Forest Ecology and Management xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Frequency and characteristics of sediment delivery pathways from forest harvest units to streams

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ARTICLE INFO

Article history:
Received 21 June 2009
Received in revised form 21 September 2009
Accepted 23 September 2009

Keywords:
Sediment
Connectivity
Timber harvest
Skid trails
Streamside
Management zones
California

ABSTRACT

Timber harvest is typically the largest area of anthropogenic disturbance in forested watersheds, and harvested areas may generate from one to five times more erosion than undisturbed areas (Motha et al., 2003). When sediment from harvested areas reaches stream channels it can degrade water quality and aquatic habitat. Streamside management zones (SMZs) are often prescribed to minimize sediment delivery, but there is little information about sediment delivery through these zones. Hence the objectives of this study were to: (1) determine the frequency of sediment delivery pathways ("features") from timber harvest units; (2) measure the physical characteristics and connectivity of these features; and (3) develop models to predict the length and connectivity of features from harvest units to streams.

Nearly 200 harvest units with streamside management zones were assessed on four National Forests in the Sierra Nevada and Cascade Mountains of California. Only nineteen features were found below harvest units ranging in age from 2 to 18 years. Feature lengths ranged from 10 m to 220 m, and the length was significantly related to mean annual precipitation, cosine of the aspect, elevation, and hillslope gradient (R^2 = 64%, p = 0.004). Six of the nineteen features were connected to streams and five of the six connected features originated from skid trails. The results indicate that timber harvest alone rarely initiated large amounts of runoff and surface erosion, particularly when newer harvest practices were utilized. Sediment delivery from timber harvest may be further reduced by locating skid trails away from streams, maintaining high surface roughness downslope of water bars, and promptly decommissioning skid trails following harvest.

1. Introduction

Anthropogenic sediment sources on forested hillslopes include roads, skid trails, and timber harvest units (e.g., Megahan, 1972; Beschta, 1978; Croke et al., 1999; Barrett and Conroy, 2001; Motha et al., 2003). Most recent research has focused on roads (e.g., Luce and Black, 1999; Jones et al., 2000; Lane and Sheridan, 2002; Coe, 2006), but timber harvest units represent the largest areas of anthropogenic disturbance and can increase erosion rates by one to five times relative to undisturbed areas (Motha et al., 2003).

The delivery of overland flow and sediment from disturbed hillslopes contributes to cumulative effects such as an increase in the size of peak flows (e.g., Jones, 2000; MacDonald and Stednick, 2003), the alteration of channel morphology (Troendle and Olsen, 1994; Madej and Ozaki, 1998), degradation of aquatic habitat (Shaw and Richardson, 2001), reductions in reservoir storage, and increases in pollutant transport (EPA, 2003). The delivery of sediment from hillslope sources to the stream network and the watershed outlet has been defined as sediment connectivity (Bracken and Croke, 2007). Connectivity of hillslope sediment pathways can be in the form of sediment plumes when there is an excess of sediment relative to overland flow, or in the form of rills and gullies when the transport capacity is greater than the sediment load.

For this paper a rill was defined by having incised banks with no minimum depth. Gullies were defined as incised features greater than 30 cm deep or with a cross-sectional area larger than about 1000 cm^2. Rills, gullies, and sediment plumes are collectively described as features in this paper, and we use the term rills for both rills and gullies unless otherwise specified.

In recent years forest management techniques have been modified to minimize surface runoff, erosion, and connectivity. Skid trails are often designed to follow hillslope contours (Kreutzweiser and Capell, 2001). Streamside management zones (SMZs) are intended to provide vegetative roughness and maintain infiltration rates that can slow or absorb overland flow and filter sediment out of the overland flow before it reaches a stream or water body (Kreutzweiser and Capell, 2001; Hairsine et al., 2002).

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doi:10.1016/j.foreco.2009.09.038

Features can penetrate SMZs and thereby connect forest harvest units to streams (Lacey, 2000; Rivenbark and Jackson, 2004). In the Georgia Piedmont, USA, there was an average of one feature for every 20 acres of clearcut and site prepared land, and these were associated with convergent topography, steeper slopes, larger contributing areas, and less ground cover (Rivenbark and Jackson, 2004). In Australia 10-m wide buffer zones reduced the delivery of sediment from skid trails to streams by 95% (Lacey, 2000).

Measuring and modeling connectivity and sediment delivery are critical for quantifying and predicting the cumulative effects of timber harvest activities in forested watersheds (Bracken and Croke, 2007). The fieldwork described in this paper evaluated whether the areas disturbed by timber harvest and skid trails are connected to stream channels by rills and sediment plumes. The specific objectives were to: (1) determine the proportion of timber harvest units that generated rills or sediment plumes that penetrated at least 10 m into an adjacent SMZ; (2) measure the site characteristics, size, and connectivity of rills and plumes to stream channels; and (3) develop models to predict the length and connectivity of rills and sediment plumes originating from timber harvest units.

2. Study area

The study area included timber harvest units on the Eldorado, Lassen, Plumas, and Tahoe National Forests (NF) in the Sierra Nevada and Cascade mountains of California (Fig. 1). The area has a Mediterranean climate with moist air flows from the Pacific Ocean. The amount and type of precipitation is heavily influenced by the high elevations and rain shadow effect of the mountains so that mean annual precipitation ranges from as much as 2000 mm on the west side to as little as 370 mm on the east side (Teale GIS Solutions Group, 1997). Ninety-five percent of the precipitation occurs during the winter wet season, and above 1500 m the precipitation falls mostly as snow (USDA Forest Service, 1986). Summer convective thunderstorms are more frequent on the east side of the mountains than on the west side (USDA Forest Service, 1983).

Forests on the west side are composed primarily of ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), Douglas fir (*Pseudotsuga menziesii*), red fir (*Abies magnifica*), white fir (*Abies concolor*), and incense cedar (*Libocedrus decurrens*) (USDA Forest Service, 1983, 1986, 2002). The dominant understory shrubs are green leaf manzanita (*Arctostaphylos patula*), huckleberry oak (*Quercus vaccinifolia*), and mountain whitethorn (*Ceanothus cordulatus*). Forests on the drier east side consist primarily of ponderosa pine, Jeffrey pine (*Pinus jeffreyi*), and white fir, with some lodgepole pine (*Pinus contorta*), western juniper (*Juniperus occidentalis*), and black oak (*Quercus kelloggii*). Most forest harvest takes place on soils weathered from andesitic, granitic, and meta-sedimentary material (USDA Forest Service, 1983, 1986, 2002).

3. Methods

3.1. Data collection

The study was conducted on the four NFs shown in Fig. 1 because they have higher levels of timber harvest than the other eighteen NFs in Region 5 of the USDA Forest Service (USFS). Most of the recent timber management projects in these NFs tend to be larger-scale projects of about five hundred to several thousand hectares. Individual harvest units within these project areas average 15 ha with a general range of 1–80 ha (Tangenberg, USFS, pers. comm., 2008).

Harvest projects with erosion and sedimentation problems were identified by direct discussions with USFS personnel and querying the USFS Best Management Practices Evaluation Program (BMPEP) database (USDA Forest Service, 2004). The BMPEP

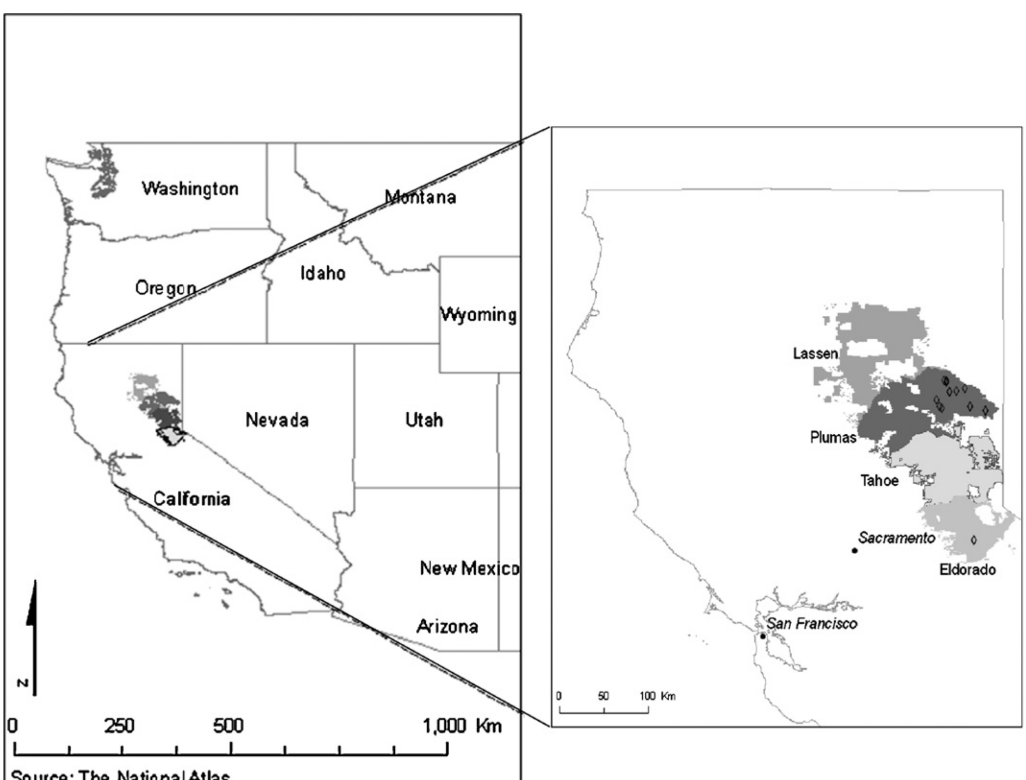

Fig. 1. Location of the four National Forests used to assess harvest unit connectivity. The open diamonds indicate the location of the rills and sediment plumes identified in this study. Given the coarse scale of this map, some diamonds represent multiple features that occurred in close proximity.

provides 29 standardized forms for USFS personnel to evaluate the effects of timber harvest, roads, grazing, mining, prescribed fires, recreation, and engineering on soils, runoff, erosion and streams. Data from about 3000 evaluations were available for this research. This approach to identifying harvest projects was used to increase the likelihood of finding rills and sediment plumes and thereby obtains an adequate sample size for modeling purposes. The resulting bias in data collection has minimal effect on the key findings and conclusions presented here.

Maps of each timber harvest project were obtained from the responsible NF and used to identify harvest units that were immediately upslope of SMZs. The lower edges of the selected harvest units were traversed on foot to identify all rills, gullies and sediment plumes entering SMZs. USFS policy requires 90-m wide SMZs along each side of perennial streams and 45-m wide SMZs along each side of all ephemeral and intermittent streams. Harvesting and machinery are not allowed within SMZs, although we did observe some vehicle tracks from heavy equipment and some skid trails crossing the SMZs.

A set of criteria was established to ensure that the erosional features being measured were only due to forest harvest activities. Post-fire salvage projects and harvest units that had burned were excluded because the effects of burning could not be separated from the effects of timber harvest. Features initiated by paved and unpaved roads were excluded; features initiated by skid trails were included. Features that ended at a road or that were extended by road drainage were excluded because we could not determine the length that a feature would have attained in the absence of the road. A minimum feature length of 10 m was used because this is the highest resolution of the digital elevation models (DEMs) being used to model cumulative watershed effects.

When a feature was found, the following data were obtained: years since harvest, mean annual precipitation (MAP), soil depth, soil erodibility (K), straight line and feature lengths, feature gradient, aspect, elevation, hillslope gradient, hillslope curvature, surface roughness, and whether or not the feature was connected. A feature was classified as connected if it extended to within 10 m of a stream channel, indicating that at least some runoff and sediment is likely to be delivered to the stream channel (Croke and Mockler, 2001). The focus on quantifying the frequency of connectivity between harvest units and streams does not necessarily mean that large amounts of runoff and sediment are being delivered or that water quality is likely to be impaired.

Years since harvest was determined from project documents or estimated from vegetation regrowth. MAP at 127 mm intervals was obtained from statewide data (Teale GIS Solutions Group, 1997) since not all NFs had isohyetal maps. Soil depth and erodibility were collected from the soil surveys for each NF. Harvest type was not available or necessarily obvious for every unit although units older than 10 years generally were clearcut and more recently harvested units were either thinned or subjected to group selection. Age of harvest was a more reliable variable in the statistical analysis than the estimated harvest type.

Feature length was measured with a flexible tape. Feature gradient was measured in the field using a clinometer and aspect was measured with a compass. The cosine of the aspect was used to convert degrees from circular (0–360°) to continuous form for statistical analysis. Elevation, hillslope gradient and curvature were derived from 10-m digital elevation models (DEMs) obtained from each NF. In the absence of a simple, quantitative measure, current surface roughness was classified into one of five qualitative categories as defined in Table 1. Current surface roughness was classified since past conditions could not be reliably determined. The drainage area that contributed to the feature was not determined because in many cases the contributing area could not be reliably identified due to the extensive regrowth, complexity of microtopography and skid trails, and subsequent disturbance by management activities.

Table 1
Description of the five classes used to qualitatively characterize the surface roughness along each of the rills and sediment plumes in this study.

Roughness class	Description
1	Bare mineral soil with little surface roughness.
2	Greater than 50% bare soil with no more than 1–2 short sections with rocks or slash.
3	Greater than 50% bare soil and more than two short sections with rocks or slash.
4	Less than 50% bare soil, and more than two short sections with rocks or slash.
5	Dense cover of vegetation or litter with extensive slash, rocks, or woody debris.

Each rill or sediment plume was divided into 10 m segments beginning at the upslope end. For each segment the gradient was measured with a clinometer and the surface roughness was estimated following Table 1. For twelve of the fifteen rills the mean width, mean depth, and maximum depth were measured for each rill segment. These values were averaged to obtain a mean width, mean depth, and mean maximum depth for each rill.

3.2. Data analysis

The dataset consisted of the independent variables characterizing the features and two response variables: feature length and connectivity class. Two-tailed *t*-tests were conducted to determine if the mean rill lengths were significantly different from the mean sediment plume lengths, and if there was a significant difference in mean gradients between rills and sediment plumes. Since the lengths and gradients were not significantly different by feature type, the features were grouped for subsequent analyses. A log transformation of feature lengths was used to obtain a more normal frequency distribution for parametric statistical analysis (Ott and Longnecker, 2001). Linear regression was used to assess the relationship between each independent variable and the log-transformed length. Associations between the independent variables were assessed using Spearman's rank correlation matrix as not all of the variables were normally distributed (Ott and Longnecker, 2001). Linear regression was used to determine whether the 10-m gradients along each feature varied with distance from the top of the feature.

The independent variables that were more strongly correlated with feature length were then used to develop a multivariate linear regression model to predict feature length. Model selection criteria were the adjusted R^2 and Mallow's $C(p)$ where $|C(p) - p|$ is closest to zero, with p being the number of parameters including the interception point (Ott and Longnecker, 2001). Partial R^2 values were calculated for each variable included in the models. Connectivity was modeled using Fisher's exact test.

4. Results

The lower boundaries of approximately 200 harvest units were surveyed. Only nineteen features were found, and these included fifteen rills or gullies and four sediment plumes (Table 2). Fourteen or seven percent of the harvest units had at least one rill or sediment plume entering the SMZ, and five of these 14 units had two features each. Sixteen of the nineteen features originated from skid trails.

The mean rill length was 43 m (S.D. = 54 m), and the range was from 11 m to 220 m (Table 2). The median rill length was only 22 m or 50% of the mean, indicating a highly skewed distribution. The median sediment plume length was 17 m (S.D. = 5 m), and the

Table 2
Mean and standard deviation (S.D.) of the characteristics of rills and sediment plumes. MAP is mean annual precipitation.

Feature ID	Rill or plume (R or P)	Total length (m)	Years since harvest	MAP (mm)	Connected (y/n)	Rill gradient (%)	Rill roughness	Aspect (°)	Soil erodibility (K)	Hillslope gradient (%)	Elevation (m)	Soil depth (m)	Sinuosity
Alder_1	R	80.0	18	1524	n	22	1	270	0.00	31	1785	0.51	1.20
Alder_2	R	68.0	18	1270	n	13	1	270	0.24	36	1756	1.14	1.41
Alder_3	R	220	18	1270	y	11	1	180	0.24	20	1750	1.14	1.31
Ant_1	R	22.0	2	635	n	26	2	250	0.23	13	1543	0.74	1.07
Ant_5	R	25.0	2	635	y	28	2	170	0.27	20	1590	0.88	1.10
BigC10_1	R	11.8	11	508	y	17	1	160	0.30	15	1747	0.87	1.11
Blak7_1	R	33.0	8	889	y	17	2	180	0.19	12	1815	1.41	1.07
Cate14_1	R	16.0	9	1016	n	18	1	0	0.18	5	1809	0.76	1.03
LC18_1	R	11.0	5	508	n	9	1	140	0.27	8	1763	1.46	1.05
Poison21_1	R	58.0	5	635	y	32	2	240	0.30	28	1698	0.87	1.12
Sieg53_1	R	11.6	4	508	n	29	2	70	0.33	29	1787	0.47	1.05
Spike2_1	R	11.8	3	762	y	12	2	225	0.27	11	1844	1.08	1.16
Spike9_1	R	29.6	11	762	n	14	3	300	0.27	11	1852	1.08	1.06
Verdi_1	R	18.3	10	762	n	14	3	220	0.00	10	1778	1.10	1.10
Ward_1	R	10.8	13	1016	n	36	2	0	0.27	29	1831	1.06	1.08
Mean		42	9	847		20	1.7	178	0.22	19	1757	1.0	1.13
S.D.		54	6	314		8	0.7	93	0.10	10	88	0.3	0.10
Ant_2	P	21.7	2	635	n	26	2	50	0.23	28	1546	0.74	1.03
Ant_3	P	19.1	2	635	n	30	3	50	0.23	32	1543	0.74	1.14
Ant_4	P	10.0	2	635	n	20	1	45	0.23	7	1536	0.74	1.05
BigC10_2	P	14.3	11	508	n	7	1	200	0.30	15	1749	0.87	1.16
Mean		16	4	603		21	1.8	86	0.25	21	1594	0.8	1.10
S.D.		5	5	64		10	1.0	76	0.04	12	104	0.1	0.06

lengths varied only from 10 m to 22 m (Table 2). The high variability in the rill lengths meant that there was no significant difference between the lengths of the rills and the lengths of the sediment plumes ($p = 0.093$).

Rills were generally small, as the median width was less than 50 cm and the median depth was only 5 cm (Table 3). The range of widths was from 15 cm to 355 cm, and the presence of several gullies resulted in an overall mean width of 90 cm (S.D. = 99 cm) and a mean maximum depth of 19 cm (S.D. = 27 cm) (Table 3). Rill depths were highly variable between and along rills so rill depth was not significantly related to rill width or rill length.

Hillslope gradient had little relationship to whether a feature was a rill or a sediment plume. The mean rill gradient was 20%, and rills occurred on hillslopes with gradients ranging from 9% to 36% (Table 2). The mean gradient for sediment plumes was 21% or nearly identical to the mean value for rills, and the plumes also occurred on hillslopes with a wide range of gradients (7–30%).

Table 3
Mean width, mean maximum depth, and mean depth for the rills and gullies. S.D. is standard deviation and N/A means the data are not available.

Feature name	Mean feature width (cm)	Mean maximum depth (cm)	Mean depth (cm)
Alder_1	355	93	47
Alder_2	117	13	6
Alder_3	177	47	24
Antelope_1	21	6	3
Antelope_5	N/A	N/A	N/A
BigC10_1	40	8	4
Blake7_1	N/A	N/A	N/A
Cate14_1	85	10	5
LowerC18_1	18	4	2
Poison21_1	34	3	2
Siegfried53_1	15	7	4
Spike2_1	25	2	2
Spike9_1	131	25	12
Verdi_1_2	58	10	6
Ward_1	N/A	N/A	N/A
Mean	90	19	10
S.D.	99	27	13

Feature gradients were generally similar to the hillslope gradients (Table 2). The lack of any significant differences between the rills and the sediment plumes in terms of their lengths, gradients, and hillslope gradients meant that these features were lumped for further analyses.

Log-transformed feature length increased significantly with MAP ($R^2 = 0.45$, $p = 0.002$; Fig. 2) and years since harvest Q1 ($R^2 = 0.34$, $p = 0.009$). The two longest features drove both of these relationships, as they were in an area with high MAP and on 18-year old clearcut units (Fig. 3). If these features are excluded, neither MAP nor years since harvest were significantly related to feature length.

Feature lengths tended to increase on steeper hillslopes, but this relationship was relatively weak ($R^2 = 0.15$, $p = 0.10$). All of the features were on hillslopes with low to moderate surface roughness (classes 1–3 in Table 1), as the mean surface roughness was 1.7–1.8 for both rills and sediment plumes (Table 2). Aspect, soil

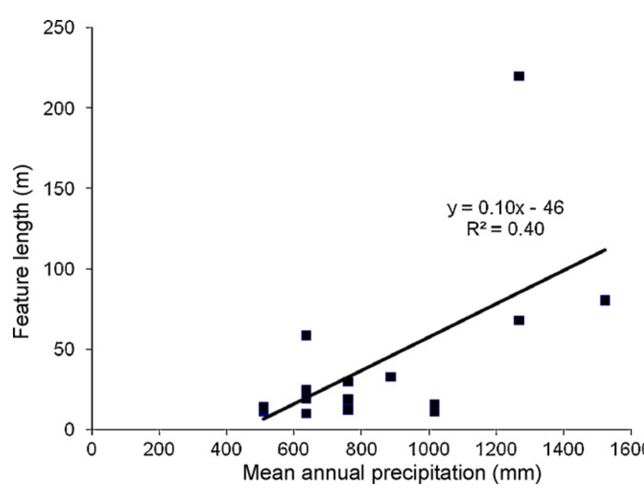

Fig. 2. Length of each rill and sediment plume plotted against mean annual precipitation.

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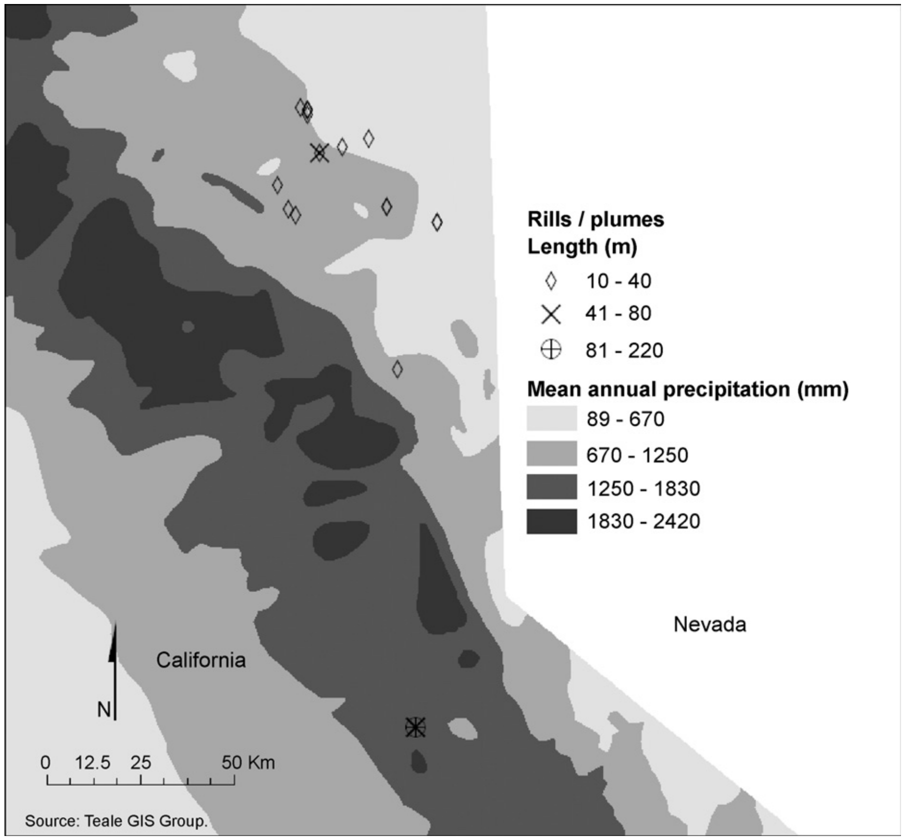

Fig. 3. Feature locations and mean annual precipitation. Given the scale of this map, one symbol may represent multiple features if they were all on the same or adjacent harvest units.

erodibility, soil depth, and the other independent variables were not significantly related to feature length.

The strongest correlations amongst the independent variables were the inverse relationship between MAP and soil erodibility ($r = -0.58$, $p = 0.01$), the inverse relationship between cosine (aspect) and soil depth ($r = -0.55$, $p = 0.01$), and the positive relationship between MAP and years since harvest ($r = 0.54$, $p = 0.02$) (Table 4). The inverse relationship between MAP and soil erodibility may be due to more dense vegetation in areas with higher MAP, as this would increase soil organic matter and permeability, and decrease surface runoff and erosion. The negative relationship between aspect and soil depth indicates that soils tended to be deeper on north-facing slopes.

The relationship between MAP and years since harvest was driven by the two longest features as noted above. MAP was weakly correlated with elevation for the fourteen sites with features ($r = 0.44$, $p = 0.06$) (Table 4). This weak relationship can be attributed to the confounding effect of the rain shadow on the eastern side of the Sierra Nevada, the relatively small range of elevations where the features were found (1536–1852 m), and the potential for the features to be formed by convective storms.

Table 4
Correlation matrix for the predictor variables with r values on top and p-values below. Significant relationships ($p < 0.05$) are in bold.

	Mean annual precipitation	Elevation	Slope	Soil depth	Soil erodibility	Cosine (aspect)	Rill roughness class
Age of harvest	**0.54** **0.02**	**0.51** **0.02**	0.21 0.40	0.38 0.11	0.02 0.95	−0.11 0.65	−0.39 0.10
Precipitation		0.44 0.06	0.15 0.54	0.26 0.27	−**0.58** **0.01**	0.08 0.74	−0.05 0.83
Elevation			−0.16 0.51	0.40 0.09	0.04 0.86	−0.04 0.87	0.13 0.60
Slope				−0.28 0.25	0.18 0.46	0.13 0.60	0.09 0.72
Soil depth					0.04 0.86	−**0.55** **0.01**	−0.02 0.93
Soil erodibility						−0.17 0.49	−0.05 0.84
Cosine (aspect)							0.08 0.75

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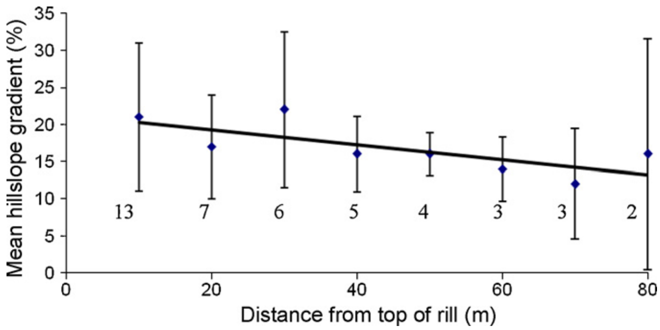

Fig. 4. Average hillslope gradients decreased with increasing distance from the top of the rills (R^2 = 0.54, p = 0.04). The bars show one standard deviation and the values below each bar represent the number of rills.

All of the independent variables that had at least a weak relationship with feature length were included in the multivariate model development. The best multivariate model for feature length (L) included MAP, hillslope gradient (S in m m^{-1}), cosine of the aspect (cos A), and elevation (E in m):

$$\log L = 1.852 + 0.0224 \times \text{MAP} + 0.0104 \times S - 0.2419 \times \cos A - 0.0007 \times E \quad (1)$$

This model had a R^2 of 0.64, a Mallow's C(p) of −0.06, and it was significant at p = 0.004. Partial R^2 values show that MAP explained 45% of the variability in feature length, followed by 9% for hillslope gradient, 7% for cosine (aspect), and 4% for elevation. The model tended to over-predict the length of shorter features and under-predict the length of longer features.

Hillslope gradients tended to decrease with distance from the top of the rills (R^2 = 54%; p = 0.03; Fig. 4). Rill width and rill depth did not show a strong, consistent relationship with the absolute or relative distance from the top of each rill. In some rills rocks, roots, or trees affected the size and shape of the rill, and the resulting abrupt changes in gradient and channel dimensions helped explain the lack of any consistent relationships between rill dimensions and the distance from the top of each rill.

Six of the fifteen rills and none of the sediment plumes were directly connected to the stream (Table 3). Five of the six connected rills originated from skid trails and the other connected rill originated from a clearcut. The connected rills ranged in length from 12 m to 220 m (Fig. 5), and the short lengths of four of the connected features indicate that these originated from skid trails in the SMZ.

Connectivity was not related to rill or hillslope gradient, as the connected rills were found on slopes ranging from 11% to 32%. The average length of connected features was 60 m as compared to 26 m for the unconnected features, but if the longest connected rill (220 m) is excluded, the mean length of the connected rills drops to 28 m, or nearly the same mean length as the unconnected features. Surprisingly, the connected features tended to occur in areas with lower MAP, as the MAP for the connected features was only 660 mm as compared to the MAP of 910 mm for the unconnected features, although this difference was not significant. Univariate analyses showed only weak relationships between connectivity and the independent variables of time since disturbance, soil erodibility, soil depth, elevation, and aspect. Efforts to predict connectivity by feature length, slope or other variables using Fisher's exact test were unsuccessful.

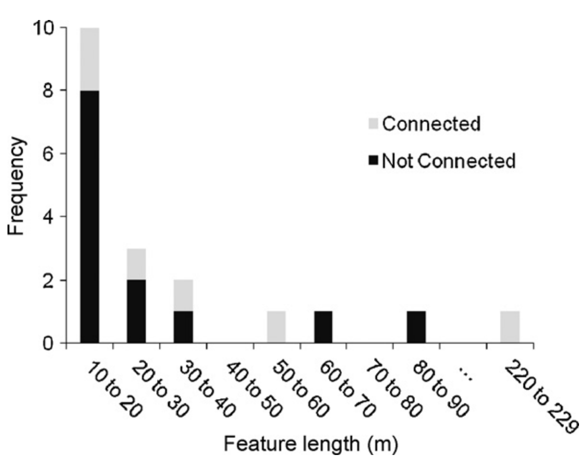

Fig. 5. Frequency and connectivity of features by length class.

5. Discussion

The source of each rill or sediment plume was either a water bar on a skid trail (n = 16) or a clearcut (n = 3), and this provides both insights into the causative processes and management implications. Like roads, skid trails are compacted relative to the adjacent areas, and the lower infiltration rate means that overland flow can be readily generated (Croke et al., 1999; Croke and Mockler, 2001; Ziegler et al., 2000; Lacey, 2000). This overland flow will increase erosion and sediment transport rates (Luce and Black, 1999; Coe, 2006), which is why water bars are required on steeper skid trails. More frequent water bars may be needed to reduce the area draining to each water bar. The resulting reduction in overland flow should reduce sediment production, and the likelihood of sediment being delivered to streams (Croke and Mockler, 2001; Coe, 2006).

Our field observations and the data both indicate that the concentrated flow from a skid trail and water bar was more likely to form a rill or sediment plume when the downslope area had low surface roughness. In some cases, tractor tracks or logs provided enough surface roughness to stop a rill from becoming deeper or longer. Sediment travel distance below water bars also can be reduced by the deposition and compaction of litter or slash to increase surface roughness (Ketcheson and Megahan, 1996). Key management implications are that the delivery of runoff and sediment to streams can be minimized by keeping skid trails out of the SMZ, increasing the frequency of water bars, and maximizing surface roughness.

Areas that have been clearcut with ground-based logging equipment also can generate overland flow and surface erosion. In recent years, the amount of clearcutting on federal lands has been greatly reduced due to the potential for adverse consequences on soils, water, plant and animal diversity, aesthetics, and recreation (Backiel and Gorte, 1992). A selection cut or thinning typically disturbs a smaller proportion of the harvest unit, and this will reduce the likelihood of overland flow and rill initiation. It is noteworthy that two of the three longest gullies came from an 18-year old clearcut with highly erodible, coarse-textured, granitic soils, a sparse grass cover with low surface roughness, and rocky outcrops that would readily generate infiltration-excess overland flow. The Forest Service has since mitigated the erosion at this site, and the implication is that older clearcuts should be checked for legacy features that may be generating and delivering sediment to streams. Such sites may need additional treatments to minimize surface runoff, surface erosion, and sediment delivery.

One of the more remarkable findings from this study is the small number of features identified by the field inspection of 200 harvest units. The increasing use and refinement of Best Management Practices (BMPs), plus the shift from clearcuts to thinning and group selection, can help explain the relative lack of rills and sediment plumes from harvest units on these four NFs.

Three of the four NFs in this study also fall within the area regulated by the 1998 Herger-Feinstein Quincy Library Group (HFQLG) Forest Recovery Act. This Act requires the retention of at least 50% of the forest canopy in the units being harvested, so the specified annual harvest of 13,000–29,000 ha (2–4% of the total Pilot Project area) is occurring through group selection, individual tree selection, or thinning (HFQLG Pilot Project Implementation Team, 2007). Both hydrologic modeling and paired watershed studies indicate that this type and intensity of timber harvest will have little or no effect on runoff at the watershed scale (Stednick, 1996; HFQLG Pilot Project Implementation Team, 2007). Since the remaining trees provide canopy cover, ground cover, and surface roughness, it should not be surprising that 84% of the rills and sediment plumes observed in this study originated from skid trails.

Most of the rills and sediment plumes were found on harvest units on the east side of the four NFs examined in this study (Fig. 3). These areas generally have lower MAP, but they are subject to higher-intensity summer convective storms (USDA Forest Service, 1983). Qualitative field observations indicated that the east-side harvest units had much less litter and ground cover than the wetter, west-side units. The multivariate model for feature length provides further evidence for the importance of surface cover, as the negative coefficient for cosine (aspect) indicates that the longer rills are associated with south-facing slopes. In this region the south-facing slopes are hotter and drier during the summer, and typically have less vegetation and litter than the sites with a north, east, or west aspect P. (Stancheff, Plumas National Forest, pers. comm., 2005). Less surface cover means that south-facing slopes are more susceptible to rainsplash and surface sealing (McIntyre, 1958; Fox and Le Bissonnais, 1998; Assouline, 2004; Larsen et al., 2009) and hence are more likely to generate infiltration-excess overland flow. A lower amount of surface cover also will reduce surface roughness, so runoff velocities will be higher and they will be more prone to surface erosion.

One caveat to the results of this study is the potential for underestimating the frequency of rills and sediment plumes as sites recover. In the Georgia Piedmont, USA, gullies associated with timber harvest filled in over one to two seasons (Rivenbark and Jackson, 2004). In Australia, skid trail erosion rates decreased by an order of magnitude by the fifth year after harvesting (Croke et al., 2001), and this would reduce the formation and persistence of rills and sediment plumes. To more accurately characterize and understand the connectivity of harvest units to streams, studies should begin immediately after harvest. Initiating a study immediately after harvest would make it easier to define the contributing area using either high resolution DEMs or field surveys. At least in our area, field studies also are necessary to determine the relative importance of rock outcrops, as these may be even more important for rill formation than contributing area.

These types of field studies should continue for several years in order to account for the effect of more extreme storm events. Studies over multiple years also will allow an evaluation of the rate at which rills and plumes recover over time and the effect of dynamic factors, such as vegetation regrowth, on feature development, length, and connectivity (Dudziak, 1974). This longer-term monitoring is essential for understanding the extent to which rills and sediment plumes can deliver runoff and sediment from forest harvest units to streams.

6. Conclusions

This study investigated the frequency of rills and sediment plumes emanating from timber harvest units and their connectivity to streams. The downslope edges of approximately two hundred harvest units on four National Forests were traversed in the Sierra Nevada and Cascade mountains of California. A total of fifteen rills and four sediment plumes were found downslope of fourteen timber harvest units. The mean length was 36 m, and the maximum feature length of 220 m occurred in an 18-year old clearcut with low surface roughness. Only six of the rills and none of the sediment plumes were connected to streams.

Sixteen of the nineteen features originated from skid trails, and the other three features originated in older clearcuts with very coarse soils and sparse vegetative cover. The majority of the features were found in drier areas, and this suggests that surface cover and surface roughness are important controls on the development of these features. Multivariate analysis showed that feature length increased with mean annual precipitation, years since harvest, cosine (aspect), and hillslope gradient ($R^2 = 0.64$). The downslope progression of features was often stopped by the presence of organic matter and surface roughness such as litter, logging slash, woody debris and bumpy microtopography.

The results indicate that the proper construction and post-harvest treatment of skid trails is critical for reducing the delivery of concentrated flow and sediment from timber harvest units to streams. The likelihood of sediment delivery from harvested areas can be greatly reduced by constructing more water bars along the skid trails to reduce the amount of concentrated flow at any one point; ripping the skid trail after harvesting to maximize infiltration; and ensuring that the hillslope below the water bar has as much surface roughness as possible. The limited number of features found in this study suggests that current forest harvest procedures and Best Management Practices are largely effective in reducing rilling and sediment delivery.

Acknowledgments

The authors are grateful to Brian Staab and Region 5 of the US Forest Service for providing the funding for this research. We also want to thank Bob Schultz, Christine Mai, Chuck Mitchell, and all of the other Forest Service personnel who provided information, maps, and bear stories. We are also grateful to Drew Coe and the two anonymous reviewers of this paper for their helpful comments.

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