CSIRO PUBLISHING

International Journal of Wildland Fire **2009**, *18*, 96–115 www.publish.csiro.au/journals/ijwf

Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States

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Abstract. Measurements of post-fire sediment erosion, transport, and deposition collected within 2 years of a wildfire were compiled from the published literature (1927–2007) for sites across the western United States. Annual post-fire sediment yields were computed and grouped into four measurement methods (hillslope point and plot measurements, channel measurements of suspended-sediment and sediment erosion or deposition volumes). Post-fire sediment yields for each method were then grouped into eight different rainfall regimes. Mean sediment yield from channels (240 t ha^{-1}) was significantly greater than from hillslopes (82 t ha^{-1}). This indicated that on the time scale of wildfire (10–100 years) channels were the primary sources of available sediment. A lack of correlation of sediment yield with topographic slope and soil erodibility further suggested that sediment availability may be more important than slope or soil erodibility in predicting post-fire sediment yields. The maximum post-fire sediment yields were comparable to long-term sediment yields from major rivers of the world. Based on 80 years of data from the literature, wildfires have been an important geomorphic agent of landscape change when linked with sufficient rainfall. These effects are limited in spatial scale to the immediate burned area and to downstream channel corridors.

Introduction

Post-fire sediment yields have been measured in the western United States since the early 1900s. Sediment yield is defined as the mass of soil eroded per unit area and transported past a designated point at the outlet of a plot, hillslope, channel, or watershed during 1 year (Mutchler *et al.* 1994). Hillslopes, in the present study, are the nearly planar or convex segments between unchannelized drainages and include rills (Moody and Kinner 2006). Drainages are any concave features (sometimes called hollows or swales), which concentrate and convey water downslope, but do not necessarily have well-defined banks.

The effects of wildfires on soil erosion properties are spatially variable (DeBano *et al.* 2005). When these effects are combined with spatially and temporally variable rainfall, episodic peaks of erosion create a punctuated sediment yield (Swanson 1981; Benda and Dunne 1997; Moody 2001; Benda *et al.* 2003) greater than the 'normal' background yield. This episodic supply of sediment often is transported as slugs through the drainage network or is deposited at various locations within the channel as in-channel fans, floodplains, or terraces (Moody 2001; Moody and Martin 2001*b*). Thus, the magnitudes of the post-fire sediment yield are critically dependent on the timing and location of post-fire studies.

Sediment yield after wildfire is a function of static and dynamic variables. Some examples of static variables are topographic slope and type of geologic terrain, which are nearly constant over fire–erosion cycles (10–100 years). Dynamic variables can change over short periods of time (minutes to a few years), such as the energy associated with each rain storm, the duration of rain storms, the shear stress associated with runoff, the actual contributing area of runoff causing erosion, and the sediment availability (Swanson *et al.* 1998; Moody and Martin, in press).

Sediment availability is a function of soil erodibility and the volume of stored sediment on hillslopes and in channels. Soil erodibility has been expressed as the ratio of the sediment yield per unit flow variable. Several different flow variables have been used, such as force per unit surface area or boundary shear stress (Elliot *et al.* 1989; Flanagan and Nearing 1995; Moody *et al.* 2005), unit stream power (Rose *et al.* 1983; Hairsine 1988; Nearing *et al.* 1997), kinetic energy per unit area (Poesen and Savat 1981), rain intensity raised to a power (Rose *et al.* 1983; Elliot *et al.* 1989; Flanagan and Nearing 1995), and soil erodibility factor or *K-factor* (Renard *et al.* 1997). The *K-factor* has several limitations (Moody *et al.* 2005), but its distinct advantage is that has been mapped over the entire western United States at a resolution of 1 km^2 (STATSGO database; Natural Resources Conservation Service 2007).

Soil erodibility depends partly on burn severity (McNabb and Swanson 1990; Neary *et al.* 2005; Moody *et al.* 2007), which has been used to describe the effect of wildfire on soil properties. Burn severity exhibits a mosaic pattern, indicating a wide range of soil and vegetation conditions that also change rapidly with time after a fire (months to years). The percentage of bare ground is one metric used to determine such descriptive terms as high, medium, or low burn severity (Robichaud and Waldrop 1994; Benavides-Solorio and MacDonald 2005). Another metric is fire-induced water repellency (DeBano 2000; Doerr *et al.* 2006), which is discrete classes defined either by a range of water-drop penetration times (Doerr 1998) or by a range of contact

 10.1071/WF07162 1049-8001/09/010096

angles measured by using mixtures of water and alcohol (Letey 1969; Doerr 1998). A quantified burn severity metric (change in the Normalized Burn Ratio) has been developed using remote sensing products by Key and Benson (2005). The metric measures (1) above-ground consumption of living vegetation and litter on the surface (obstructions to runoff before a fire); and (2) change in amount of bare soil (an indicator of the heat effects on biologic and physical properties of the soil). This quantified burn severity has been used in a functional relation to predict the runoff response from burned watersheds (Moody *et al*. 2007). Quantified values of burn severity for the sites included in the present study were unavailable, so that sediment yields in the current paper could not be related to burn severity. However, a caveat is that post-fire sediment yields may have a bias towards high burn severities because these sites are perceived as being the most likely to produce the greatest post-fire sediment yield.

The volume of stored sediment on hillslopes and in channels is largely unknown and depends on the time scale of the accumulation processes. On hillslopes, the volume is primarily a function of the rate of production of soil from the bedrock (Heimsath *et al*. 1997). In channels, the volume depends on the elapsed time since the last substantial erosional event and on the rate of replenishment by hillslope sediment transport processes. Each process, such as rainfall-generated runoff (Poesen 1993), mass wasting (Swanson 1981; Swanson *et al*. 1987), wind (Bagnold 1954; Whicker *et al*. 2006), and dry ravel (Krammes 1960; Rice 1982; Gabet 2003; Roering and Gerber 2005) has a different time scale. Dry ravel is a dominant process in the mountains of southern California (Anderson *et al*. 1959; Krammes 1965) and in the coastal mountains of Oregon (Roering and Gerber 2005) where tectonism has produced, in these terrains, steep slopes with easily erodible soil particles resting near the angle of repose. Steep slopes decrease the critical shear stress necessary for the initiation of motion of soil particles (Moody *et al*. 2005) and increase the boundary shear stress of the flowing water. Therefore, the potential to transport sediment is greater than in other terrains, so that these conditions produce high sediment availability (Milliman and Syvitski 1992).

Rainfall has kinetic and potential energy, which vary spatially and temporally. Rainfall is transformed at raindrop-impact sites (Hartley and Julien 1992) into overland flow. The impact energy (proportional to the rainfall intensity) detaches some sediment (Meyer and Harmon 1984; Gabet and Dunne 2003) and the discharge or boundary shear stress (proportional to the depth of flow) detaches and transports more sediment. Peak discharges from burned watersheds (~0.2 to 2000 ha) have been shown to be a linear function of the 30-min maximum rainfall intensity, I_{30} and an I_{30} threshold of ~10 mm h^{-1} (Moody and Martin 2001*c*; Reneau and Kuyumjian 2004; Kunze and Stednick 2006; Moody *et al*. 2007), and sediment yield from burned watersheds has been found to depend on rainfall intensity. For example, in Montana, the sediment yields were related to either I_{10} (10-min maximum rainfall intensity) or I_{30} (Spigel and Robichaud 2007), and in a burned watershed in Colorado, I_{30} explained 80–91% of the variability in sediment yields (Kunze and Stednick 2006).

What proportion of sediment yield across a landscape can be attributed to post-fire processes? A general conceptual framework of geomorphic sensitivity (a function of gradient and vegetation) in different rainfall regimes was linked by Swanson (1981) to a fire index (a function of fire intensity, frequency, and areal extent). He speculated that fire induced 70% of the total sediment yield in steepland chaparral, 30% in Cascade Mountain forest, and Robichaud (2000) estimated that in some regions, over 60% of the total, long-term landscape sediment production was fire-related. Post-fire erosion is a transient process. It has been observed to be the greatest during the first year after a wildfire (Agee 1990; DeBano *et al*. 1998; Robichaud and Brown 1999) and elevated yields only persist for 4 to 7 years after a wildfire (Moody and Martin 2001*b*; Shakesby and Doerr 2006).

Therefore, to determine the annual sediment yield linked to wildfire, we have limited the present synthesis to sediment erosion, transport, and deposition data that were collected within 2 years after a wildfire. These data were organized by rainfall regimes, which have different seasonalities and rainfall intensities. Normal background sediment yields (reported by the references in this synthesis) are included for comparison with sediment yields after wildfire.

Rainfall regimes

The United States can be divided into climatic regions with different seasonal rainfall types. These types are associated with different air-mass sources (Hirschboeck 1991), which produce six principal rainfall types (Kincer 1919; Smith 1994). Four of the rainfall types (ARIZONA, PACIFIC, SUB-PACIFIC, and PLAINS) are found in the western United States (Table 1). Some of the boundaries for these rainfall types correspond to isopluvial maps of rainfall intensity for different frequencies (1-, 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals) published by Hershfield (1961). The seasonal rainfall characteristics for each erosion site were obtained from the Climatology of the United States publications for each state (We used: 02, Arizona; 04, California; 05, Colorado; 10, Idaho; 24, Montana; 26, Nevada; 29, New Mexico; 35, Oregon; 39, South Dakota; 45, Washington; and 48, Wyoming; see NOAA 2002) and from the Western USA Climate Historical Summaries (Western Region Climate Center, www.wrcc.dri.edu, accessed 18 January 2009).

An indicator of the rainfall intensity associated with relatively frequent rain storms in burned areas in each climatic region is the 2-year 30-min rainfall intensity. Values of the 2-year 30-min rainfall intensity, $I_{30}^{2\ \mathrm{year}}$ (mm h^{-1}), for each erosion site were obtained for those areas covered by NOAA's (National Oceanic and Atmospheric Administration) National Weather Service Precipitation Frequency Data Server and from identical data in the Rainfall Frequency Atlas of the United States (Hershfield 1961) for those states not covered by the Precipitation Frequency Data Server. The rainfall intensities were separated into four conditions (LOW, MEDIUM, HIGH, and EXTREME) by using six intensities as lower boundaries (10, 15, 19, 20, 36, and 52 mm h^{-1}). The combination of four seasonal rainfall types and four rainfall intensity conditions defined 16 rainfall regimes of which 10 are in the western United States (Table 1, Fig. 1).

Sediment-yield database

Many methods have been used to measure sediment yield after wildfires for different lengths of time. Only those measurements (70 references; 135 measurements) collected within 2 years of a

Table 1. Rainfall regimes in the western United States

Rainfall regimes are a combination of seasonal rainfall type and rainfall intensity condition. The observed ratio of summer to winter precipitation is for the data presented in the current paper

Seasonal type	Characteristics	Seasonal ratio: summer rainfall : winter rainfall		Rainfall intensity condition	2-year, 30-min rainfall intensity $I_{30}^{2\ year}$ (mm h^{-1})	
		Lower	Upper		Lower	Upper
ARIZONA	Winter and summer wet	0.3	1.1	EXTREME	>52	100
	Spring dry			HIGH	>36	52
	Fall (autumn) moist			MEDIUM	>20	36
PACIFIC	Winter maximum	0.02	0.3	HIGH	>36	52
	Summer minimum			MEDIUM	>20	36
				LOW	>15	20
SUB-PACIFIC	Winter wet	0.1	0.7	LOW	>10	20
	Spring moist					
	Summer and fall dry					
PLAINS	Winter minimum	0.6	2.0	EXTREME	>52	100
	Summer maximum			HIGH	>36	52
				MEDIUM	>19	36

wildfire (Fig. 1) are included in the present synthesis. The synthesis does not include (1) extensive empirical predictions by Rowe *et al*. (1949, 1954) for watersheds in southern California; (2) other empirical predictive methods (Anderson 1974; Potts *et al*. 1985; Legleiter *et al*. 2003); (3) data from prescribed fires (Rowe 1948; DeBano and Conrad 1976; Bennett 1982; McNabb and Swanson 1990; Covert *et al*. 2005); (4) data from rainfall simulations (Benavides-Solorio and MacDonald 2001; Pierson *et al*. 2001; Robichaud *et al*. 2007), or (5) data from some control plots used to evaluate post-fire treatments (Robichaud *et al*. 2000), which had insufficient information to locate the study sites and to determine the associated variables such as topographic slope, soil erodibility, and rainfall characteristics.

Measurement methods were separated into two groups based on their location – Hillslopes and Channels. Hillslope methods were further divided into those methods that essentially measured erosion at a point (erosion pin, erosion bridge, survey transect, or grid) and those that collected eroded sediment from a plot (bounded hillslope plots, unbounded hillslope plots, and silt fences). These are referred to as the Hillslope-point and Hillslope-plot methods in the present paper. Channel methods were divided into those methods that collected suspended sediment and those methods that measured sediment volumes (such as behind dams, check dams, and debris basins, in alluvial fan deposits, and from channel erosion). These are referred to as the Channel-SS and Channel-volume methods.

These numerous measurement methods make comparison of sediment yields difficult. In addition to the reasons listed by Shakesby and Doerr (2006), the studies have used different temporal and spatial scales. Measurement time scales in these studies ranged over several orders of magnitude. For example, net erosion after a single major storm was on the order of an hour; some sediment data were collected daily, weekly or monthly; composite erosion from several storms was often published as yearly values, as were the totals for daily suspended-sediment samples. These methods also reflect spatial scales varying by many orders of magnitude. For example, erosion pins measured changes in height over an effective area of 0.0001 to 0.01 m^2; hillslope plots collected sediment from areas ranging from 1 to 1000 m^2; and dams and debris basins collected sediment from drainage areas ranging from 10^6 to 10^8 m^2. Another difficulty is that the methods used different measurement units. For example, the erosion pin method uses height, the plot method uses mass, and the debris basin method uses volume. Finally, the area that actually contributes sediment is unknown. It probably depends on sediment particle size in addition to such variables as the rainfall intensity, soil erodibility, surface roughness, and connectivity of patches with different erosional characteristics.

Aware of these limitations, but for the sake of comparison, all the reported measurements of erosion and deposition were converted to metric tons per hectare (t ha^{-1}) on an annual basis. This unit of sediment yield can be misleading, chiefly because erosion is not uniformly distributed across the landscape as the unit suggests. For example, erosion is often localized near or in channels (Florsheim *et al*. 1991; Collins and Ketcham 2001; Moody and Martin 2001*a*; Santi *et al*. 2007; Moody and Martin, in press) and the actual magnitude of sediment yield will be substantially greater if the area of the channel is used rather than the drainage area. Several assumptions were required to compute these sediment yields: (1) if no specific sediment bulk density information was given in the reference, then volumes were converted to mass using a bulk density of 1700 kg m^{-3}, which allows yields to be easily revised if density information becomes available, and is within the typical error (20%) associated with sediment erosion, transport, and deposition data; (2) point measurements were usually along a transect of length L (m), and thus the contributing area was equal to L^2 (m^2); and (3) the contributing area for plot and volume measurements was equal to the entire area of a

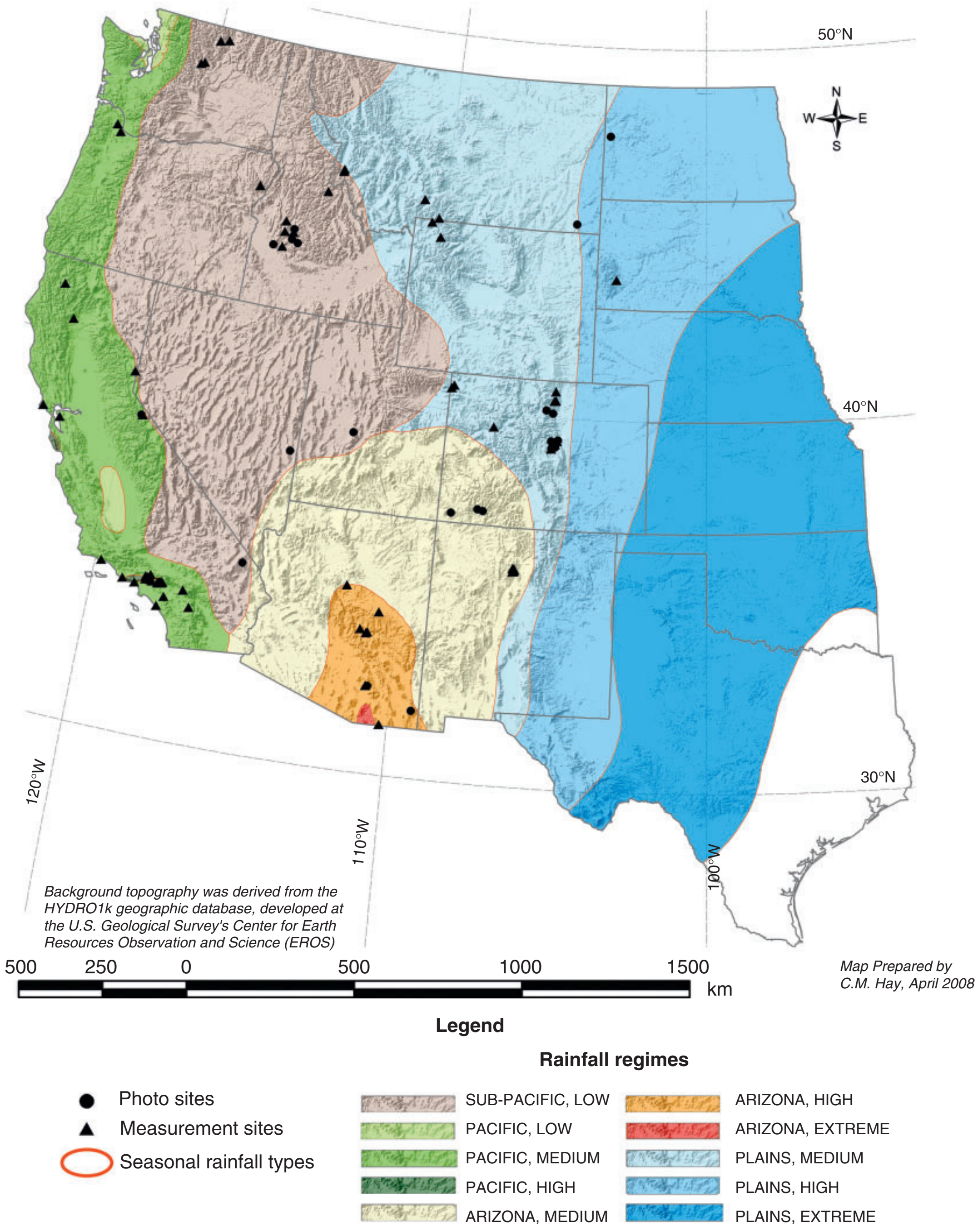

Fig. 1. Rainfall regimes in the western United States are a combination of rainfall types (ARIZONA, PACIFIC, SUB-PACIFIC, and PLAINS) and the degree (LOW, MEDIUM, HIGH, and EXTREME) of the 2-year 30-min rainfall intensity, $I_{30}^{2\,\text{year}}$. The boundaries of the rainfall types are slightly modified from those originally delineated by Kincer (1919) to conform to the isopluvial maps for the 2-year 30-min rainfall intensity, $I_{30}^{2\,\text{year}}$, published by Hershfield (1961). The locations of sites with measurements of sediment yield after wildfire published in the literature are shown as solid triangles, and sites with photographic evidence are shown as solid circles. The boundaries for the PACIFIC-HIGH are small. One is located on the coast south of San Francisco and the second is near Los Angeles but partially hidden by several solid triangles. The source of the hillshaded base map is the HYDRO1k database, US Geological Survey, Center for Earth Resources Observation and Science (EROS).

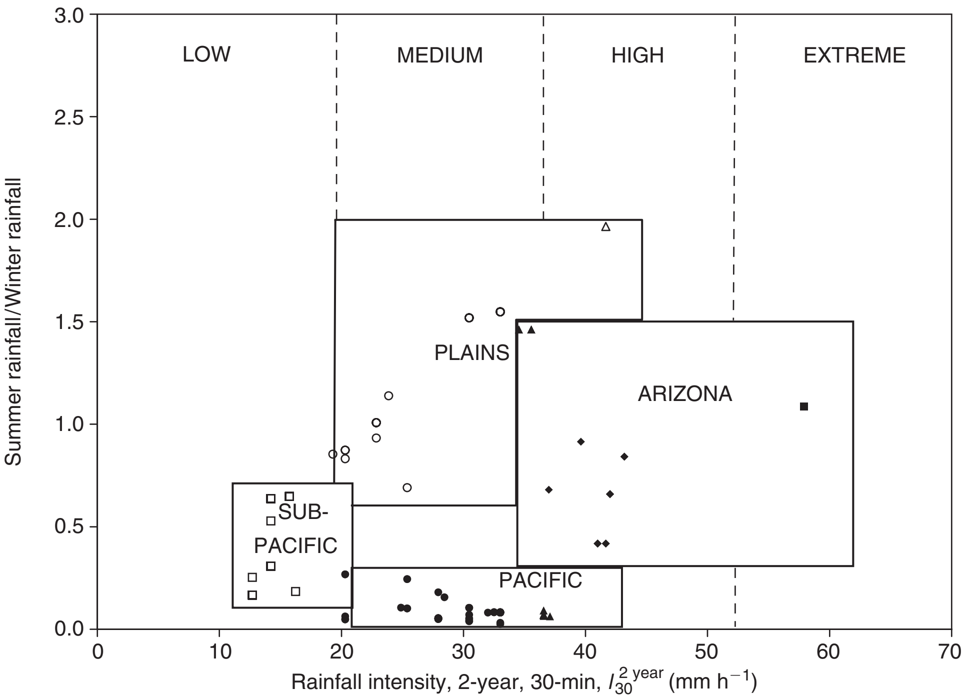

Fig. 2. The domain and range of the characteristics (rainfall intensity and ratio of summer rainfall : winter rainfall) of the rainfall regimes where sediment yield has been measured after wildfires.

plot or the drainage area upstream from the measurement site. Annual sediment yields are reported in the present synthesis for comparison.

Some slopes associated with post-fire sediment yields were reported in the references but many were not. Unknown slopes were estimated from 1 : 24 000 topographic maps at the most likely location (latitude and longitude) for the measurement site as described in each reference. In some cases, insufficient information was given to determine an exact location on a map, so that the slope was estimated for a general area based on ancillary information given in the reference. More recent publications often had better information on location. Soil erodibility is available by STATSGO for 1-km^2 grid cells (Natural Resources Conservation Service 2007), and the values of soil erodibility listed in the current synthesis correspond to the grid cell closest to the latitude and longitude of the measurement site.

Results

Post-fire sediment yields have been measured in eight of the 10 rainfall regimes in the western United States. Most measurements were in the PACIFIC-MEDIUM (56) and PACIFIC-HIGH (11) rainfall regimes and the least in the ARIZONA-EXTREME (2) and PLAINS-HIGH (1). Measurements cluster within distinct seasonal and rainfall intensity domains (Fig. 2). The ARIZONA type had the greatest $I_{30}^{2\,\text{year}}$ (58 mm h^{-1}) and the SUB-PACIFIC type had the lowest $I_{30}^{2\,\text{year}}$ (13 mm h^{-1}). Characteristics of the PACIFIC seasonal rainfall type were low values (0.024 to 0.27) of the seasonal ratio (summer rainfall : winter rainfall) and a relatively wide range of $I_{30}^{2\,\text{year}}$ (20 to 37 mm h^{-1}, Table 2). Measurements reported from the PLAINS seasonal rainfall type had the widest range of the seasonal ratio (0.69 to 2.0) and a relatively wide range of $I_{30}^{2\,\text{year}}$ (19 to 42 mm h^{-1}), with the maximum in the Black Hills of South Dakota (Table 2).

Post-fire sediment yields (135 measurements) ranged over five orders of magnitude. The greatest range was in the PACIFIC-MEDIUM rainfall regime, where the minimum was 0.033 t ha^{-1} (Hillslope-plot) and the maximum was 2800 t ha^{-1} (Channel-volume) following the Johnston Peak Fire in July 1960 (Doehring 1968). The minimum was essentially the same as the normal background sediment yield (Table 3). The mean sediment yields, listed in Table 3, range from 0.26 to 300 t ha^{-1} (Fig. 3), but if they are regrouped by the four measurement methods, the range is generally less (Fig. 4). For Channel-volume measurements, the range is 14 to 300 t ha^{-1} with a mean of 240 t ha^{-1}. For Hillslope-point measurements the range is 37 to 160 t ha^{-1} with a mean of 110 t ha^{-1}, and for Hillslope-plot measurements the range is 5.9 to 200 t ha^{-1} with a mean of 62 t ha^{-1}. The range for the Channel-SS measurements is over three orders of magnitude (0.26 to 180 t ha^{-1}) with a mean of 20 t ha^{-1}. The maximum sediment yield (180 t ha^{-1}) was a single measurement representing the total for 1 year (from the PLAINS-HIGH rainfall regime; Galena Fire in the Black Hills of South Dakota; Gundarlahalli 1990; Fig. 4). If this value is excluded, then the mean sediment yield for the Channel-SS method is 9.2 t ha^{-1}. When all the sediment yields (135 measurements) are grouped by just the measurement method reflecting the landscape location (channel or hillslope), independent of rainfall regime, then the yields vary by approximately one order of magnitude, indicating that conclusions based on these mean sediment yields have less uncertainty.

The mean sediment yields were 240, 110, 62, and 20 t ha^{-1} for Channel-volume (60 measurements), Hillslope-point (25 measurements), Hillslope-plot (34 measurements), and Channel-SS methods (16 measurements), respectively.

Discussion

Dominant processes controlling sediment yield change with spatial (Lane *et al*. 1997) and temporal scale (Schumm and Lichty 1965). Mixing the results for different temporal or spatial scales together can obfuscate the actual relation between sediment yield and drainage area (Walling 1983). Thus, results measured at one scale cannot be scaled up or down unless the dominant process is known to have the same or similar temporal and spatial scales of interest. Moreover, the numerous methods used to measure post-fire sediment yield have different intrinsic scales and this also prevents one from making any consistent conclusions relative to the scaling up or down issue. Therefore, if the sediment yields given in the present synthesis are to be generalized or used at other locations for modeling or making land management decisions, then the yields should be used at the same scale as the original measurements described by the references.

Methods used to measure post-fire sediment yields sample different particle sizes, which affects the magnitude of the sediment yields. Channel-SS data are biased toward fine-grained sediment because of the limited size of the nozzle diameter on suspended-sediment samplers (usually <10 mm, the intrinsic scale of the method), and the fact that most samples are collected during relatively low discharges when problems of clogging and damage by extreme floods are much less. Suspended-sediment particle sizes are smaller than those collected by the Hillslope-point, Hillslope-plot, and Channel-volume methods. For example, in a post-fire study in granitic terrain, the largest particle diameter of suspended sediment was ~0.25 mm, the largest diameter of eroded sediment from bounded plots was 10 mm, and the largest particles deposited in the channel were typically 10–100 mm. Under extreme flood conditions, with sufficient shear stress, field observations indicated that these channel particles were remobilized and transported in suspension, but no suspended-sediment samples were ever collected during these conditions (Martin and Moody 2001; Moody 2001; Moody and Martin 2001*a*). Probably as a result of the dearth of suspended-sediment samples collected during flood conditions, the magnitude of post-fire sediment yield based on the Channel-SS method was approximately one order of magnitude lower than yields based on the Channel-volume, Hillslope-point, and Hillslope-plot methods. Another reason may be that channel measurements of post-fire suspended sediment are often made in first-order, head-water streams. These streams are often underlain by resistant bedrock and have lower suspended-sediment concentration than higher-order streams. These first-order streams tend to be seasonal and transport less suspended sediment per year than high-order perennial streams (Hembree *et al*. 1952; Colby *et al*. 1956).

There were no significant correlations between sediment yield and the static variable of slope and the dynamic variable of soil erodibility. Slope measurements in many cases were within a few metres of the site, whereas soil erodibility calculations as reported in STATSGO represented an average over a 1-km^2 area. Slopes for Channel-volume measurements were less exact and represented an average over 1 to 10 km or were relief ratios for entire watersheds and probably do not reflect the slope of actual erosion sites. One reason for the lack of correlation may be the inability to link slopes and soil erodibility with the actual erosion sites. Soil erodibility is changed by temperature effects from fire on the time scale of hours to days (Moody *et al*. 2005), by changes in soil moisture (Van Burkalow 1945) on the time scale of days to months, and by regrowth of vegetation on the time scale of months to years. These different temporal changes may create soil erodibility values that are quite different from those given by the STATSGO database, which were used for the correlation analysis.

Large sediment yields are not solely dependent on slope in certain terrains. For example, in tectonic terrains where landforms undergo substantial alteration by earth movements such as faulting and uplift, additional variables include seismic and volcanic activity, fractured and brecciated rocks as well as steep, unstable slopes (Milliman and Syvitski 1992; Montgomery and Brandon 2002). These conditions exist in the PACIFIC seasonal rainfall type and especially in the mountains of southern California and in the Oregon Coast Range. In these mountains, dry ravel accounts for much of the background sediment yield (Anderson *et al*. 1959; Rice 1982; Wells 1987; Roering and Gerber 2005), which steadily replenishes, but does not completely refill channels with sediment in the time interval between fires. Dry ravel also supplies sediment during fires, when vegetation is burned and sediment stored uphill from plant stems is released into the channels (Krammes 1965; Wohlgemuth 2003; Roering and Gerber 2005).

Only a weak correlation was found between sediment yield and $I_{30}^{2\,\text{year}}$. The best linear correlation ($R^2 = 0.54$) was for the ARIZONA seasonal rainfall type, which had the widest range of $I_{30}^{2\,\text{year}}$ (37 to 58 mm h^{-1}) compared with other seasonal rainfall types. The weak correlation is not surprising because the $I_{30}^{2\,\text{year}}$ is a regional parameter. It was chosen only as an indicator of rainfall intensities associated with relatively frequent rain storms. Values of $I_{30}^{2\,\text{year}}$ do not represent the actual rainfall intensity, I_{30}, during an individual rainstorm, which may have a larger range than that for $I_{30}^{2\,\text{year}}$. A correlation between rainfall intensity and sediment yield may exist, but unfortunately, this hypothesis could not be tested because only a few references gave information on rainfall during the measurement period and fewer still gave information on rainfall intensity. Measurements of rainfall intensity, overland flow, and channel discharge are needed in addition to measurements of sediment yield to provide a better understanding of sediment erosion, transport, and deposition processes after wildfire.

Post-fire sediment yields from channels were greater than the yield from hillslopes. This general regional result is based on multiple sites in different rainfall regions across the western United States and represents a range of measurement time scales. The mean sediment yield from channels was 240 t ha^{-1} (60 Channel-volume measurements) and the mean sediment yield from the hillslopes was 82 t ha^{-1} (average of the combined 25 Hillslope-point and 34 Hillslope-plot measurements). The sediment yields based on the Channel-SS method have not been included as part of the channel measurement mean

Table 2. Summary of rainfall and site information for sediment yield after wildfires

C, channel; H, Hillslope; SS, suspended sediment; V, volume; Pt, point; Plot, plot; Summer (May through September); Winter (October through April). NAD, North American Datum (1983); WGS84, World Geodetic System (1984)

Fire	Reference	Summer rainfall : winter rainfall	2-year, 30-min rainfall intensity $I_{30}^{2\ \text{year}}$ (mm h^{-1})	Mean annual rainfall (mm year^{-1})	Location-Method	Max. sediment yield (ha^{-1})	Slope	Soil erodibility, *K-factor* (m^{-1})	State	Site location WGS84/NAD83 Latitude	Longitude
ARIZONA-EXTREME											
1988 June	Wohl and Pearthree (1991)	1.09	58	538	C-V	177	0.47	0.78	AZ	31.3786	−110.2418
1988 June	Wohl and Pearthree (1991)	1.09	58	538	C-V	283	0.38	0.78	AZ	31.3786	−110.2418
ARIZONA-HIGH											
1972 Rattle Burn	Campbell *et al*. (1977)	0.68	37	561	C-SS	4.3	0.20	0.03	AZ	34.9957	−111.7613
2003 Aspen	Desilets *et al*. (2007)	0.84	43	562	C-SS	6.8	0.04	0.78	AZ	32.3787	−110.7944
2003 Aspen	Desilets *et al*. (2007)	0.84	43	562	C-SS	2.2	0.04	0.78	AZ	32.3787	−110.7944
1959 June	Glendening *et al*. (1961)	0.42	42	463	C-V	205	0.22	0.53	AZ	33.8768	−111.1670
1959 June	Glendening *et al*. (1961)	0.42	42	463	C-V	21	0.22	0.53	AZ	33.8768	−111.1670
2000 Coon Creek	Gottfried *et al*. (2003)	0.66	42	573	C-V	78	0.073	0.78	AZ	33.8128	−110.9235
6 July 1957	Rich (1962)	0.66	42	573	C-V	82	0.088	0.78	AZ	33.8128	−110.9235
2002 Rodeo-Chediski	Gottfried *et al*. (2003)	0.92	40	487	H-Pt	52	0.019	0.36	AZ	34.3853	−110.6197
7 July 1942 burn	Hendricks and Johnson (1944)	0.42	41	508	H-Pt	72	0.43	0.82	AZ	33.7803	−110.9648
7 July 1942 burn	Hendricks and Johnson (1944)	0.42	41	508	H-Pt	202	0.66	0.82	AZ	33.7803	−110.9648
7 July 1942 burn	Hendricks and Johnson (1944)	0.42	41	508	H-Pt	370	0.78	0.82	AZ	33.7803	−110.9648
6 July 1957	Rich (1962)	0.66	42	573	H-Pt	86	0.09	0.78	AZ	33.8128	−110.9235
ARIZONA-MEDIUM											
1977 La Mesa	Bolin and Ward (1987)	1.46	35	481	C-SS	3.7	0.02	0.60	NM	35.8142	−106.3958
2000 Cerro Grande	Malmon *et al*. (2007)	1.46	36	481	C-SS	60	0.11	0.94	NM	35.8855	−106.3422
2000 Cerro Grande	Lavine *et al*. (2006)	1.46	36	481	C-V	22	0.07	0.60	NM	35.8842	−106.3554
2000 Cerro Grande	Malmon *et al*. (2002)	1.46	36	481	C-V	13	0.07	0.60	NM	35.8867	−106.3597
2000 Cerro Grande	Malmon *et al*. (2002)	1.46	36	481	C-V	4.8	0.07	0.60	NM	35.8867	−106.3597
2000 Cerro Grande	Johansen *et al*. (2001)	1.46	36	481	H-Pt	4.6	0.07	0.94	NM	35.8665	−106.3305
La Mesa	Wells *et al*. (1978)	1.46	35	481	H-Pt	102	0.09	0.94	NM	35.8230	−106.3497
La Mesa	Wells *et al*. (1978)	1.46	35	481	H-Pt	39	0.22	0.94	NM	35.8230	−106.3497
2000 Cerro Grande	Cannon *et al*. (2001)	1.46	36	481	H-Plot	200	0.28	0.39	NM	35.9100	−106.3958
PACIFIC-HIGH											
1975	Bruington (1982)	0.063	37	672	C-V	502	0.27	0.92	CA	34.2734	−118.2793
December 1927	Eaton (1936)	0.065	37	471	C-V	131	0.28	0.84	CA	34.1933	−118.2703
November 1933	Kraebel (1934)	0.072	37	605	C-V	336	0.19	0.85	CA	34.2614	−118.2729
November 1933	Kraebel (1934)	0.072	37	605	C-V	251	0.18	0.85	CA	34.2428	−118.2258
November 1933	Troxell and Peterson (1937)	0.071	37	536	C-V	402	0.37	0.85	CA	34.2548	−118.2267
November 1933	Troxell and Peterson (1937)	0.071	37	536	C-V	95	0.19	0.85	CA	34.2548	−118.2267
November 1933	Troxell and Peterson (1937)	0.071	37	536	C-V	226	0.37	0.85	CA	34.2548	−118.2267

Kinneloa Fire	Van de Water (2000)	0.091	37	462	C-V	642	0.30	0.85	CA	34.2068	−118.1170
1978 Mountain Trail	Wells (1982)	0.071	37	536	C-V	64	0.30	0.85	CA	34.2540	−118.2080
1979 Pinecrest Fire	Wells (1982)	0.091	37	462	C-V	530	0.30	0.85	CA	34.2068	−118.1170
1978 Mountain Trail	Wells (1987)	0.071	37	536	C-V	170	0.47	0.53	CA	34.1772	−118.0536
PACIFIC-MEDIUM											
1991 Tunnel	Booker *et al*. (1993)	0.053	28	645	C-V	6.0	0.35	0.99	CA	37.8618	−122.2293
1991 Tunnel	Booker *et al*. (1993)	0.053	28	645	C-V	9.8	0.35	0.99	CA	37.8618	−122.2293
1993 Laguna Beach	Booker (1998)	0.070	30	344	C-V	1.1	0.24	0.97	CA	33.5560	−117.7678
1968	Bruington (1982)	0.081	32	563	C-V	1120	0.29	0.85	CA	34.1751	−117.8384
1995 Vision	Collins and Ketcham (2001)	0.024	33	788	C-V	7.3	0.34	0.82	CA	38.0488	−122.8708
4 July 1950	Colman (1951)	0.10	25	346	C-V	102	0.27	0.85	CA	34.1051	−117.0104
1960	Copeland and Croft (1962)	0.27	20	265	C-V	1.3	0.21	0.58	NV	39.5401	−120.0622
Donner Ridge	Copeland (1965)	0.27	20	265	C-V	7.9	0.21	0.58	NV	39.5401	−120.0622
1987 Yellow	de la Fuente (1990)	0.10	25	1077	C-V	26	0.36	0.69	CA	41.3088	−123.2348
1987 Yellow	de la Fuente (1990)	0.10	25	1077	C-V	24	0.36	0.69	CA	41.3088	−123.2348
1960 Johnston Peak	Doehring (1968)	0.083	33	613	C-V	2800	0.65	0.85	CA	34.1608	−117.7967
1960 Johnston Peak	Doehring (1968)	0.083	33	613	C-V	31	0.65	0.85	CA	34.1608	−117.7967
1960 Johnston Peak	Doehring (1968)	0.083	33	613	C-V	126	0.65	0.85	CA	34.1608	−117.7967
1960 Johnston Peak	Hopkins *et al*. (1961)	0.080	33	560	C-V	98	0.65	0.85	CA	34.1998	−117.7818
1990 Painted Cave	Keller *et al*. (1997)	0.052	30	430	C-V	211	0.091	0.84	CA	34.4420	−119.8042
September 1919	Munns (1920)	0.080	33	560	C-V	78	0.22	0.85	CA	34.1778	−117.8242
1968 Canyon Inn	Rice (1974)	0.083	33	613	C-V	745	0.54	0.85	CA	34.1617	−117.8674
1968 Canyon Inn	Rice (1982)	0.083	33	613	C-V	745	0.54	0.85	CA	34.1617	−117.8674
1969 Canyon Inn	Rice (1982)	0.083	33	613	C-V	184	0.65	0.85	CA	34.1822	−117.7964
1999 Mixing	Robichaud *et al*. (2008)	0.16	28	611	C-V	1.4	0.19	0.60	CA	33.68	−116.73
2002 Cannon	Robichaud *et al*. (2008)	0.062	20	528	C-V	0.14	0.38	0.38	CA	38.45	−119.47
1938	San Dimas Experimental Forest Staff (1954)	0.083	33	613	C-V	44	0.02	0.85	CA	34.1964	−117.7169
1953	San Dimas Experimental Forest Staff (1954)	0.083	33	613	C-V	274	0.04	0.85	CA	34.1743	−117.7470
1960	Wells (1982)	0.050	28	480	C-V	51	0.65	0.85	CA	34.1998	−117.7818
1977 Middle	Wells (1987)	0.031	33	355	C-V	425	0.05	0.53	CA	34.3373	−118.1225
1960 Johnston Peak	Krammes (1960)	0.08	33	560	H-Pt	154	0.82	0.85	CA	34.2393	−118.1908
1960 Johnston Peak	Krammes (1960)	0.08	33	560	H-Pt	9.0	0.82	0.85	CA	34.2393	−118.1908
October 1959	Krammes (1965)	0.08	33	560	H-Pt	16	0.82	0.85	CA	34.2393	−118.1908
1960 Johnston Peak	Krammes (1960)	0.08	33	560	H-Pt	28	0.82	0.85	CA	34.2393	−118.1908
1960 Johnston Peak	Krammes (1960)	0.08	33	560	H-Pt	1.7	0.82	0.85	CA	34.2393	−118.1908
October 1959	Krammes (1965)	0.08	33	560	H-Pt	0.56	0.82	0.85	CA	34.2393	−118.1908
1960 Johnston Peak	Krammes (1960)	0.08	33	560	H-Pt	15	0.82	0.85	CA	34.2393	−118.1908
October 1959	Krammes (1965)	0.08	33	560	H-Pt	78	0.82	0.85	CA	34.2393	−118.1908
1960 Johnston Peak	Krammes (1960)	0.08	33	560	H-Pt	2.2	0.82	0.85	CA	34.2393	−118.1908
October 1959	Krammes (1965)	0.08	33	560	H-Pt	3.5	0.82	0.85	CA	34.2393	−118.1908
1934	Sampson (1944)	0.10	30	901	H-Pt	151	0.40	0.93	CA	40.4752	−122.6182

(*Continued*)

Table 2. (Continued)

Fire	Reference	Summer rainfall : winter rainfall	2-year, 30-min rainfall intensity $I_{30}^{2\ year}$ (mm h^{-1})	Mean annual rainfall (mm year^{-1})	Location-Method	Max. sediment yield (ha^{-1})	Slope	Soil erodibility, *K-factor* (m^{-1})	State	Site location WGS84/NAD83 Latitude	Longitude
1951 Fire	Sartz (1953)	0.24	25	942	H-Pt	674	0.59	0.94	OR	45.5853	−122.7978
1951	Sartz (1953)	0.24	25	942	H-Pt	570	0.61	0.94	OR	45.5853	−122.7978
1987 Angel	Schmidt (1990)	0.18	28	978	H-Pt	20	0.27	0.92	OR	45.7592	−122.9968
1991 Tunnel	Booker *et al*. (1993)	0.05	28	645	H-Plot	1.7	0.70	0.99	CA	37.8618	−122.2293
1991 Tunnel	Booker *et al*. (1995)	0.05	28	645	H-Plot	0.18	0.70	0.99	CA	37.8618	−122.2293
1991 Tunnel	Booker *et al*. (1995)	0.05	28	645	H-Plot	0.082	0.70	0.99	CA	37.8618	−122.2293
1991 Tunnel	Booker *et al*. (1995)	0.05	28	645	H-Plot	0.033	0.70	0.99	CA	37.8618	−122.2293
July 1960	Krammes and Rice (1963)	0.05	28	480	H-Plot	67	0.68	0.85	CA	34.1823	−117.8025
July 1960	Krammes and Rice (1963)	0.05	28	480	H-Plot	93	0.68	0.85	CA	34.1823	−117.8025
1966	Krammes and Osborn (1969)	0.08	33	560	H-Plot	491	0.82	0.85	CA	34.2393	−118.1908
1966	Krammes and Osborn (1969)	0.05	20	305	H-Plot	74	0.82	0.97	CA	33.8323	−117.5850
October 1967	Krammes and Osborn (1969)	0.05	20	305	H-Plot	138	0.82	0.97	CA	33.8323	−117.5850
Green Meadow	Schwarz (1997)	0.05	30	397	H-Plot	20	0.24	0.95	CA	34.1073	−119.0110
1934 Fire	Sampson (1944)	0.10	30	901	H-Plot	14	0.40	0.93	CA	40.4752	−122.6182
1934 Fire	Sampson (1944)	0.10	30	901	H-Plot	10	0.40	0.93	CA	40.4752	−122.6182
1938	Wells (1981)	0.05	28	480	H-Plot	32	0.02	0.85	CA	34.1823	−117.8025
1938	Wells (1981)	0.05	28	480	H-Plot	3.9	0.02	0.85	CA	34.1823	−117.8025
Very hot prescribed	Wohlgemuth and Hubbert (2008)	0.05	28	480	H-Plot	170	0.60	0.85	CA	34.1983	−117.7115
1993 Topanga	Wohlgemuth *et al*. (1996)	0.04	30	600	H-Plot	430	0.49	1.10	CA	34.0498	−118.6067
1993 Topanga	Wohlgemuth *et al*. (1996)	0.04	30	600	H-Plot	100	0.49	1.10	CA	34.0498	−118.6067
SUB-PACIFIC-LOW											
1970	Helvey (1980)	0.17	13	712	C-SS	0.12	0.29	0.38	WA	47.9064	−120.4643
1970	Helvey (1980)	0.17	13	712	C-SS	0.26	0.27	0.38	WA	47.9064	−120.4643
1970	Helvey (1980)	0.17	13	712	C-SS	0.40	0.27	0.38	WA	47.9064	−120.4643
1989 Lowman	Meyer *et al*. (2001)	0.31	14	662	C-V	440	0.24	0.47	ID	44.0717	−115.5092
1989 Lowman	Meyer *et al*. (2001)	0.53	14	662	C-V	420	0.26	0.31	ID	44.0489	−115.8385
Poverty Flat	Nobel and Lundeen (1971)	0.18	16	645	C-V	7.1	0.049	0.42	ID	45.3125	−114.4988
North 25 Mile Creek	Robichaud (2000*b*)	0.17	13	712	C-V	0.75	0.550	0.38	WA	47.9667	−120.3333
1951 Cottonwood Gulch	Vanoni (1977)	0.25	13	495	C-V	39	0.068	0.75	ID	43.6447	−115.8305
Pine Creek	Megahan and Molitor (1975)	0.31	14	662	H-Pt	94	0.52	0.48	ID	44.3343	−115.8525
Pine Creek	Megahan and Molitor (1975)	0.31	14	662	H-Pt	2.3	0.52	0.48	ID	44.3343	−115.8525
Pine Creek	Megahan and Molitor (1975)	0.31	14	662	H-Pt	15.3	0.52	0.48	ID	44.3343	−115.8525

August 1994	Robichaud and Brown (1999)	0.65	16	503	H-Plot	2.5	0.60	0.90	OR	45.1165	−117.0843
August 1994	Robichaud and Brown (1999)	0.65	16	503	H-Plot	2.2	0.30	0.90	OR	45.1165	−117.0843
August 1994	Robichaud and Brown (1999)	0.65	16	503	H-Plot	1.1	0.20	0.90	OR	45.1165	−117.0843
1992 McCay	Radek (1996)	0.64	14	375	H-Plot	11	0.29	0.39	WA	48.6207	−119.9293
1992 McCay	Radek (1996)	0.64	14	375	H-Plot	1.4	0.29	0.39	WA	48.6207	−119.9293
1994 Bannon, Thunder, Whiteface	Radek (1996)	0.64	14	375	H-Plot	1.5	0.29	0.69	WA	48.6858	−119.5822
1994 Bannon, Thunder, Whiteface	Radek (1996)	0.64	14	375	H-Plot	21.8	0.29	0.69	WA	48.6858	−119.5822
PLAINS-HIGH											
1988 Galena	Gundarlahalli (1990)	1.96	42	513	C-SS	175	0.06	1.27	SD	43.7926	−103.3257
PLAINS-MEDIUM											
1988 Yellowstone	Ewing (1996)	1.01	23	518	C-SS	0.67	0.45	0.39	WY	44.9292	−110.4018
1988 Yellowstone	Ewing (1996)	1.01	23	518	C-SS	0.66	0.45	0.39	WY	44.9292	−110.4018
2000 Bobcat	Kunze and Stednick (2006)	1.52	30	432	C-SS	0.38	0.32	0.65	CO	40.4711	−105.2950
2000 Bobcat	Kunze and Stednick (2006)	1.52	30	432	C-SS	1.4	0.33	0.65	CO	40.4711	−105.2950
1996 Buffalo Creek	Moody and Martin (2001*a*)	1.55	33	438	C-SS	56	0.04	0.34	CO	39.3930	−105.1767
1988 Clover-Mist	Troendle and Bevenger (1996)	1.01	23	518	C-SS	0.66	0.40	0.29	WY	44.5568	−110.0162
1988 Clover-Mist	Troendle and Bevenger (1996)	1.01	23	518	C-SS	0.41	0.40	0.29	WY	44.5568	−110.0162
1994 Storm King	Cannon *et al*. (1995)	0.69	25	455	C-V	218	0.30	0.54	CO	39.6550	−107.3953
1996 Fire	Larsen *et al*. (2006)	0.87	20	259	C-V	410	0.65	0.48	CO	40.5875	−108.9951
2001 Fire	Larsen *et al*. (2006)	0.87	20	259	C-V	380	1.47	0.48	CO	40.6719	−108.9128
1988 Yellowstone	Meyer and Wells (1997)	1.14	24	513	C-V	110	0.27	0.39	WY	45.0587	−110.1632
1996 Buffalo Creek	Moody and Martin (2001*a*)	1.55	33	438	C-V	440	0.33	0.34	CO	39.3930	−105.1767
1996 Buffalo Creek	Moody and Martin (2001*a*)	1.55	33	438	C-V	220	0.30	0.34	CO	39.3930	−105.1767
1996 Buffalo Creek	Moody and Martin (2001*b*)	1.55	33	438	C-V	320	0.20	0.34	CO	39.3930	−105.1767
2000 Valley Complex	Robichaud *et al*. (2008)	0.85	19	411	C-V	0.64	0.46	0.23	MT	45.91	−114.03
2001 Fridley	Robichaud *et al*. (2008)	0.93	23	867	C-V	6.7	0.43	0.57	MT	45.51	−110.78
2002 Hayman	Robichaud *et al*. (2008)	1.55	33	438	C-V	24	0.33	0.34	CO	39.18	−105.36
2000 Bobcat	Benavides-Soloria and MacDonald (2005)	1.52	30	432	H-Plot	9.8	0.31	0.65	CO	40.4628	−105.3450
1996 Buffalo Creek	Martin and Moody (2001*a*)	1.55	33	438	H-Plot	5.3	0.50	0.34	CO	39.3930	−105.1767
1996 Buffalo Creek	Martin and Moody (2001*a*)	1.55	33	438	H-Plot	1.1	0.50	0.34	CO	39.3930	−105.1767
1996 Buffalo Creek	Martin and Moody (2001*a*)	1.55	33	438	H-Plot	76	0.20	0.34	CO	39.3930	−105.1767
2002 Hewlett Gulch	Pietraszek (2006)	1.52	30	432	H-Plot	24	0.03	0.65	CO	40.7202	−105.3148
2002 Hayman	Pietraszek (2006)	1.55	33	438	H-Plot	11	0.07	0.65	CO	39.2960	−105.2401
2002 Hayman	Pietraszek (2006)	1.55	33	438	H-Plot	17	0.07	0.65	CO	39.2960	−105.2401
2000 Valley Complex	Spigel and Robichaud (2007)	0.83	20	402	H-Plot	38	0.56	0.22	MT	45.9688	−114.0274
2000 Bobcat	Wagenbrenner *et al*. (2006)	1.52	30	432	H-Plot	24	0.35	0.65	CO	40.4711	−105.2950

Table 3. Summary of sediment yield after wildfire for rainfall regimes in western United States

Volume, measurements of eroded or deposited volumes including sediment excavation from behind dams or debris basin; SS, suspended-sediment sampling; Point includes erosion pins, transects, erosion bridges or grids; Plot includes unbound plots, bounded plots, silt fences

Rainfall regime		Measurement method		*n*	Annual sediment yield ($t\,ha^{-1}$)			
					Minimum	Maximum	Median	Mean
ARIZONA	EXTREME	Channel	Volume	2	180	280	230	230
ARIZONA	HIGH	Channel	SS	3	2.2	6.8	4.3	4.4
ARIZONA	HIGH	Channel	Volume	4	21	200	80	97
ARIZONA	HIGH	Hillslope	Point	5	52	370	86	169
ARIZONA	MEDIUM	Channel	SS	2	3.7	60	32	32
ARIZONA	MEDIUM	Channel	Volume	3	4.9	22	13	14
ARIZONA	MEDIUM	Hillslope	Point	3	4.6	100	39	49
ARIZONA	MEDIUM	Hillslope	Plot	1	200	200	200	200
ARIZONA	Normal background yield			3	0.0030	0.16	0.070	0.078
PACIFIC	HIGH	Channel	Volume	11	64	640	250	300
PACIFIC	MEDIUM	Channel	Volume	25	0.14	2800	51	280
PACIFIC	MEDIUM	Hillslope	Point	14	0.56	670	18	120
PACIFIC	MEDIUM	Hillslope	Plot	17	0.033	490	32	97
PACIFIC	Normal background yield			26	0.027	64	5.2	12
SUB-PACIFIC	LOW	Channel	SS	3	0.12	0.40	0.26	0.26
SUB-PACIFIC	LOW	Channel	Volume	5	0.75	440	39	180
SUB-PACIFIC	LOW	Hillslope	Point	3	2.3	94	15	37
SUB-PACIFIC	LOW	Hillslope	Plot	7	1.1	22	2.2	5.9
SUB-PACIFIC	Normal background yield			4	0.0080	4.4	0.017	1.1
PLAINS	HIGH	Channel	SS	1	180	180	180	180
PLAINS	MEDIUM	Channel	SS	7	0.38	56	0.66	8.6
PLAINS	MEDIUM	Channel	Volume	10	0.64	440	220	210
PLAINS	MEDIUM	Hillslope	Plot	9	1.1	76	17	23
PLAINS	Normal background yield			7	0.12	32	0.62	8.4

because of the bias toward fine-grained sediment, whereas the Channel-volume, Hillslope-point and Hillslope-plot methods represent similar coarse-grained particle sizes. This difference between the mean sediment yield from channel and hillslopes was strongly significant based on three statistical *t*-tests using the original data ($P = 0.007$), log-transformed data ($P < 0.001$), and a non-parametric Wilcoxon–Mann–Whitney rank sum test ($P << 0.001$). Thus, in a broad sense across the western United States, when these means are converted to percentages, ~75% of the coarse-grained sediment yield comes from channels and 25% comes from hillslopes.

Field observations and measurements support this regional result. Field observations in the mountains of southern California, where dry ravel is a dominant hillslope sediment-transport process, indicate that yields from channels are greater than yield from hillslopes (P. M. Wohlgemuth, pers. comm., 2008). Dry ravel transports sediment to the dry channels, where it is stored, but available for remobilization and transport from the channel when sufficient water is delivered to the channels from the hillslopes (Anderson *et al.* 1959; Wells 1987). Measurements in the Front Range Mountains of Colorado indicated that ~80% of the sediment yield was from channels and ~20% was from hillslopes (Moody and Martin 2001*b*). Unchannelized drainages were considered part of the channel network and not part of the hillslope. This is because post-fire erosion frequently incises these unchannelized drainages, increases the connectivity and transport efficiency, expands the channelized network upslope as headcuts following the drainages between hillslope segments (Collins and Ketcham 2001; Moody and Kinner 2006), and increases the drainage density (Collins and Ketcham 2001). Thus, to apply the proportions of sediment yield from channels and hillslopes to other landscapes, it is important to keep the definitions of hillslope and channel in mind.

This general result suggests that post-fire sediment yield increases as the spatial scale increases from hillslopes ($1–1000\,m^2$) to the drainage area encompassing a channel network ($10^4–10^6\,m^2$). This relation appears contrary to the general notion that sediment yield decreases as drainage area increases (Walling 1983; Reneau and Dietrich 1991; and references cited therein; Walling and Webb 1996). However, previous work (Trimble 1976) and more recent work (Dedkov and Moszherin 1992; Walling and Webb 1996) have shown that sediment yield depends on the relative importance of channel and hillslope erosion processes (Lane *et al.* 1997). When hillslope processes dominate channel processes, sediment yield decreases as drainage area increases. When channel processes dominate hillslope processes, sediment yield increases as drainage area increases. The latter is the case after wildfires. Floods following fires remobilize sediment stored in the channel network over several time scales. Normal hillslope erosion and transport processes are slow and begin to refill gullies and channels with sediment during the time interval between wildfires (recurrence intervals are on the order of 10–100 years) at a rate that would require 1000–10 000 years (Welter 1995; Moody and

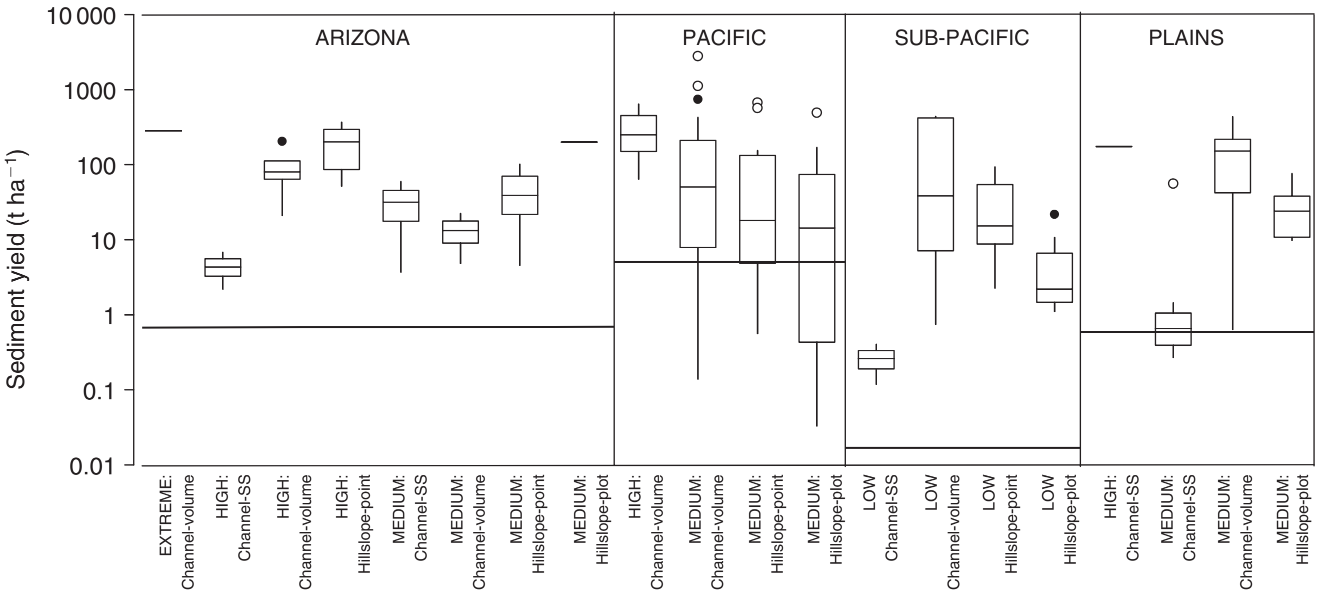

Fig. 3. Standard box and whisker plot of the annual sediment yields organized by rainfall regimes. The lower and upper limits of the box are equal to the first and third quartile and the difference equals the interquartile range, IQR. The horizontal line in the middle of the box equals the median value. Moderate outliers between the inner fence (first quartile ± 1.5 IQR) and the outer fence (first quartile ± 3.0 IQR) are shown as solid circles and the extreme outliers (those beyond the outer fence) are shown as open circles. The whiskers are drawn from the box to the highest and lowest values that lie within the inner fence. The dark horizontal bar in each rainfall regime represents the background sediment yield based on the references in the present paper.

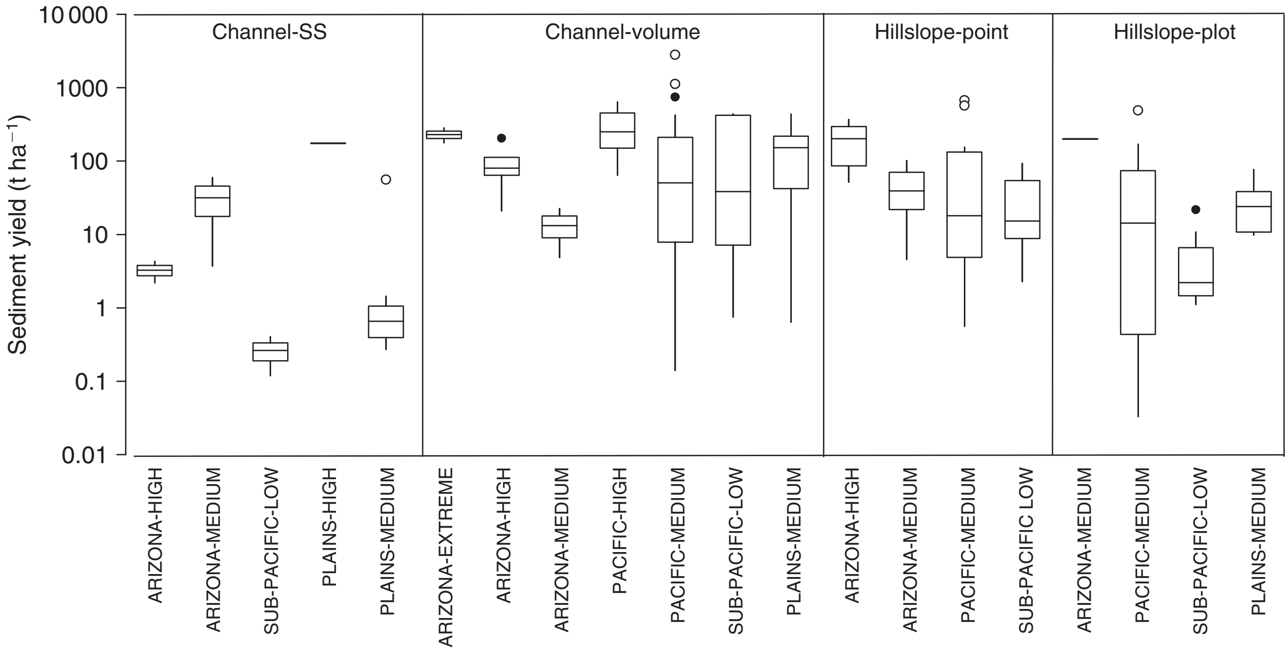

Fig. 4. Standard box and whisker plot of the annual sediment yields organized by measurement method or landscape location. The methods are the: Channel-SS (suspended sediment); Channel-volume (dams, check dams, debris basins, alluvial fan deposition, and channel erosion); Hillslope-point (erosion pin, erosion bridge, survey transect, or grid); and Hillslope-plot (bounded hillslope plots, unbounded hillslope plots, and silt fences). The lower and upper limits of the box are equal to the first and third quartile and the difference equals the interquartile range, IQR. The horizontal line in the middle of the box equals the median value. Moderate outliers between the inner fence (first quartile ± 1.5 IQR) and the outer fence (first quartile ± 3.0 IQR) are shown as solid circles and the extreme outliers (those beyond the outer fence) are shown as open circles. The whiskers are drawn from the box to the highest and lowest values that lie within the inner fence.

Martin 2001*b*). However, if this slow process is interrupted by a sequence of wildfire followed by substantial flooding, then some fine-grained sediment eroded from hillslopes and greater amounts of coarse-grained sediment eroded from drainages are deposited in the channel network (San Dimas Experimental Forest Staff 1954; Moody and Martin 2001*a*). This sediment becomes a legacy for the next fire–flood sequence (Fig. 5) and in the case of the Buffalo Creek Fire was estimated to have a residence time on the order of 300 years (Moody and Martin 2001*b*). Thus, there is a lag time between when sediment is actively stored in the channel and when it is remobilized by floods following wildfires. Post-fire sediment eroded from channels is generally older and coarser than sediment eroded from hillslopes.

Channels provide several sources of sediment. These are the upstream extension of headcuts, lateral bank erosion, undermining and collapse of banks supporting stored colluvium, and the channel bed (Florsheim *et al*. 1991; Collins and Ketcham 2001; Santi *et al*. 2007; Moody *et al*. 2008). Direct measurements of post-fire channel erosion have been made at three sites in each of three rainfall regimes (SUB-PACIFIC, low; PACIFIC, Medium and PLAINS, Medium) by Santi *et al*. (2007). The average erosion was 2.5 $m^3 m^{-1}$ with values ranging up to 22.3 $m^3 m^{-1}$ in southern California. Similar values of channel erosion (1.1 and 3.2 $m^3 m^{-1}$) were measured in two watersheds in the Front Range Mountains of Colorado (Moody and Martin 2001*a*). These are equivalent to sediment yields of 220 and 440 t ha^{-1} (Table 3) if the drainage area is used. If channels are the source of sediment, then the appropriate normalizing area is the wetted surface area of the channel and not the drainage area encompassing the channel network. However, the necessary channel geometry measurements are rarely published. For this last set of measurements, the channel geometry is available for two watersheds in Spring Creek (subwatersheds W1165 and W960; Moody and Martin 2001*a*; Moody and Kinner 2006). The sediment yields normalized by the wetted surface area for the smallest first order through the larger fourth order channels in W1165 are 17 000, 15 000, 5700 and 4300 t ha^{-1}, and for the first, second, and third order channels in W960, the yields are 32 000, 18 000 and 11 000 t ha^{-1}. These sediment yields are two orders of magnitude greater than the averaged yields normalized by the drainage area (220 and 440 t ha^{-1} for W1165 and W960, respectively). This example emphasizes that (1) channel erosion is localized; (2) actual yields from channels are definitely much greater than yields from hillslopes; and (3) the sediment yields decreased as the wetted surface area increased. This last point suggests that the relation between sediment yield and area is not contrary to the general notion mentioned above, if the appropriate area is used to normalize the eroded sediment volume or mass.

Maximum, mean post-fire sediment yields from each of the eight different rainfall regimes (Table 3) are episodic in nature but comparable in magnitude with long-term sediment yields from major rivers of the world (120 to 535 t ha^{-1}; Walling and Webb 1996). Long-term yield is a metric for landscape change, which includes 'frequent flows of moderate magnitude' (Wolman and Miller 1960, p. 60) that account for 50% of the yield, and includes less frequent flows of 'giant' magnitude that account for the other 50% of the yield. Similarly, fire-related sediment yield is a metric of landscape change and was two to four orders of magnitude greater than the short-term background sediment yields reported for the duration of each study included in the current synthesis. The fact that fire-related sediment yields are comparable with long-term yields supports the earlier speculation of Swanson (1981) and the statement by Robichaud (2000) that fire is an important geomorphic agent in the western United States. The landscape is altered at the spatial scale affected by fire, but some geomorphic effects of the fire extend beyond the immediate perimeter of the fire. For example, the Buffalo Creek Fire burned an area of 4700 ha. Coarse- and fine-grained sediment were transported outside this area but trapped by a water-supply reservoir, Strontia Springs, with a contributing area of 668 000 ha. Diversion and flood control dams farther downstream trapped additional fine-grained sediment. Without these dams, fire-related sediment would probably have been transported and deposited as alluvial fans exiting the mountains. However, this expanded geomorphic effect of fire is limited to the channel corridor and not the entire drainage area. Interestingly, post-fire sediment can affect the quality of the water collected in reservoirs from much larger areas than that of the immediate fire (Moody and Martin 2001*a*; Moody and Martin 2004; Lavine *et al*. 2006) and the growing awareness of this effect is the basis for current efforts to identify potential impairment of water supplies (LeMaster *et al*. 2007). The episodic nature of post-fire erosion and transport coupled with vegetation regrowth limits the temporal scale to a few years after a wildfire (Moody and Martin 2001*a*).

Post-fire sediment yields depend on the timing of rainfall relative to the onset of the fire season, except in the case of dry ravel released during a fire. The wildfire season in the western United States begins in the ARIZONA seasonal rainfall type (dry desert and semi-desert regions of the south-west) and in the SUB-PACIFIC seasonal rainfall type (eastern parts of Washington, Oregon, and California, and in Nevada) in May or June (Kaye and Swetnam 1999; Brown *et al*. 2001). In the ARIZONA type, monsoons rains begin in July and August, whereas in SUB-PACIFIC, these months are dry. The fire season then progresses into the PACIFIC and PLAINS regions (Hostetler *et al*. 2005). Late-season fires in the northern part of the PLAINS (for example, 2000 Valley Complex Fires in Montana, Spigel and Robichaud 2007) in July and August may be followed in a short time by winter snow and freezing temperatures in September and October. Sediment yields are restricted to a shorter period than in the other rainfall regimes such that there may be no erosion, transport or deposition until spring temperatures thaw the soil. Sediment yields will then continue at rates that depend on the sequence and magnitude of the rainstorms and the regrowth of the vegetation. In contrast, late-season fires in September and October in the PACIFIC region of southern California are usually followed by the peak rainfall period during winter producing substantial sediment yield.

At this point, it seems appropriate to speculate about how climate change may affect sediment yields after wildfire. Some climate analyses indicate that more precipitation is now falling as rain instead of snow (Knowles *et al*. 2006). A shift from snowfall to rainfall could prolong the erosion season and increase the sediment yields after fire in some rainfall regimes. Moreover, additional climate analysis suggests that precipitation has increased by ~10% across the United States, and importantly,

Fig. 5. Examples of the legacy of sediment deposited after a fire–flood sequence. (*a*) Tributary alluvial fan on 7 August 1997. The fan was deposited during a flood approximately one month after the 1996 Buffalo Creek Fire in Colorado was contained. It is on the right bank of Spring Creek and 780 m upstream from the confluence of Spring Creek and the South Platte River. Flow in the main channel is from right to left. The person is ∼2 m tall. The fan was truncated by later floods but left some fire-related sediment along the channel margin. (*b*) Main channel terrace and floodplain on 18 May 2005. View is looking upstream in the main channel of Spring Creek burned by the 1996 Buffalo Creek Fire in Colorado. This deposit of fire-related sediment was essentially an in-channel fan and was ∼680 m upstream from the confluence of Spring Creek and the South Platte River. The coauthor is sitting on a terrace surface deposited by a flood in 1998, which is on top of sediment deposited in 1996. The deposit was not incised until the winter of 2004–05 when runoff left an ∼2 m high terrace as a legacy of fire-related sediment, which may be remobilized by future extreme floods. The lower surface, corresponding to the foreground, has been vegetated and stabilized and is becoming a floodplain but also is a legacy of fire-related sediment.

approximately half of the increase is the result of an increase in the intensity of rainstorms (Karl and Knight 1998; Schneider 2004). Thus, sediment erosion may increase in each of the rainfall regimes in response to changes in the timing and intensity of rainfall, and consequently, these changes may alter the balance between soil production and the removal of soil by post-fire erosion (Roering and Gerber 2005).

Climate change effects on post-fire sediment yields are undoubtedly complex. Connections between climate and wildfire have been established and discussed by several authors (Flannigan *et al*. 2000; Brown *et al*. 2004; Bachelet *et al*. 2007; and references therein; Holden *et al*. 2007), but the predictions of post-fire sediment yields based on these connections will depend on the exact magnitude, frequency, duration, and the sequence of the climate changes. The role of climate change in influencing sediment yields has been considered in the scientific literature (Bull 1991; Knox 1993; Favis-Mortlock and Savabi 1996; Molnar 2001), though no systematic analyses have been published of the complicated links between climate change, vegetation, wildfire characteristics (such as frequency, size, and severity), and post-fire sediment yields. It is beyond the scope of the present synthesis to hypothesize about or model changes in post-fire sediment yields under different climatic scenarios, but it is certain that burned landscapes will exhibit complex non-linear responses characterized by threshold, feedbacks, and sensitivity (Schumm 1973; Phillips 2003; Peters and Havstad 2006; Moody and Martin, in press).

Summary and conclusions

A comprehensive dataset of post-fire sediment erosion, transport, and deposition measurements (135) was compiled from the published literature (1927–2007) for sites across the western United States where measurements were made within 2 years of a wildfire. Post-fire sediment yields were computed and grouped into four measurement methods: Hillslope-point (erosion pin, erosion bridge, survey transect, or grid), Hillslope-plot (bounded hillslope plots, unbounded hillslope plots, and silt fences), Channel-SS (suspended-sediment measurements), and Channel-volume (dams, check dams, debris basins, alluvial-fan deposition, and channel erosion). The computed sediment yields were grouped according to rainfall regimes. Ten rainfall regimes were defined by the combination of four rainfall types in the western United States (ARIZONA, PACIFIC, SUB-PACIFIC, and PLAINS) and four rainfall intensity conditions: LOW (10 to 20 mm h^{-1} and 15 to 20 mm h^{-1}), MEDIUM (19 to 36 mm h^{-1} and 20 to 36 mm h^{-1}), HIGH (36 to 52 mm h^{-1}), and EXTREME (>52 mm h^{-1}). Post-fire annual sediment yields were calculated for eight rainfall regimes.

When post-fire annual sediment yields (normalized by the drainage area) were grouped by rainfall regimes, the magnitudes varied over five orders of magnitude. Sediment yields were expected to vary across the rainfall regimes, but a major source of variance was the different methods used within each rainfall regime to measure post-fire sediment yield. Each measurement method had different intrinsic temporal and spatial scales and collected different sediment particle sizes. However, when the mean sediment yields were grouped by measurement method or landscape location (channel or hillslope), the sediment yields only varied by approximately one order of magnitude, indicating that the associated uncertainty was less for conclusions based on these means.

A primary conclusion drawn from the grouping by landscape location was that post-fire sediment yields from channels were greater than yields from hillslopes across the western United States. The mean post-fire sediment yield from channels was 240 t ha^{-1} and the yield from hillslopes was 82 t ha^{-1}. The dataset represents a robust sampling of channels and hillslopes from multiple burned areas and from different rainfall regimes such that the difference between the channel and hillslope post-fire sediment yields was strongly significant ($P < 0.007$). Thus, ~75% of the post-fire sediment yield comes from channels and 25% comes from hillslopes; however, most of the runoff, which erodes sediment from the channels, comes from the hillslopes. Post-fire sediment yields did not show a significant correlation with topographic slope or soil erodibility. This suggests that sediment availability may be more important than slope or soil erodibility in predicting post-fire sediment yields. These results can be used to guide the prioritization of post-fire land management policies and they identify the need to develop techniques to measure sediment availability for use in predictive models of post-fire sediment yield.

Although the nature of post-fire sediment yields is localized and episodic, the maximum, mean post-fire sediment yields in the rainfall regimes of the western United States were comparable with long-term sediment yields from major rivers of the world. This result, based on data collected over 80 years, suggests that wildfires have been an important geomorphic agent of landscape change when linked with sufficient rainfall. Possible changes in the rainfall associated with climate change in the future may increase the geomorphic impact of wildfire on the landscape. The geomorphic effect of wildfire is limited in spatial scale to the immediate burned area and to the channel corridor downstream; however, this effect may increase if the frequency, size, and severity of wildfires continue to increase in the future.

We encourage authors to include quantitative data related to burn severity, rainfall intensity, overland flow discharge, channel geometry, and channel discharge in future publications on sediment erosion, transport, and deposition after wildfire. This type of data will facilitate understanding the complex links between climate, rainfall, vegetation, wildfire, and subsequent yields and will aid in the development of physically based models designed to predict sediment yields and their associated uncertainties.

Acknowledgements

The present project started in 1996 as a multi-disciplinary effort within the US Geological Survey (USGS) supported by the National Research Program of the USGS Water Resources Discipline to visit burned areas across the western United States in order to learn about fire regimes, post-fire consequences, invasive species, research gaps, and data needs. We extend our heartfelt gratitude to the land managers and scientists within the USDA Forest Service, Bureau of Land Management, National Park Service, and elsewhere who took their time to show us sites, and share published literature and unpublished reports and their knowledge gleaned from burned watersheds. Many of these site visits have led to fruitful multiagency collaborations. We particularly thank Craig Allen, USGS-Biological Resources Discipline, for his generous support for additional site visits and this synthesis through the project, 'Response of Western Mountain Ecosystems to Climatic Variability and Change: the Western Mountain Initiative'. Thanks to

Dr Claire Hay, Metropolitan State College of Denver, for helpful discussions and the GIS map in the present report. The manuscript has been considerably improved by suggestions by Waite Osterkamp, USGS, and Tom Lisle, USFS, and the insightful comments of two anonymous reviewers.

References

Agee JK (1990) The historical role of fire in Pacific Northwest forests. In 'Natural and Prescribed Fire in Pacific Northwest Forests'. (Eds JD Walstad, SR Radosevich, DV Sandberg) Ch. 3, pp. 25–38. (Oregon State University Press: Corvallis, OR)

Anderson HW (1974) Sediment deposition in reservoirs associated with rural roads, forest fires, and catchment attributes. In 'Effects of Man of the Interface of the Hydrological Cycle with the Physical Environment Symposium', International Association of Hydrological Sciences, Publication No. 113, pp. 85–95. (Wallingford, UK)

Anderson HW, Coleman GB, Zinke PJ (1959) Summer slides and winter scour – dry–wet erosion in Southern California Mountains. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Technical Paper Number 36, 1–12. (Berkeley, CA)

Bachelet D, Lenihan JM, Neilson RP (2007) Wildfires and global climate change: The importance of climate change for future wildfire scenarios in the Western United States. Excerpted from the full report in 'Regional Impacts of Climate Change: Four Case Studies in the United States'. (Pew Center on Global Climate Change: Arlington, VA) Available at http://www.pewclimate.org/docUploads/Regional-Impacts-West.pdf [Verified 23 January 2009]

Bagnold RA (1954) 'The Physics of Blown Sand and Desert Dunes.' (Methuen & Co.: London)

Benavides-Solorio JD, 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

Benavides-Solorio JD, MacDonald LH (2005) Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire* **14**, 457–474. doi:10.1071/WF05042

Benda L, Dunne T (1997) Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* **33**(12), 2865–2880. doi:10.1029/97WR02387

Benda L, Miller D, Bigelow P, Andras K (2003) Effects of post-wildfire erosion on channel environments, Boise River, Idaho. *Forest Ecology and Management* **178**, 105–119. doi:10.1016/S0378-1127(03)00056-2

Bennett KA (1982) Effects of slash burning on surface soil erosion rates in the Oregon Coast Range. MSc thesis, Oregon State University, Corvallis.

Bolin SB, Ward TJ (1987) Recovery of a New Mexico drainage basin from a forest fire. In 'Proceedings of the Vancouver Symposium on Forest Hydrology and Watershed Management', August 1987, Vancouver, BC. International Association of Hydrological Sciences, Publication No. 167, pp. 191–198. (Wallingford, UK)

Booker FA (1998) Landscape and management response to wildfires in California. MSc(Geology) thesis, University of California, Berkeley.

Booker FA, Dietrich WE, Collins LM (1993) Runoff and erosion after the Oakland Firestorm – expectations and observations. *California Geology* **46**(6), 159–173.

Booker FA, Dietrich WE, Collins LM (1995) The Oakland Hills Fire of 20 October 20 [sic, 1991]: An evaluation of post-fire response. In 'Brushfires in California Wildlands: Ecology and Resource Management'. (Eds JE Keeley, T Scott) pp. 163–170. (International Association of Wildland Fire: Fairfield, WA)

Brown PM, Kaye MW, Huckaby LS, Baisan CH (2001) Fire history along environmental gradients in the Sacramento Mountains, New Mexico: Influences of local patterns and regional processes. *Ecoscience* **8**, 115–126.

Brown TJ, Hall BL, Westerling AL (2004) The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. *Climatic Change* **62**, 365–388. doi:10.1023/B:CLIM.0000013680.07783.DE

Bruington AE (1982) Fire-loosened sediment menaces the city. In 'Proceedings of the Symposium on Dynamics and Management of Mediterranean-type Ecosystems'. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-58, pp. 420–422. (Berkeley, CA)

Bull WB (1991) 'Geomorphic Responses to Climate Change.' (Oxford University Press: New York)

Campbell RE, Baker MB, Jr, Ffolliott PF, Larson FR, Avery CC (1977) Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Paper RM-191. (Fort Collins, CO)

Cannon SH, Powers PS, Pihl RA, Rogers WP (1995) Preliminary evaluation of the fire-related debris flows on Storm King Mountain, Glenwood Springs, Colorado. US Geological Survey, Open-File Report 95–508. (Denver, CO)

Cannon SH, Bigio ER, Mine E (2001) A process for fire-related debris flow initiation, Cerro Grande fire, New Mexico. *Hydrological Processes* **15**, 3011–3023. doi:10.1002/HYP.388

Colby BR, Hembree CH, Rainwater FH (1956) Sedimentation and chemical quality of surface waters in the Wind River Basin, Wyoming. US Geological Survey, Water-Supply Paper 1373. (Washington, DC)

Colman EA (1951) Fire and water in southern California's mountains. USDA, California Forest and Range Experiment Station, Miscellaneous Paper No. 3. (Berkeley, CA)

Collins LM, Ketcham B (2001) Fluvial geomorphic response of a northern California coastal stream to wildfire. National Park Service, Point Reyes National Seashore. (Berkeley, CA)

Copeland OL, Jr (1965) Land use and ecological factors in relation to sediment yields. In 'Proceedings of the Federal Interagency Sedimentation Conference', 28 January–1 February 1963, Jackson, MI. USDA Agricultural Research Service, Miscellaneous Publication No. 970, Paper No. 11, pp. 72–84.

Copeland OL, Jr, Croft AR (1962) The Dog Valley Flood of August 12, 1961. *Journal of Geophysical Research* **67**(4), 1633.

Covert SA, Robichaud PR, Elliot WJ, Link TE (2005) Evaluation of runoff prediction from WEPP-based erosion models for harvested and burned forest watersheds. *Transactions of the American Society of Agricultural Engineers* **48**(3), 1091–1100.

de la Fuente J (1990) Effects of the intense summer storms at Kanaka and Olsen Creeks, Salmon River Ranger District. USDA Forest Service, Klamath National Forest, Reply to 2550/2880. (Yreka, CA)

DeBano LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **231–232**, 195–206. doi:10.1016/S0022-1694(00)00194-3

DeBano LF, Conrad CE (1976) Nutrients lost in debris and runoff water from a burned chaparral watershed. In 'Proceedings of the Third Federal Interagency Sedimentation Conference', 22–25 March 1976, Denver, CO. (Eds Subcommittee on Hydrology) pp. 3–13 to 3–29. (Sedimentation Committee Water Resources Council)

DeBano LF, Neary DG, Ffolliott PF (1998) 'Fire's Effects on Ecosystems.' (Wiley: New York)

DeBano LF, Neary DG, Ffolliott PF (2005) Soil physical properties. In 'Wildland Fire in Ecosystems: Effects of Fire on Soil and Water'. (Eds DG Neary, KC Ryan, FL DeBano) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42-vol. 4, Ch. 2, pp. 29–51. (Ogden, UT)

Dedkov AP, Moszherin VI (1992) Erosion and sediment yield in mountain regions of the world. In 'Erosion, Debris Flows and Environment in Mountain Regions: Symposium Proceedings', July 1992, Chengdu, China. (Eds DE Walling, TR Davies, B Hasholt) International Association of Hydrological Sciences, Publication No. 209, pp. 29–36. (Wallingford, UK)

Desilets SLE, Nijssen B, Ekwurzel B, Ferré TPA (2007) Post-wildfire changes in suspended sediment rating curves: Sabino Canyon, Arizona. *Hydrological Processes* **21**, 1413–1423. doi:10.1002/HYP.6352

Doehring DO (1968) The effect of fire on geomorphic processes in the San Gabriel Mountains, California. In 'Contributions to Geology', Vol. 7(1). (Ed. RB Parker) pp. 43–65. (University of Wyoming: Laramie, WY)

Doerr SH (1998) On standardizing the 'water drop penetration time' and the 'molarity of an ethanol droplet' techniques to classify soil hydrophobicity: A case study using medium-texture soils. *Earth Surface Processes and Landforms* **23**, 663–668. doi:10.1002/(SICI)1096-9837(199807)23:7<663::AID-ESP909>3.0.CO;2-6

Doerr SH, Shakesby RA, Blake WH, Chafer CJ, Humphreys GS, Wallbrink PJ (2006) Effects of differing wildfire severities on soil wettability and implications for hydrological response. *Journal of Hydrology* **319**, 295–311. doi:10.1016/J.JHYDROL.2005.06.038

Eaton EC (1936) Flood and erosion control problems and their solution. *Transactions American Society of Civil Engineers* **101**, 1302–1362. [Paper No. 1950]

Elliot WJ, Liebenow AM, Laflen JM, Kohl KD (1989) A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments 1987 and 88. Ohio State University and USDA Agricultural Research Service, National Soil Erosion Research Laboratory Report No. 3, Parts A & B. (Columbus, OH)

Ewing R (1996) Post-fire suspended sediment from Yellowstone National Park, Wyoming. *Water Resources Bulletin* **32**(3), 605–627.

Favis-Mortlock DT, Savabi MR (1996) Shifts in rates and spatial distributions of soil erosion and deposition under climate change. In 'Advances in Hillslope Processes', Vol. 1. (Eds MG Anderson, SM Brooks) pp. 529–560. (Wiley: New York)

Flanagan DC, Nearing MA (1995) USDA-Water Erosion Prediction Project, Hillslope profile and watershed model documentation. USDA-ARS National Soil Erosion Research Laboratory, National Soil Erosion Research Laboratory Report No. 10. (West Lafayette, IN)

Flannigan MD, Stocks BJ, Wotton BM (2000) Climate change and forest fires. *The Science of the Total Environment* **262**, 221–229. doi:10.1016/S0048-9697(00)00524-6

Florsheim JL, Keller EA, Best DW (1991) Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California. *Geological Society of America Bulletin* **103**, 504–511. doi:10.1130/0016-7606(1991)103<0504:FSTIRT>2.3.CO;2

Gabet EJ (2003) Sediment transport by dry ravel. *Journal of Geophysical Research* **108**(B1), 2049. doi:10.1029/2001JB001686

Gabet EJ, Dunne T (2003) Sediment detachment by rain power. *Water Resources Research* **39**(1), 1002. doi:10.1029/2001WR000656

Glendening GE, Pase CP, Ingebo P (1961) Preliminary hydrologic effects of wildfire in chaparral. In 'Modern Techniques in Water Management, Proceedings of Fifth Annual Arizona Watershed Symposium', September 1961, pp. 12–15. (Arizona Water Resources Committee)

Gottfried GJ, Neary DG, Malchus BB, Jr, Ffolliott PF (2003) Impacts of wildfires on hydrologic processes in forest ecosystems: two case studies. In 'Proceedings, First Interagency Conference on Research in the Watersheds', 27–30 October 2003, Benson, AZ. (Eds KG Renard, SA McElroy, WJ Gburek, HE Canfield, RL Scott) USDA Agricultural Research Service, pp. 668–673. Available at http://www.tucson.ars.ag.gov/ICRW/Proceedings/Gottfried.pdf [Verified 23 January 2009]

Gundarlahalli JR (1990) Chemical and biological characteristics of Grace Coolidge and Bear Gulch Creeks after the Galena Forest Fire in Custer State Park, South Dakota. MSc(Civil Engineering) thesis, South Dakota School of Mines and Technology, Rapid City, SD.

Hairsine PB (1988) A physically based model of the erosion of cohesive soils. PhD thesis, Griffith University, Brisbane.

Hartley DM, Julien PY (1992) Boundary shear stress induced by raindrop impact. *Journal of Hydraulic Research* **30**(3), 341–359.

Heimsath AM, Dietrich WE, Nishiizumi K, Finkel RC (1997) The soil production function and landscape equilibrium *Nature* **388**, 358–361. doi:10.1038/41056

Helvey JD (1980) Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* **16**(4), 627–634. [Paper No. 79119]

Hembree CH, Colby BR, Swenson HA, Davis JR (1952) Sedimentation and chemical quality of water in the Powder River drainage basin, Wyoming and Montana. US Geological Survey Circular C170. Available at http://pubs.er.usgs.gov/usgspubs/cir/cir170 [Verified 18 January 2009]

Hendricks BA, Johnson JM (1944) Effects of fire on steep mountain slopes in central Arizona. *Journal of Forestry* **42**, 568–571.

Hershfield DM (1961) Rainfall Frequency Atlas of the United States for Duration from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years. US Department of Commerce, Technical Paper No. 40 (Washington, DC).

Hirschboeck KK (1991) Climate and floods. In 'National Water Summary 1988–89: Hydrologic Events and Floods and Droughts'. (Eds RW Paulson, EB Chase, RS Roberts, DW Moody) US Geological Survey, Water-Supply Paper 2375, pp. 67–88. (Reston, VA)

Holden ZA, Morgan P, Crimmins MA, Steinhorst RK, Smith AMS (2007) Fire season precipitation variability influences fire extent and severity in a large south-western wilderness area, United States. *Geophysical Research Letters* **34**, L16708. doi:10.1029/2007GL030804

Hopkins W, Bentley J, Rice R (1961) Research and a land management model for southern California watersheds. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Miscellaneous Paper No. 56. (Berkeley, CA)

Hostetler SW, Bartlein PJ, Solomon AM, Holman JO, Busing RT, Shafter SL (2005) Climate controls of fire in the western United States: from the atmosphere to ecosystems. Joint Fire Science Program, Final report for Project 01–1-6–05. (Boise, ID)

Johansen MP, Hakonson TE, Breshears DD (2001) Post-fire runoff and erosion from rainfall simulation: contrasting forest with shrublands and grasslands. *Hydrological Processes* **15**, 2953–2965. doi:10.1002/HYP.384

Karl TR, Knight RW (1998) Secular trends of precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorological Society* **79**(2), 231–241. doi:10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2

Kaye MW, Swetnam TW (1999) An assessment of fire, climate, and Apache history in the Sacramento Mountains, New Mexico. *Physical Geography* **20**(4), 305–330.

Keller EA, Valentine DW, Gibbs DR (1997) Hydrological response of small watersheds following the southern California Painted Cave Fire of June 1990. *Hydrological Processes* **11**, 401–414. doi:10.1002/(SICI)1099-1085(19970330)11:4<401::AID-HYP447>3.0.CO;2-P

Key CH, Benson NC (2005) Landscape assessment: ground measure of severity, the Composite Burn Index; and remote sensing of severity, the Normalized Burn Ratio. In 'FIREMON: Fire Effects Monitoring and Inventory System'. (Eds DC Lutes, RE Keane, JF Caratti, CH Key, NC Benson, S Sutherland, LJ Gangi) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-164-CD, LA1–51. (Ogden, UT)

Kincer JB (1919) The seasonal distribution of precipitation and its frequency and intensity in the United States. *Monthly Weather Review* **47**(9), 624–631. doi:10.1175/1520-0493(1919)47<624:TSDOPA>2.0.CO;2

Knowles N, Dettinger MD, Cayan DR (2006) Trends in snowfall versus rainfall in the western United States. *Journal of Climate* **19**, 4545–4559. doi:10.1175/JCLI3850.1

Knox JC (1993) Large increases in flood magnitude in response to modest changes in climate. *Nature* **361**, 430–432. doi:10.1038/361430A0

Kraebel CJ (1934) The La Cresenta Flood, real origin of California's New Year catastrophe traced to mountain slopes recently swept by fire. *American Forests* (June), 251–287.

Krammes JS (1960) Erosion from mountain-side slopes after fire in southern California. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Research Note No. 171. (Berkeley, CA)

Krammes JS (1965) Seasonal debris movement from steep mountainside slopes in southern California. In 'Proceedings of the Federal Interagency Sedimentation Conference', 28 January–1 February 1963, Jackson, MS. USDA Agricultural Research Service, Miscellaneous Publication No. 970, pp. 85–88.

Krammes JS, Osborn J (1969) Water-repellent soils and wetting agents as factors influencing erosion. In 'Proceedings of the Symposium on Water-Repellent Soils', 6–10 May 1968. (Eds LF DeBano, J Letey) pp. 177–187. (University of California: Riverside, CA)

Krammes JS, Rice RM (1963) Effect of fire in the San Dimas Experimental Forest. In 'Proceedings 7th Annual Meeting Arizona Watershed Symposium', 18 September 1963, Phoenix, AZ. pp. 31–34.

Kunze MD, Stednick JD (2006) Streamflow and suspended sediment yield following the 2000 Bobcat Fire, Colorado. *Hydrological Processes* **20**, 1661–1681. doi:10.1002/HYP.5954

Lane LJ, Hernandez M, Nichols M (1997) Processes controlling sediment yield from watersheds as functions of spatial scale. *Environmental Modelling & Software* **12**(4), 355–369. doi:10.1016/S1364-8152(97)00027-3

Larsen IJ, Pederson JL, Schmidt JC (2006) Geologic versus wildfire controls on hillslope processes and debris flow initiation in the Green River canyons of Dinosaur National Monument. *Geomorphology* **81**, 114–127. doi:10.1016/J.GEOMORPH.2006.04.002

Lavine A, Kuyumjian GA, Reneau SL, Katzman D, Malmon DV (2006) A five-year record of sedimentation in the Los Alamos Reservoir, New Mexico, following the Cerro Grande Fire. In 'Proceedings of the Eighth Federal Interagency Sedimentation Conference and 3rd Federal Interagency Hydrologic Modeling Conference', April 2006, Reno, NV. Available at http://www.fws.gov/fire/ifcc/Esr/Library/LARsedimentaton.pdf [Verified 18 January 2009]

Legleiter CJ, Lawrence RL, Fonstad MA, Marcus WA, Aspinall R (2003) Fluvial response a decade after wildfire in the northern Yellowstone ecosystem: a spatially explicit analysis. *Geomorphology* **54**, 119–136. doi:10.1016/S0169-555X(02)00332-X

LeMaster DC, Guofan S, Donnay J (2007) Protecting Front Range (Colorado) forest watersheds from high-severity wildfires. An assessment by Pinchot Institute for Conservation for the Front Range Fuels Treatment Partnership. (Washington DC). Available at http://www.frftp.org/docs/FINAL_Protecting_Front_Range_Forest_Watersheds_081407.pdf [Verified 20 January 2009]

Letey J (1969) Measurement of contact angle, water drop penetration time, and critical surface tension. In 'Proceedings of the Symposium on Water-Repellent Soils'. 6–10 May 1968, University of California, Riverside. (Eds LF DeBano, J Letey) pp. 43–47. (University of California: Riverside, CA)

Malmon DV, Katzman D, Lavine A, Lyman JE, Reneau SL (2002) Sediment budget for a small canyon downstream of the Cerro Grande wildfire, New Mexico. In '2002 Denver Annual Meeting', 27–30 October 2002, Denver, CO. Geological Society of America, Paper No. 206-16. (Boulder, CO)

Malmon DV, Reneau SL, Katzman D, Lavine A, Lyman J (2007) Suspended sediment transport in an ephemeral stream following wildfire. *Journal of Geophysical Research* **112**, F02006. doi:10.1029/2005JF000459

Martin DA, Moody JA (2001) The flux and particle size distribution of sediment collected in hillslope traps after a Colorado wildfire. In 'Proceedings of the Seventh Federal Interagency Sedimentation Conference', 25–29 March 2001, Reno, NV. (CD-ROM) (Subcommittee on Sedimentation, Interagency Advisory Committee)

McNabb DH, Swanson FJ (1990) Effects of fire on soil erosion. In 'Natural and Prescribed Fire in the Pacific Northwest Forests'. (Eds JD Walstad, SL Radosenvich, DV Sanberg) Ch. 14, pp. 159–176. (Oregon State University Press: Corvallis, OR)

Megahan WF, Molitor DC (1975) Erosional effects of wildfire and logging in Idaho. In 'Proceedings: Symposium on Watershed Management by ASCE Irrigation and Drainage Division', 11–13 August 1975, Logan, UT. pp. 423–444. (American Society of Civil Engineers: New York)

Meyer GA, Wells SG (1997) Fire-related sedimentation events on alluvial fans, Yellowstone National Park, USA. *Journal of Sedimentary Research* **67**(5), 776–791.

Meyer GA, Pierce JL, Wood SH, Jull AJT (2001) Fire, storms, and erosional events in the Idaho batholith. *Hydrological Processes* **15**, 3025–3038. doi:10.1002/HYP.389

Meyer LD, Harmon WC (1984) Susceptibility of agricultural soils to interrill erosion. *Soil Science Society of America Journal* **48**, 1152–1157.

Milliman JD, Syvitski JPM (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *The Journal of Geology* **100**, 525–544.

Molnar P (2001) Climate change, flooding in arid environments and erosion rates. *Geology* **29**(12), 1071–1074. doi:10.1130/0091-7613(2001)029<1071:CCFIAE>2.0.CO;2

Montgomery DR, Brandon MT (2002) Topographic controls on erosion rates in tectonically active mountain ranges. *Earth and Planetary Science Letters* **201**, 481–489. doi:10.1016/S0012-821X(02)00725-2

Moody JA (2001) Sediment transport regimes after a wildfire in steep mountainous terrain. In 'Proceedings of the Seventh Federal Interagency Sedimentation Conference', 25–29 March 2001, Reno, NV. (CD-ROM) (Subcommittee on Sedimentation, Interagency Advisory Committee)

Moody JA, Kinner DA (2006) Spatial structures of stream and hillslope drainage networks following gully erosion after wildfire. *Earth Surface Processes and Landforms* **31**, 319–337. doi:10.1002/ESP.1246

Moody JA, Martin DA (2001*a*) Hydrologic and sedimentologic response of two burned watersheds in Colorado. US Geological Survey, Water Resources Investigation Report 10–4122. (Denver, CO)

Moody JA, Martin DA (2001*b*) 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 (2001*c*) Post-fire, rainfall intensity–peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes* **15**, 2981–2993. doi:10.1002/HYP.386

Moody JA, Martin DA (2004) Wildfire impacts on reservoir sedimentation in the western United States. In 'Proceedings of the Ninth International Symposium of River Sedimentation', 18–21 October 2004, Yichang, China. pp. 1095–1102. (International Research and Training Center on Erosion and Sedimentation: Beijing, China)

Moody JA, Martin DA, Forest fire effects on geomorphic processes. In 'Restoration Strategies after Forest Fire'. (Eds A Cerdá, PR Robichaud) Ch. I.2. (Science Publishers, Inc.: Enfield, NH), in press.

Moody JA, Smith DJ, Ragan BW (2005) Critical shear stress for erosion of cohesive soils subjected to temperature typical of wildfires. *Journal of Geophysical Research* **110**, F01004. doi:10.1029/2004JF000141

Moody JA, Martin DA, Haire SL, Kinner DA (2007) Linking runoff response to burn severity after wildfire. *Hydrological Processes* **22**, 2063–2074. doi:10.1002/HYP.6806

Moody JA, Martin DA, Cannon SH (2008) Post-wildfire erosion response in two geologic terrains in the western USA. *Geomorphology* **95**, 103–118. doi:10.1016/J.GEOMORPH.2007.05.011

Munns EN (1920) Chaparral cover, run-off, and erosion. *Journal of Forestry* **XVIII**(3), 806–814.

Mutchler CK, Murphree CE, McGregor KC (1994) Laboratory and field plots for erosion research. In 'Soil Erosion Research Methods'. (Ed. R Lal) Ch. 2, pp. 11–37. (Soil and Water Conservation Society: Ankeny, IO)

Natural Resources Conservation Service (2007) US General Soil Map (STATSGO) for State. (US Department of Agriculture) Available at http://soildatamart.nrcs.usda.gov [Verified July 2007]

Nearing MA, Norton LD, Bulgakov DA, Larionov GA, West LT, Dontsova KM (1997) Hydraulics and erosion in eroding rills. *Water Resources Research* **33**(4), 865–876. doi:10.1029/97WR00013

Neary DG, Ryan KC, DeBano FL, Landsberg JD, Brown JK (2005) Chapter 1: Introduction. In 'Wildland Fire in Ecosystems: Effects of Fire on Soil and Water'. (Eds DG Neary, KC Ryan, FL DeBano) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42-vol. 4. (Ogden, UT)

NOAA (2002) Monthly station normals of temperature, precipitation, and heating and cooling degree days 1971–2000. National Oceanic and Atmospheric Administration, Climatography of the United States No. 81. (Ashville, NC)

Nobel EL, Lundeen LJ (1971) Analysis of rehabilitation treatment alternatives for sediment control. In 'Proceedings of A Symposium on Forest Land Uses and Stream Environment', 19–21 October 1970, Corvallis, OR. pp. 86–96. (Oregon State University: Corvallis, OR)

Peters DPC, Havstad KM (2006) Non-linear dynamics in arid and semiarid systems: interactions among drivers and processes across scales. *Journal of Arid Environments* **65**, 196–206. doi:10.1016/J.JARIDENV.2005.05.010

Phillips JD (2003) Sources of non-linearity and complexity in geomorphic systems. *Progress in Physical Geography* **27**(1), 1–23. doi:10.1191/0309133303PP340RA

Pierson FB, Robichaud PR, Spaeth KE (2001) Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. *Hydrological Processes* **15**, 2905–2916. doi:10.1002/HYP.381

Pietraszek JH (2006) Controls on post-fire erosion at the hillslope scale, Colorado Front Range. MSc thesis, Colorado State University, Fort Collins.

Poesen JWA (1993) Mechanisms of overland flow generation and sediment production on loamy and sandy soils with and without rock fragments. In 'Overland Flow; Hydraulics and Erosion Methods'. (Eds AJ Parsons, AD Abrahams) pp. 275–305. (Chapman Hill: New York)

Poesen JWA, Savat J (1981) Detachment and transportation of loose sediments by raindrop splash, part II. Detachability and transportability measurements. *Catena* **8**, 19–41. doi:10.1016/S0341-8162(81)80002-1

Potts DF, Peterson DL, Zuuring HR (1985) Watershed modeling for fire management planning in the northern Rocky Mountains. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Research Paper PSW-177. (Berkeley, CA)

Radek KJ (1996) Soil erosion following wildfires on the Okanogan National Forest: initial monitoring results. In 'Erosion Control Technology ... Bringing It Home, Proceedings of Conference XXVII', 27 February–1 March 1996, Seattle, WA. pp. 499–504. (International Erosion Control Association)

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). US Department of Agriculture, Agriculture Handbook No. 703. (Washington, DC)

Reneau SL, Dietrich WE (1991) Erosion rates in the southern Oregon Coast Range: evidence for equilibrium between hillslope erosion and sediment yield. *Earth Surface Processes and Landforms* **16**, 307–322. doi:10.1002/ESP.3290160405

Reneau SL, Kuyumjian GA (2004) Rainfall–runoff relations in Pueblo Canyon, New Mexico, after the Cerro Grande Fire. US Department of Energy, National Nuclear Security Administration, Los Alamos National Laboratory, Report LA-UR-04–8810. (Los Alamos, NM)

Rice RM (1974) The hydrology of chaparral watersheds. In 'Proceedings of Symposium on Living with the Chaparral', 30–31 March 1973, Riverside, CA. (Ed. M Rosenthal) Ch. 4, pp. 27–33. (Sierra Club: Riverside, CA)

Rice RM (1982) Sedimentation in the chaparral: how do you handle unusual events? In 'Workshop on Sediment Budgets and Routing in Forested Drainage Basins'. (Tech. Eds FJ Swanson, RJ Janda, T Dunne, DN Swanston) USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-141, pp. 39–49. (Portland, OR)

Rich LR (1962) Erosion and sediment movement following a wildfire in a ponderosa pine forest of central Arizona. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Notes No. 76. (Fort Collins, CA)

Robichaud PR (2000) Forest fire effects on hillslope erosion: what we know. *Watershed Management Council Networker* **9**(1). Available online at http://watershed.org/news/win_00/2_hillslope_fire.htm [Verified 18 January 2009]

Robichaud PR, Brown RE (1999) What happened after the smoke cleared: onsite erosion rates after a wildfire in eastern Oregon. In 'Proceedings AWRA Specialty Conference Wildland Hydrology', 30 June–2 July 1999, Bozeman, MT. (Eds DS Olson, JP Potyondy) pp. 419–426. (American Water Resources Association: Herndon, VA)

Robichaud PR, Waldrop TA (1994) A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. *Water Resources Bulletin* **30**(1), 27–34. [Paper No. 93019]

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)

Robichaud PR, Pierson FB, Brown RE, Wagenbrenner JW (2007) Measuring effectiveness of three post-fire hillslope erosion barrier treatments, western Montana, USA. *Hydrological Processes* **22**(2), 159–170. doi:10.1002/HYP.6558

Robichaud PR, Wagenbrenner JW, Brown RE, Wohlgemuth PM, Beyers JL (2008) Evaluating the effectiveness of contour-felled log erosion barriers as a post-fire runoff and erosion mitigation treatment in the western United States. *International Journal of Wildland Fire* **17**, 255–273. doi:10.1071/WF07032

Roering JJ, Gerber M (2005) Fire and the evolution of steep, soil-mantled landscapes. *Geology* **33**(5), 349–352. doi:10.1130/G21260.1

Rose CW, Williams JR, Sander GC, Barry DA (1983) A mathematical model of soil erosion and deposition processes: I. Theory for a plane land element *Soil Science Society of America Journal* **47**, 991–995.

Rowe PB (1948) Influence of woodland chaparral on water and soil in central California. USDA Forest Service, California Forest and Range Experiment Station. (CA)

Rowe PB, Countryman CM, Storey HC (1949) Probable peak discharges and erosion rates from southern California watersheds as influenced by fire. USDA Forest Service, California Forest and Range Experiment Station. (Berkeley, CA)

Rowe PB, Countryman CM, Storey HC (1954) Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in southern California watersheds. USDA Forest Service, California Forest and Range Experiment Station. (Berkeley, California)

Sampson AW (1944) Effect of chaparral burning on soil erosion and on soil-moisture relations. *Ecology* **25**(2), 171–191. doi:10.2307/1930690

San Dimas Experimental Forest Staff (1954) Fire–flood sequences on the San Dimas Experimental Forest. USDA Forest Service, California Forest and Range Experiment Station, Technical Paper No. 6. (Berkeley, CA)

Santi PM, deWolfe VG, Higgins JD, Cannon SH, Gartner JE (2007) Sources of debris flow material in burned areas. *Geomorphology* **96**(3–4), 310–321. doi:10.1016/J.GEOMORPH.2007.02.022

Sartz RS (1953) Soil erosion on a fire-denuded forest area in the Douglas-fir region. *Journal of Soil and Water Conservation* **8**(6), 279–281.

Schmidt JC (1990) Watershed response to timber harvest and subsequent wildfire, South Fork Cow Creek, Oregon. US Geological Survey, Cascades Volcano Observatory, Informal Report. (Vancouver, WA)

Schneider SH (2004) Abrupt non-linear climate change, irreversibility and surprise. *Global Environmental Change Part A* **14**, 245–258. doi:10.1016/J.GLOENVCHA.2004.04.008

Schumm SA (1973) Geomorphic thresholds and complex response of drainage systems. In 'Fluvial Geomorphology: a Proceedings Volume of the Fourth Annual Geomorpholgy Symposia Series', 27–28 September 1973, Binghamton, NY. (Ed. M Morisawa) Ch. 13, pp. 299–310. (State University of New York: Binghamton, NY)

Schumm SA, Lichty RW (1965) Time, space, and causality in geomorphology. *American Journal of Science* **263**, 110–119.

Schwarz KM (1997) Variable hillslope erosion in a post-fire chaparral environment. In 'AGU 1997 Fall Meeting', 8–12 December 1997, San Francisco, CA. Abstract H51A-15. (American Geophysical Union)

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

Smith DM (1994) The forests of the United States. In 'Regional Silviculture of the United States', 3rd edn (Ed. JW Barrett) pp. 1–30. (Wiley: New York)

Spigel KM, Robichaud PR (2007) First-year post-fire erosion rates in Bitterroot National Forest, Montana. *Hydrological Processes* **21**, 998–1005. doi:10.1002/HYP.6295

Swanson FJ (1981) Fire and geomorphic processes. In 'Proceedings of the Conference on Fire Regimes and Ecosystem Properties', 11–15 December 1978, Honolulu, HI. (Eds HA Mooney, TM Bonnicksen, NL Christensen, JE Lotan, WA Reiners) USDA Forest Service, General Technical Report WO-26, pp. 401–420. (Washington, DC)

Swanson FJ, Benda LE, Duncan SH, Grant GE, Megahan WR, Reid LM, Ziemer RR (1987) Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. In 'Streamside Management: Forestry and Fishery Interactions, Proceedings', 12–14 February 1986, Seattle, WA. (Eds EO Salo, TW Cundy) Ch. 2, Contribution 57. (University of Washington, Institute of Forest Resources: Seattle, WA)

Swanson FJ, Johnson SL, Gregory SV, Acker SA (1998) Flood disturbance in a forested mountain watershed. *Bioscience* **48**(9), 681–689. doi:10.2307/1313331

Trimble SW (1976) Sedimentation in Coon Creek Valley, Wisconsin. In 'Proceedings of the Third Federal Interagency Sedimentation Conference', 22–25 March 1976, Denver, CO. pp. 5-100–5-112. (Water Resources Council: Washington, DC)

Troendle CA, Bevenger GS (1996) Effect of fire on streamflow and sediment transport, Shoshone National Forest, Wyoming. In 'Proceeding of the Second Biennial Conference on the Greater Yellowstone Ecosystem: the Ecological Implications of Fire in Greater Yellowstone', 19–21 September 1993, Yellowstone National Park, WY. (Ed. J Greenlee) pp. 43–52. (International Association of Wildland Fire: Fairfield, WA)

Troxell HC, Peterson JQ (1937) Flood in La Cañada Valley, California, January 1, 1934. US Geological Survey, Water-Supply Paper 796-C. (Washington, DC)

Van Burkalow A (1945) Angle of repose and angle of sliding friction: an experimental study. *Bulletin of the Geology Society of America* **56**, 669–707. doi:10.1130/0016-7606(1945)56[669:AORAAO]2.0.CO;2

Van de Water R (2000) Burned Area Emergency Rehabilitation report. US Forest Service, Klamath National Forest. (Yreka, CA)

Vanoni VA (1977) 'Sedimentation Engineering.' (American Society of Civil Engineers: New York)

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

Walling DE (1983) The sediment delivery problem. *Journal of Hydrology* **65**, 209–237. doi:10.1016/0022-1694(83)90217-2

Walling DE, Webb BW (1996) Erosion and sediment yield: a global overview. In 'Erosion and Sediment Yield: Global and Regional Perspectives, Proceedings of the Exeter Symposium', 15–19 July 1996, Exeter, UK. International Association of Hydrological Sciences, Publication No. 236, pp. 3–19. (Wallingford, UK)

Wells WG, II (1981) Some effects of brushfires on erosion processes in coastal southern California. In 'Erosion and Sediment Transport in Pacific Rim Steeplands', International Association of Hydrological Sciences, Publication No. 132, pp. 305–342. (Wallingford, UK)

Wells WG, II (1982) The storms of 1978 and 1980 and their effect on sediment movement in the eastern San Gabriel Front. In 'Storms, Floods, and Debris Flows in Southern California and Arizona 1978 and 1980, Proceedings of Symposium', 17–18 September 1980. pp. 229–242. (National Academy Press: Washington, DC)

Wells WG, II (1987) The effects of fire on the generation of debris flows in southern California. In 'Debris Flows/Avalanches: Process, Recognition and Mitigation; Reviews in Engineering Geology' vol. VII, (Eds JE Costa, GF Wieczorek) pp. 105–114. (Geological Society of America: Boulder, CO)

Wells SG, White W, Anderson S, Dingus PR (1978) Geomorphic effects of recent forest-fire devegetation, Frijoles Canyon Watershed, Bandelier National Monument, New Mexico. Final Grant Report for the National Park Service, Southwest Regional Office, Grant no. PX7029–7-0809. (University of New Mexico, Albuquerque, NM)

Welter SP (1995) Topographic influences on erosion and soil development in hollows of the Rampart Range, Colorado. PhD dissertation, University of Colorado, Boulder.

Whicker JJ, Pinder JE, III, Breshears DD (2006) Increased wind erosion from forest wildfire: implications for contaminant-related risks. *Journal of Environmental Quality* **35**, 468–478. doi:10.2134/JEQ2005.0112

Wohl EE, Pearthree PP (1991) Debris flows as geomorphic agents in the Huachuca Mountains of south-eastern Arizona. *Geomorphology* **4**, 273–292. doi:10.1016/0169-555X(91)90010-8

Wohlgemuth PM (2003) Hillslope erosion following the Williams Fire on the San Dimas Experimental Forest, Southern California. In 'Proceedings 2nd International Wildland Fire Ecology and Fire Management Congress', 16–20 November 2003, Orlando, FL. (American Meteorological Society: Orlando, FL) Available at http://ams.confex.com/ams/pdfpapers/67248.pdf [Verified 18 January 2009]

Wohlgemuth PM, Hubbert KR (2008) The effects of fire on soil hydrologic properties and sediment fluxes in chaparral steeplands, southern California. In 'Proceedings of the 2002 Fire Conference: Managing Fire and Fuels in the Remaining Wildlands and Open Spaces of the Southwestern United States', 2–5 December 2002, San Diego, CA. (Tech. Coord. MG Narog) USDA Forest Service, Pacific Southwest, Research Station, General Technical Report PSW-GTR-189, pp. 115–121. (Albany, CA)

Wohlgemuth PM, Beyers JL, Conard SG (1996) Post-fire hillslope erosion in southern California chaparral: a case study of prescribed fire as a sediment management tool. In 'Proceedings of the Symposium on Fire Economics, Planning, and Policy Bottom Lines', 5–9 April 1999, San Diego, CA. (Tech. Coords A González-Cabán, PN Omi) USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-173, pp. 269–276. (Albany, CA)

Wolman MG, Miller JP (1960) Magnitude and frequency of forces in geomorphic processes. *The Journal of Geology* **68**, 54–74.

Manuscript received 4 November 2007, accepted 15 May 2008