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Lower Snake River Programmatic Sediment Management Plan, Final Environmental Impact Statement

Appendix C - Upland Erosion Processes in Northern Idaho Forests

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EROSION PROCESSES AND PREDICTION WITH WEPP TECHNOLOGY IN FORESTS IN THE NORTHWESTERN U.S.

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ABSTRACT. *In the northwestern U.S., the greatest amounts of forest erosion usually follow infrequent wildfires. Sediment from these fires is gradually routed through the stream system. The forest road network is usually the second greatest source of sediment, generating sediment annually. Erosion rates associated with timber harvest, biomass removal, and prescribed fire are generally minimal with current management practices. Landslides and debris flows can contribute significant amounts of sediment during infrequent wet years or following wildfire. A relatively new source of sediment in forested watersheds is recreation, particularly all-terrain vehicle trails. Stream channels store and route sediment; in the absence of channel disturbance, they tend to reach an equilibrium condition in which sediment entering a given reach is balanced by sediment carried downstream. At times, sediment from roads, wildfire, or landslides may accumulate in channels until higher flow rates, often associated with rainfall on melting snow, flush it downstream. Prediction tools are needed to aid forest managers in estimating the impacts of soil erosion on upland productivity and the risks of sediment delivery to downstream habitats and water users. Tools have been developed to aid in estimating long-term, low-level erosion in undisturbed forests and delivery of sediment from roads, and tools for estimating short-term, event-driven sediment from disturbed forests have also been developed. Online and GIS interfaces were developed using the Water Erosion Prediction Project (WEPP) model, including soil, vegetation, and climate databases. The online interfaces were developed to allow users to more easily predict soil erosion and sediment delivery for a wide range of climatic and forest conditions, including roads, fires, and timber harvest. There have been ongoing efforts to improve the online watershed interface to better model channel processes, road networks, and spatial variability associated with wildfire and weather.*

Keywords. *ATV impacts, Channel erosion, Forest roads, Logging, Mass wasting, Wildfire.*

The objective of this article is to provide an overview of erosion and sedimentation processes in northwestern U.S. forests, in particular the states of Washington, Idaho, and Oregon. This article discusses the role of wildfire, forest management (including the road network), and weather on upland erosion rates and sediment delivery. It then describes a suite of erosion prediction tools that have been developed specifically for forested conditions, based on the Water Erosion Prediction Project (WEPP) model.

The combined area in forests in the three northwestern states is about 40 million ha (Bolsinger, 1973; Idaho Forest Products Commission, 2012). These forests provide timber for construction, fiber for paper and other industrial applications, habitat for a host of terrestrial and aquatic wildlife, recreational opportunities, and carbon sequestration. Forested watersheds are recognized for the high quality of surface water they generate (Dissmeyer, 2000). This is particularly true in the western U.S., where water is in great demand for both human activities and for sustaining aquatic ecosystems. Patric et al. (1984) observed that, in the coastal forests of the western U.S., sediment delivery from watersheds was greater than from forests elsewhere in the country.

Both hillside erosion and sediment delivery are important to forest managers. Detachment and displacement of sediment can adversely affect forest soil productivity (Elliot et al., 1999a), and delivered sediment adversely impacts aquatic habitat (Bisson et al., 2003) and reduces the quality of water for downstream users (Dissmeyer, 2000). Sediment from forest watersheds is generated by three main processes: surface erosion, mass wasting, and stream channel erosion (Elliot et al., 2010b). The three processes often overlap or complement each other. For example, following a wildfire, surface erosion may exceed the capacity of a channel to transport the eroded sediments, so sediment deposits in flood plains. In the decades that follow, the deposited sediments are gradually entrained and transported further downstream. A landslide may expose bare mineral soil, aggravating surface erosion. Streambank erosion may undercut a steep bank at the toe of a marginally stable hill, resulting in a landslide (Reid, 2010).

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Surface erosion is generally minimal unless a hillslope is disturbed (Megahan and King, 2004, Elliot et al., 2010b). The two main disturbances in forests are wildfire and the road network. Other disturbances are associated with timber harvest, prescribed fire, recreational access, and animal activity. Superimposed on these surface disturbances are climatic factors that lead to major runoff events, such as heavy rainfall, rapid warming resulting in high snowmelt rates, or heavy rain falling on a snow pack (i.e., rain-on-snow; McClelland et al., 1997). Weather events that result in most of the erosion occur only about once in ten years (Gares et al., 1994; Kirchner et al., 2001). The variability in forest erosion is increased with the variability of wildfire (McDonald et al., 2000), after which surface erosion risk is the greatest (Megahan and King, 2004; Elliot et al., 2010b; Robichaud et al., 2011). Recent studies over several decades have suggested that sediment yields in forests range from 0.02 to 0.1 Mg ha^{-1} $year^{-1}$ (Kirchner et al., 2001). However, Kirchner et al. (2001) reported that cosmogenic studies indicate that true long-term (thousands of years) erosion rates are likely to be 1 to 5 Mg ha^{-1} $year^{-1}$, and they attributed this difference to infrequent fires and severe storms following those fires. Table 1 summarizes observed sediment delivery rates from roads and forests in the northwestern U.S. All values were converted to common units for comparison, with the road values assuming a road density of 2.5 km of road per km^2 of forest. Ranges are given for the values in table 1 because the observed erosion rate during a given study is highly dependent on the weather events during that study. Frequently, there is no observed sediment delivery associated with forest management (Covert, 2003; Elliot and Glaza, 2009; Robichaud et al., 2011).

In order to minimize the generation of excessive sediment in forest watersheds, managers need to understand the processes that generate sediment in forest watersheds, and they need access to tools that can aid in assessing the impacts of forest management on sediment generation. The objectives of this article are to describe the processes of sediment generation in forested watersheds in the northwestern U.S. and present methods to estimate erosion rates and sediment delivery associated with forest management to aid watershed managers in prioritizing forest activities that reduce the likelihood of generating excessive sediment. This article focuses on erosion and sediment delivery processes and predictions in the northwestern U.S., but many of the processes are common in all forested watersheds (Patric, 1976; Patric et al., 1984; Ice and Stednick, 2004; Lafayette et al., 2012).

Table 1. Observed annual sediment delivery rates based on Robichaud et al., 2010b; Covert, 2003; and Robichaud et al., 2011.

Source	Sediment Delivery Rate ($Mg\ km^{-2}\ year^{-1}$)
Undisturbed forest	0 to 8
Low traffic roads	0.5 to 7[a]
High traffic roads	1.8 to 100
Timber harvest	0 to 13
Prescribed fire	0 to 110
Wildfire	0 to 2450

[a] Assuming 2.5 km road per km^2 and road width of 4 m.

SURFACE EROSION

In forests, surface erosion is generally found on disturbed forested hillslopes and on forest road networks. Roads and other forest access corridors, such as skid trails and off road vehicle trails, tend to erode every year that they are used and are considered a chronic source of sediment, whereas forested hillslopes generally only experience erosion in the year or years following a disturbance.

DISTURBED FORESTED HILLSLOPES

Undisturbed forest hillslopes have minimal surface erosion (Patric, 1976; Megahan, 1975). Disturbances, whether natural or anthropogenic, can sometimes generate sediment greater than that of undisturbed forest hillslopes (Ice and Stednick, 2004; Elliot et al., 2010b). Natural disturbances, such as landslides and wildfire, are the most common natural sources of sediment (table 1). Wildfire is the natural disturbance (fig. 1) that generates the greatest amount of sediment (table 1).

Wildfire

Plant communities in forest ecosystems in the northwestern U.S. are adapted to infrequent wildfire disturbance (Graham et al., 2010). Intervals between wildfires can vary from 50 to 300 years (Agee and Skinner, 2005; McDonald et al., 2000; Graham et al., 2010). The accelerated erosion rates following wildfire depend on the weather the following year (Megahan and King, 2004; Robichaud et al., 2007; Robichaud et al., 2011) and typically range from 1 to 20 Mg ha^{-1} in the year following the fire (Robichaud et al., 2010a, 2011).

The attribute of wildfire that is most closely linked to soil erosion is burn severity. Severity is the degree to which an ecosystem has changed because of the fire (Lentile et al., 2006; French et al., 2008). Severity is frequently classified as unburned, low, moderate, and high. Figure 2 shows a typical distribution of severity, in this case from the 2010 Four Mile Canyon fire near Boulder, Colorado. Severity is highly variable, as can be noted in figure 2. Severity depends on the amount and type of fuel (Turner et al., 1999; Bigler et al., 2005); the ground cover that was available before the fire (Bigler et al., 2005); the slope steepness, aspect, and shape (Robichaud and Miller, 1999; Lewis et al., 2004; Bigler et al., 2005; Dobre, 2010); fuel moisture (Bigler et al., 2005); and wind direction and velocity (Roccaforte et al., 2008). South-facing slopes tend to be drier, experience a more intense fire, and have less ground cover remaining after the fire and thus are more susceptible to erosion (Dobre, 2010; Robichaud and Miller, 1999). Convex hillslopes tend to have less ground cover remaining after fire than concave hillslopes (Dobre, 2010). Because the severity is so highly variable, so are the erosion rates following wildfire. Covert (2003) and Elliot and Glaza (2009) observed zero or near-zero erosion rates on sites that had experienced moderate severity fires. Robichaud et al. (2011) performed a series of studies on eight sites that had experienced high severity fires exclusively and observed erosion rates on small watersheds ranging from zero to more than 20 Mg ha^{-1} in the first year following wildfire.

Figure 1. Severe rill erosion following the Klamath Complex wildfire near Happy Camp, California (source: N. Wagenbrenner).

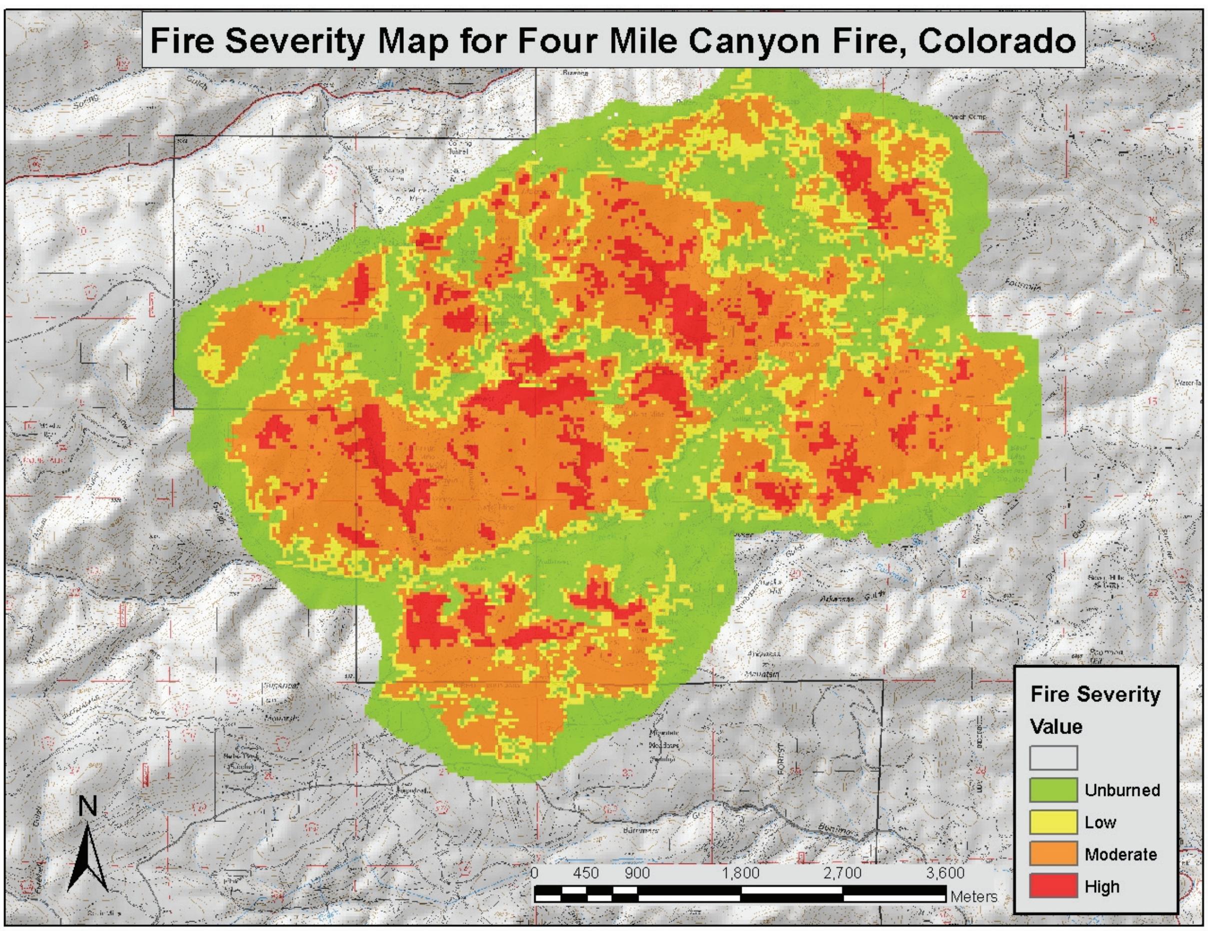

Figure 2. Fire severity map of the 2010 Four Mile Canyon fire near Boulder, Colorado.

Following wildfire in this region, soils can become water repellent (DeBano, 2000; Lewis et al., 2004). Organic chemicals are vaporized by the fire. In soils with a high degree of porosity, these vapors can coalesce around soil particles in the top 10 to 50 mm of soil and make the surfaces of the particles water repellant. The hydraulic conductivity of such soils can be reduced by around 40% (Robichaud, 2000), leading to increased runoff, erosion rates, and sediment delivery (Robichaud, 2005; Robichaud et al., 2011; Foltz et al., 2008). The degree of repellency may decline over several years, may persist for many years, or may always be present when the soils are dry (DeBano, 2000).

Following wildfire, forest managers may attempt to reduce runoff, erosion, and sediment delivery in sensitive watersheds (Robichaud, 2005; Robichaud et al., 2010a). The most common hillside treatments are installation of erosion barriers, such as logs generally cut from fire-killed trees on the site or straw wattles on the contour, mulching with straw or other organic products, or hydromulching, (Robichaud et al., 2010a). Robichaud et al. (2010a) reported that sediment reduction from barriers ranged from negative (erosion increased) to 80%. The most effective treatments for reducing erosion have been mulching treatments, with a reduction in sediment delivery ranging from 20% to more than 90%. Road networks may also be treated following wildfire by installing larger culverts and employing other methods to cope with the anticipated increase in runoff (Foltz et al., 2008).

Forest Management

In the last half of the 20th century, timber harvest was the dominant forest management practice and provided building materials for the post-WWII building boom (Megahan and King, 2004). In addition to timber harvest, forest managers adhered to a proactive fire suppression strategy. These two practices have resulted in forests with an overabundance of even-age timber with a considerable amount of understory (Agee and Skinner, 2005; Graham et al., 2010). This type of stand is highly susceptible to wildfire (Turner et al., 1999; Bigler et al., 2005), and the frequency and severity of wildfire in this type of stand have been increasing in recent decades (Graham et al., 2010).

In the past decade, management of federal forests has focused on fuel management to reduce the risk of high severity wildfire (Agee and Skinner, 2005; Graham et al., 2010). The most common fuel management practices are thinning, particularly to remove the understory, and the use of prescribed fire (fig. 3). Recent studies have shown that these practices do not necessarily reduce the likelihood of a wildfire occurring, but they tend to reduce the severity of the fire (Reinhardt et al., 2008). Elliot and Glaza (2009) did not find any change in sediment due to thinning, whereas Karwan et al. (2007) noted that removing half the trees from half the subwatershed doubled the sediment yield. In the study by Karwan et al. (2007), clearcutting half of a subwatershed followed by an underburn increased sediment delivery by a factor of 3 in the year following the treatment. Hubbart et al. (2007) reported the runoff associated with the management practices in the Karwan et al. (2007) study. Hubbart et al. (2007) observed increases in runoff in excess of 270 mm year^{-1} associated with harvesting and thinning. From these two observations, Karwan et al. (2007) suggested that the increase in sediment yield associated with harvesting and thinning may be more linked to increased channel erosion than hillslope erosion, and they suggested that a future study focus on the sources of detached sediment following timber harvest (hillslope vs. channel).

Figure 3. Fire line around a prescribed burn to reduce ground fuel loads in the Priest River Experimental Forest in northern Idaho (source: J. Sandquist).

Interest in using forests as a source of biomass for fuels is increasing (Elliot, 2010; Rummer et al., 2003). Rummer et al. (2003) reported that predicted erosion rates following the removal of forest biomass for fuel ranged from 0 to 0.4 Mg ha^{-1}, depending on climate and topography. This analysis included consideration of both increased road erosion and erosion from the harvested areas.

Forest Access

Forest roads serve a multitude of uses, including timber production, grazing, and recreation, as well as fire suppression activities. The forest road network is further augmented with temporary or long-term trails that can be made by logging skidders, all-terrain vehicles (ATVs), bicycles, wild and domestic animals, and humans. In the absence of wildfire, forest roads are generally recognized as the greatest generator of sediment within our forests (Megahan and King, 2004).

Forest Roads

Forest roads have long been identified as a significant source of sediment in forested watersheds (Megahan and Kidd, 1972; Packer and Christensen, 1977; Fransen et al., 2001; Megahan and King, 2004). Road erosion rates range from less than 1 to 100 Mg ha^{-1}, compared to undisturbed forests with erosion rates of less than 0.1 Mg ha^{-1}. Sediment delivery from roads depends on the road surface conditions, road location, topography, soil properties, design, use, and management. The increase in erosion on forested hillslopes due to timber harvest, fuel reduction, or biomass removal will likely be minimal (Karwan et al., 2007; Elliot and Glaza, 2009), but greater traffic levels on roads and the construction of skid trails and temporary roads can increase overall erosion associated with forest management (Rummer et al., 2003; Elliot et al., 2010b; Robichaud et al., 2010b). This fact is supported by previous research by Foltz et al. (2009). They observed that roads become overgrown with vegetation if not used. Should a road be cleared and used for logging traffic, the erosion rates increased considerably when vegetative cover is removed because hydraulic conductivity decreases and interrill erodibility increases.

Newly constructed or reconstructed roads generate much more sediment than older roads (Megahan and King, 2004; Karwan et al., 2007). Karwan et al. (2007) noted that sediment yields generally increased when roads were reconstructed in relatively undisturbed watersheds, but they stated that "the impacts corresponding to road construction remain difficult to discern." Even older roads will tend to generate some sediment unless they become fully vegetated, including all fillslopes and cutslopes (Foltz et al., 2009; Megahan and King, 2004). Older roads are also a perpetual risk of significant sediment generation from blocked culverts (Gucinski et al., 2001). Blocked culverts can lead to overtopping of the road surface, causing the road to wash out (Foltz et al., 2008), severe ditch erosion (Copstead and Johansen, 1998), or road fill failure (Elliot et al., 1994; Copstead and Johansen, 1998).

The road surface has a much lower hydraulic conductivity than the surrounding forest, with measured values from less than 1 mm h^{-1} to about 10 mm h^{-1} (Elliot et al., 1999b; Foltz et al., 2009, 2011). In contrast, the hydraulic conductivity of the surrounding forest ranges from 20 mm h^{-1} to more than 100 mm h^{-1} (Robichaud, 2000; Foltz and Elliot, 2001). The differences make the road a source of surface runoff and detached sediment, whereas the forest can serve as a buffer area for runoff infiltration and sediment deposition (Elliot et al., 2010b).

Road erosion can be minimized by preventing rut formation (fig. 4) by applying quality gravel (Foltz, 2003), minimizing traffic when the road is wet (Gucinski et al., 2001), or reducing the tire pressure of logging trucks (Foltz and Elliot, 1998). Sediment delivery from roads can be reduced by diverting runoff either directly to the fillslope with an outsloped road or to an inside ditch with an insloped road, if the inside ditch is well-vegetated or armored with rock. Gravel increases the ability of the road to carry traffic without rut formation. However, the gravel itself can be a source of fine sediment (Foltz and Truebe, 2003). Another factor that influences road erosion is traffic. Roads with heavy traffic generate 4 to 5 times the sediment of roads with light traffic (Bilby et al., 1989; Coker et al., 1993; Foltz, 1996; Luce and Black, 1999; Fransen et al., 2001; Elliot et al., 2010b).

Cutslope and fillslope erosion are dependent on cover and road design. Luce and Black (2001) were unable to measure any effects of cutslope height on sediment delivery from road ditches at the base of the cutslope. They suggested that the effects may have been masked by sediment generated from the insloping section of road, or that the exposed C horizon did not erode on larger road cuts, only the A and B horizons. Tysdal et al. (1997) and Elliot et al. (1999b), using the watershed version of the WEPP model, predicted that cutslope sediment delivery was less than 10% of the total for cutslopes up to 9 m high regardless of cover. Their modeling runs attributed about a third of the road sediment as coming from the road surface, and two-thirds from the ditch. Field observations of roads with cutslopes that appear to be eroding frequently show a significant amount of deposited sediment in the inside road ditch, suggesting that delivery of sediment from roads with eroding cutslopes and lower road grades may be limited by the transport capacity of the road ditch flow. In very sensitive watersheds, such as the Lake Tahoe basin, mulching cutslopes and incorporating mulch into the cutslopes has been shown to be effective in reducing cutslope runoff and sediment generation to zero or nearly zero (Grismer and Hogan, 2005).

Outsloped roads seldom deliver any sediment through a vegetated buffer area between the road and a nearby stream unless they are paved (Benik et al., 2003), although there may be some evidence of erosion on the fillslope. However, on rutted and insloped roads, sediment collected in the ruts and/or the inside ditch can be transported downslope to a stream if the cross drain delivers the runoff to a swale or ditch that is directly connected to a stream (Elliot and Tysdal, 1999). In these cases, there is a risk that fillslope or offsite erosion may generate more sediment than was generated from the road itself (Elliot and Tysdal, 1999). Foltz and Elliot (2001) noted that filter windrows would

Figure 4. Measuring rut development on a logging road in the Willamette National Forest, Oregon (source: W. Elliot).

likely eliminate this erosion risk because of the high hydraulic conductivity under the filter windrow (up to 200 mm h^{-1}). Grace (2002) found that wood excelsior mats and seeding with exotic or native vegetation species all reduced runoff by about 50% and erosion by 90% on forest road cutslopes and fillslopes.

Conversely, once the sediment leaves the road, the buffer area between the road and a channel can be a source of sediment if the contributing area of the road is high compared to the length of the buffer, or an area of deposition if the buffer is sufficiently long compared to the road length (Tysdal et al., 1997). Ketcheson and Megahan (1996) noted that the presence of large debris on the buffer, such as logs and rocks, influenced sediment deposition on the buffer and delivery from the buffer.

Skid Trails

Logs are generally collected from forests with rubber-tired forwarders (on slopes less than about 10%), with tracked or rubber-tired skidders (on slopes less than 25%), and with overhead cables (on steeper slopes) (Elliot et al., 2008; Rummer, 2010) and delivered to a road or landing (Rummer, 2010). Cable operations tend to cause fewer disturbances than skidders, although the steepness of the cable corridor is usually greater than with ground-based skidders (Elliot and Miller, 2004). Erosion rates of skid trails depend on how many passes of the skidder they have experienced, the soil water content at the time of skidding (Han et al., 2006), and, as with roads, where they are located on the landscape. The greater the distance of a skid trail from an upland channel or stream, the less potential there is to deliver sediment to the stream system (Litschert and MacDonald, 2009).

Loss of ground cover (Robichaud, 1996; Elliot, 2010) and compaction (MacDonald and Seixas, 1997; Han et al., 2006; Elliot, 2010) are the main attributes of skid trails that lead to increased erosion risk. Following skidding, erosion risk is frequently reduced by installing water bars to prevent accumulation of overland flow (Seyedbagheri, 1996) or by mulching with slash (Seyedbagheri, 1996; Han et al., 2006; Elliot, 2010). Other common practices to minimize erosion on skid trails are to rip or scarify skid trails, and to apply grass seed following harvesting operations (Seyedbagheri, 1996).

In most harvesting operations, streamside buffers are required that either restrict traffic within a specified distance of a stream, and restrict or limit log removal (Gray and Megahan, 1981; Seyedbageheri, 1996).

Recreation

One of the growing uses of forested areas is for recreation. Recreational impacts include campgrounds, increased traffic on forest roads, and erosion associated with ATV trails and other trails. Campgrounds generally are on flat areas that are covered with grass, and most erosion is limited to roads or parking areas. The effect of increased traffic on road erosion was discussed previously. Erosion from human or animal trails is likely to be limited, as trails are small, but could be significant where steep trail segments converge on or intersect streams (Ayala et al., 2005), as was previously studied for skid trails (Seyedbagheri, 1996). ATV trails are a growing risk for sediment generation in forests. The erosion risk from unmanaged ATV trails may equal that of a road network in a forest (Meadows et al., 2008). This has resulted in restrictions on ATV access to sensitive parts of forested watersheds (Meadows et al., 2008).

Mass Wasting

Mass wasting is most often associated with weather patterns that lead to saturated soils on steep slopes, as common in the Washington and Oregon Coast Ranges (McClelland et al., 1997; Robison et al., 1999; Jones et al., 2000). Several different types of mass wasting are common, including translation slides where the soil moves as a mass, and debris flows where soil, water, and rock mix into supersaturated slurry following a steep ephemeral channel (McClelland et al., 1997, Robison et al., 1999; USGS, 1999; Jones et al., 2000; Reid, 2010).

One of the primary elements stabilizing slopes is tree roots. If the trees are harvested, or killed by wildfire or disease, the roots will decompose, and several years following tree removal or death, steep slopes are susceptible to failure (Hammond et al., 1992; Prellwitz et al., 1994). Harvesting of trees can also impact mass wasting, but in this case reducing the risk as the surcharge from the trees is removed from the slope. Gorsevski et al. (2006a) found the number of years following the removal or loss of trees to be important. They attributed this increase in stability to the regeneration of tree roots. Reid (2010) stated that increased vegetation growth resulted in increased evapotranspiration, and hence drier, more stable soils on steep slopes. Robison et al. (1999) did not show any significant difference in landslide occurrence due to tree age, but they noted that the lowest frequency of landslides occurred with trees 10 to 100 years old. This suggests that evapotranspiration was more important than root strength for Robison et al. (1999), as evapotranspiration tends to increase until forests are about 10 to 15 years old (Ziemer, 1964; Jassal et al., 2009). Recent studies have shown that evapotranspiration rates may decline in old-growth forests (Hubbart et al., 2007; Jassal et al., 2009; Marshall and Kavanagh, 2011; Wu et al., 2012), leading to wetter soils and the increased density of landslides noted in older forests by Robison et al. (1999).

Stream erosion at the base of steep slopes and road cuts on steep lands also can lead to instability (Robison et al., 1999; Reid, 2010). In forests with active timber harvesting, roads often are associated with landslide initiation due to over-steepening of both the cutslopes and fillslopes (Fransen et al., 2001; Jones et al., 2000; McClelland et al., 1997). McClelland et al. (1997) estimated that half the sediment from a forest watershed in northern Idaho over a 20-year period could be attributed to landslides occurring during several winter rain storm events in 1973-1974, and many of those landslides were associated with roads. In another study of the same data set used by McClelland et al. (1997), Gorsevski et al. (2006b) developed a GIS method to predict the likelihood of a landslide occurring in a given 30 m cell. They found that different models were needed for cells containing roads than for cells without roads to predict the probability of a landslide occurring. Both predictive models included climate and slope shape and aspect factors, but the probability of a landslide occurring in a given cell for cells without roads also had an elevation term. Jones et al. (2000) stated that roads were often associated with debris flows because of the over-steepening of fragile slopes and the concentration of runoff.

Channel Erosion and Sediment Delivery

In forested watersheds, channels are dynamic, as they receive, route, store, and entrain sediment generated by disturbed hillslopes and roads. Sediment detachment processes can be divided into channel bed scour, channel bank scour, and bank mass erosion (Reid, 2010; Huffman et al., 2011).

Channel bed erosion generally is a function of the size of material on the bed and the ability of the streamflow to entrain that material (Huffman et al., 2011; Ward and Trimble, 2004). The greatest amount of sediment movement in northwestern streams is associated with runoff events that occur once every one to two years (Wolman and Miller, 1960; Simon et al., 2004; Ward and Trimble, 2004). Roads, wildfire, and upstream erosion can generate fine sediment in excess of the sediment transport capability of some stream segments, and the bed can become covered with fines (Bisson et al., 2003; Elliot, 2006). These fines tend to accumulate during years with low runoff events, but post-wildfire erosion and mass wasting or flood flow events replenish coarse sediment and large wood (Bisson et al., 2003). Wildfires are infrequent, occurring once every 20 to 300 years in northwestern forests (McDonald et al., 2000), so forest streams are in an ongoing process of routing sediment every year, with inferquent replenishment following wildfire. Since wildfire is widely distributed across forest landscapes, there is wide range of streambed conditions within the landscapes (Bisson et al., 2003). During larger events, the material may be mobilized and deposited farther downstream on bars within the channel, or overbank on adjacent flood plains (Committee on Riparian Zone Functioning and Strategies for Management, 2002; Ward and Trimble, 2004).

Streambank erosion is driven by larger flow events. Bank erosion is much greater than channel bed erosion since it is caused by mass failure as well as hydraulic shear from the flowing water. Bank erosion is initiated when the toe of a bank is undercut by channel erosion, followed by a period of high flow that can saturate the bank, and then a drop in flow, leaving the bank weakened by saturation and unstable from undercutting (Simon and Pollen, 2006; Elliot et al., 2010b). The bank will then topple into the stream (fig. 5), and gradually the toppled blocks will be eroded and the sediment transported downstream during high flows. When channels or banks are not disturbed, channels will reach an equilibrium condition. This process may take years following many of the above disturbances. Until it reaches equilibrium, the channel will tend to be a source of additional sediment.

Figure 5. Measuring toppled banks along a forest meadow stream in the lower reaches of the Upper Truckee River, California (source: W. Elliot).

Streambank erosion also can be aggravated by straightening the channel or diverting it around developed areas. This can lead to increased meandering and increased bank erosion (Elliot et al., 2010b; Huffman et al., 2011). The bank erosion in figure 5 was a result of diverting the downstream channel around an airport runway.

PREDICTION TOOLS

A number of prediction tools have been developed for estimating soil detachment, transport, and deposition in forests (Elliot et al., 2010b), including the Universal Soil Loss Equation (Dissmeyer and Foster, 1985) and its derivatives (Elliot et al., 2010b), WEPP-based technologies (Flanagan et al., 2013), a number of regional models (USFS, 1990), and GIS tools such as SEDMODL, SWAT, and GeoWEPP (Dubé and McCalmon, 2004; Arnold et al., 1998; Flanagan et al., 2013; Elliot et al., 2010b). These prediction tools are frequently incorporated into interfaces targeting specific user needs (Elliot et al., 2010b; Flanagan et al., 2013). This discussion focuses on the application of the WEPP technology that has been developed to predict surface erosion in forested environments.

THE WEPP MODEL

The WEPP model was developed between 1985 and 1995 by an interagency team of scientists led by the USDA Agricultural Research Service. The core team included agencies such as the USDA Soil Conservation Service, which was later called the Natural Resource Conservation Service, the U.S. Department of Interior Bureau of Land Management, and the USDA Forest Service (Laflen et al., 1997; Flanagan et al., 2007). WEPP was developed to replace the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). The USLE predicted erosion rates on the eroding part of a hill but did not consider the role of either non-eroding ridge tops nor areas of deposition at the base of many hills. The WEPP model first predicts runoff from the ridge to a delivery point or channel and subsequently predicts erosion, sediment transport, deposition, and delivery along that flow path (Flanagan and Nearing, 1995; Laflen et al., 1997). WEPP was originally run through an MS-DOS interface (Flanagan et al., 1994), and later a Windows 95 interface was developed (Flanagan et al., 1998). Elliot and Hall (1997) developed WEPP input files to describe road segments and disturbed forest hillslopes for the Windows interface.

In 2000, an online suite of interfaces was published (Elliot, 2004) for forest road segments and hillslopes that could be accessed by any computer with a web browser. The WEPP model can require hundreds of input variables to run (Flanagan and Livingston, 1995), but these online interfaces require only a minimal amount of input, relying on large online databases to provide the necessary inputs (fig. 6). The interfaces also provide simplified outputs with customized features for forest conditions. The interface for predicting road erosion provides average annual values for road erosion and sediment delivery because roads erode every year, making the average value useful. The disturbed hillslope interface not only provides average values but also predicts the probability of annual erosion rates and sediment yields because increased erosion risk is likely isolated to the year of the disturbance, so a long-term average value is of less interest. The interface developed for wildfire provides probability of single-storm erosion events in the first five years following a wildfire, reflecting the need to evaluate risks of erosion associated with large runoff events rather than annual or average annual values (Robichaud et al., 2007). These interfaces performed reasonably well for the low erosion rates observed on

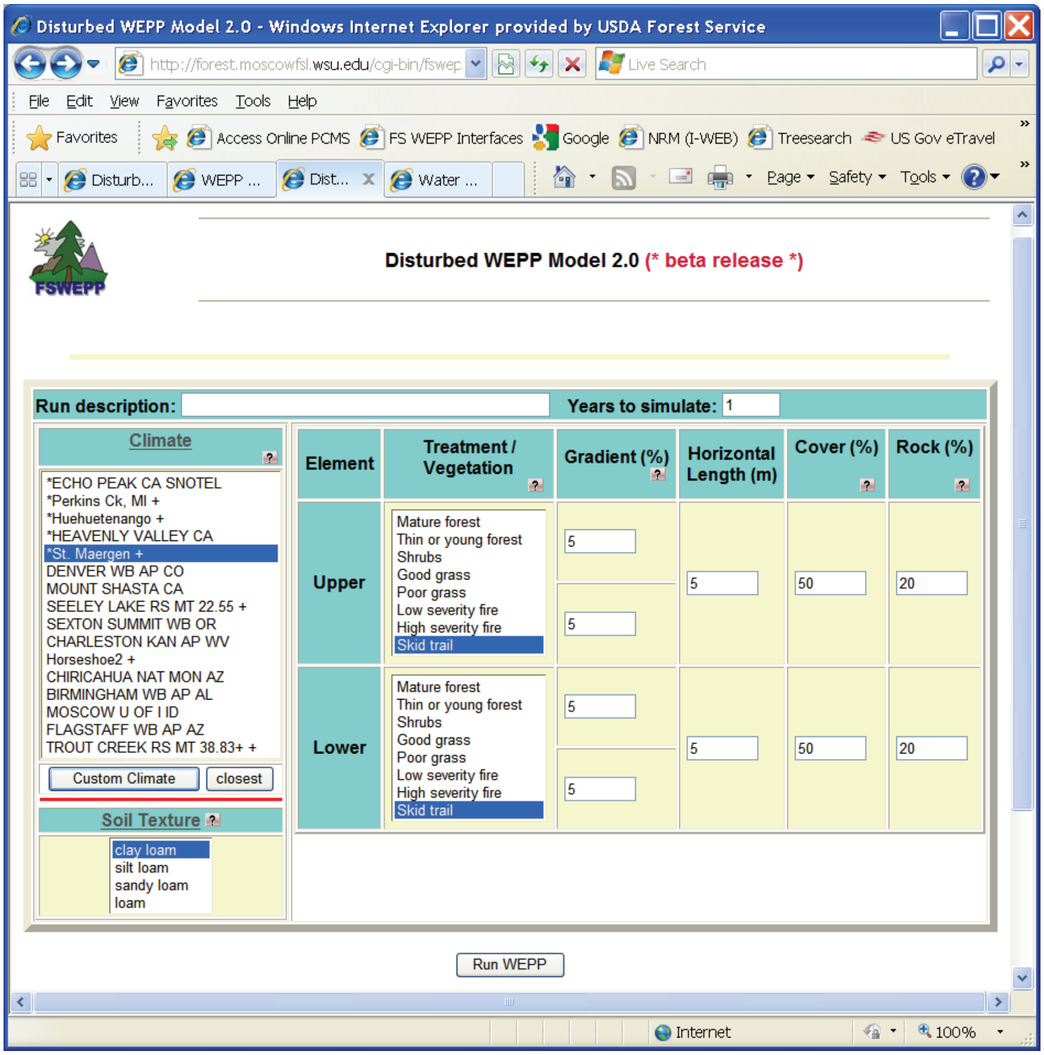

Figure 6. Version 2011 input screen for the Disturbed WEPP online interface, requiring the user to specify four input conditions and provide ten input variables describing key topographic, vegetation, and soil conditions.

forested hillslopes (Elliot and Foltz, 2001) and better than RUSLE technology for higher erosion rates following forest fires (Larsen and MacDonald, 2007). For the higher erosion rates on forest roads, Elliot and Foltz (2001) found that predictions were reasonable, and Grace and Elliot (2008) observed that both road erosion rates and sediment deposition rates were predicted well.

WEPP was released in 1995 with two versions, a hillslope version and a watershed version (Flanagan and Nearing, 1995). The watershed version links together hillslope polygons, channel segments, and in-channel impoundments. Applying this tool to any watershed with more than two or three channel segments and associated hillslopes using WEPP Windows file builders is a difficult task, so GIS tools were developed to build the necessary files to run the watershed version of WEPP (Renschler, 2003; Elliot et al., 2006; Flanagan et al., 2013). The GIS tools were developed for general applications to agricultural, rangeland, and forested watersheds. One of these tools that was under development targeted erosion risk following wildfire, but it was not widely distributed (Collins et al., 2010). The post-wildfire watershed tool was designed to incorporate fire severity maps prepared to aid in planning post-fire rehabilitation to address the spatial variability common after wildfire (fig. 2). However, preparation of the GIS files necessary to run these tools requires a high degree of GIS application skill, so the GIS tools have not been widely used.

The most recent WEPP erosion prediction tool is an online watershed interface (Flanagan et al., 2013; Frankenberger et al., 2011) developed specifically for forested watersheds. This tool accesses numerous U.S. national databases for land cover and soil properties where they are available. On some federal lands, the national soil database is not available and users must rely on alternative sources to determine the distribution of soil properties and manually enter those properties. The current version of the online watershed interface focuses only on hillslopes and channels and does not model erosion from road networks. In the case of wildfire, the distribution of the severity of the fire must be entered manually, as the current tool has no way of incorporating the variability of wildfire severity within a watershed. Development is ongoing to incorporate road networks and wildfire severity maps into the online watershed interfaces.

One of the challenges in modeling forest watersheds in the northwestern U.S. is that climate variability within watersheds is considerable. If the area of the watershed is greater than several square kilometers, it is not unusual to have a difference of a factor of 2 or more in annual precipitation within the watershed due to orographic and rain shadow processes. During a rainfall event on larger watersheds, smaller, more intense storms may occur on one part of a large watershed but not elsewhere (Ward and Trimble, 2004). In addition, if there is a large elevation difference within a watershed, some parts of the watershed may have rain leading to runoff, and some snow, or some parts may have melting snow and some parts not (McCabe et al., 2007).

WEPP Model Input Requirements and Sensitivity

All applications of the WEPP model have four input files: topography, soil, vegetation, and weather (Flanagan and Livingston, 1995). For a single hillslope run, the number of variables required can be in the hundreds, but databases have been developed for all of the common forest erosion prediction needs. Databases for these variables are distributed with the Windows version of WEPP and are incorporated into the online hillslope and watershed interfaces.

When applying WEPP, users have found that runoff is correlated with both hillslope length and steepness (Zhang et al., 2009; Miller et al., 2011). In the original version of the WEPP technology, Lane and Nearing (1989) found that sediment delivery predicted by WEPP was less sensitive to slope steepness than was the case with the RUSLE model, and that the sensitivity of sediment delivery to slope length depended on steepness, with greater sensitivity on steeper slopes. Zhang et al. (2009) found that sediment delivery was related to hillslope length but not steepness. Miller et al. (2011) also found that sediment delivery was sensitive to slope steepness. However, Miller et al. (2011) found that sediment delivery predicted by WEPP was not sensitive to slope length in a drier climate (annual precipitation = 400 mm year^{-1}), but it was in a wet climate (annual precipitation = 2200 mm year^{-1}).

When using watershed tools to determine slope length and steepness values, Zhang et al. (2009) found that, in a smaller watershed (106 ha), using a 30 m digital elevation model (DEM) resulted in a hillslope erosion rate that was three times the amount generated by a 10 m DEM. In a larger watershed (177 ha) that had the small watershed nested within it, the predicted erosion rate was 50% greater with a 10 m DEM (table 2). The reasons for this discrepancy are discussed by Zhang et al. (2009) and are related to the interactions of slope steepness and length due to DEM resolution. In the smaller watershed, the length was shorter, but the hillslope was steeper with the 10 m DEM, and the net effect was a larger predicted erosion rate for the 10 m DEM compared to the 30 m DEM. Zhang et al. (2009) also suggested that the finer resolution allowed the model to better discern the presence of low-gradient sites of deposition at the bottom of the hillslopes. Yao et al. (2010) found a similar response to topography when comparing 10 m and 30 m DEMs on nearby agricultural sites using RUSLE2 (table 2), but in their study, the predicted erosion rate was greater with the 10 m DEM. In the larger watershed in the Zhang et al. (2009) study, the overall steepness was less on the larger watershed compared to the smaller watershed nested within it, but as with the smaller watershed and the Yao et al. (2010) study, the 10 m DEM predicted steeper slopes than the 30 m DEM (table 2). In the larger watershed, the average hillslope length was longer when using the 10 m DEM, resulting in a greater predicted erosion rate with the 10 m DEM. When comparing WEPP's predictions using LIDAR for finer DEM resolutions, Moreira et al. (2011) focused on steepness only, fixing the slope length from 1 m DEM analysis (table 2). They noted that at resolutions below 10 m, average steepness declined at higher resolutions, as did the predicted sediment delivery rate. Zhang et al. (2009) noted the same trend, as predicted erosion rates dropped for the 4 m LIDAR-derived DEMs in their larger watersheds (table 2). Moreira et al. (2011) suggested the reason for the decline in sediment delivery was that the finer resolutions had more areas of deposition predicted along the hillslope, reducing the overall generation and delivery of sediment.

The single most important soil variable for a smaller storm is the saturated hydraulic conductivity, and the rill erodibility value for a larger storm (Lane and Nearing, 1989). Saturated hydraulic conductivity is reduced within the WEPP technology in direct proportion to the soil rock

Table 2. Effect of DEM resolution on hillslope topography and predicted erosion rate.

DEM Resolution (m) and Source[a]	Number of Eroding Hillslopes	Avg. Length (m)	Avg. Steepness (degrees)	Predicted Erosion Rate (Mg ha^{-1} year^{-1})	Source
4 (LIDAR)	2	212.9	21.5	0.8	Zhang et al., 2009 (Watershed 5)
10 (NED)	2	189.5	20.4	0.3	
30 (NED)	2	207.3	18.9	0.9	
4 (LIDAR)	5	187.7	20.2	1.9	Zhang et al., 2009 (Watershed 6)
10 (NED)	4	209.4	18.9	8.7	
30 (NED)	5	204.7	17.6	5.2	
10 (NED)	18	57.3	10.6	23.99	Yao et al., 2010
30 (NED)	18	69.16	8.4	22.84	
Observed topography	18	-	-	28.94	
1 (LIDAR)	4	945.38	21.63	0.13	Moreria et al., 2011
3 (LIDAR)	4	945.38	22.78	0.15	
5 (LIDAR)	4	945.38	22.85	0.14	
10 (LIDAR)	4	945.38	24.27	0.16	

[a] NED = National Elevation Data Set (USGS, 2006); LIDAR = Light Detection and Ranging data collected by fixed-wing aircraft for a specific area.

content, and like Lane and Nearing (1989), Miller et al. (2011) found that WEPP was more sensitive to rock content altering hydraulic conductivity in a dry climate than in a wet climate.

In a forest environment, vegetation, or degree of disturbance, has more influence on runoff and erodibility than the soil physical or chemical properties (Robichaud et al., 1993; Elliot and Hall, 1997; Elliot, 2004; Robichaud et al., 2007). Because of this, the WEPP soil databases in WEPP Windows, the online WEPP hillslope interfaces, and the online WEPP watershed interfaces all have soils categorized by one of eight of the surface vegetation classes (mature forest, young forest, shrub, bunch grass, sod grass, low severity fire, high severity fire, and skid trail) and only four textural categories (Elliot, 2004). A similar approach was adopted by the developers of the Rangeland Hydrology and Erosion Model (Nearing et al., 2011), which categorizes soils into eleven textural classes and four "dominant plant growth forms" (bunch grass, forbs and/or annual grasses, shrubs, and sod grass). In addition to selecting the correct soil and vegetation condition, the other critical vegetation input variable is the surface cover (Elliot, 2004; Miller et al., 2011). In earlier applications of WEPP to forest conditions, the surface cover had to be defined by altering the biomass conversion ratio to generate biomass, plant senescence, and residue decomposition rate (Elliot and Hall, 1997; Elliot, 2004; Dun et al., 2009). In the current online versions of WEPP, and in several of the WEPP Windows databases, these values have all been zeroed out, and the user simply enters a constant for the ground cover variable.

The weather file to run WEPP is generally stochastically generated by an internal climate generator (Flanagan and Nearing, 1995). The database with the climate statistics for this generator includes about 2600 NOAA weather stations (Scheele et al., 2001). However, this is a problem for most forest users, as the weather stations in the western U.S. tend to be located in valleys that are relatively dry, whereas the forests are found in the mountains that can have much higher precipitation amounts. To address this, the PRISM monthly precipitation database (Daly et al., 1994) was incorporated into the online interfaces (Scheele et al., 2001). This database estimates the average monthly precipitation amounts at a grid size of 4 km. In the online watershed interface (Frankenberger et al., 2011), the grid size is reduced to 800 m. Miller et al. (2011) clearly showed the difference in predicted erosion rates as a function of climate, with predicted erosion rates following wildfire varying from about 5 to 120 Mg ha^{-1} $year^{-1}$ as precipitation was varied from 400 to 2900 mm $year^{-1}$. The online hillslope interface (Elliot, 2004) includes instructions to download PRISM data to use with the WEPP Windows interface. The ArcGIS version 9.3 of GeoWEPP includes the same PRISM database as the online hillslope interfaces (Flanagan et al., 2013). In addition, the online hillslope interface and GeoWEPP interface allows users to specify their own monthly precipitation amounts and temperatures if they have local information. This feature can be used to develop climates for anywhere in the world (Elliot, 2011).

Limitations to WEPP Technology in Forests

WEPP is a physically based model, and databases have been developed to describe the soil, climate, and vegetation conditions in western U.S. forested watersheds. The primary limitation of the current WEPP technology for forest application is the size of the watershed that can be modeled. There are three reasons for this limitation. The first is that, in the western U.S., there is a considerable variation in precipitation amounts and distribution (Daly et al., 1994) within larger forest watersheds. Both the current Windows and online watershed interfaces assume that the same climate should be applied to the entire watershed. Although PRISM monthly weather statistics are now available on an 800 m grid, the WEPP interfaces assume that a single climate is applied to the entire watershed. This leads to errors in both timing and rates of runoff, especially in snow-dominated watersheds, where lower-elevation hillslopes melt early in the spring, generating surface runoff and lateral flow, whereas snow on higher-elevation hillslopes does not melt until late spring. Research is ongoing to develop methods for applying variable weather conditions within a large watershed (Brooks et al., 2010). The second limitation for applying the WEPP technology to large watersheds is that current versions of the WEPP watershed tool do not incorporate base flow (Zhang et al., 2009; Elliot et al., 2010a). Brooks et al. (2010), Elliot et al. (2010a), and Srivistava et al. (2013) present a method currently under development to address this shortfall using a groundwater linear flow model that predicts base flow as a function of the deep seepage predicted by WEPP and geology. The third limitation for larger areas is that the current WEPP watershed version uses a modified rational method for estimating peak runoff rates (Flanagan and Nearing, 1995). This method is not applicable to large watersheds, where it may take more than 24 h to route a storm. This limitation is currently being addressed by developing a channel routing technology based on a discrete Hayami convolution method (Wang et al., 2009; Wang, 2012).

The current WEPP online and standalone GIS tools do not have the ability to delineate road networks and analyze sediment generated from those networks. Batch processing has been developed for road segments (Brooks et al., 2006), and a batch processer is now included with the online interfaces not only for roads but also for running batches of forested hillslope polygons. Work is ongoing to incorporate advanced GIS techniques to simplify delineating road networks and predicting erosion from individual segments within that network.

Modeling Approach to Forest Management

There are three major areas where WEPP technology has been developed for forests: forest road management, forest management, and post-wildfire management. For forest road modeling, managers generally use a combination of field surveys, mapping, and GIS tools to estimate road segment length and gradient, road width, road surface condition (rutted, insloped, outsloped, or crowned), road ditch condition (bare or vegetated), and traffic level. These variables are then entered into either the WEPP road

Table 3. Example of applying the WEPP hillslope tools to support management of a forested hillslope.

No Treatment	Sediment Delivery	Average Annual Delivery	Treated	Sediment Delivery	Average Annual Delivery
Forest		0.49 t acre^{-1}			0.49 t acre^{-1}
			Thinned forest	0.54 t acre^{-1}	
			Treatment interval	20 years	0.03 t acre^{-1}
High severity wildfire	12 t acre^{-1}		Reduced severity wildfire	3.48 t acre^{-1}	
Fire return interval	50 years	0.24 t acre^{-1}	Fire return interval	70 years	0.05 t acre^{-1}
Average annual erosion		0.73 t acre^{-1}			0.57 t acre^{-1}

interface (Elliot, 2004) or the batch interface (Brooks et al., 2006). In many instances, only a fraction of the roads are inspected, and the rest of the road network is assumed to have similar sediment delivery characteristics (Formica et al., 2004). Luce and Black (2011) developed a road network inventory procedure that is linked to GIS tools to predict sediment delivery from road networks. With the Luce and Black (2011) tool, sediment delivery can be estimated with WEPP technology or with a simplified regression equation developed for roads in the Oregon Coast Range.

The online Disturbed WEPP interface is frequently used to evaluate the impacts of forest management on erosion and sediment delivery (Elliot, 2006, 2010; Elliot et al., 2010b). It not only predicts average annual erosion rates and hillslope sediment delivery but also the annual erosion rates associated with several different return periods. For forest management, the general approach that has been developed is to estimate the erosion from an undisturbed forest and the erosion from a wildfire using the online Disturbed WEPP interface (fig. 6, Elliot, 2004). The wildfire erosion rate is divided by the frequency of the wildfire to get an "average" erosion rate. This average is added to the undisturbed forest value to estimate a "background" erosion rate. Erosion rates associated with thinning, harvesting, and prescribed fire are then estimated and also averaged over the frequency of occurrence. The wildfire erosion rate may be recalculated for the treated forest assuming that it may be less severe or less frequent with the removal of fuel (Reinhardt et al., 2008), and a managed scenario can be created to compare to the background value. Table 3 presents a typical example of this application. A spreadsheet can be downloaded from the Disturbed WEPP website to run batches of hillslopes, to allow the user to consider multiple treatments on a single hillslope or multiple hillslopes. In addition to the forest hillslope analysis shown in table 3, managers generally add in the sediment contribution from the road network. This series of steps has been combined into a single online interface called WEPP:FuME (Elliot and Robichaud, 2006). These same steps can be followed for carrying out a watershed analysis, although the disturbances on individual hillslope polygons need to be distributed in time and space, requiring a separate run for each year with the disturbances and recoveries from previous disturbances noted for each year's run. Such an approach is similar to that developed by the USDA Forest Service in the WATSED model (USFS, 1990).

A different approach is used to model erosion following wildfire. Rather than use average annual sediment delivery values as described for managed forest hillslopes, a single storm probability approach has been developed with the Erosion Risk Management Tool (ERMiT, Robichaud et al., 2007, 2011). ERMiT is also a single hillslope tool, requiring input similar to the Disturbed WEPP interface in figure 6. ERMiT considers the variability associated with fire severity, spatial variability, and weather to predict the probability of exceeding a given sediment delivery. Like the Disturbed WEPP interface, it is run for a single hillslope at a time, and it can also be run as a batch. ERMiT also has a unique feature in that the output screen is interactive, allowing the user to consider different probabilities for an event, or to evaluate different treatments. Figure 7 shows the output table of the erosion rates expected to be exceeded 20% of the time. The results from a series of ERMiT runs can be used to aid natural resource managers in determining whether hillslope treatments are needed and can also be beneficial following a given fire. Future work is focusing on combining the WEPP technology with forest fire spread models and optimization models to aid in targeting forest fuel management activities to minimize fire spread and/or post-wildfire erosion based on current or future forest conditions (Jones, 2012).

If users are interested in more complex output analysis, such as individual event analysis, comparisons between dry years and wet years, long-term averages, or single-storm effects, then the WEPP Windows interface can be used. The database with the Windows interface contains the same files as those used to support the online interfaces but offers a much more flexibility to model complex conditions. In recent years, these applications have included erosion from mineral development, probabilities of runoff and erosion associated with winter events only on a feedlot, and risk of summer pesticide delivery.

Mitigation Treatment Comparisons					
Probability that sediment yield will be exceeded	Event sediment delivery (ton ac^{-1})				
	Year following fire				
20 %	1st year	2nd year	3rd year	4th year	5th year
Untreated	5.59	4.41	1.64	1.05	0.49
Seeding	5.59	2.22	1.37	0.94	0.49
Mulch (0.5 ton ac^{-1})	2.4	2.09	1.64	1.05	0.49
Mulch (1 ton ac^{-1})	2.2	1.47	1.64	1.05	0.49
Mulch (1.5 ton ac^{-1})	2.2	1.43	1.64	1.05	0.49
Mulch (2 ton ac^{-1})	1.5	1.42	1.64	1.05	0.49
Erosion Barriers: Diameter .5 ft Spacing 50 ft					
Logs & Wattles	0	0.6	0	0	0

Figure 7. Typical output screen from an ERMiT run showing a 20% chance of exceeding the stated sediment delivery value for a single runoff event for the given treatment and year following a wildfire, based on the input soil texture, fire severity, climate, and topography.

METHODS FOR VALIDATING THE WEPP MODEL

The WEPP model predicts runoff, upland erosion, sediment delivery at the bottom of a hillslope, and sediment delivery from a channel. Different monitoring methods are needed for each of these processes. The ability of WEPP to predict the timing and amount of runoff from a hillslope can be tested on small plots with tanks, as described by McCool et al. (2013). On larger plots, ranging from a fraction of a hectare to several square kilometers, outlet weirs and flumes are generally used, as described by Foltz (1996), Zhang et al. (2009), and Robichaud et al. (2011). Erosion rates on forested hillslopes are most easily measured using silt fence collectors (Robichaud and Brown, 2002; Elliot and Miller, 2004). Sediment delivery from small watersheds can be collected in tanks (Luce and Black, 1999; McCool et al., 2013) or with sediment basins (Foltz, 1996; Elliot and Glaza, 2009). On larger watersheds, generally a proportional sampler is used in conjunction with a weir or flume (Fransen et al., 2001; Schleppi et al., 2006). In most weir installations, a sediment trap upstream is used to collect bed load (Fransen et al., 2001), as the sediment collected by the proportional sampler is considered suspended sediment. The rate of sampling for sediment concentration is increased as the depth of flow in a weir or flume increases. In all cases, it is essential to have accurate weather data collected close to the plot to avoid errors associated with differences in elevation. In larger watersheds, multiple locations of precipitation and temperature monitoring equipment are essential (MacKenzie et al., 2007). If snow accumulation and melt are a concern, then snow depth observations may be essential for calibrating and validating runoff and sediment models (Srivistava et al., 2013).

SUMMARY AND CONCLUSIONS

The greatest amounts of erosion are associated with infrequent wildfires in forests in the western U.S. The sediment from these fires is gradually routed through the stream system. The greatest amounts of sediment transport are associated with the one-year to two-year peak streamflows. The forest road network is the second greatest source of sediment and continuously generates sediment. Recreation may be an increasing source of sediment in forest watersheds. At times, eroded sediment may accumulate in channels until higher flow rates flush it downstream. Landslides and debris flows can contribute significant amounts of sediment during infrequent wet years or following wildfire. Stream channels store and route sediment; in the absence of channel disturbance, they tend to reach an equilibrium condition in which the sediment entering a given reach is balanced by sediment carried downstream. Prediction models are available for hillslope and road segment processes, but additional research is needed to develop watershed models that can incorporate road networks, flood routing, and spatial variability associated with wildfire severity and weather.

REFERENCES

Agee, J. K., and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecol. and Mgmt.* 211(1-2): 83-96.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. S. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Rec. Assoc*. 34(1): 73-89.

Ayala, R. D., P. Srivastava, C. J. Brodbeck, E. A. Carter, and T. P. McDonald. 2005. Modeling sediment transport from an off-road vehicle trail stream crossing using WEPP model. ASABE Paper No. 052017. St. Joseph, Mich.: ASABE.

Benik, S. R., B. N. Wilson, D. D. Biesboer, B. Hansen, and D. Stenlund. 2003. Evaluation of erosion control products using natural rainfall events. *J. Soil and Water Cons. Soc*. 58(2): 98-104.

Bigler, C., D. Kulakowski, and T. T. Veblen. 2005. Multiple disturbance interactions and drought influence fire severity in Rocky Mountain subalpine forests. *Ecology* 86(11): 3018-3029.

Bilby, R. E., K. Sullivan, and S. H. Duncan. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. *Forest Sci.* 35(2):453-468.

Bisson, P. A., R. E. Reiman, C. Luce, P. F. Hessburg, D. C. Lee, J. L. Kershner, G. H. Reeves, and R. E. Gresswell. 2003. Fire and aquatic ecosystems of the western USA: Current knowledge and key questions. *Forest Ecol. and Mgmt.* 178(1-2): 213-229.

Bolsinger, C. L. 1973. Changes in commercial forest area in Oregon and Washington, 1945-1970. Res. Bull. PNW-RB-046. Portland, Ore.: USDA Forest Service, Pacific Northwest Research Station.

Brooks, E. S., J. Boll, W. J. Elliot, and T. Dechert. 2006. Global positioning system/GIS-based approach for modeling erosion from large road networks. *J. Hydrol. Eng.* 11(5):418-426.

Brooks, E. S., W. Elliot, J. Boll, and J. Wu. 2010. Final report: Assessing the sources and transport of fine sediment in response to management practices in the Tahoe basin using the WEPP model. Albany, Cal.: USDA Forest Service, Pacific Southwest Research Station. Available at: www.fs.fed.us/psw/partnerships/tahoescience/sediment_sources.shtml. Accessed January 2011.

Coker, R. J., B. D. Fahey, and J. J. Payne. 1993. Fine sediment production from truck traffic, Queen Charlotte Forest, Marlborough Sounds, New Zealand. *J. Hydrol. (N.Z.)* 31(1): 56-64.

Collins, B. M., W. J. Elliot, I. S. Miller, J. D. Miller, H. D. Safford, and S. L. Stephens. 2010. Watershed impacts of wildfire and simulated fuel reduction treatments for a burned watershed in northern Nevada. Poster presented at the Conference on Pre- and Post-Wildfire Forest Management for Ecological Restoration and Fire Resiliency. Moscow, Ida.: USDA Forest Service, Rocky Mountain Research Station.

Committee on Riparian Zone Functioning and Strategies for Management. 2002. *Riparian Areas: Functions and Strategies for Management*. Washington, D.C.: National Academy Press.

Copstead, R. L., and D. K. Johansen. 1998. Water/road interaction: Examples from three flood assessment sites in western Oregon. Report 9877 1805-SDTDS. San Dimas, Cal.: USDA Forest Service, Technology and Development Program.

Covert, S. A. 2003. Accuracy assessment of WEPP-based erosion models on three small harvested and burned forest watersheds. MS thesis. Moscow, Ida.: University of Idaho.

Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteorol*. 33(2): 140-148.

DeBano, L. F. 2000. Water repellency in soils: A historical overview. *J. Hydrol.* 231-232: 195-206.

Dissmeyer, G. E., ed. 2000. Drinking water from forests and grasslands: A synthesis of the scientific literature. Gen. Tech. Report SRS-39. Ashville, N.C.: USDA Forest Service, Southern

Research Station.

Dissmeyer, G. E., and G. R. Foster. 1985. Chapter 45: Modifying the universal soil loss equation for forest land. In *Soil Erosion and Conservation*, 480-495. Ankeny, Iowa: Soil and Water Conservation Society of America.

Dobre, M. 2010. Assessing spatial distribution of fire effects in forests using GIS. In *Proc. 2nd Joint Federal Interagency Conference*. Reston, Va.: U.S. Geological Survey. Available at: acwi.gov/sos/pubs/2ndJFIC/Contents/SP06_Dobre_03_29_10_paper.pdf. Accessed November 2011.

Dubé, K., and M. McCalmon. 2004. Technical documentation for SEDMODL road erosion/delivery model, version 2.0. Research Triangle Park, N.C.: National Council for Air and Stream Improvement. Available at: www.ncasi.org/support/downloads. Accessed February 2013.

Dun, S., J. Q. Wu, W. J. Elliot, P. R. Robichaud, D. C. Flanagan, J. R. Frankenberger, R. E. Brown, and A. D. Xu. 2009. Adapting the Water Erosion Prediction Project (WEPP) model for forest applications. *J. Hydrol*. 336(1-4): 45-54.

Elliot, W. J. 2004. WEPP internet interfaces for forest erosion prediction. *J. American Water Resour. Assoc.* 40(2): 299-309.

Elliot, W. J. 2006. Chapter 17: The roles of natural and human disturbances in forest soil erosion. In *Soil Erosion and Sediment Redistribution in River Catchments*, 177-185. P. N. Owens and A. J. Collins, eds. Wallingford, U.K.: CAB International.

Elliot, W. J. 2010. Effects of forest biomass use on watershed processes in the western United States. *Western J. Appl. Forestry* 25(1):12-17.

Elliot, W. J. 2011. Building WEPP climate files for countries outside the U.S. Unpublished. Available from author. Moscow, Ida.: USDA Forest Service, Rocky Mountain Research Station.

Elliot, W. J., and M. Foltz. 2001. Validation of the FSWEPP interfaces for forest roads and disturbances. ASAE Paper No. 018009. St. Joseph, Mich.: ASAE.

Elliot W. J., and B. D. Glaza. 2009. Impacts of forest management on runoff and erosion. In *Proc. 3rd Interagency Conference on Research in the Watersheds: Planning for an Uncertain Future: Monitoring, Integration, and Adaptation*, 117-127. USGS Scientific Investigations Report 2009-5049. R. M. T. Webb and D. J. Semmens, eds. Reston, Va.: U.S. Geological Survey.

Elliot, W. J., and D. E. Hall. 1997. Water Erosion Prediction Project (WEPP) forest applications. Gen. Tech. Report INT-365. Ogden, Utah: USDA Forest Service, Intermountain Research Station.

Elliot, W. J., and I. S. Miller. 2004. Measuring low rates of erosion from forest fuel reduction operations. ASABE Paper No. 045018. St Joseph, Mich.: ASABE.

Elliot, W. J., and P. R. Robichaud. 2006. WEPP FuME fuel management erosion analysis. Moscow, Ida.: USDA Forest Service, Rocky Mountain Research Station. Available at: http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/fume/fume.pl. Accessed September 2012.

Elliot, W. J., and L. M. Tysdal. 1999. Understanding and reducing erosion from insloping roads. *J. Forestry* 97(8): 30-34.

Elliot, W. J., T. E. Koler, J. C. Cloyd, and M. Philbin. 1994. Impacts of landslides on an ecosystem. ASAE Paper No. 947517. St. Joseph, Mich.: ASAE.

Elliot, W. J., D. Page-Dumroese, and P. R. Robichaud. 1999a. The effects of forest management on erosion and soil productivity. In *Soil Quality and Erosion*, 195-208. R. Lal, ed. Boca Raton, Fla.: CRC Press.

Elliot, W. J., R. B. Foltz, and C. H. Luce 1999b. Modeling low-volume road erosion. *Transportation Research Record* 1652: 244-250.

Elliot, W. J., I. S. Miller, and B. D. Glaza. 2006. Using WEPP technology to predict erosion and runoff following wildfire. ASABE Paper No. 068011. St. Joseph, Mich.: ASABE.

Elliot, W., W. Miller, B. Hartsough, and S. Stephens. 2008. Vegetation management in sensitive areas of the Lake Tahoe basin: A workshop to evaluate risks and advance existing strategies and practices. Incline Village, Nev.: Tahoe Science Consortium.

Elliot, W., E. Brooks, T. Link, and S. Miller. 2010a. Incorporating groundwater flow into the WEPP model. In *Proc. 4th Federal Interagency Hydrologic Modeling Conf.* Reston, Va.: U.S. Geological Survey.

Elliot, W. J., I. S. Miller, and L. Audin, eds. 2010b. *Cumulative Watershed Effects of Fuel Management in the Western United States*. Gen. Tech. Report RMRS-GTR-231. Fort Collins, Colo.: USDA Forest Service, Rocky Mountain Research Station.

Flanagan, D. C., and S. J. Livingston, eds. 1995. *WEPP User Summary*. NSERL Report No. 11. West Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.

Flanagan, D. C., and M. A. Nearing, eds. 1995. *USDA Water Erosion Prediction Project (WEPP) Hillslope Profile and Watershed Model Documentation*. NSERL Report No. 10. West Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.

Flanagan, D. C., D. A. Whittemore, S. J. Livingston, J. C. Ascough, and M. R. Savabi. 1994. Interface for the Water Erosion Prediction Project model. ASAE Paper No. 942105. St. Joseph, Mich.: ASAE.

Flanagan, D. C., H. Fu, J. R. Frankenberger, S. J. Livingston, and C. R. Meyer. 1998. A Windows interface for the WEPP erosion model. ASAE Paper No. 982135. St. Joseph, Mich.: ASAE.

Flanagan, D. C., J. E. Gilley, and T. G. Franti. 2007. Water Erosion Prediction Project (WEPP): Development history, model capabilities, and future enhancements. *Trans. ASABE* 50(5): 1603-1612.

Flanagan, D. C., J. R. Frankenberger, T. A. Cochrane, C. S. Renschler, and W. J. Elliot. 2013. Geospatial application of the water erosion prediction project (WEPP) model. *Trans. ASABE* 56(2): 591-601.

Foltz, R. B. 1996. Traffic and no-traffic on an aggregate surfaced road: Sediment production differences. In *Proc. Seminar on Environmentally Sound Forest Road and Wood Transport*, 195-204. Rome, Italy: United Nations FAO.

Foltz, R. B. 2003. Environmental impacts of forest roads: An overview of the state of the knowledge. In *Proc. 2nd Forest Engineering Conf.*, 121-128. Uppsala, Sweden: Skogforsk.

Foltz, R. B., and W. J. Elliot. 1998. Measuring and modelling impacts of tyre pressure on road erosion. In *Proc. Seminar on Environmentally Sound Forest Roads and Wood Transport*, 205-214. Rome, Italy: United Nations FAO.

Foltz, R. B., and W. J. Elliot. 2001. Infiltration characteristics of forest road filter windrows. In *Proc. Intl. Symp. on Soil Erosion Research for the 21st Century*, 13-15. J. C. Ascough II and D. C. Flanagan, eds. St. Joseph, Mich.: ASAE.

Foltz, R. B., and M. Truebe. 2003. Locally available aggregate and sediment production. *Transportation Research Record* 1819: 185-193.

Foltz, R. B., P. R. Robichaud, and H. Rhee. 2008. A synthesis of post-fire road treatments for BAER teams: Methods, treatment effectiveness, and decision making tools for rehabilitation. Gen. Tech. Report RMRS-GTR-228. Fort Collins, Colo.:USDA Forest Service, Rocky Mountain Research Station.

Foltz, R. B., N. Copeland, and W. J. Elliot. 2009. Reopening abandoned forest roads in northern Idaho, USA: Quantification of runoff, sediment concentration, infiltration, and interrill erosion parameters. *J. Environ. Mgmt*. 90(8): 2542-2550.

Foltz, R. B., W. J. Elliot, and N. S. Wagenbrenner. 2011. Soil erosion model predictions using parent material/soil texture-based parameters compared to using site-specific parameters.

Trans ASABE 54(4): 1347-1356.

Formica, S. J., M. A. Van Eps, M. A. Nelson, A. S. Cotter, T. L. Morris, and J. M. Beck. 2004. West Fork White River watershed: Sediment source inventory and evaluation. In *Proc. Conf. on Self-Sustaining Solutions for Streams, Wetlands, and Watersheds*. St. Joseph, Mich.: ASABE.

Frankenberger, J. R., S. Dun, D. C. Flanagan, J. Q. Wu, and W. J. Elliot. 2011. Development of a GIS interface for WEPP model application to Great Lakes forested watersheds. ISELE Paper No. 11139. Presented at the International Symposium on Erosion and Landscape Evolution. St. Joseph, Mich.: ASABE.

Fransen, P. J. B., C. J. Phillips, and B. D. Fahey. 2001. Forest road erosion in New Zealand: Overview. *Earth Surf. Proc. and Landforms* 26(2): 165-174.

French, N. H., E. S. Kasischke, R. J. Hall, K. A. Murphy, D. L. Verbyla, E. E. Hoy, and J. L. Allen. 2008. Using Landsat data to assess fire and burn severity in the North American boreal forest region: An overview and summary of results. *Intl. J. Wildland Fire* 17(4): 443-462.

Gares, P. A., D. J. Sherman, and K. F. Nordstrom. 1994. Geomorphology and natural hazards. *Geomorphology* 10(1-4): 1-18.

Gorsevski, P. V, P. E. Gessler, J. Boll, W. J. Elliot, and R. B. Foltz. 2006a. Spatially and temporally distributed modeling of landslide susceptibility. *Geomorphology* 80(3-4): 178-198.

Gorsevski, P. V., R. B. Foltz, P. E. Gessler, and W. J. Elliot. 2006b. Spatial prediction of landslide hazard using logistic regression and ROC analysis. *Trans. in GIS* 10(3): 395-415.

Grace III, J. M. 2002. Effectiveness of vegetation in erosion control from forest road sideslopes. *Trans. ASAE* 45(3):681-685.

Grace III, J. M., and W. J. Elliot. 2008. Determining soil erosion from roads in coastal plain of Alabama. In *Proc. Conference 39: Environmental Connection '08*. Denver, Colo.: International Erosion Control Association.

Graham, R. T., T. B. Jain, and S. Matthews. 2010. Fuel management in forests of the inland west. In *Cumulative Watershed Effects of Fuel Management in the Western United States*, 19-68. Gen. Tech. Report RMRS-GTR-231. W. J. Elliot, I. S. Miller, and L. Audin, eds. Fort Collins, Colo.: USDA Forest Service, Rocky Mountain Research Station.

Gray, D. H., and W. F. Megahan. 1981. Forest vegetation removal and slope stability in the Idaho batholith. Research Paper INT-271. Ogden, Utah: USDA Forest Service, Intermountain Research Station.

Grismer, M. E., and M. P. Hogan. 2005. Simulated rainfall evaluation of revegetation/mulch erosion control in the Lake Tahoe basin: 3. Soil treatment effects. *Land Degrad. Develop.* 16(4): 397-404.

Gucinski, H., M. J. Furniss, R. R. Ziemer, and M. H. Brookes, eds. 2001. Forest roads: A synthesis of scientific information. Gen. Tech. Report PNW GTR-509. Portland, Ore.: USDA Forest Service, Pacific Northwest Research Station.

Hammond, C., D. Hall, S. Miller, and P. Swetik. 1992. Level I Stability Analysis (LISA). Documentation for Version 2.0. General Technical Report INT-285. Ogden, Utah: USDA Forest Service, Intermountain Research Station.

Han, H.-S., D. Page-Dumroese, S.-K. Han, and J. Tirocke. 2006. Effects of slash, machine passes, and soil moisture on penetration resistance in a cut-to-length harvesting. *Intl. J. Forest Eng*. 17(2): 11-14.

Hubbart, J. A., T. E. Link, J. A. Gravelle, and W. J. Elliot. 2007. Timber harvest impacts on water yield in the continental/maritime hydroclimate region of the U.S. *J. Forestry* 53(2): 169-180.

Huffman, R. L., D. D. Fangmeier, W. J. Elliot, S. R. Workman, and G. A. Schwab. 2011. *Soil and Water Conservation Engineering*. 6th ed. St. Joseph, Mich.: ASABE.

Ice, G. C., and J. D. Stednick, eds. 2004. *A Century of Forest and Wildland Watershed Lessons*. Bethesda, Md.: Society of American Foresters.

Idaho Forest Products Commission. 2012. Look to the future, look to the forest. Boise, Ida.: Idaho Forest Products Commission. Available at: www.idahoforests.org/brochure09.htm. Accessed November 2012.

Jassal, R. S., T. A. Black, D. L. Spittlehouse, C. Brümmer, and Z. Nesic. 2009. Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands. *Agric. Forest Meteorol.* 149(6-7): 1169-1178.

Jones, G. 2012. OptFuels: Fuel treatment optimization. Missoula, Mont.: USDA Forest Service, Human Dimensions Program. Available at: www.fs.fed.us/rm/human-dimensions/optfuels/main.php. Accessed September 2012.

Jones, J. A., F. J. Swanson, B. C. Wemple, and K. U. Snyder. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biol.* 14(1): 76-85.

Karwan, D. L., J. A. Gravelle, and J. A. Hubbart. 2007. Effects of timber harvest on suspended sediment loads in Mica Creek, Idaho. *Forest Sci.* 53(2):181-188.

Ketcheson, G. L., and W. F. Megahan. 1996. Sediment production and downslope sediment transport from forest roads in granitic watersheds. Research Paper INT-RP-486. Ogden, Utah: USDA Forest Service, Intermountain Research Station.

Kirchner, J. W., R. C. Finkel, C. S. Riebe, D. E. Granger, J. L. Clayton, J. G. King, and W. F. Megahan. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* 29(7): 591-594.

Lafayette, R., M. T. Brooks, J. P. Potyondy, L. Audin, S. L. Krieger, and C. C. Trettin, eds. 2012. Cumulative watershed effects of fuel management in the eastern United States. Gen. Tech. Report SRS-161. Asheville, N.C.: USDA Forest Service, Southern Research Station.

Laflen, J. M., W. J. Elliot, D. C. Flanagan, C. R. Meyer, and M. A. Nearing. 1997. WEPP: Predicting water erosion using a process-based model. *J. Soil and Water Cons.* 52(2): 96-102.

Lane, L. J., and M. A. Nearing. 1989. USDA Water Erosion Prediction Project: Hillslope profile model documentation. NSERL Report No. 2. W. Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.

Larsen, I. J., and L. H. MacDonald. 2007. Predicting post-fire sediment yields at the hillslope scale: Testing RUSLE and Disturbed WEPP. *Water Resources Res*. 43(11): W11412, doi: 10.1029/2006WR005560.

Lentile, L. B., Z. A. Holden, A. M. S. Smith, M. J. Falkowski, A. T. Hudak, P. Morgan. S. A. Lewis, P. E. Gessler, and N. C. Benson. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. *Intl. J. Wildland Fire* 15(3): 3119-345.

Lewis, S. A., J. Q. Wu, and P. R. Robichaud. 2004. Assessing burn severity and comparing soil water repellancy, Hayman fire, Colorado. *Hydrol. Proc*. 20(1): 1-16.

Litschert, S. E., and L. H. MacDonald. 2009. Frequency and characteristics of sediment delivery pathways from forest harvest units to streams. *Forest Ecol. and Mgmt.* 259(2): 143-150.

Luce, C. H., and T. A. Black. 1999. Sediment production from forest roads in western Oregon. *Water Resources Res.* 35(8): 2561-2570.

Luce, C. H., and T. A. Black. 2001. Spatial and temporal patterns in erosion from forest roads. In *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*, Vol. 2: 165-178. M. S. Wigmosta and S. J. Burges, eds. Washington, D.C.: American Geophysical Union.

Luce, C. H., and T. A. Black. 2011. Focus: GRAIP, Quantifying and prioritizing road impacts. Moscow, Ida.: USDA Forest Service, Rocky Mountain Research Station. Available at: www.fs.fed.us/rm/boise/AWAE/briefing/Luce_FocusOnGRAIP.pdf. Accessed March 2013.

MacDonald, T. P., and F. Seixas. 1997. Effect of slash on forwarder soil compaction. *J. Forest Eng.* 8(2):15-26.

MacKenzie, K., B. Urbonas, M. Jansekok, and J. Guo. 2007. Effect of raingauge density on runoff simulation modeling. In *Proc. World Environmental and Water Resources Congress 2007: Restoring our Habitat*. Reston, Va.: ASCE.

Marshall, J., and K. Kavanagh. 2011. Species impacts on carbon gains and water yields. Abstract. In *Proc. Priest River Experimental Forest 100-Year Anniversary Agenda*, 19-20. Moscow, Ida.: USDA Forest Service, Rocky Mountain Research Station.

McCabe, J. G., M. P. Clark, and L. E. Hay. 2007. Rain-on-snow events in the western United States. *Bull. American Meteorol. Soc.* 88(3): 319-328.

McClelland, D. E., R. B. Foltz, W. D. Wilson, T. W. Cundy, R. Heinemann, J. A. Saurbier, and R. L. Schuster. 1997. Assessment of the 1995 and 1996 floods and landslides on the Clearwater National Forest. Missoula, Mont.: USDA Forest Service, Northern Region.

McCool, D. K., S. Dun, J. Q. Wu, W. J. Elliot, and E. S. Brooks. 2013. Seasonal change of WEPP erodibility parameters for two fallow plots on a Palouse silt loam. *Trans. ASABE* 56(2): 711-718.

McDonald, G. I., A. E. Harvey, and J. R. Tonn. 2000. Fire, competition, and forest pests: Landscape treatment to sustain ecosystem function. In *Proc. Joint Fire Science Conference and Workshop*, 195-211. L. F. Neuenschwander and K. C. Ryan, eds. Moscow, Ida.: University of Idaho. Available at: www.treesearch.fs.fed.us/pubs/23565. Accessed January 2013.

Meadows, D., R. B. Foltz, and N. Geehan. 2008. Effects of all-terrain vehicles on forested lands. 0823 1811-SDTDC. San Dimas, Cal.: USDA Forest Service, San Dimas Technology and Development Center.

Megahan, W. F. 1975. Sedimentation in relation to logging activities in the mountains of central Idaho. In *Proc. Sediment Yield Workshop: Present and Prospective Technology for Predicting Sediment Yields and Sources*, 74-82. Oxford, Miss.: USDA Sedimentation Laboratory.

Megahan, W. F., and W. J. Kidd. 1972. Effect of logging roads on sediment rates in the Idaho batholith. Research Paper INT-123. Ogden, Utah: USDA Forest Service Intermountain Forest and Range Experiment Station.

Megahan, W. F., and J. G. King. 2004. Erosion, sedimentation, and cumulative effects in the northern Rocky Mountains. In *A Century of Forest and Wildland Watershed Lessons*, 201-222. G. G. Ice and J. D. Stednick, eds. Washington, D.C.: Society of American Foresters.

Miller, M. E., L. H. MacDonald, P. R. Robichaud, and W. J. Elliot. 2011. Predicting post-fire hillslope erosion in forest lands of the western United States. *Intl. J. Wildland Fire* 20(8): 982-999.

Moreira, E. P., W. J. Elliot, and A. T. Hudak. 2011. Effects of DTM resolution on slope steepness and soil loss prediction on hillslope profiles. Presented at the XXXIII Congresso Brasileiro de Ciência do Solo. Vicosa, Brazil: Sociedade Brasileira de Ciência do Solo.

Nearing, M. A., H. Wei, J. J. Stone, F. B. Pierson, K. E. Spaeth, M. A. Weltz, D. C. Flanagan, and M. Hernandez. 2011. A rangeland hydrology and erosion model. *Trans. ASABE* 54(3):901-908.

Packer, P. E., and G. F. Christensen. 1977. Guides for controlling sediment from secondary logging roads. Ogden, Utah: USDA Forest Service, Intermountain Forest and Range Experiment Station.

Patric, J. H. 1976. Soil erosion in the eastern forest. *J. Forestry* 74(10): 671-677.

Patric, J. H., J. O. Evans, and J. D. Helvey. 1984. Summary of sediment yield data from forested areas in the United States. *J. Forestry* 82(2): 101-104.

Prellwitz, R. W., T. E. Koler, and J. E. Steward, coords. 1994. Slope stability reference guide for national forests in the United States. EM-7171-13. Washington, D.C.: USDA Forest Service, Engineering Staff.

Reid, L. M. 2010. Chapter 10: Cumulative effects of fuel treatments on channel erosion and mass wasting. In *Cumulative Watershed Effects of Fuel Management in the Western United States*, 101-125. Gen. Tech. Report RMRS-GTR-231. W. J. Elliot, I. S. Miller, and L. Audin, eds. Fort Collins, Colo.: USDA Forest Service, Rocky Mountain Research Station.

Reinhardt, E. D., R. E. Keane, D. E. Calkin, and J. D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *Forest Ecol. and Mgmt.* 256(12): 1997-2006.

Renschler, C. S. 2003. Designing geo-spatial interfaces to scale process models: The GeoWEPP approach. *Hydrol. Proc.* 17(5): 1005-1017.

Robichaud, P. R. 1996. Spatially varied erosion potential from harvested hillslopes after prescribed fire in the interior northwest. PhD diss. Moscow, Ida.: University of Idaho.

Robichaud, P. R. 2000. Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA. *J. Hydrol.* 231-232: 220-229.

Robichaud, P. R. 2005. Measurement of post-fire hillslope erosion to evaluate and model rehabilitation treatment effectiveness and recovery. *Intl. J. Wildland Fire* 14(4): 475-485.

Robichaud, P. R., and R. E. Brown. 2002. Silt fences: An economical technique for measuring hillslope soil erosion. Gen. Tech. Report RMRS-GTR-94. Ft. Collins, Colo.: USDA Forest Service, Rocky Mountain Research Station.

Robichaud, P. R., and S. M. Miller. 1999. Spatial interpolation and simulation of post-burn duff thickness after prescribed fire. *Intl. J. Wildland Fire* 9(2): 137-143.

Robichaud, P. R., C. H. Luce, and R. E. Brown. 1993. Variation among different surface conditions in timber harvest sites in the southern Appalachians. In *Proc. Russian, U.S., and Ukraine Intl. Workshop on Quantitative Assessment of Soil Erosion*, 231-241. J. A. Larionov and M. A. Nearing, eds. West Lafayette, Ind.: Purdue University, Center for Technology Transfer and Pollution Prevention.

Robichaud, P. R., W. J. Elliot, F. B. Pierson, D. E. Hall, and C. A. Moffet. 2007. Predicting post-fire erosion and mitigation effectiveness with a web-based probabilistic model. *Catena* 71(2): 229-241.

Robichaud, P. R., L. E. Ashmun, and B. Sims. 2010a. Post-fire treatment effectiveness for hillslope stabilization. Gen. Tech. Report RMRS-GTR-240. Fort Collins, Colo.: USDA Forest Service, Rocky Mountain Research Station.

Robichaud, P. R., L. H. MacDonald, and R. B. Foltz. 2010b. Chapter 5: Fuel management and erosion. In *Cumulative Watershed Effects of Fuel Management in the Western United States*, 79-100. Gen. Tech. Report RMRS-GTR-231. W. J. Elliot, I. S. Miller, and L. Audin., eds. Fort Collins, Colo.: USDA Forest Service, Rocky Mountain Research Station.

Robichaud, P. R., W. J. Elliot, and J. W. Wagenbrenner. 2011. Probabilistic soil erosion modeling using the erosion risk management tool (ERMiT) after wildfires. ISELE Paper No. 11039. Presented at the International Symposium on Erosion and Landscape Evolution. St. Joseph, Mich.: ASABE.

Robison, E. G., K. Mills, J. Paul, L. Dent, and A. Skaugset. 1999. Storm impacts and landslides of 1996. Forest Res. Tech. Report 4. Salem, Ore.: Oregon State University, Department of Forestry.

Roccaforte, J. P., P. A. Fulé, and W. W. Covington. 2008. Landscape-scale changes in canopy fuels and potential fire behaviour following ponderosa pine restoration treatments. *Intl. J. Wildland Fire* 17(2): 293-303.

Rummer, B., 2010. Tools for fuel management. In *Cumulative Watershed Effects of Fuel Management in the Western United States*, 69-78. Gen. Tech. Report RMRS-GTR-231. W. J. Elliot, I. S. Miller, and L. Audin, eds. Fort Collins, Colo.: USDA Forest Service, Rocky Mountain Research Station.

Rummer, B., J. Prestemon, D. May, P. Miles, J. Vissage, R. McRoberts, G. Liknes, W. D. Shepperd, D. Ferguson, W. Elliot, S. Miller, S. Reutebuch, J. Barbour, J. Fried, B. Stokes, E. Bilek, and K. Skog. 2003. A strategic assessment of forest biomass and fuel reduction treatments in western states. Washington, D.C.: USDA Forest Service, Research and Development. Available at: www.fs.fed.us/research/pdf/Western_final.pdf. Accessed April 2010.

Scheele, D. L., W. J. Elliot, and D. E. Hall. 2001. Enhancements to the CLIGEN weather generator for mountainous or custom applications. In *Proc. Intl. Symp. on Soil Erosion Research for the 21st Century*, 392-395. J. C. Ascough II and D. C. Flanagan, eds. St. Joseph, Mich.: ASAE.

Schleppi, P., P. A. Waldner, and B. Fritschi. 2006. Accuracy and precision of different sampling strategies and flux integration methods for runoff water: Comparison based on measurements of the electrical conductivity. *Hydrol. Proc*. 20(2): 395-410.

Seyedbagheri, K. A. 1996. Idaho forestry best management practices: Compilation of research and their effectiveness. Gen. Tech. Report INT-GTR-339. Ogden, Utah: USDA Forest Service, Intermountain Research Station.

Simon, A., and N. Pollen. 2006. A model of streambank stability incorporating hydraulic erosion and the effects of riparian vegetation. In *Proc. 8th Federal Interagency Sedimentation Conference (8th FISC)*, 870-877. Reston, Va.: U.S. Geological Survey.

Simon, A., W. Dickerson, and A. Heins. 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: Transport conditions at the bankfull and effective discharge. *Geomorphology* 58(1-4): 243-262.

Srivastava, A., M. Dobre, J. Wu, W. Elliot, E. Bruner, S. Dun, E. Brooks, and I. Miller. 2013. Modifying WEPP to improve streamflow simulation in a Pacific Northwest watershed. *Trans. ASABE* 56(2): 603-611.

Turner, M. G., W. J. Romme, and R. H. Gardner. 1999. Prefire heterogeneity, fire severity, and early post-fire plan reestablishment in subalpine forests of Yellowstone National Park, Wyoming. *Intl. J. Wildland Fire* 9(1): 21-36.

Tysdal, L., B. Elliot, C. Luce, and T. Black. 1997. Modeling insloping road erosion processes with the WEPP watershed model. ASAE Paper No. 975014. St. Joseph, Mich.: ASAE.

USFS. 1990. R1-WATSED Region 1 water and sediment model. Missoula, Mont.: USDA Forest Service, Northern Region.

USGS. 1999. San Bernardino report: Debris flows at Forest Falls, San Bernardino County, Cal. Reston, Va.: U.S. Geological Survey. Available at: http://landslides.usgs.gov/recent/archives/1999sanbreport.php. Accessed December 2012.

USGS. 2006. National elevation dataset. Reston, Va.: U.S. Geological Survey. Available at: ned.usgs.gov. Accessed March 2013.

Wang, L. 2012. Channel routing using discrete Hayami convolution method with applications to the Water Erosion Prediction Project (WEPP) model. PhD diss. Pullman, Wash.: Washington State University.

Wang, L., J. Q. Wu, W. J. Elliot, S. Dun, S. Lapin, F. R. Fiedler, and D. C. Flanagan. 2009. Implementation of channel-routing routines in the Water Erosion Prediction Project (WEPP) model. Presented at the 2009 SIAM Conf. on Mathematics for Industry. Philadelphia, Pa.: Society for Industrial and Applied Mathematics.

Ward, A. D., and S. W. Trimble. 2004. *Environmental Hydrology*. 2nd ed. Boca Raton, Fla.: Lewis Publishers.

Wischmeier, W. H., and D. D. Smith. 1978. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning.* Agric. Handbook No. 282. Washington, D.C.: USDA.

Wolman, M. G., and J. P. Miller. 1960. Magnitude and frequency of forces in geomorphic processes. *J. Geology* 68(1): 54-74.

Wu, C.-D., C.-D. Cheng, and Y.-C. Chuang. 2012. Spatial variability of evapotranspiration of old-growth cypress forest using remote sensing: A case study of Chilan Mountain cypress forest in Taiwan. *Canadian J. Forest Res*. 42(6): 1060-1071.

Yao, C., D. K. McCool, and W. J. Elliot. 2010. DEM resolution effects on hillslope length and steepness estimates for erosion modeling. ASABE Paper No. 1009979. St. Joseph, Mich.: ASABE.

Zhang, J. X, J. Q. Wu, K. Chang, W. J. Elliot, and S. Dun. 2009. Effects of DEM source and resolution on WEPP hydrologic and erosion simulation: A case study of two forest watersheds in northern Idaho. *Trans. ASABE* 52(2): 447-457.

Ziemer, R. R. 1964. Summer evapotranspiration trends as related to time after logging in forests in Sierra Nevada. *J. Geophysical Res*. 69(4): 615-620.