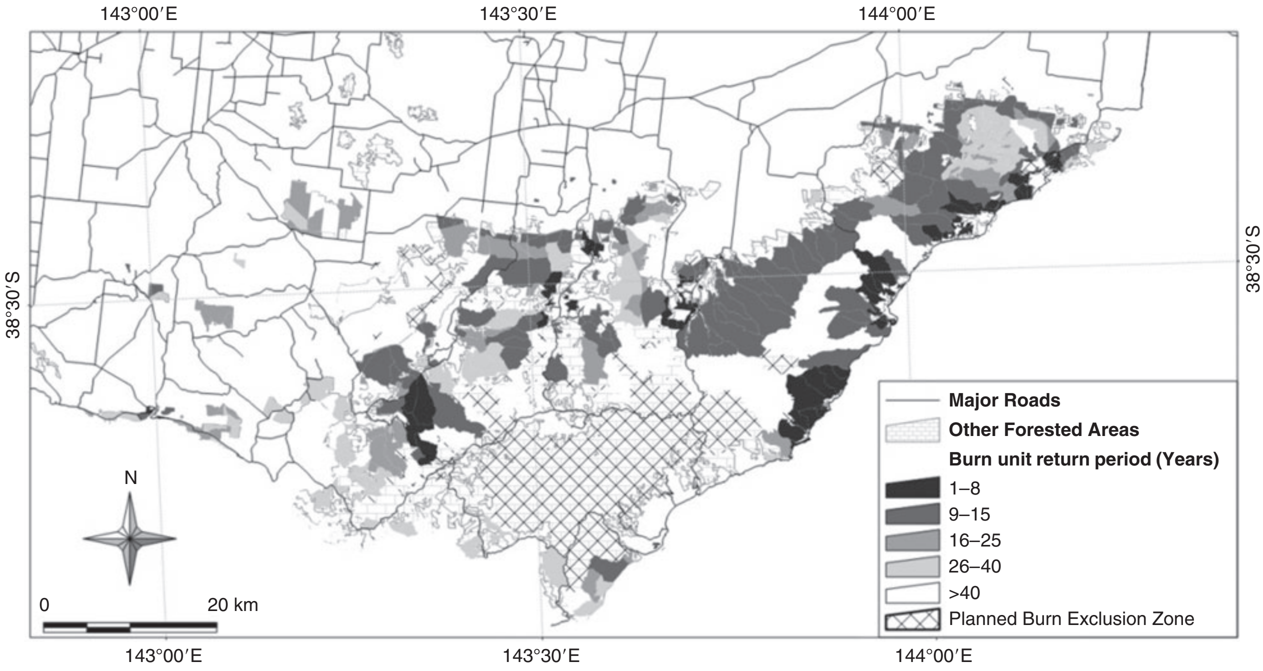


**Fig. 6.** Endorsed fuel management strategy. Map shows variation in return periods for the Otway Ranges. Darker areas represent frequent burning and lighter areas less frequent burning.

creation of an additional set of alternatives treatments that incorporated design elements from the three most supported strategies, A6, A7 and A10, that aided operational delivery. From this additional set of alternatives, one strategy was selected for implementation (Fig. 6). The selected strategy focused on burning every 5–8 years within 2 km of high-risk townships and burning every 10–13 years in strategic locations on the northern side of the Otway Ranges to mitigate wildfire impacts. Several areas in the landscape were identified to have no planned burning or infrequent planned burning (1–2 times within the 40-year period) to enable ecological goals to be achieved. The selected strategy placed importance on risk mitigation to many towns (not just the highest-risk towns), vulnerable ecosystems and local industry while maintaining good habitat outcomes for most fauna species. This combination of outcomes had strong community support.

## Discussion

We used a SDM approach to enable local land managers to select preferred alternative fuel management treatments that combined estimated consequences and articulation of value preferences. Psychologists distinguish between System 1 and System 2 reasoning (Stanovich and West 2000; Kahneman 2011). System 1 is the rapid processing of information using raw intuition. System 2 is slower, more deliberate and considered (Kahneman 2011). Although contrasts in outcomes between System 1 and System 2 can lead to important insights (Hawkins 1994; Fischer *et al.* 1999; Lichtenstein *et al.* 2007), consistency across the two modalities provides confidence in decision-making. The majority of participants had a strong correlation between System 1 and System 2 thinking (Fig. 4) and we could infer from this that A6, A7 and A10 as the best alternatives are a robust outcome. Further support for A6, A7 and A10 was gained through the preferred alternative treatments continuing to be selected in the sensitivity analysis of human life loss.

### *Making trade-offs using explicit estimation of lives lost*

Life loss is often cited as the most impactful consequence of wildfires (Fernandes and Botelho 2003; Thompson *et al.* 2017) and minimising life loss to civilians and firefighters is consistently identified as a priority objective in wildfire management (USDA and USDI 2014; Emergency Management Victoria 2016). This emphasis was also highlighted in the results of our study with the human life objective given the highest weighting by a majority of the participants in both stakeholder groups. Given the high value placed on human life, it is surprising that greater emphasis has not been placed on directly predicting life loss outcomes for alternative treatment options. This is particularly striking given the prevalence of life loss as a performance measure in fields such as medicine (Andersson *et al.* 2013; Yang *et al.* 2014; World Health Organization 2014; Lêng *et al.* 2016) and for many natural hazard types such as floods, dam safety risk, tropical cyclones, storm surge and tsunamis (see Smith and Rahman 2016 for a summary of natural hazard life loss methods). This reticence may stem from a lack of hazard specific agent-based models, or sensitivity of governing bodies to the reporting of life loss, and the taboo trade-offs such reporting invokes. Despite difficulties with taboo trade-offs, based on the stakeholder results, stakeholder feedback (RMCG, unpubl. data) and our observations, the use of life loss as a performance measure is to be encouraged when utilised in SDM processes.

### *Estimation of consequences related to fundamental objectives*

In the last two decades, many studies have analysed the effectiveness of fuel management activities and either reported on means based objectives or used proxy measures to represent fundamental outcomes. Examples include area burnt by wildfire (Bentley and Penman 2017; Furlaud *et al.* 2018), likelihood of fire reaching the interface (Ager *et al.* 2010; Price *et al.* 2015*a*), reduced probability of home exposure or habitat to wildfire (Bentley and Penman 2017), proportion of area below or above TFI (McCarthy *et al.* 2001; Penman *et al.* 2011*a*), growth stage structure (GSS) and GMA (Di Stefano *et al.* 2013; Kelly *et al.* 2015).

Measures related to means-based objectives or proxy measures such as TFI, GMA and GSS aid in the design of landscape fuel management strategies and have proved useful to land managers in south-eastern Australia as has been demonstrated in this study. However, results of all three measures have subsequently proved difficult to communicate to internal and external stakeholders and to provide a meaningful measure to evaluate trade-offs. For example, it can be difficult for stakeholders to comprehend what a 10-point GMA variation between alternatives signifies for native species populations. Similarly, a 10% reduction in the wildfire size is open to stakeholder interpretation when considering outcomes to multiple values.

In contrast, we set out to estimate consequences using natural measures linked to fundamental objectives. Where possible, we aimed to use existing datasets and methods. As noted by Thompson *et al.* (2017), fundamental objectives often do not have well-developed methodologies to enable the calculation of natural performance measures, with some notable exceptions such as house loss estimation (Tolhurst *et al.* 2013; State of Victoria 2015*b*). Subsequently, the estimation of consequences proved to be a substantial task and many of the models used were by necessity fairly simple.

The use of natural measures also assists in identifying stakeholder values that may be less sensitive to strategy design differences or where the magnitude of impact is quite small. For example, in our study, stakeholder preferences (Table 5) showed that the viticulture and water provision objectives had the least influence on the selection of strategies and could have been excluded in the first step of the trade-off process. Although these objectives had the least influence on the selection of the preferred strategy, the inclusion of these objectives in the consequence table ensures that all stakeholders have a common understanding of which values are more influential in the selection of preferred strategies. This level of transparency also has been invaluable when communicating to stakeholders not involved in the study *why* the selected strategy was the preferred option.

### *Strategy design*

The magnitude of reduction in wildfire extent through use of planned burning has been described as leverage (Loehle 2004; Price *et al.* 2015*b*) and typically follows a non-linear decay relationship that suggests that as planned burning levels increase, the level of effectiveness decreases (King *et al.* 2008; Boer *et al.* 2009; Price 2012). A similar relationship existed for the agriculture and plantation objectives in our study.

In comparison, for objectives that benefited from optimised outcomes created using the MIP solver such as fixed private capital assets, life loss, township risk reduction and fauna decline, there was significant deviation away from a non-linear decay relationship, indicating that the effectiveness of planned burning is increased with the strategic placement of planned burns.

Consistent with the findings of other studies (Bradstock and Price 2010; Penman *et al.* 2014; Ager *et al.* 2016; Bentley and Penman 2017), the highest leverage was gained from frequent burning directly adjacent to the values of interest. However, our results also showed that outcomes can be further enhanced by the inclusion of burning in high-wildfire-risk pathways and increasing the depth of burning close to assets. This is reflected in the differences between alternative treatments A3 and A12.

### *Outcomes for fauna species*

Predominately, the selected strategy offered an improvement for most objectives over the status quo – particularly in relation to fauna and human life outcomes, which were the two highest-weighted objectives in our study. Although fauna outcomes improved for most species, several species were forecast to decline locally under the selected strategy. These species have a known habitat preference for older vegetation (Wilson *et al.* 2001*a*; 2001*b*) and occur in the study area where frequent planned burning is scheduled to minimise the bushfire risk to nearby townships. This highlights that additional operational scheduling considerations may be required in several areas that have been prioritised for community risk reduction outcomes. Operational controls could include reducing planned burn coverage and minimising treatment during times when species may be more sensitive to disturbance, such as during drought conditions or during the primary breeding season.

### *Limitations of our work*

We used a Monte Carlo simulation approach to examine a large number of combinations of inputs and associated outcomes. However, we acknowledge that further testing of model input sensitivity would be valuable. For instance, it is known that outcomes in the PHOENIX model are particularly sensitive to ignition location and further work should investigate whether a finer ignition grid size would significantly modify modelled outcomes. Other input areas requiring further sensitivity testing include ignition time and suppression travel times.

We were limited in this study to utilising existing datasets and drew on published methodologies for calculation of estimated consequences where they existed. However, many of the models are still in their infancy and there are many data gaps that limit the strength of some of the modelling methodologies. In particular, the indirect estimation of life loss has several limitations. Specifically, the assumption of a ratio of 16.5 : 1 for house loss and life loss is calculated based on losses recorded across Australia between 1901 and 2011 (Blanchi *et al.* 2012). This may not capture local landscape wildfire risks associated with peak tourism along the Great Ocean Road coinciding with peak fire danger periods or represent recent operational policy changes associated with stronger emphasis on leaving early and human survival. Also, no account has been made of post-trauma suicide and other non-fatal impacts.

### *Future studies*

As shown by our study, the use of the SDM framework provides a solid basis on which to structure complex decisions related to fire management. We would encourage additional focus on the development of forecasting methodologies that report on natural measures connected to fundamental objectives. This will greatly aid decision makers and significantly improve the communication of outcomes.

Also, although the fire modelling approach was robust, ideally, we would create complete fire histories for each year. That is, create thousands of combinations of bushfire and planned burning for all 40 years of the analysis period. Further automation of this type of process would be particularly useful to land managers.

## Conclusions

The consideration of a broad range of alternative treatment designs promotes understanding of the magnitude of leverage that planned burning can deliver over time. Further, this ensures our assumptions and narratives of what is possible are challenged and tested. From this study, we have identified that reasonable outcomes are possible through strategically focused burning of 4000–5000 ha per annum for a subset of values (e.g. high-risk townships, life, tourism, non-threatened fauna). To obtain good outcomes for the majority of values, planned burning needs to treat 7000–8000 ha per annum. Above this amount, there are diminishing returns on investment for most objectives.

This exploration of alternative treatments has also provided local land managers with insights into the limitations of planned burning to reduce bushfire risk. For example, even under an aggressive planned burn regime (A2), risk to human life still remained. As suggested by others (Bentley and Penman 2017; Furlaud *et al.* 2018; Penman *et al.* 2019), fuel management actions will need to be combined with other treatment types to further lower bushfire risk.

The SDM framework advances the possibility of realising the difficult but important objectives of fire management planning. The framework has provided a rare opportunity for combining community and organisational values with credible predictive science to inform sound policy, improve fire management decision making and grow community resilience and regional relationships.

Utilising a logical framework such as SDM guides investment effort and data collection and assists in the identification of suitable performance measures at the start of the decision-making process. The focus on deliberation in the process is a significant strength of this framework and gives stakeholders ownership of the outcomes. The SDM framework enables the stakeholder group to communicate *why* we apply fire in the way we do, which is partially facilitated through an emphasis on natural measures.

The selected strategy has subsequently been endorsed by the State of Victoria as the updated fuel management strategy for the Barwon Otway Landscape. The endorsed strategy ultimately provides a hypothesis or narrative that can be tested though monitoring over time. This project has demonstrated that an SDM approach can be successfully applied to fire management.

## Conflict of interest

The authors declare no conflicts of interest.

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