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Current research issues related to post-wildfire runoff and erosion processes

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ABSTRACT

Research into post-wildfire effects began in the United States more than 70 years ago and only later extended to other parts of the world. Post-wildfire responses are typically transient, episodic, variable in space and time, dependent on thresholds, and involve multiple processes measured by different methods. These characteristics tend to hinder research progress, but the large empirical knowledge base amassed in different regions of the world suggests that it should now be possible to synthesize the data and make a substantial improvement in the understanding of post-wildfire runoff and erosion response. Thus, it is important to identify and prioritize the research issues related to post-wildfire runoff and erosion. Priority research issues are the need to: (1) organize and synthesize similarities and differences in post-wildfire responses between different fire-prone regions of the world in order to determine common patterns and generalities that can explain cause and effect relations; (2) identify and quantify functional relations between metrics of fire effects and soil hydraulic properties that will better represent the dynamic and transient conditions after a wildfire; (3) determine the interaction between burned landscapes and temporally and spatially variable meso-scale precipitation, which is often the primary driver of post-wildfire runoff and erosion responses; (4) determine functional relations between precipitation, basin morphology, runoff connectivity, contributing area, surface roughness, depression storage, and soil characteristics required to predict the timing, magnitudes, and duration of floods and debris flows from ungaged burned basins; and (5) develop standard measurement methods that will ensure the collection of uniform and comparable runoff and erosion data. Resolution of these issues will help to improve conceptual and computer models of post-wildfire runoff and erosion processes.

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1. Introduction

The number and severity of wildfires in the United States and in other parts of the world have become a major concern in recent decades. This partly stems from second-order impacts and concerns about carbon storage, water quality, and ecosystem disturbance, but mostly from concerns related to the increases in population in or near wildfire-prone areas where post-wildfire enhanced runoff and erosion can result in catastrophic damage and loss of life by destructive floods and debris flows (Neary and Gottfried, 2002; Pausas et al., 2008). Post-wildfire responses tend to be disproportionately large compared to the size of the burned basin. For example, peak discharges can be as large as 300 $m^3\ s^{-1}\ km^{-2}$ (Brown, 1972; Moody and Martin, 2001a; Gartner et al., 2004; Moody et al., 2008a; Smith et al., 2011a), which is comparable to and in some cases greater than the maximum rainfall–runoff floods in unburned conditions (Costa, 1987). Furthermore, the impacts of climate change on wildfire ignitions and behavior have been actively researched for some time (Flannigan et al., 2000; Westerling et al., 2003; Bachelet et al., 2007; Littell et al., 2009; Moritz et al., 2010; Westerling et al., 2011), but the implications for post-wildfire runoff and erosion are only now being explored (Pierce and Meyer, 2008; Moody and Martin, 2009a; Goode et al., 2012).

Continued progress in understanding and predicting post-wildfire runoff and erosion processes is hindered by a number of limitations. First, the responses of burned areas are transient, often lasting less than 7 years, depending on various aspects, notably the speed of vegetation recovery, post-wildfire weather conditions, sediment availability, and basin morphology (Rowe et al., 1954; Cerdà, 1998a; Moody and Martin, 2001b; Gartner et al., 2004; Shakesby et al., 2007; Sheridan et al., 2007; Cannon et al., 2010). Such a transient response limits the duration of the research window (Moody and Martin, 2009b) so that most studies are focused on the first few years after a wildfire limiting the acquisition of sufficient data to establish the statistical significance of observed physical relations. Second, the high-magnitude responses tend to be episodic and destructive with relatively short time scales of minutes to hours that make collection of field data difficult. Third, the response can depend upon the sequence of rainstorms of differing magnitudes (Germanoski et al., 2002; Moody et al., 2008a) making data interpretation complicated. Additionally, completely burned basins are often relatively small (hectares to a few tens of km^2 in size; Gartner et al., 2004), and nested within much larger regional basins. As a result, they can be affected by meso-scale (~1–10^4 km^2), short-duration and spatially variable precipitation. Such precipitation cells are frequently embedded within larger-scale regional precipitation patterns. To date, the characteristics of these storms have been far less predictable than those of regional larger-scale and longer-duration precipitation. Fourth, runoff and erosion from recently burned hillslopes do not always lead to significant floods or major erosion events such as debris flows, either due to inadequate rainfall or limiting geomorphic conditions (Cannon et al., 2001a, 2003; Larsen, 2003; Pausas et al., 2008; Robichaud et al., 2008a; Cannon et al., 2010). Runoff and erosion are unsteady (variable in time) and non-uniform (variable in space) processes, so that existing theories and methods developed for steady, uniform flows responding to steady, uniform precipitation must first be modified (Candela et al., 2005; Moody and Martin, 2009b). Fifth, the hydrological and geomorphic processes are typically non-linear and thus controlled by numerous physical thresholds (such as infiltration-excess overland flow and debris flow initiation), which add to the complexity. And lastly, investigations have been confounded by a multiplicity of measurement methods and scales, making comparisons between studies difficult (Shakesby and Doerr, 2006; Moody and Martin, 2009a).

A spectrum of post-wildfire hydrologic and sedimentologic responses ranging from no response to catastrophic floods, deadly debris flows, and damaging sedimentation has been documented in many different locations throughout the world (Rowe et al., 1954; Brown, 1972; Helvey, 1980; Scott and van Wyk, 1992; Shakesby et al., 1993; Cerdà, 1998a; Prosser and Williams, 1998; Conedera et al., 2003; Nishimune et al., 2003; Coelho et al., 2004; Lane et al., 2006; Tomkins et al., 2008; Silins et al., 2009; Cerdà and Robichaud, 2009; Dunkerley et al., 2009; Shin, 2010; Shakesby, 2011), and has provided a wealth of empirical data. A few of these field studies strive to understand and predict the underlying processes, but most have not (Larsen et al., 2009, p. 1394). The inability to accurately predict post-wildfire responses given all the different conditions such as rainfall characteristics, soil properties, and basin morphology (as summarized, for example by Shakesby and Doerr, 2006; Pausas et al., 2008; Moody and Martin, 2009a) highlights the need to organize these empirical data according to similarities to provide better understanding of post-wildfire processes. Better understanding of the processes will lead to improved predictive capabilities of post-wildfire models.

The purpose of this review is therefore twofold: first, to suggest an organizing framework to help synthesize the data by identifying common patterns and generalities that will help discover physical reasons for differences in responses, and second to identify priority research issues whose resolution will advance our understanding of the four major processes (precipitation, infiltration, runoff, and soil and sediment erosion and transport) controlling post-wildfire runoff and erosion responses.

2. Framework for organizing post-wildfire runoff and erosion responses

We propose an organizational framework that first groups the wide range of post-wildfire hydrologic and geomorphic responses into post-wildfire response domains. These domains are conceptually composed of a fire regime, precipitation regime, and hydro-geomorphic regime with broadly similar ranges of quantifiable metrics. The ultimate goal is to organize and synthesize the vast amount of empirical data from different post-wildfire domains in order to better understand each process, the reasons for differences in response, and to specifically predict, as close to real time as possible, the post-wildfire runoff and erosion response after new wildfires in any post-wildfire domain.

2.1. Fire regimes

Fire regimes are derived from fire behavior characteristics and effects (Agee, 1993; Neary et al., 2005). Characteristics include the temporal distributions (i.e. recurrence interval and fire duration), the spatial distribution (i.e. area affected and pattern), and the behavior (i.e. type of fire, combustion process, and vegetative type) (Neary et al., 2005; Krebs et al., 2010). Dominant drivers of fire behavior vary according to the different temporal and spatial scales (Whitlock et al., 2010a). Effects are most frequently assessed in relation to ecological (i.e. vegetation mortality and fire severity) and socio-economic (i.e. cost and damage to property) consequences (Krebs et al., 2010), but there has been little focus on the hydrologic and sedimentologic consequences. Most fire regimes have been described in a semi-quantitative way by using a quantitative metric of fire interval (alternatively fire frequency, fire recurrence interval, or fire rotation) but only a qualitative description for either burn intensity (Heinselman, 1981) or burn severity (Hardy et al., 1998; Brown, 2000; Keeley, 2009). For a given general area, fire intervals can be estimated using the 'individual-tree approach', 'composite approach' (Baker and Ehle, 2001), or a function of area (frequency–area statistics, Malamud et al., 2005).

What is important for a post-wildfire response organizational framework is to identify those characteristics and effects of fire regimes that most directly affect hydrologic and sedimentologic responses and are readily available throughout the world. Fire intensity represents the energy released above ground and is not a good measure of the amount of heat transmitted into the soil (Neary et al., 2005). Burn severity generally has referred to ecological above-ground and below-ground effects (Neary et al., 2005). Burn severity does affect infiltration, runoff, and erosion, is patchy, and unfortunately is not readily available throughout the world. 'Depth of burn' is a metric that reflects the consumption of above-ground litter, duff, and woody material, which obstruct overland flow (Ryan, 2002); however, it is a qualitative metric. Soil temperature has been shown to have direct effects on chemical transformations and losses (Giovannini and Lucchesi, 1983; Giovannini et al., 1988), organic matter destruction, seed and plant mortality, water loss (Ryan, 2002), and soil erodibility (Moody et al., 2005). Soil temperature would be an ideal quantifiable metric; however, direct quantitative measurements of soil temperature are nearly impossible to make during wildfires in contrast to prescribed fires (Bento-Gonçalves et al., 2012), and thus, researchers have resorted to indirect qualitative metrics such as depth of burn and visual indicators of soil burn severity (Parsons et al., 2010). Post-wildfire hydrologic and geomorphic responses have been related to fire recurrence intervals (Swanson, 1981; Loomis et al., 2003; Shakesby and Doerr, 2006), and fire recurrence intervals are readily available so this metric seems to be the best quantifiable metric to characterize fire regimes for the purpose of an organizational framework. Estimates of fire intervals have been based on alluvial chronology (Meyer et al., 1995; Bigio et al., 2010), lake sediments (Roering and Gerber, 2005; Turner et al., 2008; Vannière et al., 2008; Whitlock et al., 2008), dendrochronology (Veblen et al., 2000; Heyerdahl and Alvarado, 2003; Kitzberger and Veblen, 2003; Swetnam and Baisan, 2003; Veblen et al., 2003), or frequency–area statistics (Nakagoshi et al., 1987 [Japan]; Archibald et al., 2005 [South Africa]; Díaz-Delgado et al., 2004 [Spain]; Malamud et al., 2005 [United States of America]; Jiang et al., 2009 [Canada]; Krawchuk and Moritz, 2009 [China]; O'Donnell et al., 2011 [Australia]; Berner et al., 2012 [Siberia], Kharuk et al., 2012 [Russia]; Sass et al., 2012a [Switzerland]; Tessler, 2012 [Israel]). Fire intervals based on frequency–area statistics are then given for a specified size or area of the wildfire, $A_F \geq 0.01$ km^2 or ≥ 10 km^2 (Malamud et al., 2005; Jiang et al., 2009). We refer the reader to several recent efforts to refine the fire-regime concept and to develop models to understand fire–climate interactions and socio-economic effects (e.g. Whitlock et al., 2010b; Bowman et al., 2011; Murphy et al., 2011). Fire intervals are affected by human population distribution and land use (Veblen et al., 2000; Pausas and Fernández-Muñoz, 2011; Pezzatti et al., 2011) and climate changes (Baker, 2003; Swetnam and Baisan, 2003; Roering and Gerber, 2005; Whitlock et al., 2010b; Pausas and Fernández-Muñoz, 2011), but the fire recurrence intervals probably will not change appreciably within the next decade, which is the intended timeframe of this review.

2.2. Precipitation regimes

Precipitation is the important driver of post-wildfire response. Quantifying precipitation regimes appears easier than fire regimes because of the numerous available metrics (see Section 3.2 for examples), yet deciding which metrics relate best to post-wildfire responses is more difficult. They include interval metrics that quantify temporally varying characteristics (such as total precipitation depth, intensity, duration, and recurrence intervals), sequence metrics that characterize the temporal sequencing of rainfall (Germanoski et al., 2002; Dunkerley, 2011), spatial metrics (such as extent and gradient of rainfall intensity), the type of precipitation (convective storm, cyclonic storm, hail, snow, and rain-on-snow), scale similarity (Menabde et al., 1997; Harris et al., 1998), and space–time properties (Eagleson and Shack, 1966; Venugopal et al., 1999; Bernardara et al., 2003). Depth–duration–frequency analysis characterizes rainfall regimes as the probable depth that would accumulate during rain storms with a duration of m-hours and a frequency of once per n-years (recurrence interval, Hershfield, 1961; Miller et al., 1973; Pilgrim, 1987; Institution of Engineers, 1998; Brown et al., 2010; NOAA, 2012). Because of the large spatial scale, river flood predictions often are based on rainfall durations of several hours (typically 6- and 24-h) and longer recurrence intervals (10-, 50-, or 100-year) in order to characterize the less frequent, rare extreme flood, which can be more damaging and thus are of more concern. Post-wildfire floods and debris flows can be as damaging, but generally respond to much shorter duration (5-, 15-, or 30-min) and more frequent (1-, 2-, or 5-year recurrence intervals) rainfall because of the changes in the rainfall–runoff processes caused by burning (Shakesby and Doerr, 2006; Moody and Martin, 2009b). Numerous papers have reported that peak discharge and sediment flux correlate with maximum rainfall intensities that are 30-min or less in duration (Moody and Martin, 2001a; Kunze and Stednick, 2006; Mayor et al., 2007; Spigel and Robichaud, 2007; Cannon et al., 2008; Moody et al., 2008a; Robichaud et al., 2008a; Cannon et al., 2010; Dunkerley, 2010; Cannon et al., 2011; Kean et al., 2011; Moody, 2012; Robichaud et al., 2013a,b), and that low-recurrence interval rainstorms can produce floods that normally are associated with a high recurrence interval.

These low-recurrence intervals can be as short as 2-years (Moody and Martin, 2001a; Conedera et al., 2003; Reneau and Kuyumjian, 2004; Kunze and Stednick, 2006). While analysis based on 1-hour duration rainfall is common, those for durations of less than 1 h are not; however, relations between longer and shorter durations have been developed (Hershfield, 1961; Miller et al., 1973). Thus, we suggest that the 2-year, 30-minute rainfall intensity be used as a quantifiable metric to characterize rainfall regimes associated with post-wildfire responses.

2.3. Hydro-geomorphic regime

The hydro-geomorphic regime can be quantified by such metrics as topographic slope, soil hydraulic properties, soil and sediment erodibility, and sediment supply. Slope essentially represents the force of gravity that drives the hydrologic (infiltration and overland flow) and sedimentologic responses (detachment, transport, and deposition). Slope here refers to a topographic facet (Daly et al., 1994), which has approximately the same orientation or aspect, rather than a point measurement. Slope alone is insufficient to completely characterize the regime in that the erosion component depends primarily on soil erodibility (Elliot et al., 1989; Flanagan and Nearing, 1995; Foster et al., 1995; Moody et al., 2005; Mataix-Solera et al., 2011) and secondly on the volume of stored sediment or sediment supply. We agree with Bryan (2000, p. 408) that “soil erodibility is not a single, simply identified property” but feel that the soil erodibility factor (*K*-factor) used by the Revised Universal Soil Loss Equation (RUSLE) is a good first approximation for an organizational framework (Renard et al., 1997). Values of the *K* factor [L^{-3} T^3] are available for many regions throughout the world (Foster et al., 1981; van Rompaey et al., 2003; ASRIS, 2012), or can be predicted using the conventional soil erodibility nomograph (Wischmeier et al., 1971; Wischmeier and Smith, 1978), or alternatively, site-specific values can be calculated based on soil physical and chemical properties (Lu et al., 2001; Vaezi et al., 2011). Slope is easily computed for digital elevation models, but the appropriate horizontal scale needs to be selected to represent the process. These two variables can be combined into one by considering the usual form of the equation for soil detachment (Foster et al., 1977, 1995; Moody et al., 2005), $D = kx$, which assumes that the amount of eroded soil per unit area, D, is proportional to some driving force, rain energy, or flowing water, x (such as rain intensity, boundary shear stress or stream power) where the proportionality constant k is a form of the erodibility. Shear stress and stream power contain the slope, S, so that a possible hydro-geomorphic metric is the product of the soil erodibility *K*-factor and slope or *KS* [L^{-3} T^3].

2.4. Post-wildfire response domains

Post-wildfire response domains can be quantified by the fire recurrence interval; the 2-year, 30-minute rainfall intensity; and the erodibility-slope product. The three metrics proposed here have a precedent in that they are similar to those used by Swanson (1981, p. 411) “to rank ecosystems in terms of fire's potential for impacting geomorphic processes …” and to define a wildfire impact index based on physical principles of sediment transport (Moody and Martin, 2004). For example, in southern California the post-wildfire response frequently takes the form of sediment-laden floods and debris flows (Cannon et al., 2008, 2011; Kean et al., 2011; Schmidt et al., 2011; Robichaud et al., 2013b) and sediment-limited responses are rare. This domain has a Mediterranean-type climate, low elevation (maximum, 400 m), and fire-adapted chaparral vegetation with fire intervals < 10 years (Keeley et al., 2008). The precipitation regime typically comprises long-duration winter frontal storms with some embedded cells of high intensity rainfall (Pacific-Medium rainfall regime; median 2-year, 30-minute intensity of 30 mm h^{-1}: Moody and Martin, 2009a) and the hydro-geomorphic regime is tectonically active with steep, rugged mountain ranges with median slopes of 0.56 (Moody and Martin, 2009a), resulting in an abundance of erodible material (median erodibility 0.034 t-ha^{-1}/MJ ha^{-1} mm h^{-1}) and a median value of *KS* is 0.019 t-ha^{-1}/MJ ha^{-1} mm h^{-1}. In contrast, the montane ecosystems often dominated by lodgepole pine (*Pinus contorta*; elevation 2500–2700 m; Weber, 1976) in the intermountain western United States have experienced infrequent wildfires (fire interval is 300 to 600 years; Romme and Knight, 1981; Westerling et al., 2011) whereas in the foothill ecosystems often dominated by ponderosa pine (*Pinus ponderosa*; elevation 1800–2500 m; Weber, 1976) have experienced more frequent wildfires (fire interval is 15–40 years; Veblen et al., 2000). Most runoff and erosion in both ecosystems are a response to high-intensity convective storms during the summer season (median 2-year, 30-minute intensity is 23 mm h^{-1} for the 1988 Yellowstone Fire in the montane ecosystem and 33 mm h^{-1} for the foothill ecosystem along the Colorado Front Range; Hershfield, 1961; Moody and Martin, 2009a; Moody, 2012). In the volcanic areas burned by the 1988 Yellowstone Fire median slopes are 0.40, erodibility 0.016 t-ha^{-1}/MJ ha^{-1} mm h^{-1}, and *KS* is 0.0064 t-ha^{-1}/MJ ha^{-1} mm h^{-1} (Moody and Martin, 2009a). In the granitic core of the Front-range Mountains of Colorado, the median slopes for multiple burned areas are 0.31, median soil erodibility is 0.014 t-ha^{-1}/MJ ha^{-1} mm h^{-1}, and *KS* is 0.0043 t-ha^{-1}/MJ ha^{-1} mm h^{-1} (Moody and Martin, 2009a). These post-wildfire domains are less erodible than the southern California domains. Estimates of these quantifiable metrics can be plotted to identify domains with similar regime characteristics (Fig. 1) and maps showing the spatial variability of the three regimes for different wildfire prone areas in the world would be valuable as additional organizational aids.

Any specific post-wildfire response is composed of four major processes: precipitation, infiltration, runoff, and soil and sediment erosion and transport. These are linked by states (i.e. soil moisture and surface roughness) and by feedback mechanisms. For example, the land surface albedo changes after a wildfire (Wendt et al., 2007; Tryhorn et al., 2008; Montes-Helu et al., 2009; Beck et al., 2011). This may affect the precipitation process and precipitation changes soil moisture, which in turn affects runoff processes (Chen et al., 2001; Tryhorn et al., 2008). Prioritization of research issues in this review has been assessed based on the number of major processes that are dependent on the resolution of a research issue. Issues that involve feedback mechanisms (e. g. Sections 3.3, 3.4, and 6.1) increase their priority. Each process is discussed in a separate section of this review and can be read quasi-independently. Section 3 discusses precipitation, Section 4 covers infiltration and soil properties, Section 5 focuses on runoff, and Section 6 deals with soil and sediment erosion and transport processes. Future resolution of the priority issues in each section should provide specific quantitative physical relations for future modification or development of physically-based models of post-wildfire runoff and erosion responses.

3. Precipitation: research issues related to the temporal and spatial variability of meso-scale precipitation

3.1. Background

Precipitation is a primary variable for the other post-wildfire processes (infiltration, runoff, and soil and sediment erosion and transport) all of which have their own specific spatial and temporal scales. A priority issue is to determine the most appropriate parameterization to use in quantifying spatially and temporally variable rainfall as a variable for the other processes. These spatial and temporal scales may be interdependent because they are linked dynamically (Ormsbee, 1989; Foufoula-Georgiou and Krajewski, 1995; Venugopal et al., 1999; Bernardara et al., 2003), which may simplify quantifying and downscaling of combined space–time rainfall fields to the meso-scale (1–10^4 km^2). Constraints on predicting the meso-scale

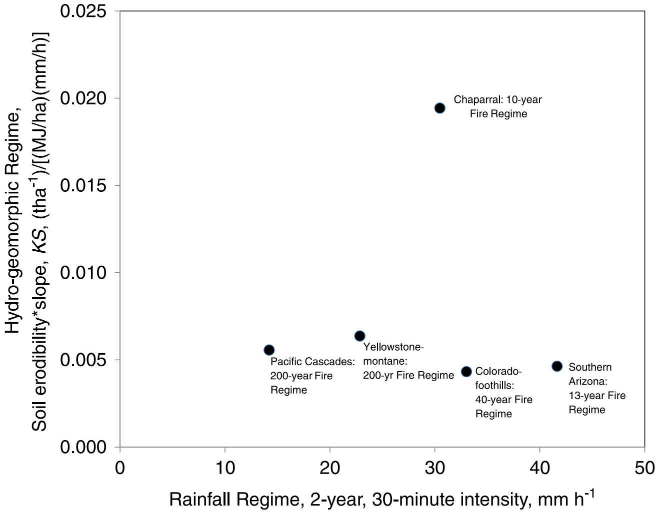

Fig. 1. An example of a two dimensional plot showing selected post-wildfire response domains. This organizational framework identifies broad regime similarities, which can then be further examined to explain response differences. See text for details of the Chaparral, Yellowstone-montane, and Colorado-foothill sites. The fire interval for the Pacific Cascades is taken from Swanson (1981); for Chaparral from Keeley et al. (2008); for Yellowstone-montane from Westerling et al. (2011), for Colorado-foothills from Veblen et al. (2000); and for southern Arizona from Swetnam et al. (1992). Rainfall regime and hydro-geomorphic regime metrics were taken from Table 2 published by Moody and Martin (2009a) (*K*-factor in Table 2 must be multiplied by 0.040142 to convert to (t-ha^{-1})/(MJ ha^{-1} mm h^{-1}).

rainfall distribution (defined as a scale sufficiently small to be unaffected by the Earth's Coriolis force) have limited the success of predicting post-wildfire runoff and erosion. However, the scale of measurement (i.e. point scale for rain gages and areal for radar) may be different from that of the 'effective' parameters needed in models (Beven, 1996). Hydrologic models for rainfall–runoff predictions are large-scale (10,000–100,000 km^2; Finnerty et al., 1997; Leavesley and Hay, 1998; Smith et al., 1999; Yates et al., 2000) and are often based on 1- to 6-h mean areal precipitation, which obscures any meso-scale variability embedded within regional weather systems. It is this meso-scale variability, however that drives the rapid urban (Cowpertwait et al., 2004) and post-wildfire (Moody and Martin, 2001a; Etheredge et al., 2004: Cannon et al., 2008; Kean et al., 2011) responses at hillslope and small basin scales (1–10 km^2). Meso-scale variability can change seasonally within a specific precipitation-regime, but also can vary between precipitation regimes, ranging from low-intensity, long-duration spatially homogeneous to high-intensity, short-duration spatially heterogeneous rainfall. Some recent meteorological research (Chen et al., 2001; Vivoni et al., 2009; Moreno et al., 2012) has focused on meso-scale, physics-based rainfall models (Grell et al., 1994; Skamarock, 2004), which attempt to incorporate meteorological processes at hillslope or small basin scales. Collaboration between post-wildfire researchers and meso-scale meteorologists will be needed to advance the measurement, understanding, and prediction of temporal and spatial variations in rainfall over burned areas. While the temporal and spatial variations of rainfall may be linked at the meso-scale, we explore them separately in the following sections.

3.2. Temporal variations in precipitation

Rainfall accumulation during a storm is a discontinuous function of time-punctuated by intermittent short-duration, rain-free interludes followed by rapid accumulation associated with rain cells embedded in a storm. In view of this pattern, we consider here two properties: first, the rainfall totals for a given period (interval parameters), and second, the nature of the rainfall within a storm and during a sequence of storms (sequence parameters).

Different parameterizations of rainfall intensity and its thresholds have been used as basic variables to predict infiltration, runoff, and subsequent floods (Reaney et al., 2007). For simplicity, most predictions of post-wildfire infiltration have assumed constant rainfall intensities (Robichaud, 2000; Woods and Balfour, 2008) in modeling infiltration into the unsaturated zone (Green and Ampt, 1911; Horton, 1939; Mein and Larson, 1973; Smith and Parlange, 1978; Kutílek, 1980; Smith et al., 2002). A few methods predict only runoff volume (curve number, Mockus, 1972; Hawkins, 1973, 1993; Foltz et al., 2009) without considering rainfall intensity, but most methods predicting runoff rates (such as instantaneous unit hydrograph, Sherman, 1932; or the curve number method, Soil Conservation Service, 1972) use constant rainfall intensities compatible with the use of design storms for flood risk assessment. Now, however, with the increased use of rain gages with high temporal resolution (enabling near-continuous measurements) and improved numerical models capable of handling long time series, the most important issue becomes: 'What is the appropriate time-averaging interval for meso-scale rainfall that best quantifies rainfall properties as drivers of post-wildfire response' (Fig. 2)? For example, 10-minute rainfall intensities were found to correlate best with soil erosion rate (Spigel and Robichaud, 2007), 15-minute rainfall intensities were found to correlate best with debris-flow timing (Kean et al., 2011), and 30-minute rainfall intensities were found to correlate best with peak flood discharge (Moody, 2012). A problem with averaging data is that it may result in the loss of important process details such as lag times between peak rainfall and peak runoff (Yu et al., 1997). Rainfall is usually expressed as a depth accumulated during a given interval (e.g. 5-min, 1-h, or 1-day) or as the time taken to accumulate a constant amount (e.g. 1-mm or 0.01 inch). Rainfall metrics that have been used include:

(1) Total precipitation amount (Robichaud et al., 2006a, 2008a, 2008b; Cannon et al., 2010; Robichaud et al., 2013a, b);

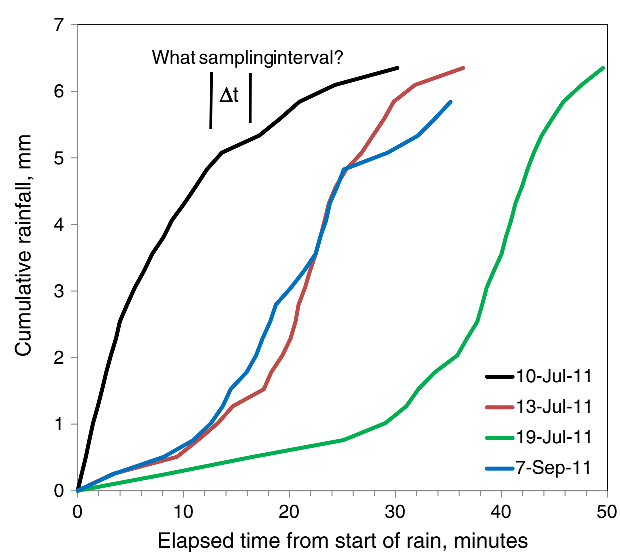

Fig. 2. Temporal variability of meso-scale rainfall. Examples of cumulative rainfall profiles collected in an area burned by the 2010 Fourmile Canyon Fire in Colorado. The cumulative data are basic rainfall data from a 15-cm diameter tipping-bucket rain gage where each tip represents 0.254 mm of rain and have irregularly spaced time intervals. The elapsed time for 7 Sep 2011 has been divided by 10 in order to show it here on the same plot with the other rain storms. The problem is what sampling interval, Δt, is appropriate to use to relate the rainfall intensity to observed runoff and erosion processes. The corresponding rainfall profiles are shown in Fig. 3.

(2) Average storm intensity (Cannon et al., 2010);
(3) Intra-event rainfall intensities for varying duration (Moody and Martin, 2001a; Kunze and Stednick, 2006; Robichaud et al., 2006a; Mayor et al., 2007; Spigel and Robichaud, 2007; Cannon et al., 2008; Moody et al., 2008a; Robichaud et al., 2008a, b; Cannon et al., 2010; Dunkerley, 2010; Cannon et al., 2011; Kean et al., 2011; Robichaud et al., 2013a, b);
(4) AI_{15} (amount of rainfall multiplied by the maximum 15-minute intensity; Mayor et al., 2007)
(5) A theorized geomorphically effective rainfall intensity (Flanagan and Nearing, 1995);
(6) Rainfall erosivity (Renschler et al., 1999; Kunze and Stednick, 2006; Pietraszek, 2006; Wagenbrenner et al., 2006; Spigel and Robichaud, 2007); and
(7) Temporally continuous intensity–duration relations (Cannon et al., 2008, 2011; Staley et al., 2012).

Although some of these interval metrics seem to make intuitive sense, only a few have been directly linked to physical processes in burned areas (Kean et al., 2011), and some have been used to define geomorphic thresholds (Cannon et al., 2011). Multivariate statistical analysis has been used to identify the most significant rainfall metrics to explain post-fire debris-flows and their volumes (Gartner et al., 2008; Cannon et al., 2010), but the physical significance of such metrics is unclear, so that future research should focus on establishing a physical basis for quantifying rainfall at time scales determined by the spatial scale of interest—i.e. point, plot, hillslope, or basin.

A basin's temporal runoff response to rainfall is inherently linked to spatial scales, determined by the infiltration process, the drainage network pattern, and flow velocities within this network. Rather than being a direct response to rainfall, runoff responds to the actual rainfall intensity minus the infiltration rate and topographic storage (effective rainfall). This produces a non-linear response (Overton, 1970) often characterized by thresholds (Doehring, 1968; Inbar et al., 1998; Reneau and Kuyumjian, 2004; Kunze and Stednick, 2006; Kean et al., 2011; Moody, 2012) and other factors that need to be considered in selecting a suitable scale for quantifying rainfall. For example, time-to-concentration (Barfield et al., 1981; Dick et al., 1997) may be an appropriate time scale to determine the time-averaging interval for rainfall, but in some precipitation regimes in some arid and semi-arid landscapes (which may respond similarly to bare, burned areas in terms of runoff and erosion) the time-to-concentration for continuous flow down slopes is often longer than the duration of the rainstorm (Yair and Raz-Yassif, 2004). With an increase to the basin scale, the runoff response to high-frequency (short-duration) fluctuations in rainfall intensity is damped (Eagleson and Shack, 1966) by the increase in and variability of times (time-to-concentration) required to route water through the different parts of the drainage network (Milly and Wetherald, 2002; Wainwright and Parsons, 2002; Smith et al., 2004). These network effects on basin response have been investigated using the geomorphic instantaneous unit hydrograph (Rodriguez-Iturbe and Valdes, 1979; Rinaldo et al., 1991), which initially assumed effective rainfall and constant drainage velocity although the latter assumption was later modified to include variable velocities (Robinson et al., 1995; Saco and Kumar, 2002). Additionally, as spatial scale increases, the threshold rainfall intensity for runoff generation in semi-arid landscapes increases from about 4 mm h^{-1} for an area of 10 m^2 to 22.5 mm h^{-1} for an area of 10^6 m^2 (Cammeraat, 2004). Thus, the rainfall interval metric must take account of the following factors: spatial scale, geomorphic characteristics of drainage network patterns, infiltration process, the effects of the remaining patchy distribution of litter or duff, and the distribution of topographic depressions (see Section 4).

Parameterizing the rainfall intensity as the total rainfall over a given time interval gives no information about the temporal sequence of intra-storm rainfall intensities. The detailed sequence within a storm may be important in terms of process response (Beven, 1996) and downscaling or disaggregation methods, assuming the distribution in shorter intervals is proportional to that in larger intervals (Ormsbee, 1989). Temporal sequences can have very different patterns but the same averages and peak intensities. Intensity may rise rapidly, reach a peak and gradually decline (Fig. 3A), or it may gradually rise towards the peak (Fig. 3C) or there may be several peaks with gaps of variable duration (Fig. 3D). Early efforts to characterize temporal rainfall variability focused on classification. For example, based on the result that the majority of rain measured in a network of 49 recording rain gages in east central Illinois, USA fell within a brief period of the total rainfall profile, a classification scheme was based on dividing the rainfall profile into four equal parts and determining in which quarter (1st, 2nd, 3rd, or 4th) the heaviest rain fell (Huff, 1967). This temporal rainfall variability is often referred to as the rainfall pattern (Smith, 1972; Xue and Gavin, 2008) or event profile (Dunkerley, 2011). It can affect infiltration response (Winchell et al., 1998; Xue and Gavin, 2008), time-to-ponding (Smith, 1972), runoff response (Reaney et al., 2007; Dunkerley, 2011), and erosion response (Lanini et al., 2009). Differences in the sequence of rainfall intensities within a rain storm may explain why the same basin can respond differently to rainstorms with similar interval metrics (Dick et al., 1997; Reaney et al., 2007). Also storm metrics such as coefficient of variation and the time between storm pulses have been shown to affect runoff coefficients and runoff flow distances (Reaney et al., 2007).

3.3. Spatial variations in precipitation

Wildfires are common in mountainous terrain with complex topography, and thus, spatial variations in rainfall are linked to topography and to variations in landscape surface properties. Regional orographic effects on rainfall associated with cyclonic storms have been known for a long time (Spreen, 1947; Burns, 1953; Linsley, 1958), and these effects have more recently been incorporated into digital models (e.g. Precipitation-elevation Regressions on Independent Slope Model, PRISM; Daly et al., 1994), but less is known about effects on smaller meso-scale, convective-storms. Spatial analyses of convective rainfall data indicate that there are “genesis zones” or “hotspots” with higher intensity rainfall than in surrounding areas (Henz, 1973; Banta and Schaaf, 1987; Williams and Moody, 2003; Hanshaw et al., 2008). They are common in the terrain of the Colorado Rocky Mountains and probably exist in other precipitation regimes. Although the scale of these hot spots has been identified for some precipitation regimes, the effect on runoff remains unknown. Future research needs, first, to identify them and understand the physical processes that create them. Further collaboration with meteorologists is needed to develop ways of quantifying rainfall in far more detail than is currently done using rain gage networks and conventional weather radar. Some possibilities are using portable C-band (Jorgensen et al., 2011) and X-band radars (Matrosov et al., 2013) that can collect dual-polarized measures of rainfall intensities at appropriate scales necessary for characterizing spatial and temporal properties of meso-scale storms as they pass across burned terrain. An example is the concept of a ‘footprint’ or the size of the storm, which may depend on the topography. Analysis of historical Doppler radar has shown that footprint size depends on rainfall intensity, which decreases exponentially (Fig. 4) with the increase in area coinciding with the 30-minute maximum intensity (Williams and Moody, 2003). Analysis of dual-polarized rainfall measurements over specific topography also can be used to improve rainfall downscaling methods (Ormsbee, 1989; Cowpertwait et al., 2004) for estimating temporal as well as spatial characteristics of meso-scale rainfall, and for identifying and understanding storm trajectories. Post-wildfire basin response depends upon the direction of storm movement relative to the drainage network in unburned (Ogden et al., 1995) and burned basins. High resolution rainfall data from these radars

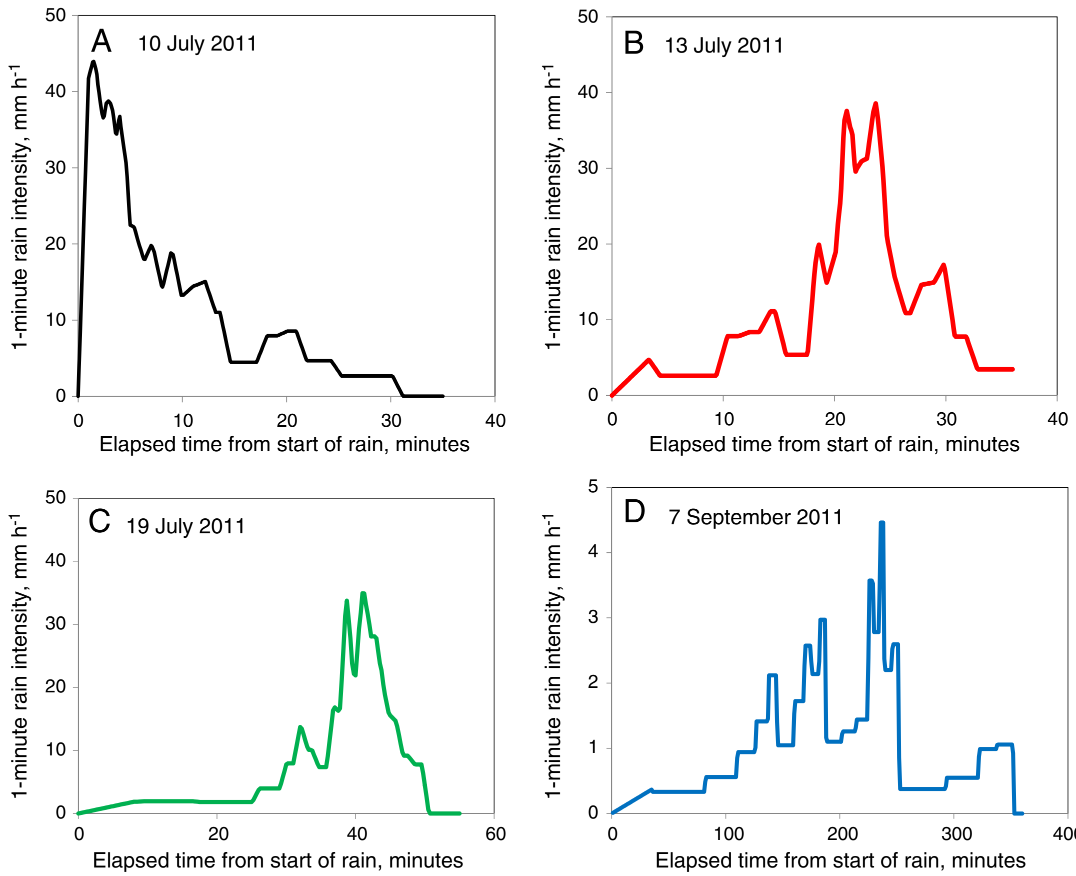

Fig. 3. Examples of rainfall intensity profiles measured in an area burned by the 2010 Fourmile Canyon Fire in Colorado. These rainfall intensity profiles correspond to the cumulative profiles in Fig. 2. Profiles for 10, 13, and 19 July 2011 correspond to short-duration, high-intensity convective storms and the interpolated sampling interval was equal to 1-min. The profile for 7 September 2011 corresponds to a long-duration, low-intensity frontal storm.

could improve input into a stochastic daily weather generator such as CLIGEN (Nicks et al., 1995), which is now parameterized by the regional-scale PRISM (Daly et al., 1994) and the Rocky Mountain climate generator (Rock:Clime; Elliot et al., 1999; Robichaud et al., 2007b; Elliot and Hall, 2010) models. These models are used in the Water Erosion Prediction Project (WEPP; Flanagan and Nearing, 1995) as part of the Erosion Risk Management Tool (ERMiT; Robichaud et al., 2006b). However, the CLIGEN and Rock:Clime models now assume that storms have fixed time-varying intensity specific to each site, are uniformly distributed over the model's spatial domain, and are stationary—all of which limit their performance. In many burned basins, the spatial variability, or patchiness, of rainfall during a storm can be so great that the concept of a constant-intensity design storm is unrepresentative of actual conditions and therefore has limited use (Moody and Martin, 2001a) because antecedent conditions (e.g. soil water content and surface-storage detention) are often neglected (Ormsbee, 1989).

In addition to topography, the spatial distribution of landscape surface properties can influence meso-scale rainfall through feedback mechanisms. Generally, these properties include soil characteristics and micro-topographic effects on surface water detention. Conceptually, soil hydrology acts like a low-pass filter (Wu et al., 2002) of high frequency rainfall. Water is stored in the soil and released slowly back to the atmosphere. This provides a feedback mechanism, whereby rainfall from an earlier storm can directly affect later storm rainfall. Thus, the sequence of rain storms linked by soil moisture conditions can affect the post-wildfire response (Chen et al., 2001; Germanoski et al., 2002). Since burned areas have a lower albedo (Chen et al., 2001; Randerson et al., 2006; Tryhorn et al., 2008; Tsuyuzaki et al., 2009) and tend to dry more quickly than vegetated areas (Moody et al., 2007), surface temperature can also be higher than on the surrounding unburned areas. Such a warm surface temperature anomaly was created by an area burned by the 1996 Buffalo Creek Fire in the Colorado Front Range Mountains and cool surface anomalies were created by previous rain showers near the burned area (Chen et al., 2001). This temperature distribution had a sufficiently large effect to cause a convective storm to be confined to the warmer (~6 °C higher) burned surface, resulting in a 100-year rain storm over the burned area (Chen et al., 2001). The size of the burned area (4700 ha) may not by itself have been sufficient to create the local convective circulation, but instead may have triggered convective rainfall, which was poised near a threshold. Thus, the spatial distributions of soil properties provide a possibly important link between the precipitation regime and burned landscapes.

3.4. Future research priorities

Meso-scale rainfall is known to be the primary driver for post-wildfire runoff and erosion response, and is characterized by short-duration, high frequency temporal and spatial variability, which is influenced by complex topography and soil surface properties. How to quantify its effects will require collaborative research with meteorologists, which has so far been largely absent. The four research priorities below are related to the temporal and spatial variability effects of meso-scale rainfall on post-wildfire runoff and infiltration. The first two are broad and concern the role of soil properties in linking precipitation to infiltration and runoff. The third priority addresses a possible feedback mechanism between soil

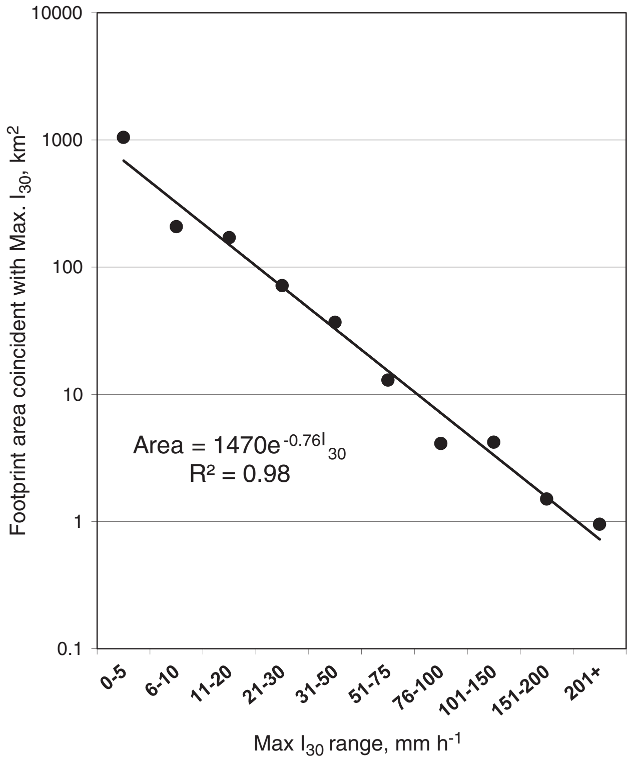

Fig. 4. Areal footprint of rainfall versus rainfall intensity. Relation between one possible rainfall variable, the maximum 30-minute rainfall intensity (I_{30}), and the coincident rainfall area or 'footprint' on the ground. The data are from the analysis of historical Doppler radar data for 20 storms (1995–2001) over an area burned by the 2002 Hayman Fire in Colorado (Williams and Moody, 2003).

properties, and the fourth considers topographic effects on meso-scale rainfall.

(1) Which time-interval metrics best explain post-wildfire infiltration and runoff responses at a given spatial scale, and how do these metrics change with spatial scales or post-wildfire domain? This will require better temporal resolution of rainfall and improved understanding of post-wildfire spatial variation in infiltration rates.
(2) Which sequence metrics best represent the within-storm temporal change (rainfall profile), the pattern of multiple storms, and dry intervals, and how do they influence post-wildfire infiltration and runoff response? What factors control the key rainfall sequence metrics, and are there similarities across post-wildfire domains?
(3) What is the magnitude of the possible feedback mechanisms in a burned area between the spatial distribution of soil properties and that of the meso-scale rainfall? What is the dominant control on this feedback mechanism (soil moisture, burn severity, or vegetation), and how does the feedback change over time with post-wildfire recovery?
(4) How does topography affect the spatial distribution of meso-scale rainfall, and how important is it in controlling the locations of genesis zones or hotspots of persistent high intensity rainfall and the rainstorm 'footprint'?

4. Infiltration: quantifying soil properties and hydraulic effects

4.1. Background

Wildfires cause several geomorphically important changes in soil properties, including modification of the pre-fire soil profile and development of spatial variation of soil properties. Combustion removes some or all of the litter and duff layers (Robichaud and Miller, 1999), modifies the mineral soil layer at varying depths depending upon the fire regime (Doerr et al., 2009), may induce or enhance a water-repellent layer (Krammes and Osborn, 1969; DeBano, 2000; Doerr et al., 2000; Coelho et al., 2004; Woods et al., 2007; Finley and Glenn, 2010), and deposits a surface layer of ash (Fig. 5) containing varying quantities of mineral soil and organic substances as a result of increased wind transport during the wildfire (Byram and Martin, 1970). This ash layer is generally hydrophilic (Kinner and Moody, 2010; Woods and Balfour, 2010), though hydrophobic ash has been reported (Bodi et al., 2011). Increased runoff from burned areas can be caused either by infiltration-excess or saturation-excess overland flow or by some combination of both (Sheridan et al., 2007; Onda et al., 2008; Ebel et al., 2012). Increased runoff is often attributed to soil water repellency (SWR), the increase in amount of bare ground (Benavides-Solario and MacDonald, 2005; Larsen et al., 2009), the decrease in canopy interception (Stoof et al., 2012), and the lack of any surface water storage. Any remaining unburned duff 'layer' (partially decomposed litter with humus, Robichaud and Miller, 1999) below the ash layer can also create water repellent patches when dry, yet water absorbent patches when moist. This patchiness increases the spatial variability of the soil properties (Moody et al., 2007) and adds complexity to understanding post-wildfire runoff and erosion responses. Even when SWR is extreme, prolonged rainfall can cause the soil to be transformed to a 'normal' wettable state (Doerr et al., 2000; Stoof et al., 2011a), but soil can regain its repellent state once dry conditions return (Shakesby et al., 2000). Additionally, the effect of water repellency decreases with an increase in spatial scale (Larsen et al., 2009). Low runoff has been documented in areas where SWR is high (Stoof, C., Cornell University, per. commun. 2013), and high post-wildfire runoff has also been documented where SWR is absent, thus indicating that the presence of SWR is not always necessary for producing extreme floods (Meyer and Wells, 1997; Cannon et al., 2010).

The properties and spatial distribution of ash (Goforth et al., 2005; Kinner and Moody, 2008; Pereira et al., in press), duff (Robichaud and Miller, 1999) and fire-affected mineral layers (Ulery et al., 1996; Woods et al., 2007) are not well known and research has focused on the plot scale, sometimes the hillslope scale (Robichaud and Miller, 1999), but not on the basin scale. However, the limited results obtained indicate sufficient spatial variability to suggest that the concept of an ash or SWR 'layer' is perhaps misleading and should be replaced by one of 'patches' or more specifically a 'mosaic of patches with varying thickness' (Woods et al., 2007; Kinner and Moody, 2010; Pereira et al., in press). This concept of patches is supported

Fig. 5. Black ash layer about 1 cm thick and the underlying mineral soil layer in a burned area in Colorado.

by DeBano et al. (1998) who stated that “water repellency produced by fire is usually confined to areas beneath plant canopies” (Fig. 6). Thus, overland flow generated on these water repellent patches can infiltrate via wettable ash and soil patches (Shakesby et al., 2000; Doerr et al., 2009; Jackson and Roering, 2009). Soil heating below these patches can modify soil erodibility by destroying the organic

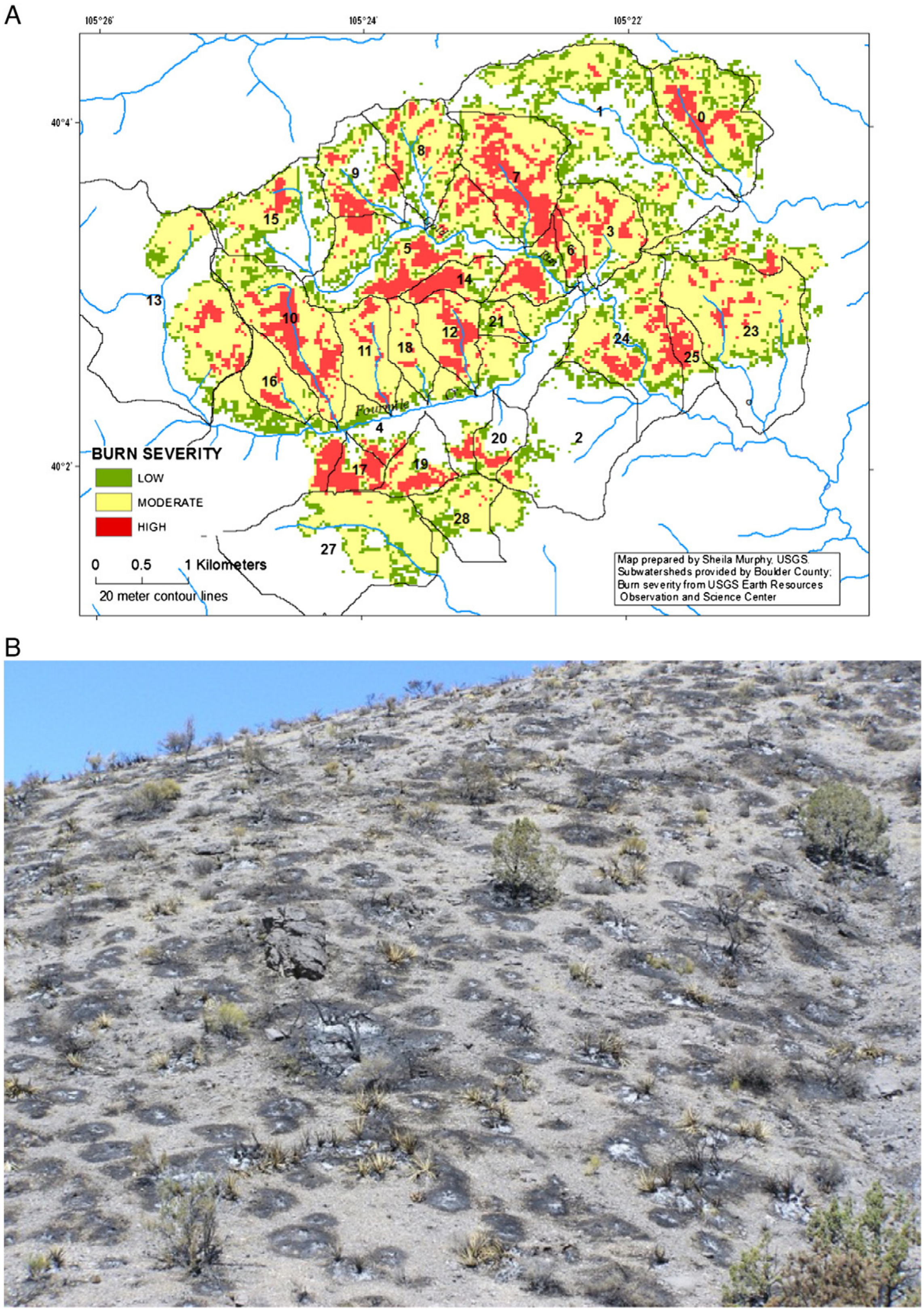

Fig. 6. (A) Burn severity map for the 2010 Fourmile Canyon Fire west of Boulder, Colorado, USA. This Burn Area Reflectance Classification map (BARC map) is based on grouping values of ΔNBR. The large-scale spatial variability in severity is evident. (B) Small-scale spatial variability of fire severity associated with the spatial distribution of vegetation on a hillslope burned by a wildfire in the Mojave Desert, California, USA. Areas of white ash indicate more complete combustion, and thus greater burn severity (caused by higher temperatures and/or longer duration) than areas of dark gray ash. Areas of light grayish-brown color are bare soil.

and chemical bonds (Giovannini and Lucchesi, 1983; Giovannini et al., 1988) within the soil to reduce the critical shear stress required to initiate erosion (Moody et al., 2005). Finally, severe wildfires can produce numerous burnt-out stump and root holes (Fig. 7), which augment the existing patchy pre-fire depression storage on the soil surface and may cause increased pipe flow. The magnitudes and spatial extent of these fire-affected patches are indicators of the burn severity.

4.2. Burn severity and soil hydraulic properties

Post-wildfire infiltration into the unsaturated zone is controlled by fire-induced changes in rainfall interception, soil-water storage, and soil hydraulic properties. Fire effects are often described by qualitative indices such as fire severity, burn severity (Keeley et al., 2008; Keeley, 2009), or soil burn severity (Parsons et al., 2010), which describe the above-ground organic matter consumption in qualitative terms (such as high, moderate, and low; Keeley et al., 2008), but do not directly relate to changes in soil hydraulic properties. Only recently, fire effects have been related to quantifiable metrics (bare soil exposed, fine root damage, water repellency, color change, and soil structure, Parsons et al., 2010). Organic matter consumption is spatially variable and often reflects the spatial distribution of pre-fire vegetation (DeBano et al., 1998) in addition to fire behavior (Fig. 6).

Fire effects on soil properties have been characterized indirectly by two burn severity metrics associated with two different spatial scales. The SWR metric (King, 1981; Letey et al., 2000) is measured on the ground at point to plot scales (1 cm^2–100 m^2) and is attractive because of its simplicity. Three SWR metrics are frequently used to assess burn severity: (1) the water drop penetration time test (WDPT, DeBano, 1981; Letey et al., 2000; Huffman et al., 2001), which represents persistence (Karunarathna et al., 2010) or the time needed for the contact angle to change to permit infiltration (Regalado and Ritter, 2009); (2) the molarity of ethanol droplet test (MED, Letey et al., 2000; Woods et al., 2007), which measures the critical surface tension; and (3) volume water that infiltrates in 1 min (1VOL) from a tension infiltrometer (Robichaud et al., 2008c). The other metric (change in the normalized burn ratio, ΔNBR, Key and Benson, 2004; van Wagtendonk et al., 2004) is measured remotely from satellite images at the hillslope to basin scales (10^2–10^6 m^2), and is attractive because of its large spatial coverage. The change in normalized burn ratio, ΔNBR, represents the difference between post- and pre-fire images of land surface reflectance for two bands measured by the Landsat satellite. One band is sensitive to green vegetation (near infrared) and the other to bare ground (short-wave infrared). The ratio ranges from about −100 (unburned) to 1000 (severely burned), and they are verified on the ground using standardized, but subjective, methods to assess soil burn severity (Parsons et al., 2010). Values of ΔNBR are then grouped into qualitative values of high, moderate, and low soil burn severity classes, which are shown on burn severity maps (e.g. Chafer, 2008). Neither metric gives a direct measurement of fire-affected, soil-hydraulic properties such as hydraulic conductivity or sorptivity (Smith et al., 2002), but they do provide independent assessments of fire effects. Other metrics that might be promising include hyperspectral and multispectral remote sensing measurements (Kokaly et al., 2007; Robichaud et al., 2007c; Lewis et al., 2008).

Unfortunately, these burn severity metrics do not quantify the important soil-hydraulic functions required to study infiltration. Traditional infiltration theories require two soil-hydraulic functions (the soil–water retention curve, and the hydraulic conductivity function) to describe infiltration in the unsaturated zone (Smith et al., 2002). The soil–water retention curve is a relation between matric potential, ψ [L], and soil–water content, θ [L^3 L^{-3}], and the hydraulic conductivity function is the relation between θ and hydraulic conductivity, K [L T^{-1}], (Smith et al., 2002). Some work has been done to begin to quantify the effects of SWR (Ebel and Moody, 2012) and ΔNBR on the soil-hydraulic functions (Lewis et al., 2008) for fire-affected soils. Recent work (Bachmann et al., 2007; Karunarathna et al., 2010) for soils unaffected by fire has generated empirical models for soil–water repellency characteristic curves (i.e. SWR metrics versus θ and SWR metrics versus ψ). Thus, a research priority is to understand how SWR and ΔNBR are related to the soil-hydraulic properties of fire-affected soils. Achieving this will require more field and laboratory measurements of soil burn severity metrics together with measurements of the spatial variability of soil-hydraulic properties in burned areas (Berli et al., 2008). The results should establish a family of fire-affected soil-hydraulic functions for different values of each soil

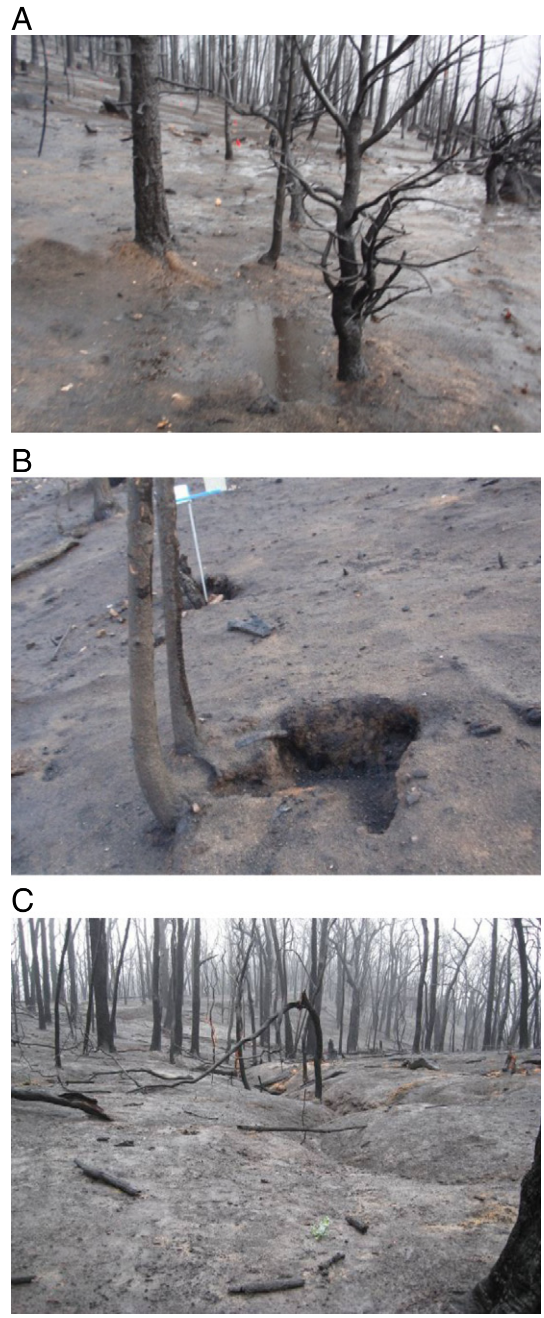

Fig. 7. (A) Overland flow connectivity on hillslope burned by the 2010 Fourmile Canyon Fire west of Boulder, Colorado, USA. (B) Depression storage and root holes (shown as cross-hatched ovals in Fig. 10) also in the area burned by the 2010 Fourmile Canyon Fire west of Boulder, Colorado, USA. (C) Surface roughness, depression storage, and drainages burned by the Black Saturday 2009 wildfires in the Kinglake area of Victoria, Australia.

burn severity metric, which can then provide the basis for modifying traditional infiltration theory.

4.3. Modification of traditional infiltration theories

Two components of traditional infiltration theories need to be addressed in order to modify these theories to predict post-wildfire infiltration. The first will be the development of the fire-affected soil-hydraulic functions described above, and second will be the inclusion of several special conditions related to wildfire. One condition is that post-wildfire responses are characteristically unsteady and transient so that the steady-state assumption is not applicable. Second is the assumption of the Green–Ampt infiltration model (Green and Ampt, 1911) used to simplify Richards equation (Richards, 1931) that the wetting front in a soil is sharply defined by uniformly wet soil above and 'dry' soil below (Hillel, 1998). This assumption is sometimes described as a 'moving piston wave' (Smith et al., 2002). Observations of the wetting front for fire-induced water-repellent soils (DeBano, 1981) and other water-repellent soils (Dekker and Ritsema, 2000) have indicated an irregular distribution of wet and 'dry' soil patches with depth, suggesting that the Green–Ampt model may not be appropriate for water-repellent soils. A third condition is that runoff from one water-repellent patch can infiltrate into another patch downslope (Sheridan et al., 2007; Larsen et al., 2009). This variability in the upper fire-affected 'layer' may be better characterized as a cumulative distribution function for the soil-hydraulic properties (Nachabe et al., 1997; Fiedler and Ramirez, 2000; Robichaud, 2000; Kinner and Moody, 2010). This approach has been incorporated into the Erosion Risk Management Tool (ERMiT) by using a distribution of hydraulic conductivity, which can also be spatially variable on a modeled hillslope (Robichaud et al., 2007a). Fourth, the increase in the amount of bare soil after a wildfire makes post-wildfire soils susceptible to soil sealing during subsequent rain storms by raindrop impact and runoff carrying ash and fine sediment particles (Martin and Moody, 2001; Larsen et al., 2009; Woods and Balfour, 2010). This fire-related condition can compact the upper soil layer with a corresponding increase in bulk density and a change in soil-hydraulic functions (Assouline, 2004). The extent of the sealing process needs to be measured, better understood, and incorporated in post-wildfire infiltration theories if appropriate. Fifth, recent observations of soil-water content immediately after a wildfire and before the first substantial post-wildfire rain storm have documented hyper-dry conditions with a threshold of $\theta < \sim 0.02$ cm^3 cm^{-3} or matric suction $> \sim 3 \times 10^5$ cm (Moody and Ebel, 2012a). For these conditions, the only available process for wetting soils is the slow diffusion–adsorption process (Moody and Ebel, 2012a). To adequately characterize rewetting, modified infiltration theories need to consider rewetting as a two-stage process in relation to a threshold. Finally, local conditions such as animal or insect burrows, burnt-out tree roots, stump holes, and high rock fragment content may provide significant megapore pathways for infiltration through otherwise impermeable water repellent soil (e.g. Shakesby et al., 2007). These megapore pathways (Fig. 7B) need to be quantified, and if their effects are important, incorporated into post-wildfire infiltration theory.

The existence of multiple and spatially variable soil 'layers' needs to be included in post-wildfire infiltration models (Berli et al., 2008), and an immediate consequence is deciding how to determine the appropriate thickness of each 'layer' (Fig. 8). In the case of the uppermost layer, this requires knowledge of the depth of influence of the heat from a wildfire, which can penetrate a few centimeters into the soil (DeBano et al., 1976; Hungerford et al., 1996; DeBano et al., 1998; Robichaud and Hungerford, 2000; Stoof et al., 2011b) and change soil properties (Humphreys and Craig, 1981; Certini, 2005; Moody et al., 2005; Neary et al., 2005; Mataix-Solera et al., 2011). At present, these changes are not sufficiently well quantified for use in models of post-wildfire infiltration and runoff processes, so collaboration with fire-effects modelers, who have developed models such as FOFEM (First Order Fire Effects Model, Campbell et al., 1995; Reinhardt, 2012) that predict the soil temperature profile during different fire behavior and fuel conditions (such as grass, canopy, and smoldering), might be highly productive.

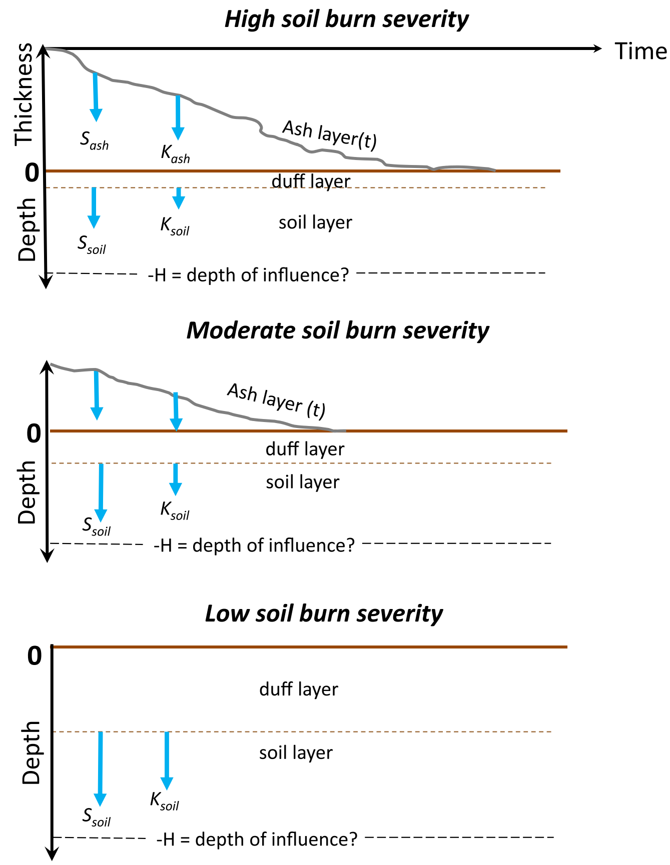

Fig. 8. Idealized two-layer post-wildfire soil system with an ash layer overlying the soil. The overlying ash layer thickness is proportional to the quantity of burned material, and is shown increasing with the degree of burn severity and decreasing with time due to removal by wind and water erosion. The duff layer is depicted as being uniform in this diagram, though in reality it varies spatially in thickness. Ash and soil have specific values of hydraulic properties like sorptivity, S, and unsaturated hydraulic conductivity, K as well as specific soil–water retention curves. H represents an unknown depth of influence of the system on runoff.

4.4. Measurements of soil hydraulic properties

One indirect method of determining soil-hydraulic properties is to solve them as theoretical model parameters that best explain the observed data. These theoretical models of infiltration are derived from the non-linear, partial differential Richards equation (Richards, 1931; Philip, 1969) by making simplifying assumptions to produce an analytical form of the equation that can be readily solved. Soil hydraulic properties are not, therefore, independent measures, but rather they depend on the simplifying assumptions of the model. These models have generally been developed for relatively rock-free agricultural soils and may not apply to rocky, mountain soils common to many burned areas or to any soil subject to heat. The fundamental property in Richards equation is the hydraulic conductivity, K [L T], which controls the gravity component of infiltration over time scales of hours to days. One method of measuring the saturated hydraulic conductivity, K_s, was to adjust K_s in a hydrologic runoff model to fit observed hydrographs (Yates et al., 2000), and another was to solve for K_s indirectly using the Hydrus 1-D model (Šimùnek et al., 2008) using actual intra-storm infiltration rates measured during natural rainfall (Moody and Ebel, 2012b). Philips (1969) derived an approximate solution for the cumulative infiltration depth, $I(t)$ [L], as a power series expansion in time, t [T], which is frequently truncated to $I(t) = S\,t^{1/2} + K_s t$, where S [L T$^{1/2}$] is called the sorptivity and can be considered as a second hydraulic property that controls the capillary component of infiltration over short-time scales of minutes to hours depending upon the soil texture (White and Sully, 1987; Smith et al., 1999). Therefore, the sorptivity of fire-affected soils may be initially more important than saturated hydraulic conductivity at the time scale of convective rainfall, which is typically short and only lasts 20–60 min but common in many post-wildfire response domains. Sorptivity is an attractive proxy for post-wildfire infiltration, but it is not a single value like K_s. Rather it is a function of the soil–water content. More measurements of the spatial distribution of K_s and S are needed as well as the temporal changes in these properties after wildfire. Cumulative distribution algorithms can provide a means to quantify the inherent spatial variability associated with these hillslope and surface conditions (Robichaud, 2000; Kinner and Moody, 2010). However, at present, the few existing measurements for fire-affected soil depend on the method of measurement and the theory used.

Several more direct methods have been used to measure soil hydraulic properties. Most measure the cumulative infiltration, $I(t)$, and focus on measuring K_s, which can range over several orders of magnitude (10^{-5} to 10^{1} mm h^{-1}, Rawls et al., 1982). The disadvantage of most methods is that they use some type of artificial wetting of the soil under constant conditions (Moody and Ebel, 2012b) applied to a small area (~1 m^2) in the field (Robichaud, 2000) or reconstituted samples in the laboratory (Fox et al., 2007; Novák et al., 2009). The most common methods are the constant-head or positive-pressure devices such as ring, drip, falling head (Nimmo et al., 2009), and disk permeameter or constant rainfall intensity simulators (Robichaud, 2000; Martin and Moody, 2001; Pierson et al., 2001; Assouline, 2004; Kinner and Moody, 2008, 2010). Positive pressure methods (12.7-mm head, Parks and Cundy, 1989; 10-mm head, Sheridan et al., 2007; 5-mm head, Nyman et al., 2011) essentially push water into the soil and may overwhelm the factors controlling post-wildfire infiltration—especially if K_s is near zero. Therefore, these methods tend to produce high estimates of K_s (Cerdà, 1996; Nyman et al., 2010; Ebel et al., 2012) that are probably inaccurate given the relatively low values of K_s for most fire-affected soils (10^0–10^2 mm h^{-1}; Imeson et al., 1992; Robichaud, 2000; Yates et al., 2000; Martin and Moody, 2001; Rulli et al., 2006; Robichaud et al., 2007b; Moody et al., 2009; Neary, 2011; Nyman et al., 2011; Ebel et al., 2012). Tension infiltrometers eliminate the positive pressure problem (Robichaud et al., 2008c; Moody et al., 2009), but frequently are difficult to interface with the coarse mountain soils characteristic of some post-wildfire response domains. Rainfall simulators often use a single, unrealistic rainfall intensity (Kinner and Moody, 2010), and the drop-size distributions, kinetic energies, or temporal variations are unrepresentative of natural rain (Renard, 1985). The few available values of sorptivity for fire-affected soils were measured using a tension infiltrometer (Mini Disk, Decagon, 2006), and range from 4.5 to 49 mm h$^{-0.5}$ (Moody et al., 2009; Ebel et al., 2012). For comparison, this range is slightly less than the range (21–73 mm h$^{-0.5}$) for unburned 'dry' sand to clay textured soils (Table 8.1; Smith et al., 2002), but similar to undisturbed field soils (10–36 mm h$^{-0.5}$, White and Sully, 1987). If we assume that soil-hydraulic functions have been developed for fire-affected soils and infiltration theory has been modified to account for the special conditions of fire-affected soils (both discussed above), then the next issue is: Which of the above methods is most appropriate for measuring the spatial and temporal variability of K_s and S in the field? Clearly, a standard method needs to be adopted so that measurements made in different post-wildfire response domains are comparable.

4.5. Time dependence issue

Some existing methods used to predict the timing and magnitude of runoff and erosion account for the spatial variability of burn severity conditions at the hillslope scale (Robichaud et al., 2007c), but not temporal changes during a given storm (Robichaud, 2000; Robichaud et al., 2007a). A water repellency index has been proposed (Pierson et al., 2001, 2008) to characterize reduced infiltration following wildfire, but any such index has only been considered to operate in a static way in a model (Robichaud et al., 2007a). Similarly, soil-hydraulic functions often represent equilibrium conditions found in a laboratory and yet dynamic conditions exist in the field, which could alter these relations (Wang et al., 1997; Hassanizadeh et al., 2002; Scheuermann, 2008). Increased understanding of short-term changes in soil-hydraulic properties caused by wetting and drying during individual rainstorms and by seasonal freezing and thawing of the soil (where winter temperatures are sufficiently low) will improve post-wildfire prediction models used by burned area assessment teams, land-managers, and emergency-responders. Additionally, at present, predictive models use effective rainfall, which is calculated as the rainfall rate (easy to measure but difficult to predict) minus the infiltration rate (difficult to measure and to predict). Thus, it is essential to understand the infiltration process in burned basins over appropriate time scales in order to understand the time-dependent effective rainfall. This new understanding can be used to further improve predictive models of post-wildfire runoff and erosion.

4.6. Future research directions

Characterizing wildfire effects on soil-hydraulic properties is pivotal to understanding infiltration, runoff, and erosion and in order to improve post-wildfire models. The priority research issues are:

(1) What are the quantitative relations between burn severity metrics, such as ΔNBR, WDPT, MED, and 1VOL, and soil-hydraulic properties such as K_s and S? Once these relations are established, researchers can define a set of soil-hydraulic functions for fire-affected soil to use as one component in modifying traditional infiltration theories.
(2) What is the relative importance of fire-related condition (fire effects), such as spatial variability of the wetting front, diffusion–adsorption process, soil sealing, mega-pore preferential flow pathways, multiple soil and ash 'layers', and the penetration depth of heating?
(3) How can the dynamic effects of changing soil-hydraulic properties be incorporated into post-wildfire infiltration models? This is needed to meet the forecasting requirements of the post-wildfire community.

5. Runoff: linking precipitation and basin morphology to post-wildfire response

5.1. Background

Post-wildfire hydrographs are difficult to predict because of insufficient data on soil properties (see Section 4) and the lack of rainfall–runoff data for burned basins, which are typically ungaged (Moody et al., 2008a). Post-wildfire hydrographs are also difficult to measure because streambed elevations often change rapidly in response to erosion and deposition, and post-wildfire flows can damage instrumentation. Therefore, much of the hydrological research literature has focused on predicting peak discharge of post-wildfire floods by using the paleoflood method (e.g. Jarrett and England, 2002), the curve number method (Hawkins and Greenberg, 1990; Cerrelli, 2005; Foltz et al., 2009), or direct measurements from burned basins (Moody and Martin, 2001a; Moody et al., 2008a; Foltz et al., 2009; Kean et al., 2011; Moody, 2012), but little has focused on predicting flood timing relative to rainfall (Elliot et al., 2010).

Most rainfall–runoff prediction methods have been developed for unburned basins, for which there is a large volume of literature (e.g. Hawkins, 1973; Interagency Advisory Committee on Water Data, 1981; NRCS, 1986; Beven, 2000; Feldman, 2000; Ries and Crouse, 2002). The focus in this review is on the rainfall–runoff process, yet snowmelt runoff from burned areas may impact water quality but is outside the scope of this review. In general, rainfall–runoff methods assume temporally and spatially uniform rainfall (which is usually not applicable to burned areas in mountainous terrain); and runoff contributions to channel flow from the entire drainage basin area (which is also questionable). Two frequently used methods are (1) regional regression equations and (2) the curve number method (Foltz et al., 2009). Both methods require some type of channel routing model (e.g. Peckham et al., 2004; Peckham, 2008; HEC-RAS, 2012) to predict the hydrograph. The first method requires knowing or assuming the increase in post-wildfire runoff in order to compute a fire-effects "modifier", which unfortunately is essentially what the method intends to predict. Both methods have difficulties accounting for fire-effects. Use of the curve number method for burned areas has produced conflicting results and demonstrates the need for further research according to Springer and Hawkins (2005).

Essential to any runoff model is a sub-model that is able to predict post-wildfire infiltration (see Section 4) and hillslope runoff contribution to channels. Depending on the post-wildfire response domain, hillslope-runoff-generating processes may switch between infiltration-excess and saturation-excess overland flow (Dunne, 1978; Wondzell and King, 2003; Keizer et al., 2005; Onda et al., 2008; Ebel et al., 2012). Intra-storm proportions of the two runoff-generating processes vary on steep hillslopes in southern California (Schmidt et al., 2011), and it is possible that they may change over intervals that are longer than individual storms. Runoff generation by infiltration excess has been found to be more sensitive to the uncertainty associated with precipitation than by saturation excess (Winchell et al., 1998). Understanding how these processes operate after wildfires is critical to runoff and flood predictions.

5.2. Factors affecting post-wildfire runoff

Explanations for increased post-wildfire runoff can be grouped into three hypotheses: (1) reduced infiltration caused by soil–water repellency (SWR), (2) increased flow velocities and connectivity as a result of the increase in percent bare-ground, and (3) reduced infiltration caused by soil-sealing and air entrapment. The significance of SWR in promoting runoff and erosion was first identified by Krammes and Osborn (1969). They attributed increased erosion to decreased infiltration and changes in soil-hydraulic properties. However, the impact of water repellency has not been isolated for large-scale field conditions (Shakesby et al., 2000), and no mathematical relations have been proposed that relate degree of SWR to runoff. The so-called bare-ground hypothesis seems to have originated with the paper by Cerdà (1998b, Figure 5), which linked post-wildfire runoff to percent vegetation cover, and later links were demonstrated between percent bare ground and runoff by using rainfall simulations (Johansen et al., 2001; Pierson et al., 2009), laboratory experiments (Pannkuk and Robichaud, 2003), and indirect evidence based on increases in sediment erosion (Benavides-Solario and MacDonald, 2005) and rill formation (Berg and Azuma, 2010) for natural rainfall. An increase in bare ground also results in an increase in the connectivity of water-repellent soil patches (Shakesby et al., 2000; Doerr and Moody, 2004; Cawson et al., 2010; Nyman et al., 2010). A possible threshold of 60–70% bare ground was found to be related to the connectivity of the bare patches (Johansen et al., 2001) and seemed to explain much of the post-wildfire erosion caused by increase runoff. The soil-sealing hypothesis originated with the paper by Rowe (1948). The role of ash in sealing was proposed by Mallik et al. (1984), and the combined hypothesis, which attributes sealing to precipitation (structural seals; Assouline, 2004) and runoff (depositional seals; Onda et al., 2008; Cerdà and Robichaud, 2009; Stoof et al., 2010; Woods and Balfour, 2010), was suggested by Martin and Moody (2001), and tested by Larsen et al. (2009). Laboratory and field experiments have shown that air entrapment (Jarrett and Fritton, 1978; Wang et al., 1997, 1998) can decrease infiltration rates (Krammes and DeBano, 1965; Suhr et al., 1984) and thus increase runoff.

It is possible that various combinations of these hypotheses are important across the spectrum of post-wildfire domains. Several runoff factors (critical thresholds, contributing area, depression storage, hydraulic roughness, and hillslope- and channel-flow connectivity) related to these hypotheses can possibly influence post-wildfire runoff in addition to the fire effects on soil-hydraulic properties (see Section 4) and characteristics of rainstorms (see Section 3 and Dunne, 1978). These runoff factors are considered in the following sub-sections.

5.2.1. Critical thresholds

Fire effects tend to reduce saturated hydraulic conductivity and sorptivity below pre-fire values, which can result in the appearance of critical rainfall-intensity thresholds controlling post-wildfire runoff. Additionally, surface ash and fire-affected soil layers can result in a critical-rainfall-depth threshold associated with either saturation-excess or infiltration-excess overland flow (Onda et al., 2008; Kirkby, 2011). Runoff thresholds may be related to the connectivity of flow paths, and the effects of subsurface connectivity have been explored using percolation theory (Lehmann et al., 2007). The post-wildfire response literature has established rainfall-intensity thresholds (Fig. 9), above which peak discharges from burned areas increase substantially (Doehring, 1968; Moody and Martin, 2001a; Reneau and Kuyumjian, 2004; Kunze and Stednick, 2006; Moody et al., 2008a; Moody, 2012), and rainfall intensity–duration threshold above which destructive debris flows of different magnitudes can be expected (Cannon et al., 2008, 2011; Staley et al., 2012). The sequence and timing of rainstorms can also affect post-wildfire response (Germanoski et al., 2002; Moody et al., 2008b: Kean et al., 2011), which may be related to scale-dependent thresholds (Cammeraat, 2004; also see Section 3) associated with the rain-free interludes. Researchers thus need to understand how these critical thresholds operate at different spatial scales.

5.2.2. Contributing area

During a rainstorm, the contributing area probably does not coincide with the topographic basin (Beven and Kirkby, 1979). Methods to predict peak discharge often assume contribution from the entire basin, just the burned area, or just the area burned at high or moderate severity. The actual contributing area may in fact not be static but change with time and this dynamic concept was the basis for the partial-area and the variable-source-area concept developed for unburned basins (Betson, 1964; Smith and Goodrich, 2000) and generally used to predict saturation-excess overland flow. Adopting some form of the partial-area concept might significantly improve the understanding of infiltration-excess runoff generation in burned areas with spatially variable patches having a range of fire-affected soil-hydraulic properties (Sheridan et al., 2007). For example, the rate of increase in the contributing area in semi-arid areas (which might be considered to be surrogates for burned areas because of the amount of 'bare' soil) tends to be high for short travel distances, but tends to be lower for longer travel distances because the probability of encountering patches with high infiltration capacity increases (Jackson and Roering, 2009; Kirkby, 2011). This spatial variability has been represented by several types of cumulative distribution functions (Hawkins, 1982; Kinner and Moody, 2010), which can provide a spatial average of an effective value of the soil-hydraulic properties. Runoff begins when rainfall intensity exceeds this effective spatial average. Additionally, some runoff prediction methods simulate

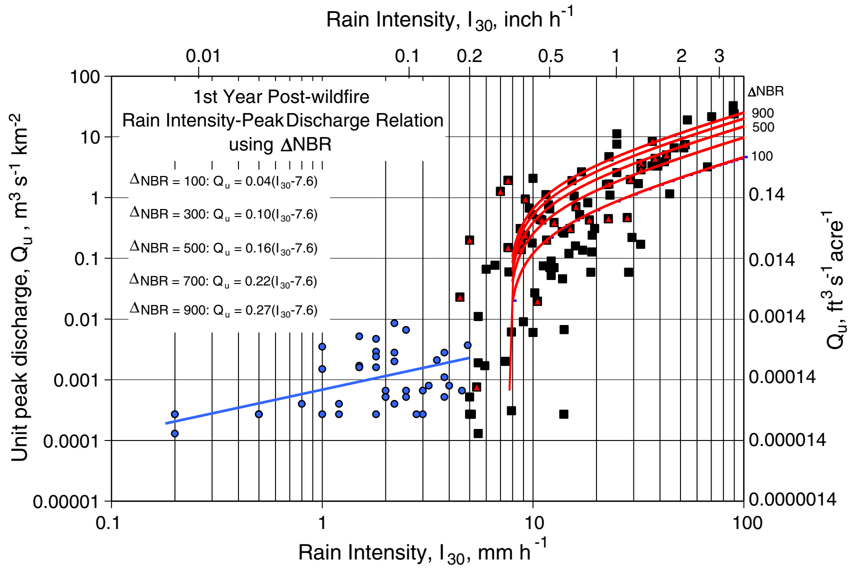

Fig. 9. Relation between peak discharge per unit burned area (Q_u) and the 30-minute maximum rainfall intensity, I_{30}, for paired rainfall and runoff data from 19 mountainous basins in different post-wildfire response domains in the western United States. The relation is based on data from basins ranging in size from 0.25 to 25 km^2. The data indicate a distinct I_{30} rainfall threshold, which is 7.6 mm h^{-1} (based on results for the first year after wildfire). Solid blue circles represent maximum $I_{30} < 5$ mm h^{-1} and correspond to perennial streams. Maximum $I_{30} > 5$ mm h^{-1} values are shown as black squares and generally correspond to ephemeral channels. Red triangles represent basins having an average value of the change in normalized burn ratio, ΔNBR = 581 ± 5%. Red lines correspond to the relation for ΔNBR = 100, 300, 500, 700, and 900. See report by Moody (2012) for more details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the spatially variable micro-topography as well as the rainfall-infiltration for shallow overland flow (Fiedler and Ramirez, 2000). The Relative Surface Connection (RSC) function determines the percentage of the depression storage (Fig. 7, and see 5.2.3 below) contributing to the outlet (Antoine et al., 2011). Contributing areas, like source areas for channel initiation, probably also depend on the topographic slope (Montgomery and Dietrich, 1988; Dietrich et al., 1992), which can be highly variable in mountainous terrain. All variables controlling the size of the contributing area (Fig. 10) during a rainstorm are as yet unclear, but it is reasonable to assume that it will depend on: (1) rainfall intensities; (2) the corresponding rainstorm "footprint" (see Section 3); (3) topographic depressions and sinks representing scattered "holes" in the contributing area, (4) the area and degree of burn severity, and (5) the storm trajectory and storm profile (see Section 3).

5.2.3. Depression storage and surface roughness

Depression storage may increase after wildfires in some forested areas because of the creation of burnt-out stump and root holes (Figs. 7B and 10), and by tree root throw during or immediately after wildfire (Gallaway et al., 2009). Some of these holes might represent additional depression storage that could create an additional runoff threshold similar to the fill and spill hypothesis for subsurface flow (Tromp-van Meerveld and McDonnell, 2006). This situation would contribute to the runoff at different times (Antoine et al., 2011). On the other hand, some holes might represent distinct flow pathways for infiltration (see Section 4) and thus reduce potential runoff (e.g. Ferreira et al., 2005; Martin et al., 2008). These effects have yet to be adequately quantified and need to be addressed.

Surface roughness is a small-scale property but it is important because it controls runoff on hillslopes and in channels through the frictional resistance parameter. Surface roughness can change after wildfire by the consumption of vegetation, litter and duff, and surface obstacles (such as branches, logs, and plant stems), and by the deposition of an ash layer of variable thickness. Post-wildfire surface roughness may appear smoother (Fig. 7C) and better connected than for pre-fire conditions at the hillslope scale (~10–100 m), but overland flow is still controlled by the large relative roughness (ratio of the micro-topographic heights, *d* [L], to the flow depth or hydraulic radius, *R* [L], Smart et al., 2002) at the point-plot scale (~0.1–1 m). The relation between the friction factor (Manning's *n* or Darcy-Weisbach friction factor, *f*) has been investigated in channels (Nikora et al., 2001) and on some unburned hillslopes (Lawrence, 1997) where $f \sim (d/R)^2$ for low-relative roughness changes to $f \sim R/d$ for high-relative roughness on hillslopes (Lawrence, 1997). Surprisingly few studies (cf. Rulli and Rosso, 2005; Wagenbrenner et al., 2010) of the effects of wildfire on surface friction have been published. Recent advances in terrestrial and airborne LiDAR continue to improve digital elevation model (DEM) resolution, so that the importance of depression storage and changes in surface roughness may be better understood with future research (Staley et al., 2010).

5.2.4. Connectivity of overland-flow generating areas

Soil patches with different size and soil-hydraulic properties combined with scattered depressions, burnt-out stumps, and root holes highlight the need to consider spatial connectivity of overland flow. Several publications have begun to address this issue. The Relative Surface Connection function (Antoine et al., 2011) calculates the proportion of depression storage connected to the drainage outlet derived from the effective rainfall intensity (see Section 3), but omits detention storage (i.e. additional water flowing over the surface). Some researchers have expressed this concept as the connectivity length scale (analogous to the correlation length scale in turbulence, Batchelor, 1982) of spatial patterns of soil properties such as soil moisture, whose value in a pixel is either above (+1) or below (0) a selected threshold (Western et al., 2001). This length scale can be calculated for isotropic patterns or along a flow path to provide a 'bulk descriptor of spatial variability' but it is scale dependent (Western et al., 2001) and not originally designed for runoff (Mayor et al., 2008). Other researchers have quantified the connectivity of runoff source areas (pixels depicting bare soil) by defining a 'Flowlength' index (Mayor et al., 2008) as the average length of all potential flow paths based on a binary map of sources (bare pixels) and sinks (vegetative pixels or micro-depressions) and a single flow direction algorithm. 'Flowlength' correlates with total runoff and total sediment yield and these correlations increase with storm size. Although the original primary focus was on vegetation distribution, this approach could include micro-topographic roughness (depending upon the pixel size of the DEM) caused by surviving post-wildfire plant mounds and probably burnt-out stump and root holes. Cawson et al. (2010) measured the effect of the length of unburned patches downslope from burned patches, and Moody et al. (2008a) defined the process-based hydraulic functional connectivity variable specifically for burned basins. This variable incorporates the magnitude of the burn severity through changes in the normalized burn ratio (ΔNBR see Section 4) and the spatial sequence of ΔNBR along flow paths with weighting proportional to the upstream contributing area.

Internal or external thresholds (Schumm, 1980; Davenport et al., 1998; Cammeraat, 2004) are important in establishing connectivity. They are often reflected as an abrupt change in runoff response highlighting the non-linear nature of this response. Future post-wildfire research needs to examine these connectivity variables, and possibly others, to determine how best to represent hydraulic properties of connectivity in order to predict post-wildfire runoff and erosion. Advances in process-based erosion modeling now allow multiple overland flow hillslope elements to capture some of the spatial variability and connectivity (Robichaud et al., 2007b), but there is room for improvement. Moreover, easily available DEMs tend to have too coarse a spatial resolution (generally 30-m pixels but sometimes 10-m pixels) to provide sufficient resolution of hillslope drainages and channels needed to apply some of these connectivity variables. Thus, an increase in DEM resolution is essential to help advance this issue of post-wildfire research. However, some hydrological models may require lower resolution than the input data, and up-scaling procedures (e.g. Milzow and Kinzelbach, 2010) would be needed to provide connectivity variables measured at plot or hillslope scale for use at the basin scale.

5.3. The significance of geomorphic properties

In general, most burned basins are ungaged before a wildfire, which highlights the need to determine the important geomorphic characteristics that might be used to predict the timing and magnitude of runoff immediately after a wildfire. These characteristics can be derived from DEMs and readily incorporated into basin response models. Typically, large wildfires in the US average no more than about 10^3 km^2 in extent (NIFC, 2011) and in southern Europe they are typically much smaller (e.g. European Commission, 2012). At this scale the detailed morphology of a burned basin, its hillslopes, as well as the valley drainage networks (Fig. 7C) could all influence the timing, shape, and magnitude of the flood or debris-flow hydrographs (Kirkby, 1976; Sun et al., 1994; Dick et al., 1997; Moody and Kinner, 2006; Kean et al., 2011). Specifically, hillslope and channel drainage morphology can affect the geomorphic instantaneous unit hydrograph (GIUH; Rodriguez-Iturbe and Valdes, 1979) used in flood hydrograph predictions (D'Odorico and Rigon, 2003). At present, though, information incorporated into the GIUH theory is limited to knowing the effective rainfall (see Section 3) and it assumes the same constant runoff velocity in the hillslope drainage networks as in channels. This requires unrealistically uniform roughness or friction factors. As described in the previous section, additional insight is needed to parameterize spatial changes in surface roughness, which would lead to incorporating variable velocities into models, and to improved predictions of time-to-peak and the peak discharge. Another approach has been to statistically evaluate multivariate combinations of larger basin geomorphic characteristics (such as relief ratio, basin ruggedness, and basin gradients) as predictors of the probability of post-wildfire debris flows and debris flow volumes (Cannon et al., 2010).

5.4. Future research directions

Post-wildfire runoff occurs predominantly in ungaged basins and generally only empirical relations are available to predict peak flood discharges and little information is available for predicting when a flood will start. Modified infiltration theory (see Section 4) needs to be included in runoff predictions in order to improve estimates of the effective rainfall that is used in most rainfall–runoff models. The additional priority research issues addressing the runoff process are:

(1) What are the effects of connectivity and surface roughness on post-wildfire runoff? How should they be parameterized and how are they linked with the spatial distribution of soil-hydraulic properties (Section 4), depression storage, and geomorphic properties of drainage networks at hillslope and possibly basin scales?
(2) How does the contributing area change with rainfall characteristics (Fig. 10) for different post-wildfire response domains, and which runoff thresholds might be connected to the contributing area?
(3) At what scales are the geomorphic characteristics of drainage patterns important in predicting post-wildfire runoff?
(4) What are the underlying scale-dependent physical causes for rainfall thresholds that affect the timing and magnitude of different post-wildfire processes? These causes are required in order to allow generalization and transfer of results to other post-wildfire domains.

6. Soil and sediment erosion and transport

6.1. Background

Variability in post-wildfire erosion responses is caused by differences in the runoff and erosion and transport processes that operate in a given domain. For instance, there are some post-wildfire domains such as the relatively flat terrain of the Alaskan-spruce bog forest that may produce no response, whereas others such as the steep, tectonically active terrain of the California-chaparral forest may produce catastrophic debris flows. Distinctiveness in responses is not caused

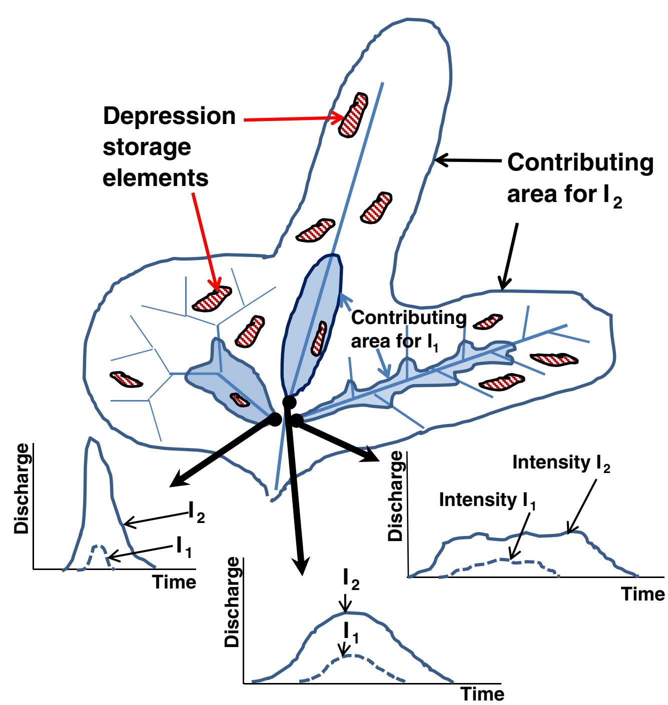

Fig. 10. A conceptual diagram showing how the morphological pattern of drainage networks in channels and on hillslopes (not shown) might affect the timing and peak values of runoff hydrographs. Three sub-basins are shown with different morphologies. There is the question of which rainfall metric should be used (see Fig. 2). The runoff hydrographs relate to two different rainfall intensities, I_1 (dotted line) < I_2 (solid line), and the corresponding contributing areas are labeled.

just by differences in topographic slope, but are complex responses (Schumm, 1973) to the temporal and spatial variability of fire-affected soils (Section 4), rainfall (Section 3), infiltration (Section 4), and runoff (Section 5) processes. These processes are often characterized by thresholds that lead to nonlinearities in the erosion response. The thresholds can be external (Schumm, 1979; Cammeraat, 2004) such as that for infiltration-excess runoff and those for rainfall-intensity associated with peak discharge (see Section 5.2.1) or they can be internal (Schumm, 1979; Cammeraat, 2004) such as the relatively abrupt temperature threshold at about 220 °C, which controls the magnitude of the critical shear stress required to initiate erosion (Moody et al., 2005), consumption of fine roots that often hold soil and soil aggregates together (Mataix-Solera et al., 2011), soil gradation (i.e. amount of fines), and the critical gradient needed to initiate dry ravel (Roering and Gerber, 2005). Additional complexity is caused by the non-uniformity in the spatial distribution of sediment sources where sudden pulses of sediment or water can change the transport process at each tributary confluence downstream (Santi et al., 2008), and feedback processes where sediment transport on hillslopes can change the surface roughness, causing changes in runoff patterns and sediment transport (Imeson et al., 1992; Kirkby, 2011).

Key variables in post-wildfire erosion responses are runoff and sediment availability. Explanations for increased post-wildfire runoff are discussed above (Section 5.2). Sediment availability denotes the sediment supply (its quantity) and its associated erodibility (cohesive soils) or mobility (non-cohesive sediment). Soil erodibility depends on the specific erosion process, has been measured primarily for relatively homogenous agricultural soils, but is rarely constant (Bryan, 2000). In the context of fire-prone terrain with heterogeneous soils, erodibility can be particularly variable in response to changes caused by heating during wildfires and to the intra- and inter-storm changes in soil moisture conditions after wildfires. Soil depth, heat-induced changes in soil properties such as critical shear stress (Florsheim et al., 1991; Moody et al., 2005) and soil aggregate stability (Mataix-Solera et al., 2011), SWR (Doerr et al., 2000, 2009) can also lead to differences, as can root characteristics (Gyssel et al., 2005; Shakesby et al., 2007; Moody and Nyman, 2012) (Fig. 11). Mobility of non-cohesive sediment in rills, gullies, and channels depends on critical shear stress to initiate motion for a given particle diameter (Wiberg and Smith, 1987). Traditional theories for small relative roughness (ratio of the particle diameter to the flow depth) predict an increase in particle mobility as the channel slope increases, but there is evidence that the critical shear stress relation differs for large relative roughness (Lamb et al., 2008) and steeper slopes, typical of post-wildfire floods and debris flows.

In general, most currently available erosion prediction models applied to forest environments have evolved from models developed using plot studies on agricultural soils on low-angled slopes (Bryan, 2000). The applicability of these models to post-wildfire conditions, therefore, has distinct uncertainties (González-Bororino and Osterkamp, 2004) because slopes are often steep (Wagenbrenner et al., 2010), with heterogeneous soil-hydraulic properties (see Section 4) and surface conditions (see Section 5). The complexities of these post-wildfire erosion responses have resulted in the development of probabilistic models for prediction (Robichaud et al., 2007b), which require information on post-wildfire soil erodibility that is currently rarely available. Given this complexity, it is not surprising that it is difficult to extract simple cause and effect relations. Because of the many types of erosion and transport processes, a brief summary of each process is described below.

6.1.1. Dry ravel

This process depends on gravity, wind, and animal activity rather than water to detach and transport soil (Anderson et al., 1959; Krammes, 1965; Rice, 1982; Florsheim et al., 1991; Gabet, 2003a; Moody, 2010). Therefore, it is sensitive to the angle of repose or critical gradient (Roering and Gerber, 2005) and the amount of sediment supply on the hillslope. Some of the dry ravel sediment is trapped by vegetation (Florsheim et al., 1991; Lamb et al., 2011), so that it becomes mobilized when the vegetation is burned. The process is thought by some to be the dominant source of post-wildfire hillslope sediment redistribution in southern California (Wohlgemuth and Hubbert, 2008; Lamb et al., 2011). Sediment mobilized in this way can reach the channel directly and can also act as a source of sediment for debris flows. Thus, dry ravel can increase sediment availability in the channels while reducing availability on the hillslopes. It has been modeled for burned areas as a non-linear function of hillslope gradient with a transport rate coefficient, k [L^2 T^{-1}], (Roering and Gerber, 2005; Rulli and Rosso, 2005). Where wildfires are frequent and post-wildfire erosion is high, the soil production rate would be expected to limit soil thickness and distribution and thus the magnitude of the dry-ravel process (Roering and Gerber, 2005), but other research suggests that increased soil production rates are unnecessary to explain substantial soil losses by fire-induced dry ravel following successive wildfires (Lamb et al., 2011). Dry ravel can mobilize large quantities of sediment and since it is independent of rainfall it has a unique position in the understanding of post-wildfire erosion response in the face of expected higher temperatures, increased dryness, and more wildfires in the future. With more wildfires and more people living in fire-prone areas where this process is common, the need to understand dry ravel is likely to increase in importance.

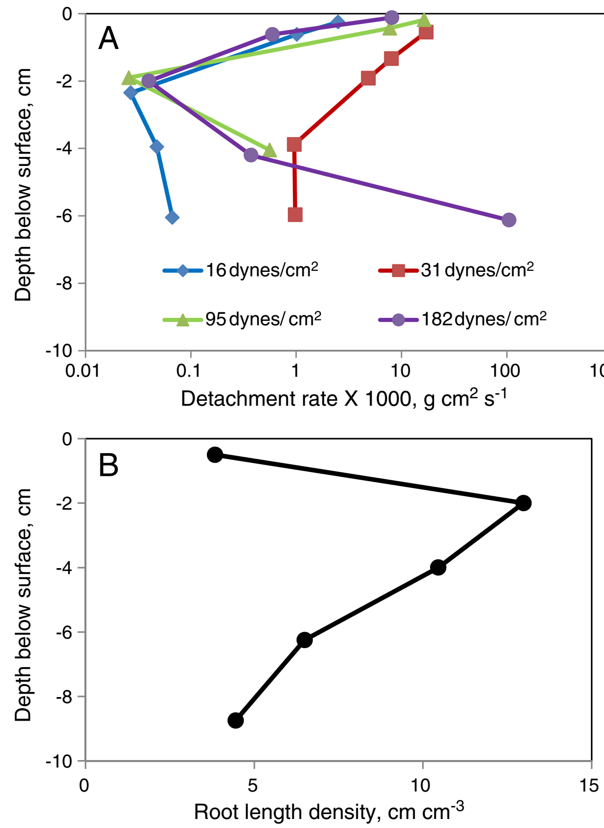

Fig. 11. (A) Measurements of soil detachment as a function of depth below the soil surface were made in a small tilting flume on soil cores with an ash layer. The soil cores were collected in the area burned by the 2010 Fourmile Canyon Fire. (B) Root length density plotted as a function of depth below the soil surface for the measurements shown in A (Moody and Nyman, 2012).

6.1.2. Raindrop, rain-flow, and interrill erosion

Raindrop impact is one of the most obvious and effective detachment processes (Gabet and Dunne, 2003). It is important on burned hillslopes where initially litter and duff has burned exposing patchy areas of bare soil, and later when the patchy ash layer has been removed re-exposing bare soil. Raindrop impact can combine with shallow overland flow near the top of hillslopes to create rain-flow transport (Moss, 1988; Moody, 2010) that can change to interrill or sheet flow further downslope (Inbar et al., 1998; Moody and Martin, 2001c; Benavides-Solario and MacDonald, 2005; Rulli and Rosso, 2005; Mayor et al., 2007; Sheridan et al., 2007). The process depends on slope angle and has been modeled at the burned basins scale using the raindrop erodibility coefficient κ_c [M^{-1} T^2 L^{-2}] (Rulli and Rosso, 2005). The detachment component of this process may also depend on air entrapment (see Section 5.2). This has been observed in laboratory flumes when trapped air escapes explosively carrying soil particles into the flow (Suhr et al., 1984; Moody et al., 2005; Moody and Nyman, 2012). However, this process has not been observed and measured in the field so that its magnitude and importance are unknown.

The combined effect of raindrop, interrill, and rill erosion can be estimated from the Universal Soil Loss Equation using the bulk soil erodibility K-factor [L^{-3} T^3] (see Section 2.3), based on total sediment yield per unit rainfall erosive index from standard plots (Wischmeier and Smith, 1978). Interrill erodibility, alone, has been modeled by assuming erosion is proportional to the rainfall intensity with erodibility equal to K_i [M T L^{-4}], (Foster et al., 1995). Why interrill erosion or sheetwash dominates in one post-wildfire domain (Fig. 12A) and rill erosion in another (Fig. 12B) may depend on fire-induced changes in soil erodibility and may be affected by root properties (Sheridan et al., 2007; Moody and Nyman, 2012).

6.1.3. Rill erosion

On some post-wildfire hillslopes, interrill or sheetflow erosion dominates (Sheridan et al., 2007) whereas on others, rill erosion dominates (Moody and Martin, 2001c; Robichaud et al., 2010; Wagenbrenner et al., 2010; Kean et al., 2011). Rill erodibility has been modeled by assuming erosion depends on either the excess shear stress (Hairsine and Rose, 1992; Foster et al., 1995; Wagenbrenner et al., 2010) with the erodibility given by K_r [T L^{-1}], or on the stream power (Wagenbrenner et al., 2010) with erodibility given by K_Ω [M L^{-1}]. Rill erodibility for areas burned at high severity has been found to be about three orders of magnitude greater than for unburned soils, and to decrease with time in response to changes in the available sediment over timescales of minutes (Pierson et al., 2008; Wagenbrenner et al., 2010). Rill erosion in steep terrain, where shear stresses and transport capacities increase rapidly with slope, may differ from that used in models developed for agricultural soils (Foster and Meyer, 1972) where slopes are less. Thus, future research into dynamic rill erosion for burned areas is required to better understand how: (1) erodibility changes with time; (2) steeper slopes can be accommodated; (3) changing sediment availability alters rill or channel shapes, and (4) changing rill or channel roughness affects rill erosion processes.

6.1.4. Landslides and slope failures

Landslides and slope failures depend on the shear strength of the soil. Shear strength is a function of soil pore-water pressure, internal friction angle, and root cohesion (Schmidt et al., 2001). Dry soils generally have negative pore-water pressure, which tend to augment shear strength (Rahardjo et al., 2005) and produce stable slopes, whereas rainfall infiltration or snowmelt can produce wet soils near saturation with low shear strength that is conducive to landslides or slope failures (Gabet and Mudd, 2006; Germer and Braun, 2011). Roots generally increase cohesion, shear strength, and slope stability. However, wildfires can kill trees and later as their roots decay, slope stability decreases and landslides and slope failures are more common (Benda and Dunne, 1997; Jackson and Roering, 2009). While old roots decay, new roots are growing so that root strength reaches a minimum 8–12 years after the trees have died, which leads to an associated increase in landslides and slope failures (Schmidt et al., 2001; Jackson and Roering, 2009).

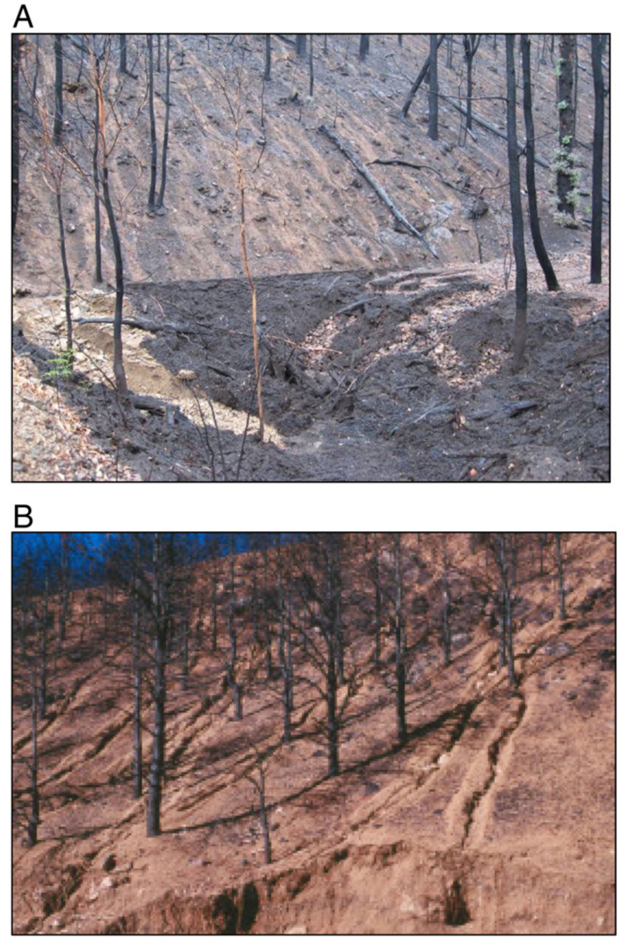

Fig. 12. (A) Sheetwash erosion with a braided pattern dominates on a hillslope burned by the Black Saturday 2009 wildfires in the Kinglake area of Victoria, Australia. Ash has accumulated in the hollow in the middle of the photograph taken in March 2009 about one month after the wildfires. (B) Rill erosion on a hillslope burned by the 1996 Buffalo Creek wildfire in the Colorado Front Range southwest of Denver, Colorado, USA.

6.1.5. Drainage, channel, and debris flow erosion

Drainages are hillslope depressions (Fig. 7C) where runoff is concentrated, but where the flow is insufficient to create a channel with distinct banks. Increased runoff from burned areas, however, can cause these features to become incised and form channels (Collins and Ketcham, 2005; Moody and Kinner, 2006; Moody et al., 2008b). At this scale, flow depth is often greater than roughness heights (low relative roughness) so that traditional sediment transport models for bed-load (Gomez, 1991) and suspended-load (Yang, 2006) may be applicable if sediment concentrations are low. But, an important caveat for the use of these models is that these channels are steeper than those for which traditional transport models have been developed, and changes in the frictional resistance equations are necessary (Armanini and de Silvio, 1991; Wohl, 2010; Lamb et al., 2011). Debris flows represent a special case of sediment-laden flow in channels. They are classed as non-Newtonian fluids with unconsolidated sediment concentration of 50–77% by volume creating an interstitial fluid of water and fine sediment resembling 'wet concrete' and capable of supporting gravel and boulders while flowing (Pierson and Costa, 1987; Costa, 1988; Iverson, 1997). They operate, however, for relatively short periods ($<10^4$ s) (Iverson, 1997), and have been reported in many different post-wildfire response domains

(Conedera et al., 2003; Van Dine et al., 2005; Cannon et al., 2010; Nyman et al., 2011; García-Ruiz et al., 2012; Sass et al., 2012b).

An important though poorly understood threshold is the triggering mechanism for debris flows in different post-wildfire response domains. One mechanism has been described as the progressive entrainment of soil eroded from hillslopes and channels by overland flow (Wells, 1987; Meyer and Wells, 1997; Cannon et al., 2001a, b; 2003; Cannon and Gartner, 2005; Santi et al., 2008) coupled with the role of ash to provide sufficient fine-grained material (Gabet and Sternberg, 2008) to support the sediment. The change from sediment being supported by fluid-turbulence forces to sediment being supported by fluid-turbulent and solid forces (Iverson, 1997) and the sediment entrainment process (McCoy et al., 2012) are not understood. A second possible mechanism is saturation of soil above the fire-induced water repellent 'layer', which initiates 'thin debris flows' (Gabet, 2003b). A third possible mechanism results from shallow landslides induced by infiltration into soils with low soil hydraulic conductivity, which increases pore pressure resulting in liquefaction and mobilization (Gabet, 2003b). This is a mechanism observed in unburned settings (Gabet and Mudd, 2006; Gabet and Sternberg, 2008) where the ratio of fines to sand-size particles appears to be as important as the hydraulic conductivity, but it cannot account for increases in the size of a debris flow (Santi et al., 2008). The first mechanism depends on soil erodibility, the second on the intensity and spatial variation in SWR patches, and the last on shear strength and hydraulic properties of subsurface soils.

6.2. Sediment availability

Wildfire directly increases sediment availability in two ways. First, the canopy, litter, and duff layers are burned, which increases the sediment supply by exposing large areas of bare soil on hillslopes to erosive forces once the protective layer of ash is removed from the system, and second, the heat pulse into the soil changes the erodibility by altering aggregate stability (Mataix-Solera et al., 2011), reducing the critical shear stress needed to initiate motion (Moody et al., 2005; Wagenbrenner et al., 2010), increasing transport rate coefficient (Roering and Gerber, 2005), and decreasing root cohesion (Moody and Nyman, 2012). However, the thickness of the erodible soil is unknown, and transient, as it is depleted by erosive forces. This eventually limits the sediment delivery to channels (Meyer and Wells, 1997; Desilets et al., 2007) as a source of sediment for floods and debris flows. Another source of potential sediment are stream banks in the riparian zone that may have been unaffected by wildfire. These sources represent an indirect increase in sediment availability as a consequence of the increased runoff response after wildfires. However, at present, no reliable methods exist for assessing the spatial distribution of these sources of sediment.

Some investigators have used time-since-last fire (Rowe et al., 1954) as a proxy for estimating the sediment supply, whereas others have used a more direct surveying method (Staley et al., 2010; Schmidt et al., 2011). This consists of differencing pre- and post-flood, high-resolution (millimeter to centimeter scale) terrestrial LiDAR surveys combined with detailed process mapping and characterization of geomorphic form to identify the locations of sediment sources (Fig. 13). Vegetation can trap sediment (Lamb et al., 2011), so that vegetation maps might provide estimates of the sediment supply for the dry ravel process (Gabet, 2003a). Determining the sediment availability for channel erosion will depend on understanding the sediment entrainment processes for flow in steep channels (Armanini and de Silvio, 1991; Takahashi and Sawada, 1994; Wohl, 2010; Lamb et al., 2008). However, additional research is needed into other fluvial and debris flow transport processes and exploration of remote sensing methods to determine to what extent the sediment supply in a basin might depend on basin and channel geomorphic and geologic properties (e.g. curvature, slope, drainage density, and bedrock geology). Determining the initial sediment availability and the changes in erodibility and supply is one of the most challenging issues of post-wildfire erosion prediction.

6.3. Post-wildfire erosion and transport measurements

In response to the variety of post-wildfire erosion and transport processes operating at different scales, a range of measurement methods have been used. 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. These different scales are also part of the reason for the numerous methods developed to measure post-fire sediment response. Some examples are: (1) ground-level changes measured with erosion pins or a micro-profiling device such as an erosion bridge; (2) surveyed hillslope or channel cross sections; (3) suspended-sediment samplers; (4) bounded and unbounded hillslope plots; (5) amounts of sediment trapped behind silt fences and debris dams; and (6) sediment accumulated in small reservoirs. Each has produced a different unit of measurement (Shakesby and Doerr, 2006; Moody and Martin, 2009a). The use of sediment yield (mass/horizontal area/year) has been inherited from past sedimentary research focusing on long-term, larger-scale questions comparing continental scale erosion over decades. The use of yield has continued, probably for the sake of comparisons, but it may not best represent small-scale erosion processes in burned basins, their episodic character (changing over minutes or hours), or the nature of post-wildfire erosion itself. Thus, a measure of sediment yield might be suitable for hillslope erosion processes, but other means of expression might be more suitable for channel erosion processes (mass/cross-sectional area/unit of time), impacts on fish habitat (mass/width/time), and denudation (depth removed/unit area/unit of time).

One problem with most field measurements of erosion is that they tend to be continued only over short periods (typically no more than 3 years) and generally span only part of the recovery period after a wildfire. Thus, long-term perspectives of wildfire impact are few (Heede et al., 1988; Cerdà and Doerr, 2005; Cerdà and Lasanta, 2005), and more are needed to understand the effect on ecosystems over longer timescales. Other methods that can provide both a perspective on the order of decades in length and a relatively large-scale view include the measurement of ^{137}Cs (Menéndez-Duarte et al., 2009), which has been used in conjunction with other cosmogenic radionuclides (Blake et al., 2009; Smith et al., 2011b,c), and assessment of the sediment volumes in reservoirs draining burned areas. The use of sediment tracers is a large field, and we refer the interested reader interested to the review by Smith et al. (2012). However, each method has its own sets of problems. Some often require very exacting conditions to be used successfully, and fire-related erosion may be difficult to separate from that produced between wildfires. Because the number of cosmogenic radionuclide applications relating to wildfire is relatively small (Smith et al., 2012) to date, there has been little opportunity to cross-check estimated erosion rates with those gathered using more conventional methods.

Prediction of erosion and deposition can be affected by the temporal variability of rain (Benavides-Solario and MacDonald, 2005; Rulli et al., 2006; Mayor et al., 2007) so that it is important to normalize erosion values according to some rainfall measure (e.g. rainfall total, rainfall intensity, or some function of rainfall intensity). Normalizing on a storm basis assumes all storms have the same duration. It also tends to bias results by excluding the long intervals between storms when there is virtually no erosion. Some published values of sediment yield have been normalized by total cumulative rainfall (Johansen et al., 2001) and rainfall erosivity (Spigel and Robichaud, 2007). All these different measurement units have made it difficult to compare post-wildfire sediment responses (Shakesby and Doerr, 2006; Moody and Martin, 2009a). An important objective for the

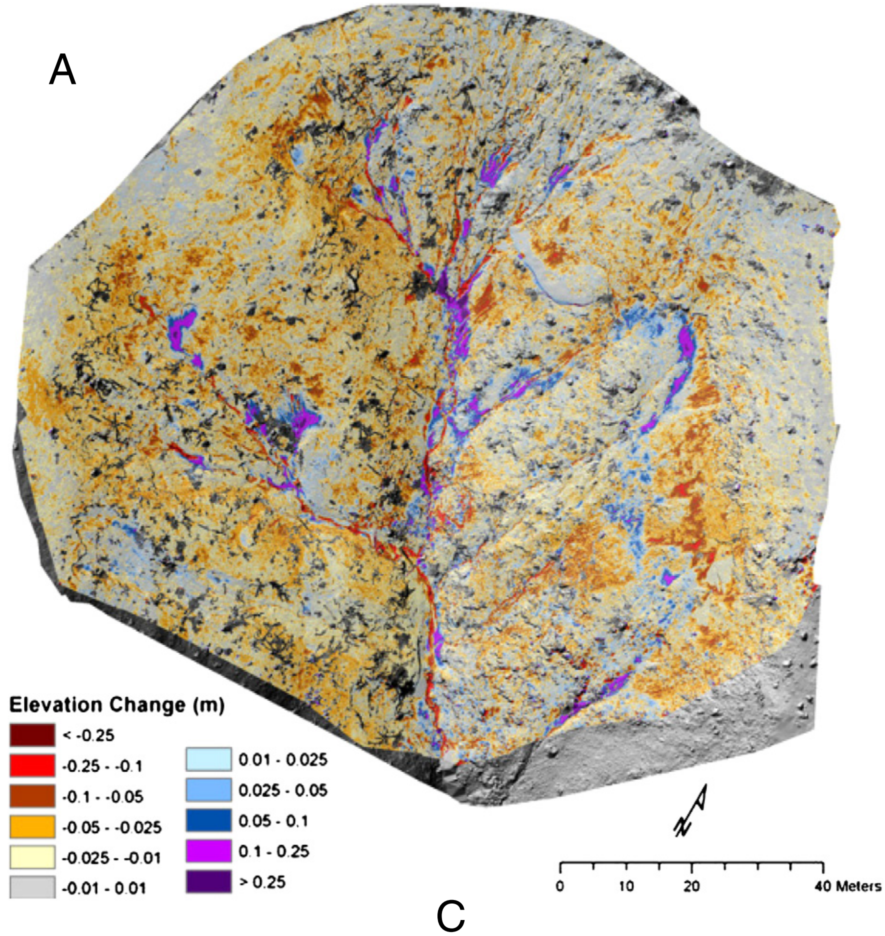

Fig. 13. A. Estimates of available sediment made by differencing two tripod mounted LiDAR surveys (September 2008 and December 2008) in a small watershed burned by the 2008 Gap Fire in California. Sediment source areas are shown in yellow–red–brown colors and depositional areas are shown in blue–violet colors (Staley et al., 2010).

future is to determine which standard measurement methods are appropriate for post-wildfire sediment research and how they can be implemented to ensure that vital, though not necessarily difficult, measurements are made (provided a researcher is aware of the need) in the future to provide comparable data. A means of speeding up the dissemination process might be to set up a website similar to that available for sediment charcoal data (International Multiproxy Paleofire Database Charcoal Sediment Data; http://www.ncdc.noaa.gov/paleo/impd/impd_char_submit.html).

6.4. Causes of differences in processes between post-wildfire domains

Post-wildfire erosion and transport are especially complex non-linear processes because they depend on a 'web-like' pattern of other non-linear processes such as meso-scale rainfall, infiltration into water-repellent soils, scale-dependent runoff, and sediment availability. It appears to be difficult to disentangle this web to identify why one process dominates in one post-wildfire domain and another dominates elsewhere. Perhaps, it should be assumed that all erosion and sediment transport processes are possible, but one or two are selected to dominate at any given time in response to the particular characteristics of the fire, precipitation, and hydro-geomorphic regimes. For example, in some domains, in response to specific storm conditions, channel erosion contributes more sediment than hillslope erosion (Moody and Martin, 2001b, 2009a; Santi et al., 2008), whereas in other domains (though also sometimes in the same domain) in response to less intense rainfall, most material is derived from hillslopes (Staley et al., 2010). In yet another domain, dry ravel is produced (without any rainfall) in abundance and contributions from hillslope and channels are considered to be about equal (Wohlgemuth per. commun. 1999; Wohlgemuth and Hubbert, 2008).

Surface erosion by infiltration-excess overland flow has been documented in many post-wildfire response domains (Martin and Moody, 2001; Kinner and Moody, 2010; Robichaud, 2000; Pierson et al., 2001, 2007; Nyman et al., 2011; Ebel and Moody, 2012; Lane et al., 2012), but does not appear to be important in others (Wondzell and King, 2003). The proportion of infiltration-excess and saturation-excess overland flow varies over long periods and shorter periods within individual storms (Schmidt et al., 2011; Ebel and Moody, 2012), and it is likely that the proportion of these mechanisms varies between post-wildfire response domains. Similarly, debris flows have different dynamics at the same site for different rainstorms (Kean et al., 2011), and debris flow initiation processes have been found to vary between runoff-dominated and infiltration-dominated (Cannon et al., 2001a, b; Jackson and Roering, 2009).

A proposed first step in understanding the reasons for the dominance of specific erosion and sediment transport processes in certain post-wildfire response domains would be to initially identify and compile in a database the quantitative metrics for the fire, precipitation, and hydro-geomorphic regimes (see Section 2) associated with each process, its magnitude, and any related thresholds. This would provide the initial framework. A second step could be to include measurements of the changes in the relevant soil and soil-hydraulic properties, which would allow further sub-classification of the processes within the organizational framework of the post-wildfire domains. These domain-specific datasets could then be synthesized and common processes, patterns, and generalities identified.

Measurements of soil properties and actual measurements of the magnitude of the post-wildfire erosion and sediment transport responses would need to be made using standard procedures in order to produce comparable data. Such a *modus operandi* would probably be best achieved through collaboration and consultation amongst experts. An international meeting or special sessions at meetings of interested scientists would provide the forum for the necessary debate leading to the choice of standard methods of measurements in order to improve comparability of results from around the world. Additionally, multiple sites could be identified and measurements continued for several years after a major wildfire (as a long-term program) to determine the impacts of wildfire on the environment. This would provide process-based data (collected using standard methods) for improving long-term post-wildfire erosion and transport models used by land and emergency managers.

6.5. Future research directions

Multiple post-wildfire processes can erode and transport soil and sediment, which depend on sediment availability. Each of the multiple processes summarized in Section 6.1 defines a different erodibility 'constant' linked to soil properties. However, erodibility is not a true constant but rather dependent on factors with different temporal scales such as soil–water content, SWR, organic matter, and sediment supply, but also on the spatial distribution of the fire-affected soil properties. The primary research issues are:

(1) What are the relations between quantitative metrics for burn severity and erodibility parameters as a function of soil depth, soil types, and root properties?
(2) What is the sediment entrainment and transport processes for flows in steep, rough channels?
(3) What standard measurement methods can be used to assess the sediment supply on hillslopes and in channels?

7. Summary

A large body of empirical data and related physical understanding now exists concerning complex post-wildfire runoff and erosion processes for many different post-wildfire domains throughout the world. A common theme within each of the four major processes (precipitation, infiltration, runoff, and soil and sediment erosion and transport) discussed has been the need to understand their temporal and spatial distributions (Fig. 14). It is evident that post-wildfire responses are the result of the superposition of the spatial distribution of precipitation upon the spatial distribution of fire-affected soil properties and complicated by changes with time on different time scales. Soil properties have been shown to be a critical link between all major processes (Fig. 14).

Thus, the highest priority for future post-wildfire runoff and erosion research is to understand the relations between soil properties

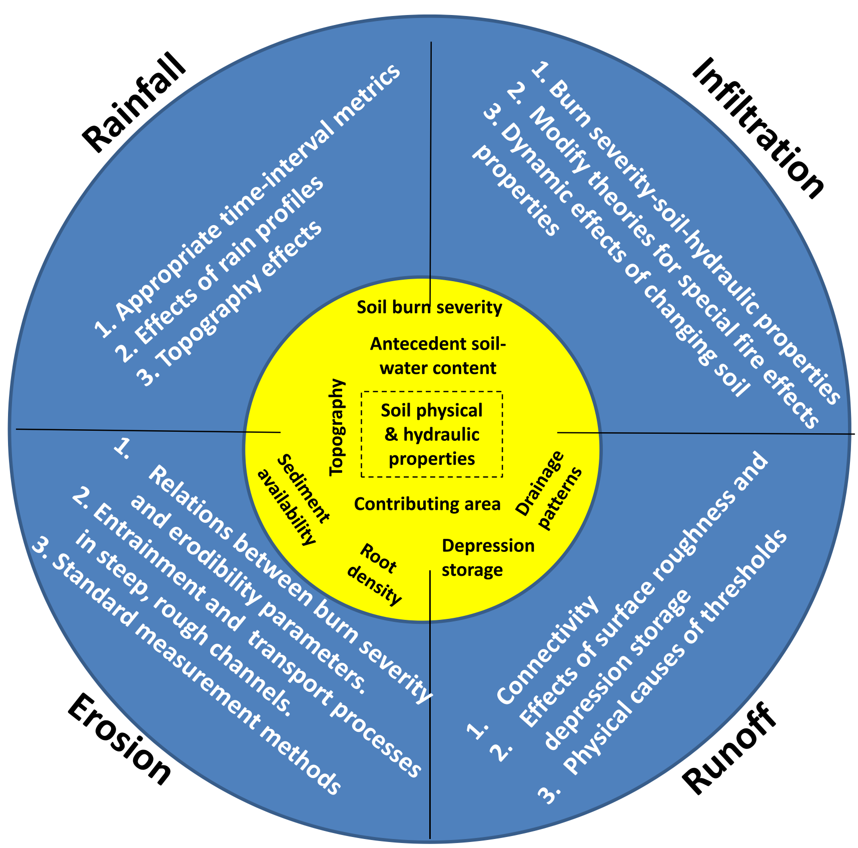

Fig. 14. Schematic representation of the research issues for the four major processes of post-wildfire runoff and erosion response discussed in the text. The thin black lines divide the diagram into the four processes (precipitation, infiltration, runoff, and erosion), where the central yellow circle represents the factors associated with each process. Where a factor spans one or more of the processes (for example, 'soil burn severity'), then a link between the respective processes is indicated. The main research issues for each process are given in the outer blue circle. The ultimate goal is to organize and synthesize the vast amount of empirical data from different post-wildfire domains in order to better understand each process, the reasons for differences in response, and to specifically predict, as close to real time as possible, the post-wildfire runoff, erosion, and sediment transport response if a wildfire should burn an unburned basin in one of the post-wildfire domains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and burn severity metrics (which include soil–water repellency metrics). Soil properties include (1) the soil–water content that may affect meso-scale rainfall, (2) the soil-hydraulic properties (soil–water retention characteristics, sorptivity, and saturated and unsaturated hydraulic conductivity) that control infiltration, connectivity, and contributing area, (3) the physical changes in soil properties that cause sealing, depression storage and changes in surface roughness, and (4) the multiple soil erodibility parameters. All these soil properties may change abruptly during a wildfire and then change more slowly after it.

The second priority is to appropriately characterize meso-scale rainfall because it is the primary driver for post-wildfire responses. The physical basis for determining the time-interval metrics that best predict runoff and erosion and how these depend on scale need to be understood if what is learned in one post-wildfire response domain is to be applied to other less studied domains. Additionally, suitable sequence metrics must be selected to represent the effects of the temporal distribution of rainfall on post-wildfire runoff and erosion (Fig. 14).

The third priority is to develop methods to determine sediment supply and to modify existing sediment transport algorithms so that they can be used to predict entrainment of soil and sediment and transport through steep, rough channels. To help overcome the lack of sufficient runoff and erosion and transport data from burned basins, the importance of morphological characteristics of the burned basins needs to be investigated so that their effects can be incorporated at appropriate spatial and temporal scales.

We have suggested a framework in which post-wildfire responses can be organized into post-wildfire response domains with three quantifiable metrics describing the range of characteristics for the fire, precipitation, and hydro-geomorphic regimes. By organizing the post-wildfire runoff and erosion responses into domains, this procedure will help to synthesize the data by identifying common patterns and generalities with the goal of understanding the reasons for different responses within and between domains.

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