GEOMORPHIC RESPONSE TO WILDFIRE IN THE OREGON COAST RANGE

by

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A THESIS

Presented to the Department of Geological Sciences
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Master of Science

June 2004

"Geomorphic Response to Wildfire in the Oregon Coast Range," a thesis prepared by Molly B. Gerber in partial fulfillment of the requirements for the Master of Science degree in the Department of Geological Sciences. This thesis has been approved and accepted by:

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An Abstract of the Thesis of

Molly B. Gerber for the degree of Master of Science

in the Department of Geological Sciences to be taken June 2004

Title: GEOMORPHIC RESPONSE TO WILDFIRE IN THE OREGON COAST RANGE

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Dr. Joshua J. Roering

Sediment transport and erosion in the Oregon Coast Range (OCR) have been well-studied, but little is known about the effect of forest fires on process rates or mechanisms. This thesis documents the significant role of post-fire erosional response at three recent burn sites (1999, 2002, 2003). In the first three months following a 2003 fire, dry ravel induced 2.4 to 5.1 mm of hillslope erosion, more than an order of magnitude higher than estimated long-term erosion rates in the OCR. Fires also damaged hillslope-stabilizing vegetation, leading to a 50% decline in Douglas-fir root strength in the first ten months after fire. With continued root decay, hillslopes will become increasingly susceptible to debris flow occurrence. These observations suggest that periods of greatly increased erosion due to wildfire punctuate the long-term erosional pattern in the OCR, possibly contributing more than 20% of the long-term sediment yield.

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Gerber, M.B., Clausen, M.C., and Carson, R.J., 2000, Geomorphic evolution of the Grande Ronde River, northeast Oregon and southeast Washington, Proceedings of the Oregon Academy of Science: McMinnville, OR.

Gerber, M.B., and Roering, J.J., 2003, Decline in root strength following wildfire in the Oregon Coast Range: Geologic Society of America, 2003 Annual Meeting, Abstracts with Programs, v. 35, p. 352.

ACKNOWLEDGMENTS

I sincerely appreciate Professor Josh Roering's guidance, encouragement, enthusiasm, funding, and extensive editing of this manuscript. Also, I owe special thanks to Professor Cathy Whitlock, whose research and teaching inspired my interest in wildfires in the Oregon Coast Range. T.C. Hales carried heavy field equipment, helped with surveys, and showed me his tricks in ArcMap. Paul Chapman, with the Campbell Group, and Dave Cramsey, with Roseburg Resources, provided helpful information on the fires and granted me access to private timberlands. Bureau of Land Management Environmental Assessments were indispensable, and BLM officials directed me to the Siuslaw River Fire. The Baldwin Award in the Department of Geological Sciences helped fund this research. Finally, Kelly Jackson deserves more thanks than I can give; he carried supplies, fortified a sediment dam, measured debris cones, reminded me to charge the GPS batteries, listened to complaints, made burritos, and made everything more fun and interesting.

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CHAPTER 1: REVIEW OF GEOMORPHIC RESPONSES TO WILDFIRE

1.1 Introduction

Geomorphic response to wildfire differs among physiographic provinces because of varying geology, topography, climate, vegetation, and fire regimes. Most research on post-fire erosion has concentrated on the interior Northwest, the Rocky Mountain region, California, and the Southwest. The primary difference in post-fire erosional response between these areas and the Pacific Northwest is the prevalence of overland flow and associated surficial erosion, including sheetwash, rilling, and gullying. Because of high infiltration rates, overland flow is not prevalent after fires in the Pacific Northwest, although it is a dominant process in other, more arid burned regions (Wondzell and King, 2003).

There is scarce literature documenting the geomorphic response to wildfire in the Oregon Coast Range (OCR), yet an abundance of information exists detailing the geomorphic response to wildfire in other areas of the western United States. This review is not comprehensive, but rather seeks to highlight common geomorphic responses to wildfire in mountainous regions, allowing us to couch our observations of the OCR in the context of other well-documented landscapes. Several papers provide extensive and thorough reviews of the literature on post-fire geomorphic response and were indispensable in this review (Swanson, 1981; McNabb and Swanson, 1990; Wondzell and King, 2003).

1.2 Motivation for Study

Previous studies have long proposed that fire is a significant mechanism accelerating erosion in western Oregon (Benda and Dunne, 1997; Swanson, 1981; McNabb and Swanson, 1990; Bennett, 1982). Swanson (1981) proposes that periods of greatly increased erosion resulting from wildfires punctuate the long-term steady erosion rate in western Oregon forests and contribute 25 percent of the overall sediment yield. Benda and Dunne (1997) postulate that root-destroying wildfires are an important perturbation in the stochastic soil-transport mechanisms of landsliding and debris flows. McNabb and Swanson (1990) demonstrate the potential for mass-wasting events associated with root systems weakened by fire in the Pacific Northwest. Personius et al. (1993) attribute a series of terraces along Coast Range rivers to aggradation resulting from increased landsliding at the Pleistocene-Holocene transition and speculate that this may have been due to a loss of vegetation resulting from natural vegetation fluctuations or an increase in fire frequency.

Despite speculation that wildfire is important in the long-term erosion of the OCR, few data exist to evaluate or support this theory. Studies of erosion in the OCR have concluded that erosion rates are spatially and temporally uniform, yet evidence at three recent fire sites indicates that periods of greatly accelerated erosion punctuate the long-term erosional pattern of the Coast Range. The purpose of this study is to investigate the geomorphic response to wildfire in the Oregon Coast Range, to compare the response to that seen in other regions of the western United States, and to evaluate the importance of post-fire erosion in the long-term erosion of the Oregon Coast Range.

Understanding the influence of wildfire on landscapes is important in terms of immediate impacts as well. As people increasingly move into fire-prone areas in the western United States, the effects of the recent century of fire suppression and indications of a warming climate are being analyzed. A buildup of woody fuels and warmer, drier conditions may produce more widespread and severe wildfires. Identifying the potential geomorphic response to fires in the OCR may help mitigate some of the hazards posed by post-fire erosion. For instance, an influx of sediment and woody debris to stream systems as a result of post-fire erosion can degrade water quality and harm already threatened fish species. Also, even after fires are extinguished, they pose potential hazards to humans and structures, as destructive debris flows often follow wildfires. Identifying areas that may experience significant post-fire erosional events, and approximating a timeline for those events can reduce potentially destructive consequences.

1.3 Review of Post-Fire Geomorphic Response in Western North America

1.3.1 Dry Ravel

In certain environments, wildfire can increase a hillslope's propensity for dry ravel, also referred to in the literature as "dry creep" (Krammes, 1960; Swanston, 1971; Krammes and Osburn, 1969), "surficial debris cascade" (Morris and Moses, 1987), "dry sliding" (Krammes, 1960; Swanston, 1971), and "debris sliding" (Doehring, 1968). Dry ravel is the process of downslope movement of sediment or organic material by rolling, sliding, or bouncing. Gravity alone drives the process, and water is not involved in the detachment or mobilization of sediment. It can occur in soils at or near their angle of

repose when animals or wind dislodge sediment, or when fire removes supportive vegetation or organic litter, releasing sediment stored uphill. In the steep chaparral drainage basins of southern California and in other arid environments, dry ravel is a dominant erosional process on unburned hillslopes in the dry summer season (Anderson et al., 1959; Krammes, 1960; Krammes, 1965; Doehring, 1968; Gabet, 2003). Wildfire can greatly accelerate dry ravel in arid environments and can induce dry ravel on hillslopes not usually subject to the process.

Following a 1959 wildfire in the San Dimas Experimental Station in southern California, Krammes (1960) documented a 10-17 fold increase over pre-fire rates in dry ravel on burned hillslopes, approximately 90% of which occurred in the first dry season after the fire. Firefighters were forced to dodge rolling rocks and debris during the fire, and in the first week after the fire, dry ravel formed debris cones large enough to block roads. Doehring (1968) studied erosional response in another drainage basin of the San Dimas Experimental Station after a July 1960 wildfire. The primary erosional response from burned hillslopes was dry ravel. During the fire and in the first two weeks after the fire, erosion rates were highly elevated, with intermittent dry ravel depositing large debris cones in channels. Even two weeks following the fire, Doehring characterized the slopes as “super-sensitive” to any disturbance that might trigger a cascade of debris. By calculating the volume of debris cones and the contributing area of the cones, he was able to calculate erosion rates from the burned hillslopes to be 40 times estimated annual erosion rates of undisturbed hillslopes. By the second summer following the fire,

Doehring estimated that this rate had decreased to five times the normal erosion rate, a rate maintained until the eighth summer, when it returned to pre-fire levels.

While studying the application of various soil-wetting agents to burned water-repellent soils, Krammes and Osburn (1969) measured volumes of sediment mobilized after fire in the San Gabriel Mountains of southern California. One third of the measured sediment on burned control plots was attributed to dry ravel. The soil-wetting agents were intended to counteract water-repellency resulting from wildfire and to reduce overland flow and associated erosion resulting from water-repellent hillslope soils. An unintended result of the wetting agents was that they reduced the amount of dry ravel by approximately 50%, a phenomenon the authors loosely connected to bulk density differences between water-repellent soils and wettable soils (Krammes and Osburn, 1969; Sidle, 1985). Sidle (1985) speculated that the lower bulk densities of water-repellent soils reduces their internal angles of friction, which causes non-cohesive soils already near their angle of repose to lose stability.

Rice (1974) estimated that dry ravel accounted for one third of sediment eroded from steep (>60% gradient) chaparral hillslopes following wildfire. In a study quantifying post-fire sediment movement in southern California, Rice (1982) documented a 28-fold increase in dry ravel in the 3 months directly after fire, calculating .0039 m^3/m^2 of erosion after the fire. In their study of a burned Arizona drainage basin, Laird and Harvey (1986) noted that dry ravel was the primary mechanism contributing soils to the tributary channels of their study area. Over a period of years, this influx of raveled

material migrated through the drainage basin channels, first causing aggradation of tributary channels and then aggradation of the main channel.

Florsheim et al. (1991) measured dry ravel deposits in channels in southern California in the first two dry seasons following a wildfire. They found that dry ravel contributed 0.2 m^3 of sediment per meter of channel length in the first month after the fire, while in the second dry season, that rate dropped an order of magnitude to .04 m^3 per meter of channel length per month. They estimated that dry ravel accounted for only 10% of total sediment contributed to the channel, attributing the remainder to rilling or small debris slides from hillslopes near the channel.

1.3.2 Increased Overland Flow and Associated Surficial Erosion

Overland flow, raindrop splash, sheetwash, and rilling commonly occur in unburned areas, but intense fires can dramatically increase the magnitude of these processes by removing vegetative cover and altering the chemical and physical properties of soils. Intense wildfire can remove all canopy cover and organic material on the forest floor, exposing the underlying mineral soil to raindrop impact and overland flow. Wildfire also breaks down interparticle soil bonds, reduces grain-size, and often blankets hillslopes with small ash particles, all of which contribute easily mobilized sediment to the surficial soil supply on hillslopes (White and Wells, 1979; DeBano, 2000; Moody and Martin, 2001). Rainsplash can also mobilize fine-grained ash and sediment and fill in pore spaces, essentially sealing the soil surface (Wells et al., 1979; DeBano, 2000; Robichaud, 2000; Meyer et al., 2001). Additionally, soil structure can change during

intense wildfire, leading to harder, more massive soils, with potentially reduced infiltration rates (Wells et al., 1979).

Wildfires can also lead to the development of hydrophobicity in soils. Hydrophobicity occurs naturally in some unburned soils, due to the presence of water-repellent organic materials at or near the soil surface (DeBano, 1981; Benavides-Solorio and MacDonald, 2001), but heating during wildfire can intensify the effect. Chaparral, a brushy species prevalent in California, is most notorious for creating water repellency, although conifers can also contribute water-repellent substances to the soil (DeBano, 1981). When fire burns these organic substances, the waxy materials volatilize, and some of the gases penetrate the soil below, where they condense in cooler areas (DeBano, 1981; Wells et al., 1979). As they condense, the organic resins coat soil particles, and create soil layers that repel water. These upper surfaces of water-repellent layers are generally within a few centimeters of the surface of the soil, and vary in thickness from around half a centimeter up to 23 cm (Wells et al., 1979). Intense fires with temperatures around 175-200°C and a large fuel load are necessary for the formation of water repellency (DeBano, 1981).

Water repellency and surface sealing act to reduce soil-infiltration rates after fire. Robichaud (2000) used a rainfall simulator to compare infiltration rates after prescribed burns of varying intensity in the Northern Rocky Mountains. The experiments revealed that on intensely burned slopes, hydraulic conductivity was reduced 10-40 % in comparison to unburned sites. This reduced conductivity was temporary, returning to normal by the third simulated rainstorm, and was attributed to water repellency and

surface sealing. Martin and Moody (2001) also simulated rainfall using a portable infiltrometer on burned and unburned slopes in Colorado and New Mexico. Comparisons of infiltration rates revealed that steady-state infiltration rates on unburned slopes were 2.5 to almost 7 times greater than on burned slopes.

Decreased interception due to the removal of canopy cover and reduced infiltration rates due to water repellency and surface sealing often result in increased surface runoff and soil transport on burned hillslopes. White and Wells (1979) found runoff on intensely burned hillslopes to be almost 60 times greater than on lightly burned hillslopes in New Mexico. They also documented a higher sediment yield from the intensely burned slopes than from lighter burned areas, although their comparisons were complicated by bioturbation and varying amounts of needlefall protecting moderately burned slopes.

Laird and Harvey (1986) studied the geomorphic response of a burned drainage basin in Arizona, finding that runoff and rilling increased following fire on the chaparral-covered slopes. Runoff following storms increased immediately following the wildfire and remained elevated for eight years before returning to pre-fire levels. Prior to the fire, erosion was negligible, but in the year after the fire, total hillslope lowering amounted to 5 mm over the entire drainage basin. Erosion declined to pre-fire levels by the third year after the fire. The initial increase in runoff incised the main channel, and the subsequent pulse of erosion caused the tributaries to aggrade.

Moody and Martin (2001) investigated two burned watersheds in Colorado and found that runoff increased for four years before returning to pre-fire levels. This

increase in runoff was accompanied by an approximately 200-fold increase in erosion rate in the first year following the fire, primarily attributed to rill and interrill erosion. By the second summer following fire, the erosion rate was only twice that of undisturbed slopes and approximated pre-fire levels in the third and fourth summers.

While investigating the influence of different site variables on runoff and erosion, Benavides-Solorio and MacDonald (2001) simulated rainfall on Colorado hillslopes with varying degrees of burn severity. The experiments revealed a small increase in runoff following fire, yet the sediment yields were 10-26 times greater on recent high-severity burns compared to low-severity burns or unburned hillslopes. The increase in sediment yield was only found on recently burned slopes (1 to 2 years old) and was negligible at a six-year-old fire site. Their results suggest that vegetation recovery is critical in the stabilization of hillslopes, as vegetation protects soils from raindrop splash and sheetwash, the dominant erosional mechanisms at their sites.

Morris and Moses (1987) found a similar relaxation time for sediment yields following wildfire in Colorado, but point to different mechanisms influencing stabilization of soils. Their study employed sediment traps to compare the erosional response of various age fire sites to erosion on unburned hillslopes. Sediment flux, attributed to dry ravel and slopewash resulting from overland flow, increased by as much as three orders of magnitude on intensely burned hillslopes. This accelerated erosion declined rapidly; one year after the fire, sediment flux rates were only 20% of the flux rates recorded immediately post-fire, still an order of magnitude higher than flux rates on undisturbed hillslopes. Vegetation did not regenerate quickly enough to explain the rapid

decline in sediment flux rates, so the authors suggest that loss of water repellency and initial removal of fine grains from the sediment supply may explain this decline.

1.3.3 Debris flows

Wildfire often increases the occurrence of debris flows from burned hillslopes. Fire-related debris flows can be divided into two types: those initiated due to increased overland flow on burned hillslopes and those resulting from soil saturation and resultant debris sliding (Wondzell and King, 2003). Because water-repellent layers often form a few centimeters below the soil surface, rainfall can penetrate the thin, wettable upper layer of soil, until the water-repellent layer below impedes further infiltration. This can saturate the upper layer of soil, leading to soil slips, rills, sheetwash, and gullies, which can progress into debris flows (DeBano, 2000). Water repellency is not necessary, though, for runoff-initiated debris flows. Recent studies have documented post-fire debris flows without the presence of water-repellent layers (Cannon and Reneau, 2000; Cannon et al., 2001a; Cannon et al., 2001b). Cannon et al. (2001a) suggest that sheetwash and rilling due to increased surface runoff can entrain abundant fine soils and burned organic material and converge to form debris flows. The presence of readily mobilized sediment, both on hillslopes and in channels, is important in the development of runoff-initiated debris flows. Runoff-initiated debris flows occur in the first few seasons following wildfire, when abundant fines are available for transport, water repellency may still be present, vegetative cover has not yet reestablished, and root strength is still high (Meyer et al., 2001).

Shallow landslide-initiated debris flows are common in soil-mantled landscapes with relatively high infiltration rates. They often initiate in areas of low root strength, due to timber harvesting or gaps in tree spacing, and occur during extended periods of rainfall in the winter months (Burroughs and Thomas, 1977; Gray and Megahan, 1981; Schmidt et al., 2001; Roering et al., 2003). The root networks of trees and smaller understory provide substantial strength to soils on hillslopes and can extend to over a meter below the soil surface. Roots resist shear displacement downslope by anchoring soil to bedrock and acting as an interlocking fibrous network connecting unstable soil columns to more stable soils. Removal or decay of this root system destabilizes hillslopes, increasing the propensity for shallow landsliding and debris flows during rainstorms (Montgomery, 2000). Stand-replacing wildfires may lead to similar root decay and increase debris-flow occurrence in the years after burning (Rice, 1974; Meyer et al., 2001; May and Gresswell, 2003). Several studies reveal that debris-slide initiated debris flows related to wildfire are most frequent more than 4 years after fire, when water repellency no longer impedes infiltration or root strength has declined significantly (Rice, 1974; Megahan et al., 1978; Gray and Megahan, 1981; Swanson, 1981; McNabb and Swanson, 1990; Meyer et al., 2001).

1.4 Studies of Post-Fire Erosion in Western Oregon

Although there have been several studies investigating the geomorphic response to wildfire in western Oregon, few have quantified the response and even fewer have examined the Oregon Coast Range. The OCR has motivated extensive examination of

uplift, erosion, soil production, sediment transport, and relationships among these processes. Yet, the effects of wildfire have not been examined in detail and may prove to be important in the long-term evolution of the landscape.

Bennett (1982) quantified rates of soil erosion and sediment transport following broadcast burning at harvested sites in the Oregon Coast Range. Her data demonstrated that slash burning dramatically increased erosion rates in the first year following a fire, and that 65 percent of the post-fire erosion occurred in the first 24 hours following a fire. The primary erosional process observed was dry ravel, which she measured using sediment traps on hillslopes during and after the fire.

Following a wildfire in southwestern Oregon, near the Klamath Mountains, Schmidt (1995) measured geomorphic response of hillslopes and channels using erosion pins and measurements of cross-sections. The mechanisms of measurement proved to be insensitive to small changes in the study basin, and results were further complicated by undocumented changes in soil bulk density. Measurements of dry ravel deposits behind logs yielded hillslope erosion rate estimates of 1 mm/year for the first winter season, though the results were not extrapolated to the entire basin. Schmidt (1995) concludes that geomorphic change following wildfire in the Pacific Northwest is negligible due to high infiltration rates and relatively low rainfall intensities. The underlying bedrock in the study area is serpentinite, and hillslope gradients average between 20 and 40 percent, much lower than hillslope gradients in the Oregon Coast Range.

McNabb et al. (1989) documented decreased infiltration rates in the Siskiyou Mountains of southwestern Oregon following wildfire in a mixed evergreen forest.

Using a portable infiltrometer, they measured infiltration rates on burned and unburned hillslopes. Infiltration rates were significantly lower on burned slopes compared to unburned slopes, although even these reduced rates were 2-3 times the estimate of the 100-year storm for the area. The reduction in infiltration was attributed to the development of a water-repellent layer, which disappeared rapidly in the beginning of the rainy season, causing infiltration rates to return to pre-fire levels.

Mersereau and Dryness (1972) measured sediment transported primarily by dry ravel after a prescribed burn in the H.J. Andrews Experimental Forest in the western Cascades of Oregon. Sediment traps on 80 percent slopes collected an average of 89.6 cubic feet per acre, while 60 percent slopes collected an average of 20.6 cubic feet per acre. Sediment transport from south-facing slopes was more that 3.5 times that from north-facing slopes, which the authors attribute to reduced cohesion due to drier southern slopes. In the second dry season after burning, soil movement was nearly undetectable, due to rapid regeneration of stabilizing vegetation. These estimates of sediment transport represent minimum values because collection boxes were installed more than 7 months after the burn, presumably after a large pulse of sediment had already been mobilized.

Sartz (1953) monitored hillslope lowering on a burned, harvested hillslope near Portland, Oregon, by measuring changing surface elevation relative to permanent tapes strung across the slopes above the soil surface. Sheetwash and raindrop splash were suspected to have lowered the hillslope surface between 21 and 55 mm in the first wet season after the fire, exposing fine roots on the hillslope and leading to some rill

formation. Before the first rains, soils were observed to be loose and porous, which may reflect a decrease in bulk density following fire, complicating interpretation of results.

1.5 Holocene Fire Frequency and Sedimentation Rates From Little Lake, OCR

Fire has been prevalent in the Oregon Coast Range for thousands of years. Charcoal and magnetic susceptibility studies on sediment cores from Little Lake, OR, in the Coast Range, provide a record of the frequency and magnitude of fires in the vicinity of the lake over the past 9,000 years (Long et al., 1998). Variations in the amount of charcoal present show that fire frequency and probably fire size and intensity have fluctuated during that time possibly in response to climate changes. The charcoal record reveals three periods characterized by lengthening fire intervals: from 9000 to 6850 years B.P., fire intervals averaged about 110 years; this was followed by a period characterized by fire intervals of approximately 160 years (6850-2750 years B.P.); the fire interval further lengthened to 230 years from about 2750 years B.P. to present (Long et al., 1998). The lake core also recorded variations in sedimentation rate in the lake, a gauge of mass movements in the watershed, and it showed an increase about 5000 years B.P. Long et al. (1998) also saw an increase in background charcoal levels about 4000 years B.P., and they postulate that the longer fire frequency at that time allowed more buildup of woody fuels, promoting more severe fires and an increase in background charcoal. Surprisingly, there is no correlation between increased sedimentation and increased background charcoal levels,

indicating that severe fires were not closely associated with increased number of sedimentation events. They suggest, rather, that the increase in sedimentation was related to a stormier, wetter climate and more stream runoff to deliver the sediment to the lake.

1.6 Discussion

There has been a profusion of research on post-wildfire geomorphic response, yet little of the research has addressed the Oregon Coast Range. Bennett (1982) conducted the only quantitative research on the significance of erosion following slash burning, and her results suggest that post-fire erosion is important in the long-term pattern of erosion in the Coast Range. In contrast, Schmidt (1995) concludes that wildfire plays a very small role in Pacific Northwest erosion, although his study was conducted on relatively gentle slopes (averaging 11 to 22 degrees) compared to the steep slopes of the Oregon Coast Range. Studies of post-fire geomorphic response in western Oregon do show one important trend: soil infiltration rates are too high for overland flow and associated erosional processes to be significant. The dominant post-fire erosional processes on hillslopes appear to be dry ravel and debris slides or debris-slide-initiated debris flows associated with decay of fire-damaged roots.

Although this review does not include an extensive discussion of channel responses to wildfire, literature on the subject is plentiful, revealing complicated patterns of response (Robinson and Minshall, 1996; Spina and Tormey, 2000; Benda et al., 2003; Legleiter et al., 2003). Channel response to wildfire is directly tied to post-fire erosion. Understanding the coupling between post-fire hillslope erosion and stream transport may

elucidate the relationship between fire and sedimentation events in the Little Lake watershed. Long et al. (1998) found little correlation between fire events and sedimentation events, even when a 50-year time lag was considered. However, a study of post-fire erosion concluded that pulses of sediment migrating through channel systems may take decades to move from hillslope sources to main channels (Laird and Harvey, 1986). Another study of post-fire runoff and erosion estimated a residence time of more than 300 years for eroded sediment stored in channels (Moody and Martin, 2001). A similar response in the Little Lake watershed may explain the lack of correlation between fire events and sediment entering the lake. Post-fire eroded sediment may have been stored on hillslopes and in lower order channels, taking decades to migrate through channels into Little Lake.

In the past few decades, the focus of research on post-fire geomorphic response has shifted slightly from descriptions and measurements of geomorphic response to attempts to model and predict post-fire erosion. As humans more frequently populate fire-prone areas and as degradation of fish habitats becomes more of a concern, it is becoming increasingly important to be able to identify areas of potentially devastating post-fire erosion. Current research focuses on processes for post-fire debris-flow initiation (Cannon and Reneau, 2000; Cannon et al., 2001a, Cannon et al., 2001b), delineation of floodplain boundary changes after fire-induced increases in runoff (McLin et al., 2001), and prediction of sediment yields after wildfire (Cannon and Reneau, 2000; Cannon et al., 2001b; Wohlgemuth et al., 2001). Additional research also focuses on rehabilitation of burned areas (Wohlgemuth et al., 2001). This review shows that

geomorphic response to fire varies and is highly dependent on vegetation, fuel load, geology, topography, and timing of precipitation, making widely-applicable models difficult to construct.

1.7 Conclusion

This literature review highlights the need for additional research in the Oregon Coast Range. Although many studies have suggested that wildfire plays an important role in the long-term erosion of the Oregon Coast Range, few studies have quantified fire-related erosion. Instead, research on post-wildfire geomorphic response has emphasized the response of more-arid regions, including the Rocky Mountain region, the interior Northwest, the Southwest, and California, where overland flow and associated erosional processes, which are nearly absent in the Pacific Northwest, dominate the geomorphic response to wildfire.

CHAPTER II: OBSERVATIONS OF GEOMORPHIC RESPONSE TO WILDFIRE IN THE OREGON COAST RANGE

2.1 Introduction

The processes that shape the Oregon Coast Range landscape are well studied, and estimates of uplift and long-term hillslope erosion rates suggest that the Coast Range is in an approximate equilibrium (Reneau and Dietrich, 1991; Personius, 1995, Heimsath et al., 2001). Although erosion rates have been considered to be spatially and temporally uniform, several studies suggest that wildfire is important in the long-term evolution of the Oregon Coast Range landscape, initiating periods of highly accelerated erosion (Swanson, 1981; Benda and Dunne, 1997). No clearly established mechanism exists to connect wildfire with widespread erosion and sedimentation in the OCR, but suggested mechanisms are pulses of dry ravel (Swanson, 1981; McNabb and Swanson, 1990; Wondzell and King, 2003) or increases in landsliding associated with a post-fire decline in root strength (Benda and Dunne, 1997; Wondzell and King, 2003).

Three recent wildfires within the Siuslaw River Basin allowed us to examine post-fire geomorphic response in the Oregon Coast Range. The fires occurred in 1999, 2002, and 2003 on clear-cut and forested slopes, providing the opportunity to examine different stages in post-fire geomorphic response. Because the 2003 fire occurred while the study was in progress, we were able to document the immediate response, which appears to be critical in total post-fire erosion.

Measurements of sediment mobilized during and after the fire allowed us to calculate post-fire erosion rates for the Oregon Coast Range and assess the significance of post-fire dry ravel in the long-term erosion of the Coast Range. We were also able to compare OCR post-fire erosion to rates measured in other post-fire erosional studies in California and Oregon.

2.2 Description of Study Areas

2.2.1 Oregon Coast Range

The three burn sites are located along a stretch of Highway 126 in the Oregon Coast Range (**Fig. 1**), which runs between the Pacific Coast and Interior Cascade Mountains along the western edge of Oregon. The OCR has not been glaciated, and it has a relatively uniform distribution of bedrock, soils, vegetation, precipitation, and land-use practices, which allows us to simplify comparisons of geomorphic response to wildfire at the three study sites. All three sites are underlain by underlain by a thick sequence of interbedded sandstones and siltstones of the Eocene Tyee Formation (Baldwin, 1964). The vegetation is dominated by Douglas-fir (*Pseudotsuga menzeisii*), with lesser amounts of western hemlock (*Tsuga heterophylla*) and western red cedar *(Thuja plicata*). Annual precipitation in the western OCR is approximately 2500 mm, which occurs predominantly in the winter months.

The OCR topography is generally steep and highly dissected, and a characteristic sequence of alternating ridges and hollows dominates the landscape (Dietrich and Dunne, 1978). Ridges are typically mantled with thin soils, whereas thick deposits of colluvium

accumulate in unchanneled hollows in steep zero-order basins (Dietrich and Dunne, 1978). The ridges shed sediment to lower-order channels, usually by some disturbance-driven transport process, such as windthrow, raindrop splash, or bioturbation (Roering, 1999). Sediment and wood accumulate in hollows until the deposits become unstable (Dietrich et al., 1982). This instability is caused when soils thicken to the point that stabilizing tree roots cannot penetrate to bedrock, creating a likely failure plane. Fire and timber harvesting can also create instability by inducing decay in root strength. When this instability is coincident with large-magnitude precipitation events, high pore pressures can initiate shallow landsliding. Shallow landslides can liquefy and develop into debris flows that travel for hundreds of meters through lower order tributaries. Debris flows remove nearly all the sediment and organic material from channels, often scouring to bedrock, and deposit levees, fans, and terraces in higher order channels. These flows are a critical sediment-transport link between hillslope creep and fluvial processes and are essential in shaping the morphology of the OCR (Benda, 1990).

Data from a study of hillslope sediment production and modern basin-wide sediment yields suggest that the Oregon Coast Range is in an approximate equilibrium (Reneau and Dietrich, 1991). In the central OCR, uplift rates calculated using terrace incision rates approximate 0.1-0.3 mm/year (Personius, 1995). Erosion rates estimated using measurements of colluvial hollow infilling (Reneau and Dietrich, 1991) and cosmogenic radionuclides (Heimsath et al., 2001) are approximately 0.1 mm/year. The similar rates of uplift and erosion have been interpreted as evidence for approximate steady state in the OCR.

2.2.2 Austa Fire Site (1999)

The Austa fire burned approximately 1062 acres of privately owned timber property and Bureau of Land Management property near the Austa Bridge on the Siuslaw River in the Oregon Coast Range. It burned from September 28, 1999 until fire crews controlled it on October 8, 1999 and created concern regarding sedimentation in nearby streams and proliferation of undesirable brushy species.

The fire occurred on very steep, dissected ridges and south-facing slopes underlain by the Tyee Formation. Valley headwalls exceed 45 degrees, and contain exposures of bedrock that were covered by mosses and thin soils and exposed following the fire. Fire intensity varied across the site, ranging from cooler underburns with low tree mortality to hot fires that incinerated forest floors and exposed much mineral soil, scorched boles, removed canopies, and killed entire stands of trees (BLM, 2000).

The fire burned clear cuts and stands of trees ranging in age from 11 to 60 years old with a few residual 200-year-old trees (BLM, 2000). The dominant tree species in the study area is Douglas-fir with scattered big leaf maple (*Acer macrophyllum*), western hemlock, and white oak (*Quercus alba*); the understory includes native grasses, sword fern (*Polystichum munitum*), bracken fern (*Pteridium aquilinum*), Oregon grape (*Berberus aquifolium*), salal (*Gaultheria shallon*), pearly everlasting (*Anaphalis margaritacea*), poison oak (*Toxicodendron diversilobum*), and blackberry. In the fourth summer following the fire, most of the burned trees were still standing, but those in high-intensity burn areas had no needles. The regenerated understory was dense, and it appeared that some of the big leaf maple had resprouted (**Fig. 2**).

2.2.3 Siuslaw Fire Site (2002)

The Siuslaw fire burned approximately 860 acres of managed forest and clear-cut land above the Siuslaw River about 7 river miles south of the Austa fire site. The fire started on August 17, 2002 and was controlled on November 8, 2002. This fire burned BLM property and private timber property, again creating the potential for an influx of sediment into nearby streams and invasion of brush species and noxious weeds.

The Siuslaw fire site is very similar to the Austa site. The topography is steep and dissected with valley headwalls in excess of 45 degrees, underlain by the Tyee formation. The vegetation includes western hemlock and western red cedar but is dominated by 14- to 52-year-old Douglas-fir stands with scattered 200-year-old trees (BLM, 2003). There was a range of fire severities (with some stands experiencing 90-100% mortality), and most of the burned trees were still standing one year after the fire, including those with complete canopy removal.

In the year following the fire, the understory at the Siuslaw site had begun to regenerate, but was not nearly as dense as that of the Austa site (**Fig. 3**). Much of the forest floor was unvegetated, the mineral soil covered only by a thick blanket of fallen Douglas-fir needles. Sword fern quickly resprouted from burned plants on the clear-cut slopes, while bracken fern exploited canopy openings resulting from needlefall. The emergency rehabilitation plan facilitated the replanting of seedlings on some slopes, including Douglas fir, hemlock, and cedar (BLM, 2003).

2.2.4 Sulphur Creek Fire Site (2003)

The Sulphur Creek fire occurred on privately-owned timber lands almost due west of the Austa and Siuslaw fire sites. It was first reported on June 27, 2003 and was reported 100% contained on July 5, 2003 after burning 650 acres (NICC incident management report).

Hillslopes average approximately 39-40 degrees, and valley headwalls reach up to 60 degrees in places. Douglas-fir dominates the vegetation, with scattered big leaf maple, cedar, and hemlock, and the understory includes such species as rhododendron, bleeding heart, blackberry, native grasses, pearly everlasting, sword fern, and salal.

The fire burned recently replanted clear-cuts, slopes covered with slash and understory, and highly managed Douglas-fir stands ranging in age from 19 to 48 years old (P. Chapman, personal communication). The fire burned severely in some stands, incinerating the forest floor, scorching canopies and trunks, and causing extensive needlefall (**Fig. 4**). On some recently replanted slopes, the fire incinerated all young Douglas-fir, undergrowth, and slash, whereas on slopes that had undergone prescribed burns, the fire burned much less intensely, leaving behind only mildly damaged young Douglas-fir. Sword fern and rhododendron had already begun resprouting 3 weeks following the fire.

The soils and hillslopes at this site exhibited a variety of responses to the fire, including extensive dry ravel, emergence of bedrock on steep slopes, and development of discontinuous hydrophobicity and many shallow soil slips.

2.3 Dry Ravel

2.3.1 Introduction

The most dominant erosional response observed at the three study sites was dry ravel: the downslope movement of sediment that occurs when vegetation or debris supporting that sediment is removed (**Fig. 5**). Dry ravel occurs when wildfire incinerates vegetation or logs acting as sediment traps, releasing sediment stored uphill of the traps. The mobilized sediment rolls or bounces downhill, dislodging additional sediment in its path, before coming to rest at lower gradients or behind new sediment traps. Fire not only initiates dry ravel, but it amplifies the process by incinerating potential downhill traps; fire essentially smoothes hillslopes, so that mobilized sediment travels further. We observed that pebbles or rocks dislodged on unburned forest or clear-cut slopes traveled very short distances (<5 meters) before lodging behind dense vegetation or downed branches and trees. At the 2003 and 2002 fire sites, dislodged sediment and field equipment traveled much further, with the larger cobbles often coming to rest in channels.

At all three fire sites, sediment mantling the hillslopes was unstable and disaggregated, and walking on the slopes dislodged much sediment. Deposits of raveled material were conspicuous on the hillslopes of the 2002 and 2003 sites as accumulations of loose pebbles and cobbles. These deposits often formed upslope of stumps or downed logs and lent a streaky appearance to the hillslopes. The material that reached the channels accumulated in the channel bottom or in fanlike deposits, termed “ravel cones,” at the transition from hillslope to channel (**Fig. 6**). These cones ranged in size from half a

meter to 6 meters wide and contained sand-sized to cobble-sized sediment, with a coarse lag deposit on the surface of the cones. The deposits on the channel bottoms were composed of larger sediments, ranging from pebbles to boulders up to 0.65 meters in diameter.

2.3.2 Estimation of Erosion Due to Dry Ravel: Methods

The 2003 fire burned a mix of forested and harvested land, including a channel that had been scoured by a debris flow in November of 2001. During an intense rainstorm, the debris flow initiated in a clear-cut hollow and scoured sediment from the upper reaches of the channel, leaving behind a channel of bedrock. Prior to the fire, we had visited this debris flow site on numerous occasions and documented its condition with photographs and observations. When the fire occurred, there had been very little infilling of the bedrock channel (**Fig. 7**). The intense fire burned the clear-cut hillslopes on both sides of the channel, consuming all vegetation and much of the litter, leaving behind only large logs, stumps, and mineral soil. During and immediately after the fire, sediment on the hillslopes was mobilized by dry ravel, and a significant volume accumulated in the valley axis. Because the channel was virtually free of sediment prior to the fire, it served as an ideal natural sediment trap to measure erosion rate from the hillslopes.

Most of the sediment appeared to have originated from one side of the basin, while the opposite slope appeared to contribute very little sediment. The ravel cones were draped almost exclusively at the transition between the west-facing hillslope and the

channel, with no observable accumulation from the east-facing hillslope (**Fig. 8**). Visually, we could detect no difference between the two hillslopes to explain the dramatically different sediment contributions other than aspect; they appeared to have similar gradients, there was no vegetation on either slope, and both were covered with loose, unstable sediment.

Following the fire, but before the first precipitation, we measured and recorded the dimensions of all the ravel cones and sediment deposits in a 144-meter length of the channel using a tape measure, handheld clinometer, and thin metal dowel to estimate the thickness of ravel deposits. In channel segments containing discontinuous deposits, we estimated numbers and median diameters of cobbles and measured dimensions of boulders. These measurements were analyzed and summed to determine total volume of sediment contributed to the length of the channel following the burn. Additionally, we surveyed the surface areas of the contributing hillslopes to determine the average eroded thickness. Using a Trimble GPS unit and laser range finder, we surveyed topography using a point spacing of approximately 7 meters. We collected approximately 200 points in each contributing area using denser point concentrations to capture breaks in slope and surface variability. The survey produced more detailed elevation models than the 10-meter USGS digital elevation models otherwise available.

Lastly, in an attempt to measure sediment transport from the channel, we installed a sediment trap at the end of our experimental section of channel (**Fig. 9**). We hoped to trap and measure all sediment being carried from the channel via fluvial entrainment. The dam was constructed by drilling nine holes across the channel using a concrete drill

and embedding lengths of ¾ inch rebar into the sandstone. We wrapped geosynthetic fabric around the rebar across the width of the channel to trap fine sediment but allow water through. To reinforce the rebar, we nailed 6x1 inch boards to the bars across the channel, leaving gaps between the boards to facilitate throughflow. For additional support, we placed large boulders across the channel on either side of the dam.

2.3.3 Estimation of Erosion Due to Dry Ravel: Results

The survey of sediment in the channel revealed 47.4 m^3 of sediment accumulation in the first 3 months following the fire, or 0.33 m^3 per meter of channel length. Most of this accumulation occurred during or directly after the fire, but small amounts of accumulation occurred even when we were performing the survey, as we occasionally had to dodge pebbles rolling down the hillslope. The survey of the contributing areas showed that the west-facing slope has a planimetric surface area of 9303 m^2 and an average gradient of 39 degrees. The east-facing slope's planimetric surface area is 10,050 m^2 with an average gradient of 40 degrees.

If only one slope were contributing sediment, the erosion following wildfire would be 5.1 mm. If we calculate erosion using both hillslopes, the amount drops to 2.4 mm. The eroded material accumulated over a three-month period immediately after the fire, and the rate of erosion declined significantly over that period. Therefore the erosion rate in the first year after fire is best approximated by averaging the measured post-fire erosion over the year, yielding post-fire erosion rates of 2.4 mm/year to 5.1 mm/year. These erosion rates are more than an order of magnitude higher than the long-term

Oregon Coast Range erosion rate of approximately 0.1 mm/year established using colluvial hollow infilling rates (Reneau and Dietrich, 1991) and cosmogenic nuclides (Heimsath et al., 2001). These data support the suggestion that background erosion rates in the Oregon Coast Range are punctuated by periods of accelerated erosion following wildfire (Swanson, 1981; McNabb and Swanson, 1990). Recognition of these periods of highly accelerated erosional episodes is critical in the calculation of long-term erosion; estimates of erosion calculated using stream sediment yields will not capture these short, but highly effective periods of erosion and result in low estimates of long-term erosion. Calculating erosion rate by using infilling of hillslope hollows (Reneau and Dietrich, 1990, 1991) or cosmogenic nuclides (Heimsath et al., 2001) is more likely to capture discrete and substantial erosional events associated with fire.

The frequency of fire occurrence in the OCR has been estimated, and we have determined a volume of hillslope lowering due to fire. Using these estimates, we can determine the fraction of total long-term erosion attributable to post-fire dry ravel using the following simple calculation:

$$\text{Fraction of total erosion} = \frac{\text{(eroded thickness after 2003 fire / OCR fire interval)}}{\text{long-term OCR erosion rate}}$$

Over the Holocene, the mean fire interval has varied from approximately 110 years in the early Holocene to 230 years in the later Holocene (Long et al., 1998). If we use an eroded thickness of 2.4 mm, a mean fire interval of 230 years, and the long-term OCR erosion rate of 0.1 mm/year, the post-fire contribution to total long-term erosion is about 10%. Holding the eroded thickness constant at 2.4 mm and decreasing the fire interval to

that of the early Holocene (110 years) yields estimates that post-fire erosion contributed 22% of total erosion during that time. If we estimate 5.1 mm of eroded thickness after each fire, these fractions increase to 22% to 46% of total long-term erosion.

Our monitoring plan to gauge sediment transport in the valley by damming the channel failed when a small debris flow flattened our dam. The debris flow initiated on December 13, 2003, near the initiation site of the November 2001 debris flow, and it scoured and redeposited much of the post-fire sediment in the channel. It occurred after a rainstorm that deposited more than 2.5 inches of rain in a 24-hour period at a weather station 30 miles east. The dam was still intact following the debris flow, but the rebar had been bent to a 90° angle downstream.

2.4 Emergence of Bedrock

Because the Oregon Coast Range is covered with a thick mantle of soil and vegetation, bedrock is rarely visible on hillslopes. Therefore, the extensive exposures of bedrock at the 1999 fire site on Highway 126 contrast sharply with surrounding unburned hillslopes. When this study was initiated, bedrock was already prevalent at the 1999 and 2002 sites, and we have seen substantial areas of bedrock emerge since the 2003 fire. Immediately following the 2003 fire, bedrock was not conspicuous, but the first rainy season exposed large expanses of bedrock.

The exposures of bedrock are on the steeper slopes of the study areas (**Fig. 10**), which are generally at the headwalls of channels and at the bases of hillslopes, where they transition to channels. BLM Environmental Assessments refer to some of these

areas as “rocky meadows” and imply that there were only thin soils, grass, and moss covering them prior to fire. Following fire, land managers were concerned that these rocky exposures would be difficult, if not impossible, to reseed. However, at the 1999 site and 2002 site, moss is spreading across the rock where moisture is available. This moss will most likely act to trap sediment and eventually facilitate soil development and reforestation.

2.5 Hydrophobicity

2.5.1 Methods

To inspect for fire-induced hydrophobicity, we performed water-drop penetration time tests in areas of the 2003 fire site that appeared to have been undisturbed in the 45 days following the 2003 fire. We used standards developed by the U.S.D.A. Forest Service (Davis and Holbeck, 2001) and described by the U.S. Fish and Wildlife Service (2003). The test sites were gently cleared of needlefall, and we dug a trench approximately 10 cm deep and inserted a ruler vertically to measure depth. Starting at the top of the soil column on the back wall of the trench, we dropped small beads of water onto the surface of the soil, recording the length of time the water droplet was stable before infiltrating. We then removed a 1-cm layer of soil from the site and repeated the process. This method allowed us to ascertain the depth and thickness of water repellent layers and the degree of severity of the hydrophobicity.

2.5.2 Results

At 8 of 9 test sites in the burned forested areas and at all 5 sites in the burned clearcut, the water drops perched on subsurface soil layers for more than 60 seconds, indicating strong hydrophobicity. The depths to the top of the water-repellent layer ranged from 1 to 3 cm, and the thicknesses ranged from 1 to 7 cm (**Table 2**).

This water-repellent layer did not appear to induce any associated erosion. Limited rilling was present, but it was associated with timber-harvest landing sites and did not appear to be related to fire-induced water repellency. During the first significant rainfall after the fire, the irregularity of the hydrophobicity became apparent. After the rain, we dug trenches on the hillslopes (parallel to slope) and observed dry soil columns indicative of hydrophobicity. Immediately adjacent to these soils were columns that had been wetted by infiltrating precipitation up to 20 cm deep (**Fig. 11**). Soils in the Coast Range have high infiltration rates and numerous macropores, so that it seems unlikely that a continuous water-repellent layer could develop and persist. The water-drop test is impractical in detecting continuity of a layer because the analyst is not likely to put a drop of water on a clearly visible conduit.

2.6 Shallow Landslides and Debris Flows

2.6.1 Introduction

Other erosional processes commonly associated with wildfires are shallow landslides and debris flows, which may result from loss of root strength or an increase in overland flow. Increased overland flow can entrain large amounts of ash, debris, and

sediment and progress into a debris flow. However, due to the high infiltration rates of the OCR soils, this style of initiation is rare. Instead, debris flows resulting from soil saturation and loss of root strength are more likely. Roots provide cohesion to soils, and a decline in root strength increases the likelihood of mass movement on slopes (as discussed in Chapter 3). When periods of depressed root strength coincide with intense or long-duration rainstorms, shallow landslide and shallow landslide-initiated debris flows may ensue. Shallow landslides initiate in shallow soils on steep planar hillslopes or in hillslope hollows and generally stop after traveling short distances, depositing material in channels or on hillslopes. Occasionally, shallow-landslides can liquefy and develop into debris flows, which travel much longer distances and transport larger volumes of colluvium than shallow landslides.

Dry ravel can also contribute to destabilization of potential debris-flow initiation sites by adding large volumes of sediment to thick colluvial deposits in bedrock hillslope hollows. Bedrock hollows serve as initiation sites for debris flows because they accumulate thick soil deposits and concentrate subsurface stormflow, which can raise pore pressures to levels where failure occurs (Dietrich et al., 1982). Dry ravel accelerates soil transport into topographic hollows and may thicken colluvial deposits such that roots from surrounding vegetation cannot penetrate deeply enough to anchor the soil to bedrock.

2.6.2 Results

We did not observe debris flows directly related to wildfire in any of the Oregon Coast Range sites. An intense rainstorm in December 2003, however, did trigger at least three debris flows at the 2003 fire site. The debris flows were most likely related to clear cut timber harvesting and road building, as they initiated in clear-cut hollows just below logging roads. While the wildfire did not directly cause the debris flows, post-fire dry ravel did contribute large amounts of sediment to the channels before the flows occurred. This large addition of sediment increased the size of the debris flows and probably increased their travel distance. Fresh charred wood, charred cobbles, and scorched sword fern root mats were found in one of the debris flow deposits, approximately 1 km from any burned hillslopes.

It does appear that shallow landslides increased in frequency following the 2002 and 2003 fires, but too much time had passed since the 1999 fire to definitively distinguish any landsliding. Four fresh soil slips were apparent at the 2002 site in one second-order drainage basin, 3 on clear-cut slopes and one in a forested area. It is possible that shallow landslides were more abundant, though they are difficult to distinguish in forested areas unless observed closely. The 2003 fire site experienced a large increase in numbers of shallow landslides in the first rainy season following the fire. Photos taken after the fire but before the onset of the rainy season document the absence of shallow hillslope failures, while comparative photos taken after the rainy

season show a landscape scarred with fresh slip faces (**Fig. 12**). Although these may be related in part to timber harvesting, destruction of understory by wildfire likely contributed to the increase in failures.

2.7 Discussion

2.7.1 Estimation of Erosion Due to Dry Ravel

Two approximations of OCR fire intervals and measurements of erosion due to dry ravel in this study suggest that post-wildfire dry ravel accounts for a minimum of 5-20% of total long-term erosion in the OCR. Because we measured only the first three months of sediment accumulation in the channel, total erosion due to dry ravel may account for more than 20% of total erosion over the past 4140 years. It is difficult to extrapolate these results because of variations in fire severity and frequency. Before 4140 years B.P. fires were more frequent, but less severe (Long et al., 1998), perhaps producing less post-fire erosion.

Another factor complicating interpretation is that erosion rates calculated in this study were determined on a clear-cut hillslope. Although current logging practices are meant to minimize soil erosion, it is likely that the harvesting on this hillslope disturbed soils somewhat, perhaps making them more prone to downslope movement. Also, substantial logging debris was present on the hillslope before burning, possibly fueling a more intense fire than would have occurred in a ‘natural’ forest.

2.7.2 Comparisons to Other Measurements of Post-Fire Dry Ravel

Previous measurements of post-fire dry ravel are summarized in **Table 3**. Most of the research was conducted in southern California, but two studies in Oregon provide useful comparisons. Measurements of dry ravel at our study site are within an order of magnitude of the volumes calculated at four southern California sites (Florsheim, 1991; Rice, 1982; Krammes and Osborn, 1969; Krammes, 1965). Doehring (1968) measured significantly higher volumes of dry ravel, though he concluded that the lower measurement better represents the typical erosion caused by post-fire dry ravel in southern California. The volume of 0.16 m^3/m^2 was calculated using a debris cone at the base of an unusually steep (47 degree) slope, uncharacteristic of the topography in the area. His results are further complicated because they are calculated from only two ravel cones, one at the base of a 47 degree slope, and one at the base of a 36 degree slope. This small sample size may bias his results toward higher erosion measurements.

The two measurements of post-fire dry ravel in Oregon present different complications. Schmidt's (1995) estimate of 0.001 m^3/m^2 of dry ravel erosion is within an order of magnitude of our measurements, but the hillslopes in his study area (11 to 22 degrees) were not as steep as those in any of the other studies, so it is not surprising that they produced smaller sediment yields. Mersereau and Dyrness (1972) report erosion of 1.4×10^{-4} to 6.3×10^{-4} m^3/m^2 of contributing area, an order of magnitude lower than that in our study from gradients comparable to those in our study area, yet their sediment traps were not installed until more than seven months after the fire. A prototype sediment trap installed 2 months before the rest of the traps were in place collected more sediment in

those 2 months than it did in the following 16 months, when all the traps were installed. Based on these numbers, Mersereau and Dyrness estimated that sediment traps missed more than 60% of mobilized sediment. 60% is a minimum estimate of excluded sediment because it neglected sediment mobilized during and immediately after the fire. If we estimate that measured dry ravel accounted for a maximum of only 40% of post-fire erosion, we can approximate that erosion was closer to 1.6×10^{-3} mm on 39 degree slopes, whereas erosion on 31 degree slopes was 3.5×10^{-4} mm. Erosion rates were most likely even larger than these approximations, yet even these approximations are close to the rates measured in our study.

2.7.3 Persistence of Elevated Dry Ravel Rates

The highly elevated erosion rates measured at the 2003 site occurred in the first dry season after the fire and are not expected to persist, though slightly elevated rates may continue until vegetation is reestablished. Though some plants resprouted at a surprisingly fast rate, large areas of the 2002 and 2003 sites are still unvegetated. Dry ravel rates decreased too quickly for regeneration of vegetation to explain the decline in sediment movement. Morris and Moses (1987) attributed a decrease in surficial soil movement following wildfire in Colorado to an initial depletion of fines, leaving behind a coarse lag on the soil surface, resistant to mobilization. Erosion after fire in the OCR may be similar: easily mobilized sediment is stored uphill of supportive vegetation, and after it has been mobilized during the initial flush of sediment, remaining sediment is

less-easily transported unless disturbed by bioturbation. Bennett (1982) found that 95% of post-fire erosion occurred in the first 8 months after fire in the Oregon Coast Range, and only 5 % of measured erosion occurred in the following 12 months.

2.7.4 The Influence of Aspect on Dry Ravel

The GPS-survey and subsequent GIS analysis of the data showed that the only significant variable that might explain the difference in sediment contribution to the channel from the two slopes is aspect. The slopes have almost identical gradients (39 and 40 degrees), a critical factor controlling erosion rates, yet one slope faces west and the other faces primarily northeast (**Fig. 13**). The slope that contributed most of the sediment is west-facing, exposing it to more intense afternoon solar radiation, while the opposite slope faces northeast, sheltering it somewhat from the drying effects of direct afternoon sunlight. The exposure on the west-facing slope may have produced drier soils and vegetation by late June (when the fire began), fueling a more intense fire. If antecedent moisture were higher in the sheltered northeast-facing slope, it may have led to a less intense burn. A study on early-season burns in Washington State (Grier, 1989) suggests that evaporative cooling at the soil surface may reduce soil heating, because for the soil temperature to exceed 100°C, soil moisture must first be evaporated. A cooler burn on the northeast-facing slope may have protected some of the surface roots and soils from damage experienced on the hotter, drier slope.

Other studies have found that post-fire erosion rates on hot, dry south-facing slopes can be up to an order of magnitude higher than on north-facing slopes (Krammes,

1960; Krammes, 1965; Mersereau and Dyrness, 1972; Marques and Mora, 1992). This difference in erosion is attributed to a number of factors: 1) more and denser vegetation on north-facing slopes creating a thicker blanket of protective ash following a fire (Marques and Mora, 1992); 2) quicker recovery of vegetation on north-facing slopes (Marques and Mora, 1992); and 3) drier and therefore, less cohesive soils on south-facing slopes (Mersereau and Dyrness, 1972). The Oregon Coast Range receives ample precipitation creating dense vegetation cover on all slopes, so the first two factors are unlikely to influence the hillslopes in our study area.

2.7.5 Bedrock Emergence

The emergence of bedrock is likely related to dry ravel and the destruction of shallowly-rooted vegetation and the protective forest floor. Prior to fire, understory and organic material covering the soil surface protected the soil from raindrop impact and provided support to non-cohesive sediment on hillslopes. Additionally, shallowly-rooted understory provided substantial strength to near-surface soils (Sidle, 1992; Sidle and Swanston, 1981; Schmidt et al., 2001). The incineration of shallow roots and understory presumably reduced cohesion of surface soils and triggered dry ravel. This stripping of soil exposed steep bedrock faces that had previously only been mantled by very thin soils. The removal of understory also exposed soils to raindrop impact, which allowed winter rains to wash away thin cohesionless soils covering bedrock. Moreover, if soil coverage were thin, water traveling along the bedrock/soil interface could conceivably entrain soils and transport them downslope, exposing bedrock.

Exposing the bedrock to physical and chemical weathering processes, such as periodic wetting and drying and freeze/thaw processes is significant in terms of soil production, as soil production increases with declining soil thickness (Heimsath, 2001). Except when uncovered by tree throw, shallow landsliding, or debris flows, bedrock is rarely witnessed at the surface. Hence, fire may prove to be important in the process of soil production as well as soil transport.

2.7.6 Debris Flows and Shallow Landslides

It is not surprising that we observed no debris flows directly related to wildfire at any of the three sites: the soil infiltration rates in the OCR are too high for runoff-initiated debris flows, and debris flows resulting from loss of root strength due to fire damage generally occur more than 4 years after wildfire (Rice, 1974; Megahan et al., 1978; Gray and Megahan, 1981; Swanson, 1981; McNabb and Swanson, 1990; Meyer et al., 2001). The decay of fire-damaged roots over the next decade will increase the propensity for debris flows on burned hillslopes. If severe winter storms occur in this interval of weakened root systems, debris flows are likely. A study of debris flow occurrence using dendrochronology in the Oregon Coast Range showed that after the last stand-replacing fire, debris-flow activity increased by 42% over background debris-flow activity (May and Gresswell, 2003).

The increase in shallow landsliding is likely associated with incineration of shallowly-rooted undergrowth, which can provide substantial strength to surficial soils after harvesting (Sidle, 1992; Schmidt, 2001). After incineration of understory and near-

surface roots, shallow soils lose mechanical strength. Combined with a decrease in interception due to loss of vegetative cover, a reduction in soil cohesion makes soils particularly susceptible to failure during winter rainstorms.

2.8 Conclusion

Observations and measurements from three recent burns support the long-established theory that wildfire is a significant mechanism driving erosion of the Oregon Coast Range. Dry ravel is the dominant short-term erosional process at the three sites, transporting large volumes of sediment from hillslopes to channels. A calculation of post-fire erosion shows that wildfire-induced dry ravel may account for more 10-40% of total long-term erosion of the OCR, and dry ravel measurements at our study sites (2.4-5.1 mm) are comparable to those observed in studies of post-fire geomorphic response in southern California.

Two other prominent responses to wildfire on steep slopes in the OCR were the emergence of large exposures of bedrock and an increase in shallow landsliding. Immediately after the 2003 fire, these responses were not observed, but after the first rainy season, soils were washed away to reveal large swaths of bedrock, and hillslopes were streaked with shallow slope failures.

Although fire-related debris flows were not observed, they are likely to occur in the next decade in response to a decline in root strength. The observation that debris

flows increase following wildfire (May and Gresswell, 2003) indicates that fire-induced erosion in the Oregon Coast Range is higher than our estimates generated using dry ravel rates.

CHAPTER III: DECLINE IN ROOT STRENGTH FOLLOWING WILDFIRE IN THE OREGON COAST RANGE

3.1 Introduction

Empirical studies have shown a rapid decline in root tensile strength following timber harvesting, yet few studies have investigated the change in root strength following fires. Wildfire and timber harvesting are often compared or grouped together under the classification of "forest vegetation removal" in discussions of slope instability following root decay (Burroughs and Thomas, 1979; Megahan et al., 1978; Gray and Megahan, 1981). Intense fires can damage the crowns, boles, and root structures of trees, which often leads to the death of the trees and subsequent loss of root strength, which increases the propensity for shallow soils slips or landslides. It has also been suggested that timber harvesting is analogous to wildfire in that it causes similar rates of erosion due to debris flows following root decay.

Studies of landslide occurrence following removal of vegetation show a lag between time of vegetation removal and time of increased landsliding. Timber harvesting has been shown to induce greatest landslide hazard four to ten years after harvesting (Megahan et al., 1978), while root decay following fire damage has been observed to increase landsliding three to four years after fire (Burroughs and Thomas, 1977), nine years after fire (Rice, 1974), and seven years after fire (Meyer et al., 2001). This lag exists because root decay occurs over a period of a few years; total root strength

is a function of decay of pre-existing roots and reestablishment of new roots by regenerating vegetation (Zeimer, 1981; Schmidt, 2001). Root strength reaches a minimum some years after vegetation removal, and if this window of landslide hazard coincides with intense or long-duration rainstorms, mass movements are likely to occur. May and Gresswell (2003) documented a 42% increase in debris flow activity over background rates following the last major stand-replacing fire in the Siuslaw River drainage basin.

Although numerous studies suggest that landsliding dramatically increases following Pacific Northwest fires (Swanson, 1981; McNabb and Swanson, 1990; Benda and Dunne, 1997), there has been little examination of the decline in root strength following wildfire. We investigated root strength and root network density at three forested OCR sites that burned in 1999, 2002, and 2003. The three sites allowed examination of the decline in root strength in the four years after wildfire. The results of this study will enable a comparison of root-strength decay following timber harvesting and wildfire in the OCR.

3.2 Previous Research

3.2.1 Root Strength Decay and Slope Stability

Ziemer and Swanston (1977) examined the decay of western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*) roots following timber harvesting in southeastern Alaska. Their study suggested that hemlock roots smaller than 25 mm in diameter lose roughly one third of their average root strength in the first 2 years

following harvesting, while Sitka spruce roots smaller than 25 mm lose approximately one half of their original root strength in the same time. Zeimer (1981) compared the effects of three different timber-harvesting practices on root strength, and developed a conceptual model showing the variation in root reinforcement in hillslope soils following harvesting. Root decay led to a period of depressed root strength after harvesting and before new seedlings established root networks, with a minimum strength occurring between 9 and 15 years after logging. This period of depressed root strength left hillslopes more vulnerable to mass-wasting events in severe storms and even in moderate storms that otherwise might not have initiated landsliding.

Reistenberg (1994) studied how variations in the root morphology of white ash (*Fraxinus americana*) and sugar maple (*Acer saccharum*) affected hillslope stability in Cincinnati. A landslide originated in a stand of widely-spaced sugar maples, a spatial distribution she concluded contributed to a lower root density and lower colluvium strength. Analysis of root morphology also showed that white ash were better soil anchors than were sugar maples because white ash taproots penetrate the soil more deeply (average 1.1 meter as opposed to approximately 0.6 meters) to stabilize soils. The more deeply penetrating taproot was better able to anchor soils to bedrock.

Wu (1995) summarized how roots stabilize hillslope soils, highlighting root properties that affect reinforcement. His summary pointed to root geometry and strength as critical variables in slope stability. He also stressed the variability of root reinforcement due to varying site conditions, distance from trunk, and number and orientation of roots in relation to displacement direction.

Schmidt et al. (2001) studied how land-use practices affected variation in root strength and how that variability is related to the occurrence of shallow landsliding in the Oregon Coast Range. They measured 25.6 to 94.3 kPa of total lateral root cohesion in natural forests, which exceeds the 6.8 to 23.2 kPa of root cohesion measured in industrial forests (including clearcuts to 100-year-old forests). They found that root contribution to soil cohesion does not exceed 10 kPa in clearcuts, and that median lateral root cohesion in clearcuts is 1.5 to 6.7 kPa. Although the density of all roots did not vary among different sites, density of live roots was much higher in natural forests than in industrial forests.

3.2.3 The Effect of Fire on Roots

Wildfire can damage or kill trees in three primary ways: by scorching the crown, lethally heating the cambium, or lethally heating the roots (Agee, 1993). Fire damage to a tree considerably impacts photosynthesis, making it more susceptible to insect attack or disease. After such damage, much of a tree's photosynthetic energy is used to repair foliage and regrow damaged tissues in the cambium or root structure, inhibiting a tree's capacity to produce defensive chemicals to ward off insects or disease. If the foliage is damaged or removed by fire, this further compromises the tree's ability to photosynthesize (Scott et al., 1996). Roots near the soil surface can experience first-order damage, such as scorching or lethal heating, which may contribute to the death of the tree in the first years following a fire. Roots may also experience second-order decay

coincident with the death of a tree due to other injuries sustained to the foliage or cambium.

Swezy and Agee (1991) investigated mortality and fine-root biomass in old-growth ponderosa pine (*Pinus ponderosa*) following prescribed burns in Crater Lake National Park. Before an experimental fire, they cored the soil to determine fine-root biomass, concluding that live roots less than 2 mm in diameter were concentrated in the forest floor and in the upper 10 cm of the soil profile. Heat-sensitive ceramic tiles revealed that approximately 75% of surface soils and soils up to 5 cm deep experienced heat lethal to tree tissue (>60°C) for a duration of 5 hours or more. For shallow soils within 2.5 meters of the bole, the percent experiencing lethal heat loads increased to 100%. Not surprisingly, live fine-root (0-5mm diameter) dry weight decreased by as much as 75% in the five months following the burn, and mortality of pines was higher in burned stands versus unburned stands. The authors suggest that bark beetles were the primary agent of mortality in the first years following the prescribed fire.

Ryan et al. (1988) modeled the mortality and decay of Douglas-fir (*Pseudotsuga menziesii*) 8 years after a prescribed burn. They concluded that the variable that best predicted mortality was the amount of dead cambium around a tree's circumference. Root damage was cited as a possible contributor to a tree's death, given a Douglas-fir's propensity to have major lateral roots at or near the upper surface of the mineral soil. Their survey of burned trees revealed several exposed and damaged roots.

Littke and Gara (1986) examined lodgepole pines (*Pinus contorta* var. *murrayana*) growing in south-central Oregon that had survived fires since 1839.

Examination of the roots and boles of the trees revealed that various fungi attack trees through fire-damaged roots, slowing tree growth and leaving them susceptible to mountain pine beetle assault.

Scott et al. (1996) summarized the physiological effects of fire on tree roots. They suggest that smaller diameter roots experienced more direct fire-damage than larger diameter roots because their bark is thinner and offers little protection from the heat of the fire. Both small and large diameter roots were damaged by large accumulations of duff, which fuels hotter fires, and which is related to fire suppression and distance from the bole of a tree. This root damage can lead to tree mortality directly through fire injuries or indirectly as a result of insect attack on weakened root systems.

3.3 Methods

3.3.1 Site Selection and Characterization

At the three different fire locations, study areas were selected with the intention of reducing variability among sites. We hand dug soil pits only in intensely burned stands, ranging in age from 40 to 60 years old with scattered older trees. To minimize the influence of other tree species and old, dead stumps, we attempted to dig only near standing Douglas fir trees. The pits were equidistant from surrounding trees (**Fig. 14**), and if large taproots were encountered, the pit was abandoned, as abundant smaller roots branching off taproots create localized high root densities. BLM Environmental Assessments were used as a guide to stand age and fire intensity in the Austa (1999) and Siuslaw (2002) sites, and the land manager provided information on stand ages at the

2003 Sulphur Creek site (P. Chapman, personal communication.) Intensely burned older stands were scarce at the Sulphur Creek site and were identified based on total loss of canopy foliage and complete incineration of understory and forest floor.

At every site, slope was measured with a hand-held clinometer, scorch height and percent of canopy burned were visually estimated, and the composition and depth of the forest floor were measured. Distance and direction from the soil pit to adjacent trees were recorded, as were the tree species and diameter at breast height and understory species.

3.3.2 Root Strength Measurements

The soil pits were dug with a hand shovel, oriented with widths parallel to slope, leaving a rectangular back wall with two triangular sidewalls (**Fig. 15**). All pits were approximately 0.7 – 1.0 meter deep and 1.0 meter wide, and the dimensions of exposed soil faces were recorded. We extracted all roots exposed in the 3 walls and recorded their species identification, vertical depth in the soil profile, diameter including bark (measured with a micrometer), and force required for tensile failure. Douglas-fir roots were identified based on their characteristic orange inner bark, while other roots were excavated to their source plant for identification or simply classified as “non-Douglas-fir” when source plants were too charred to identify.

We measured root tensile strength by attaching one end of a root to a clamp on the end of a spring scale and pulling the other root end until failure occurred. The load at

failure was recorded as a measure of root tensile strength, and we were able to measure roots up to 7 mm in diameter. If a root slipped from the clamp or broke where attached to the clamp, the maximum force was recorded but not used in analysis.

3.3.3 Analysis

The data were analyzed for trends in strength, density, and species variance over time and with depth. Tensile force was plotted as a function of root diameter at the three different age sites, and the data were analyzed for statistical significance using multiple regression analyses. The data were also compared with predictions and models from other studies of root strength (Schmidt et al., 2001; Burroughs and Thomas, 1977). Root densities were calculated using multiple methods, including number of Douglas-fir roots per square meter of soil and root area ratio, A_r/A_s, which is the proportion of total cross-sectional area of exposed roots to the area of soil exposed in the pits.

3.4 Results

3.4.1 Variation of Tensile Strength with Root Diameter

When the tensile strengths of individual roots were plotted versus their diameters, a strong relationship between root diameter and root strength was revealed. As root diameter (millimeters) increased, the force required to break the root in tension (kilograms) increased non-linearly. The lines of best fit for all three datasets are second-order polynomial equations, shown with their regression coefficients, r^2, in **Figure 16**. These regressions were chosen because they fit all three data sets well.

The strength-diameter curves suggest that root strength has declined with time since fire (**Fig. 17**). All diameter roots declined in strength following wildfire; the decline was quick in the first year and slowed by the fourth year, a trend also observed in a study of timber harvesting by Burroughs and Thomas (1977). Compared with a tensile force curve for healthy Douglas-fir roots (Schmidt et al., 2001), 4 mm roots lost approximately 50% of their strength in the first year following a wildfire (**Fig. 18**). A multiple regression analysis of the 1999 and 2002 datasets demonstrated that the data populations were statistically significant with a 90% confidence (numerator df=3; denominator df=2175; F=2.7391). Data collected from the 2003 site were not analyzed for statistical significance (see below).

3.4.2 Anomalous Data From the Sulphur Creek (2003) Site

The roots measured at the 2003 site showed a more rapid strength decline than expected. One month after fire, the roots had declined almost 50% in strength, much faster than observed in other studies (Burroughs and Thomas, 1977; Zeimer and Swanston, 1977). Moreover, in all measures of root healthiness (including root density, abundance, and strength), the root data from the 2003 site appeared depressed. The trees at the 2003 site may have had weakened root systems prior to the fire due to damage by insect infestation, fungal infections, disease, or overcrowding.

In their study of root strength and harvesting, Schmidt et al. (2001) encountered a stand of Douglas-fir that had been damaged by cable yarding logging operations. Damage to the trunks and canopies of the trees had weakened them to the point that root

strength was depressed in comparison to healthy Douglas-fir roots. When tensile strength data from the 2003 fire were plotted with strength-diameter curves from this damaged stand of trees (Schmidt et al., 2001), their trends coincided (**Fig. 19**). This complicates interpretation of strength and density data from the 2003 site and limits comparisons between these data and data from the other sites.

3.4.3 Variation in Rates of Strength Loss for Different Diameter Roots

Different diameter roots showed varying rates of strength loss (**Fig. 20**). Plotting the percent of original root strength remaining for 1-, 3-, and 5-mm diameter roots demonstrates that 1-mm diameter roots declined in strength more rapidly than did 3- and 5-mm diameter roots. In the first year following a wildfire, 5-mm diameter roots lost approximately 40% of their original strength, 3-mm diameter roots lost 50% of their strength, and 1-mm diameter roots lost almost 98% of their original strength.

These data contradict predictions of Burroughs and Thomas (1977) who modeled decline in tensile strength of coastal Douglas-fir roots following harvesting with the equation:

$$\mathrm{TS} = 1.04(2.516 * d)^{1.8-0.06\sqrt{t}}$$

where d is the diameter of the root in mm (without bark) and t is time in months since harvesting. **Figure 21** shows their predictions plotted with data from this study. Their predictions show the opposite trend in root strength decline, with 1 mm diameter roots

(without bark) losing only 15% of their original strength in the first year following disturbance. In addition, their predictions also show that larger diameter roots lose strength more quickly than do smaller diameter roots.

3.4.4 Root Densities

Root densities at the three fire sites, measured using A_r/A_s, ranged between 10^{-4} and 10^{-3} (**Fig. 22**). These root densities are similar to values derived by Schmidt et al. (2001) in the Oregon Coast Range. In industrial forests, they measured live-root densities ranging between 10^{-4} and 10^{-3}, whereas in natural forests, densities exhibited values that were an order of magnitude higher. In this study, the 2002 site had notably higher root density than the 2003 or 1999 site. Examination of the variation of root density with depth (**Fig. 23**) revealed that this pattern was consistent throughout the soil column; the 2002 site had higher root densities through the entire depth of the pit. The profiles also showed that roots were concentrated in the upper 30 cm of soil. Lower root densities at the 2003 site fit the pattern of depressed root health as discussed above, suggesting damage prior to the fire.

When considering the abundance of roots rather than their total cross-sectional areas (**Fig. 22**), the 2003 site (45-70 roots/m^2 soil) was much closer in density to the 2002 site (76-79 roots/m^2 soil), whereas the oldest site had many fewer roots than the more recently burned sites (27 roots/m^2 soil). This pattern is different than that demonstrated by other measures of root density and indicates that the 2003 site has abundant small roots. Overcrowding may explain the anomalous results at the 2003 site. If the trees

were planted too closely together, their root systems may not have had enough space or nutrients to grow larger, and this led to high densities but small root diameters and tensile strength.

3.4.5 Homogeneity of Root Species

The fraction of Douglas-fir roots varied between sites (**Fig. 24**). The 2003 site was more homogenous than the older sites, with Douglas-fir roots contributing 75-100% of the total roots. The 2002 site contained 64-83% Douglas-fir roots, while Douglas-fir made up only about 43% of the total number of roots at the 4-year-old site. The rest of the roots include swordfern, pearly everlasting, big leaf maple, Oregon grape, big leaf maple, salal, blackberry, and other unidentified species.

3.5 Discussion

3.5.1 Decline in Root Strength

Our data support the idea that root decay following wildfire mimics the response seen after timber harvesting, but responses to the two disturbances demonstrate some important differences. The decline in Douglas-fir root strength following wildfire is similar in magnitude and timing to root-strength decline resulting from harvesting. Although the mechanisms causing tree mortality differ, both result in rapid weakening of root systems. As demonstrated by numerous studies, the weakening of roots may increase a hillslope's propensity for shallow landsliding or debris flows in the decades following disturbance. An increase in mass movements has been observed on harvested

hillslopes, and mass movements can be expected on burned hillslopes in the Oregon Coast Range as well. A study of debris-flow occurrence in the OCR supports this speculation, showing that debris-flow activity increased 42% over background debris flow activity in the 30 years after the last stand-replacing fire (May and Gresswell, 2003). This increase was attributed to root-decay following death of fire-damaged trees.

Examining the details of root-strength decay reveals important differences between timber harvesting and wildfire. One major difference between this study of root-strength decline and a study of root-strength decline following timber harvesting (Burroughs and Thomas, 1977) involves tensile strength of varying root sizes. Our data point to a rapid post-fire decline in strength for smaller diameter roots (98% loss of strength in the first year following fire), whereas the Burroughs and Thomas (1977) model does not predict such a rapid response in small diameter roots (**Fig. 20**). This dissimilarity may be a manifestation of the differences in type or intensity of disturbance. Fine roots (<2 mm diameter) are concentrated in the upper 10 cm of soil and in the forest floor (Grier, 1989; Swezy and Agee, 1991). Harvesting does little to directly disturb these small roots, whereas wildfire can destroy the forest floor and increase soil temperatures to levels lethal to roots. The rapid decline in small-diameter root strength after wildfire may occur because these roots were concentrated at shallow depths where they were most subject to damage.

The immediate destruction of understory during intense wildfire is another fundamental difference between timber harvesting and wildfire. Whereas antiquated harvesting techniques seriously damaged understory on hillslopes, current harvesting

practices, including skyline yarding, are meant to minimize damage to vegetation remaining after harvesting (Robison et al., 1999). These practices leave behind a dense cover of understory on harvested hillslopes, which can provide substantial strength to soils (Sidle and Swanston, 1981; Sidle, 1992; Schmidt et al., 2001). In a study modeling slope instability after clear-cutting, Sidle (1992) demonstrated that timber practices which remove all understory (using herbicides or burning) increased the probability of slope failure up to three times that of clear-cuts with undisturbed understory, highlighting the critical contribution of understory in slope stability. Schmidt et al. (2001) also demonstrated the importance of understory in contributions to root cohesion. In recent clear-cuts (0-10 years old), lateral-root cohesion attributed to hardwood and understory plants contributed up to 12 kPa of strength. Root cohesion values for clear-cuts treated with herbicides were up to an order of magnitude lower than clear-cuts not treated with herbicide. Two photographs of a clearcut before and after the 2003 fire revealed the dense understory present before the fire and the complete incineration of all vegetation during the fire (**Figs. 25** and **26**). These data suggest that intense wildfire, like herbicide application, removes a significant amount of lateral-root cohesion that is not removed during timber harvesting. The removal of this potentially critical root cohesion may lead to more frequent or larger magnitude mass movements in the years after fire.

3.5.2 Root Density

Our measurements of root density are not particularly enlightening in terms of density changes over time or differences in root density between harvested and burned

areas. Our measurements based on number of Douglas-fir roots per square meter of soil also do not correspond to another study of coastal Douglas-fir root density. Burroughs and Thomas (1977) modeled the decline in 0-4 mm Douglas-fir root density with the equation:

$$N = 247.4e^{-\left|\frac{\frac{150-t}{250}-1}{0.39}\right|^{5}} + \left(1-\frac{t}{150}\right)10.9$$

where N is the number of roots per m^2 of soil, and t is the time in months since harvesting. Root densities in our study, measured as numbers of 0-4 mm roots per m^2 of soil, do not show the trend of rapid decline in density predicted by Burroughs and Thomas (**Fig. 27**). The 1-month-old site has values lower than predicted, wheras the two older sites have higher than predicted values. This discrepancy may result from site selection. Density of roots was highly dependent on proximity of the soil pit to large taproots and smaller lateral roots branching off the taproots. Although sites were chosen to avoid taproots, localized variation in rooting patterns may have affected our density measurements.

3.5.3 Homogeneity of Root Species

Douglas-fir roots dominated the 2003 fire site, while only 43% of the roots at the 1999 site were identified as Douglas-fir (**Fig. 24**). This pattern is likely partially explained by the rapid regeneration of understory species following wildfire at the 1999 site. Douglas-fir was the only recognizable species after the 2003 fire. In contrast,

several plants, such as bracken fern and sword fern, had resprouted in the 2002 burn area. In the 1999 burn, dense grasses and brushy species had regenerated on burned hillslopes contributing substantial numbers of roots to near surface soils (**Figs. 2, 3, 4**). The decline in Douglas-fir roots coupled with an increase in understory roots produced a low percentage of Douglas-fir roots in soil pits at the 1999 site. As Douglas-fir seedlings establish extensive root systems, they will undoubtedly contribute a larger percentage of roots to hillslope soils in the future. Other site specific factors, such as aspect, moisture availability, and reseeding potential, may have contributed to variability in species regeneration as well.

3.6 Conclusions

The role of fire in the evolution of the Oregon Coast Range landscape has not been defined or well studied. While many studies have speculated that fire plays an important part in erosion and sediment transport over the long-term history of the OCR, few data exist to quantify this process. This study of three recent fire sites investigates the importance and mechanics of the decline in root strength following wildfire.

Our results suggest that fires may significantly increase the likelihood of shallow landsliding and debris flows in the OCR. Root strength declines quickly in the first year following fire, with smaller diameter roots losing strength more quickly than larger roots. Although the timing and magnitude of decline in Douglas-fir root strength approximates the decline seen after timber harvesting, the complete removal of secondary vegetation during fires further weakens burned hillslopes.

Furthermore, estimates of dry ravel rates in this study suggest that post-wildfire erosion may contribute more than 20% of the long-term erosion. This estimate of erosion is much larger when debris flows are considered as well. A very efficient system of hillslope erosion and sediment transport develops when post-fire dry ravel induces highly accelerated input of sediment to channels, and debris flows generate widespread evacuation of these low-order channels a few years later.

These results suggest that wildfire plays an important role in the long-term erosion shaping the landscape of the Coast Range. Future studies of erosion and sediment transport must account for periods of accelerated dry ravel followed by debris flows. These results also highlight potential shorter-term implications, as increased sediment input to stream systems and destructive debris flows can harm people, structures, and fish habitats. Identification of potentially unstable hillslopes following wildfire may help mitigate some of these damaging outcomes.

Figure 1. Study area

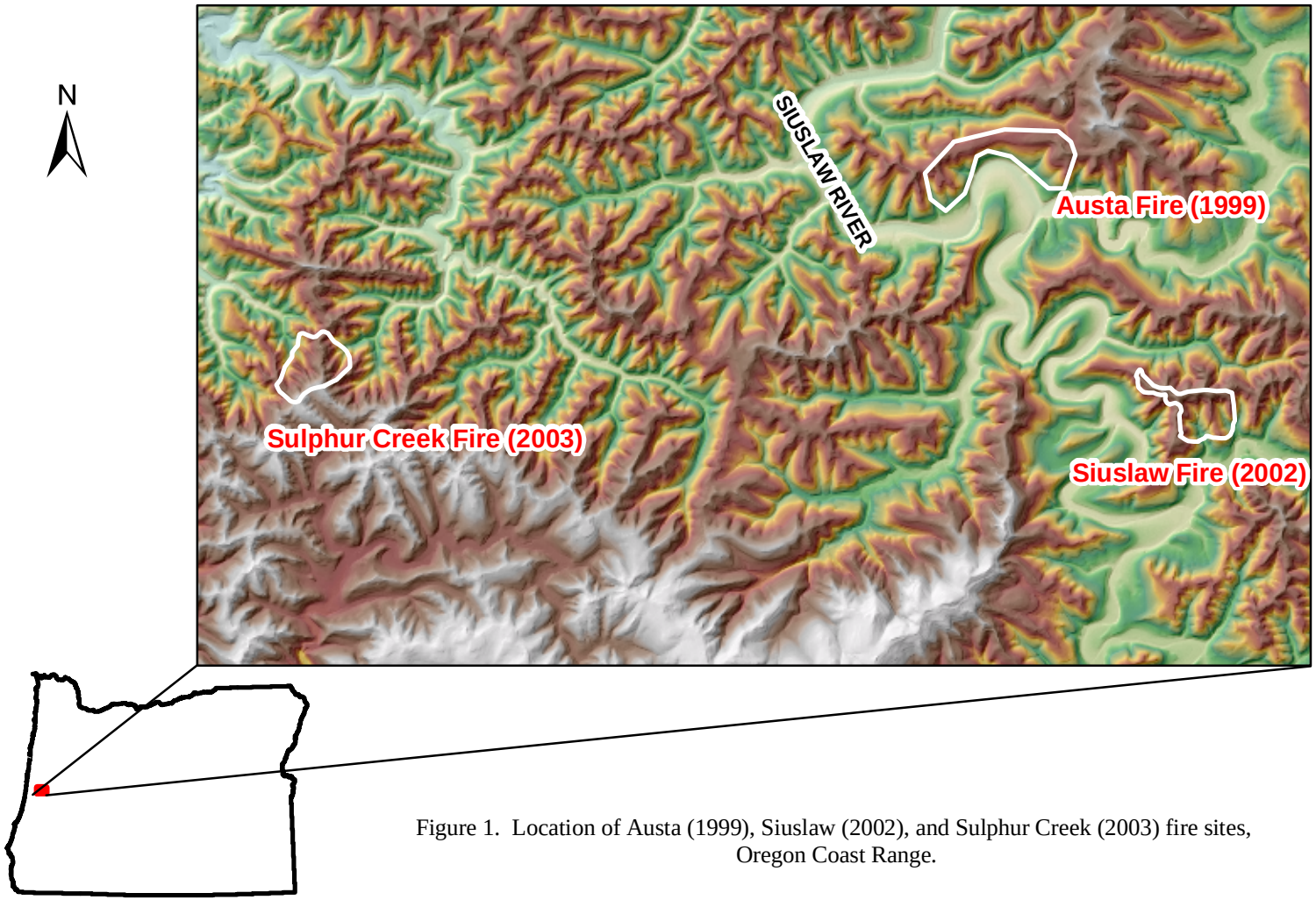

Figure 1. Location of Austa (1999), Siuslaw (2002), and Sulphur Creek (2003) fire sites, Oregon Coast Range.

Figure 2. Soil pit at Austa site (1999). Dense understory contributes roots to near-surface hillslope soils.

Figure 3. Soil pit at Siuslaw site (2002). Bracken fern, pearly everlasting, and unidentified species are visible in the photo.

Figure 4. Soil pit at Sulphur Creek site (2003). Roots protruding from back wall are Douglas-fir.

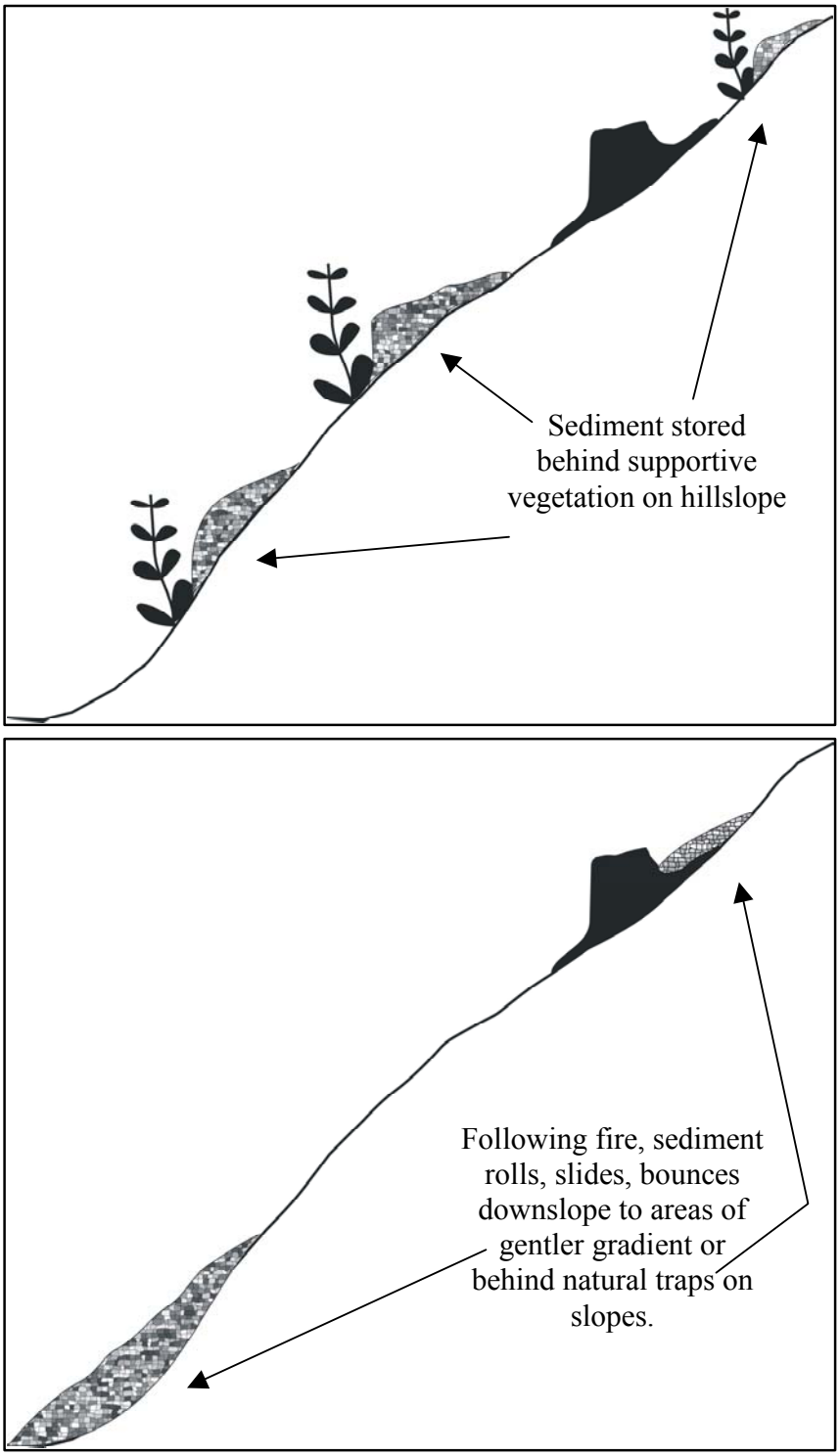

Figure 5. Illustration of dry ravel occurring after incineration of natural sediment traps on hillslope.

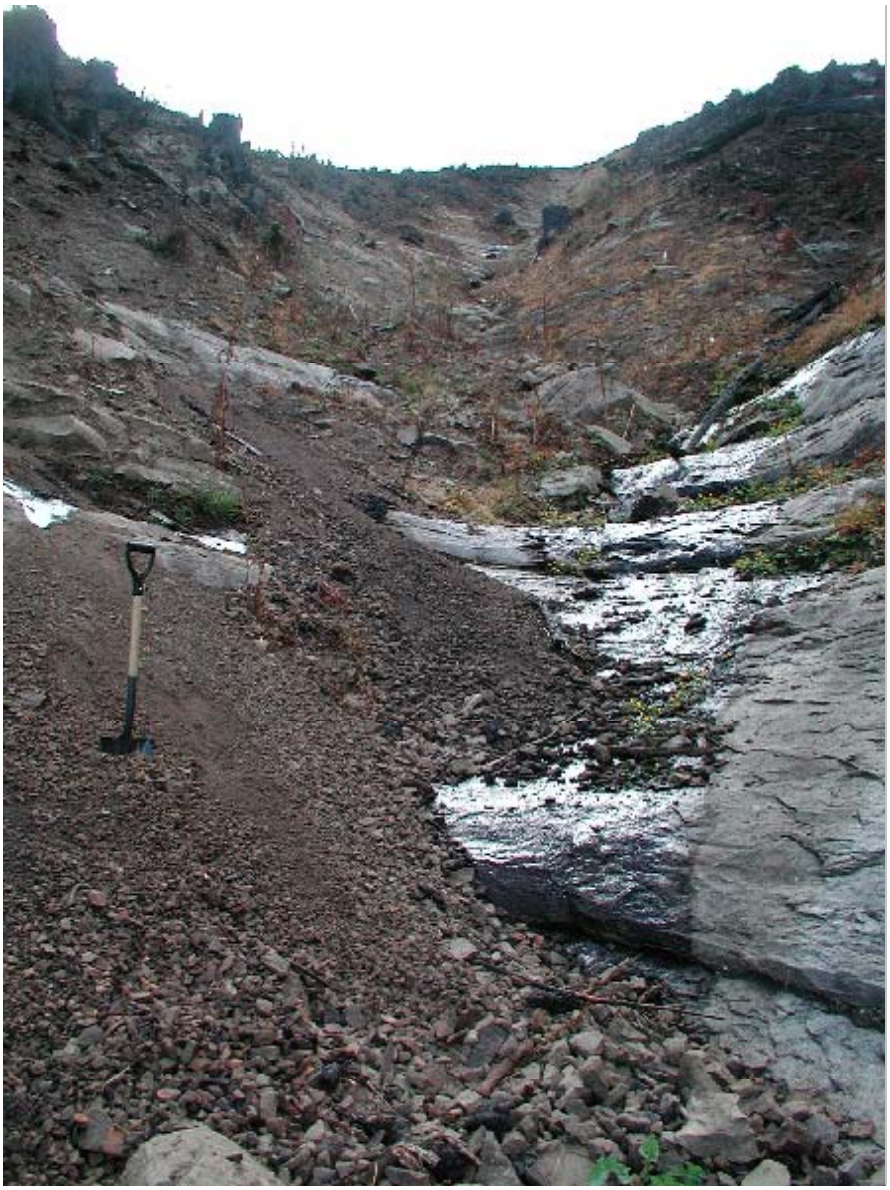

Figure 6. Dry ravel cones accumulating in old debris flow channel following 2003 fire. Photo taken looking upstream toward site of debris flow initiation.

Figure 7. Condition of debris flow prior to 2003 fire. Note lack of sediment in channel.

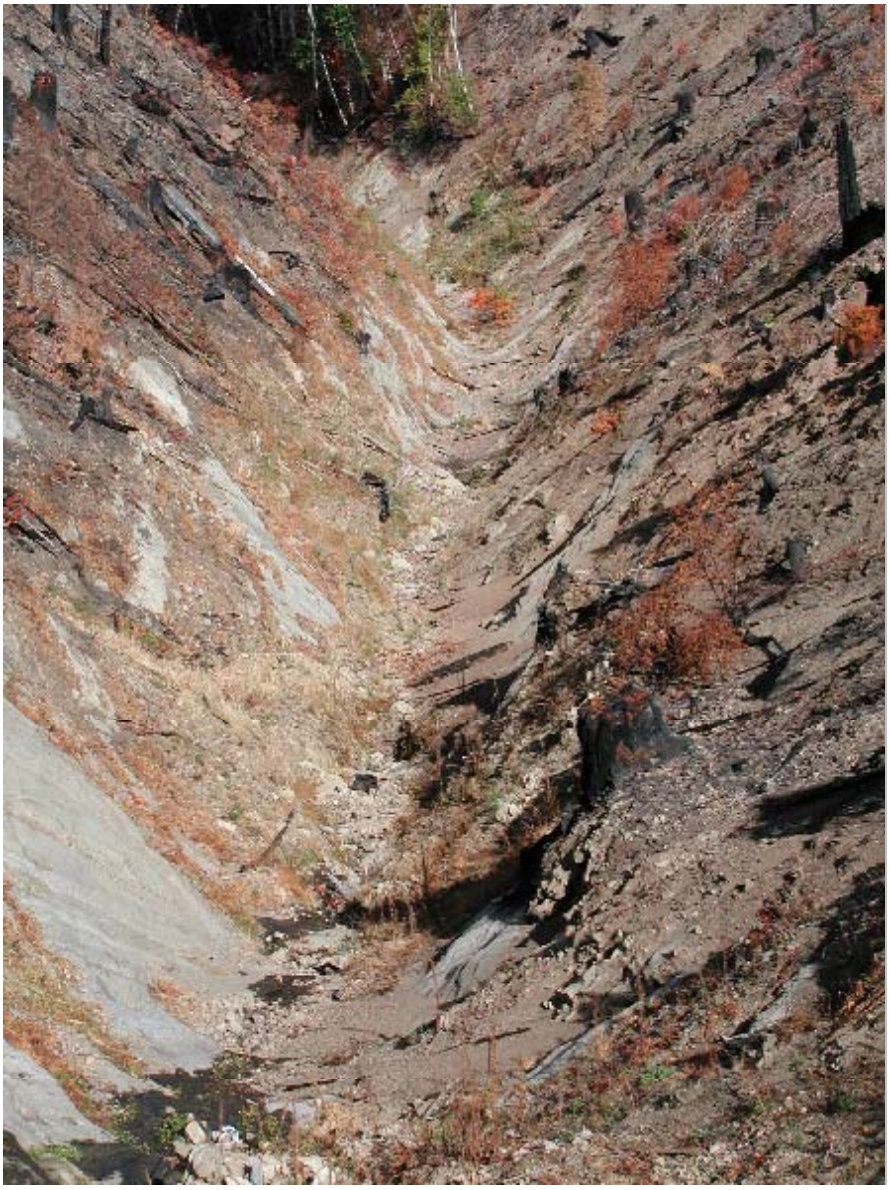

Figure 8. Sulphur Creek (2003) fire site looking down channel. Note fresh dry ravel deposits at base of west-facing slope (right).

Figure 9. Sediment trap installed in old debris flow channel.

Figure 10. Exposures of bedrock on steep slopes five months after Siuslaw fire.

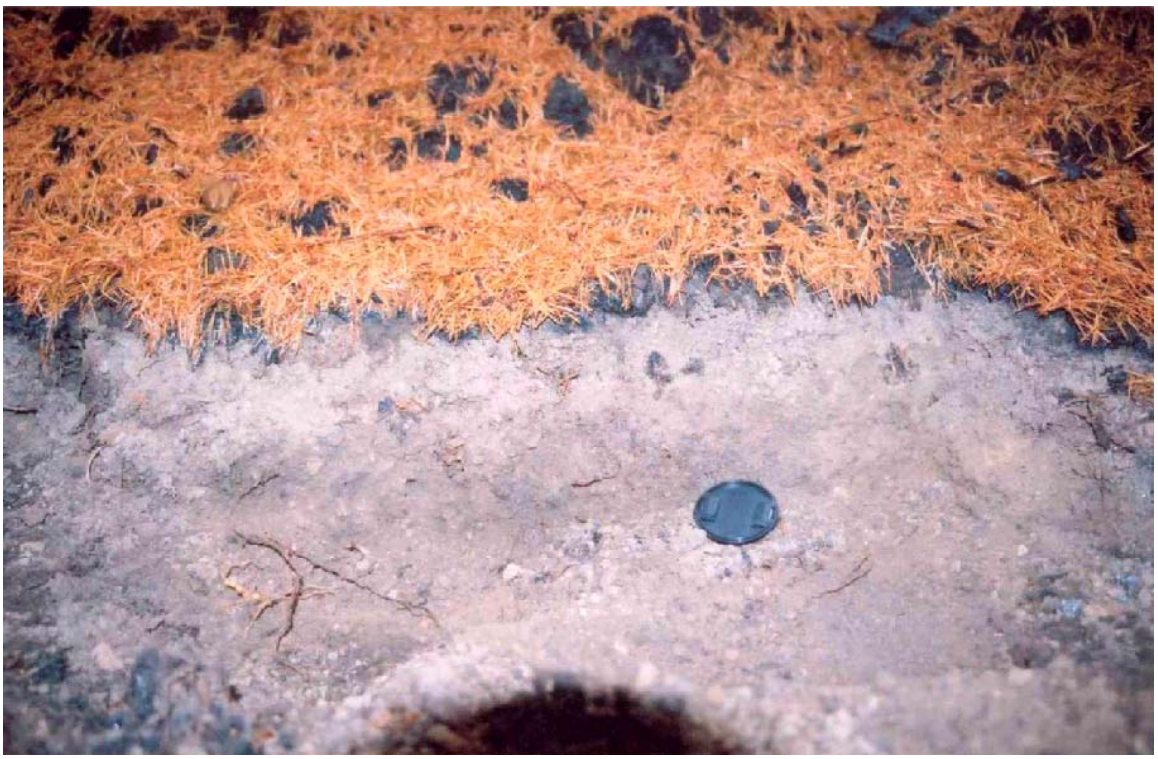

Figure 11. Discontinuous hydrophobicity protecting soils following first rainstorm after fire. Light-colored soil is dry, protected by water-repellent layer above. Dark-colored soil is wet.

Figure 12. Three shallow landslides developed after first rainy season following 2003 fire.

Figure 13

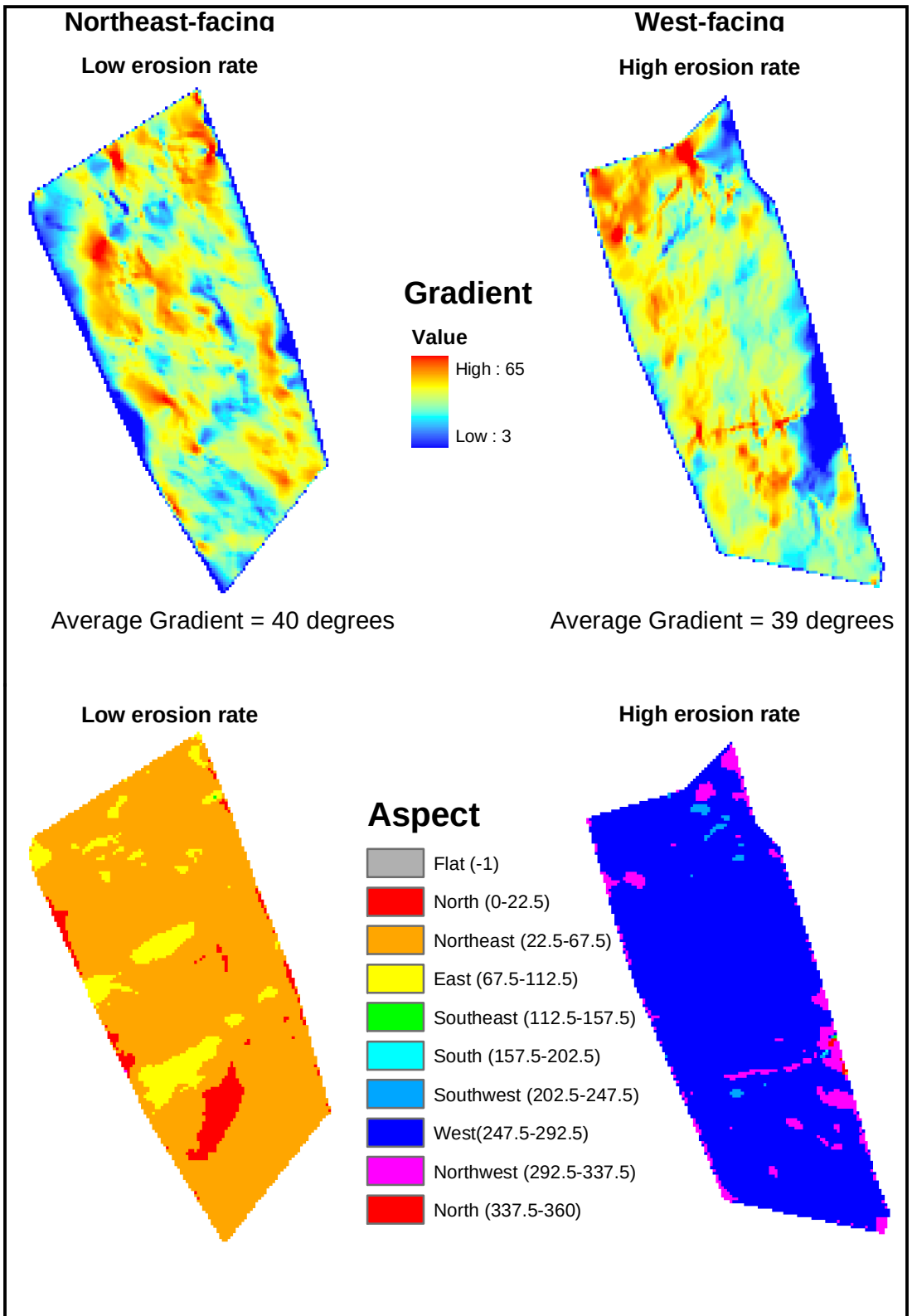

Figure 13. Average gradient and aspect of two contributing hillslopes at 2003 site.

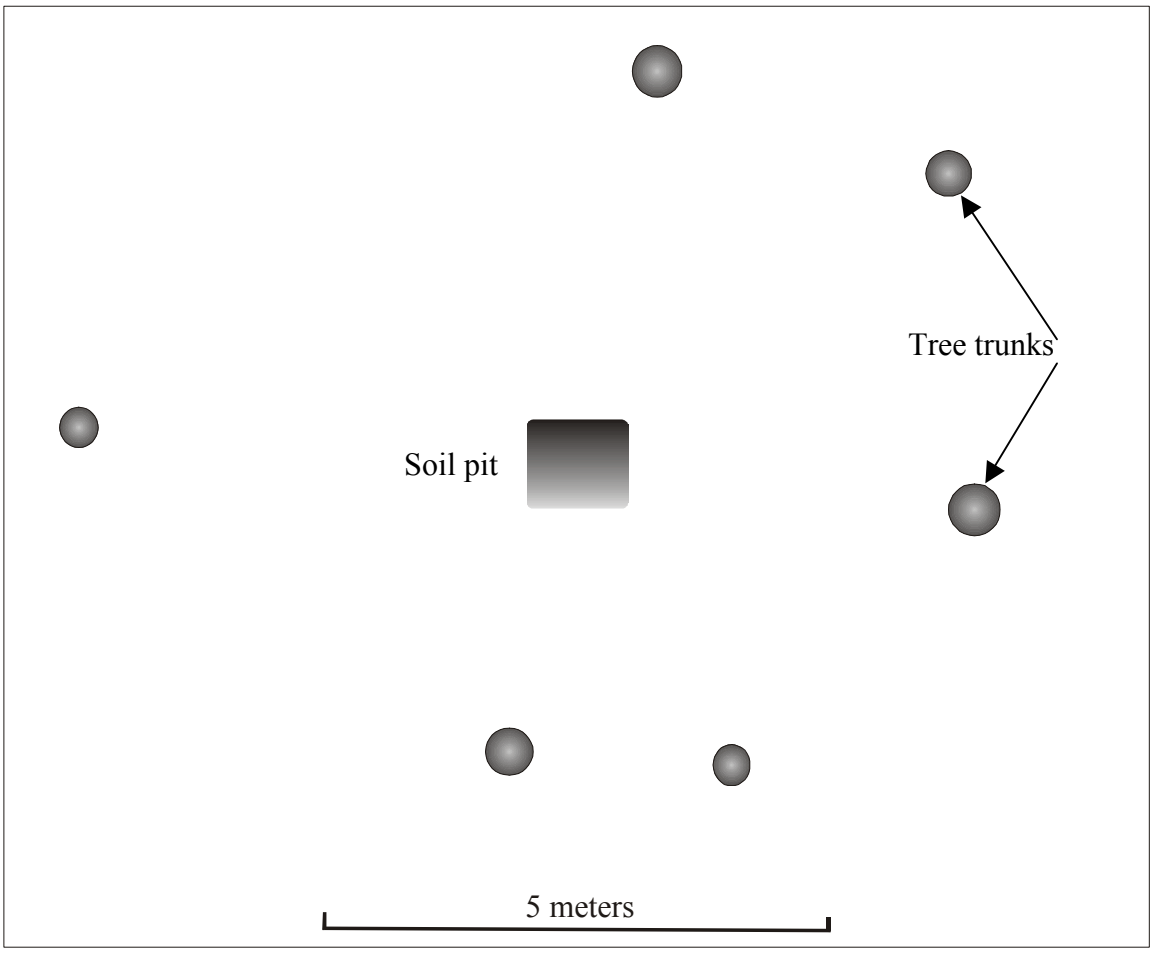

Figure 14. Soil pit and tree configuration at Siuslaw (2002) fire site.

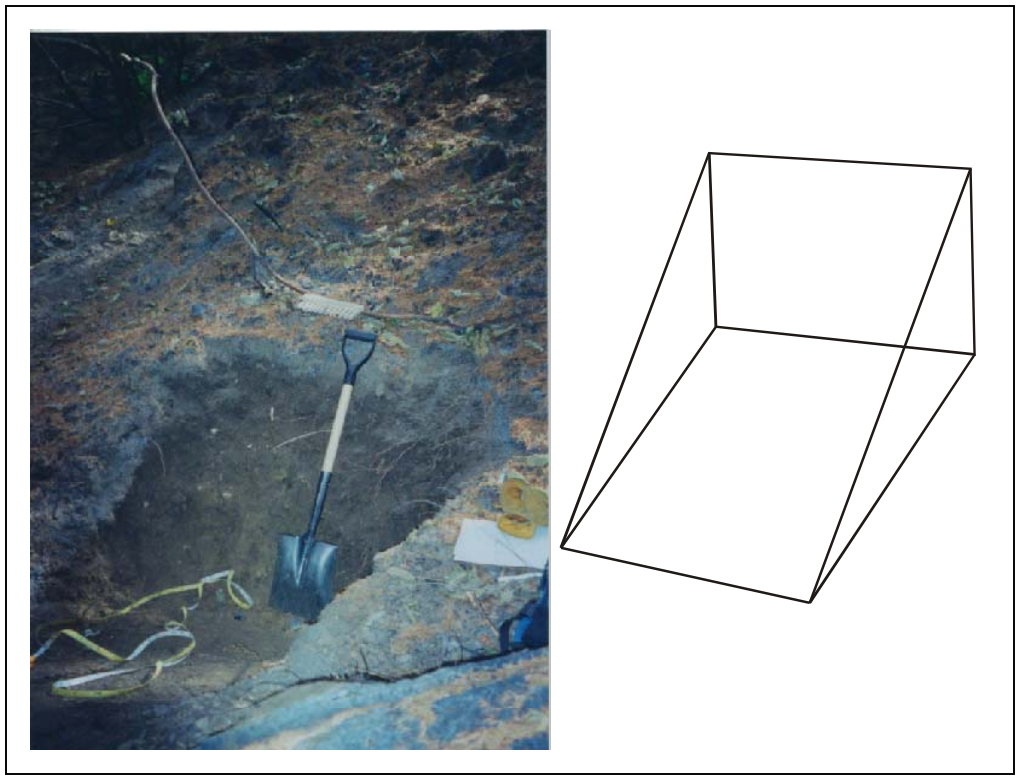

Figure 15. Soil pit at Sulphur Creek (2003) site and example of pit geometry. Roots extracted from 2 triangular side walls and rectangular back wall.

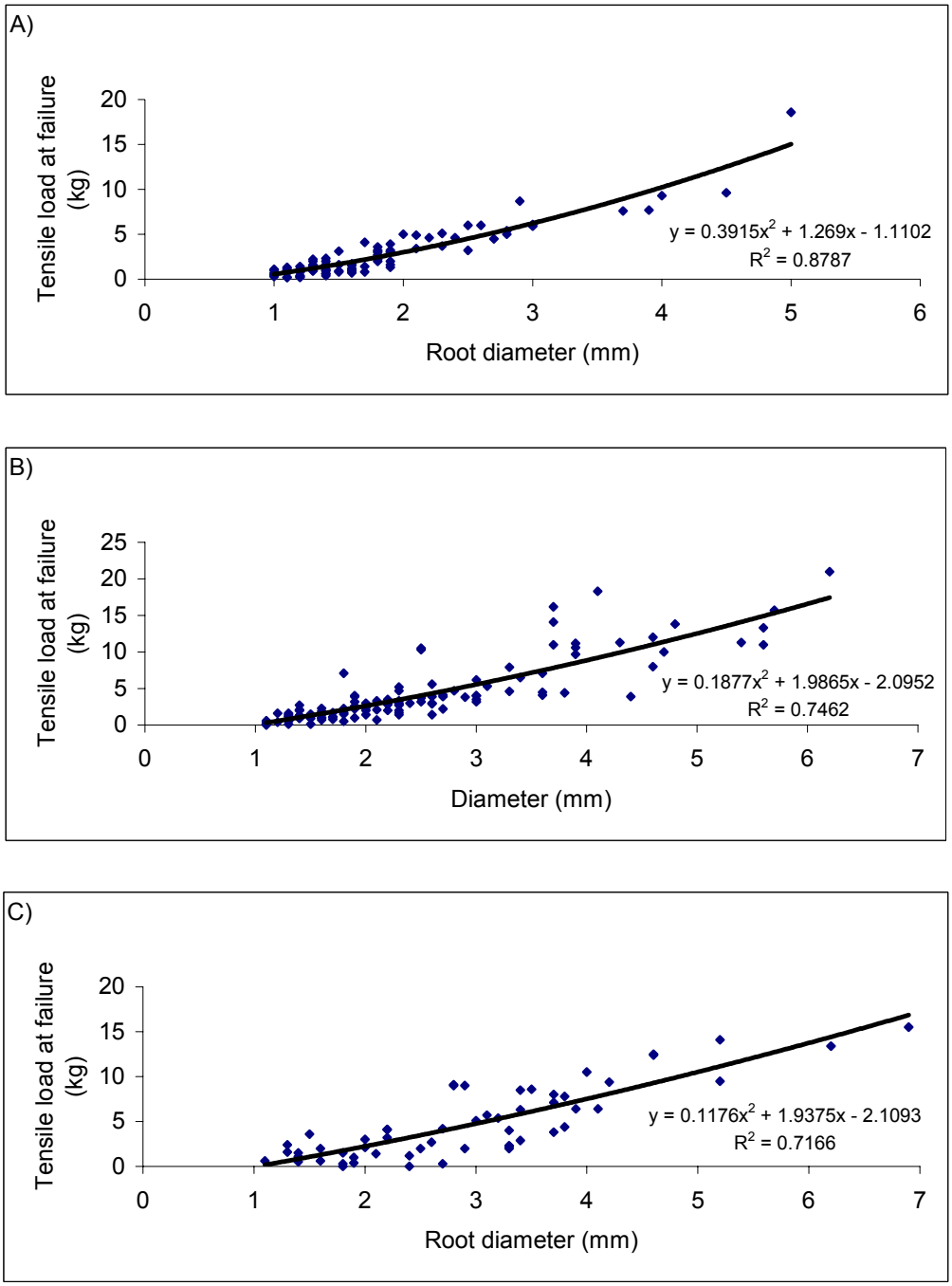

Figure 16. Variation of tensile strength with root diameter a varying times after wildfire. A) Sulphur Creek (2003), 1 month after fire; B) Siuslaw (2002), 10 months after fire; C) Austa (1999), 4 years after fire.

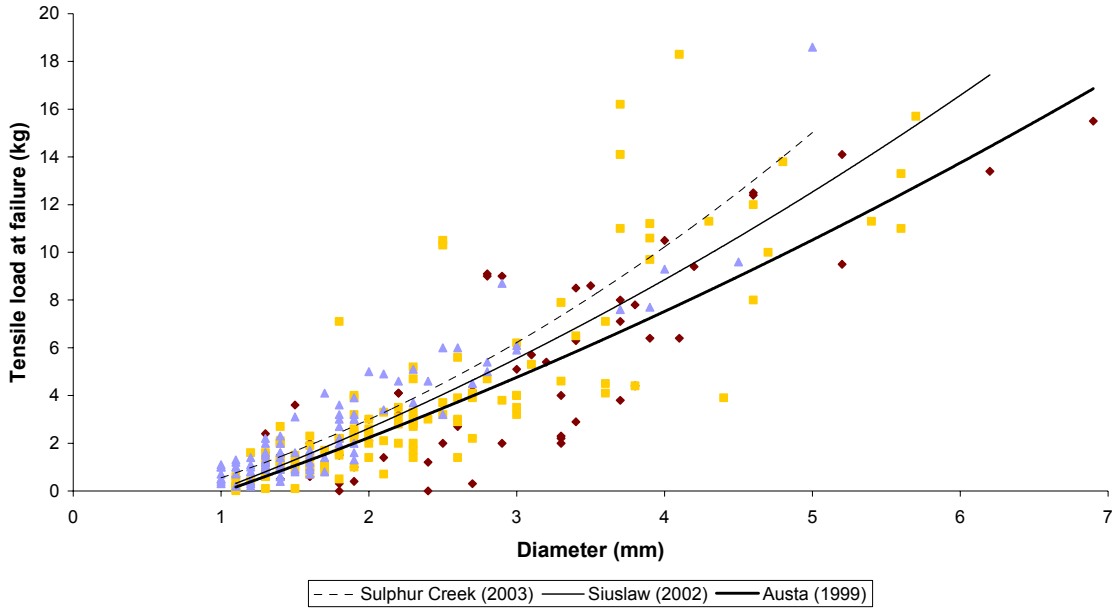

Figure 17. Data from three fire sites showing progressive decline in root strength over time.

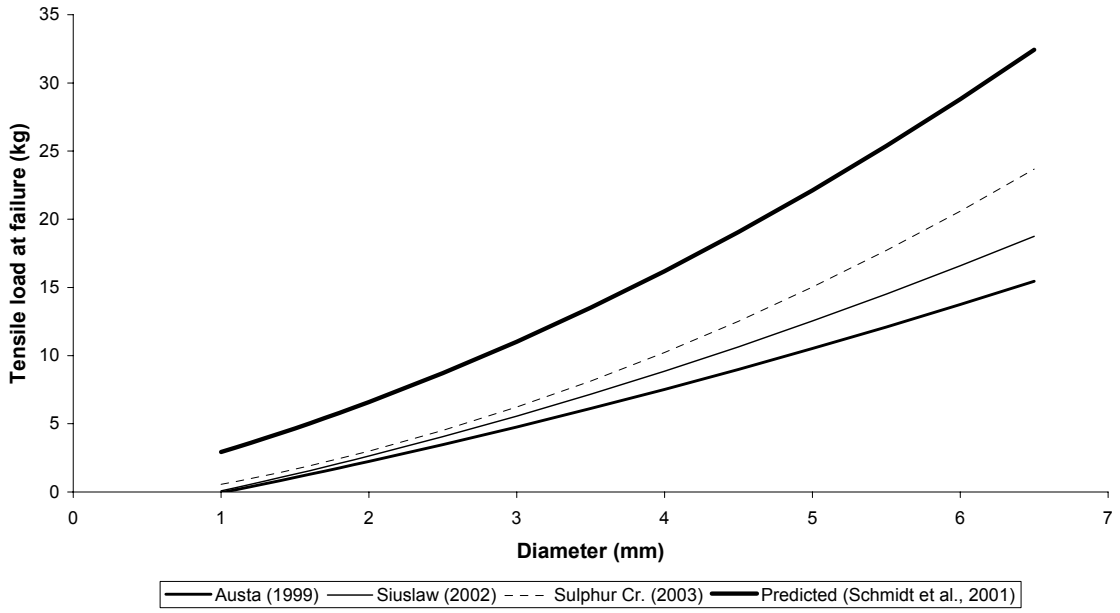

Figure 18. Trendlines from Figure 17 plotted with strenth-diameter curve for healthy Douglas-fir (Schmidt et al., 2001).

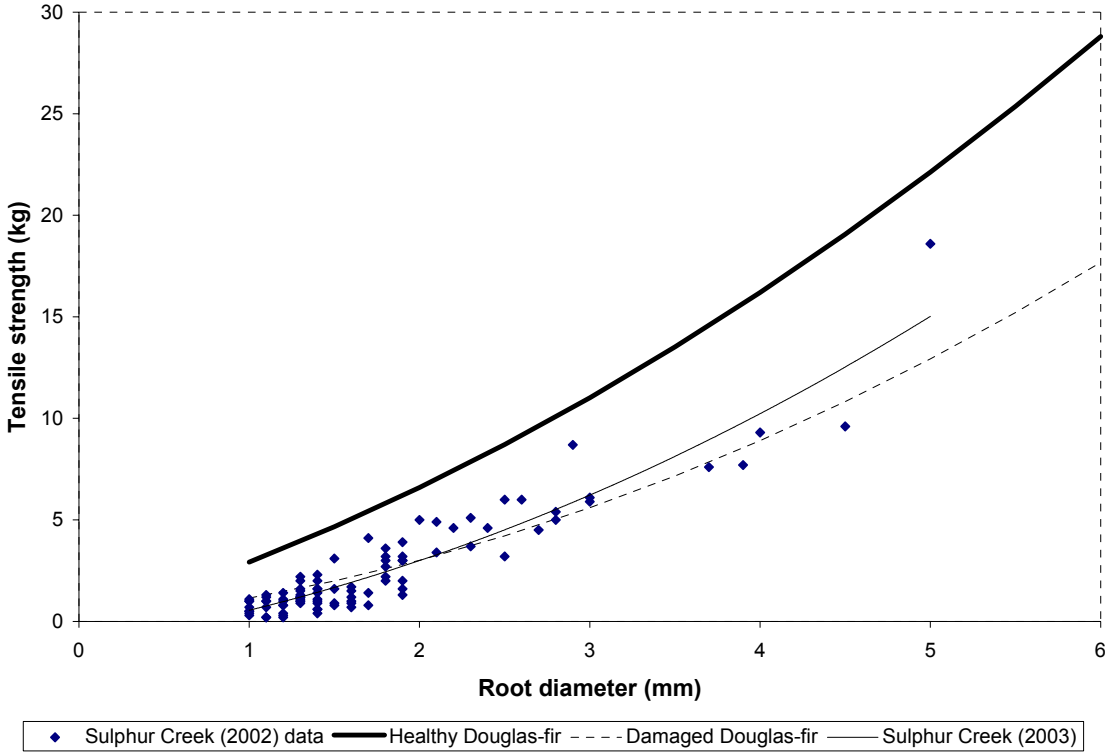

Figure 19. Sulphur Creek (2002) tensile strength-diameter curve compared to strength-diameter curves of healthy and damaged Douglas-fir roots (Schmidt et al., 2001).

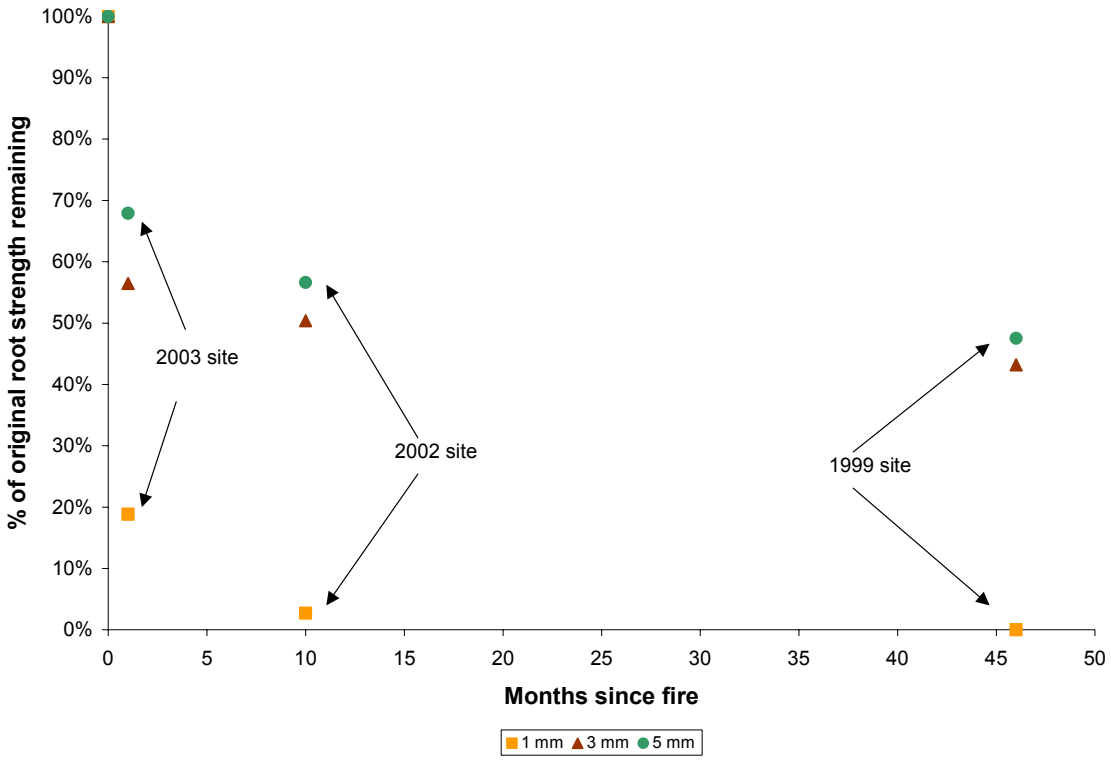

Figure 20. Percentage of original tensile remaining in the months after wildfire for 1-mm, 3-mm, and 5-mm diameter roots (with bark).

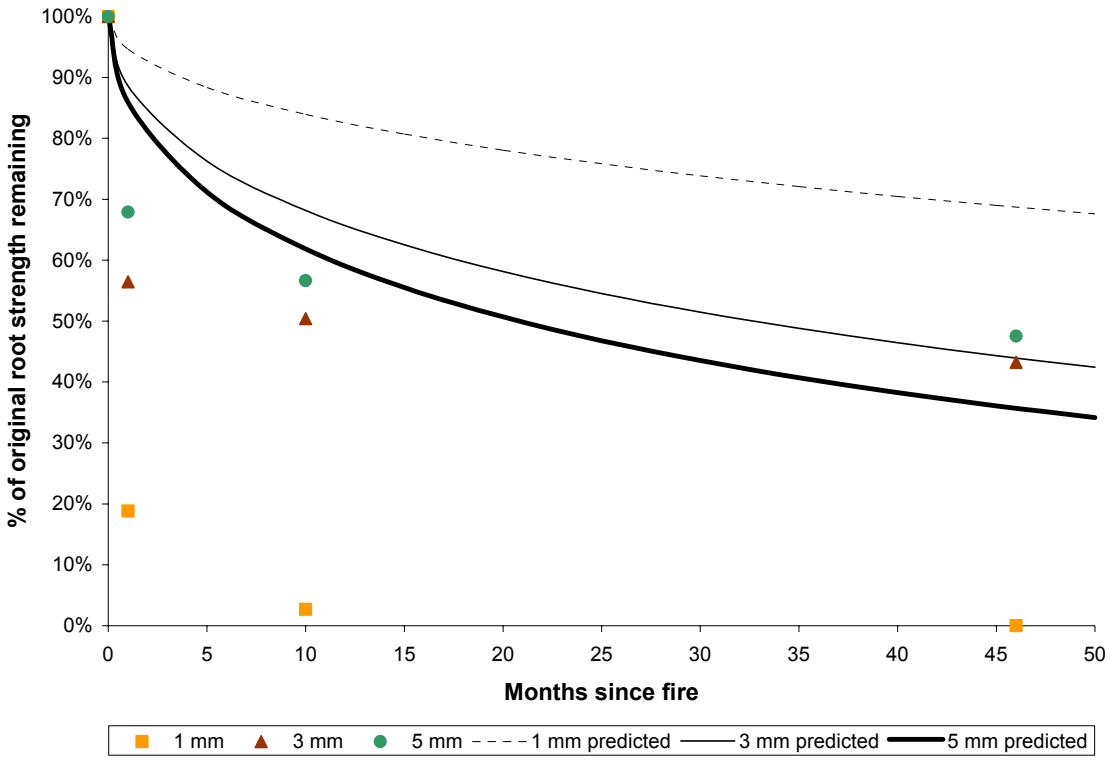

Figure 21. Percentage of original root strength remaining after wildfire plotted compared to modeled decline in root strength for different diameter roots (Burroughs and Thomas, 1977).

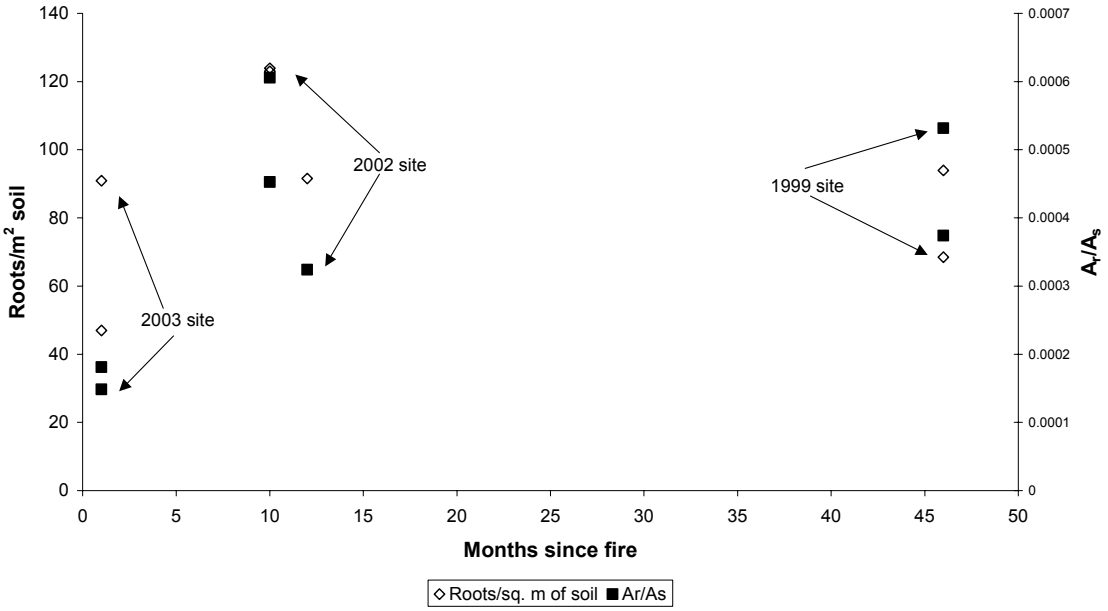

Figure 22. Two measurements of root density following wildfire.

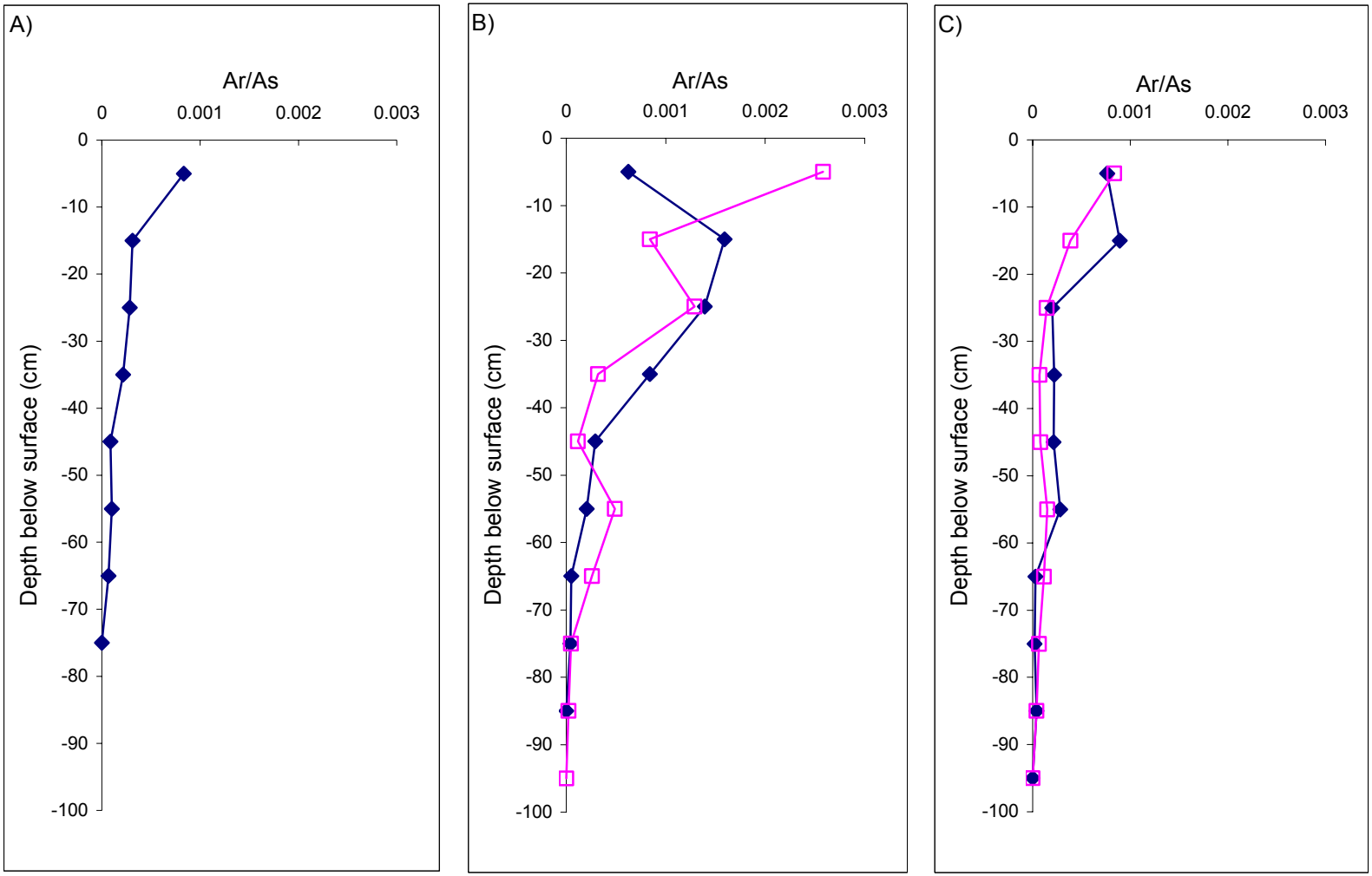

Figure 23. Variation of root density (A_r/A_s) with depth in soil pits at three different times since fire; A) Austa site (1999); B) two soil pits at the Siuslaw site (2002); C) two soil pits at the Sulphur Creek site (2003).

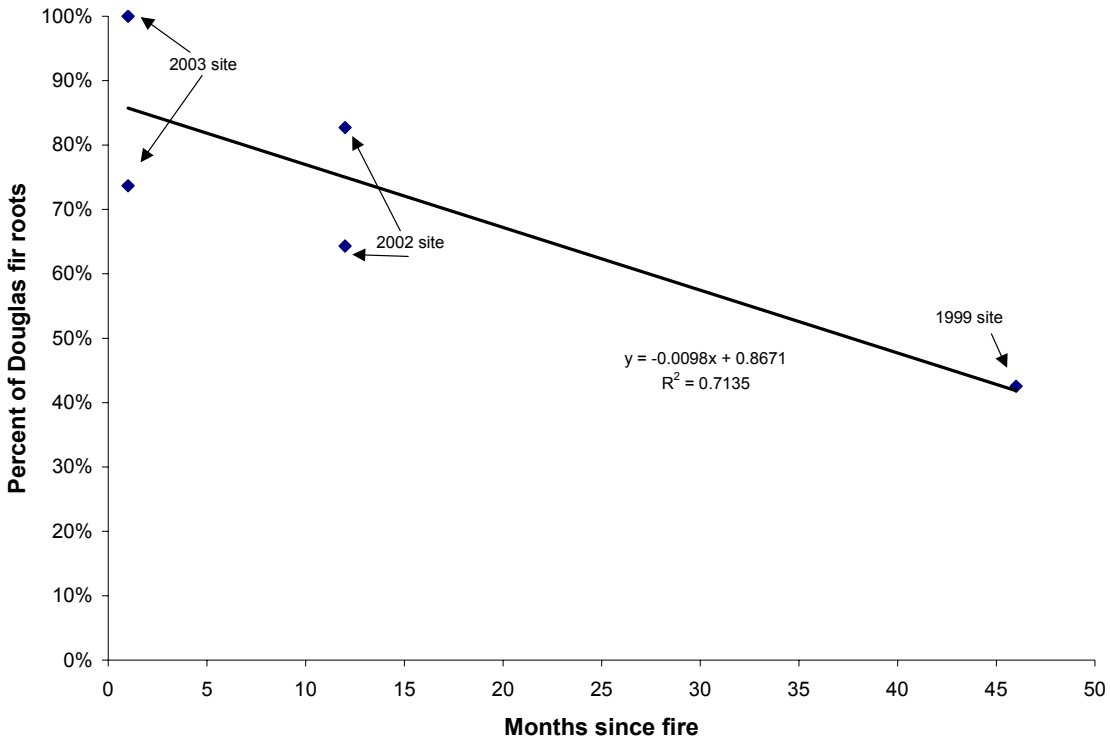

Figure 24. Decline in fraction of Douglas-fir roots over time since fire. Other roots include swordfern, pearly everlasting, big leaf maple, Oregon grape, salal, vine maple, blackberry, and other unidentified species.

Figure 25. Clearcut at Sulphur Creek (2003) site prior to burning. Dense understory and Douglas-fir seedlings cover the hillslopes.

Figure 26. Clearcut at Sulphur Creek (2003) site after fire. All understory on hillslopes has been incinerated.

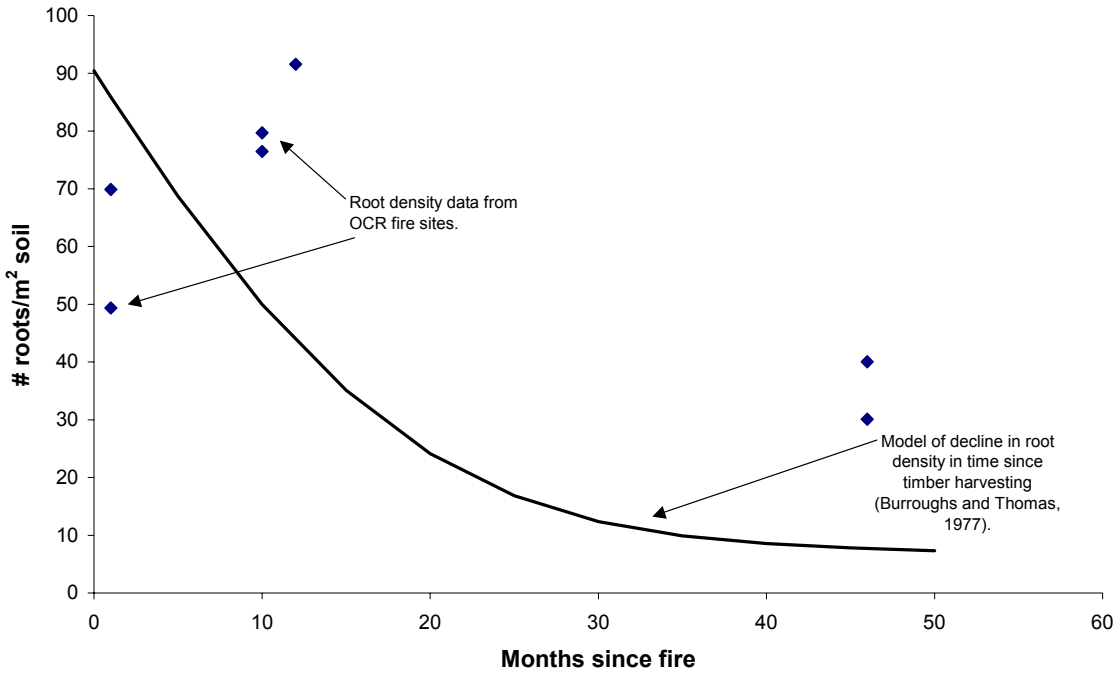

Figure 27. Decline in root density (# roots/m^2 soil) as shown by our data and a model of decline by Burroughs and Thomas (1977).

Table 1. Results of water-drop penetration time tests on intensely burned clear-cut and forested hillslopes.

Site	Depth to top of water-repellent layer	Thickness of water-repellent layer	Time to absorption	Degree of hydrophobicity
Forested #1	1 cm	5 cm	>60 sec.	Strong
Forested #2	1 cm	6 cm	>60 sec.	Strong
Forested #3	1 cm	4 cm	>60 sec.	Strong
Forested #4	0.5 cm	3.5 cm	>60 sec.	Stong
Forested #5	0.5 cm	5.5 cm	>60 sec.	Strong
Forested #6	1 cm	4 cm	>60 sec.	Strong
Forested #7	1 cm	1 cm	>60 sec.	Strong
Forested #8	1 cm	0.5 cm	15 sec.	Moderate
Forested #9	0.5 cm	6.5 cm	>60 sec.	Strong
Clear-cut #1	3 cm	2 cm	>60 sec.	Strong
Clear-cut #2	3 cm	5 cm	>60 sec.	Strong
Clear-cut #3	3 cm	7 cm	>60 sec.	Strong
Clear-cut #4	2 cm	6 cm	>60 sec.	Strong
Clear-cut #5	2 cm	5 cm	>60 sec.	Strong

Table 2. Dry ravel measurements from this study compared with previous measurements of erosion due to post-fire dry ravel in Oregon and California.

Study	Location	Average gradient of contributing area (degrees)	Sediment mobilized by dry ravel (m^3/m^2 contributing area)	Soil surface lowering	Material in channel (m^3/meter of channel length)	Method of Measurement	Duration of measurements (time after fire)
This study, 2004	Oregon Coast Range (west-facing slope only)	39	5.1×10^{-3}	5.1 mm	0.33	Measured volume of dry ravel deposits	0-2 months
	OCR (west *and* northeast-facing slopes)	39	2.4×10^{-3}	2.4 mm			
Schmidt, 1995	Southwest Oregon	11 to 22	1.0×10^{-3}	---	---	Measured volume of dry ravel deposits	First winter season after fire
Florsheim et al., 1991	Slide Creek, southern CA	---	---	---	0.2	Measured volume of dry ravel deposits	0-1 month
	Matilija Creek, southern CA	---	2.0×10^{-6}	---	---		Seven months during *second* dry season
Rice, 1982	Southern California	---	3.9×10^{-3}	---	---	Unreported	0-3 months
Mersereau and Dyrness, 1972 [1]	H.J. Andrews Exp. Forest, W. Oregon	39	6.3×10^{-4}	.36 mm	---	Sediment traps	7-18 months after fire
		31	1.4×10^{-4}				
Krammes and Osborn, 1969 [2]	San Gabriel Mountains, CA	>33	9.4×10^{-3}	---	---	Sediment traps	First year after fire
Doehring, 1968	San Dimas Exp. Forest, southern CA	47	1.6×10^{-1}	185 mm	---	Measured volume of dry ravel deposits	Immediately after fire
		36	2.1×10^{-2}	21 mm			
Krammes, 1960 and 1965 [3]	San Dimas Exp. Forest (South-facing)	42	3.9×10^{-3}	---	---	Sediment traps	1st dry season after fire
	North-facing	35	7.6×10^{-4}				
	South-facing	29-31	1.3×10^{-4}				
	North-facing	29-31	4.0×10^{-4}				

1 Severe underestimate of total post-fire volume because traps installed >7 months after fire.
2 Underestimate of total post-fire volume because significant amount of material not measured.
3 Measurements converted from mass to volume using soil bulk density of 1.16 g cm^{-3} (as reported in Hubbert et al., 2002)

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