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Communication

Fire-caused tree mortality in thinned Douglas-fir stands in Patagonia, Argentina

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Abstract. In 2003 in a municipal park near Esquel, Patagonia, Argentina, plots within a 21-year-old Douglas-fir (*Pseudotsuga menziesii*) afforested area were subjected to three silvicultural treatments (thinning to Reineke's Stand Density Index (SDI) of 900, 700, 500). In March 2007 all plots were burned by a wildfire that presented extreme fire behaviour. Three weeks after the wildfire we assessed mortality, height of scorch and percentage of crown scorch, and during three subsequent growing seasons we measured mortality and growth parameters. At the end of the study, mortality differed significantly among treatments and an untreated control, and ranged from 100% in the untreated control to 25, 10 and 5% in the SDI 900, 700 and 500 treatments. The highest growth parameters and lower mortality rates were achieved at SDI indices of 700 or 500 (i.e. in the least dense plots). Trees thinned to these densities not only appear to withstand extreme fires, at least under the conditions presented, but also to achieve the highest growth rates.

Additional keywords: extreme fire behaviour, fuel management, Reineke's index, silvicultural treatments.

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Introduction

In the Andean Piedmont of Patagonia, Argentina, conifer afforestation started 40 years ago. Today, ~80 000 ha have been planted, 80% with ponderosa pine (*Pinus ponderosa* (Dougl.) ex Laws.) and the rest with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Loguercio *et al.* 2008). Most Patagonian afforestations have not yet received silvicultural treatments and there have been few activities to reduce fire hazard. These afforested areas accumulate biomass faster than it decomposes, thereby increasing fire risk. Recent data showed that 2–3% of all Patagonian afforested areas are burnt annually by wildfires, and that this percentage may increase in the future as these forests age and climate changes (Defossé *et al.* 2011). In forest fire-prone environments such as in Patagonia, silvicultural treatments should be conducted not only to maximise growth and timber quality (Cahill *et al.* 1986), but also to modify fuel structure to reduce fire hazard (Fulé *et al.* 2012). The reduction of canopy fuels by increasing canopy base height, decreasing stem and crown density and removal from the stand the slashes produced by those activities, are basic methods to minimise the negative effects of eventual fires (Agee and Skinner 2005). Douglas-fir trees, at least the older individuals, are known to have high fire resistance due to a thick, corky bark of high insulating capacity (Brown and Davis 1973, p. 39). However, information about post-fire survival of young, even-aged Douglas-fir afforested stands subjected to different pruning and thinning densities is still scarce. In this study we took advantage of a wildfire that occurred in 2007 in a park located near the city of Esquel in Patagonia, Argentina, to determine post-fire effects on some growth parameters and mortality in three Douglas-fir stands that had been thinned to different densities in 2003. The objectives of this study were to: (1) estimate fire intensity and flame length in fire-affected Douglas-fir stands previously thinned to different densities; (2) determine primary effects three weeks after fire occurrence on stand attributes in all treatments; (3) determine post-fire effects on mortality and other growth parameters one, three, and four growing seasons after the fire and (4) determine which silvicultural treatment best achieves both fire resistance and favourable tree growth.

Materials and methods

Study area

The afforested area of this study consisted of 300 ha of ponderosa pine and Douglas-fir stands 5–26 year old within La Zeta Municipal Park (42°53′S and 71°20′W). The 950-ha park was

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formerly a shrub steppe composed of native Patagonian grasses (*Stipa*, *Poa*, *Festuca*, *Bromus* and *Hordeum* spp.) and shrubs (*Acaena*, *Colletia*, *Discaria*, *Fabiana*, *Mulinum* and *Berberis* spp). Most of this vegetation ceases aerial growth during the summer when its aboveground structures become dead or completely dry (Bertiller *et al.* 1991). This condition facilitates ignition and propagation of fires occurring in the region. The park has a typical Mediterranean climate with a mean annual rainfall of 564.8 mm (Pereyra and Abadie 1966).

Stand characteristics and treatments

In winter 2003 (August), a 21-year-old Douglas-fir stand was thinned to three different densities based on the Reineke's Stand Density Index: SDI 900, 700 and 500 (Reineke 1933; Long 1985), plus a control. One sample plot was established in each of the thinned and control areas. Plots were contiguous with each other, and each consisted of a 40 × 40-m area surrounded by a 10-m exterior (buffer) border. The SDI is a measure of the stocking of a stand, based on the mean number of trees per hectare and the mean diameter calculated from the basal area. This index assumes that even-aged, fully stocked stands of the same species always have the same number of trees when they reach a pre-determined quadratic mean diameter (*Dq*, cm). The SDI is expressed (Daniel *et al.* 1982) as:

$$\mathrm{SDI} = n\ (Dq\,25^{-1})^{1,605} \qquad (1)$$

where n is the number of trees per hectare. Because trees inside treatment plots were so uniform in size, diameter and height data were collected on only 40 systematically selected trees per treatment plot (based on the general rules for systematic sampling in Scheaffer *et al.* 1986). At the time of thinning all treatments were pruned to a height of 3.5 m and the pruning height for the control was 2.5 m. Most thinning and pruning residues were removed from the treated areas.

Weather variables and wildfire behaviour

On 4 March 2007 at 0745 hours a rapidly spreading arson fire was detected in the park. We went to observe the fire, taking *in situ* meteorological data (temperature, relative humidity and wind speed) and measuring or estimating fire behaviour variables (fire intensity, flame length, linear rate of spread and fuel consumed).

Fire intensity was estimated by applying Byram's (1959) equation, modified by Alexander (1982), as:

$$I = H\,w\,R \qquad (2)$$

where I is fire intensity (kW m^{-1}), H is the net low heat of combustion (kJ kg^{-1}), w is the quantity of fuel consumed in the active flame front (kg m^{-2}) and R is the linear rate of fire spread (m s^{-1}). For H, we used a value of 18 000 kJ kg^{-1} based on studies carried out in similar ecosystems (Beck *et al.* 2005). Since understorey fuel load previous to the fire was unknown, we estimated it by destructively sampling understorey vegetation in ten 1-m^2 plots placed randomly in the unburnt Douglas-fir stand near the treatment plots. Biomass inside these plots was collected to the ground level; taken to the laboratory, separated into time lag categories (Schlobohm and Brain 2002), oven dried to constant weight and weighed. From the total load and according to Alexander (1982), we estimated that the fuel consumed by the active flame front (w) was ~75% of the total understorey load. The linear rate of spread (R) was estimated by visual observations during the actual fire.

Flame length was estimated by applying Byram's (1959) equation adapted by Alexander (1982), as:

$$L = 0.0775\,I^{0.46} \qquad (3)$$

where L is flame length (m) and I is fire intensity (kW m^{-1}).

Fire effects

The 'direct' effects of the fire on the different treatments were determined three weeks after the fire event. Crown scorch height was determined by systematic sampling (Scheaffer *et al.* 1986) of 40 trees per treatment plot. This height was measured with a Vertex hypsometer (Haglöf, Långsele, Sweden), measuring from ground level to the highest point of each tree's crown scorch and rounded to the nearest 10 cm. In the case of SDI 500, since the crowns were neither burnt nor scorched, we measured stem char height instead. Percentage of crown scorch volume was estimated visually as the proportion of the crown scorched and killed due to fire in relation to the whole crown. Significant differences in crown scorch were determined by analysis of variance. These data were rounded to the nearest 10% according to Fowler and Sieg (2004). Tree mortality caused by the wildfire was calculated as the number of dead trees observed in each treatment plot as a percentage of the total number of trees in that plot. This measurement was repeated 1 (2008), 3 (2010) and 4 (2011) years after the fire. Stand characteristic data were collected right after thinning, and then 1 (2008) and 3 (2010) years after the fire. Mean height was measured as for crown scorch height. Quadratic mean diameter (*Dq*) was calculated from the mean basal area obtained from diameter at breast height (DBH) on the same aforementioned 40 systematically selected trees per treatment. Mean annual increment (MAI) in DBH per treatment plot was calculated right after thinning (2003) by dividing the DBH by the age of the plantation. Mean annual increment in DBH measured in 2008 was the annual growth achieved from 2003 to 2008, whereas MAI in 2010 was that achieved from 2008 to 2010. The presence of insects or pathogens was determined at the end of the first (2008), third (2010) and fourth (2011) growing seasons after the fire. Equation 4 of Bell *et al.* (1981, p. 4) modified by Davel (2008) was used to determine volume of each stand and annual growth per treatment was the total volume achieved per year.

Results and discussion

Weather variables and wildfire behaviour

Right after the fire was detected the air temperature was 13.7°C, relative humidity was extremely low (9%) and wind speed ranged from 15 to 18 km h^{-1}. At 1200 hours, temperature increased to 16°C and relative humidity rose to 35%. At that time the fire started to be driven by the wind, whose speed increased from 20 km h^{-1} at 0800 hours to 35 km h^{-1} at 1500 hours, remaining stable at that speed until 2100 hours. Under these

Table 1. Crown scorch height and crown scorch volume (mean ± standard error) three weeks after the wildfire, and mortality after one (2008), three (2010) and four (2011) growing seasons after the wildfire

Treatment ($n = 40$)	Crown scorch height (m)	Crown scorch volume (%)	Tree mortality (%)		
			2008	2010	2011
Control	14.2 ± 4.7	100 ± 0.0	100	100	100
SDI 900	7.6 ± 1.9	66 ± 5.1	20	25	25
SDI 700	5.5 ± 0.9	39 ± 4.7	5	10	10
SDI 500	1.8 ± 0.2^{A}	0	0	5	5

^{A}In SDI 500 this value corresponds to stem char height.

conditions, the rate of fire spread was $0.11\ m\ s^{-1}$ in the open, unforested area. During this major run fire presented extreme behaviour and reached the treatment sites. The rate of spread diminished to $0.042\ m\ s^{-1}$ when the fire reached the treatment and control plots. This diminution may have been due to the attenuating effects of the forest on wind speed. Total understorey fuel load was $4.36 \pm 0.54\ kg\ m^{-2}$; 52% corresponding to 1-h fuels and 48%, to 10-h fuels. Assuming 75% consumption by the active flame front, fuel consumed was $3.27\ kg\ m^{-2}$. Fire intensity inside the treatment plots was $2353\ kW\ m^{-1}$ and flame length was 2.8 m. The fire rapidly crowned in the control plot whereas flames were too small to get to the crowns in the thinned treatments, burning the foliage by heat radiation or convection alone. Flame length was fairly similar in all treatment plots, although its height was lower in the SDI 500 plot than in the other treatments. This effect may have been caused by the wind, which forced the flames to remain more horizontal in this less dense stand.

Primary fire effects

Three weeks after the fire crown scorch volume was 100% in the control plot, 66% in SDI 900, 39% in SDI 700 and, in SDI 500 crowns were not scorched at all (Table 1). Analysis of variance suggested significant differences in crown scorch due to thinning ($P < 0.001$). Analogous results were reported by Graham *et al.* (2004) for a wildfire that burned a natural stand of Douglas-fir–ponderosa pine forest in the western United States. Peterson *et al.* (1991) detected ~40% crown scorch volume in naturally grown Douglas-fir stands burned by a wildfire in the northern Rocky Mountains (USA), similar to the value recorded in our plot thinned to SDI 700. Crown scorch increases with fireline intensity (Van Wagner 1973) and in wildfires is constrained by the prevailing fuels and environmental conditions as well as crown base height and tree size (Ryan and Reinhardt 1988). In our study plots, because the environmental conditions and fuel loading were similar for all treatments, differences in crown scorch volume might be attributed to understorey fuel availability and the treatments themselves, as explained in Alexander and Cruz (2012).

Crown scorch height was significantly ($P < 0.0001$) higher (14.2 m) in the control plot than in treatment plots (7.6, 5.5 and 1.8 m (stem char height) in SDI 900, 700 and 500) (Table 1). In the Rocky Mountains Douglas-fir fire crown scorch height averaged 9.7 m (Peterson *et al.* 1991). In our study, a similar value was measured in the unthinned control and the least thinned treatment (SDI 900), suggesting that, considering the age of the stands, this thinning treatment could be highly affected by fire. The literature has established that *Pinus* and other conifer species can withstand from one- to two-thirds foliage loss due to fire without significant growth loss effects (Ryan 1982; Peterson and Arbaugh 1989; de Ronde *et al.* 1990). In our case, it seemed that the values reached in the SDI 900 treatment for both crown scorch volume and crown scorch height represent a threshold above which fire effects severely restricted Douglas-fir growth and survival (Table 1). In contrast, although the SDI 700 treatment showed some crown scorch damage it rapidly recovered and later showed growth rates similar to SDI 500, which suffered no crown scorch at all.

Tree mortality

No trees survived in the control plot, whereas the percentage of dead trees decreased as the SDI decreased (Table 1). At the end of the first growing season after the fire (2008), mortality was 20, 5 and 0% for SDI treatments of 900, 700 and 500. In 2010 mortality was 25, 10 and 5% for the same treatments, and remained unchanged for 2011 (Table 1). This suggests a stabilisation of this parameter for all treatments, and that no further mortality due to fire is expected. Our results also showed a direct relationship of crown scorch volume and stem char height (for SDI 500) with tree mortality (Table 1). Furthermore, a strong relationship ($r = 0.79$, $P < 0.001$) was found between crown scorch height and tree mortality. Our findings generally agree with Peterson (1984, 1985) and Peterson *et al.* (1991), who considered that the degree of crown injury is a critical determinant of Douglas-fir survival and growth after wildfires, and that crown scorch height and percentage of crown scorch volume are good indicators of tree damage.

Some studies in western North America found no significant differences in tree mortality due to crown scorch volume between Douglas-fir and ponderosa pine after wildfire (McHugh and Kolb 2003; Fowler and Sieg 2004; Raymond and Peterson 2005). This assertion, however, should be carefully considered if our results are intended to be expanded to similarly thinned, young ponderosa pine afforestations burned by wildfires in Patagonia. Although crown scorch volume may be similar in both species, differences in bud resistance to fire could lead to different mortality rates (Peterson and Ryan 1986). More studies will be necessary to elucidate this crucial question because ponderosa pine and Douglas-fir will continue to be the most-planted species in Patagonia. Although currently only ~2–3% of these still-young afforestations are burned by wildfires annually, it is probable that this percentage could increase

Table 2. Stand characteristic data of the treatment plots before and after the thinning (2003), and 1 (2008) and 3 (2010) years after the wildfire

Abbreviations are: SDI, site density index of Reineke; *Dq*, quadratic mean diameter; MAI, mean annual increment in diameter at breast height (DBH) (±s.e.). Heights are mean ± s.e.

Plot	SDI	Dq^B (cm)	Height (m)	MAI in DBH (cm $year^{-1}$)	Annual growth (m^3 ha^{-1} $year^{-1}$)
After thinning 2003					
Control	1354	18.7	12.9 ± 0.2	0.8 ± 0.3	16.7
SDI 900	858	17.0	12.7 ± 0.3	0.7 ± 0.2	9.8
SDI 700	680	23.4	14.5 ± 0.2	0.8 ± 0.2	9.5
SDI 500	507	18.8	13.2 ± 0.2	0.7 ± 0.3	6.2
After fire 2008[A]					
Control	–	–	–		
SDI 900	1078	21.8	14.7 ± 0.2	0.6 ± 0.2	7.0
SDI 700	878	27.8	17.4 ± 0.2	1.0 ± 0.2	11.3
SDI 500	709	23.2	16.0 ± 0.2	1.0 ± 0.2	8.8
After fire 2010[B]					
Control	–	–	–	–	–
SDI 900	1063	22.5	15.6 ± 0.5	0.4 ± 0.3	10.6
SDI 700	955	30.3	18.4 ± 0.2	1.1 ± 0.2	12.0
SDI 500	799	25.8	17.0 ± 0.4	1.0 ± 0.2	9.1

[A]Annual increment in DBH from 2003 to 2008.
[B]Annual increment in DBH from 2008 to 2010.

in the near future. Some of the causes for this increase are stands aging, reluctance of landowners to carry out proper silvicultural treatments (thinning, pruning and prescribed burning) and the increase in global mean temperatures (Defossé *et al.* 2011).

Effects of thinning on different growth parameters

Right after thinning (2003), MAI in DBH was similar (~0.8 cm $year^{-1}$) for all plots (Table 2). From 2003 to 1 year after the fire (2008), the MAI at DBH reached 1.0 cm $year^{-1}$ for both SDI 500 and 700 plots, significantly higher than the 0.6 cm $year^{-1}$ obtained in SDI 900 (Table 2). Differences in MAI in DBH found between SDI 500 and 700 as compared with SDI 900, still remained when the stands were re-measured in 2010 (Table 2), and may have been due to the combined effects of thinning and fire. Similar findings to our SDI 500 to 700 comparison were noted in a Douglas-fir afforestation in Chile grown under similar environmental conditions as those presented here. That afforestation, thinned to 775 trees ha^{-1}, produced a MAI in DBH from 0.7 to 1.6 cm $year^{-1}$ 4 years after thinning (Drake *et al.* 2003). Annual growth (in volume) measured 1 (2008) and 3 (2010) years after the fire was greater in the SDI 700 plot than in the other two treatments (Table 2). It seems then that in SDI 500 thinning was excessive, whereas thinning to SDI 900 appears to be risky if a wildfire occurs. No pathogens or insect outbreaks were observed after the wildfire in any of the treatments in 2008, 2010 or 2011. This could be due to the fact that Douglas-fir is practically a newcomer to Patagonia, and no specific insects or pathogens have been detected to attack this species yet.

Management implications

This study showed that silvicultural treatments (thinning to Reineke's SDI from 500 to 700) and removal of thinning residues could be a sound management option to achieve both the greatest growth and a considerable reduction of fire risk in Douglas-fir afforestations in Patagonia. In the future and besides thinning, other fuel reduction treatments (i.e. mastication, prescribed underburning) should be tested to reduce wildfire risk in these afforestations. This study could serve as a basis to expand our results to other Douglas-fir afforestations carried out in similar Mediterranean ecosystems around the world.

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References

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83–96. doi:10.1016/J.FORECO.2005.01.034

Alexander ME (1982) Calculating and interpreting forest fire intensities. *Canadian Journal of Botany* **60**, 349–357. doi:10.1139/B82-048

Alexander ME, Cruz MG (2012) Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. *International Journal of Wildland Fire* **21**, 95–113. doi:10.1071/WF11001

Beck J, Parminter J, Alexander M, MacDermid E, Van Nest T, Beaver A, Grimaldi S (2005) Fire ecology and management. In 'Forestry Handbook for British Columbia', 5th edn, (Eds SB Watts, L Tolland) pp. 485–521. (Forest Undergraduate Society, Faculty of Forestry, University of British Columbia: Vancouver, BC)

Bell JF, Marshall DD, Johnson GP (1981) Tariff tables for mountain hemlock developed from an equation of total stem cubic foot volume.

Oregon State University, School of Forestry, Forest Research Laboratory, Research Bulletin 35. (Corvallis, OR)

Bertiller MB, Beeskow AM, Coronato FR (1991) Seasonal environmental variation and plant phenology in arid Patagonia (Argentina). *Journal of Arid Environments* **21**, 1–11.

Brown AA, Davis KP (1973) 'Forest Fire: Control and Use', 2nd edn. (McGraw-Hill: New York)

Byram GH (1959) Combustion of forest fuels. In 'Forest Fire. Control and Use'. (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York)

Cahill JM, Snellgrove TA, Fahey TD (1986) The case for pruning young-growth stands of Douglas-fir. In 'Douglas-fir: Stand Management for the Future'. (Eds CD Oliver, DP Hanley, JA Johnson) pp. 123–132. (College of Forest Resources, University of Washington: Seattle, WA)

Daniel PW, Helmus UE, Baker FS (1982) 'Principios de Silvicultura', 2nd edn. (McGraw Hill: Mexico City)

Davel MM (Ed.) (2008) Estimación del volumen. In 'Establecimiento y Manejo del pino oregón en Patagonia'. Manual Number 9, Centro de Investigación y Extensión Forestal Andino Patagónico CIEFAP, pp. 69–80. (Esquel, Argentina)

de Ronde C, Goldammer JG, Wade DD, Soares RV (1990) Prescribed fire in industrial pine plantations. In 'Fire in the Tropical Biota – Ecosystem Process and Global Challenges'. (Ed. JG Goldammer) pp. 216–272. (Springer Verlag: Berlin)

Defossé GE, Loguercio GA, Oddi FJ, Molina JC, Kraus PD (2011) CO_2 emissions mitigation through forest prescribed burning – options within the frame of the Kyoto Protocol: a case study in Patagonia, Argentina. *Forest Ecology and Management* **261**, 2243–2254. doi:10.1016/J.FORECO.2010.11.021

Drake F, Acuña E, Salas S (2003) Evaluación retrospectiva para determinar la oportunidad de raleo en un rodal de pino oregón de 24 años. *Bosque* **24**, 85–91.

Fowler JF, Sieg CH (2004) Postfire mortality of ponderosa pine and Douglas-fir: a review of methods to predict tree death. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-132. (Fort Collins, CO)

Fulé PZ, Crouse JE, Roccaforte JP, Palies EL (2012) Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behaviour? *Forest Ecology and Management* **269**, 68–81. doi:10.1016/J.FORECO.2011.12.025

Graham R, McCaffrey S, Jain TB (2004) Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-120. (Fort Collins, CO)

Loguercio GA, Jovanovski A, Molina JC, Pantaenius P (2008) Residuos de biomasa de forestaciones y aserraderos de la región Andina de las Provincias de Chubut y Neuquén. Centro de Investigación y Extensión Andino-Patagónico CIEFAP and Japan International Cooperation Agency JICA, Evaluación preliminar de oferta. Publicación técnica 34. (Esquel, Argentina)

Long JN (1985) A practical approach to density management. *Forestry Chronicle* **61**, 23–27.

McHugh CW, Kolb TE (2003) Ponderosa pine mortality following fire in Northern Arizona. *International Journal of Wildland Fire* **12**, 7–22. doi:10.1071/WF02054

Pereyra JA, Abadie CA (1966) 'Las lluvias del oeste del Chubut.' (Centro Regional Patagónico, Agencia de Extensión y Experimentación Esquel, Instituto Nacional de Tecnología Agropecuaria (INTA): Esquel, Chubut, Argentina)

Peterson DL (1984) Predicting fire-caused mortality in four Northern Rocky Mountain conifers. In 'Proceedings of the 1983 Convention of the Society of American Foresters New Forests for a Changing World', 16–20 October 1983, Portland, OR. pp. 276–280. (Society of American Foresters: Bethesda, MD)

Peterson DL (1985) Crown sorch volume and sorch height: estimates of postfire tree condition. *Canadian Journal of Forest Research* **15**, 596–598. doi:10.1139/X85-097

Peterson DL, Arbaugh MJ (1989) Estimating postfire survival of Douglas-fir in the Cascade Range. *Canadian Journal of Forest Research* **19**, 530–533. doi:10.1139/X89-084

Peterson DL, Ryan KC (1986) Modeling postfire conifer mortality for long-range planning. *Environmental Management* **10**, 797–808. doi:10.1007/BF01867732

Peterson DL, Arbaugh MJ, Pollock GH, Robinson LJ (1991) Postgrowth of *Pseudotsuga menziesii* and *Pinus contorta* in the Northern Rocky Mountains, USA. *International Journal of Wildland Fire* **1**, 63–71. doi:10.1071/WF9910063

Raymond CL, Peterson DL (2005) Fuel treatments alter the effects of wildfire in a mixed–evergreen forest, Oregon. USA. *Canadian Journal of Forest Research* **35**, 2981–2995. doi:10.1139/X05-206

Reineke LH (1933) Perfecting a stand density index for even aged forests. *Journal of Agricultural Research* **46**, 627–638.

Ryan KC (1982) Evaluating potential tree mortality from prescribed burning. In 'Proceedings of the Symposium on Site Preparation and Fuels Management on Steep Terrain', 15–17 February 1982, Spokane, WA. (Ed. DM Baumgartner) pp. 167–179. (Washington State University: Pullman, WA)

Ryan KC, Reinhardt ED (1988) Predicting postfire mortality of seven western conifers. *Canadian Journal of Forest Research* **18**, 1291–1297. doi:10.1139/X88-199

Scheaffer RL, Mendenhall W, Ott L (1986) 'Elementary Survey Sampling', 3rd edn. (Duxbury Press: Boston, MA)

Schlobohm P, Brain J (2002) Gaining an understanding of the National Fire Danger Rating System. USDA Forest Service. US Department of Interior, National Wildfire Coordinating Group, Fire Danger Working Team, PMS 932, NFES 2665. (Boise, ID)

Van Wagner CE (1973) Height of crown scorch in forest fires. *Canadian Journal of Forest Research* **3**, 373–378. doi:10.1139/X73-055