CSIRO PUBLISHING

International Journal of Wildland Fire **2011**, *20*, 430–442 www.publish.csiro.au/journals/ijwf

The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado[A]

Charles C. Rhoades[A,D], *Deborah Entwistle*[B] *and Dana Butler*[C]

[A]USDA Forest Service, Rocky Mountain Research Station, 240 W Prospect Road, Fort Collins, CO 80526, USA.
[B]USDA Forest Service, Arapaho and Roosevelt National Forests, Fort Collins, CO 80526, USA.
[C]USDA Forest Service, Pike and San Isabel National Forests, Pueblo, CO 81008, USA.
[D]Corresponding author. Email: crhoades@fs.fed.us

Abstract. The 2002 Hayman Fire was the largest fire in recent Colorado history (558 km^2). The extent of high severity combustion and possible effects on Denver's water supply focussed public attention on the effects of wildfire on water quality. We monitored stream chemistry, temperature and sediment before the fire and at monthly intervals for 5 years after the fire. The proportional extent of a basin that was burned or that burned at high severity was closely related to post-fire streamwater nitrate and turbidity. Basins that burned at high severity on >45% of their area had twice the streamwater nitrate and four times the turbidity as basins burned to a lower extent; these analytes remained elevated through 5 years post-fire. In those basins, the highest post-fire streamwater nitrate concentrations (23% of USA drinking water standards) were measured during spring, the peak discharge period. Summer streamwater was 4.0°C higher in burned streams on average compared with unburned streams; these persistent post-fire stream temperature increases are probably sufficient to alter aquatic habitat suitability. Owing to the slow pace of tree colonisation and forest regrowth, recovery of the watersheds burned by the Hayman Fire will continue for decades.

Additional keywords: Colorado Front Range, montane forests, nitrate, turbidity, wildfire effects.

Introduction

The effects of wildfire on aquatic conditions span from hours to centuries (Minshall *et al*. 1989). Temperatures reached during active burning can kill aquatic vertebrates and invertebrates (Dunham *et al*. 2003; Minshall 2003). Smoke and ash deposited into streams during combustion immediately change stream chemistry (Earl and Blinn 2003; Cerdá and Doerr 2008); the effects typically subside within months as precipitation transports ash from upland areas into surface or subsurface water. Sustained effects of wildfire on watershed conditions result from the loss of aboveground structure and subsequent alterations in soil and hydrological processes. Return of stream conditions (i.e. discharge, temperature, chemical composition, sediment concentration) to within their pre-fire range follows overstorey vegetation recovery, typically occurring within a few years or decades (Benavides-Solorio and MacDonald 2001; Moody and Martin 2001; Prepas *et al*. 2003; Lane *et al*. 2008), though relatively few studies have compared post-fire changes to pre-fire stream water conditions (Minshall *et al*. 2004; Burke *et al*. 2005).

The extent and severity of combustion determines the magnitude of wildfire effects on watershed processes. In North American forests, high-severity burning kills most overstorey and understorey plants, roots and rhizomes and consumes most of the surface organic matter (Keeley 2009). This type of combustion generally results in widespread change in forest structure and soil conditions that dramatically alter the watershed processes that control streamflow, peak discharge, soil erosion, channel stability and streamwater nutrient export (Spencer and Hauer 1991; Prepas *et al*. 2003; Robichaud *et al*. 2003; Lane *et al*. 2008; Blake *et al*. 2010). In contrast, low-severity fire kills few overstorey trees and has minimal effect on belowground plant structures, litter layers and watershed conditions. The vegetation and O horizon (Pannkuk and Robichaud 2003; Cerdá and Doerr 2008) remaining after moderate- and low-intensity fire both buffer against post-fire changes and facilitate watershed recovery (Wagenbrenner *et al*. 2006). The influences of fire severity on vegetation combine with the spatial variability of soil and geomorphic features to determine basin-scale consequences of wildfire (Ice *et al*. 2004; Rodríguez *et al*.

[A]This paper was written and prepared by US Government employees on official time, and therefore it is in the public domain and not subject to copyright in the US.

 10.1071/WF09086 1049-8001/11/030430

2009). In addition, post-fire water quality is typically regulated by seasonal and episodic fluctuations in stream discharge (Townsend and Douglas 2000; Prepas *et al*. 2003; Burke *et al*. 2005; Moody *et al*. 2008; Blake *et al*. 2010).

The Hayman Fire was ignited on 8 June 2002 after a period of prolonged drought in the Colorado Front Range (Graham 2003, see maps therein). Total precipitation and the water contained in the 2002 snowpack were approximately half of long-term annual averages (Western Regional Climate Center 2006). Low fuel moisture and relative humidity (5–8%) and strong, gusty winds (30–80 $km\,h^{-1}$) triggered rapid rates of spread (>3.2 $km\,h^{-1}$) and long-range spot fires (Finney *et al*. 2003). Coupled with the extreme climatic conditions, the dense, continuous horizontal and vertical fuel structure, created by decades of fire exclusion in lower montane forests (Brown *et al*. 1999; Kaufmann *et al*. 2000), allowed burning to advance for 24 days prior being declared contained on 2 July 2002 (Graham 2003). Areas of internal burning continued throughout the summer months, and the fire was not declared extinguished until 30 October 2002. High-severity crown fire killed the overstorey forest and consumed forest floor across 40% of the entire area burned. Moderate- or high-severity fire influenced 32–96% of riparian ecosystems compared with 25–62% in upland areas in first- to third-order watersheds located within the burn perimeter (Kershner *et al*. 2003).

The 558 km^2 Hayman Fire was the largest fire in recent Colorado history (Graham 2003). Its location, 75 km from 2.7 million citizens in the Denver metropolitan area, created public anxiety about protection of human safety and private property in the expanding residential areas of the Front Range foothills. Colorado receives more than 90% of is public water supply from surface water sources (Hutson *et al*. 2004) that originate from forest watersheds, so concern about protection of Denver's supply of clean water focussed attention on the watershed response after the Hayman Fire. Public awareness, raised both by the Hayman Fire and other large North American wildfires of 2002 and recent years, has prompted widespread implementation of hazardous fuels reduction projects on national forest lands (USDA/USDOI 2005). These efforts include timber harvesting, prescribed burning and fuels reduction treatments conducted in the wildland–urban interface. However, in spite of the broad mandate for this work, active management of national forestlands remains controversial (Beschta *et al*. 2004).

During the past two decades, the incidence of large, severe forest fires in the western USA (Westerling *et al*. 2006) and elsewhere globally has increased in response to warmer spring temperatures and longer fire seasons (Williams *et al*. 2001; Scholze *et al*. 2006; Intergovernmental Panel on Climate Change 2007; Flannigan *et al*. 2009) and fuel accumulation. Wildfires such as the Hayman Fire periodically disturb watersheds in Colorado's montane forest zone (Romme *et al*. 2003; Veblen and Donnegan 2005), yet the influence of wildfire and fire behaviour on aquatic processes remains poorly understood. As part of the Upper South Platte Watershed Protection and Restoration Project, a multiple-basin monitoring network was established 1 year before the Hayman Fire, which allowed comparison of streamwater properties in burned and unburned catchments for a range of burns severities and watershed characteristics. This assessment evaluated changes in streamwater chemistry, temperature and sediment beginning the month the fire was contained and continuing for 5 years.

Methods

Study site

The Hayman Fire burned in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests of the lower montane elevation zone (1980–2750 m). Mean annual precipitation within the area burned by the Hayman Fire is 41 cm (Western Regional Climate Center 2006); summer rain and snow fall contribute equal amounts of the annual precipitation.

The majority of the Hayman Fire area and the study watersheds are underlain by the Pikes Peak batholith, a coarse-grained biotite and hornblende-biotite granite (Bryant *et al*. 1981). Soils weathered from the Pikes Peak formation granite are weakly developed (Typic Ustorthents), excessively drained, coarse sandy loams (Cipra *et al*. 2003). Depth to bedrock ranges from 25 to 50 cm and coarse fragments represent 25–50% of the soil volume. A mixture of sandstone and limestone strata that form deeper soils with higher organic matter and cation content underlie a portion of the burn area involved in this study (Bryant *et al*. 1981; USDA Forest Service 1995). Soils formed from Pikes Peak formation granite can be highly susceptible to erosion, sheetwash, rilling and gullying (Robichaud *et al*. 2003; T. John, unpubl. data, 2002).

Tributaries of the Upper South Platte supply water for the Denver metropolitan area and support popular sport fishing sites. Pre-fire water quality concerns regarding sediment and temperature of several streams located in the study area resulted in their placement on Colorado's 303(d) Monitoring and Evaluation list (Colorado Water Quality Control Division 2002). Streams draining the Pikes Peak batholith also contain naturally high fluoride concentrations released by fluoride, lithium and rare earth-rich pegmatite inclusions (Simmons *et al*. 1987; Foord *et al*. 1995).

Sampling and analysis

Monthly sampling began in August 2001 on six streams (Table 1). The Hayman Fire affected half of the original basins, so our assessment compared pre- and post-fire flow-weighted streamwater concentrations in three burned and three unburned watersheds. Four additional sample locations were established following the fire to allow comparisons of the unburned drainages with drainages affected by varying fire extent (Table 1).

Monthly streamwater samples were collected for dissolved chemical constituents and sediment. Streamwater grab samples were kept cool and then filtered (0.45 μm) before analysis by ion chromatography (Waters Ion Chromatographs, Waters Corp., Milford, MA, USA, with a Dionex AS12 A Separator Anion Column, Dionex Corp., Sunnyvale, CA, USA, and Waters IC Pak Cation M/D Column, Waters; APHA 1998*a*). Detection limits were 0.01 $mg\,L^{-1}$ for NO_3-N, NH_4-N, Na^+, Cl^- and F^-, 0.02 $mg\,L^{-1}$ for Ca^{2+}, Mg^{2+} and K^+, 0.03 $mg\,L^{-1}$ for PO_4 and 0.05 $mg\,L^{-1}$ for SO_4^{2-}. Acid neutralising capacity (ANC) was measured by Gran titration (Gran 1952) and pH and electrical conductivity were analysed automatically with PC Titrate sensors (Mantech Inc., Guelph, ON, Canada).

Streamwater-suspended sediment was collected in 1-L bottles, filtered onto 0.45-μm filters and dried at 105°C (APHA 1998*b*). Turbidity was measured in the 1-L samples using the nephelometric method (APHA 1998*c*; HF Scientific Inc., Micro 100 Turbidimeter, Fort Meyers, FL, USA). On-site stream temperature and conductivity measurements complimented laboratory analyses and instantaneous discharge measurements were used to flow-weight streamwater concentrations. Storm event sampling would have allowed greater insight about water quality fluctuations during episodic high-flow events, but personnel and budgetary constraints and the remoteness of several of the sites restricted us to monthly sampling.

Pre-fire and post-fire water nitrate, temperature and turbidity were compared graphically and statistically between the three burned and three unburned basins that were part of the original sampling network. The influence of basin geology was evaluated for pre-fire streamwater chemistry, temperature and sediment among the six original sample streams using one-way analysis of variance (SPSS ver. 10.1.3, SPSS Inc., Chicago, IL, USA). Levene's statistic was used to test for homogeneity of variance. Non-parameteric Kruskal–Wallis means comparisons were made on non-normal streamwater analytes. Significance is reported at the $\alpha = 0.05$ critical value unless noted otherwise. Relationships between water quality parameters and basin characteristics were evaluated using least-squares linear regression (SPSS Ver. 10.1.3).

Results

The pre-fire chemistry of stream draining basins located solely on Pikes Peak formation granite was more dilute for many analytes than streams underlain by a mixture of granitic and sedimentary geological materials (Table 2). Streamwater Ca^{2+}, conductivity, ANC, Mg^{2+}, Na^+ and Cl^- were 1.5 to 3 times higher in mixed-geology basins; pH was 0.4 units higher. Calcium was the dominant cation followed by Na^+, Mg^{2+} and K^+ in all six streams. ANC, composed largely of bicarbonate, was the dominant anion, followed by SO_4^{2-}, Cl^- and F^-. In contrast to other streamwater analytes, NO_3-N, NH_4-N, F^-, PO_4, turbidity and suspended sediment did not differ significantly among the basins regardless of their lithology ($P > 0.1$).

Streamwater NO_3-N averaged 0.1 mg N L^{-1} in the six South Platte tributaries before the Hayman Fire. During the pre-fire period, NH_4-N was never detectable and PO_4 rarely exceeded detection limits. Pre-fire mean F^- levels (3 mg L^{-1}) exceeded the National Secondary Drinking Water Standard of 2 mg L^{-1} (US EPA 2003) due to release of fluoride and rare earth elements from pegmatite inclusions in the Pikes Peak formation granite (Simmons *et al*. 1987; Foord *et al*. 1995). Turbidity averaged 5 NTU (Nephelometric Turbidity Units) and did not exceed 10 NTU in most streams.

Fire effects

The Hayman Fire burned three of the six streams included in pre-fire sampling (Brush, Trout and Horse Creeks). All three unburned streams, as well as the four basins added to the sampling network after the fire, were located in granitic basins (Table 1). Owing to the pre-fire differences in dominant cation and anion concentrations (e.g. Ca^{2+} and ANC) between the granitic and mixed-lithology basins (Table 2), post-fire comparisons are restricted to granitic basins for these analytes. In contrast, nitrate, turbidity and sediment did not respond significantly to differences in basin lithology, so their post-fire comparisons include all 10 basins.

Average spring and summer water temperatures were 5 and 6°C higher respectively in burned catchments the year following the Hayman Fire compared with the corresponding seasonal averages for unburned streams (Fig. 1). The maximum summer temperature measured in burned streams exceeded pre-fire summer temperatures by 10°C. Winter temperatures did not differ between burned and unburned streams. In the 5 years following the burn, summer and spring temperatures averaged 4.0 and 4.5°C higher in burned and unburned streams respectively. During the post-fire years, spring streamwater temperature in burned streams was similar to the summer temperatures

Table 1. Study watersheds within and adjacent to the 2002 Hayman Fire, Upper South Platte River Drainage, Colorado

	Stream order	Watershed area (ha)	Burned area		Burn severity (ha)			Burn severity (%)		
			(ha)	(%)	Low	Moderate	High	Low	Moderate	High
Burned watersheds										
Brush	1	609	532	87.5	176	18	338	28.9	3.0	55.6
Fourmile[A]	1	2145	1513	70.5	247	217	1049	11.5	10.1	48.9
Wigwam[A]	2	5753	2742	47.7	863	123	1756	15.0	2.1	30.5
West[A]	3	17 888	8482	47.4	3942	2656	1883	22.0	14.9	10.5
Goose[A]	2	22 236	2604	11.7	904	210	1490	4.1	0.9	6.7
Trout[B]	3	30 088	2555	8.5	1102	1082	372	3.7	3.6	1.2
Horse[B]	3	48 670	11 688	24.0	5184	3848	2656	10.7	7.9	5.5
Unburned watersheds										
No name	1	345	0	0	0	0	0	0	0	0
Sugar	2	3129	0	0	0	0	0	0	0	0
Pine	2	3364	0	0	0	0	0	0	0	0

[A]Monthly sampling began in August 2002, following containment of the Hayman Fire. Sampling at other sites began in August 2001.
[B]Streams draining basins with mixed lithology.

Table 2. Pre-fire streamwater chemistry and sediment South Platte tributaries draining granitic ($n = 4$) and mixed sedimentary and granitic ($n = 2$) basins

Flow-weighted mean concentrations (and s.e.) are calculated from analysis samples collected monthly between August 2001 and May of 2002. Significance was reported at the $\alpha = 0.05$ critical value. ANC, acid neutralising capacity; NTU, Nephelometric Turbidity Units

	pH	EC ($\mu S\,cm^{-1}$)	Ca ($mg\,L^{-1}$)	Na ($mg\,L^{-1}$)	Mg ($mg\,L^{-1}$)	K ($mg\,L^{-1}$)	NH_4-N ($mg\,L^{-1}$)	ANC ($mg\,L^{-1}$)	SO_4 ($mg\,L^{-1}$)	Cl ($mg\,L^{-1}$)	F ($mg\,L^{-1}$)	NO_3-N ($mg\,L^{-1}$)	PO_4 ($mg\,L^{-1}$)	Turbidity (NTU)	Sediment ($mg\,L^{-1}$)
Basin geology															
Granitic ($n = 4$)	7.8 (0.05)	177.5 (10.7)	22.6 (1.7)	6.5 (0.4)	4.3 (0.3)	3.0 (0.3)	0.0 (0.0)	56.7 (4.2)	17.5 (1.6)	3.2 (0.6)	3.2 (0.2)	0.1 (0.02)	0.0 (0.0)	7.4 (3.5)	13.9 (4.9)
Mixed ($n = 2$)	8.2 (0.04)	329.2 (11.7)	34.2 (1.2)	18.6 (0.9)	8.4 (0.6)	3.4 (0.1)	0.0 (0.0)	115.6 (9.4)	16.8 (1.0)	9.5 (1.7)	2.6 (0.1)	0.2 (0.07)	0.0 (0.0)	5.7 (2.4)	7.7 (2.7)
Mann–Whitney *U*															
Significance	0.000	0.000	0.000	0.000	0.000	0.000	0.703	0.000	0.002	0.000	0.657	0.196	0.809	0.207	0.547

of streams draining unburned basins. As such, streamwater warmed earlier in burned basins and aquatic ecosystems were warmer for a prolonged period.

Concentrations of Ca^{2+} and ANC and conductivity increased in the months following the Hayman Fire (Fig. 2). Monthly levels measured in burned streams exceeded both average pre-fire and post-fire peaks in unburned granitic streams. Maximum post-fire Ca^{2+} concentrations were double the mean summer peak concentration of pre-fire streams and post-fire unburned streams (i.e. 56 *v.* 23 $mg\,L^{-1}$). Similarly, post-fire ANC was also twice that of the summer peak concentrations for pre-fire and unburned post-fire streams. Streamwater conductivity responded similarly. During the 2 months following the fire, conductivity and, to a lesser extent, Ca^{2+} concentrations increased in one unburned stream due to ashfall from the adjacent fire. Dissolved PO_4 was detectable in all burned streams the first sample date after the fire (July 2002; mean and maximum of 0.20 and 0.32 $mg\,L^{-1}$). The following July, PO_4 was detectable in six of seven burned streams, but for the duration of the study, PO_4 was below detection in both burned and unburned streams. Stream NH_4-N was undetectable before the fire, increased in three streams during July and August 2002 (i.e. mean and maximum of 0.21 and 0.27 mg NH_4-N L^{-1}), and was then typically below detection in burned and unburned streams for the duration of the study.

Streamwater Ca^{2+}, ANC and conductivity are typically diluted by the increased discharge volume during snowmelt. However, during the first post-fire years, the minimum values for these analytes did not drop below pre-fire or unburned peak concentrations (Fig. 2*a*, *b*). In the first winter–spring snowmelt period after the Hayman Fire, Ca^{2+}, ANC and conductivity levels were 1.5-fold higher in burned streams compared with pre-fire and unburned post-fire seasonal averages (Fig. 2). The

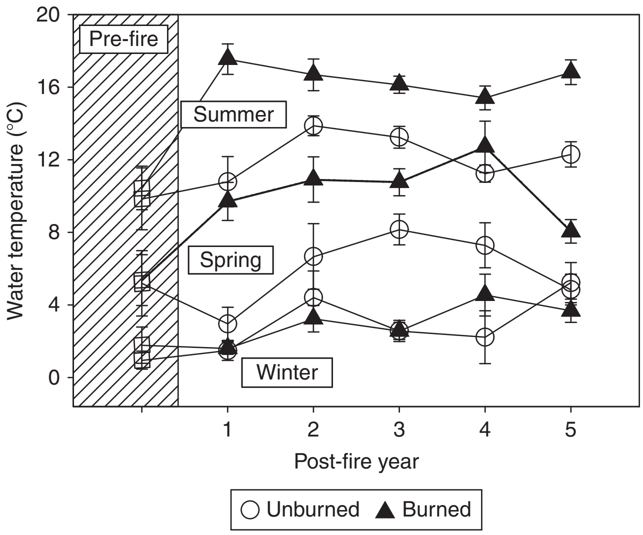

Fig. 1. Streamwater temperature of three burned and three unburned watersheds in the upper South Platte watershed. Bars show means and standard errors for 4-month periods (Winter, November–February; Spring, March–June; Summer, July–October) during the year preceding and the 5 years following the fire.

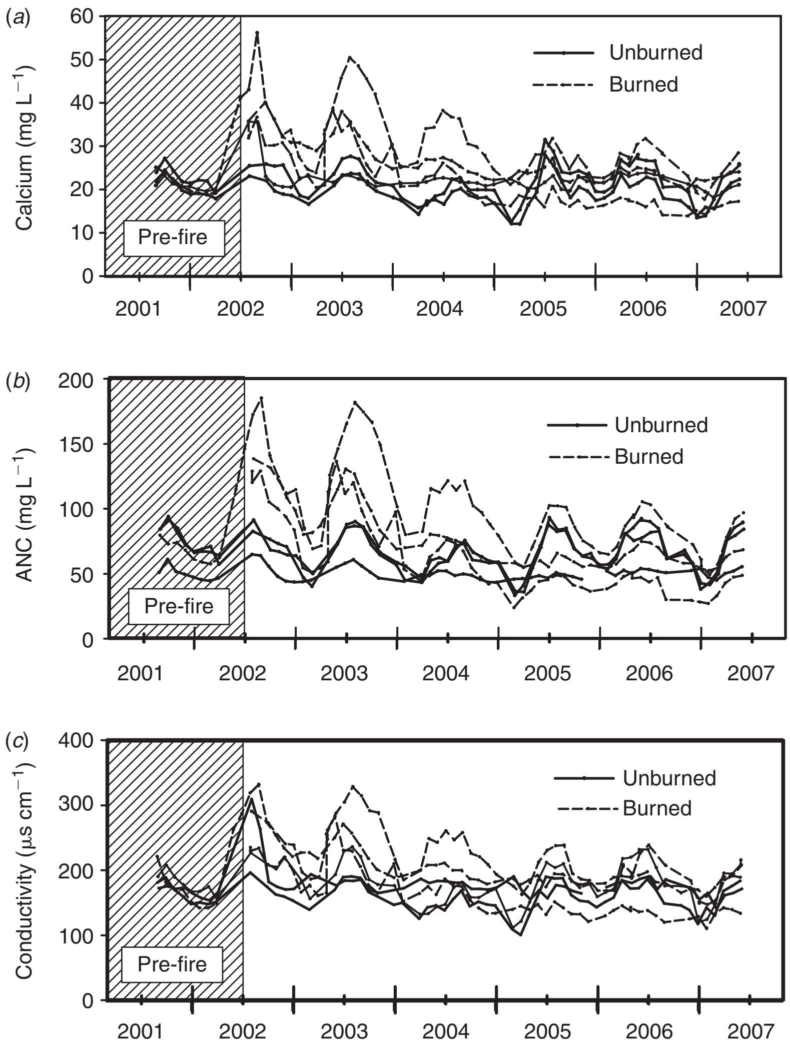

Fig. 2. Monthly streamwater concentrations of (*a*) calcium and (*b*) acid neutralising capacity (ANC) and (*c*) electrical conductivity in watersheds underlain by Pikes Peak formation granite. Dashed lines denote four burned basins and solid lines denote three streams draining basins outside the fire perimeter.

chemical effect of the fire remained evident during the second post-fire snowmelt (e.g. spring 2003–04) and summer (2004) seasons before disappearing approximately 2 years after the fire.

The Hayman Fire burned 8–87% of the basins included in our assessment (Table 1); high-severity wildfire affected 1–56% of the basins. Both streamwater nitrate and turbidity increased linearly with the proportional extent of a basin that burned or that burned at high severity (Figs 3, 4); no other chemical analyte responded significantly to fire extent or severity. Nitrate and turbidity both increased more than 4-fold across the range of proportional extent burned (Figs 3*a*, 4*a*). An apparent threshold in streamwater nitrate and turbidity occurred between the two basins that burned on >60% of their area or high-severity wildfire on >45% of their area (i.e. Brush and Fourmile Creeks) and the other five streams (Table 3). The streams draining basins affected by extensive stand-replacing fire had 3.3-fold higher nitrate concentrations on average than basins that burned to a lesser extent (Fig. 3*b*). Similarly, average turbidity was 2.4-fold greater in basins with extensive high-severity fire compared with other burned basins (Fig. 4*b*).

Streamwater nitrate fluctuated seasonally, with the highest peaks coinciding with spring snowmelt (Fig. 5). In unburned basins, peak NO_3-N concentrations averaged 0.2 mg N L^{-1} and exceeded 0.5 mg N L^{-1} on one occasion during the study period (Fig. 5*a*). For streams draining basins that burned to a low extent, pre-fire and post-fire seasonal nitrate fluctuations were of similar magnitude (Fig. 5*b*). In contrast, the two extensively burned basins had higher nitrate peaks than both unburned basins and basins burned to a lower extent (Fig. 5*c*). The seasonal peak in streamwater NO_3-N exceeded 1.5 mg N L^{-1} in extensively burned basins on average, and it reached 2.3 N mg L^{-1} during the third spring snowmelt after the fire (spring 2005). More than 10% of post-fire samples exceeded 1.1 mg N L^{-1}, a concentration threshold not reached in any basin that was unburned or burned to a small extent. Nitrate concentrations remained elevated between seasonal peaks, especially

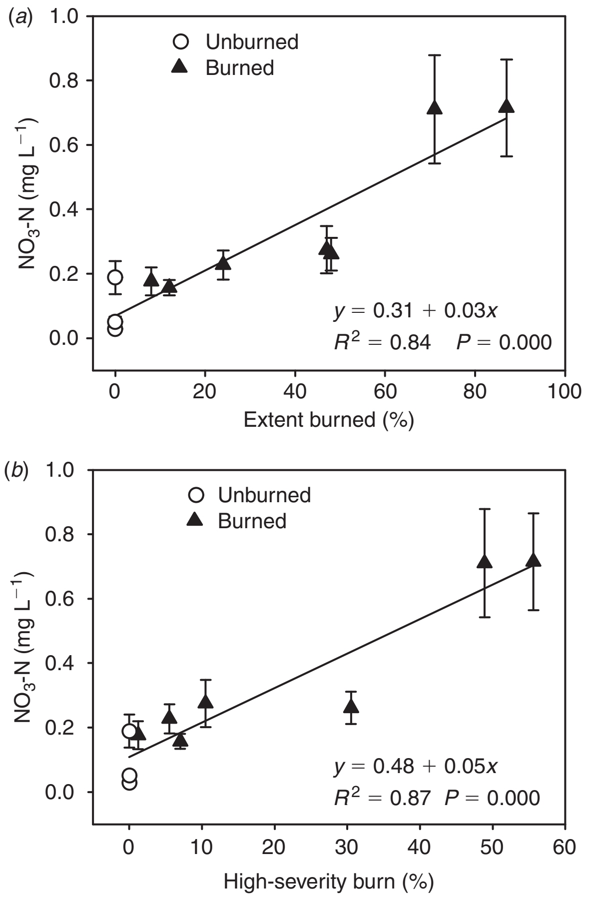

Fig. 3. Linear relationship between mean streamwater NO_3-N for individual basins during post-fire years and (*a*) the extent of each watershed burned and (*b*) the area affected by high-severity combustion during the 2002 Hayman Fire.

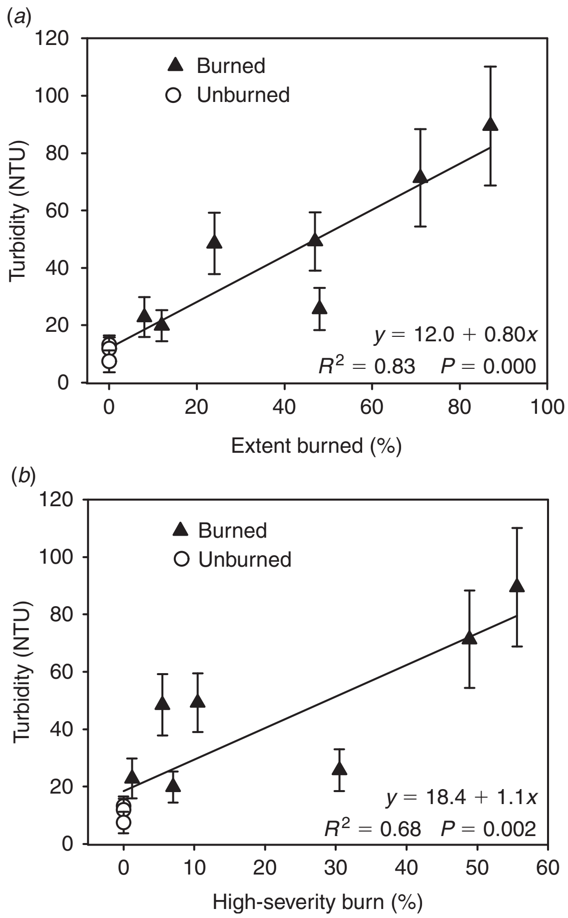

Fig. 4. Linear relationship between mean streamwater turbidity for individual basins during post-fire years and (*a*) the extent of each watershed burned and (*b*) the area affected by high-severity combustion during the 2002 Hayman Fire. NTU, Nephelometric Turbidity Units.

during the third and fourth post-fire years. In extensively burned basins, streamwater nitrate concentrations did not decline over the course of the study; the fifth post-fire peak (2007) did not differ from the previous 4 years (Table 3).

Like nitrate, turbidity increased during spring snowmelt in unburned streams (Fig. 6). For basins burned to a low extent (Fig. 6*a*), streamwater turbidity also increased after two summer rain storms. Where severe fire occurred on >45% of a basin, turbidity responded more often and to a greater degree, compared with either unburned or lesser-burned basins. Streamwater turbidity surpassed 200 NTU on 13 occasions in extensively burned basins, and higher-turbidity samples were as likely to occur during the summer as the spring snowmelt season. Stream turbidity showed no sign of decline in consecutive post-fire years (Table 3).

Stream nitrate (Fig. 7) increased with stream discharge during the post-fire period. The highest seasonal mean (Fig. 7*a*) and maximum (Fig. 7*b*) nitrate concentrations measured in the 10 study streams (1.1 and 2.3 mg N L^{-1}) occurred during the spring snowmelt when streamflow was highest. Mean streamwater nitrate in basins with extensive high-severity fire were more sensitive to increased discharge (i.e. slope was 4-fold greater) than either unburned basins or those with a lower extent of high-severity fire. Unlike stream nitrate, the highest mean (Fig. 8*a*) and maximum (Fig. 8*b*) turbidity measurements occurred during the summer season in response to storm events in 2005 and 2006, thus complicating the linear relationship with stream discharge. In contrast to our monthly collection schedule, sampling of individual storm events would have allowed a more accurate measure of peak nitrate and turbidity and would have better demonstrated how episodic discharge events regulate sediment and nutrient export.

Discussion and conclusions

Immediate and persistent effects

The chemical composition of streams draining watersheds burned by the Hayman Fire exhibited changes commonly associated with particulate and gaseous chemical inputs from ash and smoke (Minshall *et al.* 1989; Cerdá and Doerr 2008). Cation (Ca^{2+}, Mg^{2+}, K^{+}), ANC and conductivity in streams responded immediately after the fire and concentrations peaked during the 4-month period following the fire (Fig. 2). Ash deposition also altered these analytes in one adjacent unburned stream. The duration of wildfire ash effects on streamwater acid–base chemistry typically decline to pre-disturbance levels

Table 3. Post-fire nitrate (mg NO_3-N L^{-1}) and turbidity (NTU, Nephelometric Turbidity Units) for unburned basins and basins with low and high proportional extent burned by the 2002 Hayman Fire

Basins in the high-extent class burned on >60% of their area with >45% of basin area affected by high-severity wildfire. Monthly flow-weighted post-fire streamwater nitrate concentrations and turbidity were collected from August 2002 to June 2007. Significances were determined by Kruskal–Wallis non-parametric analysis of variance test and was significant at $\alpha = 0.05$

Post-fire year		Nitrate			Significance	Turbidity			Significance
		Unburned	Low extent	High extent		Unburned	Low extent	High extent	
1	Mean	0.15	0.13	0.39	0.144	4.26	31.30	71.95	0.004
	Median	0.03	0.12	0.22		2.30	32.58	48.00	
	s.d.	0.27	0.11	0.46		4.39	27.75	57.86	
	95% c.i.	(−0.13 to 0.44)	(0.01 to 0.24)	(0.03 to 0.75)		(−0.3 to 8.8)	(2.2 to 60.4)	(27.5 to 116.4)	
2	Mean	0.05	0.18	0.38	0.009	5.84	58.32	65.58	0.025
	Median	0.02	0.19	0.22		3.22	27.86	23.52	
	s.d.	0.05	0.09	0.35		5.89	77.83	90.43	
	95% c.i.	(−0.01 to 0.10)	(0.09 to 0.27)	(0.05 to 0.70)		(−0.3 to 12.0)	(−23.4 to 140.0)	(−18.1 to 149.2)	
3	Mean	0.08	0.25	0.83	<0.001	36.41	48.78	131.84	0.041
	Median	0.06	0.22	0.71		18.51	40.17	119.57	
	s.d.	0.06	0.16	0.59		36.18	35.22	86.62	
	95% c.i.	(0.01 to 0.14)	(0.08 to 0.42)	(0.34 to 1.32)		(−1.6 to 74.4)	(11.8 to 85.7)	(59.4 to 204.2)	
4	Mean	0.08	0.21	0.52	0.008	9.98	11.61	63.05	0.206
	Median	0.06	0.17	0.41		6.91	7.78	31.71	
	s.d.	0.06	0.15	0.43		10.65	9.87	74.85	
	95% c.i.	(0.01 to 0.14)	(0.05 to 0.36)	(0.15 to 0.88)		(−1.2 to 21.2)	(1.2 to 22.0)	(0.5 to 125.6)	
5	Mean	0.09	0.22	0.59	0.031	16.86	95.21	145.31	0.090
	Median	0.09	0.14	0.32		16.77	36.56	90.19	
	s.d.	0.06	0.21	0.54		10.09	147.95	149.82	
	95% c.i.	(0.02 to 0.15)	(0.00 to 0.44)	(0.14 to 1.04)		(6.3 to 27.5)	(−60.0 to 250.5)	(20.1 to 270.6)	
All years	Mean	0.09	0.20	0.54	<0.001	14.67	49.04	95.71	<0.001
	Median	0.05	0.17	0.36		8.20	28.79	61.70	
	s.d.	0.13	0.15	0.49		20.35	77.43	98.03	
	95% c.i.	(0.04 to 0.14)	(0.14 to 0.25)	(0.38 to 0.70)		(7.7 to 22.3)	(20.1 to 78.0)	(64.4 to 127.1)	

once rain storms or spring snowmelt export ash from burned watersheds. For example, experimental input of ash to a first-order tributary generated a peak of conductivity, major ions and turbidity within 1 h of starting the additions and returned to pre-fire levels less than 24 h after additions ceased (Earl and Blinn 2003). Smoke and ash elevated streamwater nitrogen and phosphorus 5- and 60-fold during wildfire in north-western Montana; the values returned to background levels within several weeks of the burn (Spencer *et al*. 2003). Similarly, concentrations of various streamwater constituents (NH_4^+, NO_3^-, K^+, P, alkalinity) that increased following wildfire in mixed-conifer, ponderosa pine and scrub oak (*Quercus turbinella*) communities returned to pre-fire levels 1–4 months following burning (Earl and Blinn 2003). Even moderate-severity prescribed fire burning in mixed-conifer forests generated immediate increases in Ca^{2+} and SO_4^{2-} (1.3- and 13-fold respectively) in streams of the Lake Tahoe Basin that returned to pre-fire levels within 3 months (Stephens *et al*. 2004).

Our monthly sampling and analysis following the Hayman Fire documented elevated Ca^{2+}, ANC and conductivity in burned streams for 2 years after the fire compared with pre-fire and unburned stream levels (Fig. 2). The extent and severity of the fire created sufficient ash to alter both summer and spring snowmelt stream chemistry before ash was completely flushed from the burned watersheds. The year after the Hayman Fire, a one-time comparison of three streams sampled inside and outside the fire perimeter found statistically insignificant increases in conductivity and cation and anion concentrations, along with fewer benthic macroinvertebrate taxa and lower invertebrate density and biomass (Hall and Lombardozzi 2008).

The Hayman Fire burned across basins with differing underlying geological materials, and the magnitude of the streamwater response to wildfire reflected pre-fire baseline differences in Ca^{2+} and ANC. High-ANC streams draining basins with a mixture of sedimentary and granitic lithology were relatively insensitive to ash inputs following the fire; the post-fire peak in these streams was indistinguishable from pre-fire fluctuations. In contrast, naturally dilute streams, draining granitic bedrock basins responded sharply to the Hayman Fire (Fig. 2). Similarly, following the 2003 wildfires in Glacier National Park in north-western Montana, the high chemical concentrations associated with the underlying carbonate-bearing geology masked post-fire changes in stream chemistry for most analytes (Mast and Clow 2008). As with dilute, low ionic-strength streams and lakes that are highly responsive to changes in atmospheric inputs (Turk and Spahr 1991), it appears that the watershed processes that regulate streamwater chemistry following wildfire are most sensitive in basins with low pre-fire concentrations of dissolved solids.

Fire effects associated with the loss of forest vegetation and altered soil processes generally reach a peak a few years after wildfire before declining towards pre-burn conditions (Minshall *et al*. 1989; Wan *et al*. 2001; Ranalli 2004; Certini 2005), though severe and extensive wildfire initiates changes in terrestrial

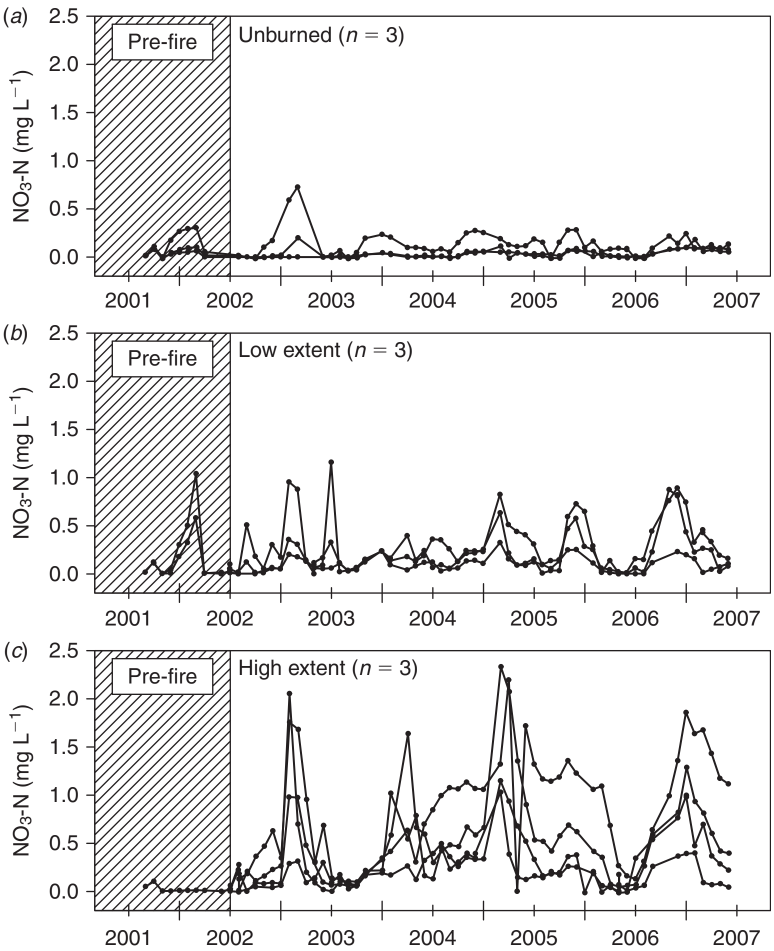

Fig. 5. Monthly flow-weighted streamwater NO_3-N before the June 2002 Hayman Fire and in 5 years post-fire for streams draining (*a*) unburned basins, (*b*) those burned to a low extent (e.g. <60% of basin area) and (*c*) those burned to a high extent (e.g. >60% of basin area with >45% of burned at high severity).

nutrient cycling that endure for decades before forest composition and soil processes return to pre-fire conditions. Five years following the Hayman Fire, streamwater temperature, nitrate and turbidity have not returned to pre-burn levels (Figs 1, 4). Winter-season streamwater nitrate concentrations remained higher for 4 years but growing-season concentrations were elevated for only 2 years after a Glacier National Park wildfire (Mast and Clow 2008); the seasonal difference was attributed to increased growing nutrient uptake by recovering and residual vegetation. Following the Yellowstone fires, streamwater nitrate remained higher than background levels for 5 years (Robinson and Minshall 1996). Higher radiation inputs to Yellowstone streams caused by the combustion of forest overstorey and riparian vegetation increased stream temperatures for 2–6 years before shade from regenerating shrub and tree canopies returned to pre-fire levels (Minshall *et al*. 1989).

Mineral and organic soil layers are the largest reservoirs of N in most forest ecosystems (Schlesinger 1991), so combustion of these N pools and the acceleration of N cycling processes can increase nutrient leaching following fire (Chorover *et al*. 1994; Murphy *et al*. 2006). Oxidation of forest biomass, litter and soil organic matter commonly increases the availability of NH_4^+ in soil for months to several years following wildfires or slash burning (Giardina and Rhoades 2001; Wan *et al*. 2001; Certini 2005). Prolonged changes in streamwater N result from the combined influence of reduced plant N demand, stimulated N mineralisation and nitrification due to increased soil temperature and pH, and subsequent release to groundwater and surface water.

The rate of forest overstorey and understorey recovery helps to explain the slow recovery of streamwater nitrate, sediment and temperature following the Hayman Fire. Monitoring plots established in upland and riparian ecosystems before the Hayman Fire document changes in the extent of vegetative cover and species composition in areas burned at high, moderate and low severity (Fornwalt *et al*. 2009). The cover of bare soil was 22% before the fire and increased to 46, 34 and 86% the year after the fire in low-, moderate- and high-severity areas respectively. In general, understorey species composition and cover returned to pre-fire conditions within 2–3 years, regardless of fire severity. Plant life history played an important role in vegetative recovery, as many of the understorey species are

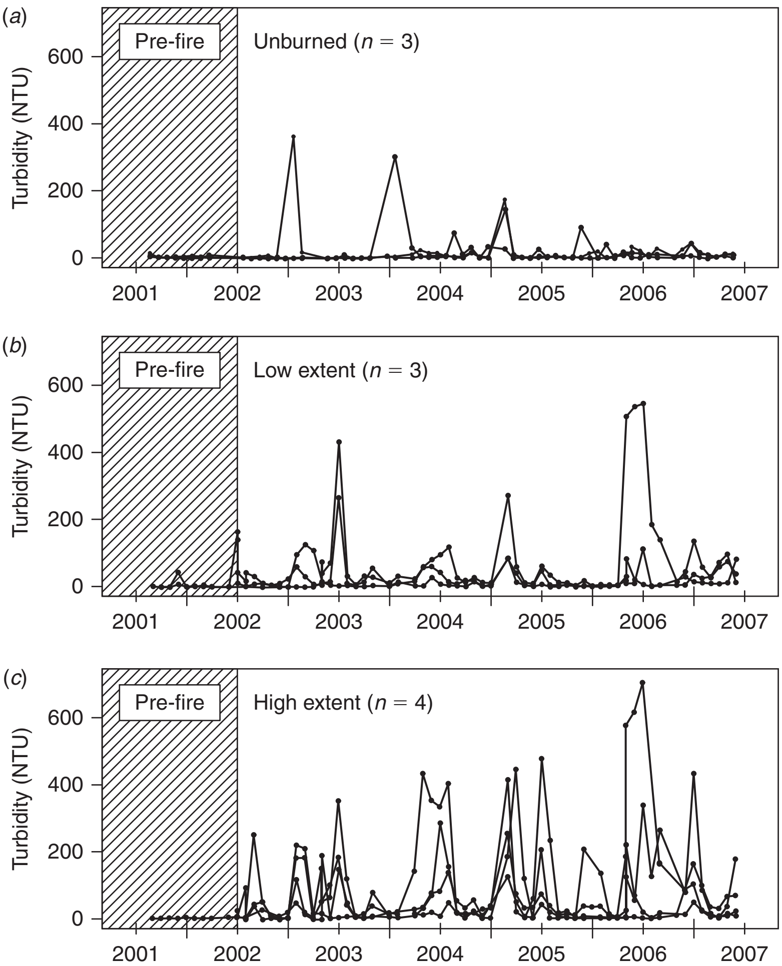

Fig. 6. Monthly streamwater turbidity before the June 2002 Hayman Fire and in 5 years post-fire for streams draining (*a*) unburned basins, (*b*) those burned to a low extent (e.g. <60% of basin area) and (*c*) those burned to a high extent (e.g. >60% of basin area with >45% of burned at high severity).

known to regenerate from either sprout or soil seed banks (Fornwalt 2009). In contrast, recolonisation of burned areas by tree seedlings is progressing more slowly. Four years after the fire (summer 2006) ponderosa pine seedlings were found in 52 and 37% of subplots located in low- and moderate-severity burn areas respectively, but none occurred in high-severity subplots (P. J. Fornwalt, pers. comm.). The extent of exposed soil declined with time since the fire, but remained more than double pre-fire conditions after 4 years. Loss of seed reserves and barriers to colonisation of extensive high-severity burn areas is expected to delay forest establishment. In spite of the rapid recovery of understorey vegetation, the extent of litter loss and the slow recolonisation by forest vegetation may influence the uptake, turnover and export of N and sediment delivery from watersheds burned by the Hayman Fire for decades.

Water quality implications

Prior to the Hayman Fire, stream temperature and sediment levels were identified as quality concerns for South Platte tributaries (Colorado Water Quality Control Division 2002). Pre-fire streamwater nitrate (Table 2) also exceeded draft numeric standards proposed by the US Environmental Protection Agency (EPA) for minimally disturbed streams in the Western Forested Mountains ecoregion (e.g. 0.01 mg NO_3-N L^{-1}; US EPA 2000). The sustained post-fire changes in these parameters further threaten the viability of the drainage's aquatic resources. For example, in basins burned extensively by the Hayman Fire peak nitrate concentrations remained more than 100-fold above nitrate concentrations typically found in minimally disturbed Western Forested Mountain streams throughout the study and they were occasionally more than 10-fold higher than proposed total N criteria (e.g. 0.12 mg N L^{-1}; US EPA 2000). Temperature increases associated with climate change projections (i.e. 1–3°C increase in air temperature) are predicted to reduce fish habitat by 15–40% in the Rocky Mountain region (Intergovernmental Panel on Climate Change 2007). Based on findings from a study of the temperature sensitivity of salmonid populations in southern Wyoming (Rahel *et al.* 1996), the 4°C increase in summer streamwater temperature measured after the Hayman fire could be expected to reduce fish habitat by 45–63%.

The highest measured post-fire nitrate concentration was 23% of the USA EPA's drinking water standard, though rain

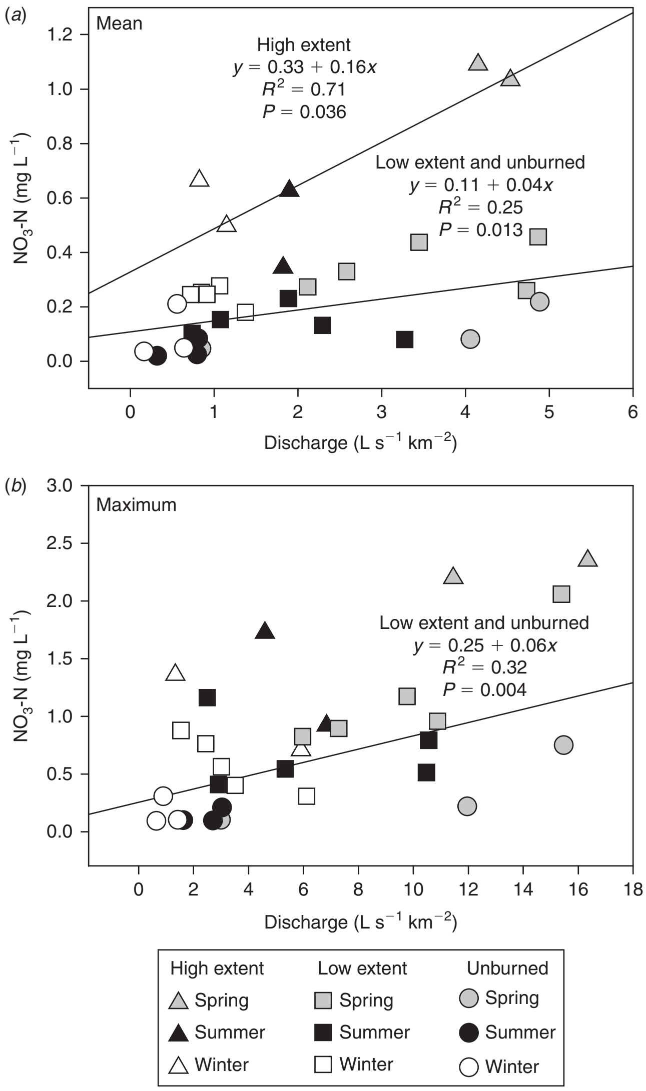

Fig. 7. Relationship between stream discharge and nitrate concentrations. Symbols show (*a*) mean and (*b*) maximum seasonal values (Winter, November–February; Spring, March–June; Summer, July–October) for streams draining unburned basins, those burned to a low extent (e.g. <60% of basin area) and those burned to a high extent (e.g. >60% of basin area with >45% of burned at high severity).

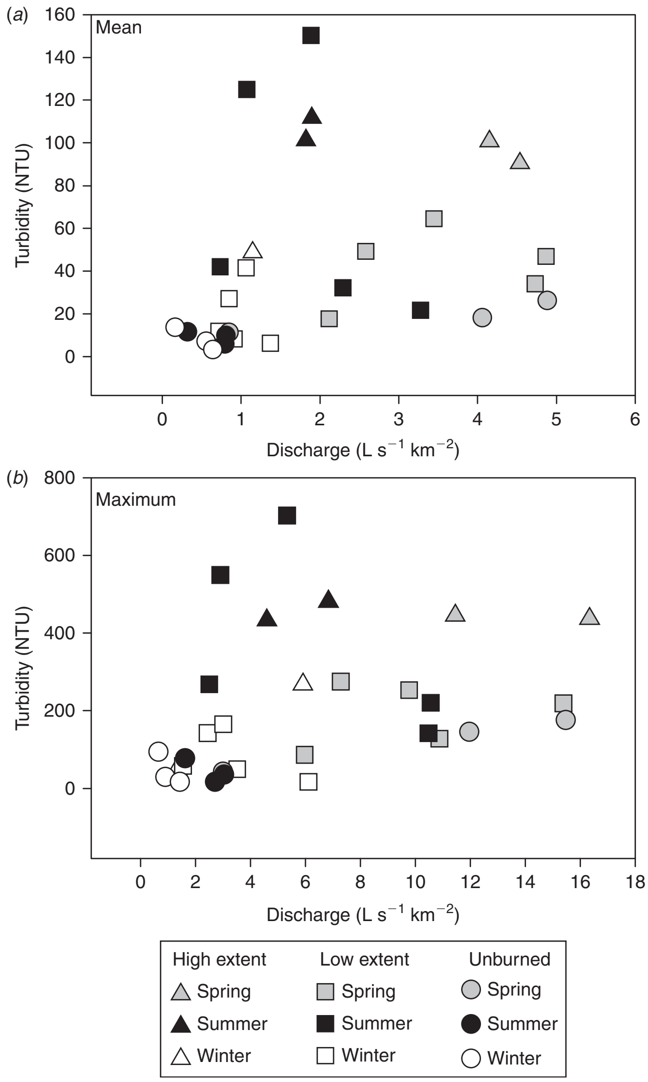

Fig. 8. Relationship between stream discharge and turbidity. Symbols show (*a*) mean and (*b*) maximum seasonal values (Winter, November–February; Spring, March–June; Summer, July–October) for streams draining unburned basins, those burned to a low extent (e.g. <60% of basin area) and those burned to a high extent (e.g. >60% of basin area with >45% of burned at high severity). NTU, Nephelometric Turbidity Units.

storms occurring between monthly sample dates may have increased discharge and nitrate above drinking water thresholds in extensively burned basins. Summer convective storms generate high-intensity rainfall (i.e. >10 mm h^{-1}) capable of producing runoff in burned Rocky Mountain watersheds (Moody and Martin 2001; Wagenbrenner *et al*. 2006; Moody *et al*. 2008). In the Colorado montane zone, storms of this nature generate peak flows of up to 2–60 $m^3\ s^{-1}$ in small basins (Benavides-Solorio and MacDonald 2001; Larsen and MacDonald 2007) when nitrate could exceed USA EPA's drinking water threshold. For example, based on the relationship between seasonal maximum discharge and nitrate concentration in extensively burned basins (Fig. 7*b*), stream discharge above 100 L s^{-1} km^{-2} (e.g. 0.1 $m^3\ s^{-1}\ km^{-2}$) would exceed 10 mg NO_3-N L^{-1}. In the 5 years following the Hayman Fire 29 summer storms occurred in the burn area; 13 produced more than 25.4 mm of rain over a 24-h period and six produced more than 40 mm of rain (Western Regional Climate Center 2006); these storms created rainfall intensities sufficient to generate surface runoff and sediment movement (Fig. 8), and likely resulted in stream nitrate peaks between our monthly sample collections.

Disturbance extent and severity

The post-fire water quality of these Hayman Fire study areas was well related to the extent of a basin burned at high severity (Figs 3, 4). Basins within the Hayman Fire perimeter that sustained high-severity wildfire on >45% of their area had streamwater nitrate and turbidity roughly 3-fold the levels measured in basins with ≤10% burned under such conditions (Fig. 3). High-severity fire released seven times more nitrate from two southern California chaparral watersheds at the US Forest Service San Dimas Experimental Forest compared with two basins burned at lower severity (Riggan *et al.* 1994). The high post-fire nitrate losses at San Dimas were attributed to increased soil nitrification combined with sediment movement from surface erosion and debris flows and chronically high atmospheric N deposition in southern California. In the New Jersey Pine Barrens, water and cation fluxes to groundwater were also highest in wildfire areas, intermediate in prescribed burned areas and lowest in unburned sites (Boerner and Forman 1982).

Post-fire streamwater conditions were related to both proportional extent burned and basin size in the Hayman, the 1988 Yellowstone and the 2003 Glacier National Park fires (Minshall *et al.* 1989; Mast and Clow 2008). Changes in streamwater chemistry and stream habitat increased with the extent burned (0–90%) across 21 basins burned by the Yellowstone fires (Robinson and Minshall 1996). Similarly, the 2003 Robert and Trapper fires burned 73 and 26% respectively of two Glacier National Park drainages and increased stream nitrate concentrations 2.5-fold in the extensively burned basin but had no effect in the other (Mast and Clow 2008). The extensively burned basin was only 15% the size of the less-responsive basin that burned to a lesser extent. Relative size also influenced the post-fire response of the Hayman study basins. For example, as basin size decreased there was an increase in the proportion of a basin that burned or that burned at high severity (extent burned: $R^2 = 0.83$, $P = 0.004$; high-severity burned: $R^2 = 0.62$, $P = 0.036$). The two smallest burned basins (Brush and Fourmile) had the highest mean streamwater nitrate concentrations and they released 4-fold more N per area than larger burned basins.

Greater streamwater discharge from larger basins dilutes post-fire increases in solutes and sediment (Lathrop 1994) and residual vegetation and O horizon retain nutrients and sediment, so the location of burning within a watershed is also important (Mast and Clow 2008).

Owing to the slow pace of tree colonisation and forest regrowth, recovery of the watersheds burned by the Hayman Fire will continue for decades. Similar to the streamwater responses we document here, post-fire forest succession will likely vary among basins due to the extent and degree of disturbance. In the lower montane ponderosa pine forests of the Rocky Mountain West, the impressive effects of the Hayman Fire and other large wildfires have become synonymous with the consequences of historic fire exclusion coupled with recent climatic conditions (Westerling *et al.* 2006; Flannigan *et al.* 2009). Use of mechanical treatments and prescribed fire to reduce hazardous fuel loads, such as those that contributed to the Hayman Fire, are being widely implemented on US Forest Service lands under the auspices of the *Healthy Forest Restoration Act* (USDA/USDOI 2005). Compared with wildfire, these management activities typically create minor changes in water quality (Richter *et al.* 1982; Stephens *et al.* 2004). In spite of current public support for hazardous fuel treatments, active management of national forestlands remains controversial (Beschta *et al.* 2004; Steelman and DuMond 2009). The large extent of forest area designated for fuel-reduction treatments, projections for longer fire seasons, increasing frequency of large, severe fires (Westerling *et al.* 2006), and the slow pace of watershed recovery from high-severity wildfire all underscore the need for comprehensive, long-term monitoring of the watershed and aquatic conditions (Stone *et al.* 2010).

Acknowledgements

This work is dedicated to the late Ken Kanaan, former soil scientist on the Pike National Forest. The stream-monitoring network was established and supported by US Forest Service hydrologists and field staff. The authors thank Natalie Quiet, Louise O'Deen and Corey Huber for streamwater analyses and Kevin Bayer and various other seasonal employees from the Pike National Forest for field assistance. Susan Miller, Dan Binkley, Bill Romme and Paula Fornwalt provided helpful comments and Rudy King, Laurie Porth and David Turner offered statistical guidance for the manuscript.

References

APHA (1998*a*) Single-column, method 4110C. In 'Standard methods for the examination of water and waste water'. 20th edn. (Eds LS Clescerl, AE Greenberg, AD Eaton) pp. 4-6–4-8. (American Public Health Association: Washington, DC)

APHA (1998*b*) Total suspended solids dried at 103–105°C, method 2540D. In 'Standard methods for the examination of water and waste water'. 20th edn. (Eds LS Clescerl, AE Greenberg, AD Eaton) pp. 2-57–2-58. (American Public Health Association: Washington, DC)

APHA (1998*c*) Nephelometric, method 2130b. In 'Standard methods for the examination of water and waste water'. 20th edn. (Eds LS Clescerl, AE Greenberg, AD Eaton) pp. 2-9–2-11. (American Public Health Association: Washington, DC)

Benavides-Solorio J, MacDonald LH (2001) Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* **15**, 2931–2952. doi:10.1002/HYP.383

Beschta RL, Rhodes JJ, Kaufmann JB, Gresswell RE, Minshall GW, Karr JR, Perry DA, Hauer FR, Frissell CA (2004) Post-fire management on forested public lands of the Western United States. *Conservation Biology* **18**, 957–967. doi:10.1111/J.1523-1739.2004.00495.X

Blake WH, Theocharopoulos SP, Skoulikidis N, Clark P, Tountas P, Hartley R, Amaxidis Y (2010) Wildfire impacts on hillslope sediment and phosphorus yields. *Journal of Soils and Sediments* **10**, 671–682. doi:10.1007/S11368-010-0201-Y

Boerner REJ, Forman RTT (1982) Hydrologic and mineral budgets of New Jersey Pine Barrens upland forests following two intensities of fire. *Canadian Journal of Forest Research* **12**, 503–510. doi:10.1139/X82-079

Brown PM, Kaufmann MR, Shepperd WD (1999) Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. *Landscape Ecology* **14**, 513–532. doi:10.1023/A:1008137005355

Bryant B, McGrew LW, Wobus RA (1981) 'Geologic map of the Denver 1° × 2° Quadrangle, North-Central Colorado. US Geological Survey, I-1163.' (Reston, VA)

Burke JM, Prepas EE, Pinder S (2005) Runoff and phosphorus export patterns in large forested watersheds on the western Canadian Boreal Plain before and for 4 years after wildfire. *Journal of Environmental Engineering and Science* **4**, 319–325. doi:10.1139/S04-072

Cerdá A, Doerr SH (2008) The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *Catena* **74**, 256–263. doi:10.1016/J.CATENA.2008.03.010

Certini G (2005) Effects of fire on properties of forest soils: a review. *Oecologia* **143**, 1–10. doi:10.1007/S00442-004-1788-8

Chorover J, Vitousek PM, Everson DA, Esperanze AM, Turner D (1994) Solution chemistry profiles of mixed-conifer forests before and after fire. *Biogeochemistry* **26**, 115–144. doi:10.1007/BF02182882

Cipra JE, Kelly EF, MacDonald L, Norman J (2003) Soil properties, erosion, and implications for rehabilitation and aquatic ecosystems. In 'Hayman Fire case study'. (Ed. RT Graham) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-114, pp. 204–219. (Ogden, UT)

Colorado Water Quality Control Division (2002) 'Colorado's 2002 303(d) and monitoring and evaluation list.' (Colorado Department of Public Health and Environment: Denver, CO)

Dunham JB, Young MK, Gresswell RE, Rieman BE (2003) Effects of fire on fish populations: landscape perspectives on persistence of native fishes and nonnative fish invasions. *Forest Ecology and Management* **178**, 183–196. doi:10.1016/S0378-1127(03)00061-6

Earl SR, Blinn DW (2003) Effects of wildfire ash on water chemistry and biota in south-western USA streams. *Freshwater Biology* **48**, 1015–1030. doi:10.1046/J.1365-2427.2003.01066.X

Finney MA, Bartlette R, Bradshaw L, Close K, Collins BM, Gleason P, Hao WM, Langowski P, McGinely J, McHugh CW, Martinson E, Omi PN, Shepperd W, Zeller K (2003) Fire behavior, fuel treatments, and fire suppression on the Hayman Fire. In 'Hayman Fire case study'. (Ed. RT Graham) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-114, pp. 33–179. (Ogden, UT)

Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. *International Journal of Wildland Fire* **18**, 483–507. doi:10.1071/WF08187

Foord EE, Cerny P, Jackson LL, Sherman DM, Eby RK (1995) Mineralogical and geochemical evolution of micas from miarolitic pegmatites of the anorogenic pikes peak batholith, Colorado. *Mineralogy and Petrology* **55**, 1–26. doi:10.1007/BF01162576

Fornwalt PJ (2009) Disturbance impacts on understory plant communities of the Colorado Front Range. PhD dissertation, Colorado State University.

Fornwalt PJ, Kaufmann MR, Huckaby LS, Stohlgren TJ (2009) Effects of past logging and grazing on understory plant communities in a montane Colorado forest. *Plant Ecology* **203**, 99–109. doi:10.1007/S11258-008-9513-Z

Giardina CP, Rhoades CC (2001) Clear cutting and burning affect nitrogen supply, phosphorus fractions and seedling growth in soils from a Wyoming lodgepole pine forest. *Forest Ecology and Management* **140**, 19–28. doi:10.1016/S0378-1127(00)00272-3

Graham RT (Ed.) (2003) Hayman Fire case study. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-114. (Ogden, UT) Available at www.fs.fed.us/rm/pubs/rmrs_gtr114/rmrs_gtr114.pdf [Verified March 2011]

Gran G (1952) Determination of the equivalence point in potentiometric titrations. Part II. *Analyst (London)* **77**, 661–671. doi:10.1039/AN9527700661

Hall SJ, 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. doi:10.3398/1527-0904-68.4.453

Hutson SS, Barber NL, Kenny JF, Linsey KS, Lumia DS, Maupin MA (2004) Estimated use of water in the United States in 2000. US Geological Survey Circular 1268. (Reston, VA)

Ice GG, Neary DG, Adams PB (2004) Effects of wildfire on soils and watershed processes. *Journal of Forestry* **102**, 16–20.

Intergovernmental Panel on Climate Change (2007) 'Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change.' (Eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson) (Cambridge University Press: Cambridge, UK)

Kaufmann MR, Regan CM, Brown PM (2000) Heterogeneity in ponderosa pine/Douglas fir forests: Age and size structure in unlogged and logged landscapes of central Colorado. *Canadian Journal of Forest Research* **30**, 698–711. doi:10.1139/CJFR-30-5-698

Keeley JE (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire* **18**, 116–126. doi:10.1071/WF07049

Kershner JL, MacDonald L, Decker LM, Winters D, Libohova Z (2003) Fire-induced changes in aquatic ecosystems. In 'Hayman Fire case study'. (Ed. RT Graham) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-114, pp. 232–243. (Ogden, UT)

Lane PNJ, Sheridan GJ, Noske PJ, Sherwin CB (2008) Phosphorus and nitrogen exports from SE Australian forests following wildfire. *Journal of Hydrology (Amsterdam)* **361**, 186–198. doi:10.1016/J.JHYDROL.2008.07.041

Larsen IJ, MacDonald LH (2007) Predicting postfire sediment yields at the hillslope scale: testing RUSLE and Disturbed WEPP. *Water Resources Research* **43**, W11412. doi:10.1029/2006WR005560

Lathrop RG, Jr (1994) Impacts of the 1988 wildfires on the water quality of Yellowstone and Lewis Lakes, Wyoming. *International Journal of Wildland Fire* **4**, 169–175. doi:10.1071/WF9940169

Mast MA, Clow DW (2008) Effects of 2003 wildfires on stream chemistry in Glacier National Park, Montana. *Hydrological Processes* **22**, 5013–5023. doi:10.1002/HYP.7121

Minshall GW (2003) Responses of stream benthic macroinvertebrates to fire. *Forest Ecology and Management* **178**, 155–161. doi:10.1016/S0378-1127(03)00059-8

Minshall GW, Brock JT, Varley JD (1989) Wildfires and Yellowstone's stream ecosystems. *BioScience* **39**, 707–715. doi:10.2307/1311002

Minshall GW, Royer TV, Robinson CT (2004) Stream ecosystem responses to fire: the first ten years. In 'After the fires: the ecology of change in Yellowstone National Park'. (Ed. LL Wallace) pp. 165–188. (Yale University Press: New Haven, CT)

Moody JA, Martin DA (2001) Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* **26**, 1049–1070. doi:10.1002/ESP.253

Moody JA, Martin DA, Haire SL, Kinner DA (2008) Linking runoff response to burn severity after wildfire. *Hydrological Processes* **22**, 2063–2074. doi:10.1002/HYP.6806

Murphy JD, Johnson DW, Miller WW, Walker RF, Carroll EF, Blank RR (2006) Wildfire effects on soil nutrients and leaching in a Tahoe Basin watershed. *Journal of Environmental Quality* **35**, 479–489. doi:10.2134/JEQ2005.0144

Pannkuk CD, Robichaud PR (2003) Effectiveness of needle case at reducing erosion after forest fires. *Water Resources Research* **39**, 1333–1342. doi:10.1029/2003WR002318

Prepas EE, Burke JM, Chanasyk DS, Smith DW, Putz G, Gabos S, Chen W, Millions D, Serediak M (2003) Impact of wildfire on discharge and phosphorus export from the Sakwatamau watershed in the Swan Hills, Alberta, during the first two years. *Journal of Environmental Engineering and Science* **2**, S63–S72. doi:10.1139/S03-036

Rahel FJ, Keleher CJ, Anderson JL (1996) Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: response to climate warming. *Limnology and Oceanography* **41**, 1116–1123. doi:10.4319/LO.1996.41.5.1116

Ranalli AJ (2004) A summary of the scientific literature on the effects of fire on the concentration of nutrients in surface waters. USGS Open-File Report 2004–1296. (Reston, VA)

Richter DD, Ralston CW, Harms WR (1982) Prescribed Fire: Effects on water quality and forest nutrient cycling. *Science* **215**, 661–663. doi:10.1126/SCIENCE.215.4533.661

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, MacDonald LH, Freehouf J, Neary DG, Martin D, Ashmun L (2003) Postfire rehabilitation of the Hayman Fire, In 'Hayman Fire case study'. (Ed. RT Graham) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-114, pp. 293–313. (Ogden, UT)

Robinson CT, Minshall GW (1996) Physical and chemical responses of streams in Yellowstone National Park following the 1988 wildfires. In

'The ecological implications of fire in greater Yellowstone'. (Ed. JM Greenlee) pp. 217–221. (International Association of Wildland Fire: Fairfield, WA)

Rodríguez A, Durán J, Fernández-Palacios JM, Gallardo A (2009) Short-term wildfire effects on the spatial pattern and scale of labile organic-N and inorganic-N and P pools. *Forest Ecology and Management* **257**, 739–746. doi:10.1016/J.FORECO.2008.10.006

Romme WH, Veblen TT, Kaufmann MR, Sherriff R, Regan CM (2003) Ecological effects of the Hayman Fire. In 'Hayman Fire case study'. (Ed. RT Graham) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-114, pp. 181–203. (Ogden, UT)

Schlesinger WH (1991) 'Biogeochemistry: an analysis of global change.' (Academic Press: San Diego, CA)

Scholze M, Knorr W, Arnell NW, Prentice IC (2006) A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* **103**, 13 116–13 120. doi:10.1073/PNAS.0601816103

Simmons WB, Lee MT, Brewster RH (1987) Geochemistry and evolution of the South Platte granite-pegmatite system, Jefferson County, Colorado. *Geochimica et Cosmochimica Acta* **51**, 455–471. doi:10.1016/0016-7037(87)90061-5

Spencer CN, Hauer FR (1991) Phosphorus and nitrogen dynamics in streams during a wildfire. *Journal of the North American Benthological Society* **10**, 24–30. doi:10.2307/1467761

Spencer CN, Gabel KO, Hauer FR (2003) Wildfire effects on stream food webs and nutrient dynamics in Glacier National Park, USA. *Forest Ecology and Management* **178**, 141–153. doi:10.1016/S0378-1127(03)00058-6

Steelman TA, DuMond ME (2009) Serving the common interest in US Forest Policy: a case study of the Healthy Forests Restoration Act. *Environmental Management* **43**, 396–410. doi:10.1007/S00267-008-9264-6

Stephens SL, Meixner T, Poth M, McGurk B, Payne D (2004) Prescribed fire, soils, and stream water chemistry in a watershed in the Lake Tahoe Basin, California. *International Journal of Wildland Fire* **13**, 27–35. doi:10.1071/WF03002

Stone KR, Pilliod DS, Dwire KA, Rhoades CC, Wollrab SP, Wollrab SP, Young MK (2010) Fuel reduction management practices in riparian areas of the western USA. *Conservation Biology* **46**, 91–100. doi:10.1007/S00267-010-9501-7

Townsend SA, Douglas MM (2000) The effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (northern Australia). *Journal of Hydrology (Amsterdam)* **229**, 118–137. doi:10.1016/S0022-1694(00)00165-7

Turk JT, Spahr NE (1991) Rocky Mountains. In 'Acidic deposition and aquatic ecosystems – regional case studies'. (Ed. DF Charles) pp. 471–501. (Springer: New York)

US EPA (2000) Nutrient criteria technical guidance M: river and streams. US Environmental Protection Agency, Office of Water, Office of Science and Technology, EPA 822-B-00-002. (Washington, DC) Available at http://www.epa.gov/waterscience/criteria/nutrient/guidance/rivers/ [Verified August 2006]

US EPA (2003) National drinking water standards. EPA 816-F-03-016. Available at http://www.epa.gov/OGWDW/consumer/pdf/mcl.pdf [Verified August 2006]

USDA Forest Service (1995) Draft Soil and Ecological Land Unit Survey: Northern San Isabel and Western Pike National Forests, Colorado. USDA Forest Service, Soil Conservation Service, and Foothills Engineering, Inc. (Pueblo, CO)

USDA/USDOI (2005) The healthy forests initiative and healthy forest restoration: interim field guide. FS-799 USDA Forest Service Technology Development Program. Available at http://www.fs.fed.us/ projects/hfi/field-guide/web/index.php [Verified August 2006]

Veblen TT, Donnegan JA (2005) Historical range of variability of forest vegetation of the National Forests of the Colorado Front Range. Final Report. USDA Forest Service, Rocky Mountain Region, agreement no. 1102-0001-99-033 with the University of Colorado, Boulder. (Golden, CO)

Wagenbrenner JW, MacDonald LH, Rough D (2006) Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range. *Hydrological Processes* **20**, 2989–3006. doi:10.1002/HYP.6146

Wan S, Hui D, Luo Y (2001) Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis. *Ecological Applications* **11**, 1349–1365. doi:10.1890/1051-0761(2001)011[1349:FEONPA]2.0.CO;2

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increases Western US forest wildfire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834

Western Regional Climate Center (2006) Monthly total precipitation Cheesman, Colorado. (WRDC Station 051528) Available at http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?co1528 [Verified August 2006]

Williams AAJ, Karoly DJ, Tapper N (2001) The sensitivity of Australian fire danger to climate change. *Climatic Change* **49**, 171–191. doi:10.1023/A:1010706116176

Manuscript received 8 August 2009, accepted 2 September 2010