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# An optimisation approach for fuel treatment planning to break the connectivity of high-risk regions

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ABSTRACT

Uncontrolled wildfires can lead to loss of life and property and destruction of natural resources. At the same time, fire plays a vital role in restoring ecological balance in many ecosystems. Fuel management, or treatment planning by way of planned burning, is an important tool used in many countries where fire is a major ecosystem process. In this paper, we propose an approach to reduce the spatial connectivity of fuel hazards while still considering the ecological fire requirements of the ecosystem. A mixed integer programming (MIP) model is formulated in such a way that it breaks the connectivity of high-risk regions as a means to reduce fuel hazards in the landscape. This multi-period model tracks the age of each vegetation type and determines the optimal time and locations to conduct fuel treatments. The minimum and maximum Tolerable Fire Intervals (TFI), which define the ages at which certain vegetation type can be treated for ecological reasons, are taken into account by the model. Examples from previous work that explicitly disconnect contiguous areas of high fuel load have often been limited to using single vegetation types implemented within rectangular grids. We significantly extend such work by including modelling multiple vegetation types implemented within a polygon-based network to achieve a more realistic representation of the landscape. An analysis of the proposed approach was conducted for a fuel treatment area comprising 711 treatment units in the Barwon-Otway district of Victoria, Australia. The solution of the proposed model can be obtained for 20-year fuel treatment planning within a reasonable computation time of eight hours.



## 1. Introduction

Uncontrolled wildfires can result in the loss of life and economic assets and the destruction of natural resources (King et al., 2008). Southern Australia, Mediterranean Europe and areas of the United States are among the top regions in the world that are affected by frequent wildfires (Bradstock et al., 2012). Coupled with the proximity of major cities to natural ecosystems prone to wildfire, the management of fuel hazard becomes an important land management policy and planning issue for the protection of human life and assets (Collins et al., 2010). However, fuel management for asset protection should not be done in isolation of the ecological requirements of the ecosystem. Maintaining the ecological integrity of the landscape must also be considered (Penman et al., 2011).

Fuel management is a method to modify the structure and amount of fuel. The methods include prescribed burning and mechanical clearing (King et al., 2008; Loehle, 2004). Fuel management programs have been extensively implemented in the USA (Ager et al., 2010; Collins et al., 2010) and Australia (Boer et al., 2009; McCaw, 2013) in an effort to lessen the risk posed by wildfire. The choice of fuel treatment location plays a substantial role in conducting efficient fuel treatment scheduling (Collins et al., 2010). Instead of randomly selecting the locations, significantly better protection in a landscape could be provided by a fuel treatment schedule that takes into account the relationships between treatment units (Schmidt et al., 2008). Research indicates that it is important to choose where to conduct the fuel treatment by considering spatial arrangement (Rytwinski and Crowe, 2010; Kim et al., 2009; Chung, 2015). The importance of landscape-level fuel treatment has been observed in a number of studies. In wilderness regions in the United States, a mosaic of varying fuel ages is formed as a result of free burning fires. A particular arrangement of old and new treatment units has been recognised to delay large wildfires in the following year (Finney, 2007). Research conducted in the Sierra

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Nevada forests of the United States has shown that wildfire size can be modified by spatial fragmentation of fuel (Van Wagtendonk, 1995). Prescribed burning has been implemented in the eucalypt forests in south-western Australia over the past 50 years. The connectivity of 'old' untreated patches has been revealed to be the main aspect that contributes to wildfire extent (Boer et al., 2009).

Previous studies have mathematically modelled fuel treatment schedules and methods to reduce wildfire fuel hazards. The studies had different objective functions and took into account various considerations in building up the models. Bettinger (2010) reviewed previous studies that incorporated wildfires into forest management using operations research models. Kim et al. (2009) utilised a heuristic optimisation method in landscape-level timber management. Using four scenarios, namely dispersed, clumped, random and regular on a real landscape, they concluded that despite the spatial arrangement of harvesting units, their approach is not effective to achieve timber management objectives while trying to mitigate wildfire behaviour in a heterogeneous landscape. Ferreira et al. (2014) proposed a stochastic dynamic programming (SDP) approach to determine the fuel treatment scheduling that produces the maximum expected discounted net revenue while mitigating the risk of fire. The method was then applied to a maritime pine forest in Leiria National Forest, Portugal. They found that the approach was efficient and can successfully help integrating wildfire risk in stand management planning. Konoshima et al. (2008) also proposed an SDP model that can maximise future timber production by considering the future fire events and spreads into fuel treatment planning. In a follow-up paper, Konoshima et al. (2010) extended their previous model by including factors such as weather condition and topography, and then conducted the model demonstrations with a hypothetical landscape comprising homogeneous hexagonal units. They found out that the spatial arrangement of management units led to differing management strategies. Garcia-Gonzalo et al. (2014) determined the optimal fuel treatment scheduling in a single-stand management for reducing expected damage and increasing the revenue to the same landscape as that of Ferreira et al. (2014). Their research shows that the fuel treatments improve productivity as well as reduce the potential damage. Rachmawati et al. (2015) proposed a model that can lessen the risk of fire by reducing the total fuel load but do not consider spatial properties or the spatial relationship between the treatment units. Wei and Long (2014) proposed a single-period model to fragment high-risk patches by considering future fire spread speeds and durations. Hof et al. (2002) formulated MIP models for fuel treatment planning to delay the fire spread from its deterministic ignition point to one or more protecting locations. Minas et al. (2014) proposed a model that breaks the connectivity of high fuel units in the landscape to prevent the fires spreading. The model proposed by Minas et al. (2014) takes into account vegetation dynamics in the landscape, but this is limited to a simplistic grid representation of a single vegetation type per treatment unit. In real landscapes, a treatment unit may comprise a number of patches with different vegetation type and age. Recent studies have utilised simulation–optimisation approach and have been applied in real landscapes comprising multiple vegetation types (Kim et al., 2009; Ferreira et al., 2014; Garcia-Gonzalo et al., 2014). Some studies still limited to single vegetation type (Minas et al., 2014), single-period fuel treatment models (Wei and Long, 2014) and single stand management (Garcia-Gonzalo et al., 2014). The study by Kim et al. (2009) has taken into account the spatial pattern at a landscape level, but the vegetation dynamic over time and the contiguity of high fuel load areas are not considered. Due to the transience of fuel load in the landscape for both treated or untreated areas, it is important to take into account the vegetation dynamic by modelling multi-period planning strategies.

In this paper, we build upon Minas et al. (2014) model by incorporating multiple vegetation types found in the landscape and within single treatment units, and take into account the spatial connectivity or fragmentation of 'high-risk' treatment units. We use a polygon-based network representation of the landscape to better capture the spatial complexity of this problem rather than a rectangular grid. Besides the negative impacts of wildfires, the role of fire in ecology has been widely acknowledged. Fire is required to maintain a healthy ecosystem and it also has a significant role in habitat regeneration. Many vegetation species in fire-adapted ecosystems need fire to reproduce. For instance, germination of seeds and successful establishment of plants in the jarrah forests of Western Australia is very rarely found without fire intervention (Burrows and Wardell-Johnson, 2003). More recently, Burrows (2008) argued that fuel management is important to support biodiversity conservation as well as to reduce the negative impact of wildfires. A recognition of vegetation dynamics over time is crucial in the planning of fuel treatment (Krivtsov et al., 2009). In this proposed model, the ecological fire requirements of each vegetation type can be described using the minimum and maximum Tolerable Fire Intervals (TFI). The minimum TFI is the minimum time required between two consecutive fire events at a location and is based on the time to reach maturity of the sensitive species in the vegetation class. The maximum TFI refers to the maximum time needed between two fire events at a location that considers the fire interval required for fire-adapted species rejuvenation (Cheal, 2010). In this paper, we use vegetation age to describe these intervals. We assume that treatment of vegetation whose age is between these two intervals will maintain species diversity and hence support the ecosystem's health. Therefore, we select not to treat a treatment unit if the age of vegetation growing in that location is under the minimum TFI. In contrast, treatment units with vegetation over the maximum TFI must be treated. In this paper, we assume that the high-risk threshold age is between these two intervals. The objective of the model proposed in this paper is to reduce the spatial connectivity of fuel hazards while still considering the fire requirements of the ecosystem. The question that then arises is when and where to conduct fuel treatment to meet this objective, that can be solved for spatially complex landscapes with long planning horizons?

A mixed integer programming (MIP) model is proposed for multi-period fuel treatment scheduling. The model tracks the vegetation age in each treatment unit yearly for both treated and untreated areas. The model is then applied to a real landscape in southern Australia that comprises different shapes and sizes of treatment units.

## 2. Problem formulation

In this section, we explain the terms 'treatment unit' and 'patch' that we use to formulate the problem. The candidate locations for fuel treatment are represented by treatment units. A treatment unit comprises multiple patches. Each vegetation type growing in a treatment unit is represented by a patch and within each patch all the vegetation is of the same age. The data in each patch includes area, vegetation type and age. Patches within a single treatment unit may have different vegetation type and age, defining a 'multi-vegetation treatment unit'.

Each vegetation type has a 'high risk' age threshold. For example, grass and bush are considered to be high risk when they reach four and seven years old, respectively. Since we know the vegetation type and age in each patch, we then know whether a patch is a high-risk patch or not at any given time. In order to disconnect the high-risk treatment units in a landscape, we need a method to determine whether a treatment unit is a high-risk treatment unit