SPECIAL ISSUE

CSIRO PUBLISHING

International Journal of Wildland Fire **2019**, *28*, 721–725
https://doi.org/10.1071/WFv28n10_FO

Foreword

The influence of wildfire on water quality and watershed processes: new insights and remaining challenges

Charles C. Rhoades[A,E], *João P. Nunes*[B], *Uldis Silins*[C] *and Stefan H. Doerr*[D]

[A]US Department of Agriculture Forest Service, Rocky Mountain Research Station, Fort Collins, CO 80526, USA.
[B]Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciencias Universidade de Lisboa, Lisbon 1749-016, Portugal.
[C]Agricultural Life and Environmental Sciences, Renewable Resources, University of Alberta, Edmonton, Alberta T6G 2P5, Canada.
[D]Department of Geography, College of Science, Swansea University, Singleton Campus, Swansea SA2 8PP, UK.
[E]Corresponding author. Email: charles.c.rhoades@usda.gov

Abstract. This short paper provides the framework and introduction to this special issue of *International Journal of Wildland Fire*. Its eight papers were selected from those presented at two consecutive conferences held in 2018 in Europe and the USA that focussed on the impacts of wildfire on factors that regulate streamflow, water quality, sediment transport, and aquatic habitats. Despite decades of watershed research, our understanding of the effects of wildfires on the processes that regulate clean water supply remains limited. Here, we summarise the key challenges and research needs in this interdisciplinary field and evaluate the contributions the eight special issue papers make to improved understanding of wildfire impacts on watershed processes. We also outline research priorities aimed at improving our ability to predict and, where necessary, mitigate wildfire impacts on watersheds. Achieving these advances is all the more pressing given the increasing extent and severity of wildfires in many areas that are the source of clean water for major population centres.

Additional keywords: drinking water, pollutants, water contamination, water supply.

Introduction

Wildfires influence watersheds from top to bottom, altering the ecosystem processes that regulate streamflow and the delivery of clean water (Shakesby and Doerr 2006; Nunes *et al.* 2018). Although the global area burned by wildland fires has declined in the past two decades, due predominantly to the conversion of savannah and grassland to agriculture (Andela *et al.* 2017), changing climate, forest conditions and land-use patterns have increased the frequency, extent, and severity of forest wildfires in many parts of the world (Dennison *et al.* 2014; Jolly *et al.* 2015; Westerling 2016; Radeloff *et al.* 2018). The associated extensive loss of life and destruction of property from recent wildfires in, for example, western North America, Portugal, Greece and elsewhere stunned the public and amplified global awareness of their destructive potential (BBC 2017; Jergler 2019) and it is widely accepted that climate and land-use changes will continue the observed increase in the extent and severity of forest wildfires in the future (Flannigan *et al.* 2013; Knorr *et al.* 2016).

These changes have crucial implications for the capacity of watersheds to conserve aquatic biodiversity and sustain drinking water supply (Bladon *et al.* 2014; Martin 2016). Learning to adapt to severe wildfires and determine how best to reduce not only threats to human life and property but also to drinking water supplies have emerged as pressing global challenges (Hallema *et al.* 2018; Robinne *et al.* 2018).

Both wildfire behaviour and watershed processes are spatially and temporally complex, and post-fire water quality and watershed responses elude simple generalisation. For example, observations of short-term effects of wildfires on aquatic biota, sediment, ash and nutrient losses are widespread, but only recently have we begun to recognise that some of these responses may persist for many years (Rust *et al.* 2018; Rhoades *et al.* 2019). Recent studies have helped increase appreciation that post-fire nutrient enrichment, carbon (C) and metal mobilisation create challenges for water treatment operations (Emelko *et al.* 2011; Bladon *et al.* 2014; Martin 2016; Hohner *et al.* 2019). Yet despite decades of watershed research, our understanding of the effects of wildfires on the processes that regulate clean water supply remains limited. Our need to adapt to future increases in wildfire size and severity (Flannigan *et al.* 2013; McWethy *et al.* 2019) requires new analytical approaches, and evaluation of various spatial and temporal scales across multiple fuel types and hydrologic regimes.

This special issue of *International Journal of Wildland Fire* addresses this need by presenting new insights from research conducted in Europe, North America and Australia with the shared objective of advancing understanding of how wildfires influence watersheds and water quality. The eight papers it contains emerged from international conferences conducted in Lisbon, Portugal (EU COST Action ES1306 Connecteur and the

H2020 PLACARD project, February 2018; Nunes *et al.* 2018) and Missoula, MT, USA (Forests-Flames-Faucets; Association for Fire Ecology and International Association of Wildland Fire, May 2018). The Lisbon meeting was convened in response to multiple extreme wildfires in 2017 that threatened Portuguese watersheds, water storage and treatment utilities and included researchers and water resource managers from Europe, the US, Canada, Australia and Israel, as well as water managers, drinking water treatment specialists and the public. Both conferences presented research on the consequences of wildfire on the factors that regulate streamflow, water quality, sediment transport, aquatic habitat and other attributes of forest watersheds. The studies included here provide new insights from wild and prescribed fires conducted at hillslope, stream and catchment scales. They highlight the links between upland, riparian and aquatic environments and surface water quality. Though much historic fire information derives from short-term studies of individual fires, this issue features four papers that evaluate water quality changes over 4 to 10-year time frames and includes papers that make comparisons involving 6 to 153 individual fires.

Linking specific contaminants and water quality assets

The research presented here helps to advance understanding of coupled response of post-fire changes in nutrients, carbon, metal, or other contaminants with aquatic ecosystem, drinking water reservoir, treatment operations, or other water assets. Harper *et al.* (2019) aimed to disentangle which individual or combined chemical constituents influence a common aquatic indicator species (*Daphnia magna*). They evaluated the toxicity of ash from wildfires that burned six distinct vegetation types collected around the world. Toxic ash had high pH, nitrate, chloride and conductivity compared with other ash types that were harmless to *D. magna*. Neither water-soluble metal or polycyclic aromatic hydrocarbon concentrations contributed to ash toxicity. Though the study provided insights about variability in ash toxicity, the authors were unable to pinpoint the specific chemical constituents directly responsible for those effects. Martens *et al.* (2019), using a multiple-taxa approach in southern Alberta, Canada, evaluated changes in the stream macroinvertebrate assemblage in response to persistent post-fire changes in stream nutrients, temperature and other resources. They found that a wildfire influenced not only water chemistry, but also the stream macroinvertebrate community for 8 years. Both the composition and abundance of stream macroinvertebrates differed between burned and long-unburned reference streams. Unburned streams had lower overall macroinvertebrate abundance and greater occurrence of disturbance-sensitive taxa (i.e. stoneflies). In contrast, burned streams and salvage-logged areas both had higher macroinvertebrate abundance and higher dominance of chironomids and caddisflies. The lasting post-fire effects were attributed to sustained increases in stream resources (e.g. stream temperature, dissolved organic C (DOC), sediment and soluble reactive phosphorus (P)).

Analytical advances continually uncover new contaminants of concern and help increase understanding of their post-fire responses and downstream consequences. Two papers from forests of the south-eastern USA apply novel laboratory (Majidzadeh *et al.* 2019) and field approaches (Olivares *et al.* 2019) to study chemical attributes of DOC and their post-fire responses that have implications for drinking water treatment. Similar to wildfires, the release of pyrogenic C and DOC following prescribed fires are synchronised with the initial post-fire rainstorms. However, detection of these short-lived C releases is complicated by abundant particulate charred material, suspended sediment, and high background stream DOC concentrations. New *in situ* ultraviolet-visible absorption (UV-VIS) sensors offer the possibility to capture storm events and provide a more complete temporal record of post-fire DOC dynamics. Olivares *et al.* (2019) evaluated this technology following a prescribed fire at the Francis Marion Experimental Forest in South Carolina, USA. The sensors captured rapid fluctuations in DOC associated with individual storm events in burned and long-unburned catchments, though the low-severity prescribed burn had little measurable effect on C release. The consequences of post-fire dissolved organic matter export, including both DOC and DON, have become crucial to drinking water utilities following enactment of regulations and monitoring for specific disinfection by-products. The *in situ* DOC sensor evaluated by Olivares *et al.* (2019) provides an example of how new analytical approaches may better address the temporal fluctuations and spatial complexity of forest watersheds to deliver timely and cost-effective water quality information to downstream users.

Contaminant mobilisation and transport

The processes that mobilise and transport sediment, nutrients, C and other constituents vary widely among watersheds and fires and further complicate assessment of post-fire water quality change (Nunes *et al.* 2018). As opposed to targeting disconnected watershed processes, a coupled evaluation of potential contaminant sources and their retention in short- and long-term vegetation, soil and burned landscape sinks may better characterise post-fire responses. Evaluation of biologic and physical nutrient retention within stream channels, hyporheic zones and flood plains have helped advance understanding of forest watersheds (Triska *et al.* 1989; Hall *et al.* 2002; Covino *et al.* 2010), though these approaches have rarely been applied to post-fire conditions. Silins *et al.* 2014; and the study presented here by Martens *et al.* (2019) found that retention of particulate-P in stream sediments following wildfire in the Canadian Rockies has led to sustained, elevated P in stream water and contributed to long-term shifts in the macroinvertebrate community.

Slow post-fire vegetation recovery likely dampens nutrient demand and retention and has been credited for persistent, elevated stream nutrients (Rhoades *et al.* 2019). Here, Rust *et al.* (2019) use publicly available stream water and wildfire data from more than 150 fires in the western US, and identified fire severity, post-fire vegetation recovery and site-specific soil properties as key contributors to post-fire stream nutrient and metal responses. The study by Williams *et al.* (2019) examining the impacts of wildfire in the southern Canadian Rockies further demonstrates that the rate of vegetation recovery determines how long wildfires will alter precipitation inputs, which in turn drive the hydrologic processes that mobilise and transport potential contaminants. Specifically, by reducing canopy foliage, crown fires reduce the proportion of precipitation that is intercepted and sublimated from the forest canopy, thus increasing the precipitation reaching the soil. The authors observed reduced rainfall interception and increased rain and snow inputs that combined to augment annual precipitation by 51%. The slow post-fire recovery of the subalpine forest canopy at that site prolonged these hydrologic effects of the wildfire for a decade. These studies suggest that, overall, a more spatially integrated assessment of retention and release processes will provide a better assessment of the likelihood that potential post-fire water quality contaminants will be delivered to receiving water bodies.

Reducing wildfire impacts on watersheds and water quality

There is widespread agreement of the need to adapt to the growing number, size and severity of wildfires, especially in areas with high-population density and around valuable water sources and storage and treatment infrastructure (McWethy *et al.* 2019). There are also numerous opportunities to manage watershed risks both before and after wildfires (Nunes *et al.* 2018). However, our limited current understanding of the probability of wildfire occurrence, fire behaviour and watershed responses prevent specific determination of where and when to invest in pre-fire fuel reduction treatments. Here, Gannon *et al.* (2019) present an optimisation model they developed and evaluated for identifying treatment locations to reduce watershed vulnerability. Their model determined that mechanical fuel reduction treatments conducted on relatively small portions of steep watersheds may be sufficient to reduce risks of post-fire erosion. However, the costs of mechanical treatment projects were prohibitively high and could not be justified solely by the potential cost savings from reduced soil erosion.

Additional information to help monetise potential benefits of mechanical and prescribed fire treatments aimed at reducing risks to aquatic ecosystems, other water quality attributes, watershed conditions and water treatment operations might alter the economic balance of pre-fire management. As one example presented here, Majidzadeh *et al.* (2019) report that periodic prescribed burning in coastal plain forests reduced DOC leaching and potentially hazardous disinfection by-products (DPBs) precursor formation, a previously unaccounted benefit of management. Prescribed fire is commonly promoted as a strategy for avoiding the negative watershed and water quality consequences of severe wildfire (Gannon *et al.* 2019). By restricting their timing, size and intensity, managed fires are expected to limit extensive loss of vegetation cover and exposure of mineral soils. However, detailed information about how to balance reduction of hazardous fuels and restoration of desired stand structure and composition with protection of source water supply and watershed condition remains sparse. Better understanding and tools are needed to help land managers compare the small, but potentially chronic, water quality changes from repeated prescribed burning and fuel reduction activities with the dramatic effects of severe wildfire. Here, Majidzadeh *et al.* (2019) report that repeated prescribed burning contributed to reduced forest floor mass and decreased DOC concentration relative to an adjacent unmanaged catchment. It also influenced the abundance of aromatic C compounds in forest floor leachate and stream water and reduced the potential to form DBPs during drinking water treatment.

Not surprisingly, there has been considerable examination of post-fire erosion control activities (Robichaud *et al.* 2000; Shakesby and Doerr 2006). Such treatments can reduce soil loss under some conditions but may also benefit other water quality attributes and enhance soil productivity and ecosystem recovery. For example, Pierson *et al.* (2019) report here that by reducing post-fire erosion mulching treatments may also limit C and N mobilisation and transport and downslope losses. They also found that eroded C and N declined within a few years. There is, however, growing evidence that post-fire stream nutrient changes may persist longer where revegetation is slow (Rhoades *et al.* 2019; Rust *et al.* 2019) and there has been little effort to date to rehabilitate lingering wildfire effects using in-stream, riparian or upland rehabilitation treatments.

Persistent and emerging knowledge gaps

Tremendous progress has been made in the past three decades in our understanding of post-fire watershed and water quality responses and on mitigating their impacts. New conceptual frameworks have recently been brought forward by Nunes *et al.* (2018) and Hallema *et al.* (2018) with the aim to accelerate progress by bridging gaps in scales, approaches and relevant disciplines. However, there remains a need to conceptualise responses across fire-sensitive hydro-climatic-geologic settings globally (Moody *et al.* 2013) and better practical knowledge is required to manage wildfire threats to drinking water supply and infrastructure. The immediate, catastrophic watershed effects of wildfires are well recognised, but their long-term consequences have only recently become apparent. Links between post-fire vegetation recovery and persistent post-fire water quality responses highlight the value of considering these disturbances from an ecosystem perspective. For example, both short- (Riggan *et al.* 1994; Rhoades *et al.* 2011) and longer-term wildfire effects on stream nutrients (Rust *et al.* 2019) relate to the extent of high-severity wildfire, and these conditions, in turn, influence post-fire vegetation recovery (Chambers *et al.* 2016; Malone *et al.* 2018). Advances in understanding of the coupled hillslope, stream-reach and catchment-scale biogeochemical processes that regulate plant and soil nutrient and C uptake and release are needed to determine the threats of potential post-fire contaminants to downstream resources. There is also growing awareness of overlapping disturbances, such as repeated wildfires, fires following insect outbreaks or associated with drought or harvesting (Harvey *et al.* 2014, 2016*a*, 2016*b*; Stevens-Rumann *et al.* 2018; Rhoades *et al.* 2018), but little information about how these may impact watershed processes or water quality. The link between long-term watershed responses and vegetation dynamics have logical implications for post-fire watershed restoration. While great effort has gone into studying short-term, post-fire erosion control (Robichaud *et al.* 2000), virtually nothing is known about what revegetation or stream restoration approaches are best suited to resolving lingering post-wildfire water quality concerns.

Linking the formation of contaminants and their downstream mobilisation is a continual challenge to predicting and managing the threats of wildfires on aquatic resources and water treatment

(Nunes *et al.* 2018). For example, recent research identified storm sewer inputs of fire-transformed contaminants from residential, commercial, and light industrial settings as a pathway of concern for municipal water supply (Burke *et al.* 2010, 2013; Stein *et al.* 2012), though little else is currently known about this water quality threat. Wildfire impacts to groundwater also remain poorly understood. Furthermore, understanding of how complex fire behaviour burning under distinct forest and climatic conditions creates, transforms and degrades C- and N-based precursors to the disinfection by-products formed during water treatment (Hohner *et al.* 2019) remains limited. The societal and ecological impacts of wildfires on water supply and aquatic ecosystems will become an increasingly critical environmental concern in coming decades (Robinne *et al.* 2018; Hallema *et al.* 2018). Current knowledge of the combined complexities of current and anticipated future wildfire behaviour and watershed responses remains too limited to adequately predict where to expect risks and how to best mitigate them. To face this challenge future research needs to focus on these persistent and emerging knowledge gaps and linkages between changing forest and fuel conditions, wildfire behaviour and watershed and water quality responses as well as their effect on downstream users and water treatment utilities.

Conflicts of interest

The special issue guest editors (CCR, JPN and US) and associate editor (SHD) declare no conflicts of interest.

Acknowledgements

CCR acknowledges funding from the Joint Agency Fire Sciences Program (#14–1-06–11) and the US Forest Service National Fire Plan. JPN acknowledges funding by a Portuguese Foundation for Science and Technology grant (IF/00586/2015). US acknowledges funding from Alberta Innovates (WIP-2343) and NSERC (05497, 494312) grants. SHD acknowledges funding by a Leverhulme Trust Fellowship (RF-2016-456\2) and Natural Environment Research Council grant (grant NE/R011125/1).

References

Andela N, Morton DC, Giglio L, Chen Y, van der Werf GR, Kasibhatla PS, DeFries RS, Collatz GJ, Hantson S, Kloster S, Bachelet D, Forrest M, Lasslop G, Li F, Mangeon S, Melton JR, Yue C, Randerson JT (2017) A human-driven decline in global burned area. *Science* **356**, 1356–1362. doi:10.1126/SCIENCE.AAL4108

BBC (2017) Portugal wildfires: why are they so deadly? *BBC News 20 June 2017*. Available at https://www.bbc.co.uk/news/world-europe-40341180 [Verified 21 September 2019]

Bladon KD, Emelko MB, Silins U, Stone M (2014) Wildfire and the future of water supply. *Environmental Science & Technology* **48**, 8936–8943. doi:10.1021/ES500130G

Burke M, Hogue T, Ferreira M, Mendez C, Navarro B, Lopez S, Jay J (2010) The effect of wildfire on soil mercury concentrations in southern California watersheds. *Water, Air, and Soil Pollution* **212**, 369–385. doi:10.1007/S11270-010-0351-Y

Burke MP, Hogue TS, Kinoshita AM, Barco J, Wessel C, Stein ED (2013) Pre- and post-fire pollutant loads in an urban fringe watershed in southern California. *Environmental Monitoring and Assessment* **185**, 10131–10145. doi:10.1007/S10661-013-3318-9

Chambers ME, Fornwalt PJ, Malone SL, Battaglia MA (2016) Patterns of conifer regeneration following high severity wildfire in ponderosa pine – dominated forests of the Colorado Front Range. *Forest Ecology and Management* **378**, 57–67. doi:10.1016/J.FORECO.2016.07.001

Covino T, McGlynn B, Baker MCG (2010) Separating physical and biological nutrient retention and quantifying uptake kinetics from ambient to saturation in successive mountain stream reaches. *Journal of Geophysical Research Biogeosciences* **115**, G04010.

Dennison PE, Brewer SC, Arnold JD, Moritz MA (2014) Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters* **41**, 2928–2933. doi:10.1002/2014GL059576

Emelko MB, Silins U, Bladon KD, Stone M (2011) Implications of land disturbance on drinking water treatability in a changing climate: demonstrating the need for source water supply and protection strategies. *Water Research* **45**, 461–472. doi:10.1016/J.WATRES.2010.08.051

Flannigan M, Cantin AS, de Groot WJ, Wotton M, Newbery A, Gowman LM (2013) Global wildland fire season severity in the 21st century. *Forest Ecology and Management* **294**, 54–61.

Gannon BM, Wei Y, MacDonald LH, Kampf SK, Jones KW, Cannon JB, Wolk BH, Cheng AS, Addington RN, Thompson MP (2019) Prioritising fuels reduction for water supply protection. *International Journal of Wildland Fire* **28**, 785–803. doi:10.1071/WF18182

Hall RJO, Bernhardt ES, Likens GE (2002) Relating nutrient uptake with transient storage in forested mountain streams. *Limnology and Oceanography* **47**, 255–265. doi:10.4319/LO.2002.47.1.0255

Hallema DW, Robinne FN, Bladon KD (2018) Reframing the challenge of global wildfire threats to water supplies. *Earth's Future* **6**, 772–776. doi:10.1029/2018EF000867

Harper AR, Santin C, Doerr SH, Froyd CA, Albini D, Otero XL, Viñas L, Pérez-Fernández B (2019) Chemical composition of wildfire ash produced in contrasting ecosystems and its toxicity to *Daphnia magna. International Journal of Wildland Fire* **28**, 726–737. doi:10.1071/WF18200

Harvey BJ, Donato DC, Turner MG (2014) Recent mountain pine beetle outbreaks, wildfire severity, and postfire tree regeneration in the US Northern Rockies. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 15120–15125. doi:10.1073/PNAS.1411346111

Harvey BJ, Donato DC, Turner MG (2016*a*) Burn me twice, shame on who? Interactions between successive forest fires across a temperate mountain region. *Ecology* **97**, 2272–2282. doi:10.1002/ECY.1439

Harvey BJ, Donato DC, Turner MG (2016*b*) High and dry: post-fire tree seedling establishment in subalpine forests decreases with post-fire drought and large stand-replacing burn patches. *Global Ecology and Biogeography* **25**, 655–669. doi:10.1111/GEB.12443

Hohner AK, Rhoades CC, Wilkerson P, Rosario-Ortiz FL (2019) Wildfires alter forest watersheds and threaten drinking water quality. *Accounts of Chemical Research* **52**, 1234–1244. doi:10.1021/ACS.ACCOUNTS.8B00670

Jergler D (2019) Insured losses from November 2018 California wildfires top $12B. *Insurance Journal 8 May 2019*. Available at https://www.insurancejournal.com/news/west/2019/05/08/525930.htm [Verified 21 September 2019]

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications* **6**, 7537. doi:10.1038/NCOMMS8537

Knorr W, Arneth A, Jiang L (2016) Demographic controls of future global fire risk. *Nature Climate Change* **6**, 781–785. doi:10.1038/NCLIMATE2999

Majidzadeh H, Coates A, Tsai KP, Olivares C, Trettin C, Uzun H, Karanfil T, Chow A (2019) Long-term watershed management is an effective strategy to reduce organic matter export and disinfection by-products (DBPs) precursors in source water. *International Journal of Wildland Fire* **28**, 804–813. doi:10.1071/WF18174

Malone SL, Fornwalt PJ, Battaglia MA, Chambers ME, Iniguez JE, Sieg CH (2018) Mixed-severity fire fosters heterogeneous spatial patterns of conifer regeneration in a dry conifer forest. *Forests* **9**, 45. doi:10.3390/F9010045

Martens A, Silins U, Proctor H, Williams C, Wagner M, Emelko M, Stone M (2019) Long term impact of severe wildfire and post-wildfire salvage logging on macroinvertebrate assemblage structure in Alberta's Rocky Mountains. *International Journal of Wildland Fire* **28**, 738–749. doi:10.1071/WF18177

Martin DA (2016) At the nexus of fire, water and society. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences* **371**, 20150172. doi:10.1098/RSTB.2015.0172

McWethy DB, Schoennagel T, Higuera PE, Krawchuk M, Harvey PJ, Metcalf EC, Schultz C, Miller C, Metcalf AL, Buma B, Virapongse A, Kulig JC, Stedman RC, Ratajczak Z, Nelson CR, Kolden C (2019) Rethinking resilience to wildfire. *Nature Sustainability* **2**, 797–804. doi:10.1038/S41893-019-0353-8

Moody JA, Shakesby RA, Robichaud PR, Cannon SH, Martin DA (2013) Current research issues related to post-wildfire runoff and erosion processes. *Earth-Science Reviews* **122**, 10–37. doi:10.1016/J.EARSCIREV.2013.03.004

Nunes JP, Doerr SH, Sheridan G, Neris J, Santin C, Emelko MB, Silins U, Robichaud PR, Elliot WJ, Keizer J (2018) Assessing water contamination risk from vegetation fires: challenges, opportunities and a framework for progress. *Hydrological Processes* **32**, 687–694. doi:10.1002/HYP.11434

Olivares C, Zhang W, Uzun H, Erdem CU, Majidzadeh H, Trettin C, Karanfil T, Chow A (2019) Optical in-situ sensors capture dissolved organic carbon (DOC) dynamics after prescribed fire in high-DOC forest watersheds. *International Journal of Wildland Fire* **28**, 761–768.

Pierson DN, Robichaud PR, Rhoades CC, Brown RE (2019) Soil carbon and nitrogen eroded after severe wildfire and erosion mitigation treatments. *International Journal of Wildland Fire* **28**, 814–821.

Radeloff VC, Helmers DP, Kramer HA, Mockrin MH, Alexandre PM, Bar-Massada A, Butsic V, Hawbaker TJ, Martinuzzi S, Syphard AD, Stewart SI (2018) Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America* **115**, 3314–3319. doi:10.1073/PNAS.1718850115

Rhoades CC, Entwistle D, Butler D (2011) The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado. *International Journal of Wildland Fire* **20**, 430–442. doi:10.1071/WF09086

Rhoades CC, Pelz KA, Fornwalt PJ, Wolk BH, Cheng AS (2018) Overlapping bark beetle outbreaks, salvage logging and wildfire restructure a lodgepole pine ecosystem. *Forests* **9**, 101. doi:10.3390/F9030101

Rhoades CC, Chow AT, Covino T, Fegel TS, Pierson D, Rhea A (2019) The legacy of severe wildfire on stream nitrogen and carbon in headwater catchments. *Ecosystems* **22**, 643–657. doi:10.1007/S10021-018-0293-6

Riggan PJ, Lockwood RN, Jacks PM, Colver CG, Weirich F, DeBano LF, Brass JA (1994) Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. *Environmental Science & Technology* **28**, 369–375. doi:10.1021/ES00052A005

Robichaud PR, Beyers JL, Neary DG (2000) Evaluating the effectiveness of post-fire rehabilitation treatments. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-63. (Fort Collins, CO, USA)

Robinne FN, Bladon KD, Miller C, Parisien MA, Mathieu J, Flannigan MD (2018) A spatial evaluation of global wildfire-water risks to human and natural systems. *The Science of the Total Environment* **610–611**, 1193–1206. doi:10.1016/J.SCITOTENV.2017.08.112

Rust AJ, Hogue TS, Saxe S, McCray J (2018) Post-fire water-quality response in the western United States. *International Journal of Wildland Fire* **27**, 203–216. doi:10.1071/WF17115

Rust AJ, Saxe S, McCray J, Rhoades CC, Hogue TS (2019) Evaluating the factors responsible for post-fire water quality response in forests of the western USA. *International Journal of Wildland Fire* **28**, 769–784. doi:10.1071/WF18191

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* **74**, 269–307. doi:10.1016/J.EARSCIREV.2005.10.006

Silins U, Bladon KD, Kelly EN, Esch E, Spence JR, Emelko MB, Boon S, Wagner MJ, Williams CHS, Tichkowsky I (2014) Five-year legacy of wildfire and salvage logging impacts on nutrient runoff and aquatic plant, invertebrate, and fish productivity. *Ecohydrology* **7**, 1508–1523. doi:10.1002/ECO.1474

Stein ED, Brown JS, Hogue TS, Burke MP, Kinoshita A (2012) Stormwater contaminant loading following southern California wildfires. *Environmental Toxicology and Chemistry* **31**, 2625–2638. doi:10.1002/ETC.1994

Stevens-Rumann CS, Kemp KB, Higuera PE, Harvey BJ, Rother MT, Donato DC, Morgan P, Veblen TT (2018) Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters* **21**, 243–252. doi:10.1111/ELE.12889

Triska FJ, Kennedy VC, Avanzino RJ, Zellweger GW, Bencala KE (1989) Retention and transport of nutrients in a third-order stream in northwestern California: hyporheic processes. *Ecology* **70**, 1893–1905. doi:10.2307/1938120

Westerling AL (2016) Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences* **371**, 20150178. doi:10.1098/RSTB.2015.0178

Williams C, Silins U, Spencer S, Wagner M, Stone M, Emelko M (2019) Net precipitation in burned and unburned subalpine forest stands after wildfire in the northern Rocky Mountains. *International Journal of Wildland Fire* **28**, 750–760. doi:10.1071/WF18181