Effects of wildfire on source-water quality and aquatic ecosystems, Colorado Front Range

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Abstract Watershed erosion can dramatically increase after wildfire, but limited research has evaluated the corresponding influence on source-water quality. This study evaluated the effects of the Fourmile Canyon wildfire (Colorado Front Range, USA) on source-water quality and aquatic ecosystems using high-frequency sampling. Dissolved organic carbon (DOC) and nutrient loads in stream water were evaluated for a one-year period during different types of runoff events, including spring snowmelt, and both frontal and summer convective storms. DOC export from the burned watershed did not increase relative to the unburned watershed during spring snowmelt, but substantial increases in DOC export were observed during summer convective storms. Elevated nutrient export from the burned watershed was observed during spring snowmelt and summer convective storms, which increased the primary productivity of stream biofilms. Wildfire effects on source-water quality were shown to be substantial following high-intensity storms, with the potential to affect drinking-water treatment processes.

Key words wildfire; Colorado Front Range; source-water quality; dissolved organic carbon; sediment; stream biofilms

INTRODUCTION

Effects of wildfire on municipal water supplies include earlier snowmelt from burned watersheds, post-fire erosion and associated transport of sediment to reservoirs and water treatment plants, and changes in source-water chemistry that may affect drinking-water treatability (Westerling *et al.*, 2006; Emelko *et al.*, 2010; Smith *et al.*, 2011). Challenges in evaluating wildfire effects on source-water quality and aquatic ecosystems include the lack of a pre-fire baseline data set, the unpredictable nature of the event, the remoteness of the terrain, and the difficulty of mobilizing scientific teams immediately after the fire to study watershed responses. It has become increasingly recognized that sampling regimes of high temporal frequency are necessary to characterize hydrological events in a representative and meaningful manner (Kirchner *et al.*, 2004; Pellerin *et al.*, 2011). Forested watersheds in the Colorado Front Range, USA, have a high risk of wildfire and post-fire erosion (Colorado State Forest Service, 2008), although studies evaluating the changes to source-water quality in these montane watersheds are limited to a few studies whose conclusions were based on monthly grab sampling (Hall and Lombardozzi, 2008; Rhoades *et al.*, 2011).

Post-wildfire, streams have shown increases in turbidity, nutrients, organic carbon, major ions and trace metals (Williams & Melack, 1997; Gresswell, 1999; Bladon *et al.*, 2008). Stream ecosystems play an important role in geochemical cycling (Allan & Costillo, 2007) and therefore affect carbon and nutrient export from watersheds (Battin *et al.*, 2003). Although nutrient cycling in streams is primarily controlled by stream biofilms (Paerl & Pickney, 1996), limited information exists on how this ecological function is affected by wildfire. Increased nutrients can stimulate development of stream biofilms, which consist of photosynthetic periphyton and heterotrophic microbes that are held together in an extra-cellular polymeric substrate (Paerl & Pinckney, 1996). Additionally, stream biofilms sequester suspended and dissolved inorganic and organic matter from the water column (Romani *et al.*, 2004). Previous studies by Stone *et al.* (2011) showed biofilm stabilization of bed sediments post-wildfire may reduce sediment export from burned watersheds.

In September 2010, the Fourmile Canyon Fire, located in the wildland–urban interface west of Boulder, Colorado, USA, burned over 2500 ha, destroyed more than 160 homes (USDA Forest Service, 2011), and threatened the water supply of the communities of Pinebrook Hills and

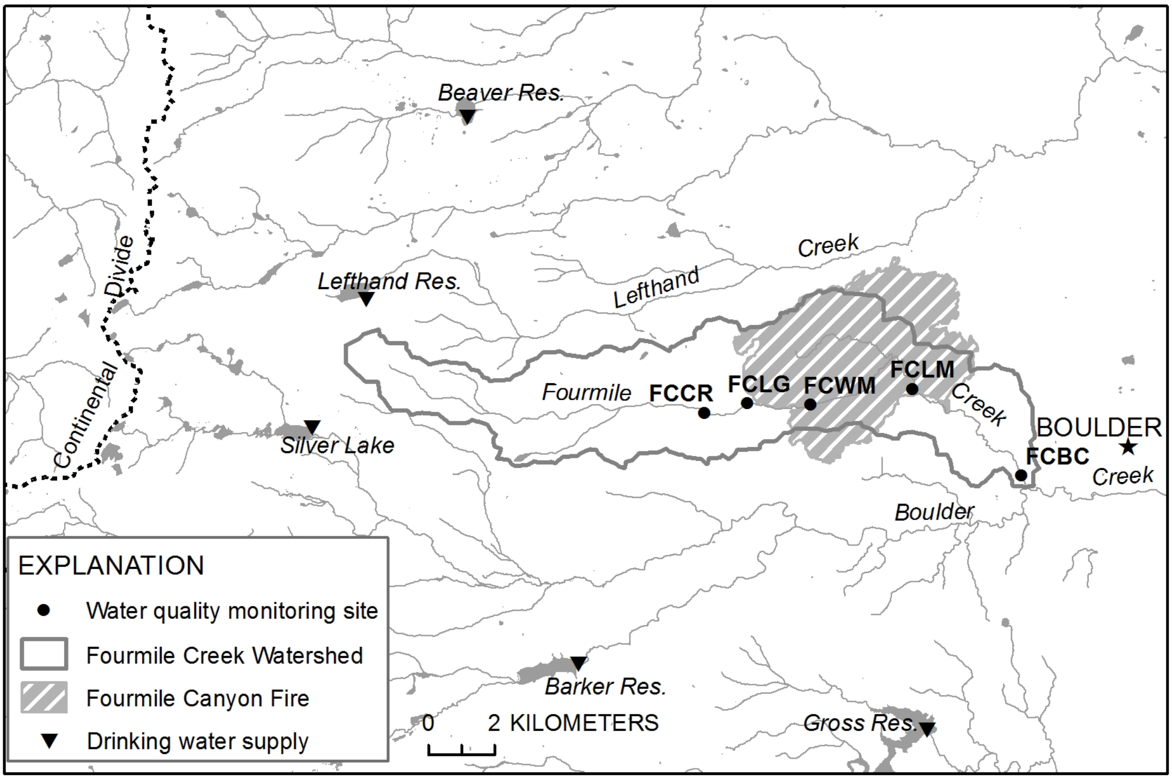

Fig. 1 Map of the Fourmile Creek watershed showing the extent of the 10–13 September 2010 wildfire and location of major water-supply reservoirs in the surrounding area.

Lafayette, which draw water from Fourmile and Boulder Creeks (Fig. 1). The primary focus of this study was to utilize high-frequency sampling to evaluate the effects of the Fourmile Canyon wildfire on water-quality and the stream ecosystem. Discharge in Fourmile Creek is dominated by spring snowmelt, although the summer convective storm season can contribute substantial short-term (less than 1 day) increases in flow.

METHODS AND MATERIALS

Precipitation, discharge and water-quality in Fourmile Creek were monitored for a year following the wildfire that occurred during 10–13 September 2010. Daily precipitation (P_{tot}) and 30-minute maximum rainfall intensity (normalized to an hour, I_{30}) at precipitation gauges, within and near the burned area, were used to characterize summer storm events (Murphy *et al.*, 2012). Water-quality monitoring sites were established at five locations on Fourmile Creek located upstream (FCCR, FCLG), within (FCWM, FCLM), and downstream (FCBC) of the burned area (Fig. 1). The watershed area and percentage of the watershed burned for each site are as follows: FCCR (26 km^2, 0%), FCLG (30 km^2, 0%), FCWM (38 km^2, 9%), FCLM (50 km^2, 25%), FCBC (63 km^2, 23%). Stream discharge was monitored at each site using a combination of methods that included discrete measurement and stream discharge estimates determined using stage measurements (for details see Murphy *et al.*, 2012). Water samples were analysed for nutrients, turbidity, major ions, trace metals, dissolved organic carbon (DOC), and UV-absorbance at 254 nm (UV_{254}) as described in McCleskey *et al.* (2012). Analytical variability based on replicate analyses of select samples for discussed parameters is as follows: nitrate (5%), DOC (2%) and UV_{254} (1%). Over specified time periods (e.g. during snowmelt runoff) statistical analysis of water samples was based on a comparison between samples collected at individual sites and on the same date using a paired t-test (Glantz, 2005).

To assess how observed increases in sediment loading, nutrients and DOC affected the stream ecosystem, the accumulation of stream biofilm on artificial substrates was monitored for three different periods post-wildfire (28 September–27 October 2010; 2 April–24 May 2011; and 21 September–19 October 2011) at sites FCCR, FCWM, and FCLM (Fig. 1) and at a reference site in Boulder Creek 2.5 km downstream from the confluence with Fourmile Creek. The Holm-Sidak multiple comparison test (Glantz, 2005) was used to statistically evaluate differences between stream biofilms at each site after 30 days.

RESULTS AND DISCUSSION

Stream discharge

Daily stream discharge (Fig. 2) was below the historical mean from April to mid-June as a result of limited snowfall in the watershed (Murphy *et al.*, 2012). In the spring of 2011, several frontal storm systems occurring in conjunction with the spring snowmelt resulted in a rapid rise in stream flow from a base flow of less than 0.06 $m^3 s^{-1}$ (2 cfs, cubic feet per second) up to a maximum measured value of 1.1 $m^3 s^{-1}$ (40 cfs). Following the spring snowmelt pulse, two substantial convective storms in July (daily precipitation 12–20 mm, maximum I_{30} 46 mm h^{-1}) produced short-term flash floods that resulted in stream discharge measurements increasing from less than 0.4 $m^3 s^{-1}$ (14 cfs) to greater than 23 $m^3 s^{-1}$ (800 cfs) during a span of less than 5 minutes (Murphy *et al.*, 2012).

Nutrient and organic carbon analysis of water samples

First flush After the wildfire, the first precipitation event occurred on 12 October 2010 (P_{tot} = 14 mm, I_{30} = 4 mm h^{-1}) and DOC concentrations substantially increased above base-flow levels (from 1.5 to 17 mg L^{-1} Fig. 2). Nitrate concentrations also increased above base-flow levels (<0.02 to 1.3 mg L^{-1}). Discharge was not measured during this storm.

Spring snowmelt DOC concentrations increased from 1 to 5 mg L^{-1} during spring snowmelt, but there was no significant difference ($p > 0.05$) between burned and unburned monitoring locations. Specific UV_{254} absorbance (SUVA, UV_{254}/dissolved organic carbon) was slightly higher ($p < 0.05$) in samples collected upstream from the burned area. Nitrate concentrations significantly increased ($p < 0.05$) at monitoring locations within and downstream from the burned area, during both spring snowmelt and low-intensity precipitation events. Ammonium concentrations were monitored throughout the study, but concentrations were generally below the detection limit (0.04 mg L^{-1}, McCleskey *et al.*, 2012).

Summer convective storms Two high-intensity convective storm events (I_{30} > 40 mm h^{-1}, Murphy *et al.*, 2012) occurred in the Fourmile Creek watershed in July 2011. The convective storms resulted in the mobilization and delivery of substantial amounts of sediment from hillslopes into Fourmile Creek. In addition, dramatic increases in DOC and nitrate concentrations were observed (DOC > 70 mg L^{-1}, nitrate > 9 mg L^{-1}) at monitoring locations within and below the burned area. The increased loading of DOC and nitrate to the stream in burned areas was more than two orders of magnitude greater than the loading from unburned areas. During convective storms, SUVA values were higher downstream from the burned areas, most likely the result of increased sediment and associated organic matter loading. As Fourmile Creek returned to base-flow discharge levels (less than 0.3 $m^3 s^{-1}$), turbidity (Murphy *et al.*, 2012), DOC and nitrate remained elevated compared to pre-storm base-flow water-quality. Additionally, a low-intensity storm on 7 September 2011 (daily precipitation 20 mm, I_{30} 8 mm h^{-1}; Murphy *et al.*, 2012) caused increases in DOC and nitrate concentrations that were not observed in pre-July storms of greater storm size and intensity. It appears lower intensity storms are remobilizing sediments deposited in the stream channel as a result of the high-intensity July convective storms, resulting in increased downstream concentrations of DOC and nitrate. It is likely that sediment stored in the stream

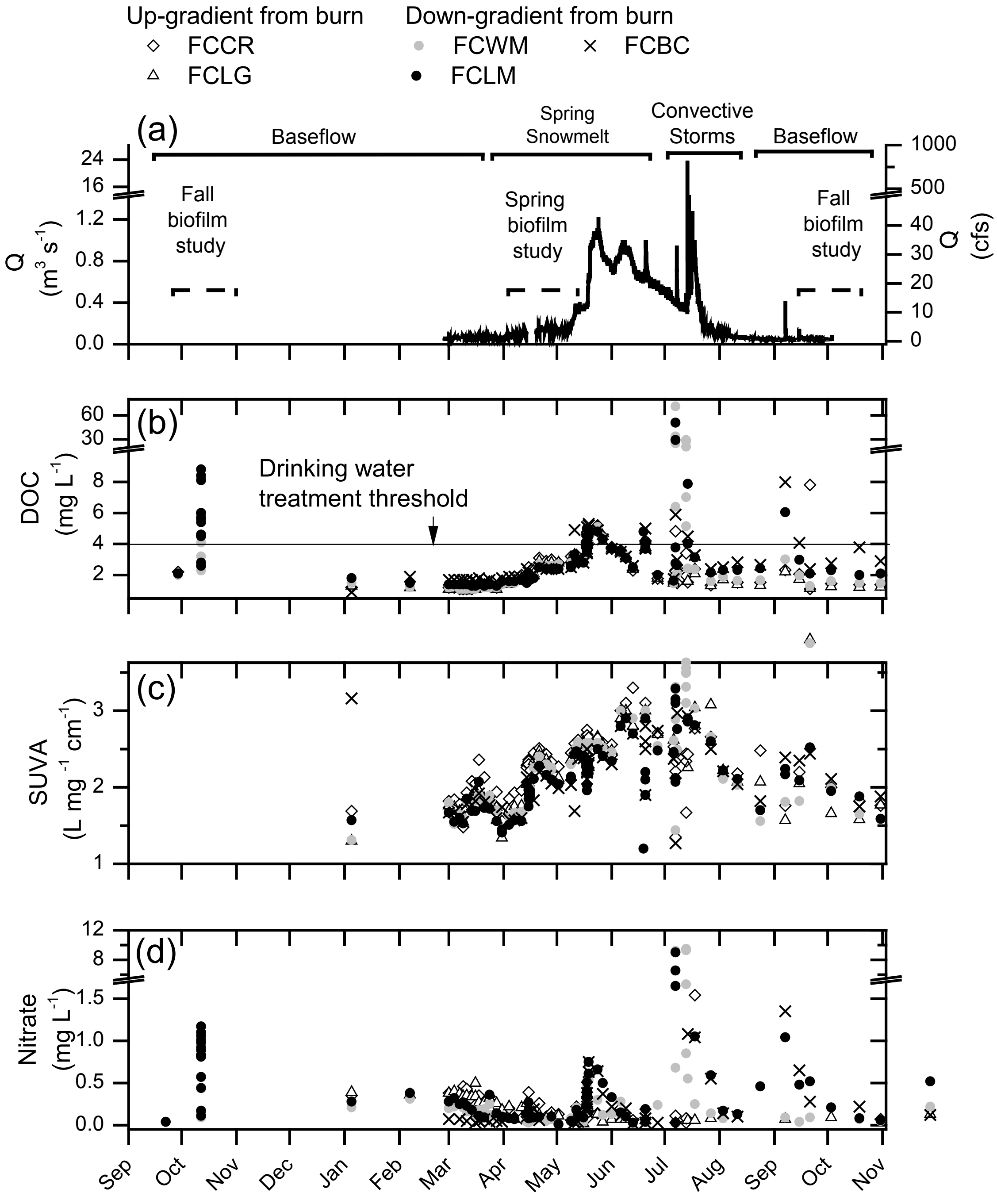

Fig. 2 (a) Stream discharge at FCLM, (b) DOC concentrations, (c) specific ultra-violet absorbance (SUVA) equivalent to UV absorbance at 254 nm normalized by DOC concentration, (d) nitrate concentrations.

channel will continue to affect water quality in the future. Research from other locales has shown wildfire-related effects on water-quality after four years of monitoring (Emelko *et al.*, 2011).

Effects of post-wildfire erosion on the stream ecosystem

The Autotrophic Index (*AI*, ratio between algal carbon and total organic matter) was used to evaluate changes in the stream biofilm community structure. After 30 days of exposure in the autumn of 2010 (after the wildfire, but before the convective storms), the Fourmile Creek sites had significantly (Holm-Sidak multiple comparison test, $p < 0.05$) lower *AI* values than the Boulder Creek reference site, indicative of nutrient limitations in Fourmile Creek. There were no significant differences in the *AI* values for all sites in the spring of 2011 exposure. However, in the autumn 2011 (post-convective storm) exposure, the *AI* values for the FCLM biofilms were similar to Boulder Creek biofilms, and significantly greater (Holm-Sidak multiple comparison test, $p < 0.05$) than the other Fourmile Creek biofilms. This increase may be indicative of increased nutrient supply benefitting the autotrophic community, and increases in both nitrate and sediment-associated phosphorus were observed (McCleskey *et al.*, 2012).

CONCLUSION AND IMPLICATIONS

This study focuses on discrete precipitation events following a wildfire and their corresponding effects on water-quality and the aquatic ecosystem. Increased erosion has been observed in several post-fire Colorado Front Range watersheds (e.g. Moody & Martin, 2001). Results from this study suggest that dramatic differences in sediment loading and associated water-quality can be expected between unburned and burned areas during high-intensity storm events. Stream discharge and turbidity increased by several orders of magnitude at monitoring locations downstream from the burned areas (Murphy *et al.*, 2012), meaning that the increased sediment-associated carbon and nutrient fluxes from burned watersheds have the potential to influence profoundly downstream aquatic ecosystems and watershed water supplies. The results also suggest that the primary productivity of the aquatic ecosystem increased as a result of increased sediment loading and associated nutrient supply (including both dissolved nitrogen species and sediment-bound phosphorus) and this response has been observed in other wildfire-affected watersheds (Emelko *et al.*, 2011; Smith *et al.*, 2011).

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REFERENCES

Allan, J. D. & Castillo, M. M. (2007) *Stream Ecology: Structure and Function of Running Waters*. Springer, Dordrecht, The Netherlands. 436 pp.

Battin, T. J., Kaplan, L. A., Newbold, J. D. & Hansen, C. M. E. (2003) Contributions of microbial biofilms to ecosystem processes in stream mesocosms. *Nature* 426, 439–442.

Bladon, K. D., Silins, U., Wagner, M. J., Stone, M., Emelko, M. B., Devito, K. J., Mendoza, C. A. & Boon, S. (2008). Wildfire impacts on nitrogen export and production from headwater streams in southern Alberta's Rocky Mountains. *Can. J. For. Res*. 38, 2359–2371.

Colorado State Forest Service (2008) Colorado Statewide Forest Resource Assessment – A Foundation for Strategic Discussion and Implementation of Forest Management in Colorado. http://csfs.colostate.edu/pages/statewide-forest-assessment.html. Accessed December 2011.

Emelko, M. B., Silins, U., Bladon, K. D. & 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 Res*. 45, 461–472.

Glantz, S. A. (2005) *Primer of Biostatistics*, 6th edn. McGraw-Hill, New York. 520 pp.

Gresswell, R. E. (1999) Fire and aquatic ecosystems in forested biomes of North America. *Trans. Am. Fisher. Soc.* 128, 193–221.

Hall, S. J. & Lombardozzi, D. (2008) Short-term effects of wildfire on montane stream ecosystems in the southern Rocky Mountains: One and two years post-burn. *Western North American Naturalist* 68, 453–462.

Kirchner, J. W., Feng, X., Neal, C. & Robson, A. J. (2004) The fine structure of water-quality dynamics: the (high-frequency) wave of the future. *Hydrol. Processes* 18, 1353–1359.

McCleskey, R. B., Writer, J. H. & Murphy, S. F. (2012) Water chemistry data for surface waters impacted by the Fourmile Canyon wildfire, Colorado, 2010–2011. *US Geological Survey Open-File Report* (in press).

Moody, J. A. & Martin, D. A. (2001) Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surf. Processes Landf.* 26, 1049–1070.

Murphy, S. F., McCleskey, R. B. & Writer, J. W. (2012) Effects of flow regimes on stream turbidity and suspended solids after wildfire, Colorado Front Range, USA. In: *Wildfire and Water Quality: Processes, Impacts and Challenges* (Proc. conference held in Banff, Canada, June 2012). IAHS Publ. 354. IAHS Press. Wallingford, UK (this volume).

Paerl, H. W. & Pinckney, J. L. (1996) A mini-review of microbial consortia: Their roles in aquatic production and biogeochemical cycling. *Microb. Ecol.* 31, 225–247.

Pellerin, B. A., Saraceno, J. F., Shanley, J. B., Sebestyn, S. D., Aiken, G. A., Wollheim, W. M. & Bergamaschi, B. A. (2011) Taking the pulse of snowmelt: *In situ* sensors reveal seasonal, event and diurnal patterns of nitrate and dissolved organic matter variability in an upland forest stream. *Biogeochem.* doi:10.1007/s10533-011-9589-8.

Rhoades, C. C., Entwistle, D. & Butler, D. (2011) The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado: *Int. J. Wildland Fire* 20, 430–442.

Romani, A. M., Guasch, H., Munoz, I., Ruana, J., Vilalta, E., Schwartz, T., Emtiazi, F. & Sabater, S. (2004) Biofilm structure and function and possible implications for riverine DOC dynamics. *Microb. Ecol.* 47*,* 316–328.

Smith, H. G., Sheridan, G. J., Lane, P. N. J., Nyman, P. & Haydon, S. (2011) Wildfire effects on water quality in forest catchments: a review with implications for water supply. *J. Hydrol.* 396, 170–192.

Stone, M., Emelko, M. B., Droppo, I. G. & Silins, U. (2011) Biostabilization and erodibility of cohesive sediment deposits in wildfire-affected streams. *Water Res.* 45, 521–534.

USDA Forest Service (2011) Fourmile Canyon Fire: Preliminary Findings. http://www.fs.fed.us/rmrs/docs/fourmile-canyon-fire/preliminary-findings.pdf. Accessed 5 March 2012.

Westerling A. L., Hidalgo, H. G., Cayan, D. R. & Swetnam, T. W. (2006) Warming and earlier spring increase Western U.S. forest wildfire activity. *Science* 313, 940–943.

Williams M. R. & Melack, J. M. (1997) Effects of prescribed burning and drought on the solute chemistry of mixed-conifer forest streams in the Sierra Nevada, California. *Biogeochem.* 39, 225–253.