Research Note

An experimental assessment of the impact of drought and fire on western larch injury, mortality and recovery

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Abstract. Climate change is increasing drought and fire activity in many fire-prone regions including the western USA and circumpolar boreal forest. These changes highlight the need for improved understanding of how multiple disturbances impact trees in these regions. Recent studies linking fire behaviour to plant ecophysiology have improved understanding of how fire affects tree function and mortality but have not investigated interactions between drought stress and fire. In this study, *Larix occidentalis* saplings were subjected to different levels of water stress followed by low-intensity surface fires in a controlled laboratory setting. Post-fire mortality, recovery and growth were monitored for up to 1 year post fire. Generally, increased pre-fire water stress resulted in decreased post-fire stem diameter (up to 5% lower) and height (up to 19% lower) growth. However, severely water-stressed saplings whose foliage had senesced before the fires had lower 1-year mortality (14%) and significantly greater post-fire bud densities than moderately stressed saplings that did not senesce (86% mortality). The mortality patterns suggest that water-stressed western larch saplings exposed to low-intensity wildfires, or prescribed fires conducted as part of forest management activities, may exhibit lower mortality rates if stress-induced foliar senescence has occurred.

Additional keywords: carbon cycling, conifers, deciduous, fire severity, post-fire impacts, sapling, tree growth, trees.

Introduction

Drought stress has produced widespread tree mortality and decreased growth in circumpolar boreal forests, including those dominated by deciduous conifers in Eurasia and evergreen-dominated forests in North America (Dulamsuren *et al.* 2010; Beck *et al.* 2011; Peng *et al.* 2011). *Larix*, a genus composed of deciduous needle-leaf gymnosperms, is a common component of many fire-prone ecosystems in these regions and plays a significant role in regional carbon cycle dynamics and surface albedo (Gower and Richards 1990; Shuman *et al.* 2011). In western North America, western larch (*Larix occidentalis* Nutt.) is a highly valued timber species, in part owing to its high growth rate (Schmidt *et al.* 1976; Rehfeldt and Jaquish 2010). Along with other regions, climate change is predicted to increase frequency and severity of droughts and fires in North America (Kharuk *et al.* 2008; Dai 2013; de Groot *et al.* 2013; Young *et al.* 2016), which could alter the biological range of productive conifer species such as western larch (Rehfeldt and Jaquish 2010; Coops and Waring 2011; Smith *et al.* 2014), yielding younger forest age class distributions (Bonan 2008) and land cover type conversions (Shuman *et al.* 2011; Millar and Stephenson 2015). However, the impacts and interaction of multiple disturbances, such as drought and fire, on tree function, mortality and post-fire recovery are poorly understood (Millar and Stephenson 2015).

Independently, drought-induced water stress and fire can substantially affect tree physiology, growth and mortality. Water-stressed trees may close stomata for extended periods to reduce cavitation in xylem tissues, leading to decreased photosynthesis and increased reliance on non-structural carbohydrate (NSC) stores (McDowell *et al.* 2011). If stomata remain closed, trees utilise NSCs for maintenance respiration, as well as osmotic and defence needs (McDowell *et al.* 2011; Adams *et al.* 2017). Under severe stress, deciduous trees can undergo leaf senescence to conserve nutrients (Silla and Escudero 2006; Marchin *et al.* 2010). Because water stress can decrease pools of NSCs, drought can potentially increase fire-induced mortality by limiting carbon (C) available for post-fire recovery.

Fires can damage trees via multiple mechanisms involving the transfer of heat to the roots, bole and crown (Michaletz and Johnson 2007). Cell death (necrosis) or deformation in tree tissues can severely impair C sequestration and vegetative bud regeneration (Michaletz and Johnson 2006, 2008). Severe crown damage (~80% crown scorch) reduces photosynthesis in

remaining live foliage (Smith *et al.* 2016a, 2017) and is linked to decreased nitrogen uptake and total NSCs in roots (Guo *et al.* 2004). Likewise, cell death or deformation in tree xylem and phloem can impair movement of water, nutrients and C (Bär *et al.* 2018). Several studies have observed heat-induced cavitation in xylem conduits of cut plant segments (Michaletz *et al.* 2012; West *et al.* 2016), and non-functioning xylem in tree cross-sections after wildfires (Balfour and Midgley 2006; Smith *et al.* 2016b), leading to the hypothesis that reduced xylem conductivity is an important mechanism of fire-caused injury and mortality (Balfour and Midgley 2006; Kavanagh *et al.* 2010).

Interactions and feedbacks between water stress and fire on tree physiology are not well understood. Pre-fire climatic stress can increase the probability that trees will die from fire-induced damage in temperate (van Mantgem *et al.* 2013) and tropical forests (Van Nieuwstadt and Sheil 2005; Brando *et al.* 2014). Yet, van Mantgem *et al.* (2016) observed lower post-fire mortality probability for some temperate conifers during a subsequent severe drought compared with unburned trees, which they attributed to lower stand densities and reduced competition for resources in burned areas. In semicontrolled nursery experiments, exposure to fire did not affect fine root growth of water-stressed *Quercus* spp. saplings (Chiatante *et al.* 2005; Di Iorio *et al.* 2011). Although these studies provide probabilistic evidence of interactions between drought and fire effects, mechanistic research is needed to support accurate predictions of ecosystem function.

Toxicological dose–response experiments provide a potential framework to study interactions of water stress and fire on trees. Previous fire dose–response studies have used well-watered saplings (Smith *et al.* 2016a, 2017; Sparks *et al.* 2016) or low-intensity prescribed fires that did not result in tree mortality (Sparks *et al.* 2017). In the present study, western larch saplings were subjected to water stress doses followed by a low-intensity surface fire that in a prior study only caused limited mortality in well-watered individuals (Sparks *et al.* 2016). Sapling is defined as the growth stage following seedlings, where seedlings are plants dependent on stored seed reserves. We tested the hypothesis presented in Smith *et al.* (2017) that pre-fire stress leads to increased mortality in fire-affected saplings (Fig. 1). We further sought to test whether the degree of pre-fire water stress amplifies the dose–response relationship; i.e. trees with greater pre-fire water stress would exhibit decreased growth, physiological function and survival post fire.

Methods

Larix *saplings and growing conditions*

Western larch (*Larix occidentalis* Nutt.) saplings ($n = 28$) were grown in a climate-controlled greenhouse in Moscow, Idaho, USA, through two growing seasons under natural light conditions. The total number of saplings used in this experiment was limited owing to the logistical limitations (nursery space and cost) of growing and conditioning these trees to multiple levels of water stress in a controlled nursery environment for this amount of time. Average ($\pm$s.e.) sapling height was 96.1 ± 0.6 cm, with a height to crown base of 36.3 ± 0.3 cm. Average diameter at root collar was 12.9 ± 0.4 mm. Over this period, nutrient solutions (N : P : K) of Peters Professional
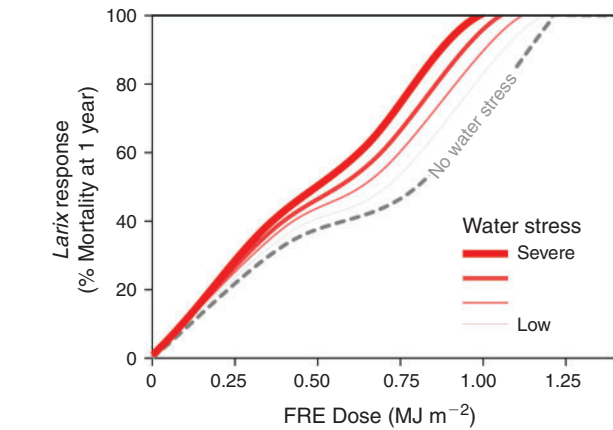

Fig. 1. Hypothesised shift of relationship between *Larix* mortality and fire radiative energy (FRE) (dose–response curve) as tree water stress increases (adapted from Smith *et al.* 2017). Dashed grey line indicates observed *Larix* mortality in Smith *et al.* (2017).

fertiliser were applied during the early (N : P : K, 10 : 30 : 20), mid (N : P : K, 20 : 7 : 19), and late (N : P : K, 4 : 25 : 35) growing season each year. Prior to the water stress and burn treatments, saplings were re-potted in a soil medium mix consisting of 50% perlite, 22.5% sphagnum peat moss, 22.5% vermiculite and 5% fine bark chips in 9.5-L pots and allowed to acclimate for 2.5 months. During this time, saplings were watered to field capacity daily to minimise water stress.

Water stress and fire treatments

We randomly divided the saplings into four groups ($n = 7$) and applied different treatments to each group. Each group was conditioned to different predawn water potentials ($\Psi_{predawn}$): control (no water stress or fire), low-water-stress ($\Psi_{predawn}$: 0 to -0.75 MPa), moderate-water-stress ($\Psi_{predawn}$: -1 to -1.75 MPa) and severe-water-stress ($\Psi_{predawn}$: -2 to -2.75 MPa). The low-water-stress $\Psi_{predawn}$ range was chosen to match $\Psi_{predawn}$ in well-watered *Larix* of similar size and age in prior studies (Sparks *et al.* 2016; Smith *et al.* 2017). The severe-water-stress $\Psi_{predawn}$ range was chosen to match values of $\Psi_{predawn}$ in water-stressed *Larix* in prior studies where net photosynthesis and stomatal conductance approached zero (Higgins *et al.* 1987), a common indicator of severe-drought stress (Rodriguez-Dominguez *et al.* 2016; Martin-StPaul *et al.* 2017). This $\Psi_{predawn}$ range also encompassed measurements of *Larix* saplings in a central Idaho forest during a severe drought year ($\Psi_{predawn} = -2.2$ MPa) (K. V. Baker and D. M. Johnson, unpubl. data) and coincided with stress-induced leaf senescence for the severe-water-stress *Larix* in this study. The moderate-water-stress $\Psi_{predawn}$ range was in between the low and severe ranges. Water was withheld from each water stress group until the desired shoot $\Psi_{predawn}$ range was reached. During the water stress treatment period, fertiliser was also withheld from all saplings to avoid confounding effects of the treatments. Low-water-stress *Larix* were watered daily to keep $\Psi_{predawn}$ above -0.75 MPa.

At the end of the water stress treatment period, each non-control *Larix* group was subjected to a surface fire of the same intensity. Following Smith *et al.* (2017) and Sparks *et al.* (2016),

we determined the fuel load (kg m^{-2}) of dry ($\sim$0% fuel moisture content) *Pinus monticola* needles needed to produce a fire radiative energy (FRE) 'dose' of $\sim$0.4 MJ m^{-2}. This dose was chosen as Sparks *et al.* (2016) demonstrated that >66% of well-watered *Larix* of similar age and size survived for 1 year at this intensity level. Saplings in the same water stress group were burned individually on the same day; low and moderate-stress groups were burned 6 days after the severe-stress group. Post burn, all saplings were immediately returned to the greenhouse and watered to field capacity daily until foliar senescence ($\sim$60 days post fire). Temperature and relative humidity were recorded in the greenhouse facility every 30 min throughout the course of the study using a model EL-21CFR-2-LCD temperature and humidity sensor (Lascar Electronics) and used to calculate the vapour pressure deficit (VPD, kPa).

Sapling physiology, growth and mortality

Shoot water potential was measured at predawn every 2 days starting at the beginning of each water stress treatment using a Model 1505D pressure chamber (PMS Instruments Co.). Additionally, $\Psi_{predawn}$ was measured on burn day (pre-burn) and at 1, 4, 14, 30 days post fire; midday water potential (Ψ_{midday}) was also acquired on burn day and at the same post-fire intervals. Shoots of $\sim$10 cm in length were used for $\Psi_{predawn}$ and Ψ_{midday} measurements. Owing to the limited number of shoots on these small saplings and the destructive nature of these measurements, three saplings from each group were randomly selected for water potential measurement per sampling interval. As other studies have shown that removal of large proportions of leaf area does not substantially affect subsequent leaf water potential (Reich *et al.* 1993; Pataki *et al.* 1998), we assumed that excising shoots did not significantly change sapling water stress.

Light-saturated (1500 μmol m^{-2} s^{-1} photosynthetic photon flux density) gas-exchange measurements were performed on the same days as $\Psi_{predawn}$ using a LI-6400XT and 6400-05 LED light source and broadleaf chamber (LI-COR Biosciences) on five randomly selected plants in each water stress group. Five needles from each sapling were used per measurement. Needle area for each sample was measured with a LI-COR LI-3100C leaf area meter and used to calculate net photosynthesis (A) and stomatal conductance (g_s) on leaf area basis. Height and diameter-at-root-collar (DRC) were measured at the same intervals as gas exchange. Relative growth measures (% deviation from pretreatment) for DRC and height were calculated as: [((growth − growth$_{avgPreTreatment}$)/growth$_{avgPreTreatment}$) × 100]. Crown scorch was visually estimated for each sapling following Sparks *et al.* (2016). Bud emergence date, density (number of buds per sapling) and general condition for each *Larix* sapling were also recorded. We defined 'immediate mortality' as tree death occurring from 1 to 60 (date of needle senescence) days post fire, whereas 'delayed mortality' was defined as tree death between 160 (date of needle emergence) and 365 days post fire. Mortality was defined as the death of all foliage and inability to regenerate shoots.

Data analysis

Arithmetic mean ± s.e. is given throughout the paper. Physiologic and growth differences between treatment groups were compared with ANOVA, and if significant ($\alpha = 0.05$), a Tukey's honest significant difference test.

Results

Impacts of water stress on pre-burn physiology and growth

$\Psi_{predawn}$ did not significantly differ ($P > 0.05$) between low-water-stress and control *Larix* at any point during the study (Fig. 2). Likewise, pre-fire physiology (Fig. 3*a*, *b*) and growth (Fig. 3*c*, *d*) of the low-water-stress *Larix* was not different ($P > 0.05$) from the control *Larix*. Moderate-water-stress *Larix* took 7 days to reach the desired $\Psi_{predawn}$ range (Fig. 2). During these 7 days, $\Psi_{predawn}$, A and g_s decreased by an average of 65% from pre-water-stress levels (Figs 2, 3*a*, *b*). On burn day, moderate-water-stress *Larix* $\Psi_{predawn}$ was more negative ($P = 0.005$) than both the control and low-water-stress groups. Height and DRC continued to increase in the moderate-water-stress group and did not differ ($P > 0.05$) from the control. Severe-water-stress *Larix* took 12 days to reach the desired $\Psi_{predawn}$ range. On burn day, $\Psi_{predawn}$ was more negative ($P = 0.005$) than all other groups. Like the moderate-water-stress larch, $\Psi_{predawn}$, A and g_s decreased by an average of 60% from pre-water-stress levels (Figs 2, 3*a*, *b*). During the last 4–5 days of the water stress period, foliage senesced sequentially in the severe-water-stress treatment, with older green foliage on each sapling turning yellow before younger foliage. Height and DRC growth were less than all other groups during this time but were not significantly different ($P > 0.05$) than the control.

Impacts of water stress and fire on physiology, growth and mortality

All burns had approximately the same duration (186 ± 0.6 s). Mean flame height (18 cm; measured using still-frame video data) was nearly half of the average height-to-crown (36.3 cm), resulting in minimal live foliage combustion (<5% of crown) across all water stress groups. There were no significant differences ($P = 0.337$) in crown scorch between low- (85 ± 3%), moderate- (87 ± 5%) and severe- (82 ± 9%) water-stress groups. For all water stress groups, $\Psi_{predawn}$ recovered to pre-fire levels immediately after rewatering (within 1 day) and did not differ ($P > 0.05$) from the control until all saplings started to senesce ($\sim$30–40 days post fire) (Fig. 2). At 30 days post fire, $\Psi_{predawn}$ was more negative in the moderate-water-stress *Larix* ($P = 0.028$) than in the control or severe-water-stress groups. Likewise, Ψ_{midday} for all water stress groups recovered to pre-fire levels immediately after rewatering (Fig. S1) and remained less negative ($P < 0.05$) than control saplings until all saplings started to senesce around early October. Minimum observed A for all water stress groups occurred 1 day post fire. A and g_s recovered to control levels within 14 days post fire in the severe- and low-water-stress groups, but A recovery took 30 days in the moderate-stress group (Fig. 3*a*, *b*).

Post-fire DRC and height growth decreased with increasing water stress, although groups did not differ significantly ($P > 0.05$) (Fig. 3*c*, *d*). Generally, post-fire DRC and height growth decreased or remained the same for the duration of the experiment (Fig. 3*c*, *d*). Post-fire bud density was consistently higher ($P < 0.0001$) in the severe-water-stress group than the
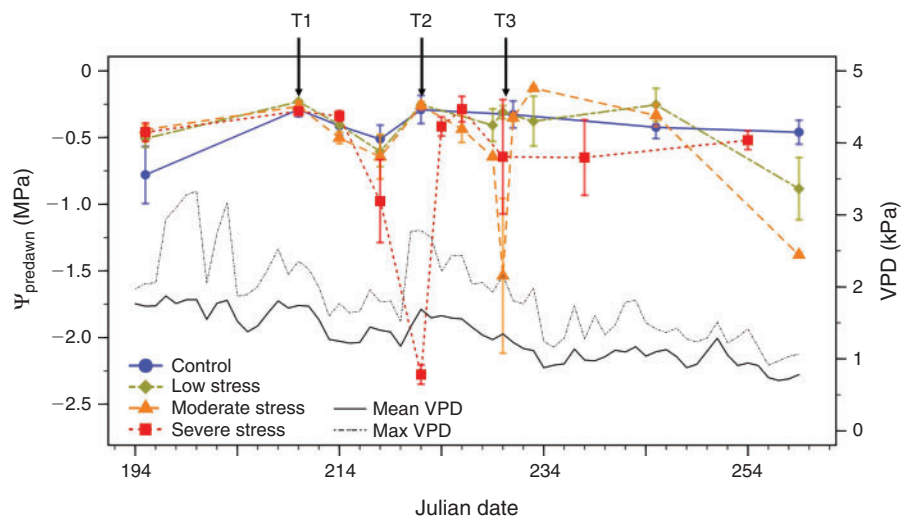
Fig. 2. Predawn water potential ($\Psi_{predawn}$, units: MPa) of *Larix* groups throughout the study period with annotations marking significant timepoints (T1–3). Timepoints are as follows: T1 – severe-water-stress *Larix* treatment starts; T2 – severe-water-stress *Larix* are subjected to fire treatment, moderate-water-stress *Larix* treatment starts; T3 – low and moderate-water-stress *Larix* are subjected to fire treatment. Error bars represent standard error ($n = 3$). Mean vapour pressure deficit (VPD, units: kPa) (solid black line) and maximum VPD (dotted black line) are also shown.

low and moderate-stress groups (Fig. 4), with nearly a 3× difference at the end of the growing season.

Immediate mortality (<60 days post fire) was greater in the moderate-stress group (43%) than the severe-stress (14%) and low-stress (0%) groups (Fig. 4). Likewise, delayed mortality (160 to 365 days post fire) was also greater in the moderate-stress group (86%) than the severe-stress (14%) and low-stress (14%) groups. No control trees died during the experiment.

Discussion

The present study supports previous experiments of the same fire intensity (0.4 MJ m^{-2}) with similarly sized *Larix occidentalis* where saplings experiencing minimal water stress ($\Psi_{predawn} > -0.4$ MPa and $\Psi_{midday} > -1.5$ MPa) had low mortality rates (<33%) up to 1 year post fire (Sparks *et al.* 2016). Likewise, observed patterns of post-fire growth reductions with increasing water stress agree with other studies where drought and fire treatments significantly reduced above- and below-ground growth in *Quercus* spp. seedlings compared with control and drought-only seedlings (Chiatante *et al.* 2015).

The unexpected mortality patterns observed among the different water stress groups indicate more complex dose–response relationships between water stress, fire and physiology than expected (Fig. 1). We hypothesise that the severe-water-stress group displayed lower mortality than the moderate-water-stress group because the severe-water-stress group were able to use nutrients and C translocated from foliage to other tree tissues during the pre-fire water-stress-induced foliar senescence. Nutrient resorption during drought-induced senescence can increase survival among deciduous plants (Munné-Bosch and Alegre 2004) and deciduous trees benefit from nutrient resorption even under extreme drought conditions (Silla and Escudero 2006; Marchin *et al.* 2010). As all treatment groups experienced

a similar amount of crown scorch (Fig. 5), the severely water-stressed trees may have had more resources available to survive and produce buds post fire. *Larix* spp. are very efficient at translocating nutrients from senescing needles to other tree tissues (Carlyle and Malcolm 1986; Gower and Richards 1990). During foliar senescence in autumn, *Larix occidentalis* has been observed to translocate ~87% of nitrogen and ~66% of phosphorus from foliage (Gower *et al.* 1989). *Larix* spp. have also been observed to have high resorption of NSC from senescing needles (Kagawa *et al.* 2006). This hypothesis is supported by the observed bud densities for the three water-stress groups. Despite similar post-fire crown loss (~85%) across all water-stress groups, severe-water-stress *Larix* had nearly triple the density of buds 30 and 60 days post fire compared with the low and moderate *Larix* (Fig. 4). Stored carbohydrates are the C source for new needle formation in deciduous trees such as *Larix* (Kagawa *et al.* 2006), and the bud density observations suggest that the severe-water-stress *Larix* had greater C reserves to regenerate foliage.

In addition to regenerating foliage, C is a critical input for refilling embolised xylem conduits (Salleo *et al.* 2009; Zwieniecki and Holbrook 2009; Nardini *et al.* 2011). Repeated embolism formation and repair, such as that likely experienced by the moderate- and severe-water-stress groups pre-fire, could have depleted C stores (McDowell *et al.* 2008) and decreased cavitation resistance (e.g. cavitation fatigue – Hacke *et al.* 2001). As drying soil can limit refilling of embolisms (McDowell *et al.* 2011), it is likely that the moderate- and severe-water-stress *Larix* had higher proportions of non-refilled conduits than the low-water-stress *Larix* that were watered pre-fire. It is possible that the fire exacerbated xylem cavitation in the saplings with higher proportions of functioning, non-senesced crown (low and moderate-water-stress *Larix*). Several studies
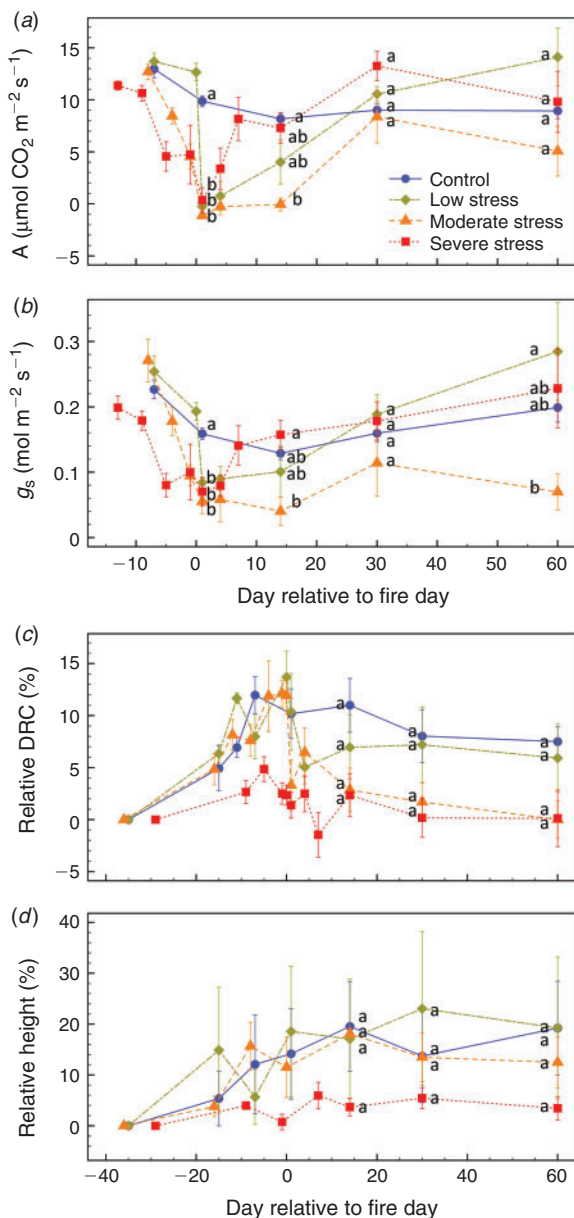
Fig. 3. *Larix* physiology and growth changes from pre-fire to post fire by water stress group. Data are displayed for (*a*) net photosynthesis (*A*); (*b*) stomatal conductance (g_s); (*c*) relative diameter at root collar (DRC); and (*d*) relative height. Mean values sharing the same letter are not significantly different ($P < 0.05$). Error bars represent standard error ($n = 5$).

Fig. 4. Bud density (buds sapling^{-1}) from 1 to 60 days post fire. Cumulative mortality (%) is also shown (bar graph) from 1 to 365 days post fire. Green diamonds and bars represent low-water-stress *Larix*, orange triangles and bars represent moderate-water-stress *Larix*, and red squares and bars represent severe-water-stress *Larix*. Mean values sharing the same letter are not significantly different ($P < 0.05$). Error bars for bud density represent standard error ($n = 5$).

have indicated that elevated VPD in the super-heated plume that rises above the surface flames may be sufficient to induce cavitation in tree canopy branches and foliage (Kavanagh *et al.* 2010; West *et al.* 2016). However, translocation of nutrients and C, either during senescence or during embolism repair, requires functioning phloem (Nardini *et al.* 2011; Hartmann *et al.* 2013). Translocation of nutrients and C under severe-water-stress conditions can be significantly impaired by decreased phloem transport (Sala *et al.* 2010). For example, Hartmann *et al.* (2013) observed that water-stressed Norway spruce (*Picea ab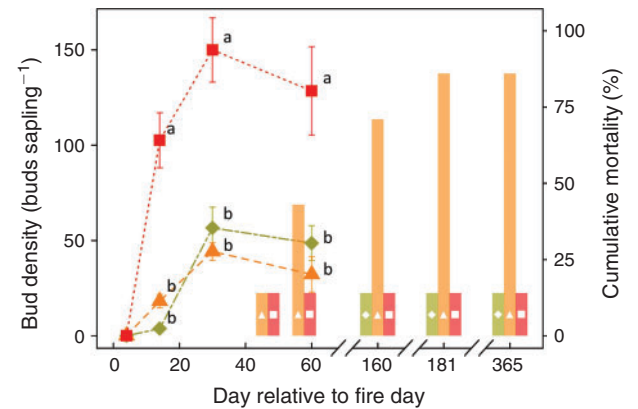ies*) saplings had higher NSC concentrations in all tissues than non-water-stressed saplings at mortality, indicating that reduced hydraulic function impaired mobilisation of NSC. Thus, while drought-induced senescence provides a mechanism that preserves nutrients and C for survival and post-disturbance bud growth, severe drought can also constrain mobilisation and utilisation of these resources.

We acknowledge that because our experiment lacked unburned water-stress treatment groups, we are assuming the observed physiological, growth and mortality differences between the drought-stress treatments were created by the fire treatments. However, previous studies provide clues to help decouple the effects of water stress and fire. Vance and Running (1985) subjected smaller *Larix occidentalis* (~15 cm in height) to water stress treatments and found that *Larix* with $\Psi_{predawn}$ of −1.5 MPa were able to survive the drought treatment. The presence of stress-induced leaf senescence was not noted. This finding suggests that the high mortality observed in the moderate-water-stress *Larix* in the present study ($\Psi_{predawn}$: −1 to −1.75 MPa) was the result of the combined effects of the drought and fire treatments.

Future research needs

Our observations suggest an intriguing possibility where *Larix* that senesce and translocate resources pre-fire may experience lower mortality in a subsequent low-intensity fire. Testing this hypothesis would require measuring translocation to assess whether senescing foliage supplies sufficient nutrients (NSC, N, P) for bud growth; xylem conductivity measurements to quantify whether heat-induced cavitation and cell deformation observed in water-bath studies (e.g. Michaletz *et al.* 2012; West *et al.* 2016; Bär *et al.* 2018) occurs under natural fire conditions; and gas-exchange measurements to gauge stomatal activity for green and senesced needles at the time of burning.

It is important to note that the mortality hypothesis presented in the present study may not translate to larger trees. For example, drought-induced crown dieback in larger trees often
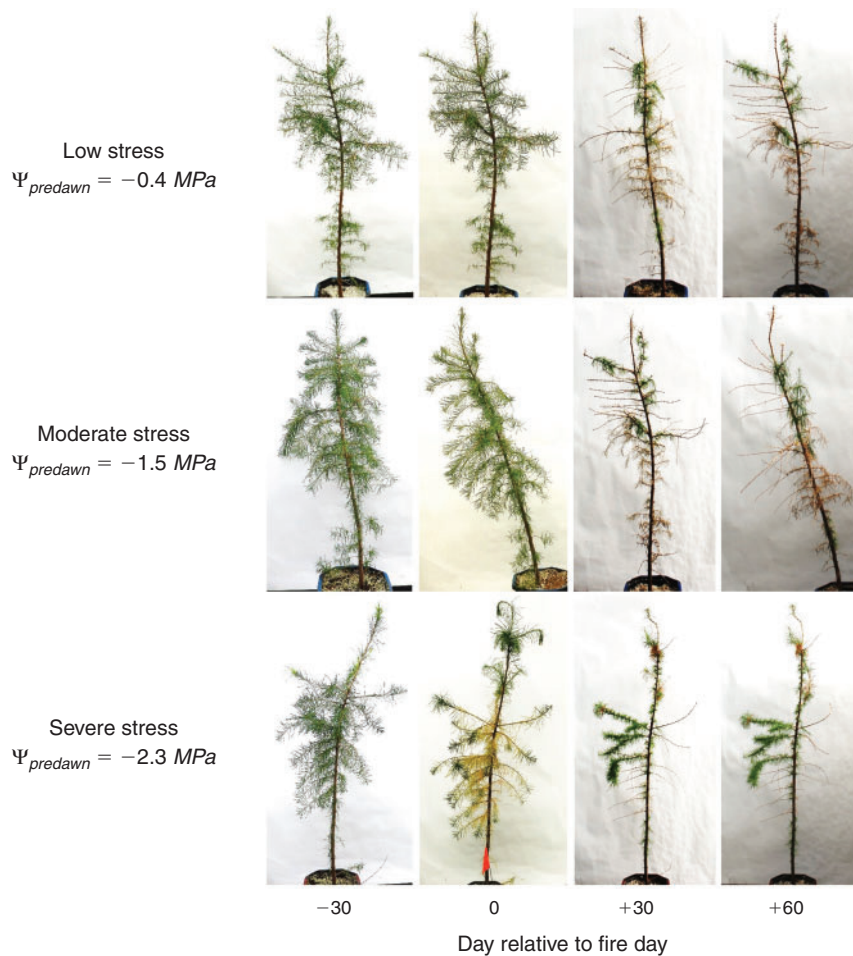
Fig. 5. Pre- and post-fire condition of representative low- (top row), moderate- (middle row), and severe-water-stress *Larix* (bottom row). Average predawn water potential for each group is denoted as $\Psi_{predawn}$. Yellow, senescing needles are clearly visible in the severe-water-stress photo on burn day (bottom row, '0' day) as well as differences in bud density between the groups at 30 and 60 days post fire.

occurs at the periphery of the tree crown (Rood *et al.* 2000; Sperry *et al.* 2002; Zhang *et al.* 2017), rather than sequential senescence observed in the current study, where older leaves senesce first to supply nutrients to younger leaves and shoots (Munné-Bosch and Alegre 2004). As low-intensity fires typically scorch tree crowns from the bottom up, senescing foliage at the periphery of a large tree crown may not provide the post-fire recovery advantage hypothesised for saplings. In fact, there is evidence from temperate (van Mantgem *et al.* 2013) and tropical forests (Van Nieuwstadt and Sheil 2005; Brando *et al.* 2014) that large trees with greater pre-fire water stress are more susceptible to fire-induced mortality. Current hypotheses for fire-induced mortality of larger trees, such as xylem dysfunction (Michaletz 2018), have been demonstrated on excised branches in laboratory water-bath experiments (Michaletz *et al.* 2012; West *et al.* 2016; Bär *et al.* 2018). In terms of natural forest fires, there is evidence that fires impair large-tree xylem hydraulics (Smith 2015; Smith *et al.* 2016*b*; Bär *et al.* 2018) and evidence that fires do not affect xylem hydraulics (Battipaglia *et al.* 2016; Thompson *et al.* 2017). Experiments that incorporate a range of tree

sizes and tree-scale treatments (Sparks *et al.* 2017) and physiology measurements are needed for an improved understanding of size-dependent mortality (McDowell *et al.* 2018).

Conclusions

We observed that western larch under greater pre-fire water stress exhibit decreased growth after a low-intensity surface fire. However, the unexpected bud density and mortality patterns observed among the different water stress groups indicate that interactions between water stress, fire and deciduous tree physiology are more complex than a linear dose–response relationship. The mortality patterns observed in this study suggest that water-stressed western larch saplings exposed to low-intensity wildfires, or prescribed fires conducted as part of forest management activities, may exhibit lower mortality rates if stress-induced foliar senescence has occurred. Although this research improves understanding of drought–fire interaction impacts on saplings, more research is needed to assess whether mortality patterns change with increasing tree size.

Conflicts of interest

Acknowledgements

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