Journal of Applied Ecology

*Journal of Applied Ecology* 2017, **54,** 1699–1709 doi: 10.1111/1365-2664.12920

# Optimising the spatial planning of prescribed burns to achieve multiple objectives in a fire-dependent ecosystem

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## Summary

**1.** There is potential for negative consequences for the ecological integrity of fire-dependent ecosystems as a result of inappropriate fire regimes. This can occur when asset (property) protection is prioritised over conservation objectives in burn programs.

**2.** Optimisation of fire management for multiple objectives is rarely undertaken. Here, we use integer linear programming to identify burn scheduling solutions that will cost-effectively achieve asset protection and conservation objectives.

**3.** An approach to burn scheduling that favours a risk-averse asset protection strategy results in poor conservation outcomes. Conversely, a conservation-focused approach achieves only modest asset protection benefits. However, when formulated as a multi-objective problem, good conservation outcomes can be realised with only a small reduction in potential benefits for asset protection.

**4.** A conservation-focused approach resulted in substantially more heterogeneity in burns at multiple spatial scales and a marked reduction in mean time since fire among all forest patches relative to an asset protection scenario. This increase in heterogeneity improves ecological integrity, while the resulting reduction in fuel load is beneficial for asset protection.

**5.** *Synthesis and applications.* Mathematical optimisation is a powerful framework for informing fire management that improves the prioritisation and scheduling of controlled burns to efficiently achieve management objectives. By quantifying the trade-offs that exist between the two competing objectives of conservation and asset protection, we demonstrate that compromise solutions can be identified that achieve good outcomes for both objectives. In a transparent and equitable manner, we show that conservation value may be improved within a fire-dependent ecosystem with only modest concession to asset protection performance. Explicitly evaluating trade-offs among competing objectives enables managers to identify potentially undesirable outcomes, and facilitate development of preferred solutions. Heterogeneous burning under the auspices of conservation also has the potential to reduce overall fuel loads within the ecosystem and thus its value for asset protection is likely underappreciated.

**Key-words:** conservation management, decision support tool, fire-dependent ecosystem, heterogeneity, integer linear programming, objectives, optimisation, recommended fire regime, trade-offs

## Introduction

There are often multiple objectives that motivate environmental management. Usually, objectives are at least partially conflicting, implying that it is not possible to maximise returns on all objectives simultaneously. However, rather than explicitly evaluate trade-offs among objectives to identify optimal solutions, managers sometimes either focus on high profile or high priority single objectives, or use simple *ad hoc* or heuristic approaches to simplify these complex problems (McDaniels, Gregory & Fields 1999; Kiker *et al*. 2005). The danger of such strategies is that management may be inefficient in that they

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achieve poor outcomes for other objectives when, in fact, there may be opportunities to achieve multiple objectives simultaneously (Maguire & Albright 2005).

Fire management decisions are complex problems as they involve uncertainty and multiple or conflicting objectives. Fire management has important consequences for the risk of catastrophic loss of life and property, which can result in risk-aversion and systematic biases that can lead to fire exclusion from fire-dependent ecosystems in some areas (potentially increasing fuel load) and too frequent burning in designated asset protection areas (potentially leading to local extinctions and compromised ecosystem health) (Driscoll *et al*. 2010a). A systematic decision-making framework can allow land managers to better explore different management options, overcome these psychological barriers and ultimately improve the quality of decisions (Richards, Possingham & Tizard 1999).

Appropriate fire regimes are essential for facilitating regeneration of fire-dependent species and maintaining critical habitats for many species of flora and fauna (Gosper, Yates & Prober 2013). Fire can also have negative consequences for people, causing damage to built assets and impacting on valued ecosystem services such as air quality and long-term carbon storage (Moritz *et al*. 2014). Thus, within the same landscape, asset protection and conservation are two important and potentially conflicting motivations for fire management (Driscoll *et al*. 2010a). Globally, conservation of fire-dependent forested ecosystems remains a major challenge due to altered fire regimes and encroachment of urbanisation into forested landscapes (Driscoll *et al*. 2010b). Fire management practices and policy are often driven by asset protection, at the expense of conservation objectives (Dellasala *et al*. 2004). In heavily urbanised landscapes, fire exclusion is the most common outcome when protection of human assets is prioritised in burn programs (Watson 2001). From a conservation perspective, fire exclusion is recognised as a key threatening process that increases the chance of localised extinctions and vegetation transition through replacement of fire-dependent species assemblages with those that are fire-sensitive (Baker & Catterall 2015).

Dry sclerophyll forests of south-eastern Australia are regarded as some of the most fire-prone forest habitats in the world (Penman *et al*. 2007), supporting high fuel loads (Price & Bradstock 2010). In this ecosystem, departure from appropriate fire regimes has the potential to alter the ecosystem state and threaten taxa that are dependent upon minimum return intervals of fire for persistence (Parsons & Gosper 2011). Additionally, property protection is a key fire management objective in south-eastern Australia due to the high population density (Tran & Wild 2000) and justification of funding for fire management is predominately driven by asset protection objectives with ecological outcomes a secondary consideration (Dellasala *et al*. 2004).

The City of Gold Coast is situated in south-east Queensland, subtropical eastern Australia (Fig. 1a), and is one of the most biodiverse areas in Australia (Caddick & Ford 2010). However rapid population growth, climate change and urbanisation are placing pressure on natural ecosystems (Caddick & Ford 2010). The Local Government Authority manages approximately 800 conservation parks, with a combined area of 12 555 ha that vary in

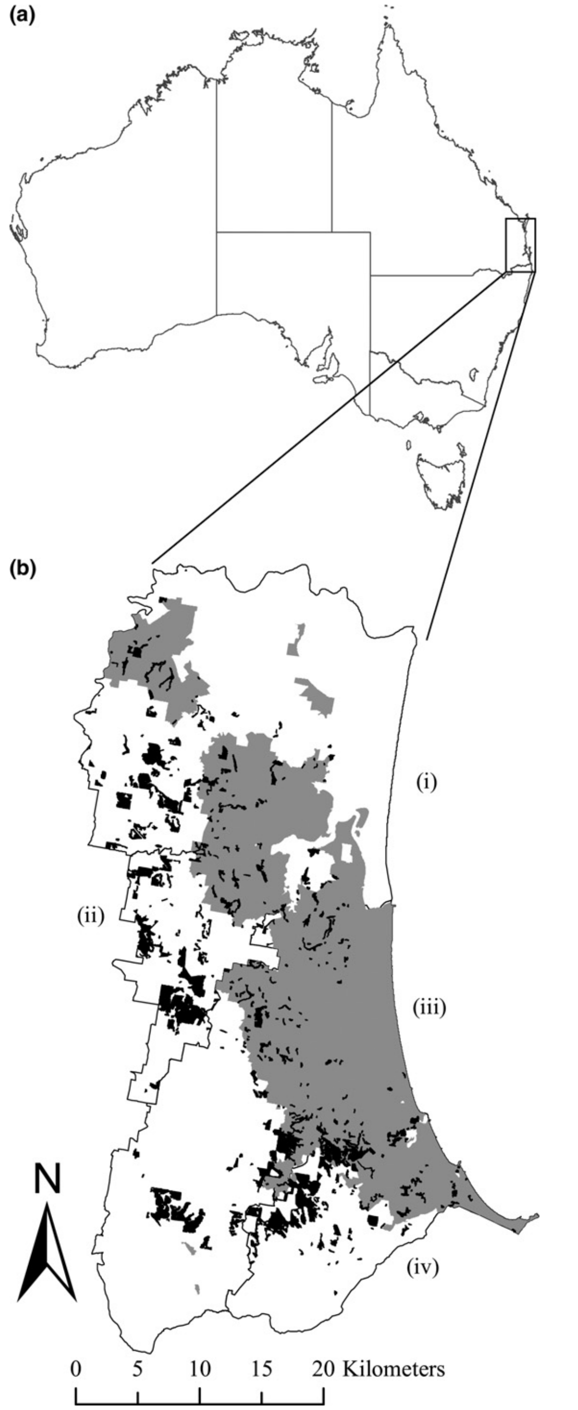



**Fig. 1.** (a) The City of Gold Coast, south-east Queensland, Australia. (b) The distribution of planning units representing patches of dry sclerophyll forest (black) and urban areas (grey). The study area City of Gold Coast divided into four geographically relevant management zones (i–iv).

size and proximity to urban areas. Dry sclerophyll forest comprises approximately 85% of the current vegetation cover within the conservation estate and is an important fire-dependent habitat to many endemic flora and fauna species (Keith 2004). The City of Gold Coast, engages The Queensland Fire and Emergency Service, to undertake hazard reduction burns in areas adjoining residential properties and in close proximity to other infrastructure to minimise bushfire risk.

Here, we develop a decision support tool that identifies spatial fire management solutions that balance the objectives of asset protection and conservation while remaining within budget constraints. We apply this approach to the dry sclerophyll forest ecosystem in The City of Gold Coast. We investigate the conservation implications of an approach to fire management that prioritises asset protection objectives in a fire-dependent ecosystem. We contrast this with compromise solutions that reflect different balances between asset protection and conservation objectives. By quantifying the trade-off between asset protection and conservation objectives, we evaluate to what extent it is possible to achieve both objectives simultaneously.

## Materials and methods

### PLANNING UNITS

We identified all patches of dry sclerophyll forests (see Table S1, Supporting Information) from digital regional ecosystem maps (Neldner *et al.* 2012). Patches smaller than 0·45 ha (the smallest previously recorded prescribed burn) were excluded from the analysis. Patches larger than 55 ha (the average size of prescribed burns over the last decade) were manually subdivided into smaller patches using a combination of pre-existing fire access trails and natural landscape features (e.g. rivers). This resulted in 726 planning units covering 5977 ha (Fig. 1b) where fire management might be applied.

For each planning unit, we determined the number of years since the previous burn ('time since fire'), the surrounding residential population density, and average slope. Consultation with land managers indicated that these were the factors most likely to influence prescribed burn activities.

#### *Time since fire*

We used historical fire event data collated by The City of Gold Coast to estimate time since fire (years), including planned (prescribed) as well as unplanned (wildfire) fire events. Event data spanned 1964–2015 and was compiled from multiple sources. Early records consisted of both field-based GPS capture and manual fire scar mapping based on expert knowledge. Post 2000, fire scar mapping was derived from Landsat satellite imagery (Queensland Government 2015c), and is expected to be more spatially accurate and comprehensive (Price & Bradstock 2010). We used time since fire as a proximate measure of fuel load (Gilroy & Tran 2009) and likely successional state of vegetation (Richards, Possingham & Tizard 1999). Planning units were classified into time since fire classes representing regionally appropriate recommended fire return intervals for the dominant regional ecosystems included as dry sclerophyll forest (Queensland Herbarium 2014; Queensland Government 2015b). Fire classes were: early successional (burnt within 0–8 years), late successional (burnt between 8 and 25 years) and transitional (25+ years). These broadly correspond with: supporting a grassy understorey, a shrubby understorey and a transitioning ecosystem (Baker & Catterall 2015; Queensland Government 2015a,b). For the purpose of this analysis, we assume all regional ecosystems conform to these fire classes though we acknowledge that in practice recommended burn regimes vary among the selected regional ecosystems (see Table S1). Only the most recent fire event for each planning unit was considered to affect current vegetation state and we assume that burnt sites revert to an early successional state regardless of their successional state immediately prior to fire (Richards, Possingham & Tizard 1999). Planning units with no recorded fire history were allocated an initial time since fire age of 40 years (greater than the oldest recorded burn of 38 years).

#### *Residential population density*

Spatial data on residential population density information (see Fig. S1) were derived from 'Risk Evaluation and Disaster Information Portal', an online interactive hazard-mapping tool designed for land managers to support hazard mitigation decisions (Queensland Fire and Emergency Services 2016b). The data comprise census records allocated to residential buildings, which provide a measure of relative human population density (Queensland Fire and Emergency Services 2016a). Fuel treatments undertaken within 500 m of residential properties provide asset protection benefits (Gibbons *et al.* 2012; Penman, Bradstock & Price 2014). We therefore use the sum of residential density values within a 500 m buffer of each planning unit as a measure of the asset protection value associated with burning that planning unit. Planning units with a residential density value of 0 are assumed to provide no direct benefit to asset protection.

#### *Slope*

An average value for slope was calculated for each planning unit using a 1 $m^2$ digital elevation model (Queensland Government 2014). For our application, we use the average slope value as this was considered to be the most appropriate metric for synthesising multiple local estimates of slope into a single value that would be meaningful for fire management.

### COST

Paucity of information on the costs of implementing prescribed burns is a common obstacle for resource allocation studies (González-Cabán 1997; Hesseln 2000; Calkin & Gebert 2006; Rideout & Omi 2016). Burn cost estimates were available from other dry sclerophyll forest ecosystems (Penman, Bradstock & Price 2014), but we estimate region-specific costs to ensure the cost model closely captured local operating procedures and constraints. In our case, information was available on aggregated annual costs of the burn program and the area burnt each year (2010–2015) (see Appendix S1: Table SA1.1) but not the cost of burning individual land parcels or quantitative information on drivers of variation in cost. *In lieu* of detailed cost information, elicitation from land managers and management personnel can be used to effectively estimate costs (Armsworth *et al.* 2011; Adams & Setterfield 2013). We administered questionnaires (see Appendix S2) to representative experts from City of Gold Coast and Queensland Fire and Rescue to estimate how proximity to residential property, slope, successional state of vegetation/fuel load and area affect burn costs. Questions were structured, so that each combination of factors potentially influencing cost was estimated relative to a standard baseline cost – in this case the cost of burning a hypothetical least expensive reference condition (see Appendix S1: Table SA1.2).

Annual costs among years were standardised to 2015 values using inflation rates based on the Australian Consumer Price Index from 2010 to 2015 (Australian Bureau of Statistics 2016). The total cost of burning a planning unit was estimated via:

$$\text{Cost} = a + bmAe^{-cA}$$

where $a$ represents the fixed baseline cost associated with burning a site regardless of area, $b$ is the additional per hectare cost of burning the reference condition, $m$ are the elicited multiplicative modifiers relating to site conditions (proximity, slope, successional state and area), $A$ is the area of the planning unit (ha), and $e^{-cA}$ is a reduction in cost associated with scales of efficiency in burning larger planning units (Appendix S1: Fig. SA1.2a,b). Minimisation of the least squares differences between the predicted and observed annual burn costs from 2010 to 2015 (40 burn events) was used to estimate parameters $a$, $b$ and $c$ ($r^2 = 0{\cdot}93$, see Appendix S1: Fig. SA1.1a–c).

## MULTI-OBJECTIVE OPTIMISATION

Our goal is to identify a set of planning units to burn each year in order to best achieve management objectives. We explicitly evaluate the trade-off between asset protection and conservation objectives using a multi-objective optimisation formulation in which the relative weights of each objective can be varied. At one extreme, the solution is driven solely by asset protection by burning planning units that limits the accumulation of fuel loads near residential areas. At the other extreme, the solution is driven solely by conservation values by identifying a burn schedule that promotes the long-term persistence of dry sclerophyll forest. Specifically, the conservation objective reduces the overall area-weighted time since fire among all planning units while also enforcing spatial heterogeneity in timing of burns at two spatial scales (among neighbouring planning units and at a regional scale by partitioning burns among four 'zones'; Fig. 1b). Intermediate solutions provide a balance between these objectives. By solving the problem over a range of objective weights, we are able to describe how asset protection and conservation returns trade-off and identify good compromise solutions.

Specifically, in each year over a specified planning horizon (years $t = 1, \ldots, T$), the planning units to burn are identified by solving the following optimisation problem:

$$\text{maximise} \quad \alpha \sum_{i}^{N} x_i w_i A_i + \beta \sum_{i}^{N} x_i r_i w_i z_i$$

$$\text{subject} \quad \sum_{i}^{N} x_i c_i \leq B_t$$

$$\sum_{i \in S_z} x_i A_i \geq Y z \in 1, \ldots, Z$$

$$\sum_{i \in S_n} s_i A_i \leq 1 n \in 1, \ldots, N$$

$$x_i \in 0, 1$$

where $x_i$ is the binary decision variable that determines if planning unit $i$ is selected for burning, $r$ is the residential population density within 500 m of the planning unit (scaled to 0–1 by dividing by the maximum value among all planning units), $w$ is a weighting factor representing the accumulation of fuel as a function of time since fire ($f$; years), $v$ is a weighting factor representing the conservation value of burning the planning unit, $A$ is the area of the planning unit (ha), and $z$ is an optional weighting factor that can be used to place greater priority on the selection of planning units that are already currently considered priority planning units for burning (see Variations below). Here, $w_i = 1 - e^{-0{\cdot}31 f_i}$ (Fox, Fox & McKay 1979)(see Fig. S2). The conservation weight $v$ is 0 when $f \leq 3$ to ensure that planning units are not burned more frequently than once every 3 years in accordance with the recommended burn regime (Queensland Herbarium 2014; Queensland Government 2015a), $v = 1$ when $f > 40$, and $v$ is an exponentially increasing function between $4 \leq f \leq 40$ (specifically, $w_i = e^{(0{\cdot}07(f-3))-1} / e^{(0{\cdot}07 \times 37)-1}$; see Fig. S2). The relative weights of each objective are determined by α and β, which we evaluate at the following relative weights: 1 : 0, 1 : 7·5, 1 : 20, 1 : 25, 1 : 30, 1 : 40, 1 : 60, 1 : 100, 1 : 150, 1 : 200, 1 : 250 and 0 : 1.

The first constraint ensures that the annual budget in year $t$ ($B_t$) is not exceeded based on the cost of burning each planning unit ($c_i$). The second constraint ensures that a minimum area target ($Y$) is burned within each zone, whereby $S_z$ is the set of planning units in zone $z$ and $Z$ is the total number of zones. Here, $Y = 28$ ha (10% of the average area of total burns across years since 2010). By distributing burns among zones, this constraint ensures that, over time, there will be considerable spatial heterogeneity in the distribution of age classes across the landscape. The third constraint ensures heterogeneity at a finer scale by preventing neighbouring planning units from burning in the same year, whereby $S_n$ is the set including planning unit $i$ and its neighbours. For the purpose of this study, planning units are considered neighbours if they are separated by a distance less than or equal to 500 m. A maximum of one member of this set can be burned in a given year. The final constraint indicates that the decision variable is binary (a planning unit is either burned or it is not).

To account for the process of succession after disturbance over time, we generated solutions annually for 10 years assuming an annual budget of AUD$1 000 000, being indicative of current management activities for the study area. The objective function is solved independently for each year with the time since fire, indicator variables and costs updated at the end of each year to reflect either the increment in time since previous burn for planning units that have not been burned that year, or setting the time since burn to zero for the planning units that have burned.

## VARIATIONS

We also subjected these scenarios to additional restrictions that are relevant to the City of Gold Coast. First, outputs were generated under increased budget scenarios of $1 500 000 and $2 000 000 per annum. Second, in practice, inaccessibility might prevent preferred burning regimes from being implemented. A major limiting factor for access is fire trails and roads. Indeed, all areas previously burnt were directly adjacent to access trails or roads. To evaluate the importance of this restriction, we repeat the scenarios excluding planning units that were deemed currently inaccessible for the purpose of fire management, i.e. to be considered accessible at least 30% of the length of a planning unit's boundary must be adjacent to a trail or a road. Finally, wildfire mitigation zones are key asset protection areas that have been previously designated by managers as important for burning for their value towards meeting asset protection/wildfire mitigation objectives. We explored the impact of weighting these areas twice and 10-fold greater than non-wildfire mitigation zones (parameter $z$ in the objective function).

### SOLUTION METHOD

Exact solutions to these integer linear programming problems were found using Gurobi Optimisation Software (Gurobi Optimization Inc 2015) and R (R Development Core Team 2015). All geospatial analysis was conducted with ArcGIS 10.3 (Environmental Systems Research Institute 2016).

## Results

### UTILITY OF SCENARIOS

We describe the characteristics of the asset protection-only ($\alpha = 1, \beta = 0$) or conservation-only ($\alpha = 0, \beta = 1$) scenarios as all intermediate solutions represent some balance between these extremes. The asset protection-only scenario was highly effective at reducing the mean time since fire in areas of high residential density while the conservation scenario only achieved 54% of this benefit after the 10 years (Fig. 2a). Conversely, the conservation-only scenario was highly effective at reducing the area-weighted time since fire across all planning units (Fig. 2b), while the asset protection scenario achieved only 15% of this benefit.

Over the 10-year period, the asset protection-only scenario resulted in an overall slight decrease in the area of early successional and transitional stage forest and a marked increase in late successional forest (Fig. 3a). In contrast, the conservation-only scenario resulted in a marked decrease in transitional stage forest and increases in the early successional and late stages (Fig. 3d). The conservation scenario resulted in an average time since fire of 17·4 years, while the asset protection scenario less effectively reduced the average time since fire to 20·4 years. Only the conservation scenario was effective in reducing exceedance of maximum recommended fire return intervals across the estate (i.e. the transitional stage) and promoting a more even mix of early and late stages (Fig. 3).

Solving the objective function over a range of objective weights ($\alpha$ and $\beta$) revealed the nonlinear frontier of possibilities for optimally trading-off between objectives (Fig. 2c). The pattern of these trade-offs over time was driven by the different rates at which asset protection and conservation objectives can be achieved. Benefits to asset protection appeared to reach an asymptote by year 6 while

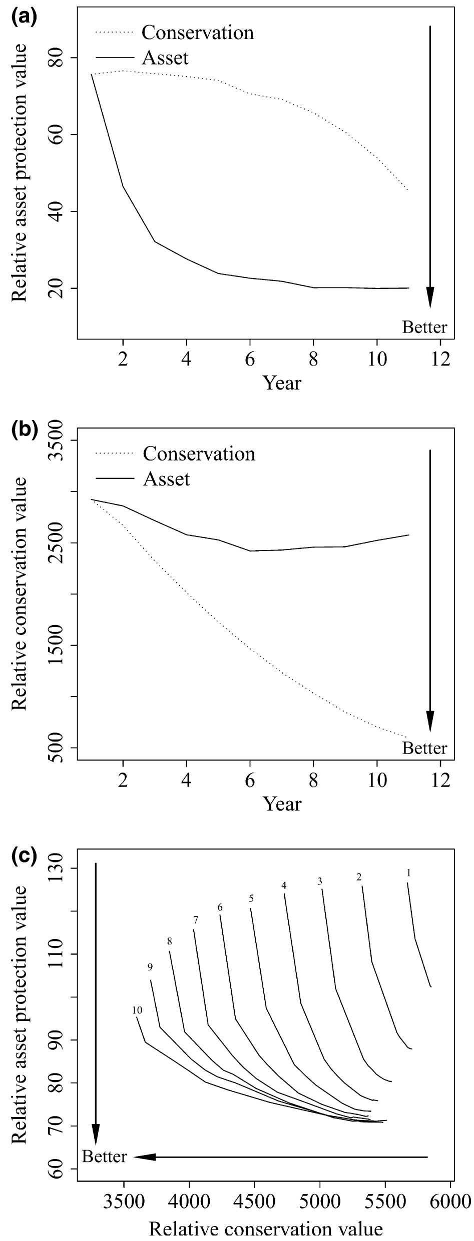



**Fig. 2.** Asset protection returns (a) and conservation returns (b) achieved over 10 years for a scenario solely prioritising conservation scenario (dotted) and a scenario solely prioritising asset protection (solid). (c) Trade-offs between asset protection and conservation objectives quantified over a 10-year period (black lines) by evaluating 12 scenarios with different relative weightings of the two objectives (see Materials and methods). The endpoints of these lines correspond to the asset protection-only and conservation-only solutions depicted in (a) and (b).

conservation benefits continued to incrementally accrue over the 10 years at a more linear rate (Fig. 2c). Hence, scenarios weighted in favour of asset protection all tend to approach this maximum before year 10, while scenarios weighted more in favour of conservation do not reach this limit (Fig. 2c). Objective weights ($\alpha$ and $\beta$) used to characterise the trade-off curves reveal the frontier of possibilities for optimally trading-off between objectives. For example,

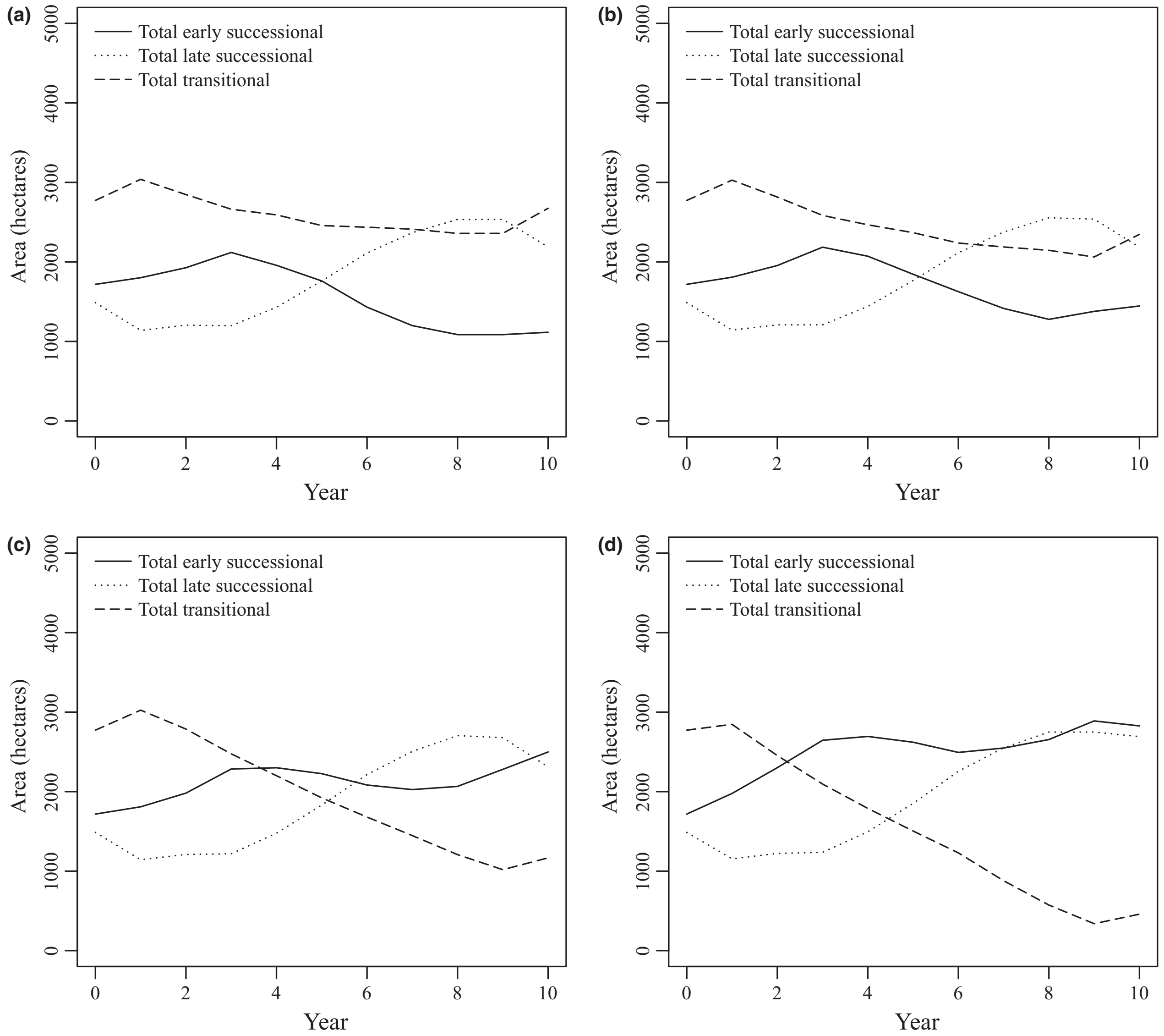


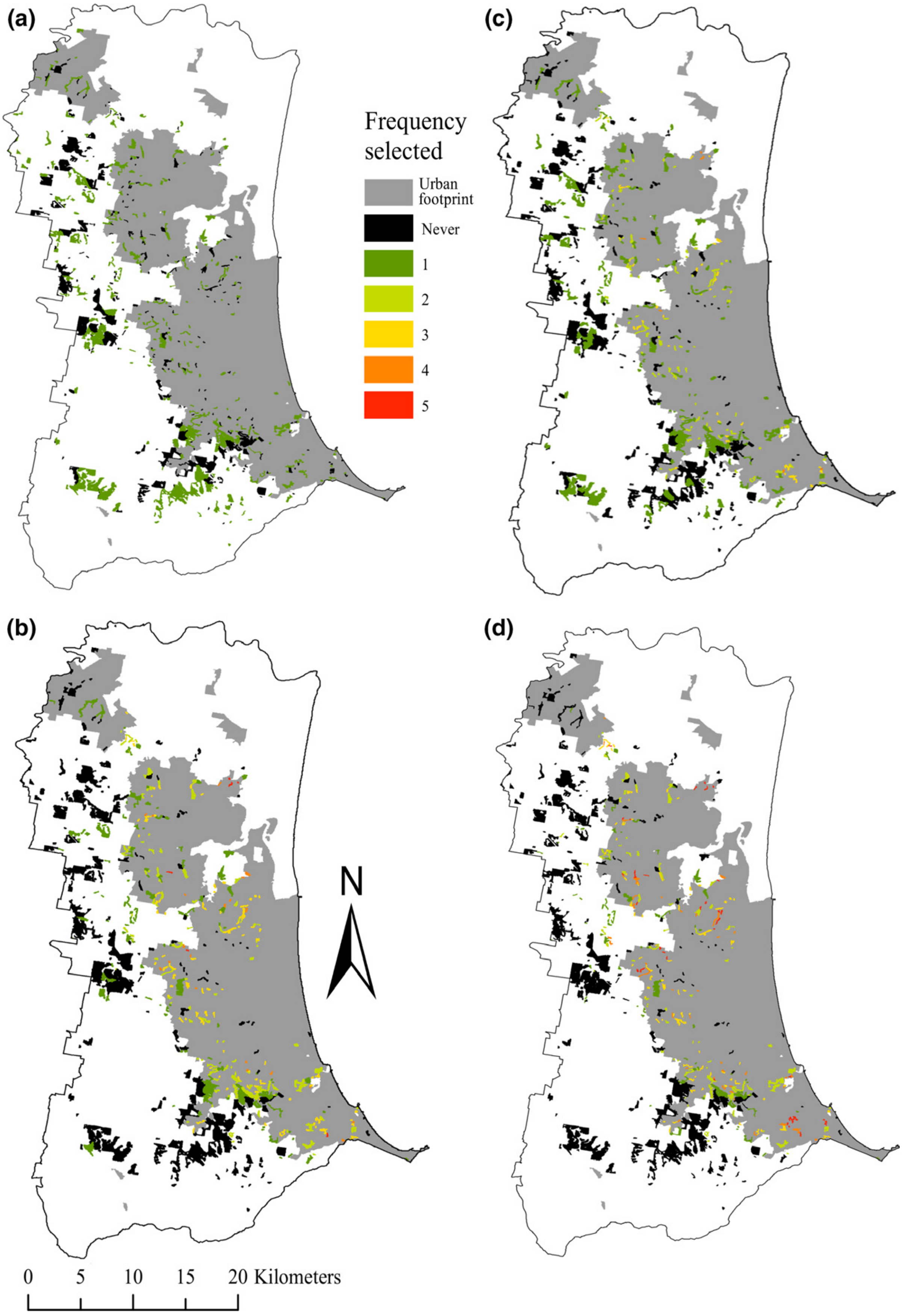

**Fig. 3.** Areas of each successional stage over time for four of the twelve scenarios evaluated, including: (a) the asset protection-only scenario ($\alpha = 1$, $\beta = 0$), (b, c) two compromise solutions with increasingly higher weighting of the conservation objective ($\alpha = 1$, $\beta = 30$ and $\alpha = 1$, $\beta = 150$ respectively) and (d) the conservation-only scenario ($\alpha = 0$, $\beta = 1$).

a weighting that evoked a modest (6%) reduction in the maximum possible gain in asset protection benefit over the 10-year period enabled 23% of the maximum gain in conservation benefit to be achieved ($\alpha = 1$, $\beta = 100$).

#### SPATIAL PATTERN OF OPTIMAL SOLUTIONS

The asset protection-only scenario favoured selection of planning units in the east of the city within the urban footprint, whereas planning units to the west and south were never selected (Fig. 4a). Conversely, the conservation-only scenario promoted a highly spatially dispersed arrangement of prescribed burning at both fine and broad spatial scales (Fig. 4d). Within the asset protection-only scenario, the repeated selection of key planning units was commonplace (Fig. 4a), whereas the conservation-only scenario never selected the same planning unit more than once over the 10 years (Fig. 4d). The intermediate scenarios reflected a balance between these two extremes (examples shown; Fig. 4b,c).

**Fig. 4.** Comparison of the spatial pattern of planning units selected for burning over 10 years under (a) the asset protection-only scenario ($\alpha = 1$, $\beta = 0$), (reduces fuel load around areas of high population density), (b, c) two compromise solutions with increasingly higher weighting of the conservation objective ($\alpha = 1$, $\beta = 30$ and $\alpha = 1$, $\beta = 150$ respectively) and (d) the conservation-only scenario ($\alpha = 0$, $\beta = 1$) (to ensure that a range of successional stages may be developed over time, and that burns be spread in a heterogeneous pattern). The frequency selected represents in how many years a planning unit was selected for burning (can only be selected once per year).


(a)
(b)
(c)
(d)
Frequency selected
Urban footprint
Never
1
2
3
4
5
N
0 5 10 15 20 Kilometers

### IMPACT OF VARYING CONSTRAINTS ON UTILITY OF SOLUTIONS

#### *Access*

We repeated the optimisation analysis using only the subset of planning units accessible by fire trails and access roads (see Appendix S3: Fig. SA3.1a,b). This precluded 2178 ha (36·45%) of dry sclerophyll forest from the analysis (see Appendix S3: Fig. SA3.1b). However, there was only a minimal impact of existing access constraints on the optimal solutions for all scenarios (see Appendix S3: Fig. SA3.2a,b,c), the extent of vegetation in each of the successional stages (Appendix S3: Fig. SA3.3a–d), and the spatial patterns developed for optimal solutions (see Appendix S3: Fig. SA3.4a–d).

#### *Wildfire mitigation zones (asset protection scenario only)*

Favouring wildfire mitigation zones using weights of 2 : 1 relative to non-wildfire mitigation zones resulted in negligible change to the asset protection-only solution (see Fig. S3b,c) but more stringent weights of 10 : 1 resulted in a notable increase in the extent of early successional stage within wildfire mitigation zones (see Fig. S3d) and a reduced asset protection benefit. Also, wildfire mitigation zones were frequently selected within the conservation scenario irrespective of its designated weighting (see Fig. S3a).

#### *Budget*

Substantial increases to the annual budget ($1 000 000) of 50% or 100% accelerated the rate at which benefits are achieved. Under the current budget scenario, asset protection asymptote by approximately year 6 and this occurred more rapidly under higher budgets (Fig. 2c; see Fig. S4a, b). Conservation objectives do not appear to reach an asymptote within the 10-year period, even under the highest budget scenario (see Fig. S4). An increased budget does facilitate, however, achieving substantially better joint asset protection and conservation outcomes across a wide range of objective weights (see Fig. S4a,b), thereby diminishing the strength of the compromise between the objectives.

## Discussion

Under a scenario that prioritises asset protection, we predict poor outcomes for conservation due to burning too frequently in some areas, and not frequently enough in others. This could result in local extinctions of species, and potentially the loss of fire-adapted ecosystems (Baker & Catterall 2015). Trade-offs between objectives in fire management have rarely been explicitly addressed (White, Halpern & Kappel 2012). Although our analysis indicates that there is a trade-off between asset protection and conservation objectives, it is possible to achieve substantially improved outcomes for conservation with only a small reduction in future gains for asset protection (Fig. 2c). Our analysis adds to a growing body of evidence that decisions tailored to achieve either asset protection or conservation objectives independently result in relatively poor outcomes for the other objective (Giljohann *et al.* 2015).

A focus on asset protection results in a strong spatial bias towards burning more eastern, coastal areas where people are concentrated at the neglect of the more western forest patches, which tend to be larger (Fig. 4a). A scenario that focuses solely on conservation never selected the same planning unit more than once over the 10 years (Fig. 4d) whereas, within a scenario that is skewed towards asset protection, the repeated selection (or burning) of key planning units was commonplace particularly in close proximity to residential areas (Fig. 4a). The frequent, repeated selection of planning units can lead to local population extinctions of serotinous obligate seeders if adults are removed before they have had the opportunity to reproduce (Keith 1996). By incorporating constraints for a diversity of successional stages throughout the ecosystem over time into the asset protection scenario, the spatial heterogeneity of the ecosystem was improved (Fig. 4b,c).

From a conservation perspective, mosaic burns are considered critical to maintaining healthy Australian forest and woodland ecosystems (Queensland Government 2013). While responses to fire are species-specific, a large proportion of Australian fauna require long-unburnt patches within an ecosystem that support a shrubby understorey, from which they may then recolonise recently burnt patches (Barton *et al.* 2014; Berry, Lindenmayer & Driscoll 2015). Local refuges from fire are important for fauna as they enhance immediate survival during fire, facilitate persistence of species after fire and aid in re-establishment of populations (Robinson *et al.* 2013). Other faunal species require grassy understories characteristic of early successional stages, as there is an increase in available seed and insects providing resources for many ground-foraging species (Howes & Maron 2009). While increasing environmental heterogeneity, the conservation scenario also selected planning units to burn that over time reduced the average time since fire across all planning units (Fig. 3d). The overall reduction in fuel load this achieves could also have positive outcomes for asset protection since the severity of wildfires in terms of intensity and spread are likely to be reduced (Bradstock & Myerscough 2005). This strategy may be a more valuable management technique for asset protection than burning only key asset protection zones (and increasing fuel load in other areas) (Bradstock *et al.* 2005; Duncan *et al.* 2015).

An analysis of the sensitivity of results to the formulation of the problem identifies three opportunities. First, results indicate that performance towards either objective within the next 10 years is not limited by the existing network of access routes (Appendix S3). Interrogation of outcomes beyond the 10 year timeframe is required to determine whether improvements in accessibility will be important longer term. Second, the low frequency of selection of established wildfire mitigation zones under the asset protection scenario (see Fig. S3b) suggests that burning of other areas might be required to maximise asset protection benefit. This suggests that there would be value in reviewing designation of wildfire mitigation zones to better incorporate quantitative data on spatial variation in residential population density and costs of prescribed burning. Finally, increasing the budget makes achieving good outcomes for both objectives possible (Fig. S4). As expected, differences in the spatial pattern of prescribed burning for asset protection and conservation mean that there is a trade-off present when we seek to maximise both objectives simultaneously. However, we show that concessions can be mediated or offset by increasing the available budget.

Defining and achieving management objectives within a fire-dependent ecosystem is a complex and multi-faceted problem (Giljohann *et al*. 2015). There are several aspects of this work that should be evaluated when implementing solutions or planning burns in other systems. First, areas selected for burning should be considered alongside expert opinion, and if deemed inappropriate or unsafe for burning may be reduced to an earlier successional stage through mechanical (or manual) management. Second, the conservation objective reduces the overall mean time since fire of the ecosystem and there is a risk that this formulation could result in excessive burning and an undesirably low mean time since fire among all planning units. In our application, there was a strong over-representation of vegetation that exceeded the recommended fire return interval for the target vegetation type (i.e. transitional stage) and the budget was sufficiently small that there was no risk of this occurring. However, when applying this framework to other problems it may be necessary to implement constraints within the objective function to ensure that excessive burning is prevented. Third, the formulation of our objective function is suitable for our application, but if applied to a different ecosystem or location it should be altered to appropriately accommodate other conditions and to achieve other desired outcomes. Asset protection objectives could benefit from improved identification of ignition hotspots and planning unit-specific conditions, costs and fuel loads. Finally, we assumed that there was only one type of burn intervention and that the ecosystem reverts to an early successional stage after a burn. An alternative approach might be to expand the toolkit of burn types to enable light burns to be implemented which would change the successional stage from transitional to late (Richards, Possingham & Tizard 1999). It is also expected that not all prescribed burns will be successful and that wildfire events will occur within the ecosystem stochastically. Although we do not explicitly consider unsuccessful burns or wildfire, it is straightforward to include these into the planning process by updating the status of planning units after these events have occurred.

## Conclusions

We have demonstrated the potential for spatial planning through optimisation to inform decision-making through the prioritisation and scheduling of controlled burns and quantifying trade-offs among multiple objectives. It is a powerful, extendable tool able to accommodate the diverse constraints that characterise fire management planning problems (such as the need for spatial heterogeneity) and local logistics (such as access requirements). Explicitly evaluating trade-offs among competing objectives enables managers to identify opportunities to achieve good returns on all objectives, and facilitates the development of transparent, preferred solutions. We further note that heterogeneous burning under the auspices of conservation has great potential to reduce overall fuel loads within the ecosystem and thus its value for asset protection is likely underappreciated. We show that ecological integrity may be improved within a fire-dependent ecosystem with only modest concession to asset protection performance.

## Authors' contributions

All authors contributed to the study design, problem formulation, analysis and writing of this paper.

## Acknowledgements

This research was conducted with the support of funding from the Australian Research Council (ARC) Centre of Excellence for Environmental Decisions, South East Queensland Fire and Biodiversity Consortium (B.A.W.) and ARC Linkage grant LP140100176 (K.A.W.). H.L.B. was supported by ARC DECRA Project DE140101389. This project was in collaboration with the Natural Area Management Unit of the City of Gold Coast. Appreciations to the Queensland Fire and Emergency Services. Ethics approval was granted by the University of Queensland, Institutional Human Research Ethics Approval, approval number 2015000481. The authors declare that there is no conflict of interest.

## Data accessibility

Data are available from Dryad Digital Repository https://doi.org/10.5061/dryad.tj4p2 (Williams *et al*. 2017).

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*Received 3 December 2016; accepted 3 April 2017*
*Handling Editor: Cate Macinnis-Ng*

## Supporting Information

Details of electronic Supporting Information are provided below.

**Fig. S1**. Residential population density layer.

**Fig. S2.** Allocated time since fire weights.

**Fig. S3.** Wildfire mitigation zone analysis.

**Fig. S4**. Budget manipulation analysis.

**Table S1.** Regional ecosystems regarded as dry sclerophyll forest.

**Appendix S1.** Development of cost estimates.

**Appendix S2.** Elicitation questionnaire.

**Appendix S3**. Accessibility analysis.