Applied Mathematical Modelling 54 (2018) 298–310

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

# Fuel treatment planning: Fragmenting high fuel load areas while maintaining availability and connectivity of faunal habitat

Ramya Rachmawati[a,b], Melih Ozlen[a], John Hearne[a,*], Karin Reinke[a]

[a] School of Science, RMIT University, Melbourne, Australia
[b] Mathematics Department Faculty of Mathematics and Natural Sciences, University of Bengkulu, Bengkulu, Indonesia

ARTICLE INFO

*Article history:*
Received 16 January 2017
Revised 14 September 2017
Accepted 20 September 2017
Available online 2 October 2017

*Keywords:*
Environmental modelling
Wildfire
Landscape management
Habitat conservation
Optimisation

ABSTRACT

Reducing the fuel load in fire-prone landscapes is aimed at mitigating the risk of catastrophic wildfires but there are ecological consequences. Maintaining habitat for fauna of both sufficient extent and connectivity while fragmenting areas of high fuel loads presents land managers with seemingly contrasting objectives. Faced with this dichotomy, we propose a Mixed Integer Programming (MIP) model that can optimally schedule fuel treatments to reduce fuel hazards by fragmenting high fuel load regions while considering critical ecological requirements over time and space. The model takes into account both the frequency of fire that vegetation can tolerate and the frequency of fire necessary for fire-dependent species. Our approach also ensures that suitable alternate habitat is available and accessible to fauna affected by a treated area. More importantly, to conserve fauna the model sets a minimum acceptable target for the connectivity of habitat at any time. These factors are all included in the formulation of a model that yields a multi-period spatially-explicit schedule for treatment planning. Our approach is then demonstrated in a series of computational experiments with hypothetical landscapes, a single vegetation type and a group of faunal species with the same habitat requirements. Our experiments show that it is possible to fragment areas of high fuel loads while ensuring sufficient connectivity of habitat over both space and time. Furthermore, it is demonstrated that the habitat connectivity constraint is more effective than neighbourhood habitat constraints. This is critical for the conservation of fauna and of special concern for vulnerable or endangered species.



## 1. Introduction

Fire plays an important role in maintaining ecological integrity in many natural ecosystems [1] but wildfires also pose a risk to human life and economic assets [2]. Climate change is expected to aggravate these risks [3] but they can be reduced through fuel management [4–6]. This is the process of altering the structure and amount of fuel accumulation in a landscape. It is achieved through the application of treatments, such as prescribed burning or mechanical clearing. To reduce the risk

* Corresponding author.
*E-mail addresses:* ramya_unib@yahoo.co.id (R. Rachmawati), melih.ozlen@rmit.edu.au (M. Ozlen), john.hearne@rmit.edu.au (J. Hearne), karin.reinke@rmit.edu.au (K. Reinke).

https://doi.org/10.1016/j.apm.2017.09.045
0307-904X/

of large wildfires, fire management agencies in Australia [7,8] and the USA [9,10] have initiated extensive fuel management programs in fire-prone areas. Fuel load or biomass accumulation is a continuous ecosystem process. Each year parts of the landscape are treated to reduce the overall fuel load for subsequent fire seasons. Treatment frequency is partially dictated by the vegetation community. Reducing the fuel load in the landscape in this way helps to prevent or minimise the spread and intensity of wildfire.

Similarities exist between the fuel treatment problem described here and the planning problem for forest harvesting. Both of these problems consider vegetation dynamics and can be seen as a ‘timing problem’ , meaning that the risk and values change over time as the vegetation grows. In the fuel treatment problem, an area is treated to reduce fuel load; in the forest harvesting problem, an area is harvested using mechanical clearing for timber production. Both activities have consequences for the habitat. Previous studies in the forest harvesting problem have taken into account some ecological requirements. For example, in [11] a Tabu search algorithm is used to schedule timber harvest subject to spatial wildlife goals. Specifically, they maintained sufficient habitat of a certain maturity within a specified distance of a hiding or thermal place. Öhman and Wikström [12] proposed an exact method for long-term forest planning to maintain the biodiversity of the forest. They believe that biodiversity in the forest ecosystem can be maintained by minimising the total perimeter of old forest patches so that the fragmentation of old forest is reduced. Hence, compactness of the habitat for species can be achieved. However, their model did not consider habitat connectivity across time. Addressing this shortcoming, a model was proposed [13] that ensures mature forest patches are temporarily connected between time-steps while scheduling forest harvesting. The model achieves this without substantial reduction in timber revenues. However, this model does not take into account the overall habitat connectivity of each period, nor does it track the habitat connectivity across the entire planning horizon, both of which are important for the persistence of species.

Various methods have been proposed for incorporating the effect of wildfires into harvest planning models. A comprehensive review is provided in [14]. More recently it was shown that including wildfire risks into a harvesting planning model with adjacency constraints can yield improved outcomes [15]. The spatial arrangement of fuel treatment planning plays a substantial role in providing better protection in the landscape [16]. Fuel arrangement can modify fire behaviour and when fragmented, can lessen the chance of large wildfires [17]. The connectivity of ‘old’ untreated patches is an important factor affecting the extent of a wildfire [8].

Wei and Long [18] proposed a model to break the connectivity of high fuel load patches by considering the duration and speed of a future fire. Their model was for a single period. Fundamental to accurate fuel treatment planning requires consideration of the vegetation dynamics over time [19]. With the objective of minimising the ‘value at risk’ [20] used simulated annealing to determine a long-term schedule for the location and timing of prescribed burns on a landscape. A multi-period model for fuel treatment planning that included the dynamics of a single vegetation type was formulated in [21]. The objective in this model was to break the connectivity of ‘old’ patches in the landscape over the entire solution period of a few decades. This model was extended by Rachmawati et al. [22] to multiple vegetation types and applied to a real landscape.

The efficacy of the application of fuel treatment remains debated among experts according to different perspectives [23]. Fuel treatments reduce the overall fuel load in landscapes but at the same time may result in significant habitat modification for fauna living within the treated area. If the right mix of habitat availability in the landscape is not maintained, populations may be adversely affected, leading to local extinctions where minimum viable population thresholds are no longer met. For example, the Mallee emu-wren, a native bird of Australia, depends on 15-year-old mallee-Triodia vegetation for survival [24]. This vegetation recovers very slowly after fuel treatments, and the Mallee emu-wren is unable to survive in vegetation aged less than 15 years. Another Australian example is the Southern Brown Bandicoot. The species requires 5–15 years old heathland [25]. Similarly, in California, frequent fires can destroy the mature coastal sage scrub habitat required for the coastal cactus wren and the California gnatcatcher on which these species rely [26]. For a given vegetation type, the age of the vegetation is the most significant factor determining its suitability as habitat for the species discussed above. Thus henceforth we refer to areas of vegetation of the appropriate age for a species simply as habitat. If we want to conserve these species, it is important to maintain the availability and connectivity of their habitats. In fact, more generally, habitat connectivity is vital to support the ecology and genetics of local populations [27,28]. The question then arises: can fuel treatments be scheduled to break the connectivity of high fuel load areas while maintaining the availability and connectivity of habitats?

Here we significantly extend current models by tracking and maintaining defined levels of habitat connectivity over time, in addition to reducing and fragmenting high fuel loads across the landscape. The model we present is the first multi-period fuel treatment model that takes into account habitat connectivity and solved using exact optimisation. The proposed model is designed for fire-dependent landscapes so additional ecological constraints are imposed based on the concept of Tolerable Fire Intervals (TFI’s) [29]. It is harmful for vegetation in an area to be subjected to another fire before a certain time (the minimum TFI) has elapsed since the last fire in that area. It is also desirable that a burn *does* take place before a certain time (the maximum TFI) has elapsed since the last fire. Thus fuel treatment in each area is constrained to occur in a time-window between the minimum and maximum TFI since the last burn in that area. The TFI’s are vegetation-dependent.

Mixed Integer Programming (MIP) models have been employed in a great diversity of problems. Applications include waste disposal [30], facility layout problems [31], oil-refinery scheduling [32] and a forest management problem [33] to list just a few. Further examples can be found in [34]. Of closer relevance to the problem considered here are the MIP papers listed in an overview of wildfire considerations in forest planning [14].