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Bare soil and rill formation following wildfires, fuel reduction treatments, and pine plantations in the southern Sierra Nevada, California, USA[1]

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Abstract. Accelerated erosion commonly occurs after wildfires on forested lands. As burned areas recover, erosion returns towards prefire rates depending on many site-specific characteristics, including fire severity, vegetation type, soil type and climate. In some areas, erosion recovery can be rapid, particularly where revegetation is quick. Erosion recovery is less well understood for many fuel load reduction treatments. The rate of post-disturbance erosion recovery affects management options for forested lands, particularly when considering the combined ramifications of multiple disturbances on resource recovery rates (i.e. cumulative watershed effects). Measurements of percentage bare soil and rilling on over 600 plots in the southern Sierra Nevada with slopes less than 75% and within 1 km of roads were made between 2004 and 2006. Results suggest that after high-, moderate- or low-severity wildfire, rilling was seldom evident more than 4 years after fire. Percentage bare soil generally did not differ significantly between reference plots and wildfire plots greater than 6 years old. Little rilling was evident after treatment with a variety of fuel reduction techniques, including burning of machine- and hand-piled fuel, thinning, mastication, and crushing. Percentage bare soil at the fuel load reduction treatment plots also did not differ significantly from reference conditions. Percentage bare soil at pine plantation plots was noticeably higher than at reference sites.

Additional keywords: cumulative effects, fire recovery, fuel treatments, prescribed burn, surface erosion.

Introduction and objectives

Wildfires, prescribed burns and other disturbances to forests and grasslands can produce accelerated erosion (Wright *et al*. 1976; Shakesby *et al*. 1993; Robichaud *et al*. 2000; Benavides-Solorio and MacDonald 2001, 2005; Neary *et al*. 2005; Russell-Smith *et al*. 2006). Although in many situations 'recovery', or return to pre-disturbance erosion rates, occurs in a few years, in environments where post-disturbance revegetation is slower, recovery can take longer. The rate of post-disturbance erosion recovery can limit management options for forested lands, particularly when considering the ramifications of resource recovery rates on cumulative watershed effects. Elevated environmental effects stemming from wildfire can be ameliorated by fuel reduction activities undertaken before the wildfire. However, this is true only to the extent that the fuel reduction activities themselves, or in combination with earlier wildfires, do not cause unduly large environmental effects. A critical factor is the time required for recovery to occur after both wildfire and fuel management actions. Slow erosion recovery rates imply the need to spread out future management actions in time, or the need to lower their intensity, until recovery is substantially complete.

Erosion potential after high-severity wildfire is often high (Helvey 1980; Meyer and Wells 1997; Moody and Martin 2001), but can diminish within a few years to near-background levels (Inbar *et al*. 1997; DeBano *et al*. 1998; Robichaud and Brown 1999; Robichaud *et al*. 2000; Benavides-Solorio and MacDonald 2005). Although there appears to be a general consensus that wildfire effects on erosion often ameliorate 3 to 6 years after a fire, recovery rates differ appreciably as a function of a range of variables, including wildfire severity, rainfall intensity, vegetation type, soil type, topography and elevation (Stednick 2000).

Compared with wildfires, the potential for erosion can be mitigated in prescribed burns, thinnings, and other fuel load reduction treatments. As prescribed burns involve lower-severity fires, retain residual duff that protects the soil surface and are patchy in nature, prescribed burns are typically considered to

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produce less erosion than wildfires (Robichaud and Waldrop 1994; Robichaud *et al.* 2005; Benavides-Solorio and MacDonald 2005). Non-commercial thinning incorporating little or no yarding (moving of felled trees to a temporary storage area) and properly installed and maintained best management practices typically cause little post-treatment erosion (MacDonald and Stednick 2003; Madrid *et al.* 2006). Higher-intensity thinning may necessitate more access to stands and consequently cause more erosion (Haupt and Kidd 1965). Less is known about post-disturbance erosion rates for mastication and some other fuel management treatments (MacDonald and Stednick 2003). However, it is believed that masticating equipment can perturb or compact soil with a concomitantly increased likelihood of erosion (Robichaud *et al.* 2005). Ice *et al.* (2007) summarise fuel management practices as causing '…small, short-term increases in sediment yields, but these increases are more than an order of magnitude less than those expected with a severe wildfire'.

This study aims to refine understanding of post-disturbance surface erosion recovery in the southern Sierra Nevada of California. Specific objectives were to quantify, at the plot scale, the duration and magnitude of indicators of surface erosion recovery after wildfire, a variety of fuel management activities and pine plantations in the Sequoia National Forest and nearby areas. Although wildfires are a common occurrence in this area, to our knowledge no known published data are available on post-disturbance erosion in the southern Sierra Nevada. This study provides information for a geographical area that currently has no known erosion recovery information. It also employs a novel study design, which could provide cost-effective data and information if applied elsewhere.

Methodology

Study design

We documented a surface erosion feature as the presence and frequency of rilling and the percentage bare soil in transects at over 600 disturbed and reference plots. The premise was that rilling is the most obvious sign of surface erosion in the study area and is a good indicator of the lack of return to pre-disturbance conditions. We did not directly measure erosion rates because direct measurement (e.g. silt fences) requires at least several years to account for a representative range of rainfall characteristics (e.g. low-, high- and moderate-precipitation years).

We further assumed that measurements made at plots at different spatial locations, and representing different times since the disturbance, can be organised into a time series representing erosion recovery. This 'trading space for time' approach has been used for testing landscape indicators for stream condition (Pitchford *et al.* 2000), frequency analysis of extreme ocean wave heights (Van Gelder *et al.* 2000) and return of vegetation indices to pre-wildfire levels (Cuevas-González *et al.* 2008). In our retrospective approach, we did not quantify variables like precipitation intensity, for which little or no data are available at the plot scale.

The use of percentage bare soil as a proxy for erosion is supported by field research in the western United States and elsewhere. For instance, Robichaud *et al.* (2005), citing other authors, state 'Erosion rates tend to be positively correlated with percent bare soil and the amount of surface disturbance…', and that bare soil percentages less than 30 to 40 are associated with 'acceptably low' erosion rates. Rainfall simulation has also shown that post-fire sediment production decreases with increasing vegetation cover (Wright *et al.* 1976, 1982; Morris and Moses 1987; Inbar *et al.* 1998; Robichaud and Brown 1999; Pannkuk *et al.* 2000; Benavides-Solorio 2003).

Reference plots were assumed to be surrogates for pre-disturbance conditions. The metrics for duration of post-disturbance erosion were the length of time the frequency of rills per plot and percentage bare soil remained above those at the reference plots. The metrics for magnitude of erosion recovery were the comparative frequency of rills per plot and percentage bare soil at any given time *v.* those at the reference plots. Recovery was assumed to have occurred when rilling frequency and percentage bare soil in the disturbed plots approximated those in the reference plots.

Disturbance type, vegetation type, years after disturbance, wildfire severity, slope, aspect, soil erodibility and annual precipitation were quantified at each plot. Plot selection was based on the first four variables; discriminant analysis and logistical regression modelling included all variables.

Study area

During the summers of 2004 through 2006, field measurements were made in the Sequoia National Forest, the adjacent Tule River Indian Reservation and sections of Sequoia National Park and the Sierra National Forest (Fig. 1). The study area included the full spectrum of vegetation zones on the western side of the southern Sierra Nevada except the alpine (grass, hardwood, shrub, mixed conifer and conifer, by increasing elevation). Annual precipitation varies on the field study plots from 200 to 1250 mm, and falls mostly between November and April. Elevations of the study plots range from 610 to 2650 m. Granitic geology is predominant in the study area, although some volcanic and metamorphic rocks occur, with the metamorphics primarily present as undifferentiated metasedimentary and metavolcanic rocks overlying the granitic batholith. The granitic soils can be highly erodible, and the modal classification of soil erosion hazard on the study plots is 'high' (USDA Forest Service 1996). Annual water year (1 October–30 September) precipitation at a site in the south-central portion of the study area (Kern River Powerhouse no. 3, 824 m) was 260 mm in water year 2004, 434 mm in 2005 and 276 mm in 2006. The long-term annual mean precipitation (1949–2006) for this station is 322 mm.

Methods

Disturbance type, vegetation type, years after disturbance and wildfire severity

Eleven disturbance types were identified from historical records and maps (Table 1). Fire-related disturbances were wildfire, prescribed burns usually older than 5 years, and recent broadcast burns. Non-fire related treatments were thinning – with disposition of slash by manual and machine methods, and burned – mastication, and crushing. Plantations were also included. Fewer than five plots had two disturbance types

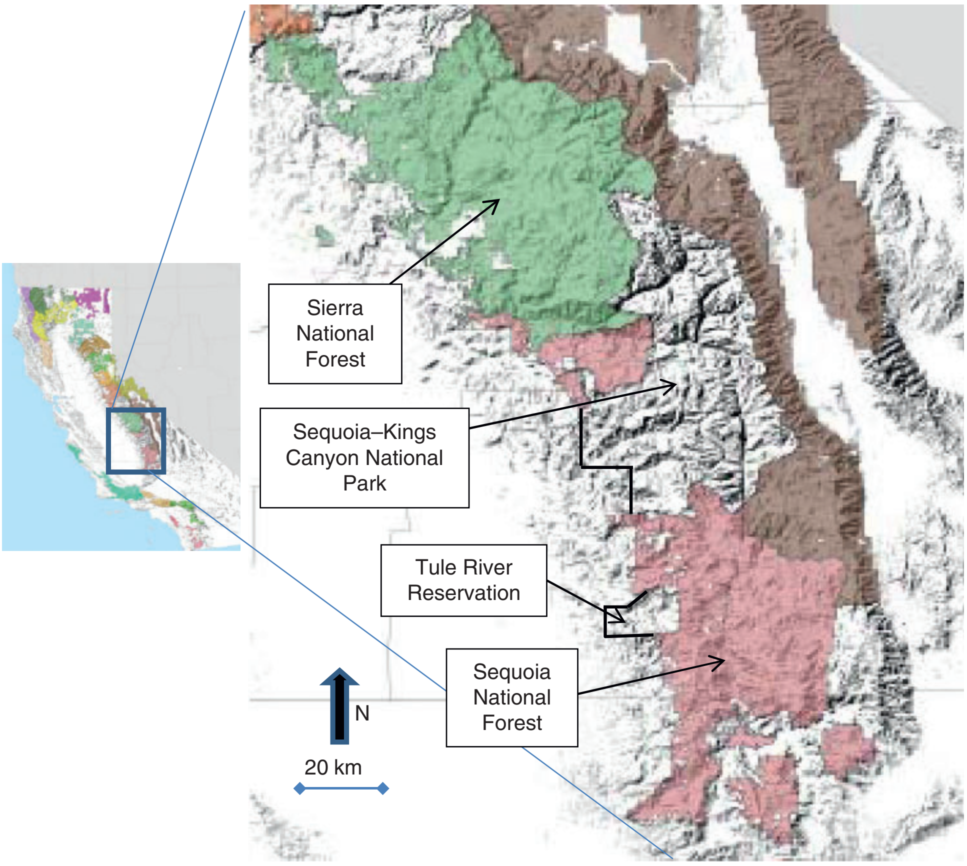

Fig. 1. Study area in the southern Sierra Nevada of California. Solid black lines designate western boundaries of Sequoia–Kings Canyon National Park and Tule River Reservation.

(e.g. wildfire overlying prescribed burn). These were classified by the most recent disturbance.

Vegetation types were initially identified by Geographic Information System (GIS) data layers developed from 1996 Landsat imagery (minimum mapping size 1 ha) (USDA Forest Service 2007) and corrected in the field. The grass type was limited to lower-elevation savannah landscapes, not higher-elevation meadows.

Current management direction on the Sequoia National Forest anticipates that erosion recovery from wildfires would occur within 30 years. It was not feasible or efficient to equally sample each year since disturbance because data on older disturbances were often not available (e.g. wildfire severity data are less abundant and less reliable for the early 1980s and 1970s). Hence for some analyses, the data were grouped into five age classes after disturbance as follows: 1–3 years, 4–6 years, 7–10 years, 11–15 years, and greater than 15 years.

Burned Area Emergency Rehabilitation (BAER) maps were the basis for determining wildfire severity, as these maps are created immediately after each fire following a nationwide standardised procedure and burn severity is directly related to post-fire erosion hazard (USDA Forest Service 2004). The three severity classes used in the BAER maps are low, moderate and high and these are defined as high: '…areas of crown fire, i.e., leaves and small twigs consumed by the fire … always stand-replacing; moderate: … areas where the forest canopy was scorched by an intense surface fire, but the leaves and twigs were not consumed by the fire … may be stand-replacing or not, depending on how many canopy trees survive the scorching; and low: … areas where the fire burned on the surface at such low intensity that little or no crown scorching occurred (may include small areas that did not burn at all) … never or rarely stand-replacing' (Romme *et al*. 2003). The 'high' and 'moderate' GIS severity classifications were adjusted on ~15% of wildfire plots up to 3 years old according to field observation of pine needles still on trees; plots having trees with no needles were classified as high severity and plots having trees with some needles were classified as moderate severity.

Field plot determination

A main objective was to extrapolate results beyond the specific measurement sites to a broader area. To help achieve this objective, plots were selected by incorporating a random component. GIS polygons for each disturbance type–age–wildfire severity–vegetation type combination were identified and one or two GIS polygons for each combination were randomly chosen. Three replicate plot locations were randomly selected within each polygon. This replication allowed quantification of variability among plots that should have identical conditions (i.e. vegetation type, wildfire severity and years after disturbance).

Table 1. Assessments of study plots among disturbance types and years since disturbance

Disturbance type	No. plots	Plots by years since disturbance					Percentage of plots
		1–3	4–6	7–10	11–15	>15	
Reference	64						10.2
Wildfires							
Low severity[A]	130	66	31	14	9	10	20.7
Moderate severity[A]	100	53	32	2	9	4	15.9
High severity[A]	89	41	25	5	10	8	14.2
Prescribed fire[B]	106	4	20	35	16	31	16.9
Broadcast burn[C]	23	23					3.7
Fuel treatments							
Thinning[D]	12	12					1.9
Machine pile[E]	12	12					1.9
Machine pile burn[F]	27	27					4.3
Hand pile[G]	8	8					1.3
Hand pile burn[H]	35	31	4				5.6
Mastication[I]	3		3				0.5
Crushing[J]	4	4					0.6
Plantation[K]	14	1	3	3	3	4	2.2
Total	627	282	118	59	47	57	

[A]Does not include multiple assessments on 29 plots in 2 different years and nine plots in 3 different years.
[B]Controlled application of low-intensity fire under specified environmental conditions to reduce hazardous fuel accumulations.
[C]A type of prescribed fire, generally in the absence of a merchantable timber overstorey, that consumes fuel that has not been piled or windrowed. The Sequoia National Forest database does not distinguish types of prescribed burns before 2001.
[D]Reduction of small-diameter tree density by hand tools or mechanical methods.
[E]Thinning by mechanical piling of slash; disposition of slash unstated.
[F]Thinning with slash piled by machine and burned.
[G]Thinning with slash piled manually; disposition of slash unstated.
[H]Thinning with slash piled manually and burned.
[I]Chopping, grinding or mowing brush and small trees, usually by mechanical means, and usually leaving the treated vegetation onsite.
[J]Use of a vehicular machine to crush and flatten small trees and brush, usually leaving the treated vegetation onsite.
[K]Forest stands established by planting or seeding.

Wildfire plot selection was constrained to wildfires greater than 405 ha because smaller fires generally did not receive BAER treatments. The available database for wildfires and undifferentiated prescribed fires in the study area covers several decades. Specifics on other types of treatments were available for only the last few years.

Reference plots were determined from historical records as locations devoid of wildfire occurrence, timber harvest or fuel load reduction activities. Any field observation of cut timber, grazing or burned wood removed candidate reference sites.

For logistical purposes, plots were selected within 1 km of a road, realising that ground slopes near roads may be relatively flat because roads sometimes follow ridges or low-gradient routes for practicality. Sites with slopes greater than 75% were not surveyed for safety reasons. Thus the results are limited to locations within 1 km of roads with slopes less than 75%.

In the summers of 2004 through 2006, over 600 plots were surveyed (Table 1). Plots were assessed on 14 wildfires that burned between 1977 and 2004. The ages (years since disturbance) of the wildfires ranged from 1 to 27 years. A total of 130 plots were assessed on low-severity wildfires, plus 100 and 89 plots respectively on moderate- and high-severity wildfires. Twenty-one prescribed burns were surveyed between 1 and 23 years after the initial burning. Between one and nine distinct units were surveyed at the more recent fuel treatment sites (e.g. nine different hand pile burn units were surveyed). Plots in younger disturbances were more intensively sampled in 2005 and 2006 when it became apparent that older disturbances showed little rilling. Consequently, almost 70% of all assessments on non-reference plots were conducted on disturbances less than 6 years old. Sixty-four reference plots were surveyed.

Bare soil and rill quantification

Percentage ground cover was quantified by a point count variant of a procedure described in FIREMON (Fire and Research Management Exchange Systems 2005). At each 625-m^2 plot, three parallel, cross-slope transects were randomly located along a 25-m baseline oriented perpendicular to the contour. Fifty point counts of ground cover were made at 0.5-m intervals along each transect, to yield 150 sample points per plot. Five ground cover categories were tallied: dead vegetation and litter; bare mineral soil; boulder or bedrock (2–256 mm long dimension); down wood as discrete dead branches, twigs or tree stems; and live vegetation. Percentage bare soil was calculated as the percentage of bare mineral soil point counts. All measurements and observations were made and recorded by the same individual. We believe consistency was enhanced by using a single observer and that any bias stemming from measurements and observations by a single individual was small in comparison with the signal within the data.

The number of rills that the transects crossed on each plot was tallied. Active rills in the study area were furrows with loose, mobile sediment and no vegetation, generally less than 2 cm deep, up to 20 cm wide and up to 10 m long. Revegetating rills that had significant vegetation within their furrows were tallied. The random location of transects along the 25-m baseline could affect the number of rills counted, although typically the rills were long enough to cross two or more transects and few rills were observed in the vicinity of the plots that were not counted within the plots themselves. We believe most rills were accounted for with this technique.

After the first summer of field work, rilled plots were often reassessed in subsequent years to document rill change through time so that a majority of rilled plots were tracked for up to 3 years. Because the original design did not call for revisiting the plots, none of the plots were located with permanent markers. Limitations in the accuracy of the global positioning system units caused minor uncertainty in returning to exactly the same plot in subsequent years, but prior-year plot photographs indicated that most of the rilled plots were accurately relocated in subsequent years.

Ancillary variables

Ancillary variables may contribute to variation in erosion recovery. For each plot, slope and aspect were measured with a clinometer and compass respectively. Plot elevation was taken from US Geological Survey 1 : 24 000-scale topographic maps. Soil erodibility and average precipitation were taken from a published soil survey (USDA Forest Service 1996).

Analytical procedures

The rilling and bare soil data were summarised with descriptive statistics and compared between disturbed and reference plots using Mann–Whitney analysis. Assessment of the relevant controlling variables separating rilled from unrilled plots was done through discriminant analysis (Mardia *et al*. 1982) and logistic regression using *S-Plus 7.0* (Insightful Corporation 2005).

Both ‘grouped’ treatments (e.g. all ‘non-burn’ treatments combined) and individual treatments (e.g. hand pile burn) were compared against reference percentage bare soil, by individual vegetation type (e.g. reference hardwood *v.* prescribed-burn hardwood). For these analyses, conifer and mixed conifer vegetation types were combined, and only treatment–vegetation type combinations with at least three plots were included. This limited the analysis of broadcast burns and machine pile treatments to conifer, mixed conifer and shrub only, of plantations to conifer, mixed conifer and grass only, and of machine pile burn, hand pile burn, hand pile, thinning, mastication and crushing to conifer and mixed conifer only.

Percentage bare soil on wildfire plots was compared for two age groups, 1 to 6 years after fire and 7 or greater years after fire, and the reference plots. Sample sizes would have been too small for comparisons of more age groups. In these comparisons, mixed conifer and conifer vegetation were grouped on the belief that post-fire erosion processes respond similarly on these two vegetation types. Because no plots were surveyed for some vegetation type–wildfire severity combinations in fires older than 6 years, some comparisons were not made for the older wildfires.

Logistic regression determines the probability of rill occurrence and discriminant analysis creates a function using associated variables that allocate an individual observation into one of two groups, with rills or without (Agresti 2002). Several discriminant models were selected and examined by using cross-validation to identify misclassifications. For both the discriminant and logistic analyses, presence or absence of rilling was the dependent variable. The independent variables were disturbance type, vegetation type, years after disturbance, wildfire severity, slope, aspect, soil erodibility and annual precipitation. Initial trials incorporating transformation of the independent variables were not promising; hence, the final models did not include any transformed variables.

Results

Percentage bare soil

Percentage bare soil on the study plots varied by disturbance type, years after disturbance, vegetation type, and fire severity. Percentage bare soil was much less on the fuel treatments and prescribed or broadcast burns than on recent wildfires. For the reference plots, the median amount of bare soil was 4% or less for hardwood, mixed conifer and conifer vegetation, 9% for grass, and 15% for shrub vegetation. Among the reference plots, the mean bare soil standard deviation was low for all vegetation types and varied from 2% (for hardwoods and mixed conifers) to 6% for (shrubs).

Wildfires

Bare soil was less evident on low- and moderate-severity wildfire plots than high-severity plots during the first year after fires (Table 2). Median (84%) and maximum (92%) bare soil values were particularly high on high-severity plots the first year after wildfire (Table 2). After the first post-fire year, both median and maximum percentage bare soil were similar among the three severity classes and the medians for all severity classes were below 25% 4 years and later after the fires (Table 2).

Percentage bare soil was almost always significantly greater than on the reference plots for the younger, 1–6-year wildfire plots but typically not significantly different on wildfire plots 7 or more years old. For wildfires less than 7 years old, median percentage bare soil was consistently highest in shrub plots, intermediate for mixed conifer and conifer plots, and lowest in hardwood plots (Table 3). Specifically, the statistical testing ($\alpha = 0.05$) suggested that compared with the reference plots, percentage bare soil (1) differed significantly at all severities for hardwood and mixed conifer and conifer vegetation on plots 1 to 6 years after wildfire; (2) differed significantly under shrub vegetation less than 7 years after wildfire for moderate- and high-severity wildfire; but (3) did not differ significantly between reference plots and wildfire plots greater than 6 years old except for hardwood vegetation in low-severity wildfires.

Prescribed fires and broadcast burns

Lumping all vegetation types together, bare soil was scarce (median under 10%) on recent broadcast burns and both recent and older prescribed fires. There was no clear trend through time in percentage bare soil on the prescribed fire plots, and the

Table 2. Median and maximum percentage bare soil by disturbance type and years since disturbance

Disturbance type	Years after disturbance								
	1	2	3	1–3	4–6	7–10	11–15	>15	All plots
Reference									4; 44
Hardwood									1; 13
Mixed conifer									3; 35
Conifer									4; 9
Grass									9; 44
Shrub									15; 28
Wildfires									
Low severity	14; 35	23; 80	16; 41	14; 80	24; 59	6; 47	4; 33	8; 21	10; 80
Moderate severity	7; 10	38; 85	18; 53	14; 85	19; 49	4; 6	5; 35	19; 21	14; 85
High severity	84; 92	36; 75	20; 31	34; 75	18; 58	1; 10	4; 17	12; 27	18; 92
Prescribed fire	2; 3			2; 3	9; 19	3; 56	7; 54	1; 26	7; 56
Broadcast burn				7; 30					7; 30
Fuel treatments									
Thinning				2; 17					2; 17
Machine pile				1; 11					1; 11
Machine pile burn				4; 25					4; 25
Hand pile				4; 9					4; 9
Hand pile burn				4; 9					4; 9
Mastication					0; 0				0; 0
Crushing				3; 13					3; 13
Plantation				35; 35	20; 21	9; 19	17; 19	17; 35	18; 35

Table 3. Median percentage bare soil for reference and wildfire plots for two post-fire age classes, by vegetation type

Significance is based on one-tail Mann–Whitney tests. NS indicates not significant

Wildfire severity and vegetation type	Years since fire	Significance	Bare soil values (%)			
			Wildfire		Reference	
			Median	*n*	Median	*n*
High						
Shrub	1–6	0.025	42	20	16	6
	7+	NS	11	9	16	6
Hardwood	1–6	0.01	10	7	1	11
	7+	NS	3	5	1	11
Mixed conifer and conifer	1–6	0.01	21	27	3	33
	7+	NS	4	8	3	33
Moderate						
Shrub	1–6	0.05	26	12	16	6
	7+	NS	7	8	16	6
Hardwood	1–6	0.01	12	16	1	11
	7+	No plots				
Mixed conifer and conifer	1–6	0.01	21	31	3	33
	7+	0.1	5	5	3	33
Low						
Shrub	1–6	NS	26	13	16	6
	7+	No plots				
Hardwood	1–6	0.01	6	16	1	11
	7+	0.01	9	8	1	11
Mixed conifer and conifer	1–6	0.01	9	32	3	33
	7+	0.1	4	19	3	33
Grass	1–6	0.01	32	17	9	13
	7+	NS	17	6	9	13

medians remained below 10% for plots as old as 23 years (Table 2). Percentage bare soil also was not significantly greater than in the reference plots for the age-grouped prescribed burn plots in mixed conifer, conifer, hardwood or shrub vegetation ($\alpha = 0.01$). For prescribed burns greater than 15 years old, percentage bare soil also did not differ significantly from reference conditions for mixed conifer, conifer, hardwood or shrub vegetation (sample size was too low to test for grass). However, the median bare soil value was significantly greater ($\alpha = 0.05$) for several specific conditions: broadcast burns in conifer and mixed conifer vegetation, all ages combined (median = 5%) *v.* reference (median = 3%), for prescribed burn in grass, all ages combined (median = 42%) *v.* reference (median = 9%) and for prescribed burns for the following age–vegetation combinations: mixed conifer and conifer 4 to 6 years (median = 9%) *v.* reference (median = 3%); and hardwood 4 to 6 years (median = 9%) *v.* reference (median = 1%).

Fuel treatments

Median bare soil percentages for the fuel treatments approximated those of the reference plots and the maximum percentage bare soil for some of the fuel treatments was less than the maximum for some of the reference plots. Median percentage bare soil was always less than 5% and as low as 1%, indicating that the fuel treatments resulted in relatively little ground disturbance (Table 2). In the statistical testing, median percentage bare soil was not significantly different between any of the fuel treatments and the reference plots. Temporal change for the fuel treatments was not possible to assess because there were very few plots on treatments older than 3 years.

Plantations

At the plantation plots, median percentage bare soil (17) was significantly greater ($\alpha = 0.05$) than for the reference plots (median = 3) for the sole vegetation type, mixed conifer, with an adequate sample size for statistical comparison. After high percentage bare soil during the first 3 years following seeding on the plantation plots, percentage bare soil decreased over the following decades to moderately high levels (median 10–20%) (Table 2).

Rills

The vast preponderance of rills observed were on young wildfire plots; very few of the fuel treatment plots exhibited rilling. A total of 6% of all survey plots were rilled, implying that surface erosion was relatively minor on the landscape scale even after high-severity wildfires.

Fires

Active rills were found on 9% (29 of 319) of plots that had burned. With one exception, the rilled wildfire plots had all burned 4 or less years before observation. The percentage of rilled plots decreased significantly with wildfire age through 4 years after fire (Fig. 2) and the percentage of rilled plots decreased in the first 4 years after burning for high-severity fires but remained relatively constant for moderate- and low-severity fires (Fig. 3).

Over 50% of the 21 high-severity 2-year-old wildfire plots were rilled, compared with 23 and 7% of the 2-year-old moderate and low-severity wildfire plots respectively (Fig. 3). Another three plots exhibited revegetating rills (two high-severity and one moderate-severity wildfire, all 3 years old). As a function of severity, the percentage of rilled plots decreased from high (16% of all high-severity plots were rilled) to moderate (9% rilled) to low (7% rilled) severity.

In 23 rilled wildfire plots revisited at least 1 year after the initial identification of rilling, the number of active and revegetating rills per plot decreased over time, suggesting that the recovery rate can be fairly rapid (Fig. 4). Fifteen of these plots

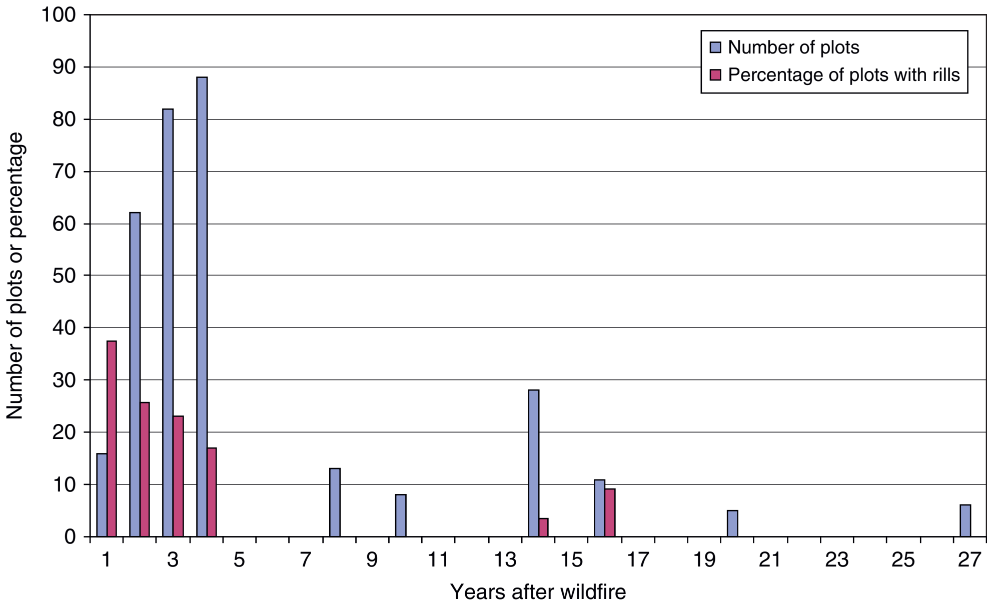

Fig. 2. Number of wildfire plots by years since burning and percentage of plots with rills.

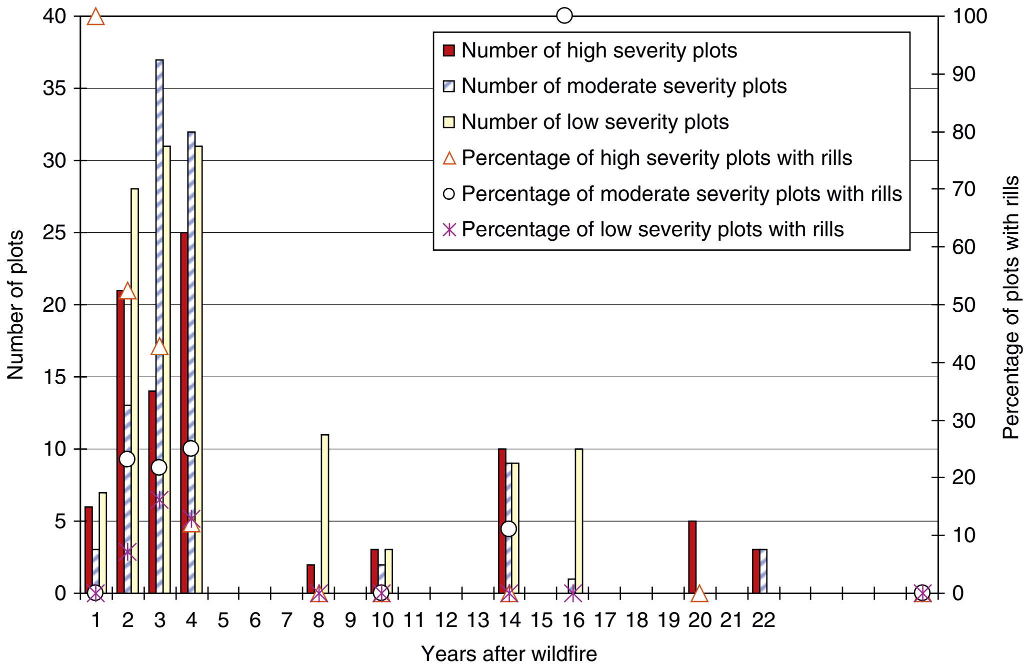

Fig. 3. Number of wildfire plots by years since burning and wildfire severity and percentage of rilled plots by severity and years after burning.

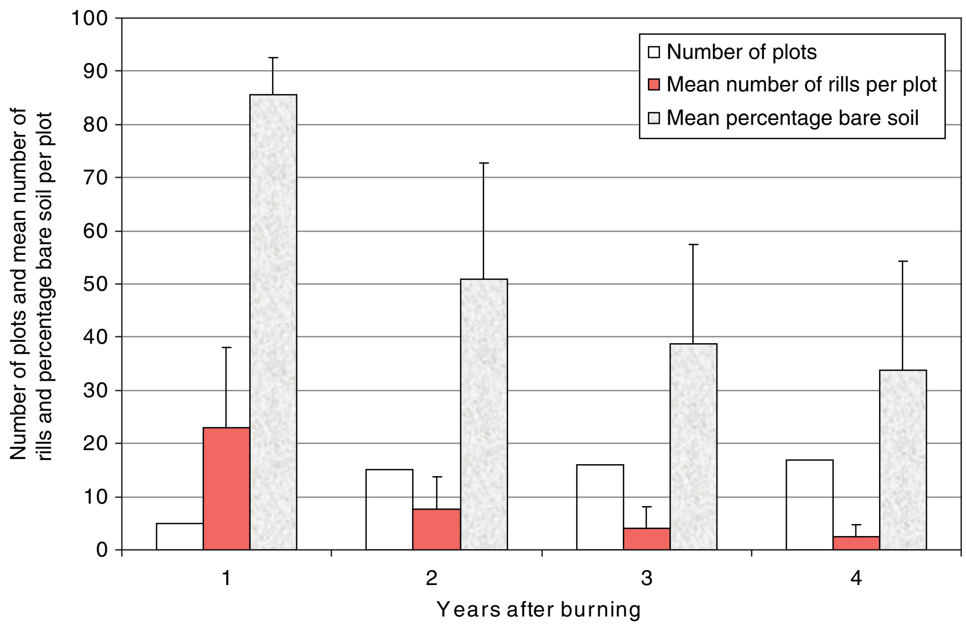

Fig. 4. Mean and standard deviation of rills and percentage bare soil per plot for plots surveyed in multiple years, for the first 4 years after wildfire. Five rills at 14 years and two rills at 16 years are not shown.

had active rills in both the second and third year, whereas seven had no rills after the second or third year of observations. Twenty-one of the 23 revisited plots had fewer rills in the second or third year of observation, and the median decrease in rill frequency was three rills per year.

The single rilled plot older than 4 years was initially surveyed in 2004, 14 years after the Stormy Complex fire. In 2006, rills were still clearly apparent on the Stormy Complex rilled plot, although the number of active rills dropped from five to two.

Other treatments

No rills were observed on the 101 plots on machine pile burn, machine pile, hand pile burn, hand pile, thinning, mastication or crushing plots. Rills were found on one 22-year-old prescribed burn, one 20-year-old plantation, and one 1-year-old broadcast burn plot. A second plantation plot (2 years old) had revegetating rills. Because so few rills were found on these treatments, quantitative assessments were not made for these treatment types.

Statistical models

The statistical assessments identified influential variables controlling rill occurrence but did not identify strong relationships between the independent and dependent variables. The best discriminant model incorporated age, slope, percentage bare soil and annual precipitation as independent variables predicting the presence of rills on the study plots. This model correctly classified over 99% of the plots without rills as not having rills but misclassified one-third of the plots with rills as not having rills. The logistical regressions identified percentage bare soil as reducing more of the residual deviation than any other independent variable. However, because an objective was to 'predict' rill occurrence, without on-site information, model development was restricted by not including percentage bare soil. The resulting discriminant and logistical regression models were less powerful but identified years after wildfire and slope as significant variables, in that order of importance.

Rilling and bare soil

Plots with high percentage bare soil value tended to have active rills also. All wildfire plots with bare soil values greater than 60% were rilled. The wildfire plots with rills had a median bare soil of 53%, compared with 13% for the non-rilled wildfire plots.

Where rilling occurred, rill frequency generally increased with increasing percentage bare soil (Fig. 5), and this relationship was largely independent of wildfire severity. If the one high-severity plot with 49 rills is excluded, maximum rill frequency per plot was bounded by mean percentage bare soil as the number of rills per plot = 0.24 × mean percentage bare soil, with $R^2 = 0.95$ (Fig. 5).

Percentage bare soil on rilled plots did not correlate highly with wildfire severity and years after wildfire. Bare soil value was very high (84%) on high-severity, 1-year-old wildfires, but otherwise bare soil vale ranged from 35 to 64% with years after wildfire and was not ordered by severity.

At rilled plots surveyed during 2 or more years, both mean percentage bare soil and the mean number of rills per survey plot decreased with time after wildfire (Fig. 4).

Discussion

Study design considerations

The 'space-for-time' focus of the study design allows collection of relevant data for a large number of study plots covering a wide range of values for the primary and ancillary variables associated with bare soil and rilling. In this sense, the space-for-time approach is effective. It does not, however, provide for direct measurement of surface erosion, nor does it provide pre-disturbance values for each specific study plot. By comparing percentage bare soil and rilling on disturbed *v.* reference plots, we followed well-established practice (USGS 2004; Lisle *et al.* 2007) and believe that our use of multiple reference plots for each vegetation type (e.g. 26 mixed-conifer reference plots) quantifies spatial variability of pre-disturbance conditions and is sufficient for statistical testing.

The study uses rilling as the direct measure of surface erosion. Rilling is common in the western United States but is not a good index of erosion in locations with little soil, extensive

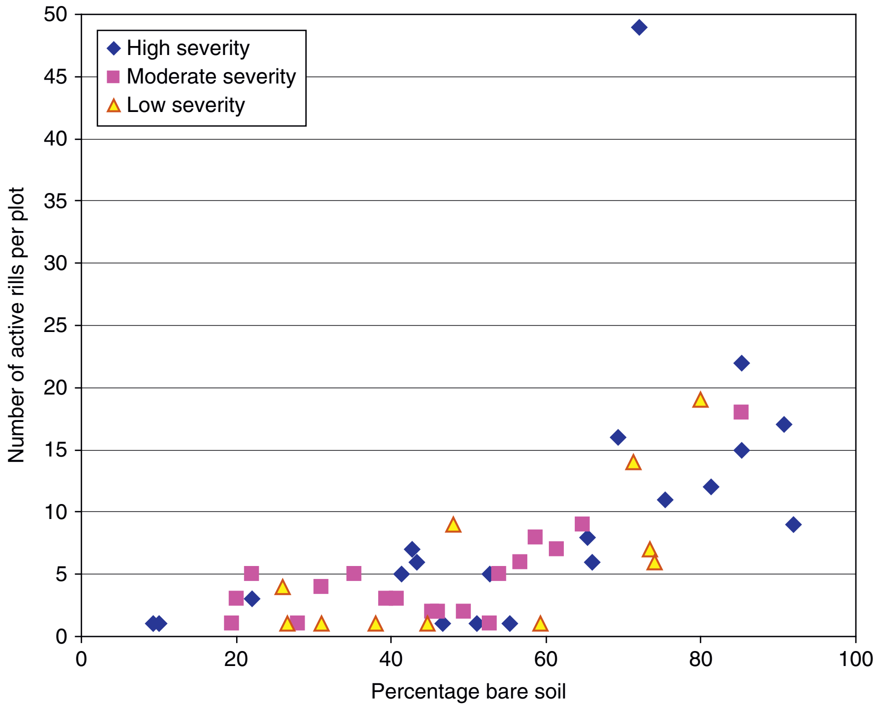

Fig. 5. Active rill frequency *v.* percentage bare soil and wildfire severity.

bedrock or boulder terrain. Consequently, this study design would not be applicable everywhere and our results are provisional in that surface erosion recovery in areas with different soil, climatic and physiographic regimes could differ.

Erosion is more directly related to ground-based fire severity than the canopy-based BAER classification, and canopy severity and the ground-based severity are not necessarily identical (e.g. a fast-moving, high-severity crown fire may not have a high ground severity). However, no other fire severity data were available before field activities and decisions on severity had to be made before the field work to allow randomisation in plot selection. Field assessment and revision of some of the *a priori* severity designations for younger wildfires potentially countered some of the potential limitations of the canopy-based severity classification.

Because there was little rilling on wildfire plots older than 4 years, it is tempting to conclude that rilling usually persists no longer than 4 years in the study area. For several reasons, this conclusion is tenuous. Only one of the four 4-year-old wildfires surveyed, the 60 466-ha McNally fire, had rills on the randomly chosen plots. However, on a second 4-year-old wildfire, minor patches of rilling were observed while moving between plots. Finally, although no 5-year-old wildfires were surveyed because none existed in the study area during the survey period, the particularly barren appearance (with high percentage bare soil) of some of the 4-year-old, high-severity McNally rilled plots suggested rilling would persist at those plots.

Some results of the statistical testing may not be as practically meaningful as others. Differences in median bare soil values below 10% are probably less relevant to erosion and erodibility than differences at higher percentages. For instance, the statistically significant bare soil value difference between broadcast burns (median = 5%) and reference (median = 3%) plots in conifer and mixed conifer vegetation is less practically relevant than the difference between plantations in conifer and mixed conifer (median = 17%) and references plots.

Plantations

Of the non-wildfire disturbances, plantations had appreciably more bare soil than the other forest treatments, and relatively high levels of percentage bare soil persisted through time. Both of these results suggest potential long-lasting concerns about erosion in plantations and further suggest that from an erosion perspective, plantations should be established at sites with a low susceptibility for erosion (e.g. with finer-textured soil, relatively low slopes, low rainfall intensity). The plantation plots were also distinctive in their heterogeneity of ground cover. Continuous needle mats up to several cm thick immediately beneath the conifer canopy commonly abutted large areas of bare soil. The bare soil areas appeared to be candidate locations for rilling, and 2 of the 14 plantation plots had either active or revegetating rills.

Rill dynamics

Although this study did not attempt to track the evolution of rills through time, at several plots surveyed in 3 successive years, vegetation was observed growing in the rills during the second and particularly the third year. At these plots, the original furrows could still be seen by the third year but they were densely revegetated in herbs and shrubs to the extent that without removal of the vegetation, mobilisation of surface material appeared to be very unlikely. This parallels research in Spain where herb and shrub vegetation (*v.* tree and dwarf shrub) reduced erosion and overland flow coefficients (Cerdá and Doerr 2005), and implies that revegetation was a significant factor in leading to rill dissolution. In contrast, lower-elevation, drier plots also surveyed in 3 successive years had rills that were bare and unvegetated during all years, and appeared as likely to transport soil material in the third year as in the first survey year.

The atypical presence of rills on a 14-year-old wildfire plot provides further information on rill evolution. Although the rilled area on this plot had relatively high slope (45%) and annual precipitation (103 cm), the soil type, slope aspect and other characteristics of the plot were well within the range of non-rilled plots of the same age, vegetation type and wildfire severity. The percentage bare soil of the rilled 14-year-old plot was, however, much higher (at 38%) than any other 14-year-old plot, suggesting that some mechanism was keeping substantial portions of the plot bare, and thereby by inference reducing revegetation of the rills. Rill evolution is probably a complex dynamic influenced strongly by soil moisture dynamics (Bryan *et al*. 1998), and driven partially by precipitation regime.

Implications to assessment of cumulative watershed effects

Concerns in Canada (e.g. Peterson *et al*. 1987; Duinker and Greig 2006), Australia (e.g. Walker 2006), the United States (e.g. Reid 1998; MacDonald 2000) and elsewhere on the effects of multiple activities over time or space (i.e. cumulative effects) usually include both natural and anthropogenic factors. In the assessment of cumulative watershed effects, the timing and magnitude of erosion recovery from wildfires is typically added to estimates of erosion caused by proposed land-management activities (e.g. fuel treatments, timber harvest, road building). High or long-lasting post-fire erosion can preclude logging or fuel treatments because the combined effect of the fire and anthropogenic-produced erosion is deemed too high. The present study suggests that for the southern Sierra Nevada study area, rilling is seldom evident beyond 4 years after wildfires and that consequently scheduling of management activities would not be 'limited' by fire-produced rilling more than 4 years after fire. The lack of rilling on the fuel treatment plots further suggests that fuel treatments do not add substantial cumulative effects, at least in terms of rilling. From a cumulative perspective, the slow recovery rate of plantations should be considered in consideration of management options. Substantial acreage in plantations, in combination with other slow-to-recover disturbances, could push for postponement of forest treatments or selection of low-impact treatments.

Comparison with findings elsewhere

The major results from this study support the findings of others (Benavides-Solorio 2003; MacDonald and Stednick 2003) that evidence of post-wildfire erosion decreases with time through the first several years after fire, and in documenting links between percentage bare soil and rilling. Our results also support findings by Cram *et al*. (2007) that light-to-moderate ground disturbance from mechanical thinning operations did not appreciably increase erosion over reference conditions. A relatively new finding from this study is the lack of rilling on plots treated for fuel reduction by mastication, crushing, and the machine and hand pile alternatives that use little or no fire. These results are not unexpected, as such treatments are designed to minimise post-treatment erosion, but in practice retaining a mulched litter layer or otherwise not leaving bare soil is probably critical in reducing erosion potential (Hatchett *et al*. 2006). To better understand the erosion potential of these types of treatments, detailed silt fence measurements, or rainfall simulation–erosion measurement studies aimed at quantifying erosion rates from these treatments are warranted, particularly at locations anticipated to be erosion-prone, such as zero-order basins on concave topography.

Some independent variables found to be important in research elsewhere, including plot elevation and soil erodibility, did not contribute significantly to the discriminant and logistic regression formulations. This may be due to the relatively small number of plots with rills (6%) in comparison with those without.

Summary and conclusions

Changes in percentage bare soil and rill frequency were quantified after wildfire and fuel treatments, and at reference sites on over 600 plots in the southern Sierra Nevada in California. Fuel treatments generated much less bare soil than recent wildfires, with bare soil values at the fuel treatments often less than at reference sites (median 4%). For low-, moderate-, and high-severity fires less than 4 years old, median bare soil value was 14, 14, and 34% respectively. Plantations were the only other disturbance type with high percentage bare soil (median 18%). Percentage bare soil at the wildfires decreased through time but remained relatively constant through time at the plantations.

Rilling also was largely limited to recent wildfires, and less than 4% of the rilled plots were on wildfires greater than 4 years old. The percentage of rilled plots decreased significantly with wildfire age through 4 years after fire, and rill frequency also decreased through time at most wildfire plots surveyed in multiple years. There was no rilling on reference plots or on any mastication, crushing, thinning, hand pile and machine pile fuel treatment plots, including those only 1 year old.

Rilling was correlated with percentage bare soil. All wildfire plots with bare soil values greater than 60% were rilled. The wildfire plots with rills had a median bare soil value of 53%, compared with 1% for the non-rilled wildfire plots.

In planning for future management activities on the Sequoia National Forest and parts of other forested locations in the southern Sierra Nevada, rilling should not be expected to typically extend more than 4 or 5 years after wildfires.

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