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Flexible planning of the investment mix in a forest fire management system: spatially-explicit intra-annual optimization, considering prevention, pre-suppression, suppression, and escape costs

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Abstract
We model intra-annual management as a multistage capacity investment problem, considering a portfolio of resources enabling fuel treatment and fire suppression, and having fires as the demand.
The solutions are spatially explicit and our Mixed Integer Programming model considers two types of flexibility: capacity commitment postponement (prevention, pre-suppression, and suppression) and spatial flexibility (ground crews and aerial resources).
The results confirm that higher volatilities in weather conditions lead to commitment postponement, and we have found that the prevention/suppression balance changes qualitatively according to the burnt hectare value. The changes in the investment mix correspond to real world behaviors and challenge several myths. We have also found that above a certain threshold for the burnt hectare value, fuel treatments are always needed.

Keywords: *forest fire management, risk management, multi-resource investment, stochastic optimization*

1. Introduction

There are few natural phenomena with the scope and complexity of wildland fires (Van Wagner 1985). Highly unpredictable factors, such as weather, suppression performance, or fire behaviour, spread, and effects, have to be addressed in most Forest Fire Management (FFM) decisions. With limited financial funds, equipment, and human resources, policy makers must decide their most efficient and effective distribution among alternative FFM options, such as community prevention, fuel treatment, pre-suppression, suppression, and restoration (Mavsar *et al.* 2010).

In Portugal, forest fires are a severe problem, accounting for more than half the fires in the EU Mediterranean region (San-Miguel-Ayanz *et al.* 2013). In recent years, the consequences of forest fires have been particularly severe, with multiple catastrophic fire seasons (2003, 2005, 2013), and every year, on average, close to 2.5% of forestland burned, total direct losses near 250 M€, and more than 120 M€ spent in fire prevention and suppression.

To help tackle some of the challenges raised by the complexity and the large uncertainties in FFM systems, we use optimization to study the relationship between different types of operational flexibility, when used to mitigate exposure to uncertainty.

2. Methods

Using data and insights from our previous studies and fieldwork, we propose a Stochastic Mixed Integer Programming (MIP) model focusing on fuel treatment planning, but taking into account escape and suppression costs. We model intra-annual FFM as a multistage capacity investment problem, considering a portfolio of resources (Chod *et al.* 2010) enabling fuel treatment and fire suppression, and having fires as the demand.

Demand uncertainty has two origins: inter-annual weather variability (oscillations in fire season severity); and uncertainty in micro-scale factors (ignition, time, place, escape probability, and specific fire severity). We focus our analysis on mismatch risk (the cost of supply differing from demand): over-investment in FFM capacity will lead to unused capacity costs, whereas under-investment will lead to forest value loss. We model inter-annual weather variability with a scenario tree (considering conditions for winter, and spring) and micro-uncertainty with a spatial grid, each cell characterized by maximum ignition probability.
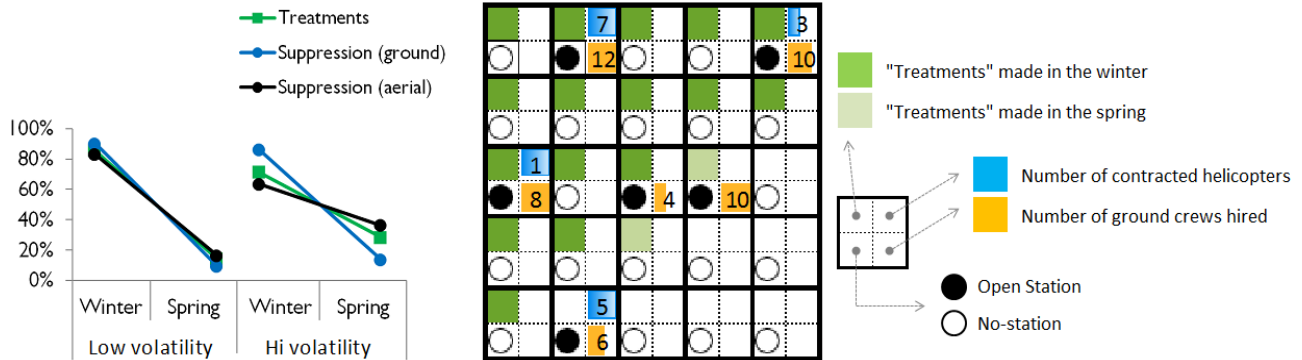

Figure 1. Low/high volatility vs. investment postponement % (left); spatial solution example (right).

We consider two types of flexibility (the ability to adapt to change): postponement of the commitment to each type of capacity (prevention and suppression), fine-tuning the capacity mix as the year evolves (and the weather conditional probabilities change); and spatial flexibility in a trade-off with the costs of the different suppression resource types (e.g., helicopters and ground crews).

3. Findings

Preliminary results point in three promising directions. First, the evolution of the investments along the year confirms that higher volatilities in weather conditions lead to their postponement (figure 1, left), and the results provide an estimate of the value for this source of flexibility. In addition, the solutions are spatially explicit (figure 1, right).

Second, we found that the balance between prevention and suppression changes qualitatively in the system (figure 2), according to the expanded cost attributed to each escaped fire (i.e., ignitions for which the initial attack fails, and come to be big or catastrophic fires), resulting in three system states. Finally, fuel treatments are always of value above a certain cost per hectare. Indeed, independently of how the escape cost rises above that threshold, the optimal absolute value of the budget for fuel treatments remains almost constant (figure 2, solid green line).
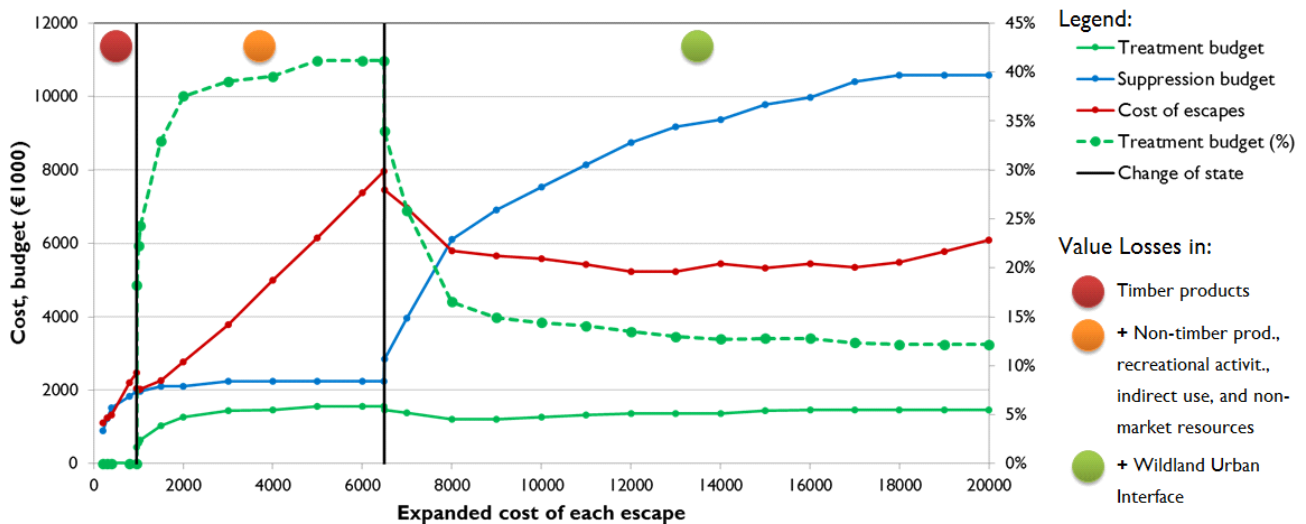
Figure 2. Global system behaviour and change of state (no prevention, prevention focused, and suppression dominance) according to the cost of each escaped forest fire.

4. Contribution

Studies addressing fuel treatment and fire suppression within the same model are scarce (Rideout *et al.* 2008), even more with the use of MIP, as in Minas *et al.* (2013), or Mercer *et al.* (2008). The latter inspired our model, which in turn modifies the standard-response model of Haight and Fried (2007) to include the effects of fuel treatment; in addition, we use insights from some of our previous studies (Collins *et al.* 2013; Pacheco *et al.* 2014).

Our results show that an integrated intra-annual FFM leads to a cost-effective allocation of the budget reducing the losses with catastrophic fires. In addition, the investment mix in each system state corresponds to different real world behaviours, challenging several FFM myths (e.g., prevention is always good; the prevention budget proportion should be at least one third; the utilization of helicopters is always a waste). Moreover, after a certain threshold the investments in fuel treatments are stable and always needed.

5. Acknowledgements

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