# NOTE / NOTE

# Examining fuel treatment longevity through experimental and simulated surface fire behaviour: a maritime pine case study

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**Abstract:** The adequate prediction of fire behaviour characteristics for both scientific and management objectives is deeply impacted by the performance of fire behaviour models. Both the lack of experimentation and limitations in fire modelling constrain current understanding of fuel treatment effectiveness and longevity. The residual effect of a 10-year-old prescribed fire was quantified by both simulating fire behaviour and observing real-world fire behaviour in treated (T10) and untreated (U25) fuels in a 25-year-old maritime pine (*Pinus pinaster* Aiton) stand in Portugal. Fire behaviour characteristics were measured in experimental surface fires ($n = 36$). Surface-fire behaviour was simulated using BehavePlus with custom fuel models for T10, U25, and U15 (the untreated fuel complex when the stand was 15 years old). The T10 fuel complex had significantly less decomposing litter load and shrub cover and load than the U25 fuel complex. The observed rate of fire spread did not differ between fuel complexes after accounting for the effects of other environmental variables, but flame length in T10 was 25% lower than that in U25. BehavePlus simulations contradicted the difference observed in flame length. Inconsistent and misleading assessments of fuel treatment effectiveness with detrimental impacts on the outcomes of fuel management may result from the generalized practice of solely using simulation in lieu of experimental fires.

**Résumé :** La prédiction adéquate des caractéristiques du comportement du feu à des fins scientifiques et pour la gestion des incendies est fortement influencée par la performance des modèles de comportement du feu. Le manque d'expérimentation et les limites de la modélisation restreignent par conséquent notre compréhension actuelle de la longévité et de l'efficacité du traitement des combustibles. L'effet résiduel d'un brûlage dirigé vieux de 10 ans est quantifié en simulant le comportement du feu et en l'observant en vrai dans des combustibles traités (T10) et non traités (U25) dans un peuplement de pin maritime (*Pinus pinaster* Aiton) âgé de 25 ans au Portugal. Les caractéristiques du comportement du feu ont été mesurées pour des feux de surface expérimentaux ($n = 36$). Le comportement des feux de surface a été simulé à l'aide de *BehavePlus* avec des modèles de combustibles sur mesure pour T10, T25 et U15, le complexe de combustibles non traités lorsque le peuplement avait 15 ans. Le complexe de combustibles T10 avait une charge de litière en décomposition ainsi qu'un couvert et une charge d'arbustes significativement moins élevés que celui d'U25. Les taux de propagation du feu observés dans les différents complexes de combustibles étaient semblables lorsqu'on tenait compte des effets des autres variables environnementales, mais la hauteur de flamme était 25 % plus faible dans le cas de T10 que dans celui d'U25. Les simulations de *BehavePlus* contredisaient les différences de hauteur de flamme observées. Des évaluations inconsistantes et trompeuses avec des impacts néfastes sur les résultats de la gestion des combustibles peuvent être le résultat de la pratique généralisée qui consiste à utiliser seulement la simulation au lieu des feux expérimentaux.

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## Introduction

Pine plantations are among the most flammable vegetation types, particularly when unthinned and unpruned and carrying high surface fuel loads (Cruz et al. 2008). In the Mediterranean Basin, pine woodlands primarily occur as extensive and poorly tended plantations (Fernandes and Rigolot 2007) that experience increasingly higher fire severities (Pausas et al. 2008). Maritime pine (*Pinus pinaster* Aiton) is a west Mediterranean native, where it occupies 4 × 10$^6$ ha within a significant range of elevation, soil, and climate conditions (Alía et al. 1996). Given its intrinsic vulnerability in fire-prone environments, maritime pine persistence in the landscape demands that proactive stand and fuel management practices are used, including prescribed burning (Fernandes and Rigolot 2007).

Fuel management in conifer forests seeks to reduce surface fuel availability, remove ladder fuels and lift the canopy, and decrease crown density (Agee and Skinner 2005).

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However, because of insufficient integration of fire behaviour and silviculture knowledge, these basic principles are not easily translated into specific fuel treatment prescriptions (Johnson and Peterson 2005). United States fire behaviour modelling systems that link models of surface fire behaviour (Rothermel 1972; Albini 1976) and crown fire initiation (Van Wagner 1977) and spread (Rothermel 1991) provide a quantitative basis to plan fuel management and are frequently used to assess the effects of fuel treatments (e.g., Stephens 1998; Schmidt et al. 2008). Fire simulation is flexible and allows exploration of alternative scenarios with fuel, stand structure, or weather conditions, but it rests more on theory than on sound field data (Raymond and Peterson 2005; Martinson and Omi 2008). After-the-fact studies of wildfires entering treated stands can offer the much needed empirical evidence of fuel treatment effectiveness and are now available for a range of North American forests (e.g., Finney et al. 2005; Raymond and Peterson 2005). These retrospective studies are invaluable, but their opportunistic nature imposes limitations on the conclusions that can be reached (Fernandes and Botelho 2003; Roccaforte et al. 2008). The ideal quantification of the effects of fuel treatment is obtained in fire experiments under weather conditions conducive to severe fire behaviour. However, experimental efforts of this nature in coniferous forest are seldom possible for obvious reasons. Only case studies examining how thinning and prescribed burning affect high-intensity fires are available, respectively, for boreal (Alexander and Lanoville 2004) and mediterranean (Fernandes et al. 2004) pine stands.

Mitigation of fire behaviour and severity by fuel management diminishes with time since treatment. Decreases in fire hazard are usually evident after the treatments are completed, but changes taking place afterwards have not received much attention and are poorly understood (Finney et al. 2005). Most modelling studies examine the immediate impact of the treatment (e.g., Stephens 1998), and only a few have addressed fire-potential development with fuel age (Brose and Wade 2002; Roccaforte et al. 2008). Relatively recent treatments also prevail in natural experiments. For example, Martinson and Omi (2003) inspected eight wildfires for fuel management performance, but most of the data pertained to treatments less than 5 years old. While the temporal dynamics of fuel accumulation and structure determine fuel treatment longevity, an experimental relation between fire behaviour and fuel age has been established directly only for a dry eucalypt forest (Gould et al. 2007).

Significant wildfire suppression problems are posed by 4-year-old fuels in northwest Portugal maritime pine stands, but concerns with the maintenance of site productivity and biodiversity recommend a minimum interval of 5 years between repeated prescribed fires (Fernandes 2002a). Fuel accumulation with time since underburning in northwest Portugal maritime pine stands has been previously described (Fernandes et al. 2002), but it is uncertain how it relates to fire hazard as time since treatment elapses. This study documents and contrasts fire behaviour in untreated fuels and 10-year-old fuels following the application of prescribed burning in a maritime pine stand, with the objective of adding to the current understanding of surface fuel treatment longevity.

## Methods

### Experimental procedures

The study site is located in Sevivas, within the Padrela plateau of northwest Portugal at 41°27′N, 07°30′W and an elevation of 970 m. The climate is mediterranean with mean annual rainfall and air temperature of 1000 mm and 12 °C, respectively. The 25-year-old maritime pine stand was unpruned and is established in schist-based soil on a gentle slope facing southeast–southwest. Plots (10–15 m²; 0.01–0.02 ha) — wide enough to reveal the fire behaviour potential associated with mild burning conditions (Wotton et al. 1999) — were prepared for experimental fires within an approximate area of 2 ha. The plots were located either in untreated fuels, hereafter referred to as U25, or in 10-year-old fuels that had developed after low-intensity prescribed burning for hazard reduction, hereafter referred to as T10. The surface fuel complex consisted of a litter layer and a contiguous low understorey of *Erica umbellata* Loefl. and *Pterospartum tridentatum* (L.) P. Gibbs, two sclerophyllous shrubs with a wide distribution in the western part of the Iberian Peninsula.

Preburn fuel characterization combined destructive and nondestructive sampling techniques and individualized the treated and untreated fuel conditions. The collection of fuel samples proceeded within the stand but outside the plots. Needle litter and fine woody particles, i.e., <0.6 cm in diameter, were harvested inside 0.07 m² quadrats, sorting the fresh material (L layer) from the decomposing fermentation (F) layer. Shrubs were collected in 1 m × 0.5 m quadrats to determine representative bulk density values (kg·m⁻³) for size classes <0.6 and 0.6–2.5 cm (Fernandes 2002b). Sample size per fuel age was $n = 15$ for litter and $n = 12$ for shrubs.

Fuel loading, i.e., the mass of dry fuel per unit area (t·ha⁻¹), was quantified for live fine fuels and for the 1, 10, and 100 h dead-fuel time lag classes, corresponding to roundwood diameters of <0.6, 0.6–2.5, and 2.5–7.6 cm, respectively (Brown 1974). Fine litter fuel loads for each fuel condition were taken as the mean values resulting from destructive sampling. The 10 and 100 h fuels are a minor constituent of this fuel type and were tallied by size class along three 15 m transects; their dry masses per unit area were then estimated with equations in Fernandes et al. (2002). Plot-level estimates of understorey mass, using bulk densities, were made possible by calculating shrub volume from measurements of understorey cover and height along line transects placed on the two plot diagonals. The percentages of standing dead shrub fuel were estimated with equations developed by Fernandes and Rego (1998) for the study region.

In-stand weather observations (i.e., ambient temperature, relative humidity, wind speed) for the duration of each experimental fire were acquired upwind of the plot at a height of 1.7 m above the ground. Moisture contents of the 1 h fuels; the F-layer of the forest floor; and the fine, live fuels were determined by oven-drying samples collected just before ignition. The fires were ignited as a line source using a hand-held drip torch on the windward plot edge and spread until reaching the opposite boundary. For fire observation, each plot was divided into sections defined by 1.5 m high metal poles placed along the plot axis at intervals of 2 or

3 m, thus minimizing any edge effect that might arise. The poles were used as reference markers to estimate certain fire behaviour characteristics. Three head-fire behaviour descriptors, rate of spread, flame height, and flame length, were measured or deduced from observation and image capture. Fire behaviour descriptors for each experimental fire were averaged from individual sections.

### Experimental data analysis

Mean values for the descriptors of the U25 and T10 fuel complexes were compared using the Tukey–Kramer honestly significant difference (HSD) test. Fire spread rate and flame length were modelled by least-squares regression. The environmental variables able to explain variation in fire behaviour were identified through correlation analysis. Scatterplots of fire behaviour characteristics versus the selected independent variables were inspected to define the form of the relationships. The dependent variables were log-transformed prior to model development because error variance increased as fire behaviour characteristics increased. Model development followed Myers (1990) and included stepwise techniques. Analysis of covariance and least-squares means comparison were then used to test whether fuel condition had an effect on fire behaviour. The threshold for statistical significance was set at the 5% level.

### Fuel modelling and fire simulation

Persistence of the fuel treatment effect was alternatively assessed by simulating surface fire behaviour with the BehavePlus fire modelling system (Andrews et al. 2008) after developing fuel models for U15 (the untreated fuel complex when the stand was 15 years old), T10, and U25. Data on fuel structure and loads for U15 were based on the destructive sampling ($n = 25$) of 1 m × 0.5 m quadrats and came from Botelho (1996). Input values for fuel surface-area-to-volume ratio were obtained from Cohen et al. (2003). Dead-fuel moisture of extinction and heat content were held constant at 45%, after Fernandes et al. (2008), and 21 500 kJ·kg$^{-1}$, respectively. The custom fuel modelling procedures of Burgan and Rothermel (1984) were adopted to summarize fuel data and calculate fuel depth before entering data into BehavePlus. No attempts have been made to adjust the resulting fuel model parameters.

Live-fuel moisture contents of 60% for *E. umbellata* and 80% for *P. tridentatum* in the region (unpublished data on file) were assumed at the summer drought peak and were used to calculate a mean value per fuel complex weighted by each species volume. As per BehavePlus, a 10 m open terrain wind speed of 40 km·h$^{-1}$ was adjusted to midflame height using 0.13 (U25, T10) and 0.16 (U15) as wind adjustment factors. Slope was set to 6°, the experimental site average. Estimates of rate of spread and flame length were obtained for T10 and U25 for the mean experimental fire environment, and for summertime wildfire scenarios for U15, T10, and U25. The simulations addressed moderate, high, and extreme fire weather scenarios, defined, respectively, by the 75th, 90th, and 97.5th percentiles of fine dead-fuel moisture content, which was estimated according to Rothermel (1983). The percentiles were calculated from 21 years of weather data from Vreia de Jales, Portugal, 10 km away from the study site.

## Results

### Experimental fire behaviour

Stand height, height to live canopy base, and basal area were 10.0 m, 3.8 m, and 32.7 m²·ha$^{-1}$, respectively. Average fuel characteristics for the untreated and treated fuel complexes are shown in Table 1. Forest floor and surface fine fuel loads were 5.3 and 2.3 t·ha$^{-1}$, respectively, higher in U25 than T10, but the differences were not statistically different ($p > 0.05$). The two fuel conditions were distinct only with respect to the F-layer load and importance of understorey vegetation. T10 had significantly lower amounts of F-layer litter, shrub cover, and shrub loading of both fine fuels (<0.6 cm) and 10 h fuels; shrub cover and composition should account for the difference in understorey biomass because shrub height did not differ by fuel condition. Estimated F-layer, fine shrub, and 10 h shrub loads in the treated plots represented on average 64%, 80%, and 47%, respectively, of the fuel loads in U25 plots. A shift in the relative composition of the understorey layer also occurred, with *P. tridentatum* increasing its relative volume by a factor of six and replacing *E. umbellata* as the dominant species in T10.

A total of 36 plots were burned in the experimental site, of which 14 plots carried 25-year-old fuels (U25) and 22 plots had been treated with a prescribed fire 10 years before (T10). The experimental fires were conducted outside the typical wildfire season in the months of November to June, thus under relatively mild atmospheric conditions (Table 2). Nonetheless, the observed variation in fire behaviour covered the entire range of surface fire activity: from slow-spreading, poorly sustained fires to high-intensity fires with flames extending into the lower canopy base and exhibiting short-range spotting (Table 2). Seven fires propagated downslope with the wind.

The analysis of fire spread rate identified wind speed, moisture content of fine, dead surface fuels, and slope as the influent independent variables. The fitted equation explained 66% of the observed variation in rate of spread. The untransformed form of the model is

[1]      $R = aU^b\exp(cM + dS)$

where $R$, $U$, $M$, and $S$ represent rate of fire spread, wind speed ($p < 0.001$), moisture content ($p < 0.001$), and slope ($p = 0.031$), respectively. The highest correlation between pairs of independent variables was with respect to $U$ and $S$ ($r = -0.13$, $p = 0.437$). There was no evidence ($p = 0.434$) of a fuel condition effect after fitting eq. 1, and the least-square means of rate of spread across the two fuel conditions were not significantly different (Table 3). Fire spread was nevertheless affected by fuel characteristics, because understorey height was significant ($p = 0.008$) when added to eq. 1 and increased model fit ($R^2 = 0.72$). No other weather-related or fuel variable could improve the fire spread model, including the moisture contents of the forest floor F layer ($p = 0.426$) and live shrubs ($p = 0.610$).

The flame length model ($R^2 = 0.75$) included rate of fire spread ($p < 0.001$), moisture content of fine, dead surface fuels ($p = 0.005$), and moisture content of the F layer ($p = 0.006$). The back-transformed model is formulated as

**Table 1.** Surface fuel descriptors of the 10-year-old (T10) and 25-year-old (U25) fuel complexes.

| Fuel variable | T10 | U25 |
|---|---|---|
| **Forest floor loads (t·ha⁻¹)** | | |
| 1 h | 4.35±0.47a | 4.91±1.23a |
| 10 h | 0.83±0.34a | 0.76±0.31a |
| 100 h | 0.51±0.28a | 0.99±0.27a |
| F layer | 7.65±2.46a | 11.96±4.85b |
| **Understorey** | | |
| Height (cm) | 50±11a | 54±12a |
| Cover (%) | 61.6±20.4a | 86.2±9.4b |
| PT volume ratio* | 0.79±0.05a | 0.13±0.03b |
| Load <0.6 cm (t·ha⁻¹) | 6.74±0.58a | 8.44±0.50b |
| Load 1 h (%) | 35.9±1.3a | 35.6±1.3a |
| Load 10 h (t·ha⁻¹) | 0.53±0.16a | 1.13±0.72b |

**Note:** Values are the means ± standard errors. Means followed by the same letter in a row are not statistically different ($p < 0.05$) according to the Tukey–Kramer honestly significant difference test.

*PT volume ratio is the *Pterospartum tridentatum* fraction of total shrub volume.

**Table 2.** Ranges in environmental conditions and fire behaviour in the experimental fires.

| Variable | T10 ($n = 22$) | U25 ($n = 14$) |
|---|---|---|
| Slope (°) | 0–9 | 0–9 |
| Mean wind speed (km·h⁻¹) | 0.9–6.0 | 1.0–6.0 |
| Air temperature (°C) | 5.8–21.7 | 5.7–18.6 |
| Relative humidity (%) | 26.7–73.9 | 26.0–70.0 |
| 1 h moisture content (%) | 9.6–41.7 | 9.8–36.6 |
| F-layer moisture content (%) | 11.1–264.3 | 21.9–273.1 |
| Live moisture content (%) | 82.3–157.6 | 82.3–105.0 |
| Rate of spread (m·min⁻¹) | 0.50–7.20 | 0.36–3.72 |
| Flame length (m) | 0.5–4.0 | 0.8–3.0 |

**Table 3.** Least-square means ± standard errors of fire behaviour of two fuel complexes in an experimental fire.

| Variable | T10 | U25 |
|---|---|---|
| Rate of spread (m·min⁻¹) | 1.26±0.11a | 1.43±0.14a |
| Flame length (m) | 1.5±0.1a | 2.0±0.1b |

**Note:** Means followed by the same letter in a row are not statistically different ($p < 0.05$).

$$[2] \quad L = aR^b\exp(cM + dM_F)$$

where $L$ is flame length and $M_F$ is the F-layer moisture content. The addition of the fuel complex type to the equation further reduced the amount of unexplained variation in flame length ($R^2 = 0.81$). The covariance analysis determined that when the other factors in the model are controlled by being set to neutral values, flame length in T10 is 25% lower than in U25 (Table 3).

### Simulated fire behaviour

The fire behaviour simulations are based on the fuel models as outlined in Table 4. The shrub layer dominates the U15 fuel complex, hence its higher depth and lower bulk density compared with that of U25 and T10. The total fuel load was higher for U25 (16.2 t·ha⁻¹) and very similar between U15 (12.4 t·ha⁻¹) and T10 (12.9 t·ha⁻¹). Table 5 contains predictions of rate of spread and flame length for U15, U25, and T10 for the mean weather and fuel moisture conditions under which the experimental fires were carried out (S1). The simulation agrees with the previous empirical analysis in that the rate of spread does not differ between U25 and T10. However, in contrast with observational evidence (Table 3), the simulation-based conclusion on fuel treatment persistence negates any difference in potential flame length between U25 and T10.

Table 5 also presents the simulated (S2) fire spread rates and flame lengths for the three wildfire scenarios and each fuel condition. The influence of increasingly drier fuels on fire behaviour is not very marked. Differences in fire potential between dead-fuel moisture content scenarios were especially less apparent in U15, probably because the relative importance of live fuels in U15 was higher than in U25 and T10 (Table 4). Fuel conditions in the 25-year-old stand, whether undisturbed or reflecting a 10 year fuel build-up, were predicted to produce decreased surface fire behaviour levels in relation to U15. Depending on fuel moisture scenario, rate of spread and flame length in U25 were, respectively, 46.1%–47.5% and 79.3%–84.4% of the U15 values. Natural fuel dynamics have thus resulted in a decline in surface fire potential with stand aging. When S2 simulations for T10 and U25 are compared, rate of spread in the former decreased by 14.3% to 15.4%, whereas flame length was virtually the same, in consonance with S1 simulations (Table 5).

### Discussion

The statistical analysis of fire spread rate and flame length variation used in this study case can be seen as a surrogate for the simultaneous ignition of fires in U25 and T10, the obvious experimental approach to detect the effect of fuel age on fire behaviour characteristics. Wind speed; moisture content of fine, dead surface fuels; and terrain slope were identified as the major influences on experimental fire spread rate, as expected from empirical work in other forest types (e.g., Forestry Canada Fire Danger Group 1992; Gould et al. 2007). Variation in rate of fire spread was further accounted for by understorey height, but because this variable did not differ between T10 and U25, its effect can only be ascribed to heterogeneity within the two fuel complex types or conditions. Field studies of shrub-dominated fire behav-

**Table 4.** Fuel conditions prior to treatment (U15), 10 year posttreatment (T10), and without treatment (U25) determined by custom fuel models.

| Fuel complex | Fuel load (t·ha$^{-1}$) | | | | SAVR (m$^{-1}$) | | Fuel depth (m) | BD (kg·m$^{-3}$) |
|---|---|---|---|---|---|---|---|---|
|  | 1 h | 10 h | 100 h | Live | 1 h | Live |  |  |
| U15 | 4.75 | 0.83 | 0.07 | 6.76 | 6736 | 7985 | 0.54 | 2.30 |
| U25 | 7.91 | 1.89 | 0.99 | 5.43 | 5809 | 8103 | 0.35 | 4.91 |
| T10 | 6.77 | 1.36 | 0.51 | 4.31 | 4844 | 5395 | 0.31 | 4.18 |

**Note:** SAVR, surface area to volume ratio; BD, bulk density.

**Table 5.** Fire behaviour in fuel complexes U15, U25, and T10: mean experimental (O) and corresponding simulated (S1) values, and simulated (S2) values for three wildfire scenarios.

| Fire scenario | Rate of spread (m·min$^{-1}$) | Flame length (m) |
|---|---|---|
| **U15** | | |
| S2 | | |
| 75th | 10.2 | 2.9 |
| 90th | 11.1 | 3.1 |
| 97.5th | 11.8 | 3.2 |
| **U25** | | |
| O | 1.6 | 2.1 |
| S1 | 1.4 | 1.1 |
| S2 | | |
| 75th | 4.7 | 2.3 |
| 90th | 5.2 | 2.5 |
| 97.5th | 5.6 | 2.7 |
| **T10** | | |
| O | 1.8 | 1.7 |
| S1 | 1.4 | 1.2 |
| S2 | | |
| 75th | 4.0 | 2.3 |
| 90th | 4.4 | 2.5 |
| 97.5th | 4.8 | 2.6 |

**Note:** 1, 10, and 100 h fuel moisture contents: 75th percentile — 8%, 9%, 10%, 90th percentile — 5%, 6%, 7%, 97.5th percentile — 3%, 4%, 5%; live woody moisture content: U15 and U25 — 62%, T10 — 72%.

iour often assume that fuel height integrates the fuel-complex structural attributes and effects on fire spread (e.g., Catchpole et al. 1998; Fernandes et al. 2000). The shift from *E. umbellata* (U25) to *P. tridentatum* (T10) as the dominant shrub species had no apparent effect on the rate of fire spread, in agreement with Fernandes et al. (2000).

Flame size expresses the heat released in the flaming front, which increases with rate of spread and the fuel available for combustion (Byram 1959). Fuel condition did not influence the experimental rate of fire spread but had a significant effect on flame length — older fuels produced larger flames, all other factors (i.e., spread rate and fuel moisture) being equal. Hence, in the absence of a fuel condition influence on rate of fire spread, one has to conclude that the fuel complex effect on flame length was exerted through fuel loading. The higher quantities of shrub and F-layer litter fuels were both responsible for the more intense

fires in U25 because moisture content of the F layer explained part of the variation in flame size. The F-layer involvement in flaming combustion is consistent with the conceptual model proposed by Cheney (1990): head fires spread across the fuel complex surface and down into the fuel complex, the latter contributing to flame length.

Experimental burning conditions were relatively mild, and so it is unclear how the assessment of fuel treatment longevity would hold under typical wildfire scenarios occurring later in the summer fire season. The forest floor and downed woody fuels would be wholly available to burn under drier fuel conditions, aggravating U25 burn severity in relation to T10.

Relative, rather than absolute estimates, can be useful to rank fire hazard conditions and assess the effectiveness or temporal persistence of a fuel treatment. The simulation outputs in Table 5 indicate not only that the fuel treatment effect on flame length is no longer present in T10 (wildfire scenarios S2-75th and S2-90th) but also that flame length can be slightly higher in T10 in relation to U25 (S1), which reverses for the S2-97th scenario. The longevity of the prescribed fire treatment impact on flame size was therefore underestimated by the simulation, with practical implications on judgments regarding burn severity and fire suppression capability.

Larger flames were measured in T10 at the lower end of the experimental fuel moisture range than were predicted for both fuel conditions under extreme weather scenarios. Flame length in BehavePlus is calculated from fireline intensity, using the empirical relationship of Byram (1959). However, the flame length – fireline intensity relationship varies with fuel complex structure (Cheney 1990), and fireline intensity was underpredicted because spread rate was underestimated and the forest floor contribution to the fuel model was restricted to surface litter, in accordance with Burgan and Rothermel (1984).

Simulation studies seldom acknowledge or discuss the limitations of fire modelling tools based on Rothermel's (1972) model. Fuel model parameters have to be adjusted to match observed fire behaviour and to circumvent the lack of experimental foundation in the model to address mixed-sized fuels, live fuels, and multilayered fuel beds. The fuel model development process is expected to include thorough testing and comparison of predictions with real-world fire data (Burgan and Rothermel 1984), but the studies that base the analysis of fuel treatments on custom fuel modelling ignore or only partially abide by such a procedure. The fire potential of shallow or compacted fuel beds is not described realistically without fine-tuning the corresponding fuel model (e.g., Hély et al. 2001; Cruz and Fernandes 2008).

On the other hand, some simulation studies of fuel treatment performance (e.g., Roccaforte et al. 2008; Schmidt et al. 2008) assume standard, stylized fuel models that depart from the specificity of local fuel conditions (Albini 1976) and in turn will not realistically depict the impact of particular treatments (Johnson and Peterson 2005).

The measurement of fire characteristics in T10 and U25 did not warrant a direct assessment of how the fuel treatment could affect wildfire behaviour and severity, but it provided empirical data useful to adjust fuel models and simulate fire behaviour under more extreme conditions than could be observed. When full-fledged outdoor fires are not feasible, fire potential can still be assessed on the basis of small-scale laboratory or field tests contrasting fire behaviour in treated and untreated fuel complexes.

Fuel dynamics is just one of the factors determining the number and timing of fuel treatments following the first intervention. In this study, a difference in flame length between the treated and untreated areas was still present 10 years after the treatment, but in an ongoing wildfire, the corresponding benefits to fire suppression operations would probably be modest, except perhaps on the least active sections of the fire perimeter. From the perspective of effective fire suppression under extreme weather conditions, the effect of prescribed burning in forests often persists for just 2–4 years after treatment, especially when the fuel complex is dominated by litter (Fernandes and Botelho 2003). Fire severity refers to the immediate impacts of fire ensuing from fuel consumption and heat release (Ryan and Noste 1985); heat pulses and tree size will interact to determine tree injury and mortality. If decreased burn severity is the primary criterion to evaluate fuel management effectiveness, then a fuel treatment will remain valuable provided that the potential energy release, as determined by fuel structure and accumulation and reflecting both flaming and smouldering combustion, is less than the potential energy release before the treatment.

## Acknowledgments

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