A spatial optimisation model for fuel management to break the connectivity of high-risk regions while maintaining habitat quality

Javier León[a,b], Victor M.J.J. Reijnders[a,c], John W. Hearne[a],

Melih Ozlen[a], Karin J. Reinke[a]

[a] RMIT University, Australia

[b] Complutense University of Madrid, Spain

[c] University of Twente, The Netherlands

Extended abstract

1 Introduction

Although some negative effects have been noted, positive effects of bush fires on the habitat for native flora and fauna have been recorded [30]. Reports indicate that areas subject to prescribed burning have more live trees, greater survival, and reduced fire intensity during wildfires compared to untreated areas [29]. Prescribed burning leads to fuel reduction [1] and areas with old vegetation (or areas with excess fuel build-up) are often targeted for treatment [11] and can help mitigate wildfire hazards [28, 3, 5], and the risk to human life and economic assets [22]. Thus it has been argued that fuel management is both necessary and important [4].

For the purposes of fuel mangement, forest and national parks are often divided into treatment units. Deciding on a schedule of treatments is a complex spatio-temporal problem [12, 26] and the resulting spatial patterns are critical [7, 16]. Operations Research methods have been applied to some of these problems [19, 20, 2, 23].

Different spatial patterns have been studied [14] and have led to interesting theoretical results. Patterns include disconnected fuel treatment patches that overlap in the direction of fire spread [8], or taking into account the natural landscape around us [9]. Also preparing explicitly for possible future fires when choosing where to apply treatment [31] taking into account fire ignition risk and probabilities of fire spread [33]. Stochastic programming with sample fires has produced some spatial and temporal relationships for where to burn [21].

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Fragmenting high fire hazard fuel patches is an aim in fuel management, so that treated units can act as a barrier between high fuel load units when a wildfire occurs. The vegetation regrows over time, and long-term planning is necessary to minimise these high-risk connections [32, 20, 24]. Where to locate fuel-breaks is highly connected to locating burn units, and finding the optimal pattern for these breaks has received attention from researchers [27].

The risk of catastrophic wildfires decreases [16, 15] with extent treated but with an optimal landscape mosaic [10] hazard reduction can be achieved without excessive costs [17]. Nevertheless vegetation regenerates, ages and eventually becomes high fuel load again. Thus multi-period scheduling of fuel treatment [20, 24] is needed.

Lowering the total fuel load has ecological consequences. Some species may rely on vegetation that would be classified as high-risk. When choosing which units to burn, we have to take into account the habitat quality for these species. These might need connected habitats for reducing local extinction, increasing recolonisation and annual migration [25], so (functional) landscape connectivity has to be taken into account [34]. Little research has been done combining multiple concerns that arise with fuel treatment in an optimisation framework [6].

In this paper we consider scheduling prescribed burning of parts of a landscape to reduce the connectivity of high-risk regions in order to reduce the fire hazards. We propose a Mixed Integer Programming (MIP) model to break these connections, taking into account the quality of the habitat for animals living there. Research has been done on breaking the connectivity between the high-risk regions, but not assessing overall and local quality of the habitat. We propose a couple of solution approaches and demonstrate these on hypothetical landscapes. A number of measures for the quality of the habitat are considered. We use fuel accumulation curves to categorize old burn units, or high risk ones (see [13]). We use fire response curves to give relative abundance of a species in years after burning (see [18]) and take this as a quality measure of the burn unit.

2 Method

Model Description

Consider a landscape comprising a mosaic of spatial units. In the context of fuel management these are referred to as 'burn units'. The age of the vegetation in each burn unit determines its fuel load and hence its risk of wildfire. Vegetation age also characterises the habitat suitability for particular fauna of each burn unit. In this model we consider a single vegetation type (heathland) and without specifying a species we consider invertebrates that prefer some predefined vegetation age. We formulate a model that each year selects the burn units to undergo fuel reduction through controlled burning or mechanical clearing. The sequence of selections is made so as to minimise the risk of wildfires. This is achieved by ensuring that after treatment the burn units remaining with high fuel loads are as fragmented as possible.

On the other hand we also want to take into account the species that might live in the landscape. As species have preferences for vegetation of a certain age, we assign a quality to each burn unit according to its area and the relative abundance of species supported by vegetation of that age. We can then only select a burn unit for treatment if the habitat quality of its neighbours is at least as high as the habitat quality of the burn unit itself. This way, we take into account the habitat needs of the species, although we realize that individuals might have to migrate from time to time.

Further constraints included in the model relate to the vegetation. To sustain the vegetation and associated ecosystem, fire should not occur more frequently than its 'minimum tolerable fire interval'. On the other hand, for fire-dependent species the 'maximum tolerable fire interval' is also important.

3 Model implementation

For our analysis we implement the developed Mixed Integer Linear Programming model on 23 randomly generated landscapes (one instance is shown in Figure 1). Each of the landscapes has 45 burn units. We perform experiments with a treatment level of 7 percent of the total area of the landscape each year. The simulations are then solved for a planning period of 20 years, with a rolling horizon of 12 years.

The solver we use is Gurobi 7.5 with the Julia 0.6.0.1 programming language using JuMP modeller.

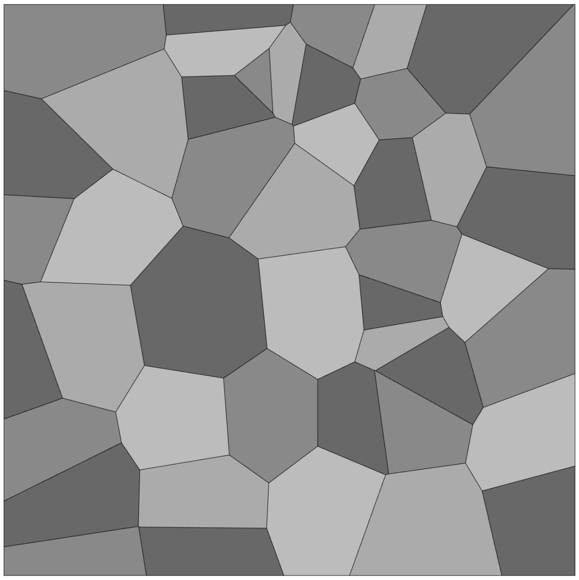

Figure 1: Randomly generated landscape with 45 units. Colours are only for distinction between burn units.

4 Results

We solve the 23 randomly generated scenarios with the rolling horizon approach (with a 12-year window) to optimality. The mean fire risk and global habitat value are shown in Figure 2.

Our objective is to get an overall minimum in the weighted connections between high-risk burn units. We see that the initial risk is quickly brought close to 0, while maintaining habitat of good quality (both local and global). For the landscape previously shown on Figure 1 we now show the initial conditions (random ages) and the solution after 3 and 19 years (Figures 3, 4 and 5).

4.1 Myopic approach

If the rolling horizon window is too short results may be unsatisfactory. We demonstrate this fact comparing the results obtained with a rolling horizon of 12 years versus the ones in which the

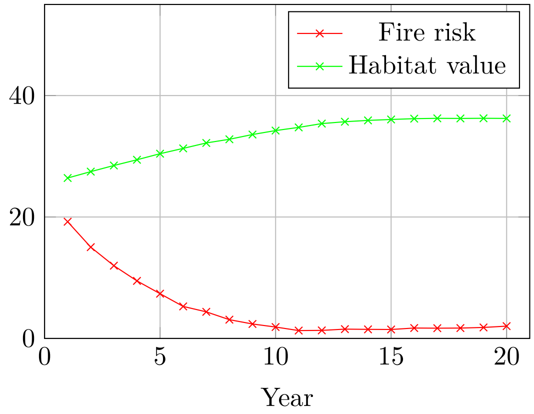

Figure 2: Mean fire risk and mean global habitat value for the 23 scenarios by year

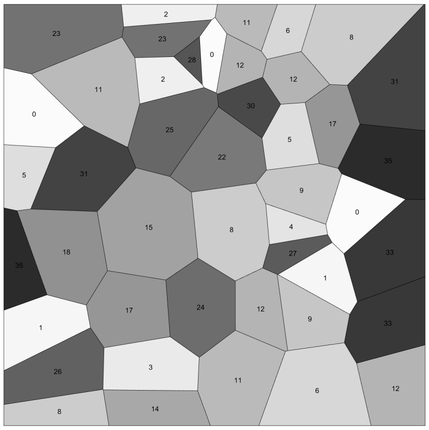

Figure 3: Ages of cells on random initial conditions for a given landscape

rolling horizon is set up to be just two years, in both cases using the model is run without habitat constraints.

Out of the 23 scenarios three of them turned to be infeasible when solved with the myopic approach. Units have to burnt if their age will exceed the parameter $maxTFI$, but the myopic approach has led in some scenarios to situations in which the amount to be burnt on one year is higher than that allowed by the budget

Year	Long term	Myopic
16	0.936	2.258
17	0.920	2.076
18	0.991	1.899
19	0.815	2.036
20	0.828	2.045

Table 1: Mean fire risk in the last years of simulation, long rolling horizon window versus myopic approach.

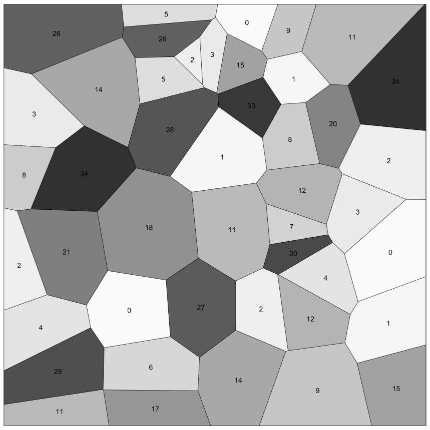

Figure 4: Ages of cells after 3 years

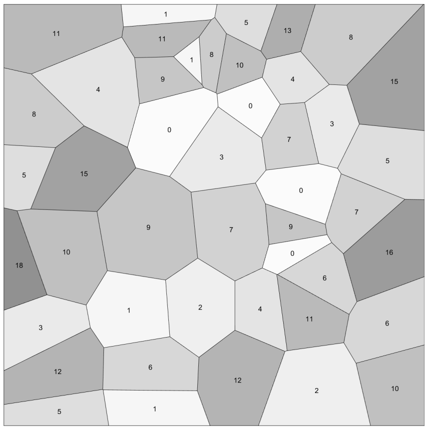

Figure 5: Ages of cells after 19 years

Table 1 reports the results obtained with both approaches, only in the last years of the planning horizon, when the solution is more stable. We can see that, even removing the scenarios in which the myopic approach was infeasible, the myopic approach yielded results much worse than that obtained with a longer planning horizon.

4.2 Lexicographical approach

On some situations it might seem unrealistic to allow a fuel management schedule that improves habitat quality while increasing the fire risk. For that purpose we have also shown that a lexicographical approach can also be used to get a good solution in terms of habitat value without increasing fire risk.

4.3 Alternative neighbourhood

Finally we aim to show how our model can easily reflect different neighbourhood definitions. For example a landscape could be located in some place where wind primarily blows in one direction, and hence fire propagation would occur mainly in that direction. If that were the case our model could easily reflect that information by just changing a neighbourhood matrix (in the model formulation the neighbourhood information is given by the set Φ_i). An example of this alternative way of defining neighbours is shown in Figure 6. Another example where fire propagation might occur mainly in one direction (and thus neighbourhoods defined in a similar way) is if the landscape has a high slope and fires are primarily topographical.

With the neighbours defined as given by Figure 6 we solve the lexicographical model explained on the previous section (minimize high fuel load connectivity through all planning horizon and then maximize habitat value without increasing fire risk), and using the same parameters. Figure 7 shows the state of the landscape n the last year of the planning period. It can be seen that the model makes use of the new definition of neighbours, as fuel load is accumulated in burn units that are geographically adjacent but were not defined as neighbours, and thus they do not pose a high fire risk.

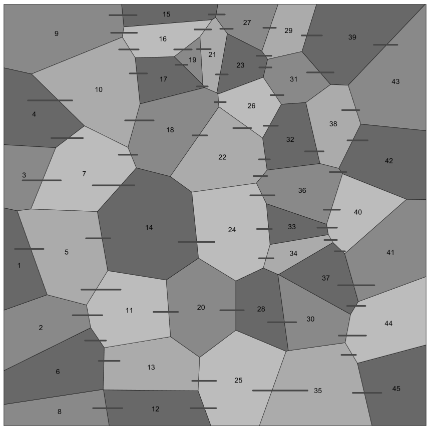

Figure 6: If the landscape has predominant winds and fires that occur in that landscape are wind-driven, the neighbourhood matrix could reflect this fact. Lines on this image show which units are defined as neighbours in case of west-east winds.

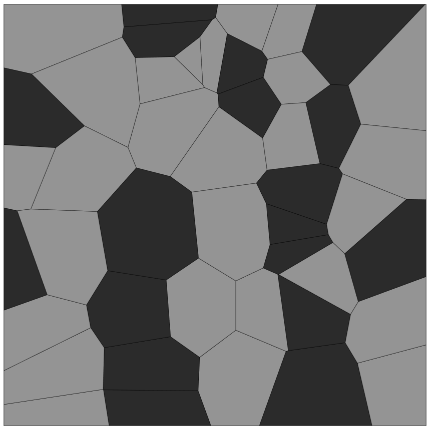

Figure 7: Solution on the last year of simulation with dark units reflecting burn units that have old fuel (their age is older than 10).

5 Conclusions

We presented a mixed integer programming model for a landscape divided into polygons representing realistic treatement units. The model aims to reduce the adjacency of high fuel load areas. We show that adopting a medium-term approach to fuel reduction using our model yields is much more effective than adopting a myopic approach. In this latter case it frequently arises that fuel reduction targets cannot be met within budget constraints.

There are ecological consequences from prescribed burning. We considered habitat quality for invertebrates on a heathland landscape. We showed that a significant range of habitat quality outcomes can be obtained without compromising the optimal fuel load goal. It is sensible therefore for habitat considerations to be included in fuel reduction plans. We show that this can be achieved for invertebrates by requiring the habitat quality in the neighbourhood of a planned burn be at least as good as the habitat quality of the area to be burnt. We also take into account landscape-level habitat quality. This consideration of local and global habitat differs from previous work. We also imposed some ecological requirements in the form of minimum and maximum tolerable fire intervals for the vegetation.

For any particular landscape, factors such as topology and prevailing winds will determine connectedness between high fuel load areas. We have illustrated that this can be handled with a redefinition of the neighbourhood of each treatment unit. In fact where fire spread is predominantly in certain directions geographically adjacent treatment units might not be in the same neighbourhood from a fuel connectedness perspective. This creates opportunities for maintaining habitat quality for species requiring older vegetation without compromising fuel reduction plans.

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